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The phosphatized sponges from the Santonian (Upper Cretaceous) of the Wielkanoc Quarry (southern Poland) as a tool in stratigraphical and environmental studies

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ABSTRACT:

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Phosphatized sponges from the Santonian of the Wielkanoc Quarry are represented by 11 species of Hexactinosida and 16 species of Lychniscosida. Their species composition is most similar to the *Micraster coranguinum* Zone fauna (Middle Coniacian – Middle Santonian) of England. Three preservational groups of sponges are distinguished: 'white', 'beige' and 'dark'. They are infilled by phosphatized foraminiferal/foraminiferal-calcisphere wackestone and are contained in the marly calcareous inoceramid packstone. The sponges indicate a calm and relatively deep (> 100 m) life environment. After burial, phosphatization and exhumation, the fossil sponges were redeposited in Upper Santonian strata. The 'white' and 'beige' groups were transported laterally over a very short distance or represent lag deposits. The rolled and crushed sponges of the 'dark' group were exhumed and phosphatized more than once. They could be redeposited (reworked) nearly in the same place and/or transported from some longer distances (but not from outside the Cracow Swell).

The phosphatized sponges document the former presence in the area of part of the Middle Coniacian through Middle Santonian succession, which was removed secondarily by subsequent erosion.

Key words: Sponges; Hexactinosida; Lychniscosida; Ecology; Phosphatization; Redeposition; Lag deposit; Upper Cretaceous; Cracow Swell; Poland.

INTRODUCTION

The basal part of the Santonian succession of the Polish Jura Chain contains numerous, mostly phosphatized fossils, among which the sponges are the most numerous. The sponges are widely noted over the entire area of the Polish Jura Chain (e.g. Golonka and Rajchel 1972; Marcinowski 1974), however, apart from some taxonomic papers on the group from Korzkiew, in the area of Cracow (Małecki 1980; Świerczewska-Gładysz 1997) they were never treated in more detail and their potential in sedimentary and environmental studies was never tested. This paper presents the results of petrological and taphonomical studies on sponges from the Santonian deposits in the Wielkanoc Quarry and shows the bearing of these sponges on the interpretation of sedimentary history, environment and biostratigraphy of the Coniacian–Santonian of the area.

GEOLOGICAL SETTING

The Wielkanoc Quarry, in the southern part of the Polish Jura Chain (Text-fig. 1), offers one of the most complete early Late Cretaceous succession of the area. The 10 m-thick Turonian limestone sequence (Marcinowski 1974; Walaszczyk 1992; Olszewska-Nejbert 2005) directly overlies Oxfordian (Upper Jurassic) massive limestone (Marcinowski 1974). The Turonian succession, assigned to the late Middle–early Late Turonian *Inoceramus lamarcki–Inoceramus perplexus* zones (Walaszczyk 1992; Walaszczyk and Wood 1998, 1999), is capped by a composite hardground (Olszewska-Nejbert 2004) and overlain by c. 1.5 m thick Coniacian sandy-glauconitic limestones. The Coniacian succession contains inoceramids of the Early Coniacian *Cremnoceramus crassus crassus/deformis deformis* Zone (Walaszczyk 1992) and is covered by glauconitic marls of Late Santonian age (see Walaszczyk 1992).

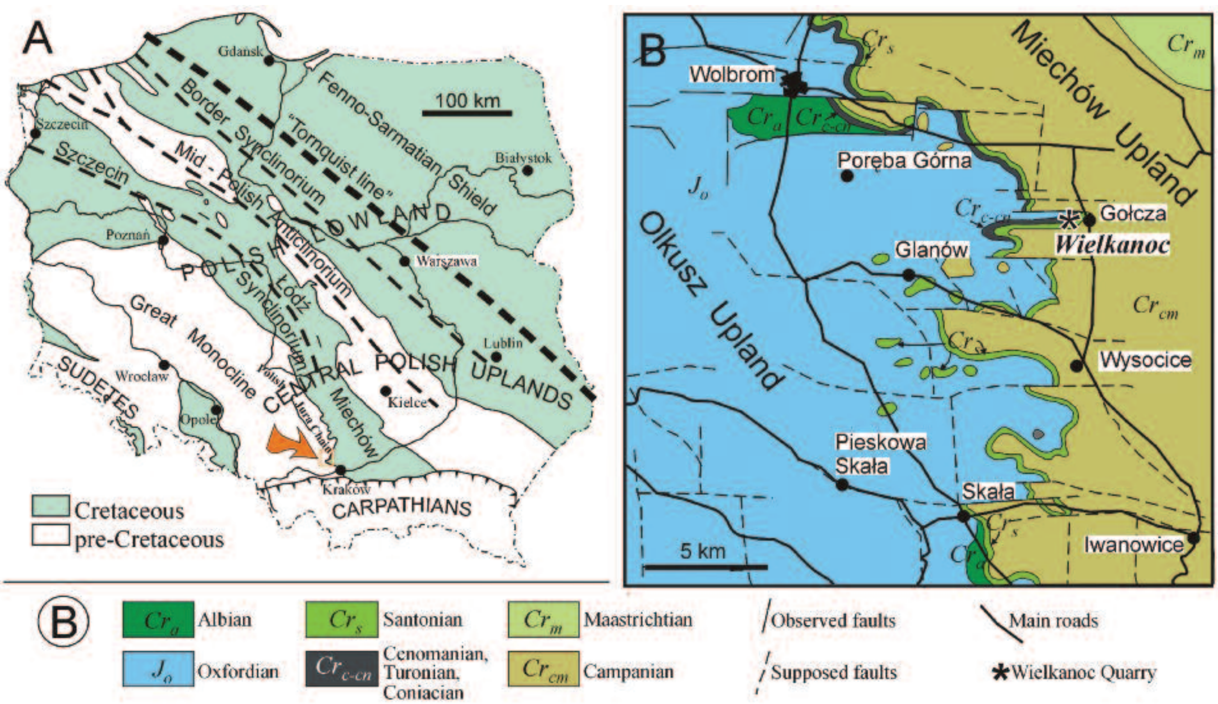
The recorded parts of the Turonian–Santonian succession in the region are only tiny fragments of the 6–7 Ma interval, most of which is represented by hiatuses (Marcinowski 1974; Walaszczyk 1992).

During the Turonian–Santonian, the Polish Jura Chain was part of the Cracow Swell (Polish Jura Swell in Marcinowski and Radwański 1983), a north-south oriented submarine high with several variously expressed discontinuity surfaces and associated stratigraphic gaps of various extents (Golonka and Rajchel 1972; Marcinowski and Szulczewski 1972; Marcinowski 1974; Marcinowski and Radwański 1983, 1989, 2009; Walaszczyk 1992; Jasionowski 1995; Krajewski *et al*. 2000; Olszewska-Nejbert 2004). The swell separated the Nida region in the east from the Opole region in the west, both with more continuous and more complete stratigraphical records (Marcinowski 1974; Marcinowski and Radwański 1983, 1989; Walaszczyk 1992; Remin 2004; Olszewska-Nejbert 2007).

MATERIAL AND METHODS OF STUDY

The sponge material collected comprises 24 specimens from the Coniacian and 149 specimens from the Santonian. As the siliceous skeletons of the sponges have been dissolved, the types of spicules were determined by the shape and distribution of the voids after the spicules. The sponges were examined by macroscopic observation and analyses of thin sections.

Polished thin sections were prepared from different types of sponges and from surrounding sediments (15 thin sections). The petrographical investigations were carried out at the Scanning Electron Microscope and Microanalysis Laboratory of the University of



Text-fig. 1 A – Tectonic sketch-map of Poland (without the Cenozoic cover) (after Marcinowski and Radwański 1983, simplified); B – Geologic sketch-map of the study area, with location of the Wielkanoc quarry (after Kaziuk 1978, modified and simplified)

Warsaw, using a Nicon ECLIPSE E600W POL optical microscope and a JEOL JSM-6380LA scanning electron microscope.

XRD analyses were undertaken on a DRON-1 diffractometer at the Institute of Geochemistry, Mineralogy and Petrology, University of Warsaw. Samples of powdered phosphatized sponges were mounted on a glassy plate and irradiated with CoK_{α} radiation. Data were collected over the range 3° to 76° 2Θ, in a step-scan mode employing 0.04 2Θ step-size, and counting time 1 s per step.

MICROFACIES ANALYSES

Lower Coniacian – *Cremnoceramus crassus crassus/deformis deformis* Zone

The Coniacian deposits, c. 1.5 m thick, consist of (Text-fig. 2): (a) [0.2 m thick] fairly solid (monolithic) limestone with glauconite; (b) [0.65 m thick] nodular limestone with rare glauconite; (c) [0.15 m thick] solid limestone with glauconite, strongly ferruginous with rare sponges and thick-shelled inoceramid bivalves or inoceramid debris; (d) [0.25 m thick] solid limestone but with rare glauconite; (e) [0.12 m thick] marly limestone with the horizon of common, horizontally lying, phosphatized sponges; (f) [0.15 m thick] solid limestone with rare glauconite and inoceramid debris, and some burrows.

The succession is built of foraminiferal or foraminiferal-inoceramid wackestone/packstone with common quartz and glauconite at the base (see Olszewska-Nejbert 2004), passing up into foraminiferal / foraminiferal-calcisphere wackestone with rare glauconite at the top (Text-fig. 2 A, B). The packstone character of the lower microfacies is a result of the abundance of quartz and glauconite, giving a grain-supported texture. The quartz content decreases towards the top. Rare echinoid and inoceramid fragments are noted in the foraminiferal/foraminiferal-calcisphere microfacies.

Upper Santonian – *Sphenoceramus patootensiformis* Zone

The Santonian is 4.3 m thick and is composed of (Text-fig. 2):

(a) [0.3 m thick] green, moderately cemented marly-glauconitic limestone, fossiliferous at the bottom, with numerous sponges, accompanied by echinoids, belemnites and gastropods. The top is marked by a horizon with small, broken sponges. The bottom layer is inoceramid packstone with numerous glauconite grains (Text-fig. 2 J, K) and rare quartz in aleuritic size. Much rarer are foraminifers, including very rare big agglutinated *Arenobulimina* sp.

(b) [4 m thick] marly-glauconitic limestone passing gradually up into glauconitic marls.

