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Quartz cementation in Cambrian sandstones on the background of their burial history (Polish part of the East European Craton)

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Cathodoluminescence (CL) study detected presence of two phases of quartz cement. Comparison of total subsidence curves with established crystallization temperature of quartz cement, and with thermal palaeogradient indicated that the main stage (second phase) of silicification began during Silurian at the depth of approximately 2 km. This process took place in the temperature range of 90–130°C.

INTRODUCTION

Because of high hydrocarbon potential of Cambrian in the Polish part of the East European Craton (Fig. 1) diagenetic processes in these rocks since many years have been a subject of interest for petroleum geologists and petrologists (W. K. Rydzewska, 1975; J. Łabęcki, 1992; M. Sikorska, 1992, 1994, 1996; M. Schleicher, 1994; F. Stolarczyk *et al.*, 1997).

A degree of diagenesis, in this case predominantly intensity of silicification, is the main factor influencing their porosity. Second, equally important factor, is the depth of burial of these rocks. Both these factors are changing in the area being a subject of this study. Current burial depth and degree of silicification are decreasing from SW towards NE.

GEOLOGICAL SETTING

Cambrian sediments comprise lower part of the sedimentary cover of the west part of the East European Craton. They are underlied by Archaean and Proterozoic igneous/metamorphic basement as well as by the Neoproterozoic sediments.

The thickness of Cambrian sediments ranges from 900 m in the western marginal part of the area to 200–300 m in the eastern portion. As a result of epeirogenic movements the Polish part of the East European Craton was divided into several structural units (Fig. 1) differing in the Cambrian sedimentation style. The most complete section, including Lower, Middle and Upper Cambrian, occurs in the west part of Peribaltic Syneclise. In the east part of the syneclise the upper portion of the Middle Cambrian as well as the Upper Cambrian are not developed. Upper Cambrian is also not developed in the Podlasie Depression and in the Lublin Slope of the Craton.

Cambrian clastic sediments are developed as interbedded sandstones, mudstones and claystones deposited on the shelf of a shallow epicontinental sea. The sandstones were formed in a high-energy tidal environment influenced by storms and are texturally mature to supermature.

Cambrian sandstones consist predominantly of fine- and very fine-grained, well to moderately sorted and well to very well rounded quartz arenites. Framework consists almost exclusively of monocrystallic quartz. Feldspar, micas, cherts and heavy minerals comprise together less than 5% of the rock content. The dominant cement consists of quartz forming syntaxial overgrowths. The sandstones contain also carbonate and clay cement as well as detrital clay matrix.

