

Opoka – a mysterious carbonate-siliceous rock: an overview of general concepts

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Abstract: The opoka is a carbonate-siliceous marine sedimentary rock, forming a thick succession of Upper Cretaceous age in Poland and in another regions of Europe. This rock has been studied for over 150 years, but only the use of modern analytical techniques enables for the formulation of its mineralogical definition, which identifies the distinct features of opoka and allows it to be distinguished from other rocks (e.g. chalk, gaize). Parallel to the petrographic research on opoka, its palaeobathymetric interpretations, which were based on the palaeotectonic models of Danish-Polish Trough inversion has been revised. Depending on the model of palaeotectonic history, opoka has been interpreted as a deep-water or shallow facies, without detailed petrographic studies of its mineralogical composition. The paper presents various aspects of opoka, including: history of the term, nomenclature, mineralogical composition, microtexture and palaeoecological significance of Cretaceous opoka. New data which permit precise definition of this rock term, and its mineralogical composition are discussed in the light of palaeoecological reconstructions, bathymetry and existing models of opoka distribution.

Keywords: Cretaceous, opoka, opal-CT, siliceous sponges, bathymetry

INTRODUCTION

During the Late Cretaceous, the area of present-day Europe was covered by an epicontinental sea in which only few emergent regions existed (Fig. 1). This region was dominated by the sedimentation of carbonate mud, forming during diagenesis, a chalk (rock composed of calcium carbonate > 95% comprised of calcite elements of coccoliths – Scholle 1977, Fabricius 2007). In parts of the basin where siliceous sponges were abundant, their loose siliceous spicules lead to the formation of opoka. This rock was first introduced to the literature by Pusch (1833, 1836), but a lack of proper mineralogical definition resulted in the term being rarely used in the

geological literature and treated as a local lithological term. Recently, the use of modern analytical techniques enables the recognition of quantitative and qualitative mineralogical composition of opoka, which enables determination of its distribution, origin, and palaeoecological significance.

In the present article, we have summarised the available data on the mineralogy and microtexture of opoka and the concepts of its formation in the Cretaceous marine environments of the European Basin. The controversy surrounding the definition, mechanism of formation, and models of environmental conditions of opoka formation are critically discussed. We believe that this overview can lead the direction for future research.

OPOKA – MACROSCOPIC AND MICROSCOPIC FEATURES

The opoka is a sedimentary rock which is known from the Late Cretaceous European Basin and locally forms a thick (500–700 m) successions (Rutkowski 1965, Walaszczyk 2004, Jurkowska 2016, Jurkowska et al. 2019b, Jurkowska & Świerczewska-Gładysz 2020a). The lack of detailed mineralogical recognition of opoka composition means that the distribution of opoka in the Europe is poorly understood and only recently conducted studies enabled documentation of its occurrence in Poland, Germany, Netherlands, France and

Denmark (Niebuhr 1995, Madsen et al. 2010, Jurkowska et al. 2019b, Jurkowska & Świerczewska-Gładysz 2020a). The lack of a usable mineralogical definition of opoka resulted in many different maps of its distribution in Poland (Leszczyński 2010, 2012, Machalski & Malchuk 2019), based on macroscopic determination. In Poland, where the name opoka originates and was first described, it crops out in the Miechów Synclinorium and Middle Vistula River sections (e.g. Rutkowski 1965, Błaszczewicz 1980, Walaszczyk 2004, Jurkowska & Świerczewska 2020a, Jurkowska 2022), which were determined as areas of typical opoka occurrence (Sujkowski 1926, 1931) (Fig. 1A).

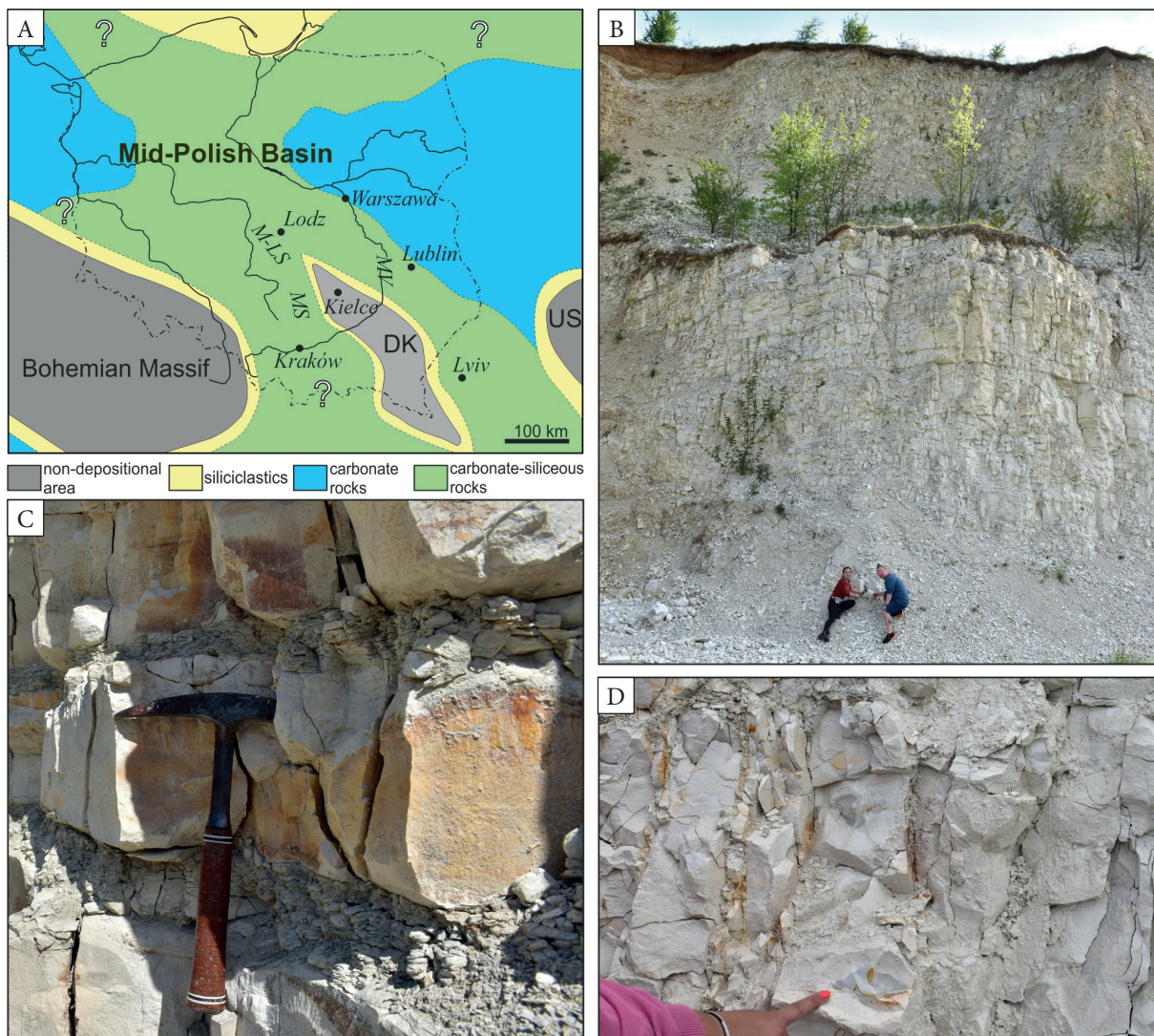


Fig. 1. A palaeogeographic map of Poland with probable distribution of the main Campanian-Maastrichtian facies; modified and compiled after: Leszczyński 2012, Jurkowska et al. 2019a, Jurkowska & Świerczewska 2020a (A); the opoka section in Rzeżuśnia (middle Campanian, Miechów Synclinorium) (B); the intercalations of marls in Biela Wielka opoka succession (lower Campanian, Miechów Synclinorium) (C); the chert nodule horizons in the opoka succession in Rzeżuśnia section (middle Campanian, Miechów Synclinorium) (D); photo Szymon Kowalik



