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Stratigraphy of the Albian–Cenomanian (Cretaceous) phosphorite interval in central Poland: a reappraisal

This paper appears a century after the discovery, in 1923,
of the Annopol phosphorites by the renowned Polish geologist
Jan Samsonowicz (1888–1959)

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ABSTRACT:

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Several closely-spaced phosphorite beds stand out at the Albian–Cenomanian transition in the mid-Cretaceous transgressive succession at the northeastern margin of the Holy Cross Mountains, central Poland. They form a distinctive condensed interval of considerable stratigraphical, palaeontological, and economic value. Here, we correlate the classical section at Annopol with a recently investigated section at Chałupki. We propose a new stratigraphic interpretation of the phosphorite interval, based on lithological correlations, Rare Earth Elements and Yttrium (REE+Y) signatures of phosphorites, age-diagnostic macrofossils, and sequence stratigraphic patterns. This interval has long been considered as exclusively Albian in age. However, new macrofossil data allow us to assign the higher phosphorite levels at Annopol and Chałupki, which were the primary target for the phosphate mining, to the lower Cenomanian. In terms of sequence stratigraphy, the phosphorite interval encompasses the depositional sequence DS Al 8 and the Lowstand System Tract of the successive DS Al/Ce 1 sequence. The proposed correlation suggests that lowstand reworking during the Albian–Cenomanian boundary interval played an important role in concentrating the phosphatic clasts and nodules to exploitable stratiform accumulations. Our conclusions are pertinent to regional studies, assessments of natural resources (in view of the recent interest in REE content of the phosphorites), and dating of the fossil assemblages preserved in the phosphorite interval. On a broader scale, they add to our understanding of the formation of stratiform phosphorite deposits.

Key words: Poland; Cretaceous; Phosphorites; Rare Earth Elements; Biostratigraphy; Sequence stratigraphy.

INTRODUCTION

Several closely-spaced stratiform concentrations of nodular phosphates form a distinctive interval near the Albian–Cenomanian boundary in the overall transgressive mid-Cretaceous succession exposed along the northeastern margin of the Holy Cross Mountains, central Poland (Pożaryski 1947; Cieśliński 1959, figs 1 and 2; 1976; Uberna 1967). This is a transition interval, separating Albian sands below from pelagic Cenomanian and Turonian marls, limestones and chalks above. Phosphorites in a similar stratigraphic position have also been recorded by means of boreholes in other regions of extra-Carpathian Poland (Pożaryski 1960; Uberna *et al.* 1971; Wagner 2008).

The Cretaceous phosphorites from the Holy Cross Mountains margin have attracted interest since the discovery of a condensed, phosphate-rich Albian–lower Turonian succession in the Annopol (formerly Rachów) anticline on the right bank of the Vistula River (Samsonowicz 1924a, b). The section became a benchmark for understanding the stratigraphy, depositional evolution, palaeogeography and fossil assemblages of the mid-Cretaceous transgressive succession in Poland (Samsonowicz 1925, 1934; Cieśliński 1959, 1976, 1987; Cieśliński and Milakovič 1962; Radwański 1968; Collins 1969; Popiel-Barczyk 1972; Marcinowski and Wiedmann 1985, 1990; Małkowski 1976; Marcinowski and Radwański 1983, 1989; Marcinowski and Walaszczyk 1985; Walaszczyk 1987; Peryt 1983).

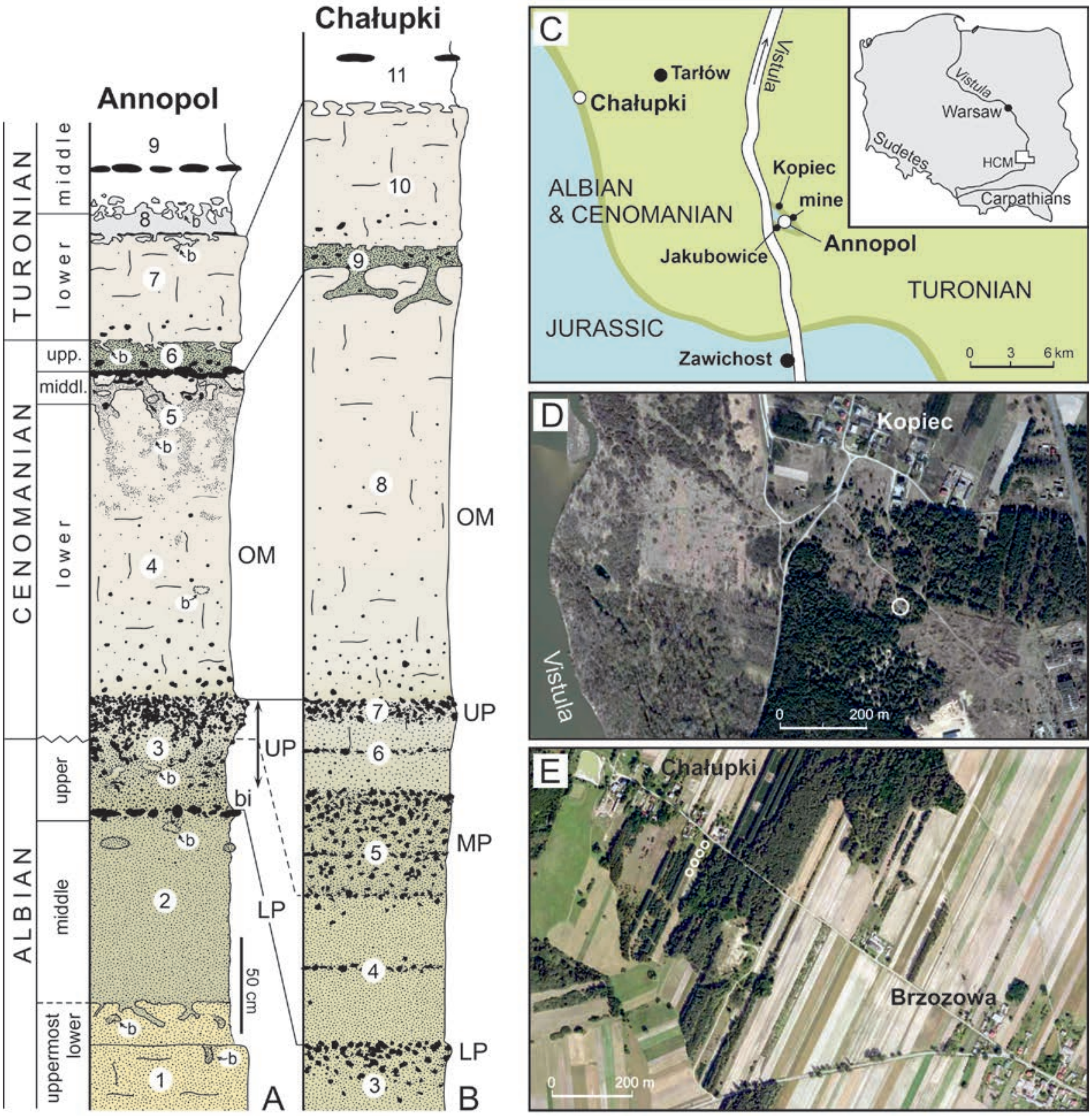
After the discovery of the phosphorites, their economic excavation for production of agricultural fertilizers started at Annopol and Chałupki (18 km to the northeast). The exploitation was first conducted by opencast mining, then in subsurface mines (Makowska and Jędrzejczak 1975). Due to economic reasons, the Chałupki and Annopol mines were abandoned in 1959 and 1970, respectively (Makowska and Jędrzejczak 1975). According to these authors, more than 940,000 tonnes of phosphate rock were obtained from the Annopol mine alone. Recently, the Annopol and Chałupki phosphorites have aroused new economic interest as a potential source of REE (Zglinicki *et al.* 2020; Mikulski *et al.* 2021).

