Annales Societatis Geologorum Poloniae (2005), vol. 75: 287–308.

ORIGIN OF CHERT NODULES FROM THE POLISH MUSCHELKALK, MIDDLE TRIASSIC

Stanisław KWIATKOWSKI

Institute of Geological Sciences, Polish Academy of Sciences, Research Centre in Kraków, Senacka 1, 31-002 Kraków, Poland

Kwiatkowski, S., 2005. Origin of chert nodules from the Polish Muschelkalk, Middle Triassic. *Annales Societatis Geologorum Poloniae*, 75: 287–308.

Abstract: In the Muschelkalk of Poland, carbonate nodules and chert nodules (siliceous and silico-carbonate ones) occur in two regions: the Upper Silesia and the Holy Cross Mountains. The chert nodules were formed by silicification of carbonate deposit, what is proved by silicified skeletal remains of carbonate fauna. The primary deposit formed in aerobic and sometimes evaporitic conditions was permeable, not lithified, and contained some per cent of SiO_2.

The silicification advanced either radially from the centre outwards, or from the outer surface inwards. In the latter case, a precursor of chert nodule was probably a carbonate nodule. The formation of chert nodules proceeded in two stages. In the first stage, the primary fabrics of rock were silicified but preserved, while in the second one they were destroyed. Simultaneously, the organic matter and iron were removed. Lithification advanced from the outer surface inwards. At first, the whole nodule was in a semi-plastic state, what is proved by the occurrence of plastic deformations. Some deformations have been induced by earthquake tremors. With aging of the nodule, only its outer, indurated part underwent cracking. The cortex was developed mostly after nodule's lithification at the expense of the outer part of the nodule, and it entered into the nodule's interior along the cracks. The transformations in particular nodules were stopped in various stages of their development.

Key words: chert nodules, silicification, earthquakes, Muschelkalk, Poland.

Manuscript received 15 March 2005, accepted 30 November 2005

INTRODUCTION

The aim of this study is to present a short characteristics of the types of chert nodules in the Muschelkalk of Poland, and an attempt at explaining their origin. The paper does not concern those few questions, for which no new data were available, like, for instance, transformations: opal A – opal CT – quartz, or the relation of silicification to dolomitization. The material consists of field observations and laboratory examination of 198 samples of chert nodules, carbonate nodules and host rock, gathered at 14 localities in the Upper Silesia (Górny Śląsk) and the Holy Cross Mts (Góry Świętokrzyskie; Fig. 1). The research includes observations on 110 polished slabs and 115 thin sections, and 22 complete chemical analyses and 192 incomplete chemical analyses. In the last century, the Triassic chert nodules in Poland were reported in many publications, but the descriptions were usually limited to the dimensions, form and colour of nodules.

HOST ROCKS AND DISTRIBUTION OF CHERT NODULES

This paper concerns chert nodules which occur in the Upper Silesia and the Holy Cross Mts.

CHERT NODULES IN THE MUSCHELKALK SEQUENCES

The Upper Silesian sequence (Lower Anisian–Lower Illyrian)

Gogolin beds (Lower Anisian)

The Gogolin beds are dark, bioclastic limestones, locally dolomitic, with intercalations of marls, intraformational conglomerates and wavy limestones. The Lower Gogolin beds were deposited in aerobic conditions, whereas the Upper Gogolin beds originated in an anaerobic environment (Szulc, 1990). The boundary between the Lower and Upper Gogolin beds is marked by cavernous limestone, locally including chert nodule (Fig. 2). According to Szulc (1990), the cavernous limestones were formed during a shallowing or even emersion, which was accompanied by precipitation of evaporites. Rarely, the chert nodules occur in other levels of the Gogolin beds (Różycki, 1924; Bojkowski, 1955).

Gorażdże beds (Lower Pelsonian)

The Gorażdże beds are composed of light-coloured, bioclastic, oolitic and oncoidal limestones with intercala-

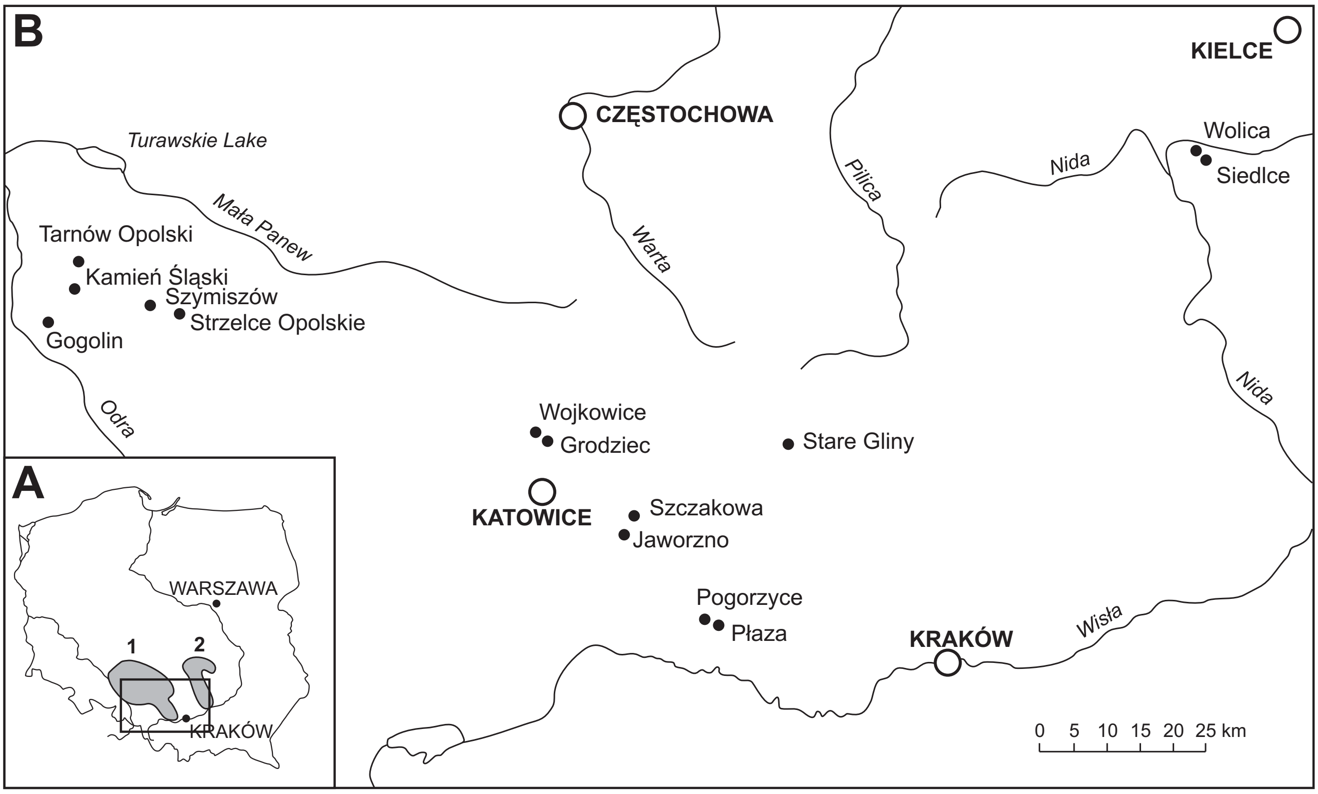


Fig. 1. **A** – Regions of the occurence of chert nodules in Muschelkalk. 1 – Upper Silesia; 2 – Holy Cross Mountains; **B** – Distribution of the investigated outcrops of the Muschelkalk bearing chert nodules

tions of pelletic limestones, dolomitic limestones and dolomites. According to Szulc (1990), they were deposited in a well-ventilated environment. They contain numerous chert nodules, mostly in the lower part (Fig. 2).

Terebratula beds (Middle Pelsonian)

This interval consists of dark, micritic limestones with a bed of crinoidal limestone. According to Szulc (1990), the Terebratula beds were deposited in dysaerobic conditions at the time of the maximum Muschelkalk transgression. These beds bear no cherts (Fig. 2).

Karchowice beds (Upper Pelsonian and lowest Illyrian)

These bioclastic, pelletic or oncoidal limestones contain chert nodules preserved in their middle part (Fig. 2; Strzelce Opolskie member; Bodzioch, 1997), in pelitic and crinoidal limestones, and in sponge bioherms. They were deposited in aerobic conditions (Bodzioch, 1997).

Diplopora beds (Lower Illyrian)

The Diplopora beds are represented by light, yellow dolomites and dolomitic limestones, rich in bioclasts, oolites, oncoids and stromatolites, deposited in aerobic and evaporitic conditions. They contain abundant chert nodule (Fig. 2).

Ore-bearing dolomites (Anisian)

These epigenetic dolomites, occurring mostly in the eastern part of Upper Silesia, correspond with the Gogolin, Gorażdże, Terebratula, and Karchowice beds. In Szczakowa quarry, where the studied specimens of chert nodules were collected, the dolomites are probably exposed parallel to the Gorażdże beds. Chert nodules are very abundant in this place.

The Holy Cross Mts sequence

Łukowa beds (Upper Bithynian–Lower Pelsonian)

These beds consist of micritic and pelletic, light limestones with algal structures and intercalations of spiculitic limestones. They were deposited in aerobic conditions. Chert nodules occur throughout the section, either scattered throughout the rock or confined to distinct levels (Fig. 2).

Lima striata beds (Middle and Upper Pelsonian)

The Lima striata beds are composed of lumachells, pelletic and detritic limestones with algal structures, deposited in aerobic conditions, showing some evaporitic fabrics in the upper part (Kostecka, 1978). The chert nodule levels occur mostly in the lower portion of the evaporitic part (Fig. 2).

To sum up, chert nodules were formed in carbonate sediments deposited in aerobic conditions, either in organodetritic limestones (Gorażdże, Karchowice and Łukowa beds, and the lower part of Lima striata beds), or in carbonate rocks deposited in evaporitic regime (cavernous limestone in the Gogolin beds, Diplopora dolomites, the upper part of Lima striata beds). Such occurrence of chert nodules appears to be a typical one. They are often formed on the border between the decaying organic matter and the oxidising zone (Siever, 1962; Zijlstra, 1987; Maliva & Siever, 1989). In the evaporitic zone, the conditions for silica precipitation are generated by the activity of bacteria, causing the reduction of sulphates and a decrease of pH (Birnbaum & Wireman, 1984; Clayton, 1986). The chert nodules from limestones formed in the evaporitic zone were described from the Röt at Gogolin (Kwiatkowski, 1991; Bodzioch & Kwiatkowski, 1992). Chert nodules are absent or rare in those carbonate rocks which were deposited in reducing conditions.

GEOGRAPHICAL DISTRIBUTION OF THE MUSCHELKALK CHERT NODULES

Chert nodules in the Muschelkalk of Poland are known from two regions only: the Upper Silesia and the Holy Cross Mts (Fig. 1). In western, northern and eastern Poland, no chert nodules in the Muschelkalk have been found. On the peripheries of the Upper Silesia and Holy Cross Mts regions the number and dimensions of chert nodules are reduced (Doktorowicz-Hrebnicki, 1935; Assmann, 1944; Dembowska, 1957; Moryc, 1971; Wyczółkowski, 1978; Zawidzka, 1984).

Dr. J. Szulc called my attention to the relation between the geographical position of the regions of chert nodules occurrence and the position of gates in the Vindelico-Bohemian Massif. The regions of chert nodules occurrence were situated close to the connections between the Tethys Ocean and the Muschelkalk sea: the East Carpathian Gate straight for the Holy Cross Mts region, and the Silesian-Moravian Gate for the Upper Silesia region (cf. Szulc, 2000, fig. 12B).

The chert nodules of the Gorażdże beds in Upper Silesia correspond with those of the Łukowa and Lima striata beds in the Holy Cross Mts. region, while chert nodules of the Karchowice beds and Diplopora dolomites in Upper Silesia have no counterparts in the Holy Cross Mts (Fig. 2). Hence, formation of chert nodules must have persisted longer in Silesia than in the Holy Cross Mts. The occurrence of chert nodules in both regions is not laterally continuous (Alexandrowicz, 1972; Kotlicki & Radek, 1975; Kostecka, 1978). The chert nodules occurring in cavernous limestones at Wojkowice and Grodziec, described in this study, are absent from the same level in the vicinity of Chrzanów (Siedlecki, 1952).

In many places, instead of chert nodules, there occur carbonate rocks impregnated with silica (Pastwa-Leszczyńska, 1962; Śliwiński, 1964, 1969; Łabęcki, 1990; Senkowiczowa, 1970). Probably the formation of chert nodules or impregnations with silica in the carbonate rocks depends on permeability of deposit. In argillaceous carbonates, only slightly permeable, the chert nodules do not form. According to Cayeux (1929), the chert nodules in the Chalk of France were formed when there were few crystallization centres. In some places where the crystallization centres were numerous the silica remained disperced.

To sum up these observations we can conclude that:

1. The occurrence of chert nodules in the Muschelkalk of Poland is confined to the Upper Silesia and Holy Cross Mts. regions. From these regions the chert nodules declined gradually outwards.

2. The occurrence of chert nodules, although condensed in some levels, is not continuous.

3. In the rocks slightly permeable chert nodules are replaced by impregnations with silica.

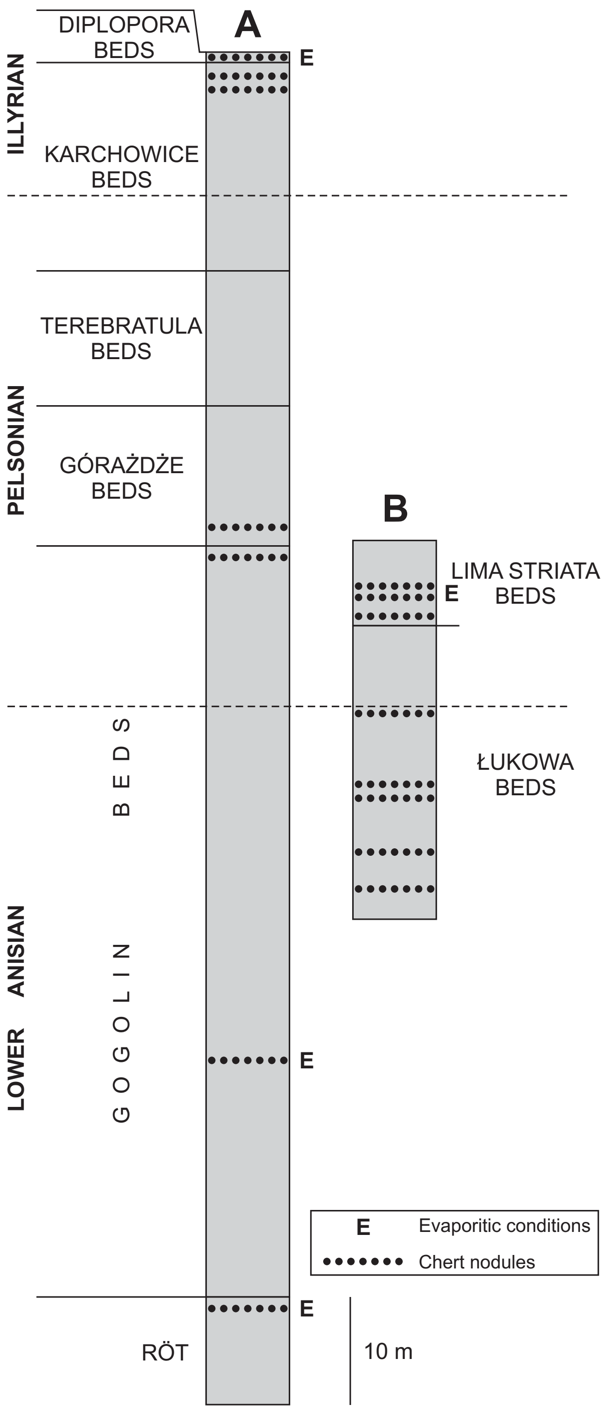


Fig. 2. Distribution of chert nodules in sections of the Muschelkalk in Upper Silesia (**A**) and the Holy Cross Mountains (**B**)

CONTENT OF SILICA IN ROCKS ENCLOSING CHERT NODULES AND IN ROCKS DEVOID OF CHERT NODULES

Extensive data of the content of silica in carbonate rocks of the Muschelkalk in Upper Silesia are given in papers by Assmann (1914, 1944). As one compares the chert-bearing formations (Gorażdże, Karchowice, and Diplopora beds) with those poor in cherts (Gogolin and Terebratula beds) it becomes obvious that the silica content is lower in the first type than in the second one.