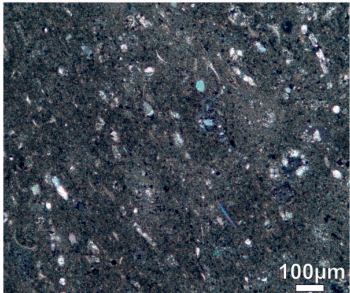
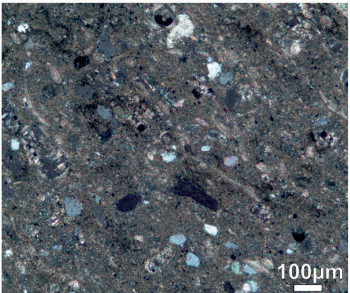
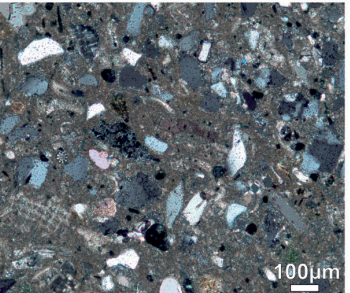
	opoka	gaize	
rock samples			
microfacies		type 1 	type 2 
XRD analysis	<p>quartz 5.9% calcite 59.4% opal-CT 25.1% clays 9.6%</p>	<p>quartz 18.9% calcite 47.6% opal-CT 14.5% clays 17.3% clinoptilolite 3.7%</p>	<p>quartz 18.4% calcite 40.0% opal-CT 26.6% clays 1.5% clinoptilolite 2.3% microcline 1.2%</p>

Fig. 2. The comparison of microfacies and mineralogical composition (XRD data after Jurkowska 2022) of opoka from Biała Wielka section (lower Campanian) and two types of gaize: type 1 from Strzeżów 1 section (upper Campanian) and type 2 from Strzeżów 2 section (lower Maastrichtian)

Moreover, outcrops of this rock were described from other localities from south-eastern (Lublin area, Roztocze Hills) and central Poland (e.g. Bełchatów Coal Mine and Mogilno near Łódź) (Pożaryski 1938, Pożaryska 1952, Klatkova 1987, Walaszczyk & Remin 2015, Remin 2015, 2018, Pękala 2019) and its known from many boreholes (Leszczyński 2010) (Fig. 1A).

In a single section, the opoka forms a layers (30–60 cm) interbedded with horizons of cherts (10–20 cm) and marly intercalations (10–20 cm) (Sujkowski 1931) (Fig. 1B–D). Opoka is usually rich in fossils, represented mainly by numerous siliceous sponges, echinoids, cephalopods and others molluscs (e.g. Kowalski 1948, Hurcewicz 1966, 1968, Błaszkiwicz 1980, Abdel-Gawad 1986, Machalski 2005, Świerczewska-Gładysz 2006, Jurkowska 2016), but poorly fossiliferous layers of opoka are also noted (Walaszczyk 2012). Microscopically

an opoka is a packstone/wackestone with foraminifers and spicules (Sujkowski 1931, Jurkowska & Świerczewska-Gładysz 2020a) (Fig. 2).

OPOKA – HISTORY OF THE TERM

The ‘opoka’, a term of Polish origin, has been in use since the 18th century in reference to hard rock used as building material in the Central Polish Uplands. In the geological literature, the term was first introduced in 1833–1836 by geologist and palaeontologist Georg Gottlieb Pusch, who adopted it from Polish miners to describe Cretaceous deposits. Pusch (1833, 1836) applied the name opoka (referred by him as the ‘Polnische Opoka’) to distinguish the hard carbonate rocks covering the major parts of the Central Polish Uplands from the ‘soft writing chalk’ covering the Lublin Upland (NE Poland). Pusch (1833, 1836) indicated

that chalk and opoka are laterally correlative facies of Cretaceous age. Despite the poor mineralogical and petrographic recognition, the term opoka has spread throughout the literature and has been widely used to characterise various carbonate rocks in Poland as well as in other countries of Europe: Germany (Niebuhr 1995, Niebuhr & Prokoph 1997, Niebuhr et al. 1997, Wilmsen & Niebuhr 2017), the Czech Republic (Bosák 2000, Mikuláš 2006, Cajz & Valečka 2010), Cyprus (Bragina & Bragin 1996), Lithuania (Kavaliauskait et al. 2006), Ukraine (Machalski & Malchuk 2016).

In 1931, Sujkowski presented an extensive field and petrographic study on the Upper Cretaceous opoka of the Central Polish Uplands and proposed a definition of opoka. This study defines the opoka as a porous, Upper Cretaceous carbonate rock used as a building material. The main feature of this rock, which distinguished it from other carbonate rocks (limestones, marls), is a significant amount of siliceous sponge spicules. Because the definition of opoka was based on field observations one of the main criteria used was its weak reaction with HCl, after which the rock does not disintegrate (see Sujkowski 1931: 493–494). Moreover, Sujkowski (1931) determined the main features of opoka as high calcium carbonate content, presence of dispersed silica in a matrix (from sponge spicules dissolution) and low content of terrigenous minerals (<4%). Due to lack of advanced analytical techniques which enable the estimation of quantitative and qualitative mineralogical rock composition as well as identification of silica polymorphs Sujkowski (1926, 1931) and other authors (Pożaryski 1938, Kowalski 1948), in the petrographic description of the opoka, included a percentage [%] content of fossil skeletons of rock forming organisms. Such an approach to the definition of opoka resulted in the rock being described in terms of its percentage content of sponge spicules, foraminifers and radiolarians (Sujkowski 1931, Pożaryski 1938). The first one has been treated as an exponent of the silica content in the rock, what resulted from the conclusion that the silica present in opoka originates from the dissolution of siliceous sponge skeletons (Sujkowski 1931, Pożaryski 1938). The quantitative composition of opoka, including the biogenic elements and quartz were estimated based on counting the area occupied by

each component in thin section in the field of view under the microscope (Sujkowski 1931, Pożaryski 1938). The sponge spicules were counted with no distinction as to whether they are preserved as empty casts, casts with secondary calcite in-fillings or preserved as silica. For the estimation of the calcite and clay contents, Sujkowski (1931) dissolved the rock samples in 13% HCl and estimated the calcite content by measuring CO₂ content in the Geissler equipment. The clay content has been measured as the weight difference between the rock sample and its calcite content (defined as particles larger than 0.01 mm) (Sujkowski 1931). Although these analyses were time-consuming and tedious they did not enable the definition of opoka in terms of mineralogy but rather as a carbonate-siliceous rock with a significant content of sponge spicules, foraminifers and subordinate content of quartz, clays and glauconite (Sujkowski 1931, Pożaryski 1938). The first semi-quantitative mineralogical analysis of opoka was presented by Pożaryska (1952), who used the chemical method (for detailed description of the method see below) for the determination of the content of calcium carbonate, quartz and dispersed silica. Based on those study, Pożaryska (1952) estimated that the mineralogical composition of opoka was: calcium carbonate (50–70%), nondetrital quartz (20%), opal (10%) and clays (6%).

OPOKA – NEW LIGHT ON MINERALOGICAL COMPOSITION

In recent studies, a compilation of a large dataset of opoka samples (Jurkowska et al. 2019a, 2019b, Jurkowska & Świerczewska-Gładysz 2020a, 2020b, Jurkowska 2022), derived mainly from Poland and western parts of Europe, have indicated that opoka is a carbonate rock composed of calcite (38–90%) and an insoluble residue (10–62%), whose main component is authigenic opal-CT (4–46%) (Fig. 3) forming a distinctive siliceous rock framework (Fig. 4B) (Jurkowska 2022). The subordinate components of the insoluble residue are: clays (<10%), detrital quartz (<10%) and rarely zeolites (clinoptilolite <5%) (Jurkowska 2022) (Fig. 3). The characteristic feature of opoka is the small (<10%) content of terrigenous material comprising detrital quartz and clays.

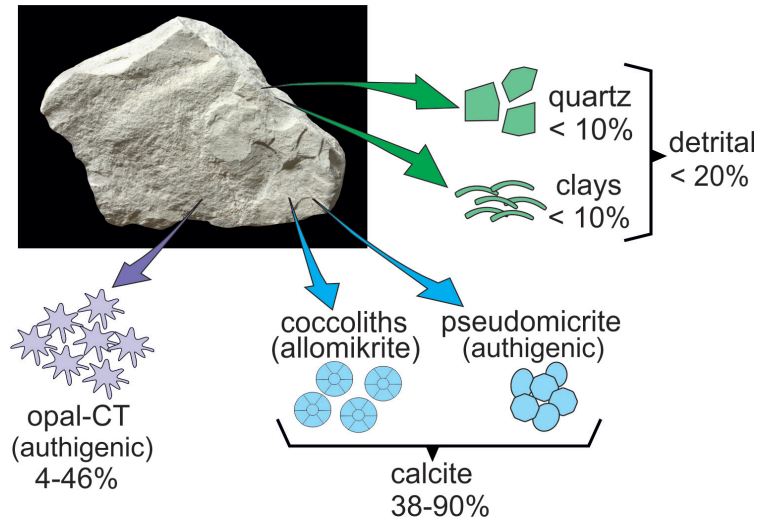


Fig. 3. The main mineralogical components of opoka, according to the definition of Jurkowska (2022)