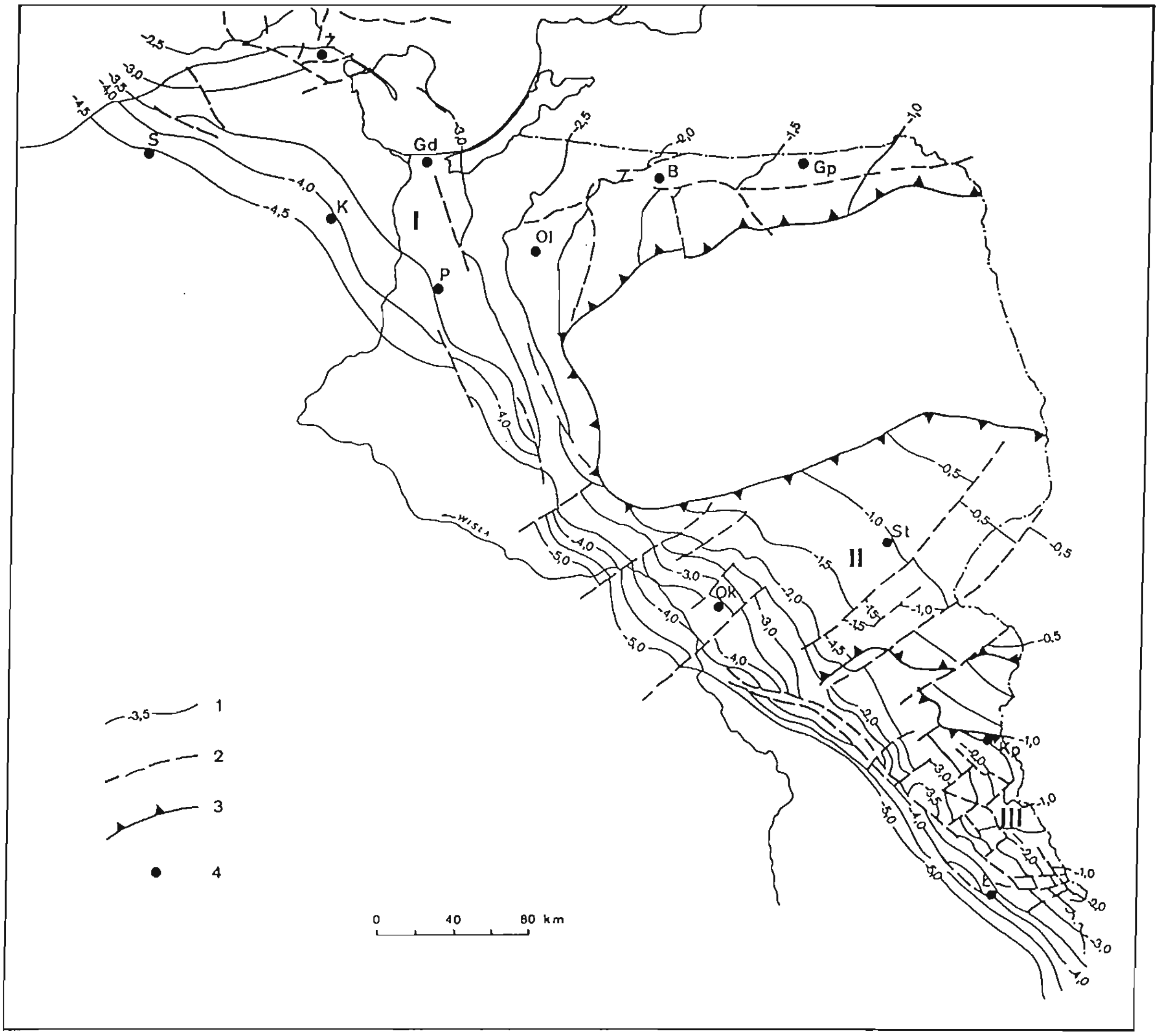

Fig. 1. Structural sketch of the top of Cambrian (based on structural map of Cambrian — Z. Modliński, A. M. Żelichowski, 1990)

1 — isohypses of the top of Cambrian in km b.s.l.; 2 — more important faults; 3 — recent extent of Cambrian sediments; 4 — boreholes: S — Słupsk IG 1, K — Kościerzyna IG 1, Ż — Żarnowiec IG 1, Gd — Gdańsk IG 1, P — Prabuty IG 1, Ol — Olsztyn IG 2, B — Bartoszyce IG 1, Gp — Gołdap IG 1, Ok — Okuniew IG 1, St — Stadniki IG 1, Kp — Kaplonosy IG 1, Ł — Łopiennik IG 1; I — Peribaltic Syneclise, II — Podlasie Depression, III — Lublin Slope of the Craton

Szkic strukturalny stropu kambru (na podstawie mapy strukturalnej kambru Z. Modlińskiego i A. M. Żelichowskiego, 1990)

1 — izohipsy stropu kambru w km p.p.m.; 2 — ważniejsze strefy uskokowe; 3 — obecny zasięg osadów kambru; 4 — otwory wiertnicze (objaśnienia jak w języku angielskim); I — synekliza perybałtycka, II — obniżenie podlaskie, III — lubelski skłon platformy

QUARTZ CEMENTATION

Tracing development of quartz cementation is difficult. Standard microscopic observations indicate that quartz overgrowths occur in almost all studied quartz arenites. The amount of quartz cement, however, clearly decreases from SW to NE, which is consistent with the decreasing depth of investigated rocks. Relationship between porosity of Cambrian rocks (microscope and laboratory measured) and the depth of their burial is presented in Figure 2. As it can be seen, initially, during gradual burial of sediment, the decrease in porosity was slow. Rapid decrease of porosity took place at the depth of 2500–3000 m and to the depth of 5000 m is not higher than an average of 1%. Opposite happens with quartz cement which increases in amount with depth (Fig. 3). It is clear that porosity and therefore also reservoir property of the Cambrian sandstones are closely related to the depth of burial of these rocks as well as to the intensity of their silicification.

Scanning microscope study indicates a gradual filling of pore space by authigenic quartz overgrowths (Pl. I, Figs. 8–11). In deeply buried sandstones the final result of this process is complete closure of pores.