In the Gorażdże beds, the content of silica ranges from 0.62% to 0.96%, and in the Karchowice beds from 0.18 to 1.2%. In the Gogolin beds from Nakło, the respective figures are from 0.15% to 5.48%, and from Gogolin – from 0.54% to 3.96%. In three analyses of rocks from the Terebratula beds, the silica content is 6.08%, 4.07% and 0.68%. Similarly, for different levels of the Gogolin beds in the vicinity of Szczakowa, Bojkowski (1955) quoted the following average silica contents: 2.28%, 5.8%, 9.8%, and 1.44%. On the other hand, the ore-bearing dolomites of this area (corresponding to the Gorażdże beds) contain 0.34% to 1.6% of silica, averaging at 0.95%.

The catalogue of chemical analyses of rocks (Łaszkiewicz, 1961) gives the following contents of silica:

1) For the rocks containing chert nodules:
- Gorażdże beds (7 analyses): 0.51–4.06%, av. 2.05%
- Karchowice beds (5 analyses): 0.19–1.07%, av. 0.64%
- Diplopora beds (13 analyses): 0.4–0.9%, av. 0.88%

2) For the rocks poor in chert nodules:
- Gogolin beds (20 analyses): 0.3–17%, av. 4.39%
- Terebratula beds (5 analyses): 0.68–6.08%, av. 4.13%.

So, the carbonate rocks bearing chert nodules are in general way poorer in silica than those devoid of chert nodules. Probably, the formation of chert nodules caused the decrease of silica content in the surrounding rocks. It can be supposed that the original deposit of the rocks, now either containing or not containing chert nodules, had a similar content of silica.

THE SIGNIFICANCE OF VOLCANIC TUFFS FOR THE FORMATION OF CHERT NODULES

According to Trammer (1977), the hornstone level in the Pelsonian sediments of the Alps corresponds with the Gorażdże beds in Upper Silesia and with the Łukowa and Lima striata beds in the Holy Cross Mts. The cause of formation of cherts in these rocks is, following Trammer (1977), the deposition of tuffs derived from volcanoes of the Balkans, Hungary, and Israel, and the subsequent development of siliceous sponges in the Muschelkalk sea. In Illyrian time, the supply of volcanic silica caused the formation of cherts in the western part of the German Basin. There are some reservations to this hypothesis:

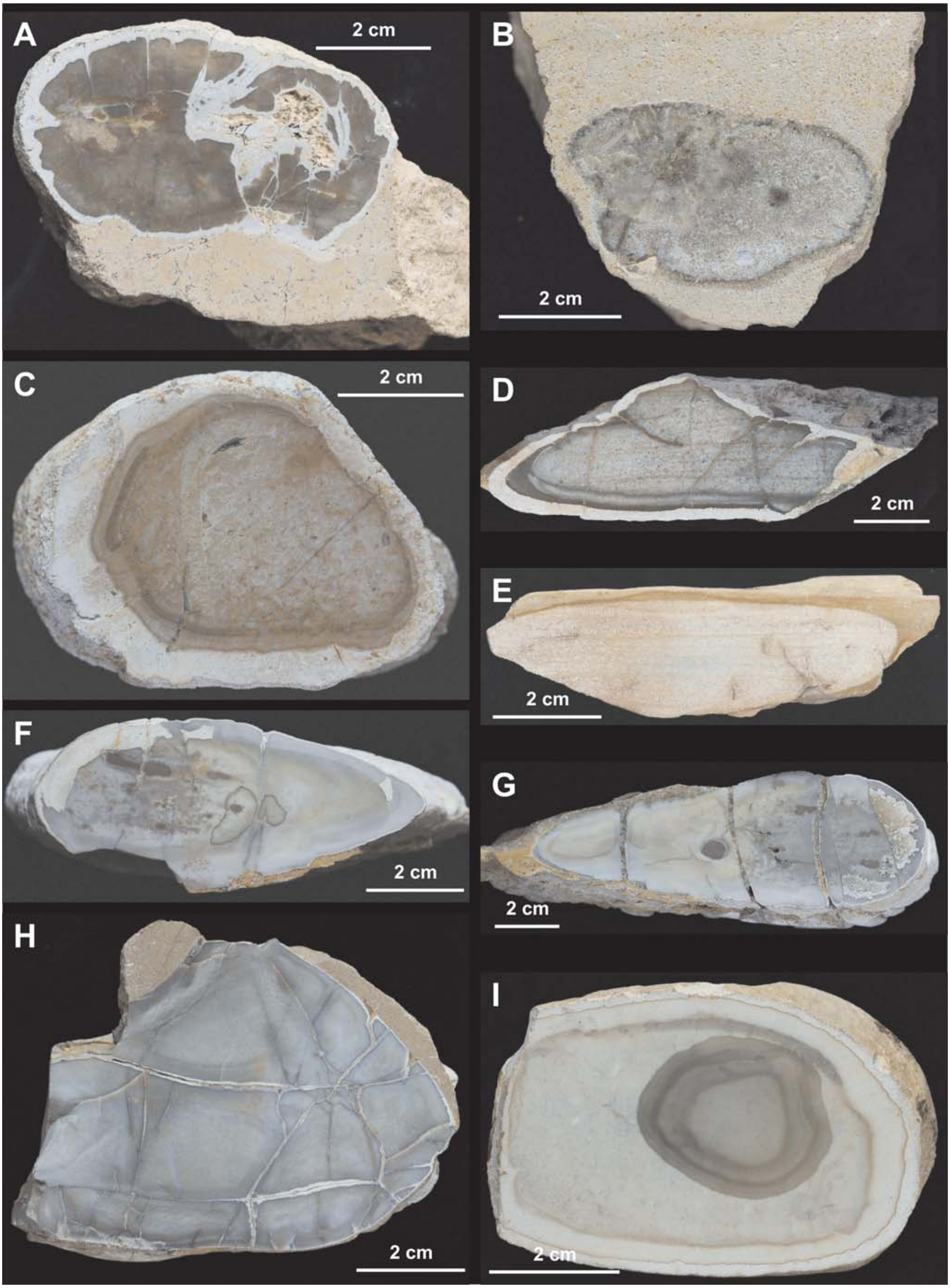
1. No increase of the silica content in rocks enclosing chert nodules was observed.
2. The quantity of tuffs observed in the Muschelkalk of Poland is negligible. There is only one observation (Kuhl, 1958) of the weathered tuff on top of the ore-bearing dolomite from Bytom in Upper Silesia.

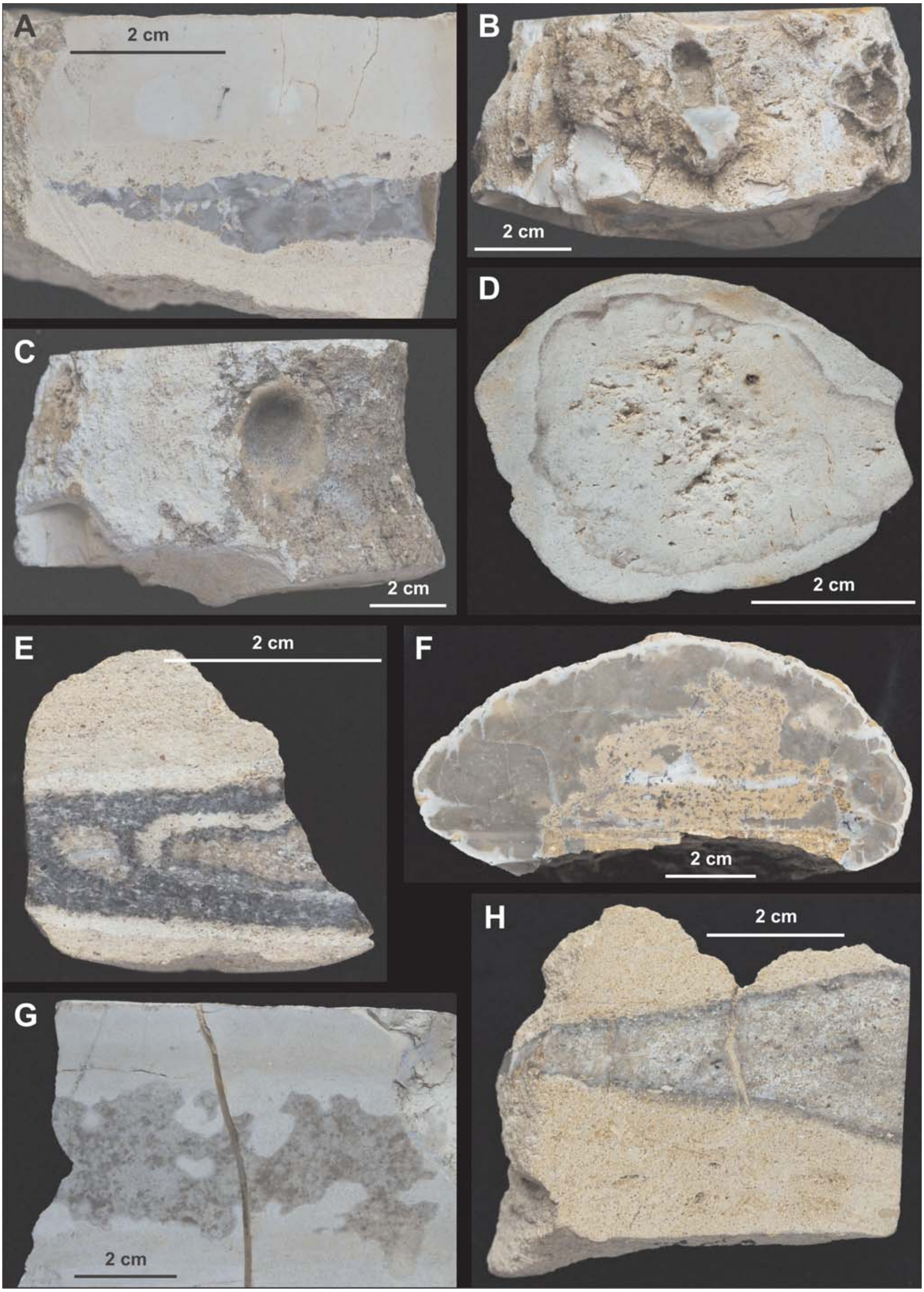
FOSSILS

The same fossils occur both in carbonate host rocks and in chert nodules. These are, in order of their frequency: siliceous sponge spicules, algae (filaments, branching threads), crinoid ossicles, ostracods, foraminifers, fragments of Lamellibranchiata tests, gastropods, and brachiopods. In lesser amount, there occur: sponge bodies (Fig. 3C), spines of echinoids, corals, bryozoans, serpulids, fish scales, bones of vertebrates, and scolecodonts. The fossils occur mostly as skeletal debris. Only some sponge bodies, some gastropods, and very small shells of foraminifers and scolecodonts are preserved intact. The fossils are preserved in calcite, calcium phosphate or silica (mostly in chalcedony). Sponge spicules are preserved as microquartz or chalcedony, sometimes as calcite.

The silicified, but originally calcareous skeletal remains prove that the chert nodules were formed by silicification of carbonate deposit. Trace fossils, common in the Muschelkalk, are very rare in the levels bearing chert nodules.

Fig. 3. **A** – Siliceous nodule. Ghost-bearing structure. In the centre relics of yellow, porous limestone, cracks mostly from the top. Cortex, thicker on the top, enters deeply into cracks. Gogolin beds, Wojkowice; **B** – Silico-dolomitic nodule. Broad banding structure developed on ghost-bearing structure. Black streak around the nodule. Thin cortex on the part of the surface of the nodule. Crack visible. Gogolin beds, Płaza; **C** – Siliceous nodule, formed on the walls of a sponge body. Thick cortex. Cracks visible. Karchowice beds, Strzelce Opolskie; **D** – Siliceous nodule. Top surface convex, bottom surface flat. Ghost-bearing structure. Lamination preserved. White cortex, thicker on flanks, enters into cracks. Great cracks vertical and oblique, approximately perpendicular to the surface of the nodule. Łukowa beds, Wolica; **E** – Siliceous nodule. Top surface flat. Ghost-bearing structure. Lamination preserved. No cortex. Shallow cracks. Ferrugineus streak around the nodule. Gogolin beds, Wojkowice; **F** – Siliceous nodule. The nodule's interior with ghost-bearing structure, the outer parts with the homogenous structure. White cortex, thicker from one side, enters deeply inwards. Thin pipe passes from the top to the bottom, with cortex entering in it from one side and deposit entering shallowly from the other. Ore-bearing dolomite, Szczakowa; **G** – Siliceous nodule. In the centre a small area is occupied by thin banding structure disrupted. In thicker part of the nodule ghost-bearing structure predominates, in thinner part (left side) homogenous structure prevails. Thin cortex. Great vertical cracks filled with calcite. Ore-bearing dolomite, Szczakowa; **H** – Siliceous nodule, strongly cracked. Homogenous structure. Thin cortex enters deeply in the net of cracks. Locally, a deposit enters shallowly into the cracks. Ore-bearing dolomite, Szczakowa; **I** – Siliceous nodule. Broad banding structure developed mostly on the ghost-bearing structure, and in part (the darkest and the lightest bands) on the homogenous one. White cortex. No cracks. Gorażdże beds, Płaza


A
2 cm
B
2 cm
C
2 cm
D
2 cm
E
2 cm
F
2 cm
G
2 cm
H
2 cm
I
2 cm


A
2 cm
B
2 cm
C
2 cm
D
2 cm
E
2 cm
F
2 cm
G
2 cm
H
2 cm

Trammer (1975) stated that the chert nodules in the Muschelkalk of the Holy Cross Mts occur exclusively in beds rich in sponge spicules and are absent from beds without spicules. He deduced from this observation that chert nodules were formed by silica derived from siliceous sponges. In the material investigated in the present study, the carbonate beds enclosing chert nodules are rich in sponge spicules, too. The beds devoid of chert nodules were not investigated. The observation of Trammer (1975) indicates that the migration of silica for the nodules proceeded at relative short distances.