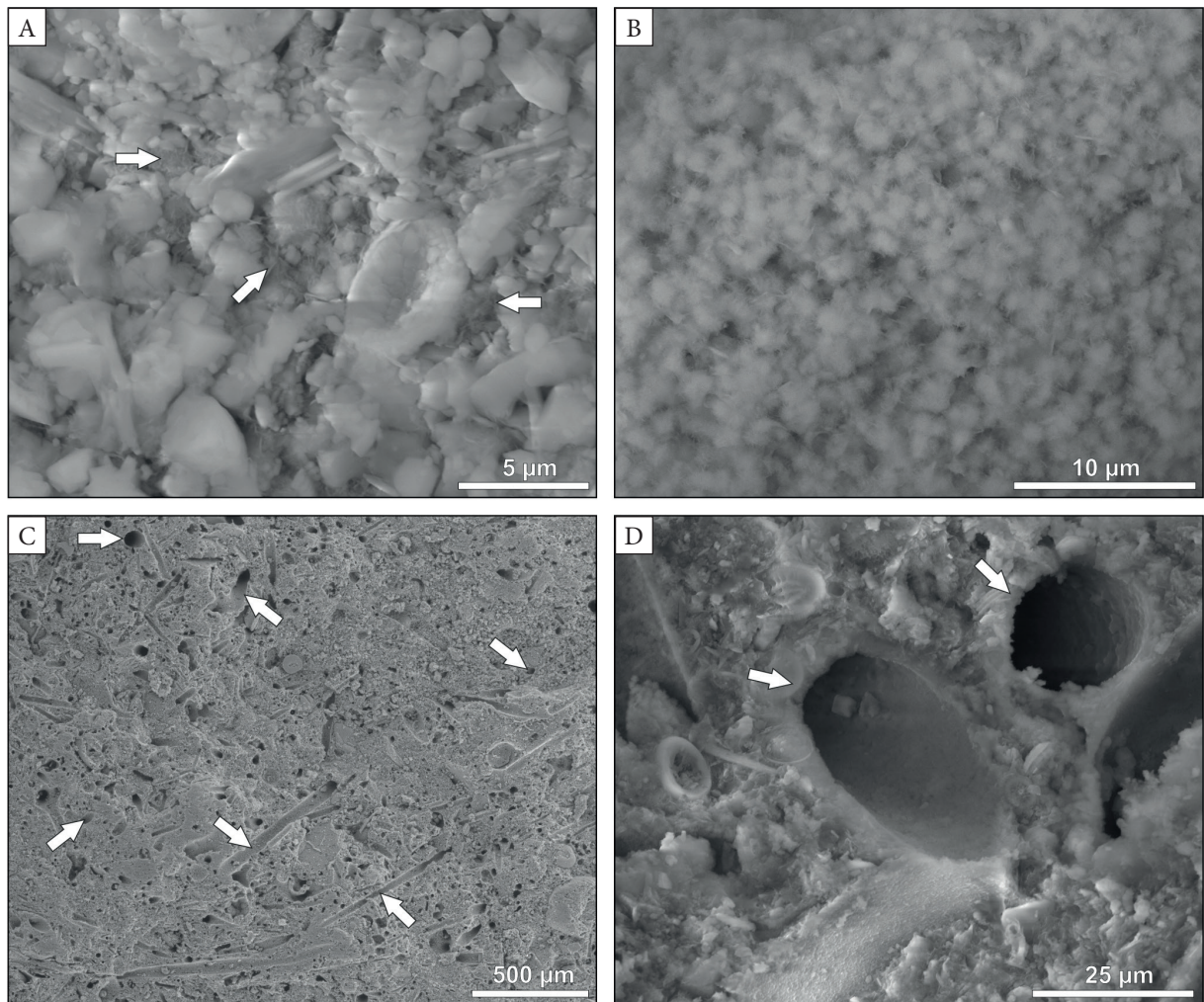


Fig. 4. Opal-CT lepispheres forming an opoka siliceous network: the lepispheres (arrowed) occupy the voids between the calcite grains (mainly coccoliths and authigenic micrite), sample: Wierzbica 1_15 (A); the framework of opal-CT lepispheres of the opoka seen after removal of calcite, sample: Wierzbica 1_15 (B); the voids left after sponge spicule dissolution (arrowed), sample: Dorotka 1_1 (C); the voids left after spicules dissolution (arrowed), covered by single layer of opal-CT hemispheres, sample: Raj N 1_4 (D)

The presence of a siliceous rock framework is one of the most distinctive features of opoka rock (Jurkowska et al. 2019b, Jurkowska & Świerczewska-Gładysz 2020a). This rock framework is formed of opal-CT lepispheres (spheres of blades) (Wise & Kelts 1972) adjoining each other (Fig. 4A, B). The opal-CT lepispheres are of various sizes ranging from 2 to 30 μm in different types of opoka, but of equal size in any one sample. The sharply edged blades forming an opal-CT lepispheres usually reach the sizes of 0.5–0.05 μm (Jurkowska & Świerczewska-Gładysz 2020a).

In general, the opoka definition of Jurkowska (2022) includes all the observations that have been made by previous authors (Sujkowski 1931, Pożaryski 1938, Pożaryska 1952, Rutkowski 1965), supplemented by the identification of the silica polymorph, which is the most distinguishable feature of this rock.

This definition includes all the mineralogical and microtextural features of opoka, which enables distinction from other similar rocks. The distinctive mineralogical composition expressed as opal-CT and insoluble residue content distinguishes opoka from chalk, which is almost pure calcium carbonate (Saiag et al. 2019). The difference between opoka and gaize (another carbonate siliceous rock which also contain opal-CT) is the higher (>10%) content of detrital quartz in gaize (Cayeux 1929, Sujkowski 1931, Jurkowska 2022). Marls differ from opoka in the higher content of clays (>10%), while cherts (which occur in opoka succession in form of horizons of siliceous nodules) can be distinguished by different microtexture and higher content (>50%) of opal-CT (Jurkowska & Świerczewska-Gładysz, 2020b).

Although the presence of silica was documented in opoka by the previous mineralogical studies, it was usually described as dispersed silica, amorphous silica or opal (Sujkowski 1931, Pożaryska 1952). The modern techniques used for the determination of quantitatively and qualitatively mineralogical composition of opoka also indicate that the methods used by the previous authors, although the best option in previous times are very imprecise in comparison with modern XRD techniques. The Pożaryska (1952) analysis with NaOH for the determination of amorphous silica was later questioned by

Rutkowski (1960), who indicate that this method cannot be used for the separate determination of the content of amorphous silica and detrital quartz. Moreover, the semi-quantitative titration method that has been commonly used for the estimation of the calcium content in the rock gives a result with a large scale of error, what has been as analytically proven by Jurkowska et al. (2019b, tab. 1).

Although modern XRD and SEM techniques enable the identification of opoka they do not resolve the problem of its macroscopic recognition in the field. Only the weak reaction with HCl, after which the opoka does not dissolved completely, as the siliceous rock framework stays in the form of a hard rock chips, could be used for the separation of opoka and chalk during fieldwork. This method has been used by previous researchers who concentrated their studies on the Cretaceous marine carbonate successions (Sujkowski 1931, Pożaryska 1952). Unfortunately, the weak reaction with HCl is also a distinctive feature of gaize. Similarly, the commonly used microfacies analysis may also fail to distinguish opoka from gaize (Fig. 2). As can be seen on Figure 2, the assumptions of quantitative quartz content (essential for gaize determination) could be misleading when are based solely on microfacies analysis. The observations of quartz content in thin section reflects rather the quartz grain size than its percentage content. To summarize, only XRD techniques supplemented with SEM observations allow the certain determination of carbonate-siliceous rocks.

OPOKA – SYNONYMS USED IN THE LITERATURE

Unfortunately, many incorrect synonyms of opoka have been created in the literature. Some of them are still in use even though the opoka definition and recommendation of the analytical techniques which enable to distinguish it have been given (Jurkowska et al. 2019, Jurkowska & Świerczewska-Gładysz 2020a, Jurkowska 2022). The term siliceous chalk was commonly used also for describing opoka from Poland (Machalski & Jagt 1998, Peryt 2000, Walaszczyk 2012, Machalski & Malchlyk 2016, Remin et al. 2021, 2022), which resulted in further confusion around the

term. From a mineralogical perspective, siliceous chalk is a carbonate rock which contain > 95% calcium carbonate in the form of coccoliths and micritic grains Fabricius (2007) (chalk) with chalcedony (= quartz) aggregates (Faÿ-Gomord et al. 2016) and authigenic nano- α -quartz (Jakobsen et al. 2000, Lindgreen et al. 2011). This definition clearly indicates that opoka and siliceous chalk are completely different rocks, reflected in mineralogical composition of silica polymorphs (quartz vs opal-CT) and the higher content of calcite in chalk (>95% in chalk vs <90% in opoka). The insufficient recognition of opoka mineralogy resulted in non-acceptance of the term in the worldwide geological literature and rocks of Cretaceous age which are carbonates (composed of coccoliths and pseudomicrite grains) and contain opal-CT were called silica-rich chalk (e.g. Noe-Nygaard & Surluk 1985, Madsen et al. 2010, Saïag et al. 2019).