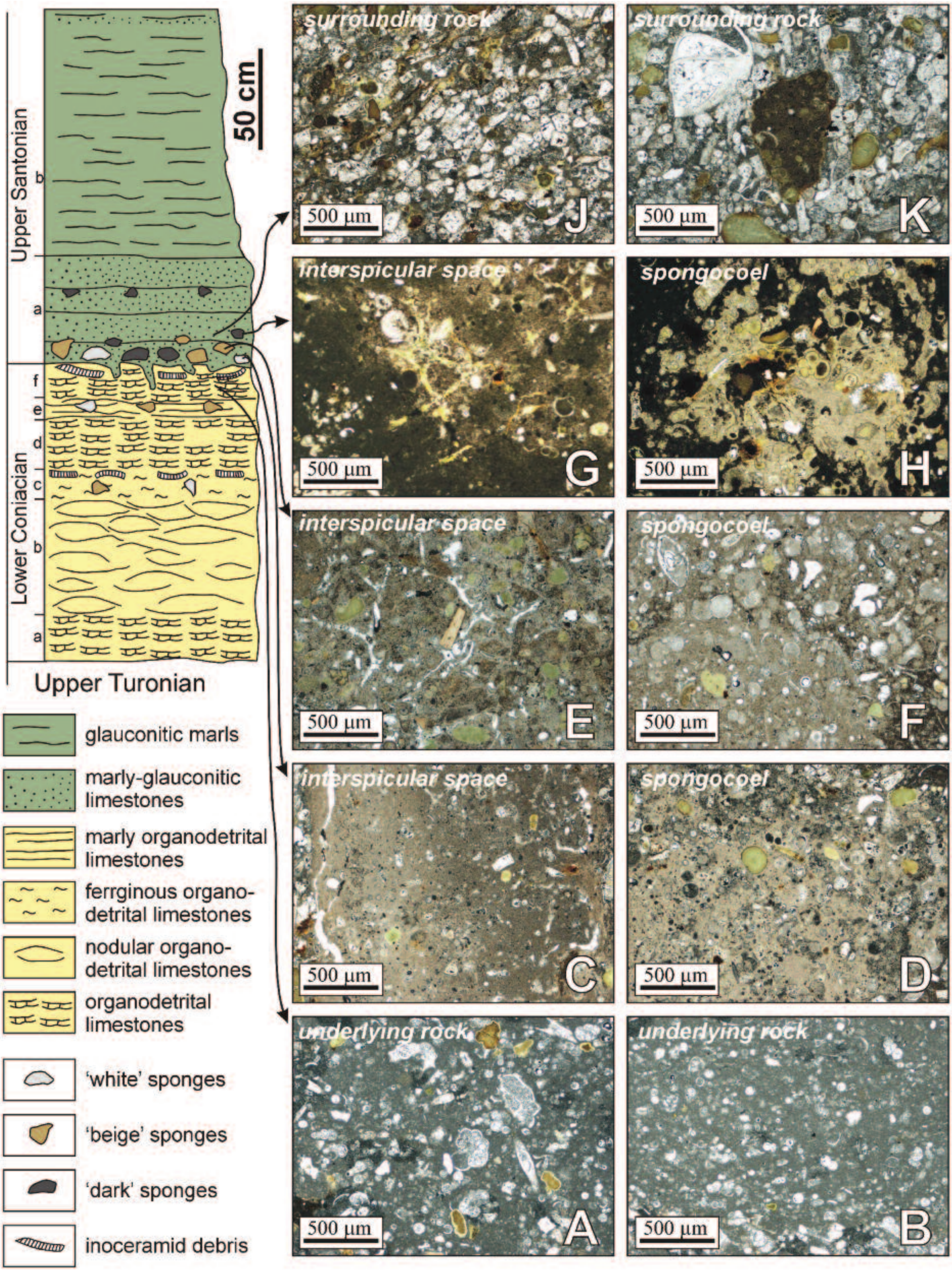
Based on inoceramids, the Santonian in the Wielkanoc section was referred to the Late Santonian *Sphenoceramus patootensiformis* Zone (Walaszczyk 1992). The foraminifers indicate a Middle–Late Santonian interval (Kopaevich in Walaszczyk 1992, p. 94).

PETROLOGY OF THE SPONGE FAUNA

Three groups of sponges and 'beige'clasts were distinguished macroscopically (Text-figs 3, 4) in the material studied:

(i) **'white'** [17 specimens]; the sponges of this group (Text-fig 3A) are white, with rare grains of glauconite, and are poorly cemented. The sponges are not destroyed, but the morphology of their outer surface is not clear, due to poor cementation. The interspicular space and spongocoel are infilled by phosphatized foraminiferal or foraminiferal/calcisphere wackestone with rare glauconite (Text-fig. 2C, D). Rarer particles include echinoid and inoceramid fragments, and very rare quartz grains. The characteristic element of the spongocoel infilling are rare large agglutinated foraminifers (*Arenobulimina* sp.), about 1 mm in size, similar to those known from Santonian deposits. In SEM images it is possible to see that the interspicular spaces and spongocoels are infilled by hexagonal francolite plates about 2.5 μm (Text-fig. 5B-E). Spaces after siliceous spicules are usually empty (Text-fig. 5A). Calcite relicts are visible in SEM images (Text-fig. 5F) and XRD investigation shows a constant admixture of calcite (Text-fig. 8A). Besides francolite and calcite, quartz has been identified from XRD data (Text-fig. 8A). The calcite could have come from non-dissolved calcareous mud infilling the interspicular space and/or spongocoel, and from secondary infillings of spicules or foraminiferal chambers by calcite. The francolite crystallized from pore water, strongly saturated in ions of HPO_4^{2-}. The quartz could be detrital and/or represented by non-dissolved relicts of siliceous spicules (the second variety is rather rare).

(ii) **'beige'** [92 specimens]; sponges of this group are beige, contain glauconite grains, and are well cemented. These sponges are not destroyed (Text-fig. 3B), and the morphology of the outer surface is clearer. The interspicular space and spongocoel are infilled by phosphatized foraminiferal or foraminiferal/calcisphere wackestone with glauconite (Text-fig. 2E, F). Less common particles include echinoid and inoceramid fragments and very rare quartz grains. In SEM images, interspicular



space and spongocoel are seen to be infilled by hexagonal francolite plates about 2.5 μm and clay minerals (Text-fig. 6). Spaces after former siliceous spicules are empty (Text-fig. 6A) or infilled by secondary calcite cements (Text-fig. 6F). Glauconite is quite common, sometimes infilling the foraminiferal chambers (Text-figs 2E and 6D), whereas the original calcite wall of the foraminifera is dissolved (Text-fig. 6C). XRD patterns show smaller amounts of calcite, a larger amount of francolite, and similar amounts of quartz (Text-fig. 8B) in comparison to the XRD patterns of sponges of the 'white' group (Text-fig. 8A).

(iii) **'dark'** [40 specimens] The sponges of this group (Text-fig. 3C) are dark-coloured with rare grains of glauconite, and strongly cemented. These sponges are destroyed, crushed and with an obliterated outer morphology. The interspicular spaces and spongocoels are also infilled by phosphatized foraminiferal or foraminiferal/calcisphere wackestone with glauconite (Text-fig. 2G, H). Much less common are echinoid and inoceramid fragments, and quartz grains are very rare. In SEM images, interspicular space and spongocoel are seen to be infilled by hexagonal francolite plates about 2.5 μm and by a large amount of clay minerals (Text-fig. 7). The spaces after siliceous spicules are poorly preserved and infilled by glauconite (Text-figs 2G and 4C, D) or secondary calcite cements. Glauconite is quite common, sometimes also infilling the foraminiferal chambers (Text-fig. 2G). Coccolith plates, with francolite hexagonal plates and clay minerals, are common in the spongocoel (Text-figs 7D). XRD patterns show smaller amounts of calcite and larger amounts of francolite compared to the mineralogical composition of both groups described above (Text-fig. 8C).

(iv) **'beige'clasts**; they consist of fragments of 'dark'sponges (Text-fig. 4). The interspicular space and spongocoel of these sponge fragments are infilled by phosphatized foraminiferal or foraminiferal/calcisphere wackestone with glauconite (Text-fig. 4C–G); the beige matrix of the clasts (Text-fig. 4B–H) is phosphatized wackestone. The difference is only in colour; the matrix is similar to the material of the 'beige' sponges.

All groups of sponges and the 'beige' clasts occur in the lower part of the Santonian glauconitic marly limestone; 'white' and 'beige' sponges are found in the Coniacian limestone. Transitional forms exist between the 'white' and 'beige' sponges.