THE DIMENSION AND FORM OF CHERT NODULES

The chert nodules are 3 to 30 cm long (usually 10–15 cm) and 2 to 10 cm thick. The relation of length to thickness varies from 1.5 to 13, usually from 1.5 to 3. This ratio is greater in the limestones and dolomites deposited in an evaporitic regime (in cavernous limestone at Wojkowice averaging at 4.26, and at Grodziec 6.33). In all other beds this relation is weaker (on the average: Gogolin beds at Płaza 2.45; Gorażdze beds at: Płaza 2.16, Pogorzyce 3.6, Szczakowa 2.8, Strzelce Opolskie 3.3; Karchowice beds at: Strzelce Opolskie 2.0, Tarnów Opolski 2.2, Kamień Opolski 3.13). The horizontal elongation of chert nodules is controlled by the permeability of host deposit, being greater horizontally than vertically (Hsü, 1976). So, the supply of dissolved silica for the growing chert nodule or of calcium carbonate for the carbonate nodule was greater in the horizontal direction. It is possible that in evaporitic sediments the difference between the horizontal and vertical permeability was greater than in other sediments.

The shape of chert nodules is approximately ellipsoid, flattened to a variable degree. Some nodules are reniform, spindle-shaped or irregular in many ways. The top surface of a nodule is often flat and the bottom surface is convex, although sometimes a reverse is to be found.

The chert body encompasses sometimes also the cracked parts of the host rocks. This proves that the host rocks were being partly lithified before their silicification. Sometimes the outer surface of the chert nodule is stopped on a fossil shell (Fig. 4C). In this case, the nodule was probably formed in unconsolidated sediment and the direction of its growth was from the centre outwards. Few coalesced nodules occur in the Gogolin beds at Wojkowice and Płaza, and in ore-bearing dolomite at Szczakowa. These nodules grew from the centre outwards, too. Probably, the chert nodules of regular shapes were formed in homogenous sediment, while irregular nodules originated in an inhomogenous or partly consolidated sediment.

The chert nodules are confined to the middle of beds, their longest axes being horizontal. This position is interpreted by Trammer (1975), who writes: "the bedding of the limestone surrounding the flints is of envelope type, which indicates the syngenetic character of the flints". This conclusion is misleading, because all the chert nodules of the Muschelkalk were formed by the silicification of the carbonate sediment during early diagenesis. The envelope type of limestone bedding around nodules proves that at the time of carbonate compaction the chert nodules were already consolidated and hard. The increased porosity of the host rock seems to favour the chert nodules formation (Rio, 1982). In the Gorażdże beds at Pogorzyce, a thin nodule of chert is situated in a lens of porous limestone (Fig. 4A).

COLOUR

The colour of chert nodules is usually connected with that of the host rock. In white rocks it is usually grey or ashy, and in the yellow ones chiefly creamy, yellow or brown. In the Gogolin beds at Wojkowice and Grodziec, the colour of chert nodules is white, rarely light-grey and exceptionally pink or bluish, whereas at Płaza it is grey. In the Gorażdże beds at Płaza, the colour is creamy, light-grey and grey with brown blots, at Strzelce Opolskie light-grey, creamy or brown, and at Szczakowa white, light-grey or ashy. In the Karchowice beds at Kamień Opolski, Tarnów Opolski, Szymiszów and Strzelce Opolskie, the colour is yellow, yellow-brown, and sometimes reddish-brown. In the Diplopora beds at Kamień Opolski and Stare Gliny, the colour is whitish, light-grey, rarely yellow. In the Łukowa beds at Wolica and Siedlce the colour is light-grey, dark-grey, and rarely grey-brown, whereas in the Lima striata beds at Wolica it is white or ashy, sometimes ashy-bluish, exceptionally pink-cream or pink-white.

Yellow and brown colours of chert nodules dominate in the western part of Upper Silesia, whereas grey and white colours prevail in the eastern part of Upper Silesia and in the Holy Cross Mts. The chert nodules are dyed yellow and brown by iron hydroxides. The dark colouration of chert nodules depends on the content of pyrite, organic matter and water, as well as rock porosity.

Fig. 4. **A** – Siliceous nodule in a lens of porous limestone. Ghost-bearing structure, thin cortex, small cracks. Gorażdże beds, Pogorzyce; **B** – Outer surface of siliceous nodule with cavities after dissolved tests. Gorażdże beds, Płaza; **C** – Outer surface of siliceous nodule with a fragment of shell, which locally stopped the nodule growth. Karchowice beds, Strzelce Opolskie; **D** – Silico-calcareous nodule. Thick, white cortex. Holes after limestone relics dissolved by HCl treatment; no cracks. Łukowa beds, Siedlce; **E** – Siliceous nodule. Broad banding structure developed on ghost structure. The light bands more porous than the dark ones; no cracks. Gorażdże beds, Pogorzyce; **F** – Silico-calcareous nodule. In the centre yellow, dolomitic limestone surrounded by grey silica with ghost-bearing structure. White cortex enters into shallow cracks. Gogolin beds, Wojkowice; **G** – Siliceous nodule. In the centre dark silica with ghost-bearing structure surrounded by light silica with homogenous structure. Thin cortex on a part of the surface of the nodule. Great crack filled with ferruginous vein. Ore-bearing dolomite, Szczakowa; **H** – Siliceous nodule. Ghost-bearing structure, without cortex, black shadow around the nodule, crack filled with deposit. Gogolin beds, Płaza

TYPES OF NODULES AND THEIR COMPOSITION

TYPES OF NODULES

The nodules in the Muschelkalk of Poland can be divided into three categories: 1) the chert nodules, which are siliceous with a carbonate admixture up to 13%; 2) the silico-carbonate nodules with carbonate content of 13–30%; 3) the carbonate nodules with an admixture of silica up to 5% (Table 1).

All these types do not differ in size, shape and colour, and they occur together in the same horizons and outcrops. From the investigated 160 nodules, 119 (75%) were siliceous, 35 (21%) silico-carbonate, and 6 (4%) carbonate.

Table 1

Chemical content of nodules (in weight %)

Locality	Formation	SiO_2	$CaCO_3$	$MgCO_3$	Type of nodule
Wojkowice	Gogolin beds	89.41	9.1	0.12	siliceous
Wojkowice	Gogolin beds	88.87	7.0	2.86	siliceous
Wojkowice	Gogolin beds	74.43	23.7	0.73	silico--carbonate
Grodziec	Gogolin beds	86.51	8.1	4.18	siliceous
Grodziec	Gogolin beds	87.1	11.5	0.52	siliceous
Płaza	Gogolin beds	72.2	16.93	9.7	silico--carbonate
Płaza	Gogolin beds	80.05	11.2	7.5	silico--carbonate
Płaza	Gorażdże beds	98.4	0.52	0.19	siliceous
Płaza	Gorażdże beds	99.06	0.15	0.04	siliceous
Płaza	Gorażdże beds	96.5	0.09	0.1	siliceous
Szczakowa	Gorażdże beds	93.11	2.21	2.6	siliceous
Pogorzyce	Gorażdże beds	70.47	18.4	8.8	silico--carbonate
Pogorzyce	Gorażdże beds	98.1	0.71	0.17	siliceous
Pogorzyce	Gorażdże beds	97.0	1.25	0.84	siliceous
Siedlce	Łukowa beds	80.24	18.2	0.14	silico--carbonate
Wolica	Łukowa beds	97.94	1.43	0.12	siliceous
Wolica	Lima striata beds	3.48	92.66	2.09	carbonate
Wolica	Lima striata beds	4.68	89.75	1.78	carbonate

SILICA

Silica occurs as microcrystalline quartz, mega-quartz, chalcedony and, more rarely, length-slow chalcedony (quartzine), flamboyant quartz, and lutecite. The microcrystalline quartz (grain diameter ranging from 0.001 to 0.02 mm) is a result of silicification of micrite and forms a matrix. According to Maliva and Siever (1988), the crystals of such size were derived from the transformation of opal CT into quartz. Mega-quartz forms aggregates (0.1 to 10 mm in diameter) as infill of voids and veins. Chalcedony fills voids, forms veins, replacing micrite and carbonates in skeletal remains and forming streaks in carbonate rock. Chalcedony commonly occurs as spherolites, 0.04 to 0.5 mm in diameter. The crystals of chalcedony and mega-quartz are much greater than micro-quartz crystals what, following Maliva and Siever (1988), proves that they must have been derived from immediate replacement of carbonate by quartz or from crystallization of quartz in voids. Length-slow chalcedony was observed as fillings of voids in Lima striata beds at Wolica, and as spherolites in the Gogolin beds at Wojkowice (0.1–0.2 mm in diameter), as well as in the Karchowice beds at Kamień Opolski. Lutecite occurs in the matrix of the Łukowa beds at Siedlce and in sponge spicules at Wolica. Length-slow chalcedony and lutecite are commonly formed in evaporitic deposits (Arbey, 1980).

The silicification of skeletal remains can be either complete or partial. Sometimes in one thin section a part of skeletal remains is preserved as calcite and a part as silica. Often, silicification encompasses the interior of skeletal remains and the external part of a fossil remains calcitic. The mineral most often replacing calcite in skeletal remains is chalcedony, rarely microcrystalline quartz or mega-quartz. Skeletal remains are often dissolved, forming voids. This is especially common for big shells, for instance those of gastropods. There are pockets, up to 2 cm deep, which are going from the outer nodule's surface inwards (Fig. 4B). Probably, the nodule grew from the centre outwards and omitted the shell, which remained calcitic. Later, the shell was dissolved and a pocket was formed. The sponge bodies are sometimes silicified as a whole in life position.

The matrix of oncoidal and oolitic limestones in the Gorażdże beds (Płaza and Pogorzyce) is usually replaced by coarse-grained or spherulitic chalcedony. The oncoids and ooids are often partly silicified with microcrystalline quartz and micro-chalcedony. Commonly, silicification occupies only the centres of ooids and oncoids, and the external parts of them remain unchanged (Fig. 5C). Similar observations were accomplished by Łabęcki (1990) in the upper part of the Muschelkalk, by Bilan and Golonka (1972) in the Diplopora dolomites, and by Chudzikiewicz (1982) in the Gogolin beds.

CARBONATES

Two genetically distinct types of carbonates occur in chert nodules: the primary carbonates, which were not silicified, and the secondary ones, which were formed in the already existing chert nodules. The original carbonates occur in the form of micrites, sparites, pellets, oolites and oncoids, and they do not differ much from the rocks enclosing the nodules. Relics of the original carbonate rocks (2 to 30 mm in diameter) occur usually in the central parts of chert nodules in the Gogolin (Płaza and Wojkowice), Gorażdże (Pogorzyce and Szczakowa), and Karchowice beds (Szymiszów), as well as Diplopora dolomite (Kamień Śląski) and Lima striata beds (Wolica) (Figs 3A, 4D). They have irregular shapes, sometimes with corroded surfaces. They differ from the secondary carbonates by their, usually strong, porosity.

The secondary carbonates comprise calcitic veins and aggregates, calcified sponge spicules, and small rhombohedrons dissipated in the rock. The veins of coarse-grained calcite occur in chert nodules in many levels and outcrops, and are especially common in the Łukowa beds at Wolica and Siedlce, and in Karchowice beds at Kamień Śląski. The aggregates of calcite occur as fillings of voids. The carbonate rhombohedrons (Fig. 5B), commonly containing iron, few decimals of millimetres in diameter, dissipated in the chert nodules occur abundantly in the Gorażdże (Strzelce Opolskie, Szczakowa), Karchowice (Szymiszów, Tarnów Opolski, Kamień Śląski), and Diplopora beds (Kamień Śląski). They do not occur in eastern Silesia, except one locality (Szczakowa), and in the Holy Cross Mts. These rhombohedrons are completely lacking in the host carbonate rocks. They usually underwent decay, starting from their centres.

Very similar rhombohedrons were described by Mišik (1993) from chert nodules in the Mesozoic rocks of the Western Carpathians. They occur in two-third of the investigated by him nodules and are absent from the enclosing rocks. The rhombohedrons are composed of calcite, Fe-calcite, Fe-dolomite and ankerite and, according to Mišik (1993), they were formed during early diagenesis.

In the ore-bearing dolomite at Szczakowa, the calcitic brushes are overgrowing either entire chert nodules (being the thickest on the top) or only the tops of nodules. Probably, at the time of dolomitization and the abrupt increase of rock porosity, the nodules were sinking under their own weight, and over the top of a nodule a void was formed which was later filled with calcite.