The next commonly used term is a siliceous limestone (Jurkowska 2016, Remin 2018, Machalski & Malchuk 2019, Remin et al. 2022), which indicates that the rock is a limestone – carbonate rock composed of variable calcite/aragonite crystals/grains. In that sense, chalk and opoka are special types of limestone in which the calcite consists mostly of coccolith skeletons. Although the usage of that term seems to be correct, we do not recommend it because the term siliceous limestone does not reflect the distinctive features of opoka.

Another term that has been used a synonym for opoka is spiculitic limestone (Machalski & Malchuk 2019). This term suggests that opoka is a carbonate rock (limestone) and also contains spicules (or voids left after their dissolution). Besides the term lacking any mineralogical information, the preservation of spicules in opoka depends on geochemical condition during diagenesis, and cannot be treated as a distinctive feature. This term probably originates from the older studies in which the amount of spicules preserved in the rock were considered to represent the silica content of the rock (Sujkowski 1931, Pożaryski 1938). We do not recommend usage of this term as a synonym of opoka, because it reflects only a primary observation not a distinctive feature of mineralogical composition.

In the Middle Vistula River sections, the term opoka was synonymized with siliceous marls (e.g. Abdel-Gawad 1986, Walaszczyk 2012, Niechwe-dowicz et al. 2021). The opoka differs from marls, by lower content of clays (below <10% in opoka vs. ~20% in marls), moreover the microtextural difference causing by the high content of clays is distinctive feature of marls (Jurkowska 2022, Fig. 4D, E). All these features clearly indicate that siliceous marl is an incorrect synonym for the opoka. Moreover, the quantitative and qualitative mineralogical studies of some Campanian-Maastrichtian sections of the Middle Vistula River valley confirmed that the rocks which cropping out there are opoka and the content of clays is insufficient to determine them as marls (Jurkowska & Świerczewska-Gładysz 2020a).

Another term that has been used as a synonym of opoka is porcellanite (porcelanite). We do not recommend the usage of this term, which describes siliceous nodules composed of > 50% of opal-CT (Bramlette 1946, Calvert 1974, 1977, Jeans 1978, Riech & von Rad 1979, Clayton 1984, Mortimore & Wood 1986, Hesse 1988, Maliva & Siever 1989, Maliva et al. 1989, Behl 2011, Varkouhi et al. 2020, Jurkowska & Świerczewska-Gładysz 2020b). Porcellanites differ from opoka by their high content of opal-CT (>50%) and occurrence in the form of nodules. Moreover, recently conducted studies also revealed that the cherts (porcellanites) have a variable microtexture of opal-CT lepispheres, which distinguished them from opoka.

Based on macroscopic and field observation of the main rock features some authors, distinguished different types of opoka e.g., pure opoka, marly opoka, clayey opoka, porous opoka, hard opoka, argillaceous opoka or silty opoka (e.g. Pożaryska 1952, Jaskowiak-Schoeneichowa 1981, Walaszczyk 2004, Leszczyński 2010, Jurkowska et al. 2019a). These types of opoka were distinguished mostly on macroscopic studies or microfacies and further studies are needed to confirm if the features observed in a field are reflected in mineralogical composition. We recommend the use of these types – only for a local distinctions or during fieldworks.

DISCUSSION

The thick succession of opoka indicates: (1) that during the precipitation of silica polymorphs the DSi (= dissolved silicon) was available in a significant concentration (environmental factor) and (2) the massive precipitation of silica polymorphs took place after burial, during diagenesis.

Sources of silicon (Si) in opoka formation – a palaeoenvironmental link

The three prominent Si sources in the marine environment are: (1) skeletons of siliceous organisms (diatoms, siliceous sponges, and radiolarians); (2) volcanic and hydrothermal processes connected with major plate tectonic rearrangements (3) terrestrial weathering (Racki & Cordey 2000, Jurkowska & Świerczewska-Gładysz 2020a, Tréguer et al. 2021). These sources change over Earth's history as a result of the biological evolution of silicifiers and major palaeogeographic rearrangements affecting terrestrial weathering and submarine volcanic and hydrothermal activities (Racki & Cordey 2000, Conley et al. 2017).

Silicifers

Among the silicifers in Cretaceous period siliceous sponges and radiolarians were of significant importance whereas diatoms were not important before the Eocene. Of the two abundant groups of siliceous organisms siliceous sponges mainly occurred in epicontinental seas, while radiolarians were restricted mostly to deeper slope settings of oceanic environments.

The presence of abundant fossils of siliceous sponges (Bieda 1933, Hurcewicz 1966, 1968, Świerczewska-Gładysz 2006, 2012) as well as voids left after spicule dissolution in Cretaceous opoka (Sujkowski 1926, 1931, Pożaryska 1952, Pożaryski 1960, Rutkowski 1965, Świerczewska-Gładysz 2012, Jurkowska et al. 2019b) (Fig. 4C, D), led to the conclusion that the silica (opal-CT) present in opoka is biogenic and originates from spicule dissolution (Sujkowski 1931, Pożaryska 1952, Rutkowski 1965, Maliva & Siever 1989). Moreover, the stratigraphic distribution of opoka rocks correlates with periods of significant siliceous sponge

development (Pisera 1999, Cárdenas 2020) and indicates that opoka formation is linked to the mass occurrence of siliceous sponges (Jurkowska & Świerczewska-Gładysz 2020a).

The abundant voids of spicules of siliceous sponges documented in Cretaceous opoka indicates that after the decomposition of organic membranes, the opal-A of sponge spicules underwent dissolution and, in the form of DSi, saturated the porewater to a level enabling opal-CT precipitation at an early stage of diagenesis (Jurkowska & Świerczewska-Gładysz 2020a, Jurkowska 2022). In this concept, the biogenic source of Si must exist and deliver significant amount of DSi to the porewater. This observation could be confirmed with equal and similar morphology and sizes of opal-CT lepispheres observed in single samples indicating the permanent stable process of opal-CT precipitation. Such conditions could not be achieved if the process was not under the biological control, but induced spontaneously by abiotic events (as during chert nodule formation).

The difference in the opoka microtexture of opal-CT lepispheres is noted in horizons of siliceous nodules (cherts) which probably reflect variable mechanism of Si condensation and diffusion within the porewaters of the seabed mud (Jurkowska & Świerczewska-Gładysz 2020b). The densely packed large (up to 300 μm) opal-CT lepispheres documented in Cretaceous chert nodules reflect rapid opal-CT precipitation, which is characteristic for elevated DSi concentration over a short period of time (Kastner et al. 1977). The availability of an increased amount of Si could be generated by temporal events (e.g. oceanic inflows of DSi of volcanic and hydrothermal origin). In this concept, the biogenic source of Si had a subordinate role in the formation of chert horizons (Jurkowska & Świerczewska-Gładysz 2020b). According to the laboratory experiments of Kastner et al. (1977), loosely packed small (1–10 μm) lepispheres noted in Cretaceous opoka are typical in conditions of continuous DSi availability at a level enabling opal-CT precipitation. These conditions could be easily sustained by the constant delivery of siliceous sponge spicules to the seabed mud, which took place in the continuous sedimentation during opoka formation (Jurkowska 2022).