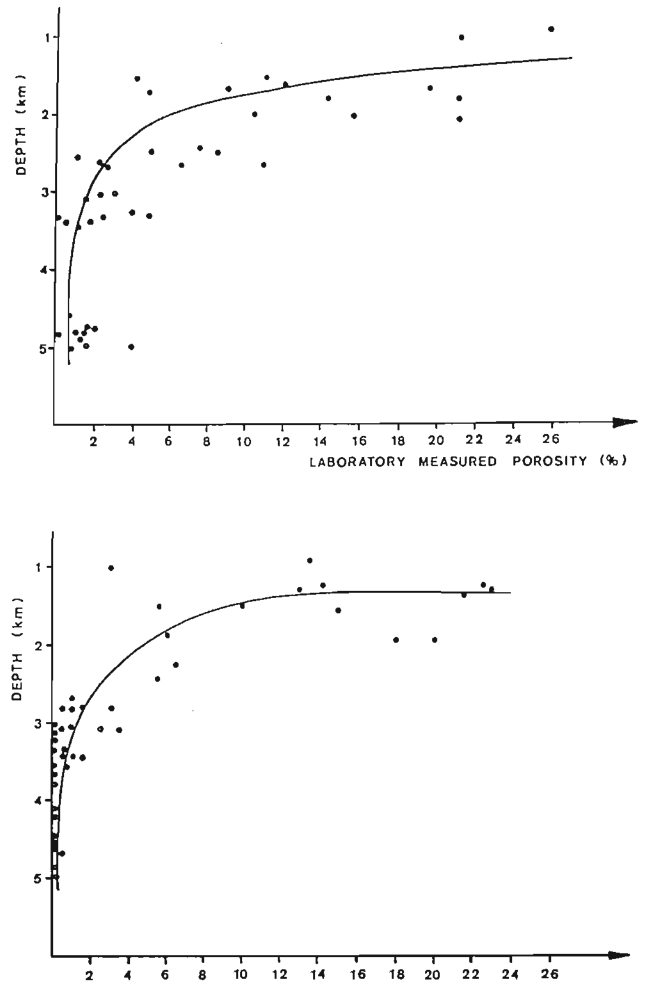

Fig. 2. Relation between porosity (above: laboratory measured, below: microscope measured) and the depth

Zależność porowatości piaskowców mierzonej laboratoryjnie i mikroskopowo od głębokości

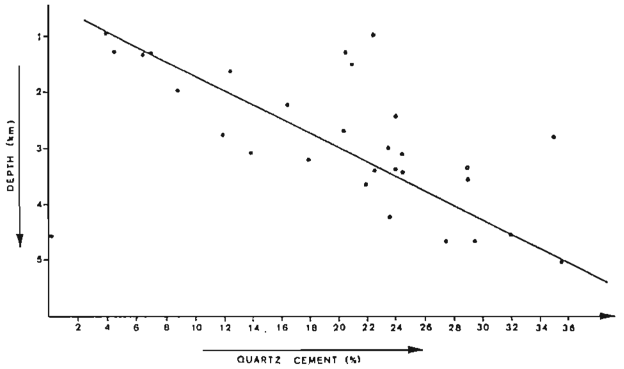

Fig. 3. Relation between quartz cement content and the depth

Zależność zawartości cementu kwarcowego w piaskowcach od głębokości

Cathodoluminescence (CL) study provided new data on silicification. Two phases of development of quartz cement were detected on some CL images (Pl. II, Figs. 12, 13): older, with brown luminescence and younger — nonluminescent, which is black. The older phase occurs as minute fragmental growths and does not form continuous overgrowths. It appears, that the first phase of silicification developed early and was related to influx of meteoric water during break of sedimentation (in the upper part of Middle Cambrian), as well as to expelling of formational water resulting from mechanical compaction. The source of silica for the second, main silicification phase, which took place during deep diagenesis, were probably changes in clay minerals (transformation of smectite into illite) in interbedded shales, dissolution of feldspars, replacement of quartz and feldspar by carbonates, as well as pressure solution of detrital quartz along stylolites and grain contacts.

Microthermometric study of fluid inclusions in quartz cement conducted by K. Jarmołowicz-Szulc (*fide* M. Sikorska, 1996) showed that quartz overgrowths formed at the temperature range of 90–130°C. This temperature range refers to the second, nonluminescent phase of silicification. There is also some correlation between homogenization temperature of fluid inclusions and the depth of rock samples. On the basis of the above presented data on approximate timing of quartz cementation can be deducted. To achieve this curves of cumulative thickness of deposits, reflecting changes of the burial depth of Cambrian sediments during their geological past, need to be constructed.

TOTAL SUBSIDENCE CURVES

Curves of cumulative thickness of deposits representing total subsidence of the bottom of Cambrian were constructed according to method described by J. E. van Hinte (1978) and A. J. Witkowski (1989).

The horizontal axis represents a linear time scale and shows chronostratigraphic divisions after J. W. Cowie and M. G. Bassett (1989). The vertical axis reflects cumulative thickness of deposits. The total subsidence curves provided sufficient data to determine timing and depth of quartz cementation process. Corrections for decompaction and palaeobathymetry factors were not necessary in this case. The initial data for construction of total subsidence curves were stratigraphic profiles from drilling documentations as well as lithofacial-thickness and structural maps.