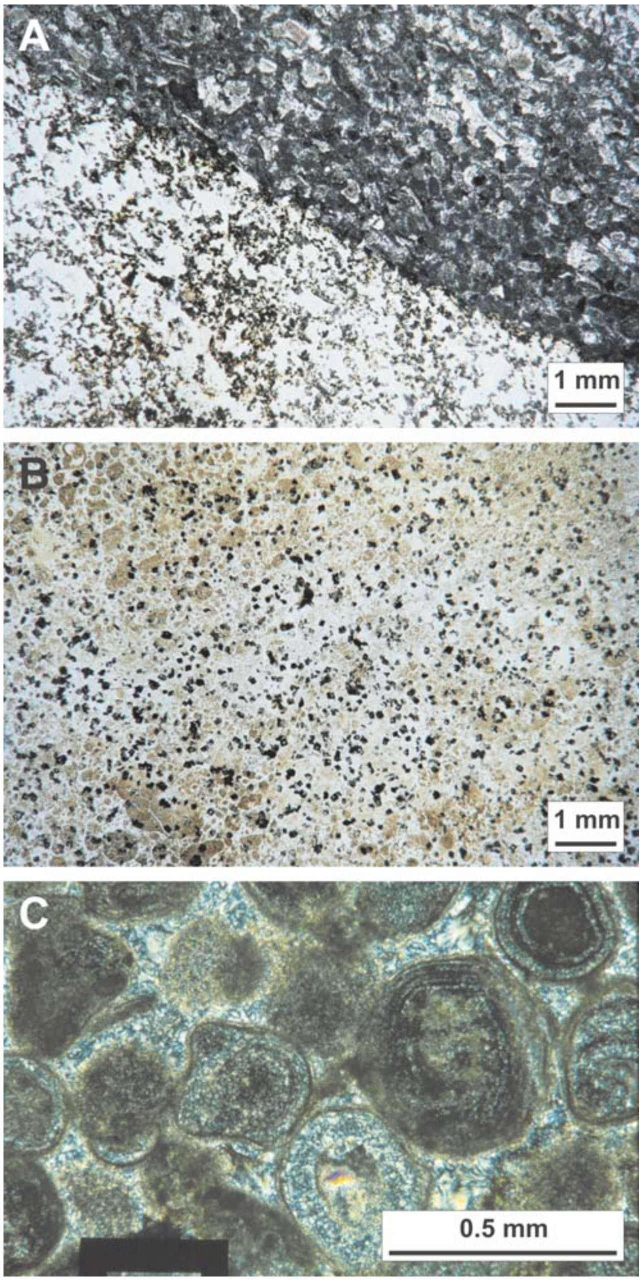


Fig. 5. **A** – Two parts: contaminated zone dominated by carbonate (dark), and a zone dominated by silica (light). Sponge spicules visible. Łukowa eds; Wolica; **B** – The micro-quartzitique and micro-chalcedonic chert with silicified pellets and carbonate rhombohedrons decaying in the centres. Karchowice beds, Tarnów Opolski; **C** – Silicified oncoidal limestone. Oncoids silicified to a different degree. Chalcedonic matrix. Gogolin beds, Płaza

DISTRIBUTION OF SILICA AND CARBONATES

The distribution of silica and carbonates varies in particular chert nodules. There are zones, different in shape and size, either with predominance of silica or carbonates. In those zones where carbonates predominate, the silica occurs most often as disseminated quartz grains and aggregates, chalcedonic spherulites, and skeletal remains, either in part or completely silicified. Locally, only the voids are filled with microcrystalline quartz or micro-chalcedony. The zones dominated by silica are usually composed of microcrystalline quartz with aggregates of mega-quartz and spherulites of chalcedony. In some chert nodules from the Łukowa beds at Siedlce, the skeletal remains in such a zone are preserved in calcite. In one chert nodule from the Gorażdże beds at Pogorzyce, particular ooids in such a zone are preserved in calcite, too.

As can be seen under the microscope, the areas of carbonate predominance are strongly contaminated with dark brown pigment, while the areas dominated by silica are almost pure. The microcrystalline quartz is sometimes a little contaminated, but mega-quartz and chalcedony are usually quite pure (Fig. 5A). The solutions of organic acids dissolve silica and form the soluble silico-organic combinations (Bennett & Siegel, 1987; Bennett, 1991). It can be supposed that the introduced silica could have caused the removal of organic matter.

The transition from the zone of silica predominance to the zone of carbonate predominance is usually gradational and rarely sharp. Sometimes these zones form a series of alternating bands. Very often, the zone of carbonate predominance is located in the centre of the nodule and is surrounded by either continuous or discontinuous siliceous zone (Fig. 4D, E, F). Such nodules occur in the Gogolin (Wojkowice), Gorażdże (Pogorzyce), Karchowice (Strzelce Opolskie and Szymiszów), and Łukowa beds (Wolica). In these nodules, silicification advanced from the surface inwards, and their precursor could have been a carbonate nodule.

Sass and Kolodny (1972) described from the Cretaceous of Israel calcareous concretions with siliceous rings and crusts. These concretions were formed in the carbonate-opal-apatite mud with rich organic matter in generally aerobic conditions, but with some small centres of anaerobic conditions. In these centres, hydrocarbons were oxidized to HCO_3, Eh was low, pH was high, and calcium carbonate was precipitated. The silica was dissolved, carried outwards, and precipitated at the boundary of the anaerobic centre. More frequently, the silicification of carbonate occurs due to silica input from the outside. McBride (1988) described river pebbles with their exteriors either partly or completely silicified by hot waters from tuffs. Similar silicifications of marine pebbles was noted by Martin Penela and Barragán (1995). The surface of the limestone body in an unconsolidated deposit is susceptible to silicification. According to Dickson and Barber (1976), a rapid flow of the silica solution leaves the carbonate deposit unchanged, while a slow flow leads to silicification. It is also likely that the convexity of calcareous body favours silicification.

MINERAL ADMIXTURES

The Fe_2O_3 content in chert nodules, investigated in 47 analyses, varies from 0.014% to 1.56%, averaging at 0.34%. One exception is a sideritic-siliceous nodule from the Diplopora beds at Kamień Śląski, bearing 6.8% of Fe_2O_3. On the basis of four analyses of host rock with 0.25% to 3.07% of Fe_2O_3, it seems likely that the host rock could be richer in iron as compared to the chert nodules. Iron minerals in nodules are: pyrite, syderite, oxides and hydroxides. Pyrite occurs locally as black, cubic crystals dissipated in the rocks of the Gorażdże (Strzelce Opolskie and Szczakowa) and Karchowice beds (Tarnów Opolski, Kamień Śląski, Szymiszów). The occurrence of pyrite means that reducing conditions must have occurred at some time at these places in some of the nodules. The iron oxides and hydroxides form veins and red-brown pigment, which locally, at the boundary between the nodule and the host rock, dyes the latter or forms a streak (Figs 3E, 6D). According to Swett (1965), the silicification leads sometimes to the removal of iron from chert nodules, which is later precipitated in the adjacent rock. Following Cressman's (1962) opinion, the content of iron in layered cherts is usually lesser than in adjacent rocks.

The MgO content in chert nodules, studied in 51 analyses, varies in a wide spectrum from 0.02% to 20.93%; therefore, calculation of its average is not justified. In some chert nodules, the MgO content is very high and in others very low. In chert nodules of the ore-bearing dolomite in Szczakowa, the MgO content is relatively low (0.04% to 1.24%). This proves that the chert nodules were formed before ore-bearing dolomitization, which did not reach the nodule's interior.

The Al_2O_3 content in chert nodules, investigated in 17 analyses, is low and relatively equal: from 0.081% to 0.55%, averaging at 0.23%.

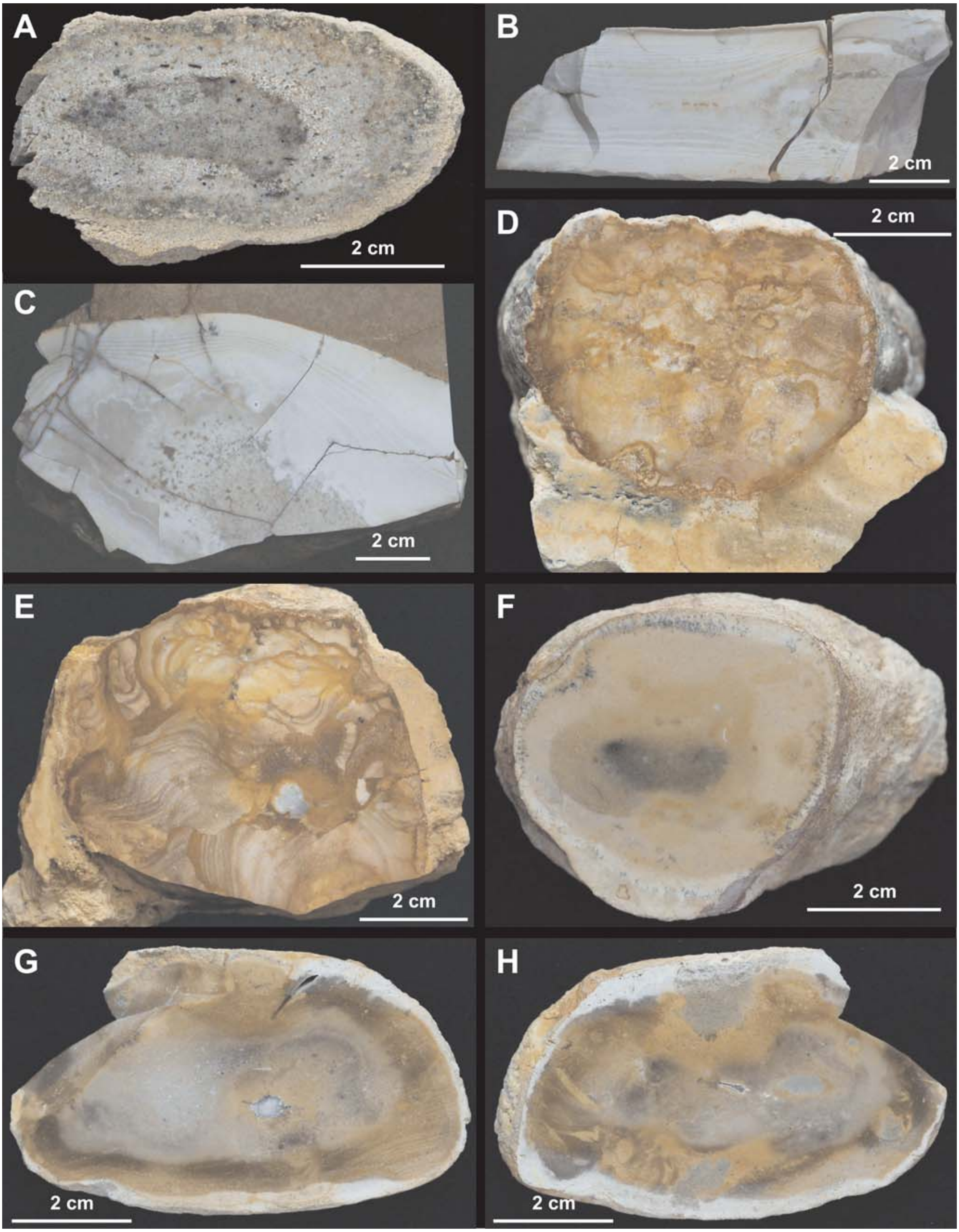
The organic carbon, investigated in 32 analyses, occurs in small quantities, from 0.008% to 0.128%. The average contents in particular stratigraphical levels are very uniform

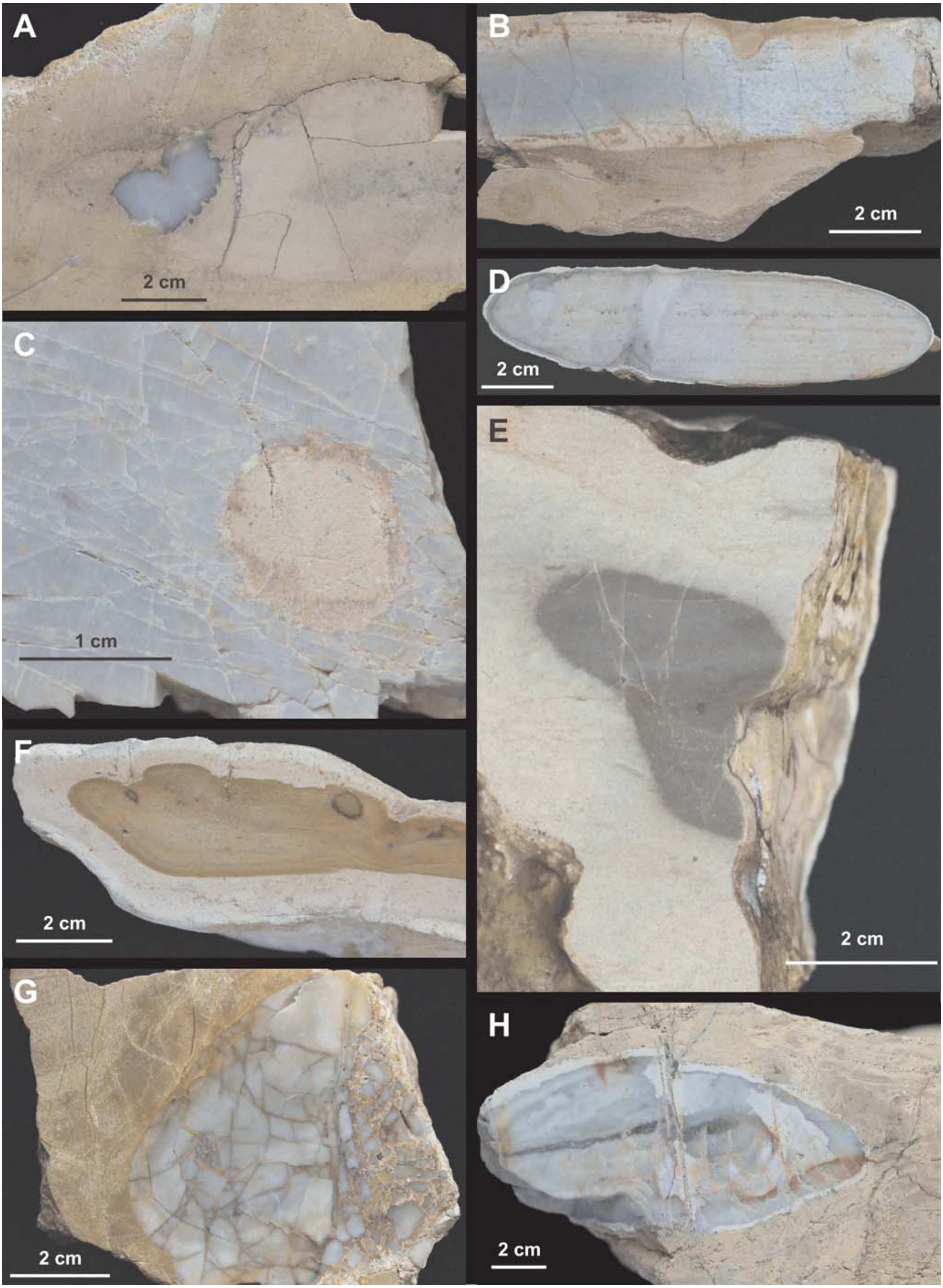
The TiO_2 content, investigated in 51 analyses, is from 0.00% to 0.098%. The difference between its content in Upper Silesia and the Holy Cross Mts is notable. It is greater in the Holy Cross Mts (av. 0.033%) than in Upper Silesia (av. 0.0102%). No difference in the TiO_2 content between chert nodules and the host rock was observed.

The content of phosphorus was measured in 19 samples. In five samples, the phosphorus was lacking and in the remaining fourteen its content varied from 4 to 55 ppm. The calcium phosphate was observed in skeletal remains in the Gorażdże (Strzelce Opolskie), Karchowice (Szymiszów), Lima striata (Wolica), and Łukowa beds (Wolica and Siedlce). It also occurs in the matrix of the Gorażdże (Strzelce Opolskie) and Karchowice beds (Szymiszów).