The role of individual groups of sponges as a source of DSi

In opoka, representatives of all groups of siliceous sponges are noted, but their frequency and their contribution in delivering biogenic silica (opal-A) for opal-CT precipitation and rock formation are different. The main source of silica in opoka are dispersed spicules of non-rigid demosponges (Jurkowska et al. 2019b, Jurkowska & Świerczewska-Gładysz 2020a). The presence of loose spicules in opoka was previously described by many researchers (Sujkowski 1931, Pożaryski 1938, Pożaryska 1952), but the fact that these spicules originate from non-rigid demosponges was noted for the first time by Świerczewska-Gładysz (2012). The non-rigid sponges are at present the largest and most taxonomically diverse (informal) group of siliceous sponges. Moreover, the size and organization of non-rigid sponge megascleres are variable in different taxa. Therefore, the silica content of sponge tissue also varied, e.g. in sponges from

the Ligurian Sea this value ranges from about 9 to 632 g/cm³ depending on the species (Bavestrello 1996). The taxonomic composition of non-rigid demosponge assemblages from the opoka are very poorly recognized, because body-preserved specimens are extremely rare (Fig. 5A) (Hurcewicz 1966, Świerczewska-Gładysz 2006, Jurkowska et al. 2019b) while their loose spicules dispersed in opoka are usually observed only as voids. Moreover, their microscleres which are important in taxonomic classification of sponges are only exceptionally found in opoka (Jurkowska et al. 2019b). Among the recognized Cretaceous taxa of non-rigid demosponges in opoka, representatives of *Stolleya* Schrammen, 1899, *Theneopsis* Zittel, 1878 and *Geodiopsis* Schrammen, 1910 seem to be most important silica-bearing taxa suitable for opoka formation, because their skeletons consist of extremely densely packed, relatively large (usually a few millimetres long) megascleres (oxeas and protriaenes or anatriaenes).

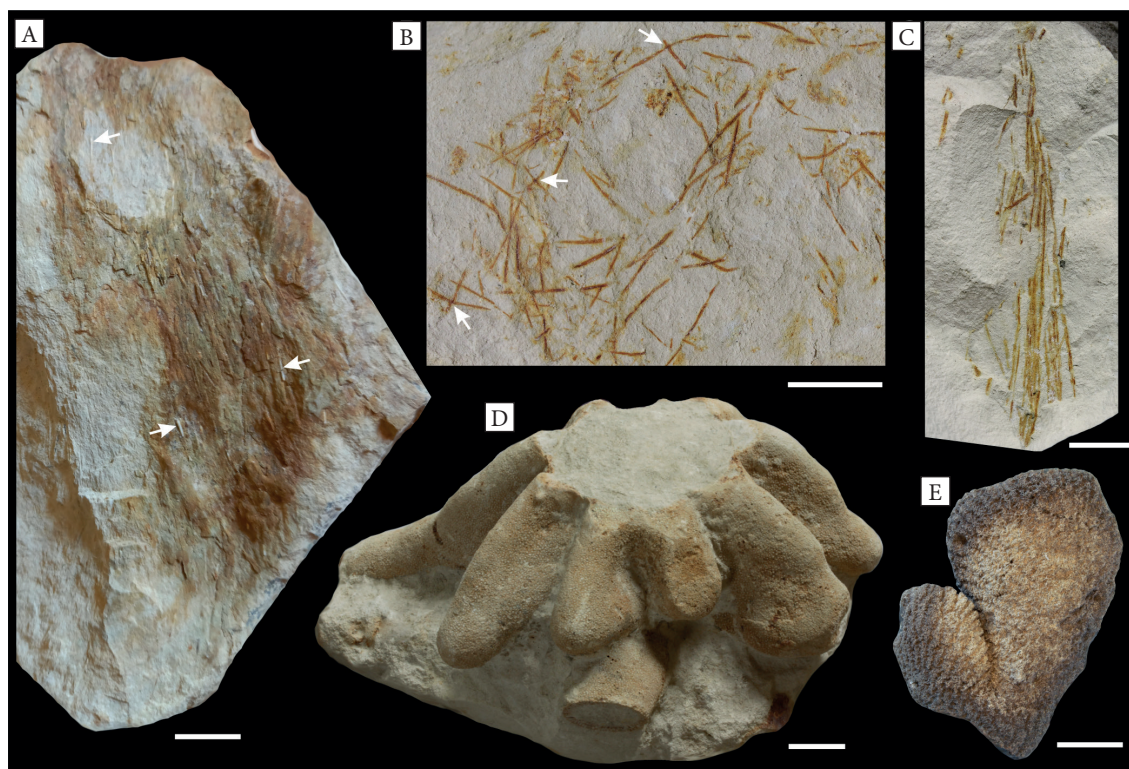


Fig. 5. Sponges from opoka: A) fragment of non-rigid demosponge (*Geodiopsis cretacea* Schrammen, 1899); visible rare siliceous protriaenes (arrowed) and dense packed limonitized oxeas; upper Campanian, Jędrzejów; B) disintegrated skeleton of non-rigid hexactinellid sponge (*Chaunoplectella* sp.); visible hexactines (arrowed) and diactines; upper Campanian, Jędrzejów; C) root tufts of non-rigid hexactinellid sponge; middle Campanian, Rzeżuśnia; D) hexactinellid sponge with rigid skeleton (*Aphrocalistes cylindrodactylus* Schrammen, 1912); E) secondary siliceous lithistid demosponge with rigid skeleton (*Rhagadina rimosa* Roemer, 1864); lower Campanian, Jędrzejów; scale bars represent 1 cm; photo Piotr Czubla

A skeleton consisting of loose spicules is also characteristic for a few groups of hexactinellid sponges. Locally in modern sea, mainly in the Antarctic shelf, these sponges are very numerous (Kersken et al. 2016) and their spicules are a significant component of spiculite mats formed on the sea bottom (Gutt et al. 2013). The mass occurrence of Late Cretaceous non-rigid hexactinellids is known only from the Coniacian of Denmark (Brückner 2006) and they probably were the main source of opal-CT presence in this rock (Madsen et al. 2010), interpreted by Jurkowska et al. (2019b) as opoka. The representatives of non-rigid hexactinellids, mainly from order Lyssacinosa Zittel, 1877, were also documented in the opoka from Poland (Fig. 5B, C) (Świerczewska-Gładysz & Jurkowska 2013), but due to their low frequency they had little participation in the formation of opoka.

Almost all body preserved sponges in opoka are represented two groups of hexactinellids – lychniscosidan and hexactinosidan (Fig. 5D) and seven groups (pleromids, isoraphiniids, corallistids, phymarphiniids, theonellids, phymatellids and rhizomorinids) of lithistid demosponges (Fig. 5E). All these sponges have rigid main (choanosomal) skeletons and a small amount of loose (mainly ectosomal) spicules. The rigid skeletons, like the spicules scattered in opoka, are also most often dissolved, but these sponges were of minor importance for the formation of opoka (Jurkowska & Świerczewska-Gładysz 2020a). Lychniscosidan and hexactinosidan sponges are usually numerous in opoka, but observation of living sponges indicates that these sponges grow very slowly and build very delicate skeletons. Therefore, their role as a source of BSi (= biogenic silica) is insignificant. Lithistids with a massive, hyper-silified skeletons could provide more BSi, but they are rare in opoka and only in some layers, e.g. in the lower Campanian of the Miechów Synclorium or the uppermost Campanian of the Middle Vistula River section (Hurcewicz 1966, 1968, Świerczewska-Gładysz 2012, 2016, Świerczewska-Gładysz & Jurkowska 2022).

The terrestrial source of DSi

The continental source of DSi comprises the DSi transported by rivers to the estuaries, the particulate silica transported by rivers which dissolves

into DSi and submarine groundwater influx (Tréguer & De La Rocha 2013). The DSi discharge of the first two processes is reduced due to existence of reverse weathering processes in deltaic and estuarine systems, where the early diagenetic precipitation of silicate diminishes the rate of DSi delivery to the seawater (Michalopoulos & Aller 2004, Presti & Michalopoulos 2008, Varkouhi et al. 2020, Varkouhi et al. 2021). In the recent Si cycle in marine environments, the overall DSi input from terrestrial sources is of subordinate importance compared to the hydrothermal input (Tréguer et al. 2021)

During the Late Cretaceous, the elevated sea levels and the significant reduction of land/island areas probably resulted in considerable reduction of terrestrial weathering influx. In the Polish part of the European Basin an emerged landmass existed with well-developed deltaic systems (Remin et al. 2016, Jurkowska & Barski 2017, Remin et al. 2022) and were a source area for terrestrial input. The petrographic analysis of nearshore argillaceous opoka deposits which were sedimented in areas adjoining the Łysogóry-Dobrogea Land revealed that the main source of DSi for diagenetic silica precipitation and opoka formation originated from siliceous sponges, which mainly settled in the offshore zone (Jurkowska et al. 2019a). Pożaryski (1938), based on the observed match between maxima of detrital quartz content and sponge spicules (noted in selected sections of the Middle Vistula River) assumed that the increasing input of terrigenous quartz was linked to the abundance of siliceous sponges. This assumption has been interpreted by Machalski & Malchyk (2019) as proof of the terrigenous source of silica for the sponge development. However, it is notable that Pożaryski (1938) observed that when the quartz content was above 2%, the opposite trend of quartz input and sponge spicule abundance was observed. Besides the fact that the mineralogical measurements of Pożaryski (1938) need to be verified, this correlation has not been observed in other part of the European Basin, where abundant sponge spicules occur also in pelagic opoka facies in which detrital quartz and clay content was insignificant (<1%) (Jurkowska et al. 2019b, Jurkowska & Świerczewska-Gładysz 2020a, Jurkowska 2022). Moreover, articles published recently by these

authors indicate that the state of preservation of sponge spicules, in addition to the voids left after their dissolution, strongly depend on geochemical conditions within the seabed mud (Jurkowska & Świerczewska-Gładysz 2020a, Jurkowska 2022) and the correlation presented by Pożaryski (1938), who used semi-quantitatively methods to estimate of sponge spicules abundance, cannot be used as a parameter controlling siliceous sponge palaeoecological distribution. At the present day, the geographical distribution of the largest non-rigid demosponge assemblages (the skeletons of which were the main suppliers of DSi for the opoka formation) are not dependent on terrigenous DSi influx, but correlate with influxes of volcanic and hydrothermal DSi (e.g. Maldonado et al. 2005, Kelly 2007, Bertolino et al. 2017). The occurrence of abundant siliceous sponges and opoka in the areas near emerged land could be linked to the oceanic contourite currents, which acted parallel to the shoreline of Łysogóry-Dobrogea Land (Krzywicz et al. 2009, 2018, Remin et al. 2022).