Recent palaeontological exploration of the Annopol anticline initiated in 2009 by the first author (Machalski *et al.* 2009), resulted in a series of publications. These dealt with ammonites and their taphonomic pathways (Machalski and Kennedy 2013; Kennedy and Machalski 2015; Machalski and Olszewska-Nejbert 2016), crustaceans (Fraaije *et al.* 2016), lamniform sharks (Siversson and Machalski 2017), chimaeroids (Popov and Machalski 2014), chelonioid sea-turtles (Kapuścińska and Machalski 2015), nautilids (Machalski and Wilmsen 2015), ichthyosaurs and plesiosaurs (Bardet *et al.* 2016; Madzia and Machalski 2017), and pterosaurs (Machalski and Martill 2013). Dubicka and Machalski (2017) provided new foraminiferal data from the section, assessed its stratigraphical completeness, and proposed its interpretation in terms of the mid-Cretaceous sea-level changes.

Samsonowicz (1925, 1934) assigned the (bipartite) phosphorite interval at Annopol (Text-fig. 1A) to the middle Albian, upper Albian ('Vraconnian'), and to the lower Cenomanian ('Tourtia'). He listed common Albian and very rare Cenomanian ammonites from the phosphorite interval (Samsonowicz 1925, 1934). The same author assigned the entire (tripartite) phosphorite interval at Chałupki (Text-fig. 1B) to the lower Cenomanian, on the basis of ammonites (Samsonowicz 1937; see also Bolewski 1937, 1946). Pożaryski (1947) assigned the lower phosphorites at Annopol to the Albian, and the upper phosphorites to the Cenomanian.

Cieśliński (1959) made a significant change to the stratigraphic interpretation of the phosphorite interval, assigning the upper phosphorites at Annopol (his 'phosphorites in marls' or A_8 interval) to the uppermost Albian. This conclusion was essentially based on a single specimen of the ammonite *Stoliczkaia* cf. *notha* (Seeley, 1865) from the upper phosphorites. Subsequent authors accepted the Albian age for the whole phosphorite interval at Annopol (Marcinowski and Wiedmann 1985, 1990; Marcinowski and Radwański 1983, 1989; Marcinowski and Walaszczyk 1985; Walaszczyk 1987; Machalski and Kennedy 2013; Kennedy and Machalski 2015; Machalski and Olszewska-Nejbert 2016; Dubicka and Machalski 2017). The Albian age of the phosphorite interval was extended to the whole northeastern border of the Holy Cross Mts., including the section exposed at Chałupki (Cieśliński 1959, fig. 2, 1976, 1987; Cieśliński and Pożaryski 1970, fig. 3), and to other areas in Poland as well (Uberna *et al.* 1971; Wagner 2008).

The key specimen *Stoliczkaia* cf. *notha* as described by Cieśliński (1959) from the upper phosphorite bed at Annopol was reinterpreted by Machalski and Kennedy (2013) as a specifically indeterminate *Stoliczkaia* sp. which may not exclude an early Cenomanian age (Wright and Kennedy 1978). More importantly, Machalski and Kennedy (2013) and Machalski and Olszewska-Nejbert (2016) reinterpreted this specimen as a phosphatic cast of an ammonite replica preserved as attachment scar on an oyster shell ('pseudo-steinkern' of Machalski and Olszewska-Nejbert 2016). According to these authors, the formation of such pseudo-steinkerns may significantly postdate the original stratigraphic ranges of ammonites cast in this way. In addition to the former records of Cenomanian ammonites from the Annopol and Chałupki phosphorites (Samsonowicz 1925, 1934, 1937), this puts a serious question mark against the exclusively Albian age of the phosphorite interval as established by Cieśliński (1959). The reader is referred to Table 1 for the ammonite-based subdivision of the Albian and Cenomanian.



Text-fig. 1. Geological setting and location of the studied outcrops of the phosphorite interval at the northeastern border of the Holy Cross Mts. A – The composite section and subdivision of the Annopol succession based on data from Kopiec and the abandoned ugerground mine (adapted from Machalski and Kennedy 2013, fig. 1; Kennedy and Machalski 2015, fig. 1 and Machalski and Dubicka 2017, fig. 1, with modifications). B – The composite section of the Chałupki succession (based on this paper). C – Location of the studied area in Poland (insert) and simplified geological map of the study area (adopted from Cieśliński 1959, fig. 1) with marked positions of the localities mentioned in text. D – Location of the Kopiec site (circle) in the Annopol area. E – Location of the Chałupki site (circles). D and E based on the satellite photos, modified from Google Maps. Abbreviations: b – burrow; LP – Lower Phosphorite; bi – 'barren' interval; MP – Middle Phosphorite; UP – Upper Phosphorite; OM – Overlying Marls; HCM – Holy Cross Mts. For further explanations see text.

In view of the foregoing, a stratigraphic reappraisal of the phosphorite interval has become necessary. We performed it on the basis of new data obtained during field work at Chałupki in 2015–2017 and on partial reinterpretation of the data from Annopol (Text-fig. 1A–E). We base our correlations and stratigraphical inferences on the lithology and the Rare Earth Elements (REE) and Yttrium (Y) sig-

Substage	Ammonite Zones	Ammonite Subzones
LOWER CENOMANIAN (lower part)	*Mantelliceras mantelli*	*Mantelliceras saxbii* *Sharpeiceras schlueteri* *Neostlingoceras carcitanense*
UPPER ALBIAN	*Praeschloenbachia briacensis*	
	Mortoniceras perinflatum	
	Mortoniceras rostratum	
	Mortoniceras fallax	
	Mortoniceras inflatum	
	Mortoniceras pricei	
	Dipoloceras cristatum	
MIDDLE ALBIAN	*Euhoplites lautus*	*Anahoplites daviesi* *Euhoplites nitidus*
	Euhoplites loricatus	*Euhoplites meandrinus* *Mojsisovicsia subdelaruei* *Dimorphoplites niobe* *Anahoplites intermedius*
	Hoplites dentatus	*Hoplites spathi* *Lyelliceras lyelli*
LOWER ALBIAN (upper part)	*Otohoplites auritiformis*	*Lyelliceras pseudolyelli* *Pseudosonneratia steinmanni* *Otohoplites bulliensis* *Protohoplites puzosianus* *Otohoplites raulinianus*

Table 1. Ammonite-based subdivison of the Albian to lower Cenomanian interval in the Boreal Realm, adopted from Machalski and Kennedy (2013, table 1) and references quoted therein, modified after Siversson and Machalski (2017).

natures of the phosphorites, and on macrofossil data. Based on sequence stratigraphy patterns, we also present a sequence stratigraphy model for the interval studied. We hope that our results will be useful for further scientific and possibly economic exploration of the phosphorite interval at the northeastern margin of the Holy Cross Mts.

MATERIALS AND METHODS

Field work

The material studied comes from the environs of the town of Annopol on the right bank of the Vistula, and from Chałupki, a small village c. 18 km northeast of Annopol (Text-fig. 1C). At Annopol, most of the material came from a series of temporary trenches dug between 2010 and 2016 in an area of several hundred square meters, north of the old sandstone quarry, south of the village of Kopiec and north of Annopol (Text-figs 1C, D). This location is referred to as the locality Kopiec (e.g. Walaszczyk 1987 and Machalski and Kennedy 2013). The regional dip of the Cretaceous strata in this sector of the Annopol anticline is 4° NE (Samsonowicz 1925) which results in an almost horizontal stratification. Some fossils were picked out from the walls of the excavations but most of the material originates from screen washing of samples from the phosphorite interval and adjacent deposits (units 2–4 in Text-fig. 1A). This operation was conducted directly in the field, with the use of screens and a motorized water pump. Additional observations in the Annopol area have been made subsurface during exploration of the abandoned phosphorite mine (Text-fig. 1C). The section in Text-fig. 1A is compiled from data gained at Kopiec and in the mine.