The manganese content in chert nodules, investigated in 19 analyses, spans a wide interval between 4 and 3,500 ppm. The presence of manganese is marked by dark film on

Fig. 6. **A** – Siliceous nodule. Broad banding structure developed on the ghost-bearing structure with preserved ooids. Cortex on one side of the nodule. No cracks. Gogolin beds; Płaza; **B** – Siliceous nodule. Thin banding structure. Core partly with ghost-bearing structure (dark part) and partly with homogenous structure (light part). Great crack filled with quartz vein, and at the surface of the nodule filled with deposit. The bands are banded outwards at the vein. The cortex, visible on one side, enters inwards along the crack. Ore-bearing dolomite, Szczakowa; **C** – Siliceous nodule. The dark centre with ghost-bearing structure, surrounded by generally lighter silica with homogenous structure and partly thin banding structure. Cracks with ferrugineous veinlets. On one side (left) the nodule is almost brecciated. Ore-bearing dolomite, Szczakowa; **D** – Silico-calcareous nodule. Mottled structure. Thin cortex on one side of the nodule. No cracks. Karchowice beds, Tarnów Opolski; **E** – Siliceous nodule. Mottled structure formed from broad banding structure. Bands disrupted and mottled. Without cortex and cracks. Karchowice beds, Kamień Śląski **F**, **G**, **H** – Parallel sections of a silico-calcareous nodule, from one flank (F) to the centre (G) and a little farer (H). Disturbances in the broad banding structure probably resulted from an earthquake and led to formation of the mottled structure. No cracks. Karchowice beds, Tarnów Opolski; **F** – Brown band, a little mottled. Cortex with variable thickness, with dendrites; **G** – Bands more mottled than in section F; **H** – Bands strongly disturbed and disrupted


A
2 cm
B
2 cm
C
2 cm
D
2 cm
E
2 cm
F
2 cm
G
2 cm
H
2 cm


A
2 cm
B
2 cm
D
2 cm
C
1 cm
E
2 cm
F
2 cm
G
2 cm
H
2 cm

some joints and by dendrites. The dendrites occur in the form of twigs, starlets, spots, and double parentheses on joints, perpendicularly to these joints, on outer surfaces of nodules, and at the boundaries between the cortex and the core of nodule inwards (Fig. 6F), and also inside nodules without visible relation to cracks. The number of dendrites in particular outcrops is very differentiated. Dendrites are ubiquitous at Szczakowa, Płaza and Siedlce. At Wolica, they occur in the host rock and are absent from the chert nodules. No correlation between manganese content and the occurrence of dendrites was documented. Probably, the majority of manganese is not hosted in dendrites. Formation of dendrites in chert nodules was one of the last processes after the nodules' consolidation.

CARBONATE NODULES AND THEIR SILICIFICATION

The carbonate nodules occur in the Lima striata and Łukowa beds at Wolica, and in the Gogolin beds at Płaza. They differ from the host rock by lesser porosity, darker colour, and easy separation of their surface from the enclosing rock. In the Lima striata beds at Wolica, there occur calcite concretions described by Kostecka (1972). This author concluded that these structures were at first aragonitic concretions which passed into calcitic ones, and later went under silicification in their central parts. They have the radial texture and are quite different regarding their shape, texture, and size from the chert and carbonate nodules described in this paper.

There is ample literature pertaining to the carbonate nodules, their occurrence and genesis. Their shape and dimensions are the same as those of chert nodules. The lack of compaction effects proves that they were formed during early diagenesis. They often form around organic remains and their formation is caused by the decay of organic matter (Weeks, 1953). The decomposition of proteins comes first, producing NH_4OH. Hence, alkalization comes before acidification, and the precipitation of calcium carbonate predates that of silica. According to Raiswell (1976), the formation of carbonate nodules is caused by microbiological reduction of sulphates in the presence of decaying organic matter. Often, carbonate nodules are in part or completely silicified (Hayes, 1964; Makedonov, 1966; Durga Prasada Rao, 1982). All these authors assume that the formation of carbonate nodules occurred first and that silicification proceeded later one.

STRUCTURES OF CHERT NODULES

Two basic structure types were distinguished on the basis of preservation or lack of preservation of elements of the original rock: the ghost-bearing structures and homogenous structures. Moreover, four structure types of the second order were distinguished, which are developed on one or both of the basic types. Sometimes, one structure covers the entire nodule, but more often in one nodule two or more structures occur. The identification of structures is possible macroscopically on polished slabs, but it is difficult or impossible on the original, outer surfaces of nodules.

GHOST-BEARING STRUCTURE

The elements of primary carbonate rocks, like: skeletal remains, ooids, oncoids, pellets, stromatolites and lamination are preserved in the chert nodules of this structure (e.g., Figs 3B, E, 4G, H, 6A, C). Oolites occur in nodules of the Gogolin, Gorażdże, and Diplopora beds. Oncoids (Fig. 5C) occur in nodules of the Gogolin beds, pellets in nodules of the Gorażdże, Karchowice, Lima striata, and Łukowa beds, and stromatolites in nodules of the Diplopora beds. Lamination is preserved (Figs 3D, E, 7D) in nodules of the Gogolin, Gorażdże, Karchowice, Lima striata, and Łukowa beds. These elements reveal various degrees of preservation. The ghost-bearing structure is most common. It occurs in all the levels and at all outcrops. In particular nodules it covers the entire nodule or occurs together with other structures, most often with the homogenous one. Usually, the ghost-bearing structure passes into the homogenous one gradually by obliteration of the outlines of the preserved elements and diminution of their number. Sometimes, the contact between these two structures is sharp. The pores occur in two-third of the investigated ghost-bearing structure specimens. Pores are most common at the periphery of nodules under the cortex. In the interior of nodules, pores are more rare and locally absent. The rocks of this structure are usually dark. Grey, dark-grey, ashy and black colours prevail (about 56%), less often the colours are creamy, yellow or brown (25%), and rarely white (18%).

Fig. 7. **A** – Siliceous nodule, lens-shaped. Ghost-bearing structure, obliterated in the outer parts. Silica with crystalline structure (blue) in the centre. Great and small cracks. Karchowice beds, Kamień Śląski; **B** – Silico-calcareous nodule. Ghost-bearing structure. Load cast of the overlying limestone on top of the nodule. No cortex. Cracks visible. Lima striata beds, Wolica; **C** – Horizontal section through the same nodule (7B). A pipe (yellow) passing from the top to the bottom, filled with limestone; **D** – Siliceous nodule. Ghost-bearing structure. Lamination preserved. Thin cortex discontinuous. Pipe passing from the top to the bottom, filled with silica. Shallow hollows corresponding to the pipe visible on the nodule's surface. Ore-bearing dolomite, Szczakowa; **E** – Agglomeration of dark silica. Homogenous structure. Boundary uneven, marked by change of colour. Łukowa beds, Siedlce; **F** – Siliceous nodule. Broad banding structure, developed on the ghost-bearing structure. Thick cortex divided into two bands: the outer band light and more porous, and the internal band beige, entering inwards along the cracks. Gorażdże beds, Strzelce Opolskie; **G** – Siliceous nodule brecciated more strongly (fragments lesser and more pushed apart) at one side. Dolomitic matrix. No cortex. Ghost-bearing structure passing into the homogenous one. Ore-bearing dolomite, Szczakowa; **H** – Siliceous nodule. Broad banding structure. Cortex of variable thickness. A normal fault of 2 mm throw, displacing the cortex, too. The nodule is surrounded by limestone in an envelope type. Gogolin beds, Wojkowice

HOMOGENOUS STRUCTURE

This structure (Figs 3H, 4G) is uniform, devoid of primary elements or with very rare ghosts of those elements, which usually can be distinguished under high magnification only. The porosity was only observed in one-third of the investigated specimens, where the pores are always rare. Light colours are dominant: white and grey typify 65% of specimens, creamy and yellow about 18%, dark-grey, ashy and black 16%. The darker colour of the ghost-bearing structure is probably induced by a greater content of organic matter and water.

DISTRIBUTION OF GHOST-BEARING AND HOMOGENOUS STRUCTURES

Theoretically, the difference between the ghost-bearing and homogenous structures could have been inherited after primary carbonate rock: the ghost-bearing structure after organogenic, oolitic or laminated limestone, and the homogenous structure as a result of silicification of micritic limestone. Such genesis is possible in the case of alternation of the ghost-bearing and homogenous structures, and perhaps in the case of a sharp boundary between both structures. However, transition from the ghost-bearing structure to homogenous one through the gradual obliteration of outlines of fossils, ooids, etc. proves that both structures were formed independently of the kind of carbonate sediment.

When both structures co-occur in one nodule, their spatial relation may be variable, but usually the ghost-bearing structure occupies the interior of the nodule, and the homogenous structure builds nodule's peripheries (Figs 3F, G, 4G, 6C). We can assume that silicification was running in two stages: the ghost-bearing structure was formed in the first stage, and the homogenous structure in the second one. Transformation of the ghost-bearing structure into homogenous structure advanced from the exterior to interior of the nodule. Probably, this transformation was connected with a new supply of silica into the nodule. At that time, the organic matter was superseded, rock was brightening, and the porosity was diminished by precipitation of silica in pores. This transformation either covers the whole nodule or is stopped, with the interior of the nodule remaining in the ghost-bearing structure. The formation of ghost-bearing and homogenous structures has nothing in common with the opal A – opal CT – quartz transformations. Probably, all the chert nodules passed these transformations.

The occurrence of ghost-bearing and homogenous structures in chert nodules was observed and interpreted by some authors. According to Swett (1965), the original fabrics is preserved in microcrystalline cherts, but is destroyed in the fine- and medium-crystalline ones. The fabrics preservation resulted from rapid silicification. Rio (1978) documented in the Cretaceous flints of the Alps that original structures were preserved in initial stages of silicification and became obliterated in the late stages. The silicification described by Rio (1978) as accompanying the formation of ”silex cerebroide” differs totally from silicification observed in the Muschelkalk of Poland. Following Jones and Knauth (1979), the early silicification is contributing to the preservation of diagenetic textures, radiolarian, and sponge spicules. Becq-Girodon *et al.* (1992) stated that in the Ordovician chert of Montagne Noir, frequent presence of undisturbed fossil remains suggested an early formation linked to the physico-chemical modifications occurring in unconsolidated sediment around a decaying organism. Hence, all these authors consider that the ghost-bearing structure was formed during early diagenesis, and one author (Rio, 1978) concludes that it preceded the formation of the homogenous structure. On the contrary, Steinitz (1981) claims that in the earlier stage silicification tends to obliterate all constituents of the rock, and later only the matrix of the rock is silicified. On the figures in his paper (figs 36 and 37), the homogenous structure is surrounded by the ghost-bearing one.

STRUCTURE OF BROAD CONCENTRIC BANDING

This banded structure (Figs 3I, 4E, 6A, 7F) appears in all the studied horizons which bear chert nodules in the Muschelkalk. Nodules of this structure are composed of concentric bands (between 2 to 9 in one nodule). Particular bands are distinguished by colour, structure or mineral composition. In the simplest case, at the outer surface of a nodule, under 1-mm-thick cortex, a very dark band occurs showing a continuous passage to the interior of the nodule (Fig. 3B). Probably, the organic matter was concentrated at the periphery. In some cases, apart from the outer dark band, there is another dark area in the centre of the nodule (Fig. 6A). In some nodules with greater number of bands, alternation of siliceous, silico-carbonate or carbonate bands may occur. In other cases, the bands with ghost-bearing structure alternate with those with homogenous structure. The origin of this structure is not clear. In some cases, it could be formed through changes in the physico-chemical conditions at the time of the nodule's outward growth, while in other cases it could be formed during later diagenesis. Some concentric banded chert nodules in the Karchowice beds at Tarnów Opolski and Strzelce Opolskie, with a little crumpled structure of the interior, seem to present the incipient stage of the mottled structure formation.

STRUCTURE OF THIN CONCENTRIC BANDING OF THE LIESEGANG RINGS TYPE

In the ore-bearing dolomite at Szczakowa, there occur numerous chert nodules which are concentrically banded in a particular way. Three zones can be distinguished (Fig. 6B, C).

1) The core of the nodule, which is not banded, usually ellipsoidal, with the ghost structure or rarely homogenous structure. In some cases, two cores occur in elongated nodules. The thickness of the core ranges from 5 to 60 mm, its width from 10 to 110 mm, and the rate of width to thickness is usually between 1.5 and 2.7, sometimes greater.

2) The core is surrounded by a 4–17-mm-thick zone of concentrically banded, alternating light and dark streaks,

usually visible macroscopically only. The thickness of one pair of streaks is from 0.7 to 2.5 mm and it decreases from the interior of the nodule outwards. The light streaks are usually thicker than the dark ones. The number of pairs of streaks in one nodule is from 3 to 15. Probably, the dark streaks have more organic material than the light ones. The dark streak has almost always one boundary sharp and the other one diffuse. As a rule, the sharp boundary of the dark streak occurs on the outer side, farer from centre, but sometimes the reverse pattern can be seen. Exceptionally, there were observed both orientations in one nodule and also the streaks with undifferentiated boundaries.

3) The exterior zone, 1 to 13 mm thick, is formed by silica with the homogenous structure, commonly light, without banding. In few nodules, little concentrically banded centres occur, which occupy only a small part of the nodule. Very rarely, very fine streaks cross-cutting the concentric streaks occur in the nodules.

The opinions on the genesis of thin concentric banding can be divided into two groups: the first one assuming that the concentric structure was formed during the nodule's growth, and the second one assuming that it was generated in the already formed nodule. According to the first group of hypotheses (Cayeux, 1929; Pittman, 1959), the concentric streaks are traces of old cortexes of the growing nodule. According to Bissell (1959), the concentric structure is a result of rhythmical changes in physico-chemical conditions (principally pH and Eh) during the nodule's formation.

Some hypotheses of the second group assume that concentric structure was formed without any supply of the external substance. Taliaferro (1934) described flints composed of alternating, concentric streaks of chert and chalcedony. He interpreted this structure as a result of shrinkage of silica gel and the generation of concentric cracks, later filled with chalcedony. Orme (1974) assumed that the concentric structure was formed at the time of dehydration and recrystallization of flints by rhythmical segregation and migration of solutions and precipitation of admixtures. According to Wang and Merino (1990), this structure resulted from autocatalysis during gel crystallization. The catalyst Al^{2+} was alternatively enriched and impoverished. The streaks are formed by bands of chalcedony with alternately twisted and not twisted fibres and by water inclusions. The internal boundary of these streaks is sharp and the external one is obliterated. The majority of hypotheses assume that the concentric structure of the chert nodules results from diffusion of solutions and represents the Liesegang rings, in accordance with the Ostwald's theory. Such an opinion was expressed, among others by Sujkowski (1958), De Celles and Gutschick (1983), and Świerczewska (1990).

The present paper provides only scarce data pertaining to this problem. The occurrence in one nodule of the sharp boundaries, locally on the internal and locally on the external sides of dark streaks, indicates that the movement of solutions in this nodule had two directions, i.e. inwards and outwards. The nodules with concentric banding occur nearby those devoid of concentric banding. We do not know why some nodules are subjected to the intrusion of solutions and the others are not. In the Muschelkalk, the thin concentric bands structure is confined to the ore-bearing dolomite. In other formations, the structure of thin concentric bands in chert nodules occurs in limestones, too. Perhaps, the ore-bearing dolomitization created conditions favourable for the infiltration of solutions into chert nodules.