The total subsidence curves were constructed for 12 stratigraphic profiles located in the following parts of the studied area (Fig. 1): Peribaltic Syneclise (Słupsk IG 1, Kościerzyna IG 1, Żarnowiec IG 1, Gdańsk IG 1, Prabuty IG 1, Olsztyn IG 2, Bartoszyce IG 1 and Gołdap IG 1); Podlasie Depression (Okuniew IG 1 and Stadniki IG 1) and Lublin Slope of the Craton (Kaplonosy IG 1 and Łopiennik IG 1). It appeared that the curves constructed have a differing shape which depends

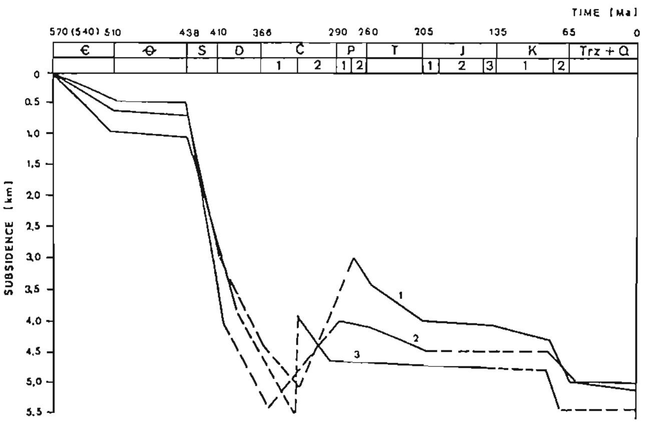

Fig. 4. Total subsidence curves of the bottom of Lower Cambrian for stratigraphic sections

1 — Kościerzyna IG 1, 2 — Słupsk IG 1, 3 — Łopiennik IG 1; broken line — interpreted subsidence

Zestawienie krzywych subsydencji ogólnej spągu kambru dolnego dla profili stratygraficznych

1 — Kościerzyna IG 1, 2 — Słupsk IG 1, 3 — Łopiennik IG 1; linia przerywana — subsydencja interpretowana

on the increasing distance from Teisseyre-Tornquist (T-T) zone. The subsidence curves can be divided into three groups including three different regions:

— area along the T-T zone with the largest (about 4000–5000 m) subsidence during Silurian–Devonian and substantial elevation (to the depth of approximately 2500–3500 m) of Cambrian sediments during the Carboniferous–Permian inversion (Fig. 4);

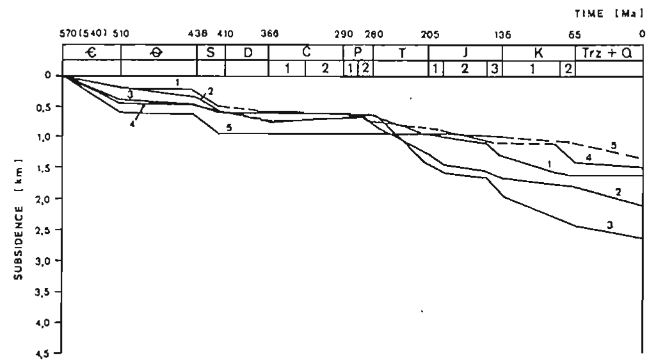

Fig. 6. Total subsidence curves of the bottom of Lower Cambrian for stratigraphic sections

1 — Gołdap IG 1, 2 — Bartoszyce IG 1, 3 — Olsztyn IG 2, 4 — Stadniki IG 1, 5 — Kaplonosy IG 1; other explanations as in Fig. 4

Zestawienie krzywych subsydencji ogólnej spągu kambru dolnego dla profili stratygraficznych

1 — Gołdap IG 1, 2 — Bartoszyce IG 1, 3 — Olsztyn IG 2, 4 — Stadniki IG 1, 5 — Kaplonosy IG 1; pozostałe objaśnienia patrz fig. 4

— zone parallel to the previous but located further east; here the Silurian–Devonian subsidence was weaker (about 2000 m) and the Carboniferous–Permian inversion lifted Cambrian sediments to the depth of approximately 1000–1500 m (Fig. 5);

— eastern area, where the Silurian–Devonian subsidence was not significant (around 500 m) and land conditions dominated during Carboniferous–Permian (Fig. 6).

DISCUSSION AND RESULTS

Diversified picture of the burial history of Cambrian sediments indicates that diagenetic processes were taking place in varying conditions. In the first zone, where subsidence was the largest, the burial process of sandy sediments with high primary porosity was fast. Such high porosity was preserved due to early stabilization of the framework during the first stage of silicification. Second important factor, apart from the rate of subsidence, was a maximum depth of burial which had a direct influence on the temperature of rocks and therefore also on the rate and direction of the diagenetic processes. Varying shapes of the subsidence curves show that the maximum temperatures under which diagenetic processes took place were different in different regions.