The Chałupki site (Text-fig. 1B, C, E) has been sampled in a similar way. Four trenches were excavated in 2015 and 2016 along a line c. 150 m long, which runs southeast of the route from Brzozowa, starting just opposite of the first buildings in Chałupki (Text-figs 1E). This is the area previously studied by Bolewski (1937, 1946), Samsonowicz (1937) and Pożaryski (1947, fig. 2, line of trenches 31; see also his plate VIII). Our material came from four trenches;

due to the relatively steep dip of the strata (16˚ NE, see Samsonowicz 1937), each trench exposed another portion of the succession, with minor overlap. In contrast to the Kopiec site, the fossils from Chałupki mostly were obtained by hand-digging from the walls of the trenches; only a minor fraction came from screen washing of sediment samples (only a one-day screen-washing operation was possible at Chałupki). According to information from local inhabitants, one of the entrances to the underground mine was located in close proximity to our sampling area. The composite section at Chałupki, compiled from partial sections, is presented in Text-fig. 1B.

Repositories

The palaeontological material studied is housed at the Institute of Paleobiology, Polish Academy of Sciences, Warsaw, Poland (collection ZPAL V. 53).

Geochemical and petrographical analyses

Rare Earth Elements and Yttrium (REE+Y) contents in rock samples are commonly used to determine the provenance of sedimentary rocks (e.g. McLennan 1989) and/or to elucidate the physico-chemical (e.g. redox) conditions during sedimentation and early diagenesis (e.g. Elderfield and Greaves 1982; Tostevin 2021). REE+Y studies are also utilized, although rather rarely, in chemostratigraphy (Craigie 2018) or to identify bentonites (Wray 1995, 1999). The phosphorites are known to be deposits enriched in REE+Y (e.g. Jarvis *et al.* 1994; Trappe 1998), occasionally in economic concentrations (Emsbo *et al.* 2015). REE+Y signatures are commonly used as a tool for the characterization of the depositional environment of ancient and modem phosphorites (Jarvis *et al.* 1994; Trappe 1998; Fazio *et al.* 2007). Herein, we focus on the correlational significance of the REE+Y signatures obtained from the phosphorite beds from Annopol and Chałupki, and on the broad environmental implications in context of the development of the marine mid-Cretaceous transgression.

Forty five lithological samples were selected for analyses from Annopol (34) and Chałupki (11). The REE concentration was determined in 26 phosphate samples and eight unphosphatized marl samples from Annopol (samples from Kopiec and the underground mine), and in 10 phosphate and a single marl sample from Chałupki. The sampled phosphates represent intraclasts, nodules, organic remains (phosphatized sponges, invertebrate phosphatic moulds and phosphatized wood) as well as the phosphatized 'bridges' connecting earlier generations of phosphatic intraclasts (Machalski and Olszewska-Nejbert 2016). The marl samples represent the material surrounding the phosphates.

For analysis, samples were cleaned with an ultrasonic cleaner in distilled water and then dried. The samples (with a weight of more than 10 g) were then crushed and chipped to c. 1 mm fraction and sent for analysis. The concentration of REE was determined by the ICP MS method in ACME Labs in Canada. REE and Y concentrations are reported in parts per million. We used the reference material of McLennan (1989) for normalization of REE+Y concentrations and all samples were normalized to Post-Archean Australian Shale (PAAS, see McLennan 1989; Pourmand *et al.* 2012). The Excel program was used to compute the data.

Based on Shields and Stille (2001) and Fazio *et al.* (2007), we defined the following anomalies and ratios to evaluate the REE behaviour of the studied samples: $Ce_{anom.} = 3Ce_N/(2La_N+Nd_N)$, $Y_{anom.} = 2Y_N/(Dy_N+Ho_N)$, La_N/Nd_N (N in subscript refers to normalization of concentration against the shale standard PAAS, see McLennan 1989), and the Y/Ho mass ratio. The Y/Ho mass ratio is defined by some authors as the Y anomaly (Tostevin *et al.* 2016).

Petrographical analyses were based on 12 thin sections, including 9 from Annopol and 3 from Chałupki; several polished rock samples from outcrops and the subsurface mine have also been examined.

Sequence stratigraphy

Sequence stratigraphy is a widely used stratigraphic tool for intra- and inter-basinal chronostratigraphic correlations, stratigraphic prediction and mapping of sedimentary facies in both academic and industrial applications (e.g. Catuneanu *et al.* 2011; Simmons *et al.* 2020). Herein, the sequence stratigraphic analysis focuses on the identification of 3rd-order sequence-bounding unconformities and corresponding depositional sequences (cf. Posamentier and Vail 1988; Posamentier *et al.* 1988; Vail *et al.* 1991). Sequence boundaries (SB) indicate substantial erosional and/or non-depositional phases (stratigraphic gaps), or are characterized by rapid basinward shifts of facies. Depositional sequences (DS) in shelf settings commonly consist of retro- and progradational facies units, i.e. transgressive and highstand systems tracts (TST, HST) while lowstand deposits (LST) are often missing or only subordinately developed due to the lack of accommodation during falling and low sea-level stands. Maximum flooding conditions are represented rather by thin stratigraphic intervals reflecting the most distal facies development within a depositional sequence than a distinct maximum flooding surface. The sequence boundary nomenclature of Haq (2014) is followed herein while depositional sequences are labelled according to their terminal sequence boundary (e.g. DS Al 8 is defined by SB KAl 7 below and SB KAl 8 above).

RESULTS

Section at Annopol

The mid-Cretaceous (lower Albian to lower Turonian) condensed succession at Annopol is 6–9 m thick, depending on location in the anticline. The succession is much thinner than the coeval strata northwest Annopol owing to its location on a submarine swell (the Vistula Swell of Cieśliński 1976, the Annopol Swell of Marcinowski and Radwański 1983; Walaszczyk 1987).

The mid-Cretaceous strata at Annopol rest with a slight angular unconformity on Upper Jurassic (Kimmeridgian) marly dolomites and oyster lumachelles (Samsonowicz 1925, 1934). The Cretaceous succession starts with light-grey sands (not shown in Text-fig. 1A) which are followed by a bed of darkgrey quartzitic sandstone, the so-called Rachów Sandstone (top of which is presented as unit 1 in Text-fig. 1A). This unit has yielded a sparse 'middle Albian' ammonite fauna (Samsonowicz 1925, 1934; Marcinowski and Wiedmann 1985, 1990) which has recently been reinterpreted as belonging to the upper lower Albian *Otohoplites auritiformis* Zone and *Pseudosonneratia steinmanni* Subzone (Machalski and Kennedy 2013, p. 546).

Locally, the Rachów Sandstone contains burrows of *Ophiomorpha nodosa* Lundgren, 1891. The sandstone is followed by yellow-grey sands of variable thickness with sparse glauconite, which are capped by a burrowed ommission surface. The overlying olive-green quartzose sands (unit 2 in Text-fig. 1A) are characterised by an upwards increasing glauconite content. An irregular level of weakly cemented sandy phosphatic nodules stands out at the top of the sands (Text-fig. 1A). No stratigraphically important fossils have been reported from this unit.

Higher up is located the phosphorite interval (unit 3 in Text-figs 1A, 2A–C), which forms the subject of the present contribution (the Phosphorite Bed of former authors). This unit is c. 50–60 cm thick and its matrix is composed of quartzose olive-green sand with abundant glauconite, passing gradually into quartz-glauconitic marl. The phosphorite interval is bipartite at Annopol, containing two phosphorite beds, referred here to as the Lower Phosphorite and Upper Phosphorite (LP and UP in Text-fig. 1A).