MOTTLED STRUCTURE

The chert nodules of this type consist of mottled and broken streaks and rolls (Fig. 6D, E). These streaks are a few millimetres thick and are separated by small dark streaks, 0.2–1 mm thick. Locally, the streaks consist of laminae, about 0.5 mm thick, alternately dark and light. These nodules occur exclusively in the Karchowice beds at Kamień Śląski and Tarnów Opolski.

It seems likely that these nodules, in a semi-plastic state before lithification, were subjected to an earthquake. The shock destroyed their original structure of broad concentric banding. These bands were broken and mottled. The perturbances were greatest in the central part of the nodule which was probably the most unconsolidated one (Fig. 6F, G, H). Probably, only a part of nodules was in a semi-plastic state. There are no cracks in nodules of this structure.

The earthquake hypothesis is confirmed by the following facts:

1. very common occurrence of structures attributed to earthquakes in rocks of the Silesian Muschelkalk (Szulc, 1989);

2. the occurrence of mottled structure is limited geographically;

3. the earlier mentioned occurrence of chert nodules showing a character transitional between the structure of broad concentric bands and the mottled structure;

4. resemblance of rolls in the mottled structure at Kamień Śląski to the "crumpled clusters" structures described by Szulc (1990, fig. 16), who attributes them to the earthquake genesis.

CRYSTALLINE STRUCTURE

In some chert nodules in the Gorażdże beds at Płaza and in Karchowice beds at Kamień Śląski (Fig. 7A), silica is partly recrystallized into a fine-crystalline quartz or medium-crystalline length-slow chalcedony. The recrystallized patches in the nodule are blue or ashy. They have mostly spherical and more rarely ellipsoidal or irregular shape, with uneven border, of diameter ranging from a few millimetres to 5 cm. They never cover the entire nodule and usually occur at its peripheries.

LOAD CASTS AND PIPES

LOAD CASTS

Load casts in chert nodules were observed in the Muschelkalk in two cases only. In the Lima striata beds at Wolica there occurs a distinct, 8 mm deep load cast of the overlying limestone on top of a chert nodule (Fig. 7B). Another, similar load cast occurs in the Karchowice beds at Szymiszów. In both cases, the chert nodules are of the ghost structure. In geological literature, different examples of a plastic state of the cherts (dykes, swells, load casts) have frequently been described (e.g., Cayeux, 1929; Steinitz, 1970).

PIPES

In the load cast-bearing chert nodule from Wolica, a vertical pipe occurs (Fig. 7C). It is up to 15 mm wide and 25 mm high, and passes through the nodule from the top to the bottom. The pipe is filled with limestone. On top of the nodule, above the pipe, there occurs a small, 10-mm-deep depression, which is a result of limestone dissolution. In the ore-bearing dolomite at Szczakowa, in a chert nodule with preserved lamination, there occurs a little dipped pipe, 30 mm long and 10 to 15 mm wide, filled with silica, and bearing corresponding shallow hollows in the top and bottom of the nodule (Fig. 7D). A vertical pipe, 70 mm high and 10 mm wide, occurs in a chert nodule in the Gorażdże beds at Płaza. Empty vertical cavities with smooth walls, up to 8 mm deep and 3 mm wide, occur in a chert nodule in the Karchowice beds at Strzelce Opolskie. They differ from the described voids after dissolved fossils by their smooth walls and vertical position.

The origin of these forms is uncertain; they probably represent canals left by ichnofauna. Undoubtedly, they were formed before the nodule's lithification. Rio (1982) described from the Cretaceous of the Alps pipes passing through chert nodules, either filled with silico-carbonate rock or empty, but he did not interpret these forms.

NODULE BORDER

SILICA AGGREGATES WITHOUT DISTINCT BORDER

Such aggregates occur in the Łukowa beds, being marked only by a darker colour than that of the surrounding rock. They have irregular or rounded shapes (Fig. 7E). In the Karchowice beds at Szymiszów and in the Diplopora beds at Kamień Śląski, there occur siliceous aggregates which form in part an acute-angled fragment with distinct boundaries, and in part a body with indistinct, blurred boundaries.

NODULES WITH DISTINCT BORDER

In these nodules, the boundaries are marked by changes in the mineral composition, texture, colour, and by a clear contrast with the surrounding rock. Some of these nodules have on the outer surface the cortex – a thin, light band surrounding partly or completely the nodule. The nodules with and without cortex occur together in the same outcrops, but usually one of these two types is predominating. For instance, in the Gogolin beds at Płaza, the chert nodules without cortex dominate, and in the Gorażdże beds at the same locality all the chert nodules have cortex. In the Lima striata beds at Wolica nodules without cortex dominate, while in the Łukowa beds nodules with cortex prevail. However, in the Łukowa beds at Siedlce chert nodules are usually lacking the cortex. We can presume that in these cases the conditions favouring (or not favouring) the formation of cortex existed longer than in those rocks where both types occur in similar quantities. The occurrence of cortex shows no relation with the nodule structure.

Nodules without cortex

The boundaries of these nodules are either rectilinear or uneven, dental, with brows and bays, especially in grained or oolitic limestones, like, for instance, in the Gorażdże beds at Pogorzyce and in the Lima striata beds at Wolica. Often, a ferruginous streak occurs on the border of a nodule (Fig. 3E). In the Gogolin beds at Płaza (Figs 3B, 4H) and in the Karchowice beds at Tarnów Opolski, the nodules without cortex are surrounded by a dark streak, which either passes continuously into the host rock or forms a sharp boundary with the latter.

Nodules with cortex

The cortex forms a streak at the outer surface of a nodule, from a fraction of a millimetre to some centimetres thick. At some outcrops, the thickness of the cortex is much greater than at other ones. For instance, in the Karchowice beds at Strzelce Opolskie the thickness of the cortex is great (Fig. 3C), and in the Gorażdże beds at Płaza it is small. The thickness of the cortex in one nodule often changes, and sometimes the cortex occupies only a part of the outer surface of a nodule. In the nodules of elongated lens-like shape, the thickness of the cortex is greater at both extremities and lesser in the middle of the nodule (Fig. 7F). The boundary between the cortex and the core of a nodule is either right or wavy.

In the majority of nodules the cortex is porous. Some nodules have compact cortex without pores; the others have mixed cortex, partly porous and partly not porous. In this case, usually the outer part of cortex is lighter and more porous than the internal part (Fig. 7F). The colour of the cortex is usually white or creamy. The white colour has been associated with porosity long time ago (Cayeux, 1929) and at present (Zijlstra, 1995). Some geologists (Shepherd, 1972) believe that the removal of water from pores is a principal reason of cortex bleaching. The black nodules submitted to roasting are whitened. Such nodules exposed later to air moisture returned to previous black colour (this experiment was repeated by Dr. R. Michniak; pers.comm.).

In many cases, cortex enters into the nodule's interior along cracks (Figs 3A, D, 4F) to a depth of a few millimetres or centimetres. Sometimes, the cortex accompanies a whole net of cracks (Fig. 3H). These facts indicate that the cracks were formed prior to the cortex. However, in some cases this sequence was reverse. The cortex in a nodule from Wojkowice in the Gogolin beds (Fig. 7G) was displaced by a fault together with the rest of the nodule. The cortex concomitant to the cracks is sometimes locally thickened to a few millimetres (Fig. 3H). When the crack cuts the structure of thin concentric bands, the cortex widens at light streaks and narrows at the dark ones. Apart from penetrating along the cracks, the cortex locally forms the swells, up to 27 mm thick, entering inwards (Fig. 4F). Under the microscope, at magnification 10x and more, the cortex does not differ from the core and its boundaries are poorly visible.

I do not know any publication describing the cortex of Triassic chert nodules, but the cortex of Cretaceous flints of France was described in detail by Cayeux (1929) (cf. Table 2). The origin of the cortex was also discussed by Sujkowski (1958) and Carozzi (1993).

According to Cayeux (1929), Sujkowski (1958), and Carozzi (1993), the cortex of Cretaceous flints is a final product of nodule's growth from the centre outwards, formed in the deposit before the end of sedimentation and before the cracking of nodules. The porosity of the cortex is formed later by dissolution and removal of opal.

The lack of opal in Triassic chert nodules is related to the age of the nodules. The oldest opal is known from the Cretaceous.

The cortex in the Muschelkalk chert nodules was formed after the cracking of nodules. Penetration of cortex into the nodule and its thickening at the edges, where the nodule is thinnest, suggests that the cortex is a result of partial transformation of the already existing nodules. It seems likely that the cortex of Cretaceous chert nodules, described by Cayeux (1929) and Sujkowski (1958), was formed in other manner than that of the Muschelkalk chert nodules.

Table 2

Differences between the cortex of chert nodules in the Triassic of Poland and the Cretaceous of France

Triassic	Cretaceous
Chert nodules with cortex and without cortex occur together.	After Carozzi (1993), all the chert nodules have cortex. After Cayeux (1929), in some levels they have cortex and in other they have not.
There is no opal in cortex.	Opal is a constituent of cortex but it is wholly or partially removed with formation of porosity.
Cortex penetrates into nodule along the cracks.	Cortex never penetrates along the cracks.
Chert nodules with calcareous interior have sometimes cortex.	Chert nodules with calcareous interior (after Cayeux growing from the exterior to the centre) have no cortex.

CRACKS

Cracks occur in the majority of chert nodules, in contrast to carbonate nodules, which contain no cracks. The chert nodules containing cracks occur in the same outcrops along with nodules without cracks. In the investigated material there is 17% of nodules without cracks. Nodules without cracks are exceptionally abundant (about 50%) in the Karchowice and Diplopora beds. Cracks are rectilinear or arcuate; sometimes in the nodules of the ghost-bearing structure these are snake-shaped. In the nodules of the thin concentric banding structure, a crack changes sometimes its direction accompanying the concentric streak. In this case, a crack was formed later than the thin concentric banding structure. In some nodules cracks form a net covering the entire nodule (Fig. 3H) or its part (Fig. 6C).

TYPES OF CRACKS

The cracks can be subdivided into penetrative, shallow, and internal small cracks.

Penetrative cracks, usually vertical ones (Figs 3G 4G, 6B), either cut the enclosing rock and the nodule, or continue into the surrounding rock, fade abruptly on leaving the nodule. They can be filled by veins of chalcedony, calcite (Fig. 3G), micro-quartz or iron minerals. Penetrative cracks occur in a half of the investigated nodules. They are very rare in the Karchowice and Diplopora beds (22%). They could have been generated by the burden of overlying strata, when the nodules were already lithified and brittle. The earthquakes could have been a triggering factor.

Shallow cracks are vertical or oblique, passing from the outer surface of a nodule inwards to a small depth. Commonly, they are relatively wide at the nodule's surface and they are narrowing inside. In some nodules, the cracks starting at the top of the nodule predominate, while in others they originate at the bottom. The oblique cracks are usually orientated perpendicular to the bent outer surface of the nodule (Fig. 3A, D). The shallow cracks are most frequent. They occur in two-third of the investigated nodules.

Many authors (e.g., Trefethen, 1947; Sujkowski, 1958; Mišik, 1971; Chanda *et al.*, 1976) maintained that the chert nodules indurated from the outer surface and that for some time the interior of a nodule remained in a semi-plastic state, being surrounded by the outer solid and brittle crust. This crust broke easily, probably due to earthquakes.

Small internal cracks are situated in the interior of nodules and are differently orientated.

FILLING OF CRACKS

Cracks filled with deposit, filled with mineral veins, and empty cracks can be distinguished.

Cracks filled with deposit identical with that of the surrounding rock commonly occur in the ore-bearing dolomite at Szczakowa, rarely in the Gogolin beds at Pogorzyce and Strzelce Opolskie, and in the Lukowa beds at Siedlce (Figs 4G, H, 6C), exclusively in siliceous nodules and not in the silico-carbonate ones. They occur in nodules of homogenous and thin concentric banding structures, rarely in nodules of ghost and broad concentric bands structures. The deposit fills sometimes the entire crack, and sometimes only a part of the crack close to the outer surface of a nodule, when the deeper part of the crack is filled with a mineral vein (Fig. 6B). The chert nodules with cracks filled with deposit occur together with those bearing empty cracks.

The cracks in chert nodules filled with deposit were described from many formations (e.g., Trefethen, 1947; Pittman, 1959; Meyers, 1977; Rio, 1982). They were formed during early diagenesis, when the chert nodules or their exterior parts were hard and brittle, and the surrounding sediment was not yet lithified. In the ore-bearing dolomite, such conditions could have existed also after dolomitization, recrystallization and solutional disaggregation of the host rock (Bogacz *et al.*, 1973).

Cracks are often filled with veins of microcrystalline quartz, chalcedony, calcite, pyrite, and iron hydroxides. Sometimes, a part of crack is filled with calcite and a part with chalcedony. Mineral veins are frequent in the ore-bearing dolomite at Szczakowa and in the Gogolin beds at Płaza. They occur sporadically at other outcrops.

FAULTS

Faults were observed in a few instances in the ore-bearing dolomites at Szczakowa, in the Gogolin beds in Wojkowice and Grodziec, in the Gorażdże beds at Płaza, and in the Karchowice beds at Tarnów Opolski and Strzelce Opolskie. These are high-angle or vertical normal faults. No compressional faults were observed. The throw is from 1 to 4 mm (Fig. 7H).

BRECCIAS

In the investigated material, breccias were rarely observed in the ore-bearing dolomite at Szczakowa, and in the Gorażdże beds at Pogorzyce. In a typical specimen (Fig. 7G), a passage is visible from a cracked nodule to breccia, from the centre outwards, exhibited by gradual expanding of fragments and diminishing size. The general shape of the nodule is however preserved. A small dislocation of the sharp stone fragments without rounding and introduction of carbonate matrix proves that brecciation took place before the consolidation of the surrounding deposit. Rapson (1962) attributed the formation of similar breccia to syneresis of siliceous gel and dessication.

GENERAL REMARKS ABOUT CRACKS

There is a question which factor was the most important one for the formation of cracks: growing burden of overlying layers, reduction of this burden by erosion, shrinkage of nodule by dewatering, transformation of opal A to opal CT and opal CT to quartz, or earthquakes. A phenomenon of co-occurrence in the same beds and outcrops of the uncracked, cracked and brecciated cherts can be explained as follows. It is possible that in one bed the nodules were formed not contemporaneously. An earthquake could have caused various results in the nodules in a different state of lithification. The spectrum of the quake-generated fabrics can range from large cracks to uncracked nodules. The intensity of vibration in an earthquake could be very diverse in various places, and locally strong enough to form breccias. Therefore, earthquakes appear to be the most probable cause of the crack formation.