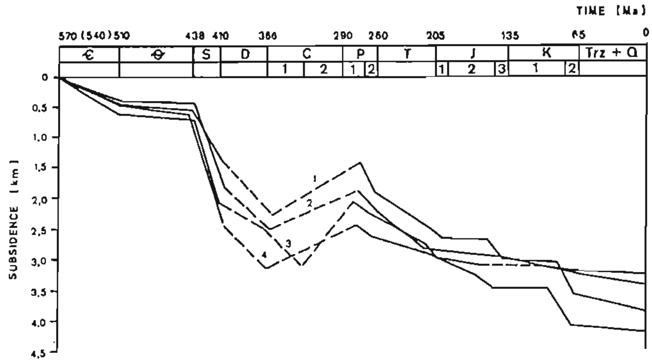

Fig. 5. Total subsidence curves of the bottom of Lower Cambrian for stratigraphic sections

1 — Prabuty IG 1, 2 — Gdańsk IG 1, 3 — Okuniew IG 1, 4 — Żarnowiec IG 1; other explanations as in Fig. 4

Zestawienie krzywych subsydencji ogólnej spągu kambru dolnego dla profili stratygraficznych

1 — Prabuty IG 1, 2 — Gdańsk IG 1, 3 — Okuniew IG 1, 4 — Żarnowiec IG 1; pozostałe objaśnienia patrz fig. 4

To establish the maximum palaeotemperatures of the Cambrian rocks during various geological periods an attempt was made to estimate thermal palaeogradient. Such gradient was, no doubt, higher than recently (S. Depowski, J. Majorowicz, 1979; A. J. Witkowski, 1989). Current thermal gradient on the East European Craton ranges from 15 to 30°C/km. The question arises how much higher were these values during Cambrian. An important information on this subject can be obtained by analysing vitrinite reflectance (R_o) (E. Swadowska, 1996). If the relation between vitrinite reflectance and the depth is modified by substituting values of R_o for the related

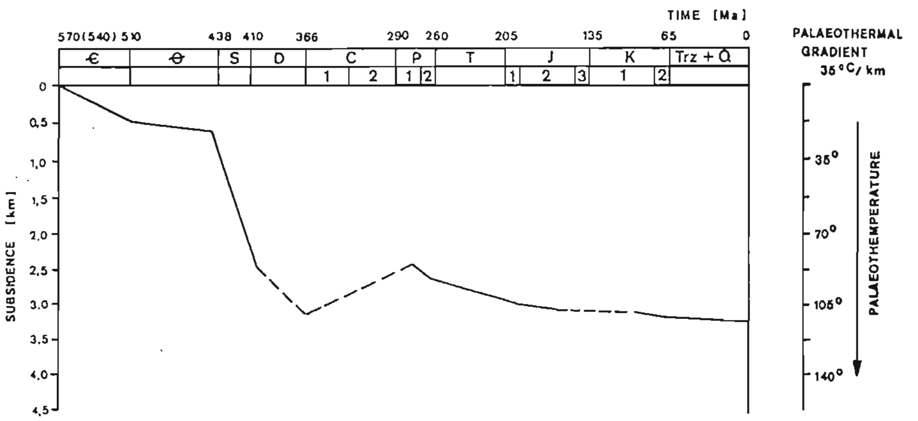

Fig. 7. Total subsidence curve of the bottom of Lower Cambrian with palaeotemperatures for stratigraphic section Żarnowiec IG 1
Broken line — interpreted subsidence

Krzywa subsydencji ogólnej spągu kambru dolnego wraz z paleotemperaturami dla profilu stratygraficznego Żarnowiec IG 1
Linia przerywana — subsydencja interpretowana

temperatures, then an approximate value of thermal palaeogradient during Cambrian can be worked out. Using the above method it was established that in the area adjacent to the T-T zone (first and partly second area) the maximum palaeogradient was 40°C/km. This value, although high, is similar to maximum palaeogradients for Cambrian accepted by other authors (J. Majorowicz *et al.*, 1983; A. P. Brangulis *et al.*, 1993). The difference between the recent and Cambrian palaeogradients (30 and 40°C/km, respectively) is therefore 10°C/km. Using this indication (a value 10°C/km higher than the recent geothermal gradient) palaeogradient was applied to each profile. This allowed to add a palaeotemperature scale to the total subsidence curves (Fig. 7). Due to such application supported by data on temperature of silicification and oil generation, the depth and timing of both these processes could be established.

In the case of quartz cement (second phase) the crystallization temperature was 90–130°C which allows to assume that the main silicification phase commenced during Silurian at the depth of about 2 km and still continued in Devonian. It means that in the area of borehole Żarnowiec IG 1 (Fig. 7), where presence of oil was detected, quartz cementation and migration of hydrocarbons took place generally in the same time. Such conclusion is in accordance with the results of fluorescence study of fluid inclusions (K. Jarmołowicz-Szulc *fide* M. Sikorska, 1996) which indicated characteristic fluorescence of hydrocarbon inclusions hosted by quartz cement.

Microscopic observations also showed that traces of hydrocarbons are present on the surfaces of detrital grains, in neogenic pores (on quartz overgrowths) and in microcracks cutting detrital grains together with quartz cement which suggests that migration took place several times.