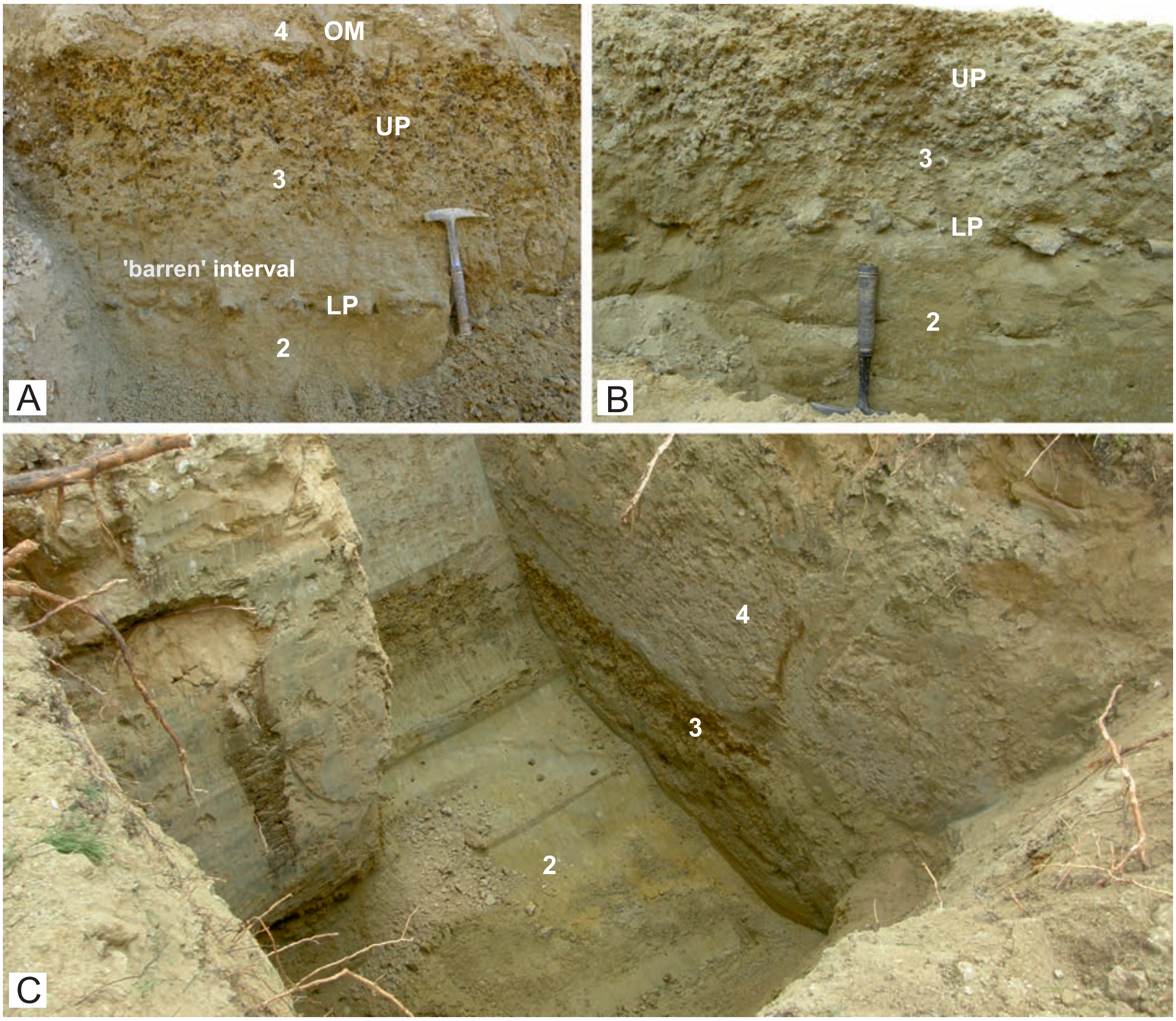
The **Lower Phosphorite** is c. 15 cm thick, composed of black and brown phosphatic nodules and clasts set in a sandy matrix (LP in Text-figs 1A, 2A, B). The phosphorite is poorly sorted, the nodules and clasts ranging from cobbles over 20 cm in diameter to tiny grains. Some of the larger nodules are of characteristic spindle-like shape due to their formation around crustacean burrows. Phosphatized fragments of *Ophiomorpha nodosa* burrows are also present. Phosphatized driftwood with borings of teredinid bivalves is relatively common.

The phosphatic clasts and nodules ('sandy phosphorites' of Cieśliński 1959 and Walaszczyk 1987) are composed mainly of densely packed quartz grains with admixture of glauconite and feldspar grains cemented by francolite (Table 2). When compared to the large nodules, the clasts are slightly enriched in glauconite and phosphate cements.

The Lower Phosphorite yields a relatively rich macrofossil assemblage, including worn, often incomplete phosphatic moulds of ammonites of wide stratigraphical range, from the *Hoplites dentatus* to *Mortoniceras fallax* zones (Samsonowicz 1925, 1934; Marcinowski and Wiedmann 1985, 1990; Kennedy and Machalski 2015; see Table 1). This corresponds to the interval from the middle Albian to the lowermost upper Albian, that is the lowermost 'Vraconnian' *sensu* Amédro (2008). Other age-diagnostic fossils comprise inoceramid bivalves, e.g. *Birostrina concentrica* (Parkinson, 1819), which occur in nests in larger nodules.

A thin sandy interval poor in phosphates follows (Text-figs 1A, 2A). This is the 'barren' interval of the miners (Uberna 1967), but it is particularly productive for palaeontologists. It yields the best preserved fossil assemblage in the succession, including isolated skeletal elements and semi-articulated parts of the skeletons of marine vertebrates (e.g. Popov and Machalski 2014; Kapuścińska and Machalski 2015; Bardet *et al.* 2016; Siversson and Machalski 2017). The 'barren' interval also contains well preserved invertebrates such as double-valved brachiopods filled with unphosphatized sand, and shells of oysters, mainly of *Pycnodonte vesiculosa* (J. Sowerby, 1823).

The number of nodular phosphates gradually increases upwards within unit 3, and they commonly



Text-fig. 2. Section at Annopol (surface locality Kopiec). A and B – Close-up views of the phosphorite interval. C – General view of one of the trenches exposing the succession studied. Abbreviations: LP – Lower Phosphorite; UP – Upper Phosphorite; OM – Overlying Marls. Numbers of units correspond to those inText-fig. 1A. For further explanations see text.

form either infillings of, or overgrowths on, the fossils; furthermore the matrix becomes more marly upwards. The **Upper Phosphorite** (UP in Text-figs 1A, 2A, B), the main target of the phosphate mining in the past, starts in this way. Its lower boundary is diffuse, apparently due to mottling of sediment by burrowing animals (Walaszczyk 1987; Dubicka and Machalski 2017, fig. 2). Locally, the Upper Phosphorite merges with Lower Phosphorite, leaving only a slightly less phosphoritic interval between (Text-fig. 2B). The top of the Upper Phosphorite is sharp and roughly planar in most outcrops.

The Upper Phosphorite is typically 30–40 cm thick and composed of densely to loosely packed phosphatic clasts set in a quartz-glauconitic marly matrix. The latter is intensively bioturbated, with the last, most discernible generation of burrows represented by *Schaubcylindrichnus* isp. typified by whitish marly linings of the walls (identification by Alfred Uchman, personal communication, 2021; *Spongeliomorpha*? *annulatum* of Kennedy 1967 from similar facies in southern England is a related ichnotaxon). The clasts are usually brown, ocasionally black, typically c. 1 cm in diameter, but in the topmost c. 20 cm interval of the Upper Phosphorite, they commonly form larger grape-like aggregates, up to 20 cm in diameter, composed of at least two generations of darker phosphoclasts bound together by beige

PHOSPHORITE BED	MATRIX	GRAINS	QUARTZ	FELDSPAR	GLAUCONITE
Lower Phosphorite at Annopol – large nodules	10–20	80–90	88	10	2
Lower Phosphorite at Annopol – intraclasts	15–25	75–85	86	6	8
Lower Phosphorite at Chałupki	15–25	75–85	88	4	8
Middle Phosphorite at Chałupki	20–30	70–80	70	5	25
Upper Phosphorite at Annopol	30–50	50–70	55–65	5	30–40
Upper Phosphorite at Chałupki	35–40	60–65	60–65	5	30–35

Table 2. Petrographical composition of phosphorites from Annopol and Chałupki. Estimated proportions (in percents) between phosphate matrix and grains (two columns in the middle) and among the main grain components (quartz, feldspar and glauconite) normalized to 100% (three columns to the right).

phosphatic matrix ('phosphatic bridges' of Machalski and Olszewska-Nejbert 2016). These 'bridges' are interpreted as pristine, that is not reworked phosphates (Machalski and Olszewska-Nejbert 2016).