PALAEONTOLOGICAL ANALYSIS

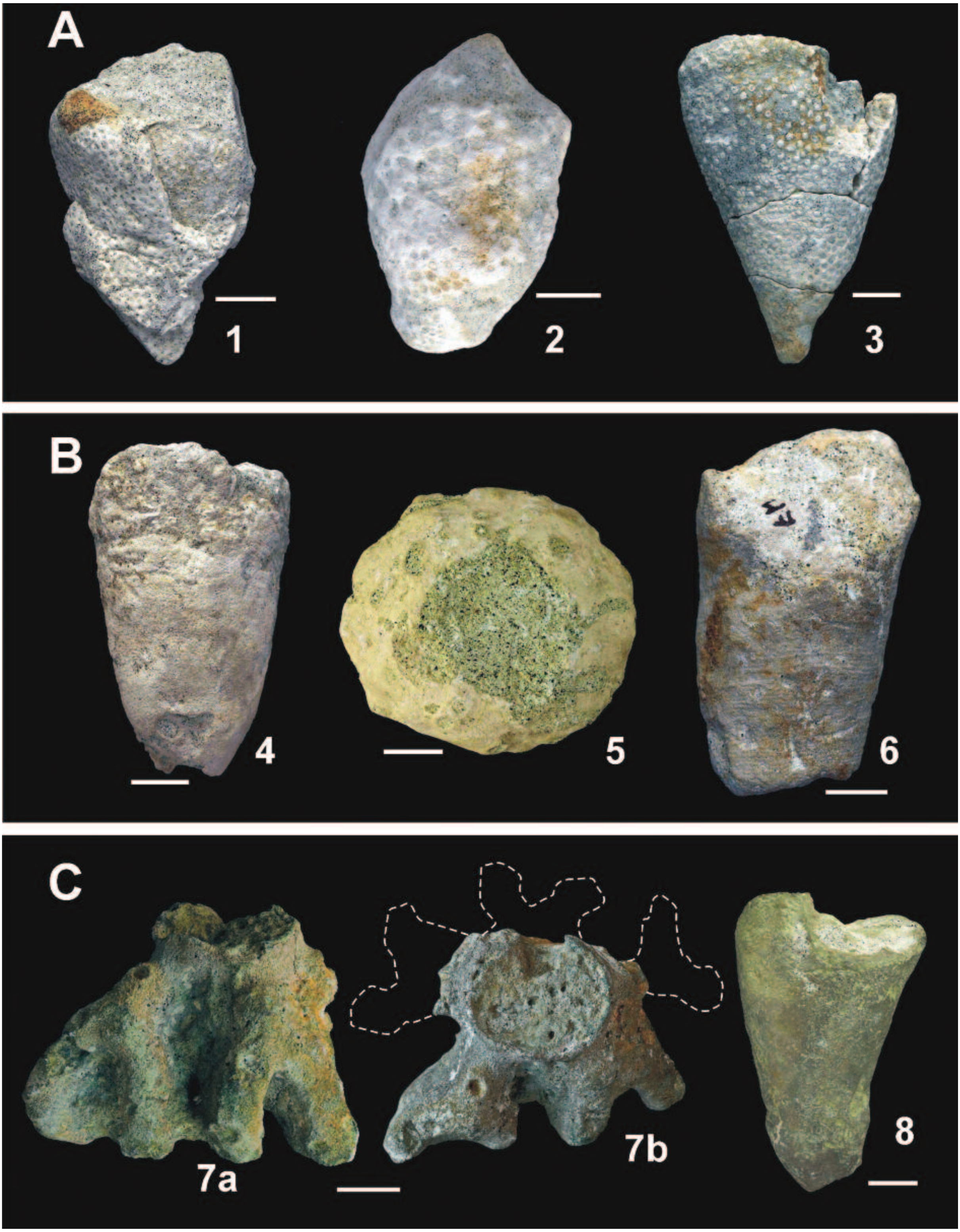
Taxonomic composition

Twenty-seven species of Hexactinellida have been recognized in the Coniacian and Santonian deposits (Table 1), representing the orders of Hexactinosida (11 species) and Lychniscosida (16 species). The presence of a lithistid group as an accessory element is proved by rare desms (rhizoclones and tetratraclones) in the phosphatized material infilling the spongocoels.

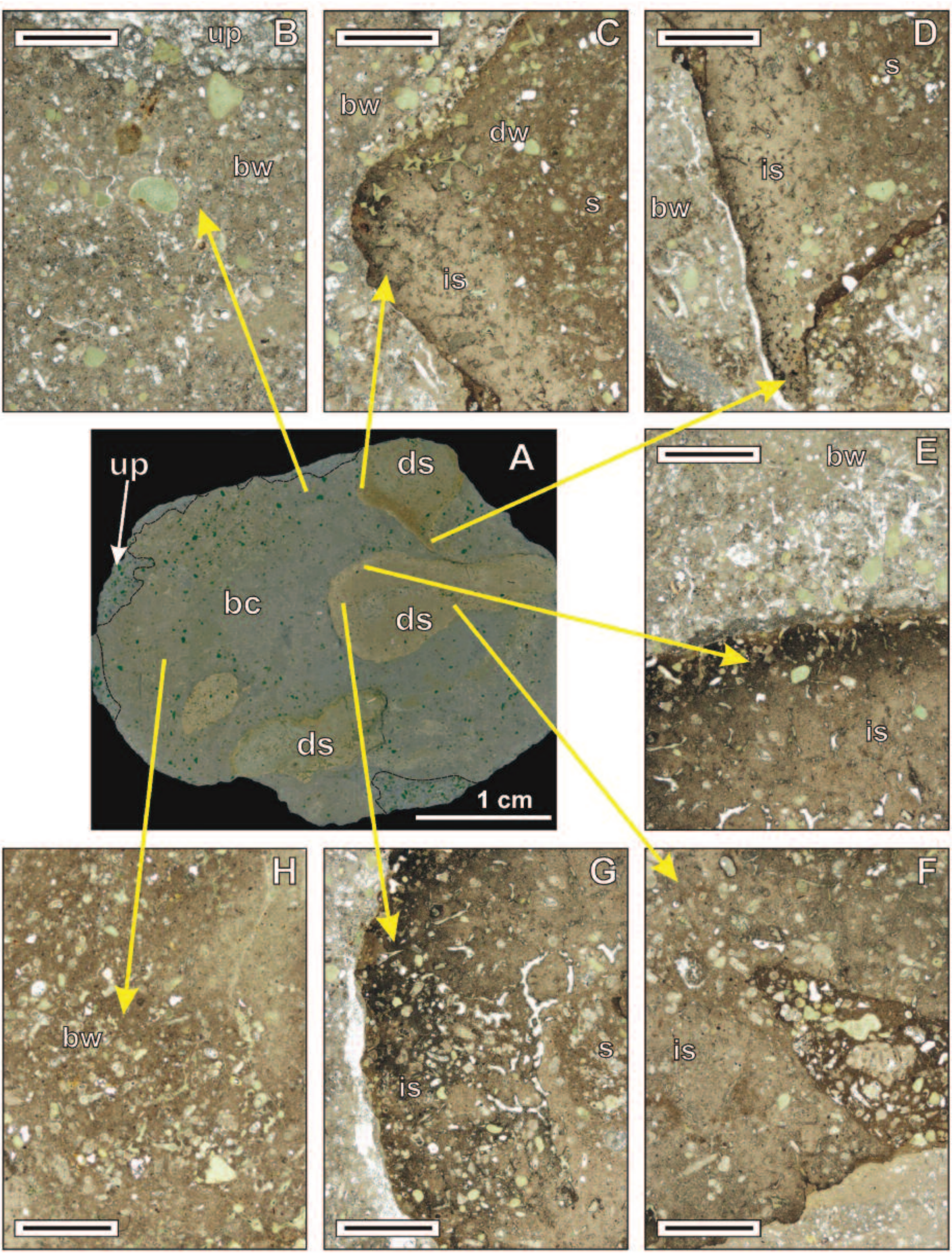
The number of species distinguished in the 'white' and 'beige' sponge groups is similar (19 and 22, respectively) (Table 1). *Coscinopora infundibuliformis* Goldfuss, 1826 and *Etheridgia mirabilis* Tate, 1864 are the most common in both groups. Some species, such as *Coeloptychium lobatum* Goldfuss, 1831, *Lefroyella favoidea* Schrammen, 1912, *Spirolophia tortuosa* (Roemer, 1841) and *Verrucocoelina alpina* Hèrenger, 1944, are represented by single specimens. 'Dark' sponges are represented by 15 species.

Although variably preserved (or perhaps also of different ages), the three groups of sponges at the bottom of the Santonian succession are taxonomically uniform. The differences in composition between the groups are slight and can probably be related to the small number of specimens examined. Eight species are recognized in the Coniacian, with every species represented in at least two groups of sponges (Table 1). The low number of species recognized in the Coniacian, when compared to the Santonian assemblages, is a sample effect; the number

Text-fig. 2. Geological log (stratigraphy after Walaszczyk 1992, with additional comments by Walaszczyk 2000, Walaszczyk and Wood 1998, 1999) of the Lower Coniacian and Upper Santonian deposits at Wielkanoc with distribution of microfacies. A, B – foraminiferal/foraminiferal-calcisphere wackestone with rare glauconite; C – phosphatized foraminiferal/foraminiferal-calcisphere wackestone with rare glauconite infilling of the interspicular space of a 'white'sponge; D – phosphatized foraminiferal/foraminiferal-calcisphere wackestone with rare glauconite infilling of the spongocoel of a 'white'sponge; E – phosphatized foraminiferal/foraminiferal-calcisphere wackestone with glauconite infilling of the interspicular space of a 'beige'sponge; F – phosphatized foraminiferal/foraminiferal-calcisphere wackestone with rare glauconite infilling of the spongocoel of a 'beige'sponge; G – phosphatized foraminiferal/foraminiferal-calcisphere wackestone with rare glauconite infilling of the interspicular space of a 'dark'sponge; H – phosphatized foraminiferal/foraminiferal-calcisphere wackestone with rare glauconite infilling of the spongocoel of a 'dark'sponge; J – inoceramid packstone with frequent glauconite; K – inoceramid packstone with frequent glauconite, intraclast of phosphatized wackestone in the centre of photo