PROPOSED SEQUENCE OF CHERT NODULES FORMATION IN THE MUSCHELKALK OF POLAND

Chert nodules were formed in calcareous aerobic sediment comprising few per cent of silica and few per cent of organic matter. A part of this sediment contained an argillaceous admixture and was less permeable. In this part, silica precipitated in numerous centres and silicified limestones were formed without nodules. Other parts of deposit, with lesser amount of clay and greater permeability, contained organic matter, either concentrated in some agglomerates or dispersed in the deposit. In the agglomerates of decaying organic matter, calcium carbonate precipitated and carbonate nodules were formed. In later phases of organic decay, pH was lowered, the silica precipitated on the walls of carbonate nodules, and silicification inwards these nodules started. In deposits showing good permeability and dispersed organic matter, the silica precipitated relatively quickly in few centres and chert nodules were growing from the centres outwards. The silicification progressed in two stages. In the first stage, the middle-sized primary elements of the deposit were preserved, and in the second stage they were obliterated, and organic matter and iron were removed. The changes in chemical and physical conditions at the time of nodule's growth could have caused development of broad concentric banding structure. At the outset, the nodules were in a semi-plastic state. In this case, earthquakes could have formed the mottled structure in nodules. Later, the nodules were hardened from the outer surface inwards. At some time, the nodule's interior was in a semi-plastic state, being surrounded by a solid and brittle crust. Then, shallow cracks, limited to this crust, were formed. The chert nodules were lithified earlier than the surrounding sediment. The cortex was formed after the lithification of nodules. The transformations in the chert nodules were stopped at various stages of their development.

CONCLUSIONS

The chert nodules in the Muschelkalk of Poland occur exclusively in two regions: the Silesia and the Holy Cross Mts. These regions correspond to the close palaeoposition of the connections between the Tethys Ocean and the Muschelkalk sea (East Carpathian Gate and Moravian Gate). In both regions, the number and size of chert nodules decrease from the centre to peripheries. The occurrence of chert nodules is irregular, although abundant in certain levels, that is in rocks formed in aerobic conditions (organogenic and oolitic limestones) and in evaporitic deposits. There occur the chert nodules (siliceous and silico-carbonate) and rare carbonate nodules.

In the rocks surrounding chert nodules, the content of silica is smaller than in the rocks devoid of chert nodules. We can assume that the silica content in primary deposit at the time of the Muschelkalk deposition was more or less equal, and the formation of chert nodules was independent of an additional, external supply of silica. The influence of volcanic tuff supply seems to be negligible.

The silicified skeletal remains, originally calcareous ones, indicate that the chert nodules were formed by limestone silicification.

The horizontal dimensions of chert and calcareous nodules are always greater than the vertical ones, and they probably correspond with greater horizontal than vertical permeability of sediment, and greater horizontal silica or carbonate supply. In the limestones formed in evaporitic conditions, the chert nodules are more flattened, so the difference between their horizontal and vertical permeability was greater than in other deposits.

In the chert nodules, silicification encompasses partly or completely ooids, oncoids and minor skeletal remains. Big calcareous tests did not undergo silicification, but were later dissolved leaving the voids. Often, in the chert nodules the relics of host rocks are left, chiefly in the centre of the nodule. Silicification superseded organic matter, probably by formation of soluble silico-organic complexes and often it superseded the iron combinations, too.

Silicification can advance from the centre of the nodule outwards or from the nodule's outer surface inwards. The cases in which the nodule's outer surface is stopped on a big shell point to an outward growth of the nodule. Probably, some nodules bearing the structure of broad concentric banding were formed also by growth proceeding from the centre outwards with changing physico-chemical conditions. In nodules with silica dominating in the exterior parts and carbonate domination in the interior ones, silicification started from the outer surface and advanced inwards. These nodules were probably formed by silicification of calcareous nodules.

Two stages of chert nodule formation can be distinguished, forming two structural types: the ghost-bearing and homogenous structures. In the ghost-bearing structure, silicified elements of primary carbonate rock are preserved (skeletal remains, ooids, oncoids, lamination). In the homogenous structure, these elements are completely or almost completely obliterated. In the ghost-bearing structure organic matter is preserved to a certain degree (usually dark colours), while in the homogenous structure this matter is poorly preserved (usually light colours). The spatial relation between these two structures is such that, usually, the ghost-bearing structure occupies the centre of a nodule, and the homogenous structure is confined to the peripheries. Some nodules present only one type. Probably, the silicification forming the ghost-bearing structure took place earlier and advanced from the exterior to the centre. Later, the transformation forming the homogenous structure followed, advancing also from the exterior to the centre and destroying, partly or entirely, the ghost-bearing structure. In the ore-bearing dolomite, the structure of thin concentric banding often developed. The origin of this structure, discussed at large in the literature, is commonly attributed to the diffusion of solutions.

At least a part of the chert nodules, at a certain stage of diagenesis, was in a semi-plastic state. Later these nodules became hardened, starting from the outer surface. It is confirmed by:

1. transformation of the structure of broad concentric banding into the mottled structure in some nodules, probably due to earthquakes at the time when the nodules were in a semi-plastic state;

2. (rare) occurrence of vertical pipes in chert nodules, filled with carbonate or silica;

3. (very rare) occurrence of load casts of the overlying limestone in the top surface of chert nodules;

4. shallow cracks formed probably at the time when only the outer part of nodules was hard and rigid.

The rarity of occurence of mottled structure, load casts and pipes proves that plastic state of chert nodules persisted for a relatively short time.

The cracks occur commonly (83%) in siliceous and silico-carbonate nodules. They are rare in nodules bearing the broad concentric banding structure, and absent from the nodules with the mottled structure, and also from carbonate nodules. The uncracked, cracked, and brecciated nodules occur together in the same outcrops. Some of the nodules have cracks filled with deposit identical with the surrounding carbonate rock, indicating that these cracks were formed before lithification of the host carbonate sediment.

The cortex surrounds, either in part or entirely, the majority of chert nodules. The cortex penetrates locally deep in the interior of nodules, chiefly along the cracks. So, the cortex was formed mostly after the nodule's lithification. Nodules with cortex and without cortex occur together.

The co-occurrence of siliceous, silico-carbonate and carbonate nodules of different structural types, nodules with and without cortex, cracked and uncracked nodules, as well as nodules with and without deposit filling the cracks indicates that the nodules developed individually. It is possible that some of the nodules were growing faster and some other slower, or some were formed earlier and some later. The chert nodules with carbonate interior, and nodules whole in ghost-bearing structure or whole in homogenous structure, or partly in ghost-bearing structure and partly in homogenous structure indicate that the diagenesis of particular nodules could have stopped at different stages of their development.

Acknowledgements

I would like to express sincere gratitude to the late Dr. Ewa Piekarska-Kwiatkowska, as well as to Dr. Anna Świerczewska, Assoc. Prof. Dr. Joachim Szulc, Dr. Ryszard Michniak, Dr. Marek Doktor, Dr. Leszek Chudzikiewicz, Dr. Tadeusz Kawiak, Małgorzata Buś, M.Sc., Barbara Kietlińska-Michalik, M.Sc., Małgorzata Zielińska, Ing., and Stanisław Olbrych. Without their help the realization of this paper would not be possible. I also thank the Authorities of the Institute of Geological Sciences, Polish Academy of Sciences, and the Authorities of the Cracow Research Centre of this institute for their good will and forbearance.

REFERENCES

Alexandrowicz, S. W., 1972. Stratygrafia dolomitów kruszconośnych okolicy Zawiercia. (In Polish). *Rudy i Metale Nieżelazne*, 17: 58–60.

Arbey, W., 1980. Les formes de la silice et l'identification des évaporites dans les formations silicifiées. *Bulletin du Centre de Recherches, Production Elf-Aquitaine*, 4: 309–365.

Assmann, P., 1914. Beitrag zur Kenntniss der Stratigraphie des oberschlesischen Muschelkalkes. *Jahrbuch der Preussischen geologischen Landes-Anstalt*, 34: 268–340.

Assmann, P., 1944. Die Stratigraphie der oberschlesischen Trias. Teil II. Der Muschelkalk. *Abhandlungen des Reichsanstalt für Bodenforschung, Neue Folge*, 2: 1–124.

Becq-Girodon, J. F., Bouille, S. & Chauvel, J. J., 1992. Genesis and significance of the silico-aluminous nodules in the Ordovician of the Montagne Noir and the Massif Armoricain

(France). *Sedimentary Geology*, 77: 77–87.

Bennett, P. C., 1991. Quartz dissolution in organic-rich aqueous systems. *Geochimica et Cosmochimica Acta*, 55: 1781–1797.

Bennett, P. C. & Siegel, D. I., 1987. Increased solubility of quartz in water due to complexing by organic compounds. *Nature*, 326: 684–686.

Bilan, W. & Golonka, J., 1972. Poziom onkolitowy w środkowym wapieniu muszlowym wschodniego obrzeżenia Zagłębia Górnośląskiego. (In Polish). *Kwartalnik Geologiczny*, 16: 491–492.

Birnbaum, S. J. & Wireman, J. W., 1984. Bacterial sulfate reduction and pH: implications for early diagenesis. *Chemical Geology*, 43: 143–149.

Bissell, H. J., 1959. Silica in sediments of the Upper Paleozoic of the Cordilleran arc. In: Ireland, H. A. (ed.), *Silica in Sediments*. *Society of Economic Paleontologist and Mineralogist, Special Publication*, 7: 150–185.

Bodzioch, A., 1997. The Karchowice Formation: definition and stratigraphy. (In Polish, English summary). *Geologos*, 2: 165–199.

Bodzioch, A. & Kwiatkowski, S., 1992. Sedimentation and early diagenesis of the cavernous limestone (Röth) of Gogolin, Silesian-Krakow Region, Poland. *Annales Societatis Geologorum Poloniae*, 62: 223–242.

Bogacz, K., Dżułyński, S. & Harańczyk, Cz., 1973. Caves filled with clastic dolomite and galena mineralization in disaggregated dolomites. *Rocznik Polskiego Towarzystwa Geologicznego*, 43: 59–72.

Bojkowski, K., 1955. Dolny wapień muszlowy w okolicy Szczakowej. (In Polish). *Instytut Geologiczny*, *Biuletyn*, 97: 229–270.

Carozzi, A. V., 1993. *Sedimentary Petrography*. Prentice Hall, Englewood Cliffs, N.J., 485 pp.

Cayeux, L., 1929. *Les roches sédimentaires de France. Roches siliceuses. Mémoires de la Carte Géologique de la France*. Imprimerie Nationale, Paris, 744 pp.

Chanda, S. K., Bhattacharyya, A. & Sarkar, S., 1976. Early diagenetic chert nodules in Bhander Limestone, Maihar, Satna District, Madhya Pradesh, India. *Journal of Geology*, 84: 213–224.

Chudzikiewicz, L., 1982. Sedimentation of the Gogolin Beds in the eastern margin of the Upper Silesian Coal Basin (Southern Poland). (In Polish, English summary). *Studia Geologica Polonica*, 75: 5–57.

Clayton, C. J., 1986. The chemical environment of flint formation in Upper Cretaceous chalks. The scientific study of flint and chert. In: Sieverking, G. & Hart, M. B. (eds), *Proceedings of the Fourth International Flint Sympodium*. Cambridge University, Cambridge, pp. 43–54.

Cressman, E. R., 1962. Data of Geochemistry. Nondetrital Siliceous Sediments. *U.S. Geological Survey Professional Papers*, 440-T: 1–23.

De Celles, P. G. & Gutschick, R. C., 1983. Mississippian Wood-Grained Chert and its Significance in the Western Interior United States. *Journal of Sedimentary Petrology*, 53: 1175–1191.

Dembowska, J., 1957. Results obtained in bore-hole Radoszyce 3: Triassic. (In Polish, English summary). *Instytut Geologiczny*, *Biuletyn*, 124: 82–93.

Dickson, J. A. D. & Barber, C., 1976. Petrography, chemistry and origin of early diagenetic concretions in the Lower Carboniferous of the Isle of Man. *Sedimentology*, 23: 189–211.

Doktorowicz-Hrebnicki, S., 1935. *Feuille Grodziec. Explication. Carte spéciale du Bassin Houiller Polonais au 25 000*. (In Polish, French summary). Instytut Geologiczny, Warszawa.

Durga Prasada Rao, N. V. N., Srikari, Y. & Behairy, A. K. A., 1982. Columnar concretions in the Visakhapatnam sediments on the east coast of India. *Sedimentary Geology*, 31: 303–316.

Grodzicka-Szymanko, W., 1973. Trias. (In Polish). In: *Dankowice IG 1. Profile Głębokich Otworów Wiertniczych*, 12: 14–18 and 33–38.

Hayes, J. B., 1964. Geodes and concretions from the Mississippian Warsaw Formation, Keokuk region, Iowa, Illinois, Missouri. *Journal of Sedimentary Petrology*, 34: 123–133.

Hsü, K. J., 1976. Paleoceanography of the Mesozoic Alpine Tethys. *Geological Society of America Special Papers*, 170: 1–44.

Jones, D. L. & Knauth, L. P., 1979. Oxygen isotopic and petrographic evidence relevant to the origin of the Arkansas Novaculite. *Journal of Sedimentary Petrology*, 49: 581–598.

Kostecka, A., 1972. Calcite paramorphs in the aragonite concretions. *Rocznik Polskiego Towarzystwa Geologicznego*, 42: 289–296.

Kostecka, A., 1978. The Lower Muschelkalk carbonate rocks of the south-western margin of the Holy Cross Mountains (Central Poland). *Rocznik Polskiego Towarzystwa Geologicznego*, 48: 211–244.

Kotlicki, S. & Radek, R., 1975. The sequence of the Lower Muschelkalk in the vicinity of Strzelce Opolskie. (In Polish, English summary). *Instytut Geologiczny*, *Biuletyn*, 282: 449–474.

Kuhl, J., 1958. Tuffogenic components in the ore bearing dolomites in the Bytom Basin (Upper Silesia). (In Polish, English summary). *Przegląd Geologiczny*, 5: 200–201.

Kwiatkowski, S., 1991. Origin of the chert laminae and silicocalcareous nodules in uppermost Röth cavernous limestone at Gogolin (Lower Silesia). *Acta Geologica Polonica*, 41: 209–214.

Łabęcki, J., 1990. Petrografia – Wapień muszlowy. (In Polish). In: *Włoszczowa IG 1. Profile* Głębokich Otworów Wiertniczych*, 70: 37–49.

Łaszkiewicz, A., ed., 1961. Katalog analiz chemicznych skał i minerałów Polski. Cz.II. 1951 – 1957. (In Polish). *Prace Instytut Geologiczny*, *Prace*, 26: 1–347.

Makedonov, A. W., 1966. Sovremennyje konkrecii v osadkach i počvach. (In Russian). *Trudy Moskovskogo Obščestva Ispytatelej Prirody*, 19: 1–284.