The clasts are grain- or matrix-supported, and reveal the same composition as the unphosphatized marl around them ('phosphorites in marls' of Cieśliński 1959; 'marly phosphorites' of Walaszczyk 1987). The grains are dominated by quartz in both sandy and silty fractions and by glauconite, with the admixture of feldspar, all bound by francolite cements (Table 2). The matrix of the phosphates contains numerous foraminifers, a distinctive feature of the Upper Phosphorite at Annopol (Walaszczyk 1987). Many clasts are fragments of phosphatized sponges.

The fossil assemblages from the Upper Phosphorite record gradual vertical changes in composition and preservation. Its lower portion, that with solitary nodular phosphates, is marked by the appearance of rare rostra of belemnites, *Neohibolites ultimus* (d'Orbigny, 1845) and *Parahibolites tourtiae* (Weigner, 1909), and the bivalve *Aucellina gryphaeoides* (J. de C. Sowerby, 1836), in addition to brachiopods and oysters. These fossils are in diverse preservation, ranging from 'clean' belemnite rostra to phosphatic moulds of bivalves and brachiopods; some specimens bear phosphatic overgrowths.

The stratigraphically most important elements in the lower portion of the Upper Phosphorite are the ammonites preserved as oyster bioimmurations (Machalski and Kennedy 2013) and phosphatic pseudo-steinkerns (Machalski and Olszewska-Nejbert 2016). These ammonites are mostly *Mortoniceras* sp., occasionally of prominent original size, which show the closest affinity to the representatives of *Mortoniceras* (*Subschloenbachia*) characteristic of the upper upper Albian *Mortoniceras perinflatum* Zone (Machalski and Kennedy 2013; Machalski and Olszewska-Nejbert 2016).

The fossil assemblage from the upper portion of the Upper Phosphorite is dominated by fragmentary phosphatized lithistid sponges and calcitic-shelled bivalves, mainly *Aucellina gryphaeoides* and *Pycnodonte vesiculosa*. The former are commonly preserved as phosphate moulds, either devoid of the shell or with shell material, commonly worn. The latter occur mainy as dissociated left valves, occassionally phosphatic moulds. Rostra of *Neohibolites ultimus* and *Parahibolites tourtiae* are common. Brachiopods with phosphatic infillings and disarticulated vertebrate remains are also present (Cieśliński 1959; Machalski and Kennedy 2013; Siversson and Machalski 2017). The fossils in the upper portion of Upper Phosphorite are poorly preserved, overgrown by phosphates and/or commonly incorporated into the grape-like phosphatic aggregates. Some of the nodules near the top of the bed are colonised by encrusting bivalves, mainly oysters and *Dimyodon* sp.

We recovered no ammonites from the upper portion of the Upper Phosphorite, but a single specimen of *Stoliczkaia*, a pseudo-steinkern (Machalski and Olszewska-Nejbert 2016) was recovered from its very top at the former exposure along the Vistula bank near the village Jakubowice (Cieśliński 1959).

The inoceramids from the Upper Phosphorite are represented by a specimen of *Birostrina concentrica* (Parkinson, 1819), recovered from the underground mine. The specimen is from the upper portion of the Upper Phosphorite and corresponds to "*Inoceramus concentricus gryphaeoides*" of Cieśliński (1987) which is specifically indeterminate according to Crampton (1996, p. 41). It is preserved in a highly polished black sandy phosphatic clast, distinctively different from the surrounding 'marly' phosphates, and is considered as derived from the Lower Phosphorite. A fragmentary phosphatized whorl of the Cenomanian ammonite *Schloenbachia varians* (J. Sowerby, 1817) recovered by us from the Upper Phosphorite is also a 'stranger'. It comes from the light marly infilling of a burrow descending from the marls above. Occasionally, such burrows let down the marly sediment even into a level below the Lower Phosphorite (Dubicka and Machalski 2017, fig. 2).

Higher up, with a sharp contact, the light grey quartzose marls of unit 4 rest on the Upper Phosphorite (Text-fig. 1A). These deposits abound in glauconite, inoceramid prisms, and phosphatic clasts, especially in the lower part. The marls are c. 170 cm thick and are referred to as the **Overlying Marls** (OM, unit 4 in Text-figs 1A, 2). This is a quartz-inoceramid packstone composed of 40% of quartz grains, 20% of glauconite grains, 40% of inoceramid debris and foraminifera, all these grain components set in a micrite matrix. The Overlying Marls become less detrital and more calcareous towards the top (Text-fig. 1A); particularly the proportion of the inoceramid debris rises up to 80% near the top of the unit.

In the basal part of the Overlying Marls, there is a concentration of dark and brown phosphatic clasts and fossils. These latter include fragmentary sponges, double-valved terebratulid brachiopods (with phosphatic or marly infillings), well preserved and abundant, usually complete and 'clean' guards of a belemnite *Neohibolites ultimus*, and abundant bivalves. These are represented by *Aucellina gryphaeoides*, mostly phosphatic steinkerns with shell occasionally adhering, and *Gnesioceramus crippsi* (Mantell, 1822), mostly fragmentary phosphatic moulds, rarely marly moulds. Oysters are not uncommon, occassionally encrusting nodules, moulds or shells. The ammonite assemblage recovered by us from the lower portion of the Overlying Marls comprises incomplete specimens in phosphatic preservation. These are typical lower Cenomanian taxa, including *Schloenbachia varians*, matching the data of earlier authors (e.g. Marcinowski and Walaszczyk 1985).

Section at Chałupki

The succession at Chałupki is similar in lithologic development, but more expanded than that at Annopol, attaining c. 18 m in thickness from the bottom of the Albian sands to the top of lower Turonian limestones (Pożaryski 1947; Cieśliński 1959). Albian quartzose sands, c. 10 m thick, rest here on Kimmeridgian marls and limestones. Pożaryski (1947) reported sandstone intercalations from the middle of the sands, probably a counterpart of the Rachów Sandstone at Annopol. Our southwesternmost excavation reached the upper portion of these sands, exposing over 3 m of yellow quartzose sands with glauconite, dispersed phosphatic nodules and two burrowed surfaces (our units 1 and 2 not shown in Text-fig. 1B, and unit 3). Fossils are represented by phosphatized sponges and corroded fragments of belemnite rostra (*Neohibolites* sp.); ichnofossils include *Ophiomorpha nodosa*, *Roselia* isp. and *Skolithos* isp.

The higher part of the succession was exposed in a trench northwest of the former one. This 'main' trench showed the phosphorite interval which forms the subject of the present paper (Text-fig. 3). The section conforms well to descriptions by Bolewski (1937), Samsonowicz (1937) and Pożaryski (1947). The phosphorite interval at Chałupki is tripartite, with three major beds referred here to as the Lower, Middle and Upper Phosphorite (abbreviated LP, MP, and UP, respectively, in Text-figs 1B, 3A, B).