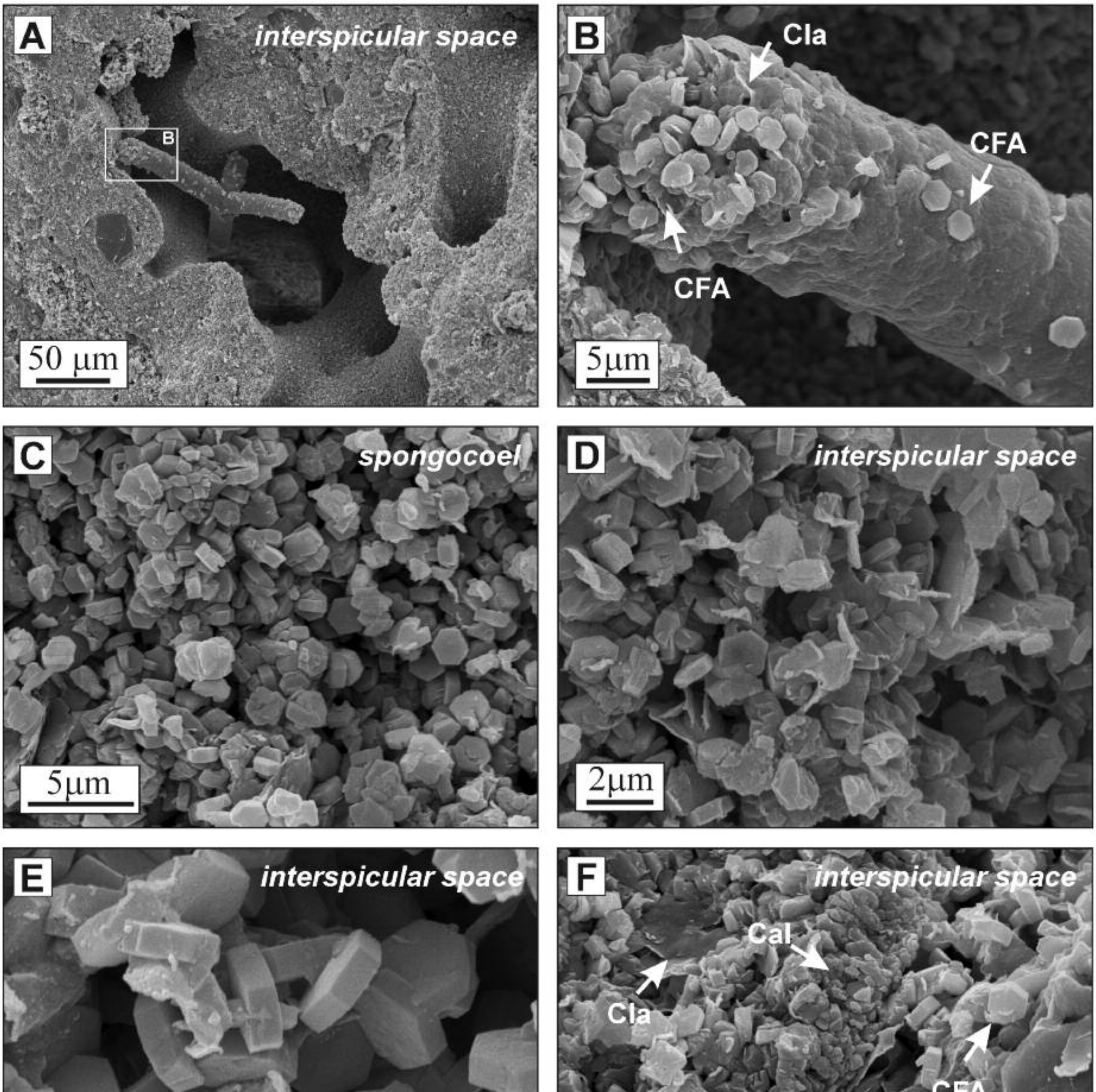
Text-fig. 3. Examples of sponges from the base of the Santonian deposits. A – 'white' sponges: 1 – *Sporadoscinia venosa* (Roemer, 1841); 2 – *Astropegma stellata* (Roemer, 1864); 3 – *Sporadoscinia alcyonoides* (Mantell, 1822). B – 'beige' sponges: 4 – *Leptophragma micropora* Schrammen, 1912; 5 – *Etheridgia mirabilis* Tate, 1864; 6 – *Wollemannia araneosa* Schrammen, 1912. C – 'dark' sponges: 7 – *Coeloptychium lobatum* Goldfuss, 1831; a – lateral view, b – view from upper side with reconstruction of broken lobes; 8 – *Napaeana striata* (Schrammen, 1902), specimens with destroyed surface; scale bars 1cm



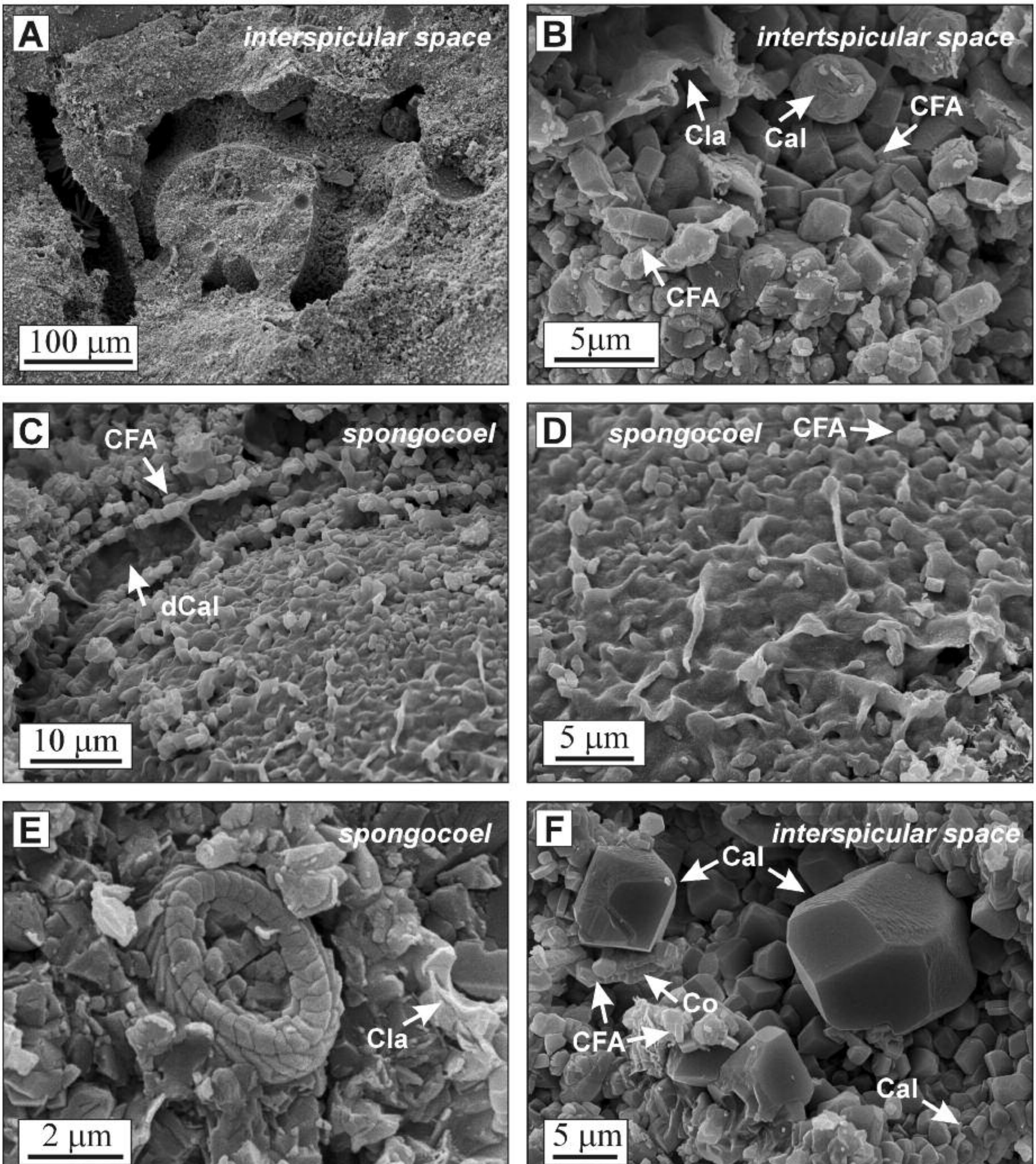
Text-fig. 4. Clast (A) consisting of fragments of different phosphatized dark sponges and surrounding phosphatized beige matrix (wackestone); bc – beige clast; ds – 'dark' sponge, up – unphosphatized packstone with glauconite attached to phosphatized clast; B-H – microfacies of phosphatized clast and sponges, is – interspicular space infilled by phosphatized wackestone, s – spongocoel infilled by phosphatized wackestone, bw – beige phosphatized wackstone; B, H – close up view of beige phosphatized wackestone with glauconite; C, D – 'dark' sponge with black envelope; note the more minute nature of the particles infilling the interspicular space than the particles infilling the spongocoel, the space after spicules infilled by glauconite; E, F, G – another 'dark' sponge with black envelope, note the secondary calcite infilling the space after spicules; scale bars 1mm of Coniacian specimens being very low. The important fact is that sponges in the Coniacian succession were buried *in situ* whereas the sponges from the base of the Santonian deposits are redeposited and condensed.

Ecology

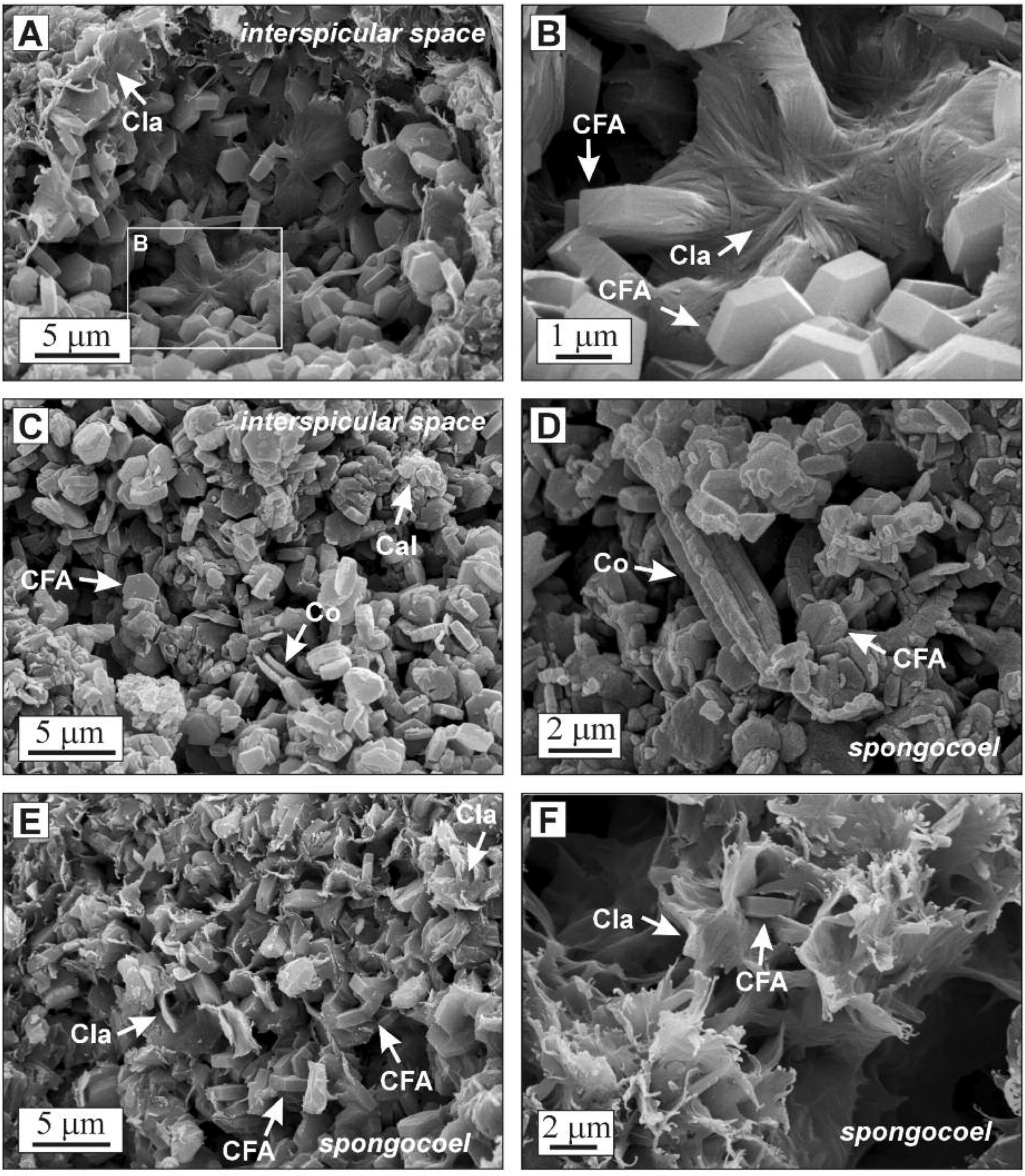
Living species of Hexactinellida are represented by sponges without a dictyonal skeleton (e.g. Lyssacinosida), as well as by Hexactinosida and very rare Ly-