Maliva, R. G. & Siever, R., 1988. Pre-Cenozoic nodular cherts: evidence for opal-CT precursors and direct quartz replacement. *American Journal of Science*, 288: 798–809.

Maliva, R. G. & Siever, R., 1989. Nodular chert formation in carbonate rocks. *Journal of Geology*, 97: 421–433.

Martin Penela, A. J. & Barragán, G., 1995. Silicification of carbonate clasts in a marine environment (Upper Miocene, Vera Basin, SE Spain). *Sedimentary Geology*, 97: 21–32.

McBride, E. F., 1988. Contrasting diagenetic histories of concretions and host rock, Lion Mountain Sandstone (Cambrian), Texas. *Geological Society of America, Bulletin*, 100: 1803–1810.

Meyers, W. J., 1977. Chertification in the Mississippian Lake Valley Formation, Sacramento Mountains, New Mexico. *Sedimentology*, 24: 75–106.

Mišik, M., 1971. Observations concerning calcite veinlets in carbonate rocks. *Journal of Sedimentary Petrology*, 41: 450–460.

Mišik, M., 1993. Carbonate rhombohedra in nodular cherts: Mesozoic of the West Carpathians. *Journal of Sedimentary Petrology*, 63: 275–281.

Moryc, W., 1971. The Triassic of the Foreland of Central Carpathians. (In Polish, English summary). *Rocznik Polskiego*

Towarzystwa Geologicznego, 41: 419–486.
Orme, G. R., 1974. Silica in the Visean limestones of Derbyshire. *Proceedings of Yorkshire Geological Society*, 40: 63–104.
Pastwa-Leszczyńska, C., 1962. An Example of Lithological Variableness of the Muschelkalk Deposits of the Olkusz Region. (In Polish, English summary). *Kwartalnik Geologiczny*, 6: 309–323.
Pittman, J. S., Jr., 1959. Silica in Edwards Limestone, Trevis County, Texas. In: Ireland, H. A. (ed.), *Silica in Sediments. Society of Economic Paleontologist and Mineralogist, Special Publications*, 7: 121–134.
Raiswell, R., 1976. The microbiological formation of carbonate concretions in the Upper Lias of NE England. *Chemical Geology*, 18: 227–244.
Rapson, J. E., 1962. The petrography of Pennsylvanian chert breccias and conglomerates. Rocky Mountains Group, Banff, Alberta. *Journal of Sedimentary Petrology*, 32: 249–262.
Rio, M., 1978. Les differentes étapes de la silicification dans les calcaires Cretacées du Dlois et des Baronnies. *Bulletin Bureau de Recherches Géologiques et Minieres*, *Serie II, Section 1*, 2: 111–123.
Rio, M., 1982. Les accidents siliceux dans lé Crétacé du bassin vocontien (sud-est de la France). Contribution a l'étude de la silicification des formations calcaires. *Documentation de Laboratoire Géologique, Lyon*, 84: 1–178.
Różycki, F., 1924. Stratigraphie du Muschelkalk de la partie Nord du Bassin Houiller de Dąbrowa. (In Polish, French summary). *Sprawozdania Państwowego Instytutu Geologicznego*, 2 (3-4): 431–495.
Sass, E. & Kolodny, Y., 1972. Stable isotopes, chemistry and petrology of carbonate concretions (Mishah Formation, Israel). *Chemical Geology*, 10: 261–286.
Senkowiczowa, H., 1970. The Stratigraphy of the Mesozoic in the margin of the Góry Swiętokrzyskie: Triassic. (In Polish, English summary). *Instytut Geologiczny, Prace*, 56: 7–48.
Shepherd, W., 1972. *Flint, its Origin, Properties and Uses*. Faber and Faber, London, 254 pp.
Siedlecki, S., 1952. Utwory geologiczne obszaru pomiędzy Chrzanowem a Kwaczałą. (In Polish). *Państwowy Instytut Geologiczny*, *Biuletyn*, 60: 1–231.
Siever, R., 1962. Silica solubility 0–200°C, and the diagenesis of siliceous sediments. *Journal of Geology*, 70: 127–150.
Steinitz, G., 1970. Chert "dike" structures in Senonian Chert Beds, southern Negev, Israel. *Journal of Sedimentary Petrology*, 40: 1241–1254.
Steinitz, G., 1981. Enigmatic chert structures in the Senonian cherts of Israel. *Geological Survey Israel Bulletin*, 75: 46.
Sujkowski, Z., 1958. Diagenesis. *American Association of Petroleum Geologists, Bulletin*, 42: 2692–2717.
Swett, K., 1965. Dolomitization, silicification and calcitization patterns in Cambro-Ordovician oolites from Northwest Scotland. *Journal of Sedimentary Geology*, 35: 928–938.
Szulc, J., 1989. Shallow-water carbonate basins of seismically active zones at the example of the Muschelkalk Basin of the Upper Silesia. (In Polish, English summary). *Przegląd Geologiczny*, 37: 248–252.
Szulc, J., 1990. Sedimentary processes and their tectonic controls. In: *International Workshop – Field Seminar. The Muschelkalk Sedimentary Environments*, Institute of Geological Science, Jagiellonian University, pp. 13–17.
Szulc, J., 2000. Middle Triassic evolution in the northern Pery-Tethys area as influenced by early opening of the Tethys Ocean. *Annales Societatis Geologorum Poloniae*, 70: 3–48.
Śliwiński, S., 1964. The Geology of the Siewierz Area (Upper Silesia). (In Polish, English summary). *Prace Geologiczne Komisji Nauk Geologicznych PAN, Oddział w Krakowie*, 25: 1–58.
Śliwiński, S., 1969. The development of ore-bearing dolomites in the Cracow-Silesian area. (In Polish, English summary). *Prace Geologiczne Komisji Nauk Geologicznych PAN, Oddział w Krakowie*, 57: 1–123.
Świerczewska, A., 1990. *Sylifikacja diagenetyczna w wapieniach jurajskich Jury Krakowsko-Wieluńskiej*. (In Polish). Unpublished Ph.D. thesis, Polish Academy of Sciences, Warszawa, 196 pp.
Taliaferro, N. L., 1934. Contraction phenomena in cherts. *Geological Society of America, Bulletin*, 45: 189–232.
Trammer, J., 1975. Stratigraphy and facies development of the Muschelkalk in the south-western Holy Cross Mts. *Acta Geologica Polonica*, 25: 179–216.
Trammer, J., 1977. SiO_2-Konzentrationen im Pelson der alpinen und germanischen Trias und ihre paläogeographische Bedeutung. *Oesterreichische Akademie der Wissenschaften, mathematisch – naturwissenschaftliche Klasse Anzeiger. Jahrgang 1976*, 113: 154–157
Trefethen, J. M., 1947. Some features of the cherts in the vicinity of Columbia, Missouri. *American Journal of Science*, 245: 56–58.
Wang, Y. & Merino, E., 1990. Self-organizational origin of agates: Banding, fibertwisting, composition and dynamic crystallization model. *Geochimica et Cosmochimica Acta*, 54: 1627–1638.
Weeks, L. G., 1953. Environment and mode of origin and facies relationships of carbonate concretions in shales. *Journal of Sedimentary Petrology*, 23: 162–173.
Wyczółkowski, J., 1978. The Lower and Middle Triassic sediments. (In Polish, English summary). *Instytut Geologiczny, Prace*, 93: 79–104.
Zawidzka, K., 1984. Stratigraphy and microfacies of the Muschelkalk in the northern part of the Miechów placosyncline. (In Polish, English summary). *Annales Societatis Geologorum Poloniae*, 54: 45–64.
Zijlstra, H. J. P., 1987. Early diagenetic silica precipitation, in relation to redox boundaries and bacterial metabolism, in late Cretaceous chalk of the Maastrichtian type locality. *Geologie en Mijnbouw*, 66: 345–355.
Zijlstra, H. J. P., 1995. The sedimentology of chalk. *Lecture Notes in Earth Sciences*, 54: 1–194.

Streszczenie

GENEZA NODUL CZERTOWYCH I WĘGLANOWYCH W WAPIENIU MUSZLOWYM POLSKI

Stanisław Kwiatkowski

W wapieniu muszlowym Polski nodule czertowe (krzemionkowe i krzemionkowo-wapienne) oraz węglanowe (Tabela 1) występują wyłącznie w dwóch regionach: górnośląskim i świętokrzyskim (Fig. 1, 2). Regiony te odpowiadają dwóm połączeniom morza wapienia muszlowego z Tetydą – bramie wschodnio-karpackiej i bramie morawskiej. W obu regionach ilość i wielkość nodul zmniejsza się ku ich peryferiom. Występowanie nodul jest nieregularne lecz obfite w niektórych poziomach (Fig. 2), w skałach osadzonych w warunkach dobrego utlenienia (w wapieniach organogenicznych lub oolitowych) i w węglanowych osadach powstających wspólnie z ewaporatami. Nodule tworzyły się w osadzie węglanowym, niezlityfikowanym, przepuszczalnym, zawierającym kilka procent krzemionki i kilka procent substancji organicznej. W skałach zawierających nodule czertowe zawartość krzemionki w samym wapieniu jest niższa niż w skałach bez nodul, co dowodzi, że zawartość krzemionki w pierwotnym osadzie była mniej więcej wyrównana i utworzenie nodul czertowych nie było powiązane z dodatkową dostawą krzemionki do osadu. Nie było też żadnego wpływu opadów tufowych. Zsylifikowane szczątki węglanowej pierwotnie fauny dowodzą, że nodule czertowe utworzyly się przez sylifikację skały węglanowej.

Poziome wymiary nodul są zawsze większe od ich wymiarów pionowych, co prawdopodobnie wynika z większej przepuszczalności horyzontalnej osadu i większej dostawy krzemionki lub węglanu w poziomie niż w pionie. Nodule utworzone w warunkach ewaporacyjnych są bardziej spłaszczone, co świadczy, że w tych warunkach różnica między przepuszczalnościami osadu w pionie i poziomie była większa niż w innych osadach.

W nodulach czertowych sylifikacja obejmowała całkowicie lub częściowo (Fig. 5C) ooidy, onkoidy i drobne resztki szkieletowe. Duże wapienne skorupki fauny były zazwyczaj rozpuszczane z pozostawieniem próżni (Fig. 4B). Często nodule czertowe zawierają relikty skały macierzystej, zazwyczaj w centrum noduli (Fig. 3A,F, 4D) oraz żyły i romboedry węglanowe utworzone w czasie diagenezy (Fig. 5B). Sylifikacja postępowała bądź od środka noduli na zewnątrz, bądź od zewnątrz ku środkowi. W pierwszym przypadku niekiedy powierzchnia noduli zatrzymywała się na dużej skorupie (Fig. 4C). Także nodule o strukturze grubych pasm powstały prawdopodobnie przez wzrost od środka w zmieniających się warunkach fizyko-chemicznych. We wnętrzach nodul tworzących się od zewnątrz węglany dominują nad krzemionką w środku noduli (Fig. 4E, F). Takie nodule powstały prawdopodobnie przez sylifikację nodul wapiennych. Części nodul, w których dominują węglany są dużo bardziej zanieczyszczone substancją organiczną niż części, w których dominuje krzemionka (Fig. 5A).

Wyróżniono dwa etapy tworzenia się noduli czertowej. W pierwszym sylifikacja obejmuje elementy pierwotnej skały – ooidy, onkoidy (Fig. 5C), szczątki szkieletowe, laminację (Fig. 3E, D, 7D) nie niszcząc ich kształtu, zachowując część pierwotnej porowatości i tworząc w ten sposób strukturę widmową, przeważnie ciemnej barwy. W drugim stadium sylifikacja powoduje zniszczenie kształtów elementów pierwotnej skały, zmniejszenie porowatości i wyparcie na zewnątrz znacznej części substancji organicznej i związków żelaza (Fig. 3E, 6D). Usunięcie substancji organicznej następuje prawdopodobnie przez utworzenie rozpuszczalnych związków organiczno-krzemionkowych i ich odprowadzenie na zewnątrz. Powstaje struktura homogeniczna (Fig. 3H, 4G), zazwyczaj jasna. Najczęściej struktura widmowa występuje w środku noduli, a struktura homogeniczna ją otacza. Niekiedy cała nodula jest zachowana w jednej strukturze widmowej lub homogenicznej.

Oprócz tych dwóch podstawowych struktur wyróżniono: 1) strukturę grubopasmową (Fig. 3I, 4E, 6A, 7F, H), w której współśrodkowe pasma różnią się składem mineralnym, strukturą lub kolorem, 2) strukturę drobnopasmową typu pierścieni Lieseganga (Fig. 6B, C), 3) strukturę kłębkową (Fig. 6D, E) porozrywanych i skłębkowanych pasm, 4) strukturę krystaliczną (Fig. 7A) drobno przekrystalizowanej krzemionki. Struktury te współwystępują ze strukturami widmową i homogeniczną. Lokalnie obserwowano przejścia od struktury grubopasmowej do kłębkowej (Fig. 6F, G, H).

Nodule czertowe były początkowo przez krótki czas w stanie półplastycznym, o czym świadczą: 1) struktura kłębkowa powstała prawdopodobnie ze struktury grubopasmowej przy trzęsieniu ziemi, 2) rzadko występujące w nodulach pionowe rurki puste lub wypełnione kalcytem lub krzemionką – prawdopodobnie ślady ichnofauny (Fig. 7C, D) i 3) rzadko występujące pogrązy wapienia w stropie nodul czertowych (Fig. 7B)

Oprócz typowych nodul czertowych z wyraźnymi granicami występują rzadko skupienia krzemionki z zatartymi granicami (Fig. 7E).

W większości nodul czertowych występują spękania, czasem przechodzące w skałę otaczającą, czasem ograniczone do samych nodul. W nodulach krzemionkowych (nie krzemionkowo-wapiennych) spękania sa często wypełnione osadem identycznym ze skałą macierzystą (Fig. 4G, H, 6C, 7G), co dowodzi, że powstały przed lityfikacją skały macierzystej. Stwardnienie plastycznych nodul zaczynało się od zewnątrz. Początkowo tworzyła się twarda skorupka otaczająca miękkie jądro. Płytkie spękania ograniczały się do tej skorupki.

Na powierzchni większości nodul występuje jasna, porowata kora (Fig. 3C, F, H), która często wnika wzdłuż spękań do wnętrza noduli (Fig. 3A, D, H, 4F). Tworzyła się więc po powstaniu spękań. Kora noduli czertowych wapienia muszlowego Polski tworzyła się inaczej niż kora czertowych noduli kredy Francji (Tabela 2).

Wspólne występowanie w tych samych odsłonięciach nodul krzemionkowych, wapienno-krzemionkowych i wapiennych, o różnych strukturach, z korą lub bez kory, ze spękaniami wypełnionymi lub nie wypełnionymi osadem dowodzi, że diageneza w poszczególnych nodulach przebiegała różnie i zatrzymywała się w różnych stadiach swego rozwoju.