The **Lower Phosphorite** at Chałupki is c. 20 cm thick (LP, top of unit 3 in Text-figs 1B, 3B). It is composed of black phosphatic nodules and clasts set in quartzose-glauconitic sand. The nodules give off a strong bituminous odour when crushed with hammer (cf. Bolewski 1937). The lower boundary of Lower Phosphorite is diffuse, possibly due to bioturbation, the top is sharp; the phosphatic bodies are more densely packed and larger towards the top of the bed.

The nodules and clasts are irregular in shape, 5–8 cm in diameter. These are sandy phosphates, composed mainly of densely packed quartz sand with admixture of glauconite and feldspar grains bound by francolite cements (Table 2). In terms of lithology the sandy phosphates from the Lower Phosphorite at Chałupki match well those of the Lower Phosphorite at Annopol (Table 2). At Chałupki, however, there are no counterparts of the large spindle-shaped nodules characteristic of the Lower Phosphorite at Annopol. In general, the phosphates appear much less diversified in terms of shape and fossil content than those from Annopol, which may in part result from our limited access to this bed (Text-fig. 3B). We identified only some phosphatized sponge fragments, disarticulated oyster shells, pieces of fossil wood, and a few fragmentary shark vertebra from the Lower Phosphorite.

Above the Lower Phosphorite there are phosphate-poor glauconitic sands with only a thin course of phosphatic gravel in the middle (unit 4 in Text-figs 1B, 3B, C). The clasts are less sandy than those from the Lower Phosphorite, being more reminiscent to those from the higher phosphorite beds. We found no fossils here, except for some indeterminate burrows.

Text-fig. 3. Section exposed in the 'main' trench at Chałupki. A – Close-up view of the the upper portion of the phosphorite interval. B – The same for the lower portion of the phosphorite interval. C – General view of the exposure. Abbreviations: LP – Lower Phosphorite; MP – Middle Phosphorite; UP – Upper Phosphorite; OM – Overlying Marls; Q – Quaternary. Numbers of units correspond to those in Text-fig. 1B. For further explanations see text.

Up-section, the **Middle Phosphorite** follows, which is the thickest phosphorite bed at Chałupki (unit 5, MP in Text-figs 1B, 3A–C). It is c. 70–80 cm thick, and is composed of irregular brown phosphatic clasts, usually 1–2 cm in diameter. Near the bottom and top of the bed, the clasts are bound together into larger concretionary aggregates by a less strongly phosphatized matrix, much like the grape-shaped aggregates from the Upper Phosphorite at Annopol. These aggregates are more fragile than those from Annopol and easily disintegrate when an attempt is made to extract them from the sediment.

The phosphatic clasts tend to float in the surrounding highly glauconitic sand, but three more densely packed concentration levels can be distinguished: at the bottom, in the middle and at the top of the unit. Some patchy concentrations of clasts occur in between, which may be ascribed to bioturbation. The upper boundary of the Middle Phosphorite is sharp (Text-fig. 1B).

The phosphates are partly grain- and partly matrix-supported. They are composed mainly of quartz and phosphatized inoceramid debris, with admixture of glauconite and feldspar grains bound by francolite cements (Table 2). Many intraclasts are recognisable fragments of phosphatized sponges. Numerous foraminifers are discernible in the francolite cements. In terms of composition and texture, the phosphatic clasts from Middle Phosphorite are similar to the 'marly' phosphates from the Upper Phosphorite at Annopol, except that they contain some inoceramid debris. They posess less quartz, and are more glauconitic and calcareous when compared to the lower phosphorite beds in both locations (Table 2).

The Middle Phosphorite contains invertebrate fossils, which are more abundant towards the top of the bed. The most common are platy sponge fragments. Mollusks are represented by calcitic-shelled bivalves, *Aucellina gryphaeoides* and *Pycnodonte vesiculosa*, often with phosphatic infillings, and rare rostra of *Neohibolites ultimus*. A fragmentary phosphatic mould of the Cenomanian ammonite *Schloenbachia varians* was found *in situ* in the middle of this bed. Some terebratulid shells, fragments of phosphatized wood, a lamniform shark tooth and a fragment of a chimaeroid fish mandible have also been recovered by screen washing of the sediment. Rare burrows of *Schaubcylindrichnus* isp. occur in the sandy matrix.

Higher up, grey green marly glauconitic sands follow, passing gradually into sandy glauconitic marls (unit 6 in Text-fig. 1B). There is a thin intercalation of phosphatic clasts near the middle of this unit, which contains similar fossils to those from the phosphorite beds below and above. Another Cenomanian ammonite was found *in situ* in close proximity to this intercalation, namely a fragmentary phosphatic mould of *Schloenbachia varians*. The sands and marls of unit 6 are riddled with *Schaubcylindrichnus* burrows with white marly linings, which give a characteristic mottled appearance to this part of the section.

The sandy glauconitic marls of unit 6 are overlain, with rather sharp contact, by the **Upper Phosphorite**, 15–20 cm thick (unit 7, UP in Text-figs 1B, 3A). The upper boundary of this bed is also sharp. The bed itself is composed of densely packed dark brown and black phosphatic clasts and nodules, usually 2–8 cm in diameter, set in a grey-green marly matrix with abundant quartz and glauconite.

The intraclasts are partly matrix- and partly grain-supported. They are composed mainly of quartz and glauconite, with admixture of phosphatized feldspar grains and francolite cements (Table 2). In the phosphatic cement, foraminifera are visible, as in the Middle Phosphorite. Numerous intraclasts consist of fragments of phosphatized sponges. The lithology of the phosphatic intraclasts from the Middle and Upper Phosphorites at Chałupki corresponds well to those from the Upper Phosphorite at Annopol (Table 2).

The Upper Phosphorite is the most fossiliferous level in the phosphorite interval at Chałupki. Fragments of platy sponges prevail, followed by numerous individuals of calcitic-shelled bivalves, often in phosphatic mould preservation, mostly *Aucellina gryphaeoides* and *Pycnodonte vesiculosa*. Rostra of *Neohibolites ultimus* are relatively common, as well as terebratulid brachiopods, and pieces of slightly phosphatized wood with bivalve borings. A fragmentary phosphatic mould of *Schloenbachia varians* was recovered *in situ* near the bottom of the Upper Phosphorite. Vertebrate remains are represented by shark vertebrae, teeth of lamniform sharks and pieces of chimaeroid mandibular plates. The taxonomic characteristics and taphonomic signatures of specimens match well those of the fossil assemblage from the Upper Phosphorite at Annopol.

Light-grey marls overlie the Upper Phosphorite at Chałupki, referred here to as the **Overlying Marls** (OM, unit 8 in Text-figs 1B, 3). They are similar in terms of lithology and fossil content to unit 4 at Annopol, although they are more sandy and glauconitic near the bottom. The marls are composed mainly of quartz, glauconite, inoceramid debris, foraminifera and micrite (the quartz-inoceramid packstone). Small brown and black phosphatic clasts are present, particularly near the bottom. Unit 8 at

Chałupki becomes less sandy and more calcareous towards its top, just like unit 4 at Annopol.

We sampled in detail only the lower part of the Overlying Marls, which yielded a rich assemblage of phosphatized sponge fragments, terebratulid brachiopods (with phosphatic or marly infilling), bivalves (*Aucellina gryphaeoides*, rare *Gnesioceramus crippsi*, *Dimyodon* sp. and oysters), as well as belemnites (*Neohibolites ultimus*). There are also fragmentary nautilid and gastropod phosphatic moulds. Ammonites are represented by relatively rare Cenomanian taxa: *Mantelliceras* spp., *Sciponoceras* sp., and *Schloenbachia varians*, preserved as fragmentary and often worn phosphatic moulds.