Volcanic and hydrothermal processes

Another source of silica for siliceous deposits in the marine environments are volcanic and hydrothermal processes that involve the transport of DSi, dissolution of Si-rich volcanic ash/glass shards, and submarine weathering of volcanic rocks (Maliva & Siever 1989, Siever 1992, Racki & Cordey 2000). This type of source has been suggested for the Late Cretaceous siliceous nodule horizons comprising quartz (flints) and opal-CT (cherts), of which the distinctive microtexture of authigenic quartz and opal-CT lepispheres is characteristic of the temporal availability of Si (in a concentration of quartz and opal-CT precipitation respectively). Thus, these occurrences could be linked to brief but significant oceanic influx containing Si of volcanic and hydrothermal origin (Jurkowska & Świerczewska-Gładysz 2020a).

The recently published data which support the model of Cretaceous opoka formation (Jurkowska, 2022) involve both biogenic and volcanic and hydrothermal potential sources of DSi in sea and porewaters. The DSi-rich waters which entered the European Basin delivered the DSi from the Atlantic Ocean, where intensive volcanic and hydrothermal processes occurred during plate-boundary

reconfigurations. During opoka formation, the siliceous sponges absorbed the DSi, the concentration of which in seawater was governed by oceanic inflows of DSi to the European Basin, where the skeletons of siliceous sponges were the source of DSi in porewaters (Jurkowska 2022). The complex process of silica polymorphs precipitation within the seabed mud involves both DSi sources and is controlled also by the geochemical conditions within the seabed mud (Jurkowska 2022).

Taking into account that the Cretaceous was well-known period of major geotectonic changes, intensive sea-floor spreading, high sea level and small areas of land, the most probable source of seawater DSi would be massive volcanic and hydrothermal activity. This process of releasing DSi or dissolvable silica particles (e.g. glass shards) was the major control on biosiliceous sedimentation in the pre-Eocene Si cycle (Racki & Cordey 2000). Moreover, the DSi content of hydrothermal fluids is much higher than the DSi input from riverine discharge (Campbell & Gieskes 1984, Cember 1996).

Mechanism of early diagenetic silica polymorph crystallization

Two main concepts explaining the mechanisms of diagenetic silica precipitation have been presented in the geological literature. Both of them were formulated based on studies of the origin of siliceous nodules and siliceous deposits of Cretaceous-Paleogene age (Calvert 1974, 1977, Wise & de Weaver 1974, Bromley 1975, Riech & von Rad 1979, Clayton 1984, 1986, Maliva & Siever 1989, Maliva et al. 1989, Madsen & Stemmerik 2010, Hesse & Schacht 2011, Lindgreen & Jakobsen 2012). The two main theories of maturation (Barton 1918, Bramlette 1946) and quartz direct precipitation (Lancelot 1973) differs in mechanisms and rates of precipitation as well as the role and significance of environmental factors. The maturation concept argued that during burial silica precipitation following the transformations pathway of opal-A → opal-CT → quartz by dissolution and reprecipitation processes (Heath & Moberly 1971, Wise & Weaver 1974, Williams et al. 1985, Maliva et al. 1989). In the classic Bramlette (1946) interpretation of the Monterey Formation the silica maturation sequence was controlled by

temperature (which increases during burial) and time (Heath & Moberly 1971, von Rad & Rösch 1974, Wise & Weaver 1974, Williams et al. 1985, Maliva et al. 1989). The maturation theory was formulated based on observations that quartz-bearing flint nodules occur mostly within older Upper Cretaceous deposits, which were subjected to the higher temperatures during burial, whereas chert nodules (of opal-CT) are mainly known from younger Eocene-Pliocene strata (Bramlette 1946). Temperature estimates for the opal-CT to quartz transformation based on for the Monterey Formation range from 55–110°C (Murata & Larson 1975, Murata et al. 1977) to 35–61°C (Pisciotta 1981). In more recent studies the lower temperatures of opal-CT to quartz transformation (17–48°C) have also been postulated (e.g. Behl 1992, Madsen & Stemmerik 2010).

Diagenetic silica polymerization and phase transformation has been interpreted as an Ostwald processes. The Ostwald ripening (a large particle grows at the expense of smaller ones) is a mechanism enabling the growth of silica polymers from a solution as well as enlargement in sizes of newly precipitated forms (Williams & Crerar 1985). The silica phase transformations from the unstable amorphous opal-A phase through intermediate opal-CT and finally to quartz (the stable phase) has been understood as an example of the Ostwald step rule (Williams & Crerar 1985, Hesse & Schacht 2011). According to the maturation theory, after opal-A dissolution, opal-CT preferentially precipitates by lowering the porewater DSi concentration to a level preventing the precipitation of opal-A. When all opal-A is dissolved, the opal-CT started to dissolve and was reprecipitated as the more ordered forms of opal-CT or quartz. Finally, when all the opal-CT has dissolved, lowering the DSi concentration, only quartz could precipitate (von Rad & Rösch 1974, Williams et al. 1985, Williams & Crerar 1985, Madsen & Stemmerik 2010).

In fact, the maturation theory contradicts the observation that in the geological record of Late Cretaceous deposits the variable authigenic silica polymorphs represented by opal-CT and quartz occur widely (Jurkowska & Świerczewska-Gładysz 2020b). Moreover, petrographic studies of Late Cretaceous chert nodules and opoka

revealed the absence of microtextural features of silica polymorphs transformations (such as co-existence of remnants of primary structures, intermediate phases, poorly developed phases, and overgrowths), which should be seen if the opal-CT to quartz conversion had occurred (Lynne et al. 2007, Jurkowska & Świerczewska-Gładysz 2020b).

The other concept presented in the literature is the quartz precipitation theory (Tarr 1917, Lancelot 1973) (see also the discussion by Jurkowska & Świerczewska-Gładysz 2020b). This hypothesises that during early diagenesis both silica polymorphs (opal-CT and quartz) could precipitate, depending on the geochemical conditions of the depositional setting. Compared to maturation theory, Lancelot's (1973) interpretation limits the role of temperature and time during deep diagenesis and rejects the silica maturation pathway governed by dissolution and reprecipitation processes. In the classical interpretation of Lancelot's (1973) quartz precipitation theory, the factor which governed silica polymorphs precipitation was the lithology of the host sediment. This assumption was based on an observation that the horizons of chert (opal-CT) nodules occur solely in zeolitic clay layers and marly tuffaceous limestones, while quartzitic flint nodules occur in chalks and limestones. The process of direct opal-CT precipitation from saturated DSi solution at a room temperature has been experimentally confirmed by Kastner et al. (1977), while the straight quartz crystallization from seawater at room temperature has been verified by Mackenzie & Gee (1971). Direct quartz precipitation, without intermediate stage of opal-CT, has been also observed by Meister et al. (2014) in Miocene deposits. Direct opal-CT and quartz precipitation during early diagenesis, without dissolution-recrystallization processes has been also confirmed in geological records of siliceous nodules and the opoka of Late Cretaceous successions (Lindgreen & Jakobsen 2012, Jurkowska & Świerczewska-Gładysz 2020b).

In the maturation theory, the Ostwald step rule has been used to explain the silica phase transformation, according to the maturation sequence, by precipitation of less stable polymorphs first as (opal-CT) which then converted into stable quartz (Heath & Moberly 1971, Wise & Weaver 1974, Clayton 1984, Williams et al. 1985, Maliva

et al. 1989). In the quartz precipitation theory, the Ostwald step rule could also be used to explain the mechanisms of silica polymorphs crystallization, but with the remark that the supersaturation of a metastable phase can prevent the formation of a stable phase (Meister 2021). In other words, in a porewater saturated with opal-CT, the opal-CT would precipitate directly out of the solution.