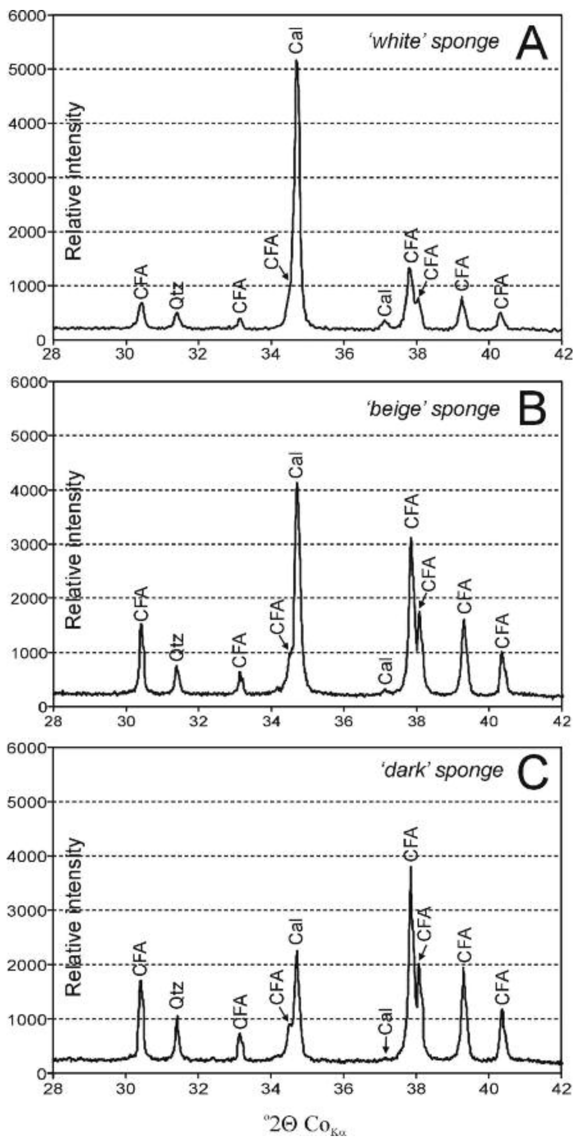
Text-fig. 5. SEM photomicrographs of phosphatized 'white' sponges; A – interspicular space, empty space after dissolved siliceous spicule with its relict; B – close-up view of relict of spicule, hexagonal francolite plates are visible on the surface; C – the spongocoel infilled by hexagonal crystals of francolite; the mean size of francolite crystal plates about 2 µm; D – interspicular space infilled by hexagonal francolites; E – hexagonal francolites infilling the foraminiferal chamber within the interspicular space; the size of crystal plates about 2 µm; F – calcite relict in the foraminiferal test, hexagonal francolites and clay minerals infilling the interspicular space. Cal – calcite, CFA – francolite, Cla – clay minerals chniscosida with a dictyonal skeleton (dictyid Hexactinellida). The constitution of all hexactinellid sponges and their vital functions (low metabolism, feeding strategy) are strictly adapted to deep-sea conditions. Most species prefer the bathyal zone, but they occur quite commonly on deeper shelves, below 100–120 m (e.g. Vacelet 1969; Soest van and Stentoft 1988; Lévi and Lévi 1988; Messing *et al.* 1990; Conway *et al.* 2001, 2007; Finks and Rigby 2004; Leys *et al.* 2004; Krautter *et al*. 2006). Some species of the Hexa-



Text-fig. 6. SEM photomicrographs of phosphatized ‘beige’ sponges; A – interspicular space, the empty space after siliceous spicule; B – the interspicular space infilled by hexagonal francolite and subordinate amount of clay mineral; the surfaces of francolite plates are distinctly wrinkled; C – foraminiferal fragment in the spongocoel, the test of foraminifera is dissolved; D – clay minerals (glauconite) with organic matter; E – infilling of the spongocoel, relicts of the calcite with well preserved plate of coccolith; F – secondary authigenic calcite cements in the space after dissolved spicule. Cal – calcite, CFA – francolite, Cla – clay minerals, dCal – empty space after dissolved calcite ctinellida appear in the abyssal zone (Koltun 1967; Tabachnick 1988; Beaulieu 2001; Reiswig 2002; Duplessis and Reiswig 2004; Finks and Rigby 2004; McClintock *et al*. 2005). The occurrence of hexactinellid assemblage in shallow water (<100 m) has been described from four localities: along the coast of British Columbia and Alaska, in submarine caves in the western Mediterranean, in fjords in New Zealand and in the Ross Sea (Reiswig 1990; Boury-Esnault and Vacelet 1994; Leys *et al*. 2004; McClintock *et al.* 2005). The



Text-fig. 7. SEM photomicrographs of phosphatized 'dark' sponges; A – hexagonal francolite with clay minerals infilling the interspicular space; B – clay minerals covering hexagonal francolite plates, close-up view of fig. A; C – hexagonal plates and clay minerals infilling the interspicular space; D – relicts of coccolith, other calcite elements, clay minerals and francolite infilling the spongocoel; E – hexagonal francolite and mineral clays infilling the spongocoel; F – clay minerals surrounding francolite hexagonal plates in the spongocoel. Cal – calcite, CFA – francolite, Cla – clay minerals, Co – plate of coccolith life of hexactinellid sponges in these places is possible due to special conditions similar to deep-water environments (low temperatures, quite cold waters, low light levels). The sponges living in these areas are represented almost exclusively by Lyssacinosida. Hexactinosan sponges are relatively common only in fjords in British Columbia (Leys *et al.* 2004). However, they are recorded at a depth of 120–160 m, whereas the shallower zones (< 20 m) are colonized exclusively by lyssacine sponges (Leys *et al.* 2004; Yahel *et al*. 2007). Only a few hexactinosan species, e.g. *Aphrocallistes vastus* Schulze and *Heterochone calyx* Schulze, tolerate shallows between 10 and 40 m (Ijima 1927; Koltun 1967, 1970; Reid 1968b; Reiswig 1990; Finks and Rigby 2004), while no species of Lychniscosida occur at depths shallower than 80 m (Finks and Rigby 2004).



Text-fig. 8. X-ray diffraction pattern of phosphatized sponges from Santonian deposits of Wielkanoc; A – 'white' sponge, B – 'beige' sponge, C – 'dark' sponge; note the differences in the height of peaks between the three groups of sponges; Cal – calcite, CFA – carbonate fluorapatite (francolite), Qtz – quartz

Hexactinosida and Lychniscosida are common in Late Cretaceous deposits (e.g. Rigby and Jenkins 1983; Krautter 2002; Pisera *et al*. 2006; Rigby *et al*. 2007), and are well known in Europe (Świerczewska-Gładysz 2006 and references therein). Using Cretaceous sponges as bathymetric indicators, the depth of the sea most probably oscillated between 100 and 350 m (Defretin-Lefranc 1960; Nestler 1961; Reid 1962, 1968b; Wagner 1963; Ulbrich 1974; Gasse *et al.* 1991; Termier and Termier 1981). Some investigators infer that fossil Hexactinosida and Lychniscosida lived in shallower zones compared to their modern descendants. According to Gammon *et al*. (2000) and Jablonski (2005), the occurrence of modern Hexactinellida in the bathyal zone is a result of migration of the group from shallower to deeper zones throughout the Cenozoic. However, on the global scale, this migration is not confirmed by the fossil record. Moreover, the structure of fossil sponges was the same as in modern sponges, indicating similar vital requirements for both fossil and modern forms (Pisera 1997).

The other important factors enabling the development of the Hexactinellida are slow sedimentation rate and low water dynamics (Pisera 1997; Krautter 1997, 1998; Duarte *et al.* 2001; Bell and Barnes 2003). Based on analogy with modern Hexactinellida, it may be stated that all the sponges from Wielkanoc lived in similar conditions, in a relatively deep sea (below 100 m), in a calm environment with slow sedimentation.

The modern species of hexactinellid sponges usually live on rocky bottoms and are attached by a basal plate and additional protrusions (Krautter *et al*. 2006). Most Cretaceous Hexactinellida were adapted to life on the soft bottom, while rare representatives preferred a hard bottom (Reid 1962). In the material from Wielkanoc, there are no species with a basal plate to suggest the temporary appearance of a hard bottom (compare Reid 1962). Moreover, the presence of rhizoid fragments in the Santonian deposits, or marks left after their breaking, found on some specimens, suggest that the sponges inhabited soft bottoms. This also applies to the representatives of the genus *Aphrocallistes* Gray. The modern *Aphrocallistes* lives on the rocky bottom (Krautter *et al*. 2006), while the Cretaceous representatives were adapted to live on soft bottoms (Helm and Kosma 2006). They produced very long processes which stabilized them in the calcareous ooze (Świerczewska-Gładysz 2006).