REE +Y signatures of phosphorites

Lower Phosphorite

At Annopol, the total REE+Y concentration is in the range 51.93–172.07 ppm for REE and 9.1–34.9 ppm for Y. The lowest concentration is in sample Ann-16 from sandy marl surrounding the phosphates; other samples are phosphatic nodules and fossils (Table 3). The content of REE+Y at Chałupki is in the range of 93–111.4 ppm for REE and 15.7–20.0 ppm for Y (Text-fig. 4C, F; Table 3 and Appendix 1, available only in on-line version).

Concentrations of REE+Y in phosphates from the Lower Phosphorite at Annopol (Text-fig. 4C) represent the patterns close to the 'flat-pattern type', 'continental-pattern type' or 'shale-type' (Jarvis *et al.* 1994; Shields and Stille 2001; Tostevin *et al.* 2016). The diagrams reveal a slightly higher content of La (Text-fig. 4C), weak depletion of LREE (La-Nd) in comparison to MREE (Sm-Ho) and HREE (Er-Lu), the lack of a Ce anomaly, and the presence of a positive Y anomaly. The higher content of La is expressed by a La_N/Nd_N ratio above 1 (Text-fig. 5B, D, F). The majority of values of the Ce anomaly are lower than 1 (Text-fig. 5A–C). All phosphatic samples have a positive Y anomaly, expressed also as a value above 1.18 (Text-fig. 5A, F). A single sample, Ann-16, from the unphosphatized marly matrix of the Lower Phosphorite at Annopol departs from the flat-pattern type characterising the phosphate samples from this level. It is typyfied by a weak negative Ce anomaly (0.83), a weak positive Y anomaly (1.03), and conspicuous enrichment in MREE in comparison to LREE and HREE. The La_N/Nd_N ratio is 0.88, clearly lower than in other samples from this unit. This pattern is very similar to those observed in marl samples from the Upper Phosphorite (Text-fig. 4B), suggesting that the geochemical environment during the deposition of the marly matrix was different from that in which the nodular phosphates originated (in match with faunistic and lithological data).

Diagrams of the concentration of REE+Y (Text-fig. 4F) in the phosphates from the Lower Phosphorite at Chałupki are of the the flat-pattern type, similar to those from the Lower Phosphorite at Annopol. The Ce and Y anomalies, as well as the La_N/Nd_N ratio (Text-fig. 5) and Y/Ho mass ratio (Text-fig. 6) also match well the Annopol phosphate samples.

Middle and Upper Phosphorites

In samples from the Upper Phosphorite at Annopol, the total REE+Y concentration is 48.18–185.88 ppm for REE and 8.6–38.9 ppm for Y. The lowest concentrations are from samples of the unphosphatized marls in which the phosphates are entombed. The content of REE+Y in samples from the Middle and Upper Phosphorites of Chałupki is in the range 186.3–312.63 ppm for REE and 37.5–73 ppm for Y. The REE+Y content at Chałupki is higher than that at Annopol (Text-figs 4B, E, 5C–E; Table 3 and Appendix 1).

At Annopol, the concentration of REE+Y in phosphates and surrounding marls represent a pattern with weak negative Ce anomaly (shallow 'v') and slight MREE-enrichment (Text-fig. 4B). The La_N/Nd_N ratios oscillate around 1 (Text-fig. 5B, D, F), which means lack of enrichment in La. All samples have a positive Y anomaly, expressed by a value above 1.06 (Text-fig. 5A, F), which is similar to that in the Lower Phosphorite. The values of the Ce anomaly are in the range 0.67–0.84 (Fig. 5A–C) which differentiates these samples from the Lower Phosphorite ones.

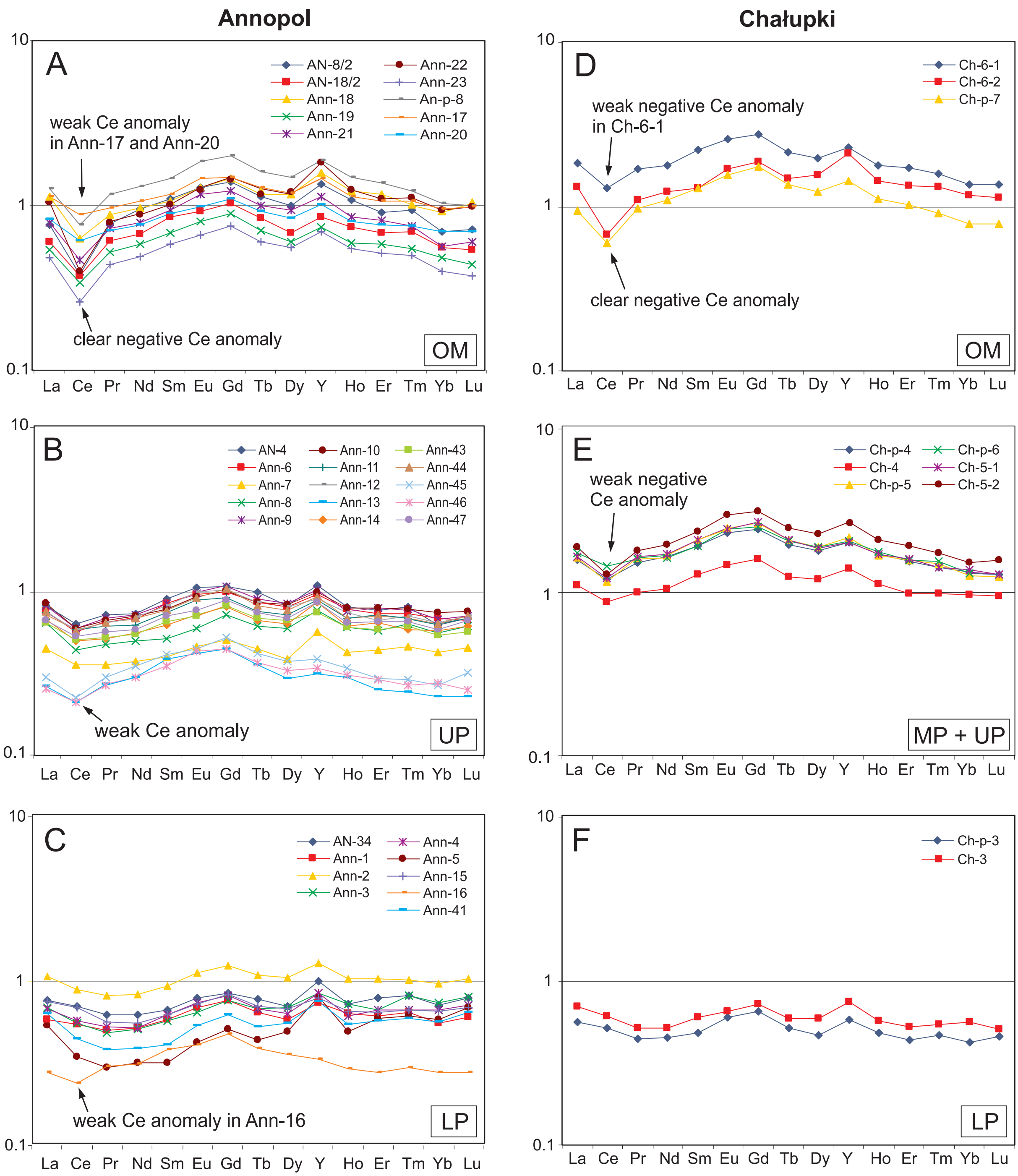
The concentrations of REE+Y in phosphatic samples from the Middle and Upper Phosphorites at Chałupki (Text-fig. 4E) present patterns similar to those from Annopol. The concentrations of sum REE have higher values (Text-fig. 5C–E), but the calculated Ce and Y anomalies, the La_N/Nd_N ratio (Text-fig. 5A, B, E), and the Y/Ho mass ratio (Text-fig. 6) fit well the data from the Upper Phosphorite at Annopol.