The mechanism of early diagenetic silica polymorphs precipitation needs a mechanism of DSi mobilization and migration in aqueous solutions. The chemical mechanism which enables the DSi mobility and condensation (in form of nodules and horizons) is a Landmesser (1995) diffusion process. This process occurs between two objects which are linked by an aquatic film and has different chemical potentials (e.g. silica phases of different solubilities or degree of crystal imperfections), from which one act as a DSi source (siliceous skeletons of organism of opal-A) and the second one as a sink (forming siliceous nodule of opal-CT). The Landmesser (1995) diffusion is contrary to the Ostwald ripening and can operate over long distances between different silica polymorphs phases and with no restriction as to the size of the final product (Rodgers et al. 2004).

Although the early diagenetic crystallisation of silica in pelagic Upper Cretaceous carbonate successions has been discussed, it is highly probable that in deeply buried successions or those which have been influenced by high temperatures, such as caused by magmatic intrusion, the maturation of opal-CT to quartz could take place following the dissolution-reprecipitation mechanisms similar to those of siliceous hot-spring deposits (Lynne et al. 2007).

The bathymetric position of opoka vs mineralogical composition

The palaeotectonic reconstructions of timing and rate of Danish-Polish Trough inversion (especially the south-eastern fragments of it) have a strong implications for the opoka and chalk palaeogeographic distribution and its bathymetric interpretation in the Late Cretaceous European Basin (Kutek & Gałzek 1972, Świdrowska & Hakenberg 1999, Świdrowska 2007, Świdrowska et al. 2008, Leszczyński 2010, 2012, Zorina & Afanas'eva 2015, Machalski & Malchuk 2016, 2020, Zorina

2020, Remin et al. 2022). Two main concepts of Mid-Polish Trough inversion have been presented in the literature and the first one indicates that the inversion started in the Maastrichtian/Paleogene (Kutek & Gałzek 1972, Świdrowska & Hakenberg 1999, Świdrowska et al. 2008), while the second one was multi-phased and started in Late Turonian-Coniacian (e.g. Dadlez 1976, 1980, Jaskowiak-Schoencheichowa 1981, Leszczyński 2000, Krzywiec 2006, Krzywiec et al. 2009). In the first interpretation of Świdrowska & Hakenberg (1999) and Świdrowska et al. (2008), which was based on facies thickness map analysis, the opoka was identified as a facies located closest to the deepest, axial part of the trough, which defines it as a deep water facies. Leszczyński (2010) did not support the Maastrichtian/Paleogene timing of the Danish-Polish Trough inversion of the Świdrowska & Hakenberg (1999) model, but assumed that the opoka was a more distal, deep-water facies while the chalk was shallower deposited in the areas more proximal to the land or in relatively shallow depth (below storm wave base) without the terrigenous input (Leszczyński 2010: 36). This view of Leszczyński (2010) was supplemented a few years later (Leszczyński 2012) who made the assumption that the main factors controlling lithofacies distribution were the distance from the shore, land topography and climate.

A series of studies performed in a last couple of years provides new data, which support the multi-phase character of the inversion and makes the tectonic history of Danish-Polish Trough even more complex by indicating that the inversion of parts of the Danish-Polish Trough started at different time and continued at different rates (Remin 2015, Jurkowska 2016). Moreover, there is a growing amount of evidence to suggest that since the ?Late Turonian or Coniacian/Santonian the axial part of the Polish Basin (Mid-Polish Trough) was an emerged landmass and acted as a barrier, rather than being the deepest part of the basin (e.g. Krzywiec et al. 2009, Walaszczyk & Remin 2015, Remin 2018). The existence of such an emerged landmass, referred to as the Łysogóry-Dobrogea Land (Samsonowicz 1925, Remin 2015, Jurkowska & Barski 2017, Remin et al. 2022) in the south-eastern axial part of Mid-Polish Trough (an areas of present-day Holy

Cross Mountains and San Anticlinorium) (Fig. 1) has been confirmed by many studies and using different methods (floral studies – Halamski 2013; foraminiferal studies – Dubicka & Peryt 2012; isotopic data – Remin et al. 2016; palynofacies analysis – Jurkowska & Barski 2017; petrographic and palynofacies analysis – Jurkowska et al. 2019b; palaeontological studies – Machalski & Malchyk 2019). This palaeogeographic reinterpretation consequently influences the interpretation of the bathymetric position of opoka, which according to the proposed facies and palaeoenvironmental models of Walaszczyk & Remin (2015), Machalski & Malchyk (2019), and Remin et al. (2022) was deposited in closer proximity to land and in a shallower setting than the offshore chalk. Moreover, according to these models, opoka is a transitional facies between the nearshore sandy deposits of significant terrigenous input, and deep water, pelagic chalk. The studies were conducted on selected Maastrichtian sections of the Middle Vistula River and Ukraine (Machalski & Malchyk 2019) and the middle Campanian of the Roztocze Hills (Walaszczyk & Remin 2015, Remin et al. 2022), which are areas lying perpendicular to the east shore of the Late Cretaceous Łysogóry-Dobrogea Land. The pattern of facies distribution presented by these authors comprises: (1) nearshore sandstone and gaize, (2) transitional opoka and marly opoka, (3) transitional marls and (4) offshore chalk, has which not been documented in the Miechów Synclinorium lying on the west shore of the Late Cretaceous Łysogóry-Dobrogea Land (Jurkowska & Barski 2017, Jurkowska et al. 2019b, Jurkowska 2022). The palynofacies analysis of Jurkowska & Barski (2017) and later detailed petrographic studies (Jurkowska et al. 2019a, 2019b, Jurkowska & Świerczewska-Gładysz 2020a, Jurkowska 2022) confirmed the existence of nearshore facies of argillaceous opoka in areas located close to the east shore of the Łysogóry-Dobrogea Land and pelagic opoka with low terrigenous input occupying the distal areas. Similarly, in the the Tercis les Bains section in western France, opoka is documented as a pelagic sediment with insignificant terrigenous input (Jurkowska et al. 2019b). This indicates that the palaeobathymetric interpretation of opoka as a relatively shallow facies deposited close to

the land is not a universal facies feature and is valid only in local reconstructions. The interpretations of opoka distribution presented by Machalski & Malchyk (2019) and Remin et al. (2022) do not rely on detailed petrographic studies, which are essential in determining if the studied rocks are really an opoka according to our definition (Jurkowska et al. 2019b, Jurkowska 2022). It could be assumed that the assumptions presented by the above-mentioned authors are a consequence of created models of palaeogeographic evolution of studied areas and, in terms of petrography, they are supplemented by the semi-quantitative analysis of mineralogical composition of rocks, including only selected components (Remin et al. 2022), or older petrographic studies based on simple analytical methods of Pożaryski (1938) (Machalski & Malchyk 2019). We would like to strongly recommend that all the facies distribution models, which include opoka and gaize should be preceded by the quantitative and qualitative mineralogical composition of rock, in order to recognize both rock types. Similar concerns have been stressed by Zorina (2020) in a response to the article of Machalski & Malchyk (2019), where she suggested that the mineralogical composition of opoka and the recognition of the origin of the silica are essential in understanding the formation of opoka and its palaeobathymetric distribution. Zorina (2020) postulated that the one of the most important component of opoka is a ‘camouflaged pyroclastic material’ comprising an assemblage of authigenic opal-CT, smectite, clinoptilolite and glauconite, co-occurring with fragments of volcanic glass (Zorina & Afanas’eva 2015). However, a mineral assemblage which is considered to be an indicator of volcanic heritage has not been detected in Polish opoka (see the discussion of Jurkowska et al. 2019b, Jurkowska 2022). This does not discredit the validity of her mineralogical analysis of opoka from the Russian Platform.