STRATIGRAPHICAL REMARKS

The sponges found at Wielkanoc are typical representatives of the Late Cretaceous epicontinental seas of Europe, with a wide stratigraphical distribution (Table 2). An exception is *Verrucocoelia alpina* Hèrenger, so far known exclusively from the Valanginian of France (Lagneau–Hèrenger 1962).

Preliminary investigations by one of us (EŚG) have shown that almost all of the examined species are also known from the redeposited fauna occurring at the base of Santonian glauconitic marls/marly clays in Korzkiew, another section of the Polish Jura Chain, farther south, near Kraków (compare Małecki 1980; Świerczewska-Gładysz 1997, 2006). Only two species (*Wollemannia araneosa* and *Coeloptychium lobatum*) present at Wielkanoc were not recognised there. The age of the sponges and of the surrounding sediment from Korzkiew is also problematic. The poorly preserved foraminifers from the glauconitic marls in Korzkiew, interpreted as Early Santonian, could have been redeposited (Machaniec and Zapałowicz-Bilan 2005), an interpretation suggested by Kudrewicz (1992) who, based on the belemnites *Actinocamax verus* Miller and *Goniateuthis westfalica-granulata* (Stolley), dated the underlying clays as Middle(?) Santonian. Certainly, these belemnites could have also been redeposited, and consequently, the clays may be even younger.

	Sponge taxa	"*in situ*" in Coniacian deposits 24 specimens	redeposited in Santonian deposits		
			'white' sponges 17 specimens	'beige' sponges 92 specimens	'dark' sponges 40 specimens
HEXACTINOSIDA	*Aphrocallistes cylindrodactylus* Schrammen, 1912		+	+	
	Aphrocallistes sp.		+		
	Laocoetis fittoni (Mantell, 1822)		+	+	
	Laocoetis virgatula (Schrammen, 1912)		+	+	
	Lefroyella favoidea Schrammen, 1912			+	
	Leptophragma micropora Schrammen, 1912		+	+	+
	Periphragella plicata Schrammen, 1902	+		+	+
	Polyopesia angustata Schrammen, 1902	+	+		+
	Verrucocoelia alpina Hèrenger, 1944			+	
	Verrucocoelia tubulata (Smith, 1848)		+	+	
	Wollemannia araneosa Schrammen, 1912		+	+	
LYCHNISCOSIDA	*Astropegma stellata* (Roemer, 1841)	+	+	+	
	Plocoscyphia communis Moret, 1926	+	+	+	+
	Cinclidella angustata (HINDE, 1884)		+	+	+
	Coeloptychium lobatum Goldfuss, 1831				+
	Coeloptychium subagaricoides Sinzov, 1872		+	+	+
	Coeloscyphia racemosa (Smith, 1848)			+	+
	Coscinopora infundibuliformis Goldfuss, 1826		+	+	+
	Etheridgia mirabilis Tate, 1864	+	+	+	+
	Leiostracosia angustata (Roemer, 1841)	+		+	+
	Napaeana striata (Schrammen, 1902)			+	+
	Porochonia simplex (Smith, 1848)		+	+	+
	Rhizopoterion cribrosum (Phillips, 1829)	+	+	+	+
	Spirolophia tortuosa (Roemer, 1841)			+	
	Sporadoscinia alcyonoides (Mantell, 1822)		+		
	Sporadoscinia stirps Schrammen, 1912		+	+	+
	Sporadoscinia venosa (Roemer, 1841)	+	+		

Table 1. The taxa composition of phosphatized sponges in 'white', 'beige' and 'dark' sponge groups

	Sponge taxa	Ber.	Val.	Hot.	Bar.	Apt	Alb	Cen.	Tur.	Con.	Sant.	Camp.	Maast.
HEXACTINOSIDA	*Aphrocallistes cylindrodactylus* Schrammen, 1912											E,I,G,P	E,P,U
	Laocoetis fittoni (Mantell, 1822)		F			E,S	E	E,F,G	E,F			G,P	P
	Laocoetis virgatula (Schrammen, 1912)					S	F					G	
	Lefroyella favoidea Schrammen, 1912											G	
	Leptophragma micropora Schrammen, 1912									E	E,G	G,P	P,U
	Periphragella plicata Schrammen, 1902								E			G	
	Polyopesia angustata Schrammen, 1902		F				F				E	G	
	Verrucocoelia alpina Hèrenger, 1944		F										
	Verrucocoelia tubulata (Smith, 1848)						F	F	E			G	
	Wollemannia araneosa Schrammen, 1912									F?	F?	F?,G,P	P,U
LYCHNISCOSIDA	*Astropegma stellata* (Roemer, 1841)										F,S	G,S	S
	Plocoscyphia communis Moret, 1926						F	F,E					
	Cinclidella angustata (Hinde, 1884)								F	E,I,F	E,I	F	
	Coeloptychium lobatum Goldfuss, 1831											G	
	Coeloptychium subagaricoides Sinzov, 1872										G,R		
	Coeloscyphia racemosa (Smith, 1848)									E,I	E,I	E	
	Coscinopora infundibuliformis Goldfuss, 1826								P	E,F,P	E	E,G	
	Etheridgia mirabilis Tate, 1864									E,I	E,I,R		
	Leiostracosia angustata (Roemer, 1841)								P			G	
	Napaeana striata (Schrammen, 1902)											G	
	Porochonia simplex (Smith, 1848)								E				
	Rhizopoterion cribrosum (Phillips, 1829)								F,P	P	E,I	E,I,P	E,I,G,P,U
	Spirolophia tortuosa (Roemer, 1841)											G	
	Sporadoscinia alcyonoides (Mantell, 1822)								E,P	A	E,R	P	P
	Sporadoscinia stirps Schrammen, 1912									E,I	E,I	G	
	Sporadoscinia venosa (Roemer, 1841)									E,I,F	E,I	E,G,P	

Table 2. Stratigraphical distribution of sponges recognised in the studied succession, as reported from various areas in Europe; E – England (after Reid 1968a); F – France (after Lagneau–Hèrenger 1962; Defretin-Lefranc 1960); G – Germany (after Schrammen 1910-12, Ulbrich 1974); I – Ireland (after Reid 1968a); P – Poland, without the Kraków-Miechów Upland (after Bieda 1933; Hurcewicz 1968; Tarkowski 1991; Świerczewska-Gładysz 2006); R – Russia, Saratov region (after Sinzov 1871-72); S – Spain (after Hèrenger 1942); U – Ukraine (after Khmilevsky 1974; Świerczewska-Gładysz 2006)

There is no *in situ* Santonian sponge assemblage described from the territory of Poland with which the studied assemblages could be directly compared. Coniacian sponges from Poland are also poorly known; besides the material studied herein, only a few species were described from the Lower Coniacian of Opole (Tarkowski 1991). Only one species from the latter area, *Coscinopora infundibuliformis*, was also recognised in Wielkanoc (Table 1). Rich sponge assemblages are known from Poland from younger Cretaceous deposits, namely from the Campanian and Maastrichtian (compare Bieda 1933; Hurcewicz 1968; Tarkowski 1991; Świerczewska-Gładysz 2006). These are, however, taxonomically completely different from the assemblages studied herein.

The Wielkanoc assemblages show, however, a high taxonomic similarity to the sponge fauna from the *Micraster coranguinum* Zone (Middle Coniacian to Middle Santonian) of England (Reid 1968a). The species common to both regions are *Coscinopora infundibuliformis*, *Etheridgia mirabilis, Coeloscyphia racemosa*, *Cinclidella angustata, Sporadoscinia venosa*, *Sporadoscinia alcyonoides*, *Leptophragma micropora* and *Rhizopoterion cribrosum*.

Critical for dating the interval studied are the inoceramids and echinoids. Of the former, the Coniacian limestones yielded *Cremnoceramus crassus* (Petrascheck), *C. ernsti* (Heinz), *C.* cf. *deformis* (Meek), *Inoceramus* cf. *madagascariensis* Heinz, and *I. lusatiae* Andert (see Walaszczyk 1992), dating this interval as late (but not the latest) Early Coniacian *Cremnoceramus crassus crassus/deformis deformis* Zone (according to the zonation by Walaszczyk and Wood 1998 and 1999). This dating is supported by the echinoids *Micraster cortestudinarium* (Goldfuss) and *Echinocorys* ex gr. *scutata* Leske. The Santonian deposits above are referred to the *Sphenoceramus patootensiformis* Zone, and the presence of the crinoid *Marsupites testudinarium* in the equivalent beds of other sections in the area suggest a Latest Santonian age (Walaszczyk 1992, fig. 29). Consequently, the sponges redeposited within the Santonian may represent forms from any interval spanning the late Early Coniacian through to Late Santonian. Unfortunately, the foraminiferal tests in the phosphatized material filling the sponges have been dissolved (see Text-fig. 6C), and hence the foraminifera have no stratigraphical value.

REMARKS ABOUT THE PHOSPHATIZATION OF SPONGES

Sponges from the orders Hexactinosida and Lychniscosida, well represented in the fossil material, have high fossilization potential. After death, their loose spicules scatter, but their rigid dictyonal skeleton may, under favourable conditions, be preserved in almost the original form. The study of Pliocene Hexactinellida from the Tyrrhenian Sea shows that, after death of the soft tissue, the calcareous ooze filling the interspicular space of sponges undergoes lithification at first, and then calcareous ooze is cemented in the spongocoel (Brachert *et al*. 1987). The calcification of sponges starts during the decay of soft tissue, when aragonite crystallizes in the interspicular spaces (Neuweiler *et al.* 2007).

According to Föllmi's (1990, fig. 6) model, phosphatization can proceed either locally around the decaying organic remains, or in the continuous layer in the suboxic zone, a dozen or so cm below the sediment/water interface. Other models assume that phosphatization takes place in the very shallow suboxic zone (down to 20 cm) below the sediment/water interface (e.g. O'Brien *et al*. 1990; Jarvis *et al*. 1994). In the suboxic zone the phosphorus is released from decaying organic matter, which leads to its increased concentration in pore waters, over-saturation and the start of phosphatization (e.g. Baturin 1982; O'Brien *et al*. 1990; Föllmi 1990, 1996; Jarvis *et al*. 1994; Krajewski *et al*. 1994; Trappe 1998).