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CEMENTACJA KWARCOWA W PIASKOWCACH KAMBRYJSKICH NA TLE HISTORII ICH POGRZEBANIA (POLSKA CZĘŚĆ PLATFORMY WSCHODNIOEUROPEJSKIEJ)

Streszczenie

Piaskowce kambryjskie w polskiej części platformy wschodnioeuropejskiej charakteryzują się intensywną cementacją kwarcową. Na wschodnich krańcach badanego obszaru sylifikacja była zdecydowanie najsłabsza. Proces ten odegrał negatywną rolę w kształtowaniu własności kolektorskich badanych skał. Na podstawie badań katodoluminescencyjnych ustalono, że sylifikacja odbywała się w dwóch fazach. Pierwsza z nich miała miejsce prawdopodobnie we wczesnym etapie diagenezy. Źródłem krzemionki mogły być wody meteoryczne penetrujące osady w czasie przerwy sedymentacyjnej (górna część kambru środkowego) jak również wody formacyjne wyciskane z osadów ilastych w czasie kompakcji mechanicznej. Pierwsza faza krystalizacji cementu kwarcowego nie była zbyt intensywna, ale na tyle ustabilizowała szkielet ziarnowy piaskowców, że mogły być one później głęboko pogrążone, zachowując jednocześnie porowatość międzyziarnową.

Z kształtu krzywych subsydencji ogólnej wynika, że utwory kambryjskie uległy zróżnicowanej subsydencji sylursko-dewońskiej. Najbardziej pogrążony został obszar przylegający do strefy Teisseyre'a-Tornquista, zaś dalej na wschód subsydencja była coraz słabsza (fig. 6–8). Na obszarach, gdzie skały pogrążone były na głębokości co najmniej 2 km i osiągnęły temperatury w zakresie 90–130°C, miała miejsce druga, zasadnicza faza sylifikacji. Na tego rzędu temperatury krystalizacji cementu kwarcowego wskazują pomiary temperatury homogenizacji inkluzji fluidalnych obecnych w regeneracyjnych obwódkach kwarcowych. W czasie subsydencji skały kambryjskie poddane były oddziaływaniu temperatury 90–130°C na głębokości ok. 2 km, co wskazuje, że druga, główna faza sylifikacji rozpoczęła się w sylurze i trwała nadal w dewonie. Źródłem krzemionki w drugiej fazie cementacji kwarcowej były prawdopodobnie przeobrażenia minerałów ilastych (smektytu w illit), zastępowanie kwarcu i skaleni przez węglany oraz procesy rozpuszczania pod wpływem ciśnienia nadkładu (na kontaktach ziarn i wzdłuż szwów stylolitowych).

EXPLANATIONS OF PLATES

PLATE I

Fig. 8. Sandstone weakly cemented by quartz overgrowths; authigenic quartz overgrowths in intergranular pores result in automorphic form of grains; Stadniki IG 1, depth 1239.6 m; SEM; scale bar — 0.1 mm

Piaskowiec słabo scementowany regeneracyjnym kwarcem; w wolnych przestrzeniach międzyziarnowych autigeniczne obwódki kwarcowe nadają ziarnom postać automorficzną; Stadniki IG 1, głęb. 1239,6 m; SEM; długość skali — 0,1 mm

Fig. 9. Sandstone strongly cemented by quartz overgrowths; no intergranular porosity; Łopiennik IG 1, depth 4536.3 m; SEM; scale bar — 0.1 mm

Piaskowiec bardzo silnie scementowany kwarcem regeneracyjnym; brak porowatości międzyziarnowej; Łopiennik IG 1, głęb. 4536,3 m; SEM; długość skali — 0,1 mm

Fig. 10. Quartz overgrowths partly filling pore space (p); Żarnowiec IG 1, depth 2717.3 m; SEM; scale bar — 0.01 mm

Kwarc regeneracyjny wypełniający częściowo przestrzeń porową (p); Żarnowiec IG 1, głęb. 2717,3 m; SEM; długość skali — 0,01 mm

Fig. 11. Quartz overgrowths completely filling pore space; overgrowths growing opposite to each other naturally adjust forming compromise boundaries; Łopiennik IG 1, depth 4465.6 m; SEM; scale bar — 0.01 mm

Kwarc regeneracyjny wypełniający całkowicie przestrzeń porową; wzrastające naprzeciw obwódki regeneracyjne dopasowują się wzajemnie tworząc kompromisowe granice; Łopiennik IG 1, głęb. 4465,6 m; SEM; długość skali — 0,01 mm

PLATE II

Fig. 12. Sandstone grains cemented by quartz overgrowths; ankerite cement (c) can also be seen; Prabuty IG 1, depth 3559.0 m; transmittent light; scale bar — 0.2 mm