From a petrographic perspective, the one parameter of opoka mineralogy that has been taken into account in the previous studies of the bathymetric position of opoka was the quartz content (Pożaryski 1938, Pożaryska 1952). The amount of quartz in opoka has been treated as an indicator of a land proximity, which in the Pożaryski (1938)

interpretation links to regressive and shallowing trends and matches the development of siliceous sponges (Pożaryski 1938). This interpretation contradicts the assumptions based on petrographic studies which define opoka as a rock with insignificant terrigenous input (Sujkowski 1931). The detailed petrographic studies of opoka conducted by (Jurkowska et al. 2019b, Jurkowska 2022) which comprise the largest dataset of opoka samples, revealed that the distinguishing factor for terrigenous input in opoka is a quantitative and qualitative mineralogical composition of clay minerals, preceded by the microtextural studies and diagnosis of their origin (authigenic, allogenic). This observation is in agreement with the general concept of a background of terrigenous input into the Late Cretaceous European Basin based on petrographic observations (Deconinck et al. 2005, Chenot et al. 2016, Püttmann & Mütterlose 2021). Unfortunately, recently proposed bathymetric models of opoka (Walaszczyk & Remin 2015, Machalski & Malchuk 2019, Remin et al. 2022) lack any petrographic studies, which could reveal the origin of quartz and clays (detrital vs authigenic) and treats the amount of those two mineral groups as a palaeoenvironmental indicator of land proximity.

The straightforward interpretation of the chalk facies as a deep water deposit in palaeobathymetric facies models on the east coast of the Łysogóry-Dobrogea Land (Walaszczyk & Remin 2015, Machalski & Malchuk 2019, Remin et al. 2022) is also an oversimplification without detailed petrographic

study. Chalk is a carbonate rock (>95% of calcium carbonate – Fabricius 2007, Saiag et al. 2019) composed of coccoliths and is known mostly from epeiric basins and continental shelf and deep sea settings, but also rarely from shallow water lagoonal settings (Bromley & Ekdale 1984, Erba et al. 1995). Although the chalk is monotonous in mineralogical composition, detailed studies of the mineralogy of its insoluble residue and calcite microtexture revealed that there is a large variety in the composition and origin of the chalk precursor sediment. These observable differences (Faÿ-Gomord et al. 2016, 2018, Saiag et al. 2019) are linked not only to diagenesis but also to palaeoenvironmental conditions including, for example, terrestrial input and bathymetry (Bromley & Ekdale 1984, Deconinck et al. 2005, Chenot et al. 2016). Assuming that the bathymetric models which determine opoka as a shallow water, transitional facies deposited in a more proximal situation than chalk are not based on detailed petrographic studies.

The bathymetric position of opoka vs siliceous sponges

The previously discussed observations of Pożaryski (1938), who linked the quartz content and occurrence of siliceous sponges with regression, indicates that all sponges noted in opoka are shallow-water organisms. This is not in agreement with the recent state of knowledge which determine that the palaeoecological preference of various groups of sponges are different (Fig. 6).

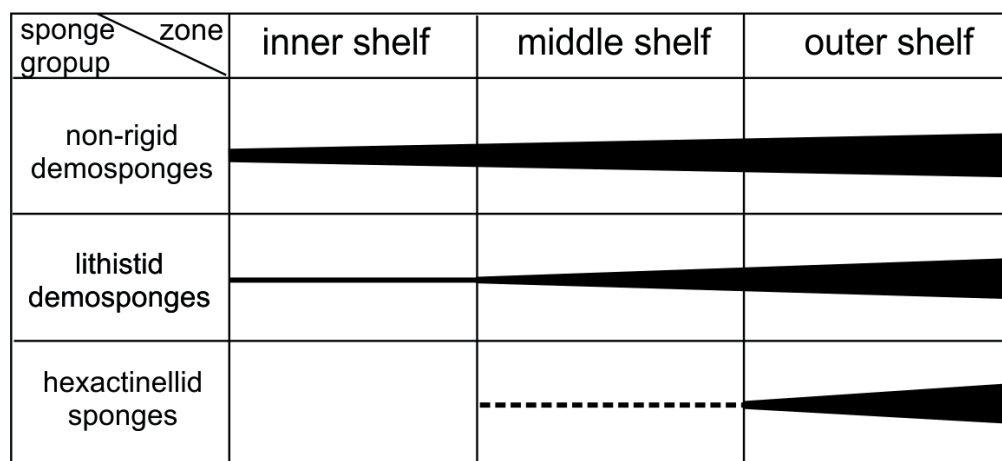


Fig. 6. Bathymetric distribution of recent group of sponges (after Hooper et al. 2002)

Recent non-rigid demosponges (which were an important group for the Cretaceous opoka formation) live at various depths, while individual groups usually prefer a narrower bathymetrical scope (Hooper et al. 2002). Some microscleres observed in the lower Campanian opoka from the Miechów Synclinorium come from representatives of the family Placospongiidae Gray, 1867, which inhabit recent seas from the intertidal zone to c. 117 m depth, and family Geodiidae Gray, 1867, which prefer mainly the bathyal zone, but occasionally occur also in deeper shelf environments (Uriz 2002). Rare body preserved specimens of non-rigid demosponges from the opoka represent Cretaceous genera which are known from outer shelf deposits of Lower Saxony Basin (Schrammen 1899, 1910) and the Opole Basin (Świerczewska-Gładysz et al. 2019), but it cannot be ruled out that these, and other unidentified taxa which contributed to the formation of opoka, lived also in shallower zones.

The best bathymetric indicators are hexactinellid sponges. These are recently known mainly from deep basin, from c. 200 to 2000 m (Hooper et al. 2002). In shallower zones (c. 100–200 m) they occur only in places with special environmental conditions (calm water, low rate of sedimentation) and where, due to the seasonal influx of ocean waters, the bottom waters are depleted in oxygen but enriched with DSi (up to 43–75 μm ; Whitney et al. 2005). Reports of these sponges at depths less than 100 m are extremely rare because their structures and life functions are adapted to slowly sedimentation and low water energy (Leys et al. 2007). The frequency of these sponges observed in situ in the opoka sections is very variable. In most of Campanian opoka sections hexactinellid are very abundant or moderately numerous (Świerczewska-Gładysz 2006), which suggested that most of Polish opoka were deposited below storm wave-base. However, in some layers of opoka from the Middle Vistula Valley (Świerczewska-Gładysz 2012) and Miechów Synclinorium (Świerczewska-Gładysz & Jurkowska 2013, Jurkowska et al. 2019a) they are very rare or only occur redeposited, and this is possibly linked to the shallowing of the sea.

Lithistid demosponges are not a good bathymetric indicator, because recent lithistids occur in

both shallow and deep waters, and some species are found at a depth of several meters (usually on coral reefs or in submarine caves). These sponges are generally not numerous in opoka and their increased abundance in some layers seems to be for various reasons. These sponges competed for habitat and nutrients with faster growing non-rigid demosponges (Świerczewska-Gładysz & Jurkowska 2022). Therefore, their appearance, as well as in parts of the white chalk (sponges beds) may be the result of a temporarily increased supply of nutrients. In these layers no decrease in the number of hexactinellida was observed. In the second case, the participation of lithistids in the sponge assemblage increases, while hexactinellids decreases, which is related to the shallowing of the Cretaceous sea (Świerczewska-Gładysz & Olszewska-Nejbert 2006, Świerczewska-Gładysz & Jurkowska 2013).

Compiling this palaeontological data with information derived from petrographic studies we assume that opoka could formed in variable depth and the bathymetry was not an essential factor which governed the opoka and chalk facies distribution.

CONCLUSION

The opoka is a sedimentary carbonate-siliceous rock that contains silica polymorphs in the form of opal-CT which forms a framework, together with a small amount of clastic material (detrital clay, quartz). The existing definition of opoka enables the distinction of this rock from other, similar facies. Laboratory techniques (XRD and SEM) allows detection of the essential component of opoka, opal-CT. The correct recognition of opoka must be based on its mineralogical composition.

The opoka is not a local facies known only from Poland but has an extensive distribution and has been noted in various sections of the Late Cretaceous European Basin. Common synonyms in the literature for opoka include: siliceous chalk, siliceous limestone, spiculitic limestone cherts should be no longer used as they are mineralogically and microtexturally imprecise.

Silica polymorphs precipitated during early diagenesis of saturated DSi porewaters. There is no microtextural or mineralogical evidence for the

formation of opoka by transformation of opal-CT into quartz during burial (maturation). The early diagenetic genesis of opoka links its origin with palaeoenvironmental conditions as well as diagenetic alternation.

According to the petrographic studies of the authors, opoka could be formed in nearshore as well as pelagic conditions, similar to chalk. The mineralogical studies enable distinction of the terrigenous component (clay and quartz) in opoka, what could be used as an indicator of source area proximity.

Regional palaeobathymetric models which define opoka as a shallow nearshore or deep offshore facies need to be underpinned by mineralogical studies in order to confirm if the studied rocks really are opoka.

Among the siliceous sponges occurring in opoka only hexactinellids are useful bathymetric indicators. Other sponges, including non-rigid demosponges, whose loose spicules were crucial for the formation of the opoka have a wide bathymetric range and do not provide grounds for assigning opoka to a strictly defined bathymetric zone.

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