Dictyid sponges, such as those described in the present study, and lithistid sponges, are commonly phosphatized (e.g. Kennedy and Garrison 1975; Jarvis *et al*. 1994; Jarvis 2006; Świerczewska-Gładysz and Olszewska-Nejbert 2006; Vodrážka *et al*. 2009). However the mechanisms leading to phosphatization of these sponges are not yet well understood. Based on the studied material, published data on modern environments of phosphatization, and Föllmi's (1990) model, the sponge phosphatization and accumulation may be described as follows.

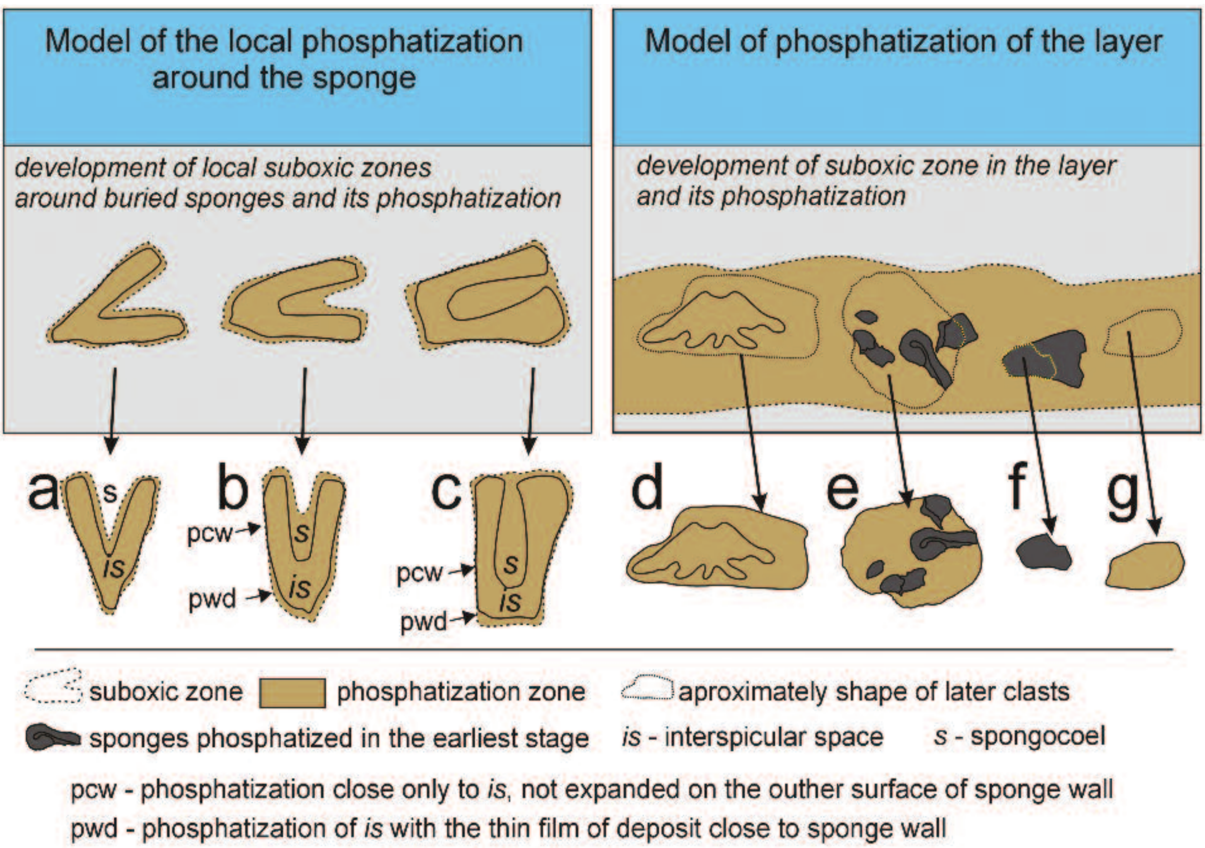
After death, the sponge soft tissue, buried in the calcareous ooze, starts to decay. Its space is filled by calcareous ooze, pellets and detrital quartz. In specimens with a dense mesh network, interspicular spaces are filled with finer material than the spongocoel (compare Text-fig. 2 C, D). When sedimentation slows or stops, entirely buried decaying sponges remain for an extended period in the same position relative to the sediment-water interface. The oxic/suboxic interface rises to the bottom or a local suboxic zone develops around the buried fauna. The pore waters are enriched in phosphorus within the first several centimetres of bottom sediment from decaying organic matter (not only from sponges). The oversaturation of phosphorus in the pore waters leads to the start of the phosphatization processes. Following Föllmi (1990), two kinds of phosphatization may be proposed (Text-fig.

9): (i) local phosphatization, and (ii) phosphatization of the layer.

(i) Local phosphatization: The sponges were centres of local suboxic zones (Text-fig. 9). The decay of organic matter in loose deposits provides phosphorus to the pore waters. The phosphatization starts through the growth of hexagonal plates of francolite precipitated in free pore spaces; firstly, the interspicular space, then the spongocoel, if the conditions promoting phosphatization (stop in sedimentation, appropriate pH, presence of a suboxic zone, and pore waters supersaturated with phosphate ions) persist long enough (Text-fig. 9a–c). The phosphatization extends to the outer wall of the sponge, but rarely to the surrounding sediment. No soft tissues of the sponge is phosphatized, similarly as in the case of higher organisms, e.g. cephalopods, arthropods and fish (see Wilby and Briggs 1997).

(ii) Phosphatization of the layer (Text-fig. 9): The entire layer of sediment close to the sediment-water interface is phosphatized (Text-fig. 9). The francolite precipitates in porous spaces within this layer, including the fauna buried in it (Text-fig. 9d). Any phosphatized buried faunal elements may undergo renewed phosphatization (Text-fig. 9e). Subsequent erosion of a bed leads to formation of phosphatized clasts (Text-fig. 9g) with sponges, phosphatized either at the same stage (Text-fig. 9d), or earlier (Text-fig. 9e).

The francolite grows in porous sediment filling interspicular spaces and spongocoels. Its crystals are evenly dispersed between relicts of calcareous ooze, which suggests that phosphatization delithified calcareous ooze. During phosphatization, calcite was entirely (Text-fig. 6C) or partly (Text-figs 5F, 6E, 7D) dissolved, and biogenic silica was mobilized and removed from the sponge spicules, leaving empty spaces (Text-figs 5A, B; 6A). In some cases, those spaces have been filled with glauconite (Text-figs 2G; 4C–E, G) or secondary calcite cements (Text-figs 2E, 6F).



Text-fig. 9. Modes of phosphatization of sponges and of host deposits in the Coniacian and Santonian of Wielkanoc. a – phosphatization of the interspicular space; b – phosphatization of the interspicular space, and partly of the deposit infilling the spongocoel; c – phosphatization of the interspicular space and of deposit infilling the spongocoel; d – the phosphatized clast comprising the sponge, e – the phosphatized clast comprising phosphatized fragments of sponges of an older generation (rare) (the example shows more than one episode of phosphatization, compare Text-fig. 4), f – the fragment of phosphatized sponge, g – the phosphatized clast (rare)

EVOLUTION OF THE STUDY AREA DURING LATE TURONIAN TO SANTONIAN TIME

Based on sedimentological, palaeontological, and petrographical observations the following stages in deposition, phosphatization and erosion in the Wielkanoc area can be distinguished (Text-figs 10, 11):

Stage A. Early Late Turonian: Calcareous (?shallow water) sedimentation (Text-figs 10A, 11) (see also Alexandrowicz 1954; Marcinowski 1974; Walaszczyk 1992; Olszewska-Nejbert 2004, 2005).

Stage B. Mid-Late Turonian (continuing possibly until the mid Early Coniacian: Halt in sedimentation and the development of a hardground and stromatolite crusts (Text-figs 10B, 11; see also Olszewska-Nejbert 2004).

Stage C. Mid-Early Coniacian: Restart of carbonate sedimentation. The upward disappearance of terrigenous input and the appearance of siliceous sponges of the orders Hexactinosida and Lychniscosida suggest the gradual deepening of the basin (Text-fig. 10C).

Stage D. Early Late (or late Middle?) Santonian: submarine erosion due to basin shallowing (early Late Santonian eustatic drop?). Exhumation of the phosphatized sponges (in place, by winnowing), and their accumulation on the sea floor (formation of the 'white' and 'beige' sponge groups) (Text-figs 10D, 11). The largely destroyed 'dark' sponges have apparently undergone a longer history; they could have been repeatedly redeposited and/or transported from relatively distant (and more elevated) areas.