Ziarna piaskowca zcementowane kwarcem regeneracyjnym; widoczny cement ankerytowy (c); Prabuty IG 1, głęb. 3559,0 m; światło przechodzące; długość skali — 0,2 mm

Fig. 13. Cathodoluminescence image (CL) of the same area as in Figure 12; primary sandstone texture and two generations of quartz cement can be seen: I — brown luminescence, II — nonluminescent; ankerite (c) does not show luminescence

Ten sam fragment płytki cienkiej jak na figurze 12 — obraz katodoluminescencyjny (CL); widoczna pierwotna tekstura piaskowca oraz dwie generacje cementu kwarcowego: I — brązowa barwa luminescencji, II — brak luminescencji; ankeryt (c) nie wykazujący luminescencji

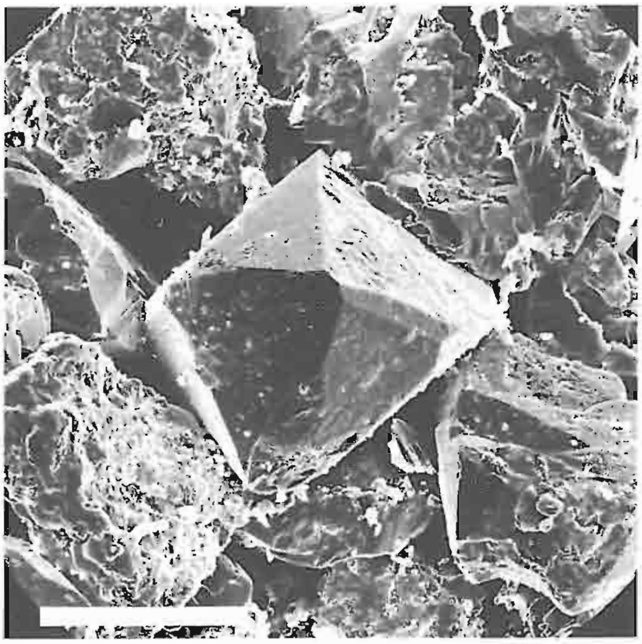

Fig. 8

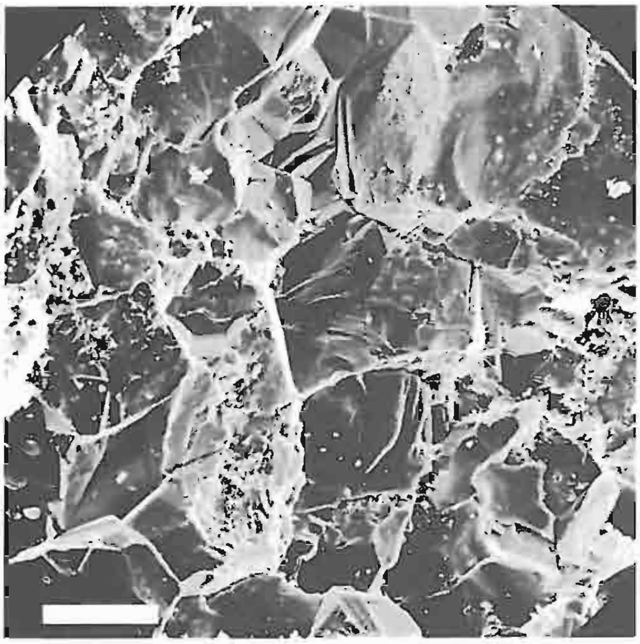

Fig. 9

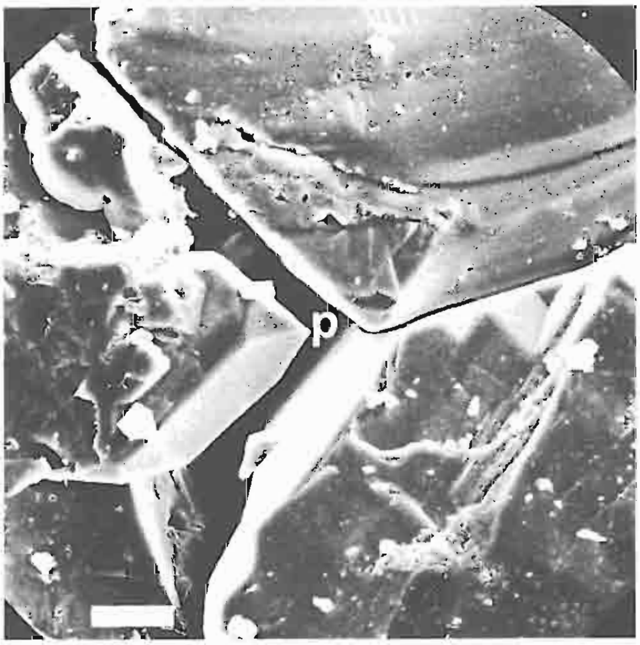

Fig. 10

Fig. 11

Magdalena SIKORSKA, Jolanta PACZEŚNA — Quartz cementation in Cambrian sandstones on the background of their burial history (Polish part of the East European Craton)

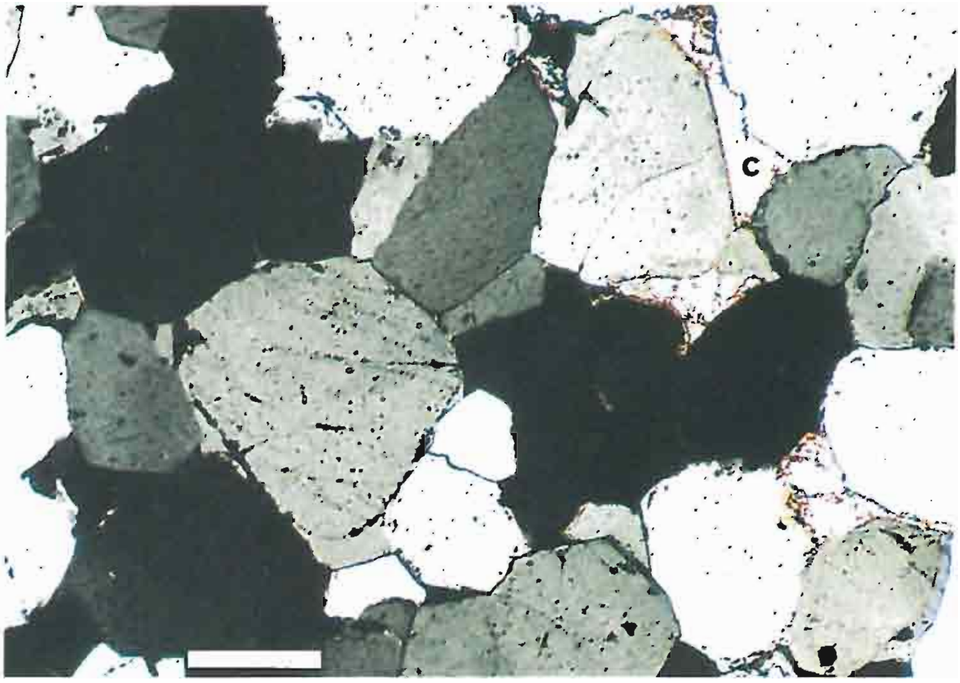

Fig. 12

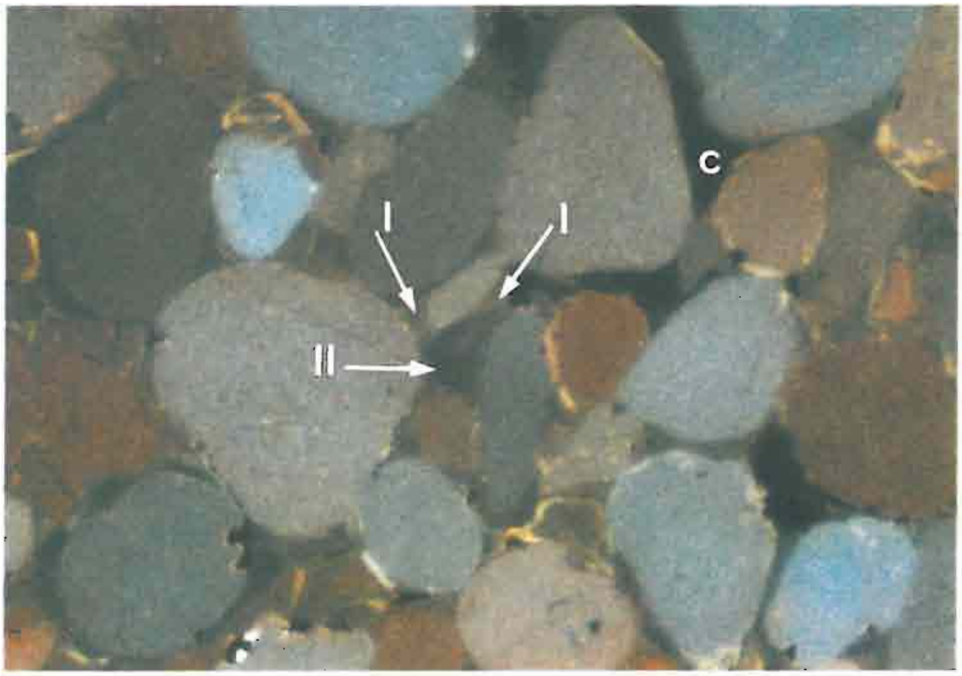

Fig. 13

Magdalena SIKORSKA, Jolanta PACZEŚNA — Quartz cementation in Cambrian sandstones on the background of their burial history (Polish part of the East European Craton)