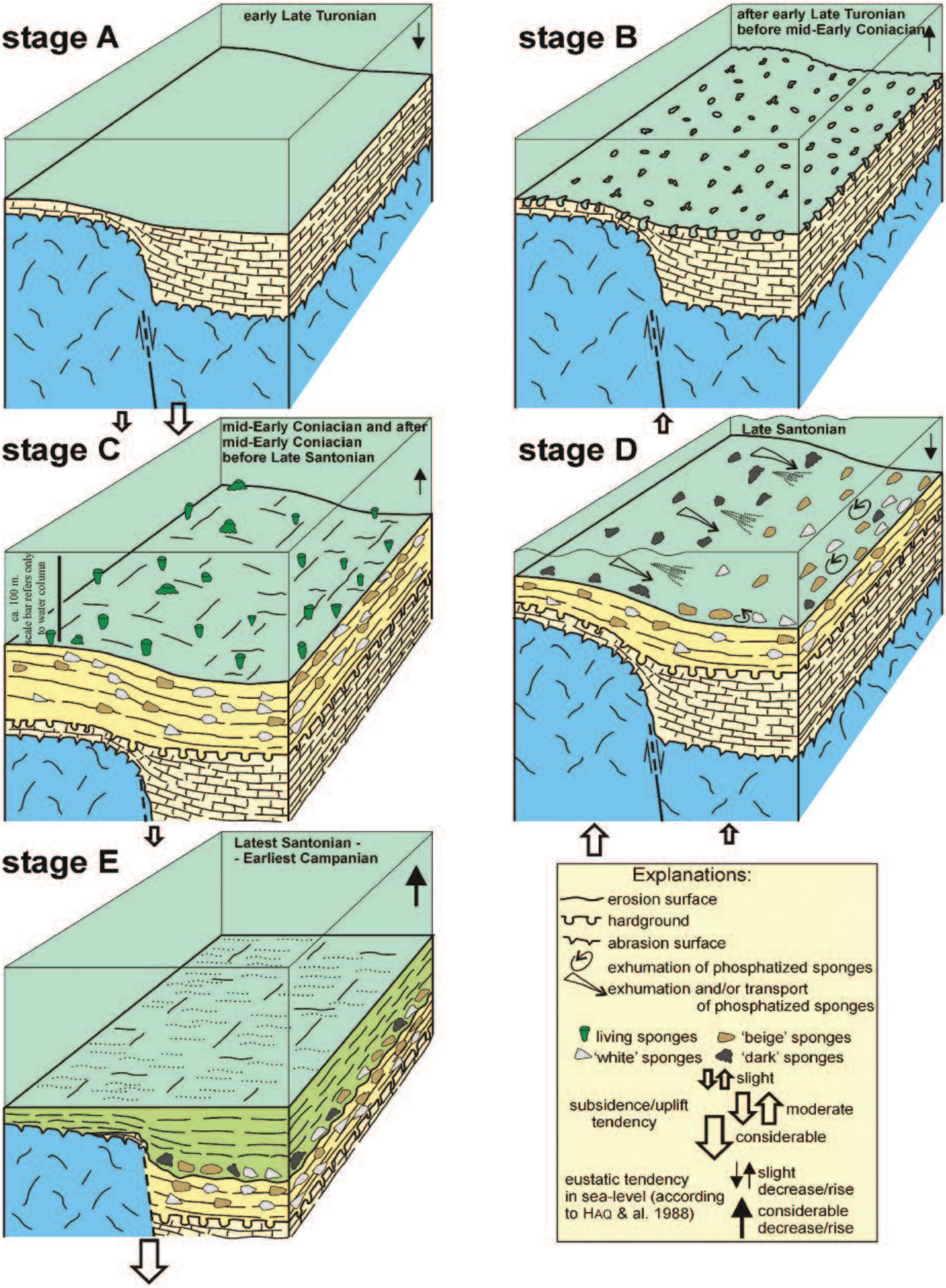
Stage E. Late Late Santonian (*S. patootensiformis* Zone) time: Restart of sedimentation, burying of the phosphatized sponges, and gradual change to low-energy conditions (Text-figs 10E, 11), with the appearance of marly, marly limestone and siliceous chalky facies, continuing in this area through much of the Campanian and Early Maastrichtian (see Rutkowski 1965; Marcinowski 1974; Walaszczyk 1992).

DISCUSSION

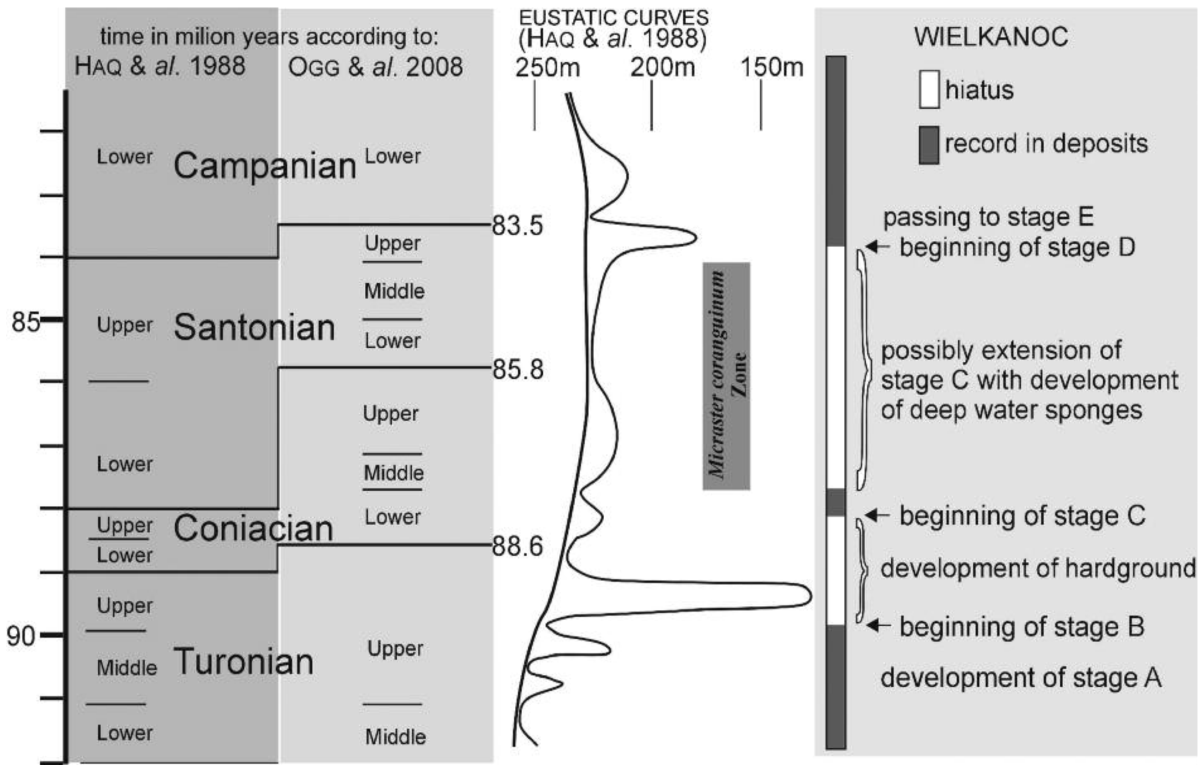
In the Late Turonian, a global sea-level drop took place (Haq *et al*. 1988), followed by sea-level rise in the latest Turonian (Text-fig. 11). In Wielkanoc, this drop is marked by the development of a composite hardground, as similarly noted throughout the Polish Jura Chain (Walaszczyk 1992); this is stage B of the present interpretation, which follows the period of sedimentation in the earlier part of the Turonian (Stage A). The restart of calcareous sedimentation, induced by the latest Turonian–Coniacian sea-level rise, commenced in the Wielkanoc area in the Early Coniacian (beginning of stage C). Little is known about the area in the time that follows until the Late Santonian. From the available record, it is inferred that the redeposition of sponges into the Upper Santonian deposits had to have taken place sometime in the Late Santonian. How much of the late Early Coniacian–Middle Santonian succession was once present in the area is unknown. The redeposition of the sponges may have been triggered by shallowing of the sea, caused either by the eustatic fall (Text-fig. 11) or by the local block movements that were apparently active at this time (compare Marcinowski 1974). The elevated blocks could have been the source areas of the 'black' sponge group. The final drowning of the area (Stage E), marked by continuous marly–limestone succession above, corresponds to the global eustatic sea-level rise (Text-fig. 11).

Taking into account the remarks made above, both eustatic sea-level changes and local tectonic (Subhercynian) movements had an important influence on the evolution of the study region (Marcinowski 1974; Marcinowski and Radwański 1983, 1989, 2009; Walaszczyk 1992; Olszewska-Nejbert 2004). The local movements were most probably associated with the activity of the Kraków-Lubliniec Fault Zone, a regional terrane boundary in the Palaeozoic basement (separating the Upper Silesian Block and the Małopolska Block; see e.g. Buła 1994; Żaba 1999). This zone, most active in the mid and Late Palaeozoic (Żaba 1999), was rejuvenated in the Mesozoic and Cenozoic (Żaba 1999; Matyszkiewicz *et al*. 2006a, 2006b, 2007; Ziółkowski 2007) and its tectonic activity continues even in the Holocene (Jurewicz *et al*. 2007).

Apart from Sujkowski (1926), who suggested continuous sedimentation from the Turonian to the Santonian in the study area, all subsequent studies have demonstrated the discontinuous character of the sedimentation on the Polish Jura Chain (e.g. Panow 1934; Różycki 1938; Alexandrowicz 1954, 1969; Bukowy 1956; Marcinowski 1974). The most recent view was presented by Walaszczyk (1992) who, based on the inoceramid record, documented the presence of thin blankets of Turonian, Coniacian and Santonian deposits that were more or less isochronous over the entire area, with distinct, biostratigraphically proven gaps in between. In the Wielkanoc succession, he demonstrated the presence of the upper Lower Coniacian covered directly by Upper Santonian. According to our investigations, the original succession could have been



Text-fig. 10. Late Turonian–Early Campanian evolutionary stages of the Wielkanoc area; see text for explanations



Text-fig. 11. Evolutionary stages of the Wielkanoc area and the eustatic sea-level changes (after HAQ *et al*. 1988); further explanations in the text

much more complete, with parts of the Middle Coniacian through to Middle Santonian once present, but subsequently removed by erosion and winnowing of loose sediment.

CONCLUSIONS

1. The studied sponges belong to the orders Hexactinosida and Lychniscosida. Their species composition is closest to that of the *Micraster coranguinum* Zone (Middle Coniacian to Middle Santonian) fauna from England, as listed by Reid (1968a).
2. All the sponges from the Santonian deposits were redeposited, whereas those from the Coniacian are preserved *in situ*.
3. The sponges underwent phosphatization just after being buried in unconsolidated sediments; francolite precipitation took place in free pore spaces. The phosphatization was controlled by the shape and internal space of the sponges.
4. Three taphonomic sponge-groups are distinguished: ‘white’, ‘beige’and ‘dark’. They differ in the degree of calcite and phosphatic cementation and in the amount of clay minerals and organic matter. All the groups are similar in microfacies and taxonomic composition, which suggests that the original sponge assemblages lived in similar environments (deeper than 100 m).
5. The Turonian–Late Santonian vertical block movements (Subhercynian phase) of the Cracow Swell, and the superimposed eustatic changes, were responsible for changing the accommodation space and the induced physical phenomena that led to the formation of the strongly reduced Turonian through Santonian succession in the area.
6. The phosphatized sponges (and their sedimentary infill) are remnants of once existing and subsequently eroded successions, representing part of the late Early Coniacian through Late Santonian time.

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