Overlying Marls

At Annopol, the total REE+Y concentration in phosphates and the unphosphatized marly matrix is in the range of 73.1–198.92 ppm for REE and 18.6–50.6 ppm for Y. The content of REE+Y in the same interval at Chałupki is similar, ranging between 160.05 and 191.42 ppm for REE and 38.5–57.2 ppm for Y.

SAMPLE	LOCALITY	BED	IDENTIFICATION
AN-34	Annopol m	LP	Phosphatic nodule
Ann-1	Annopol K	LP	Phosphatic mould of *Hoplites dentatus*
Ann-2	Annopol K	LP	Phosphatic mould of *Hoplites dentatus*
Ann-3	Annopol m	LP	Phosphatized burrow *Thalassinoides*
Ann-4	Annopol K	LP	Phosphatic clast
Ann-5	Annopol K	LP	Phosphatized wood
Ann-15	Annopol m	LP	Phosphatic clast
Ann-16	Annopol m	LP	Sandy marl surrounding Ann-15
Ann-41	Annopol K	LP	Phosphatized infilling of boring in Ann-5
AN-4	Annopol m	UP	Phosphatic clast
Ann-6	Annopol K	UP	Phosphatic mould of *Aucellina*
Ann-7	Annopol K	UP	Phosphatized sponge *Siphonia*?
Ann-8	Annopol K	UP	Phosphatized sponge *Siphonia*?
Ann-9	Annopol K	UP	Phosphatic moulds (4) of *Aucellina*
Ann-10	Annopol K	UP	Phosphatized sponge
Ann-11	Annopol m	UP	Phosphatic clast
Ann-12	Annopol m	UP	Phosphatic 'bridge' from larger aggregate
Ann-13	Annopol m	UP	Marl between clasts and 'bridge'
Ann-14	Annopol K	UP	Phosphatic clasts
Ann-17	Annopol m	OM	Phosphatic clast (apparently redeposited from UP)
Ann-20	Annopol K	OM	Phosphatic clast (apparently redeposited from UP)
Ann-43	Annopol m	UP	Phosphatic clast
Ann-44	Annopol m	UP	Phosphatic 'bridge'
Ann-45	Annopol m	UP	Marl
Ann-46	Annopol m	UP	Marl
Ann-47	Annopol K	UP	Phosphatic 'bridge' from sample Ann-14
AN-8/2	Annopol m	OM	Marl
AN-18/2	Annopol m	OM	Marl
Ann-18	Annopol m	OM	Phosphatic clast
Ann-19	Annopol m	OM	Marl
Ann-21	Annopol K	OM	Phosphatic brachiopod mould
Ann-22	Annopol K	OM	Phosphatized sponge
Ann-23	Annopol K	OM	Marl
An-p-8	Annopol K	OM	Phosphatic mould of *Schloenbachia*
Ch-p-3	Chałupki	LP	Phosphatic clast
Ch-3	Chałupki	LP	Phosphatic clast
Ch-p-4	Chałupki	MP+UP	Phosphatic mould of *Aucellina*
Ch-4	Chałupki	MP+UP	Phosphatic clasts (5)
Ch-p-5	Chałupki	MP+UP	Phosphatic clast (?sponge)
Ch-5-1	Chałupki	MP+UP	Phosphatic clasts (4)
Ch-5-2	Chałupki	MP+UP	Phosphatic clasts
Ch-p-6	Chałupki	MP+UP	Phosphatic clasts
Ch-6-1	Chałupki	OM	Phosphatic clasts (apparently redeposited from UP)
Ch-6-2	Chałupki	OM	Phosphatic intraclasts
Ch-p-7	Chałupki	OM	Marl

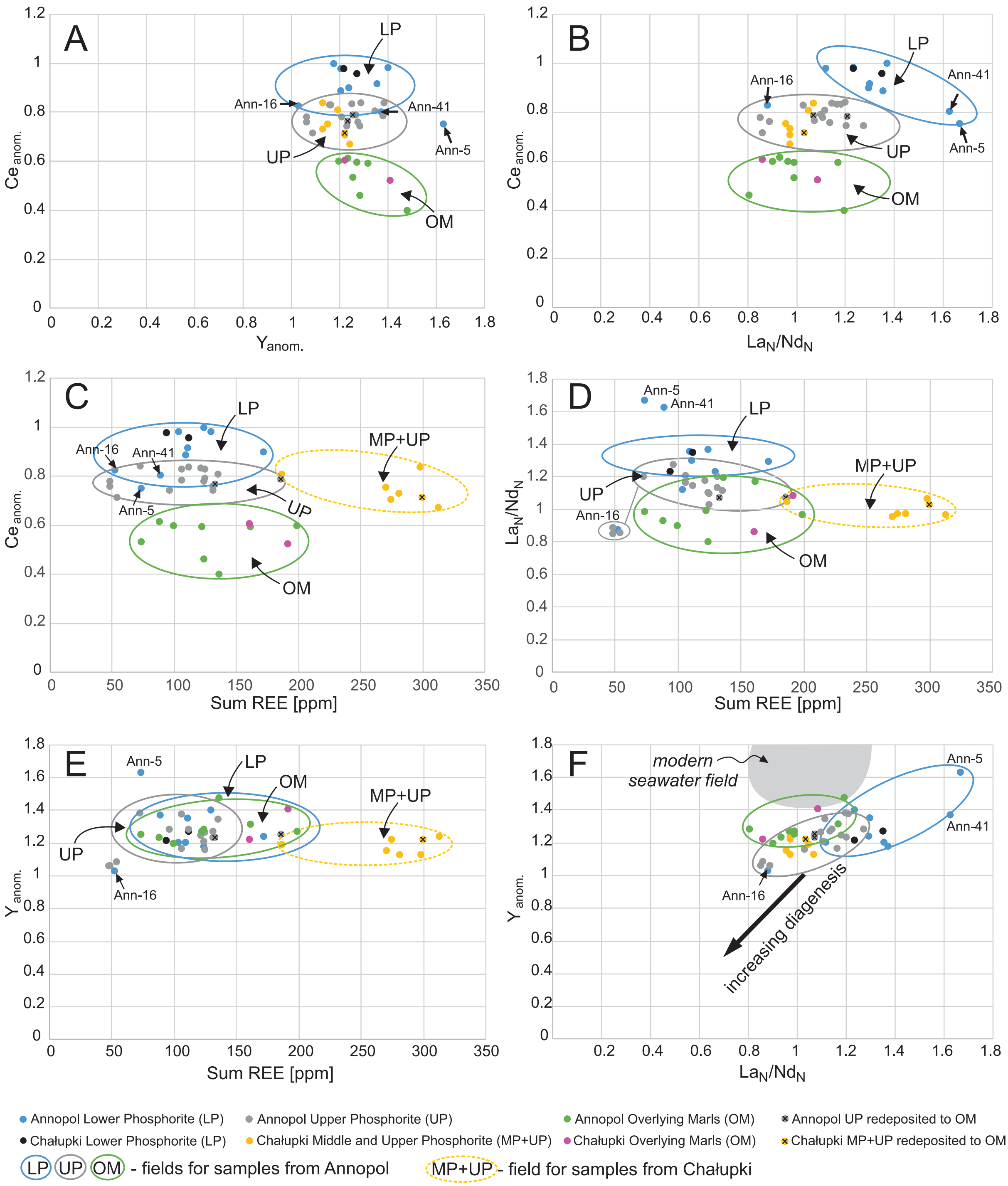
Table 3. List of analysed samples from Chałupki and Annopol. Abbreviations: LP – Lower Phosphorite; MP – Middle Phosphorite; UP – Upper Phosphorite; OM – Overlying Marls; m – subsurface mine; K – open cast locality Kopiec.



Text-fig. 4. Comparison of REE+Y patterns for phosphorites and marls from Annopol (A–C) and Chałupki (D–F). A, D – samples from Overlying Marls. B, E – samples from Middle and Upper Phosphorites. C, F – samples from Lower Phosphorite. For further explanations see text.

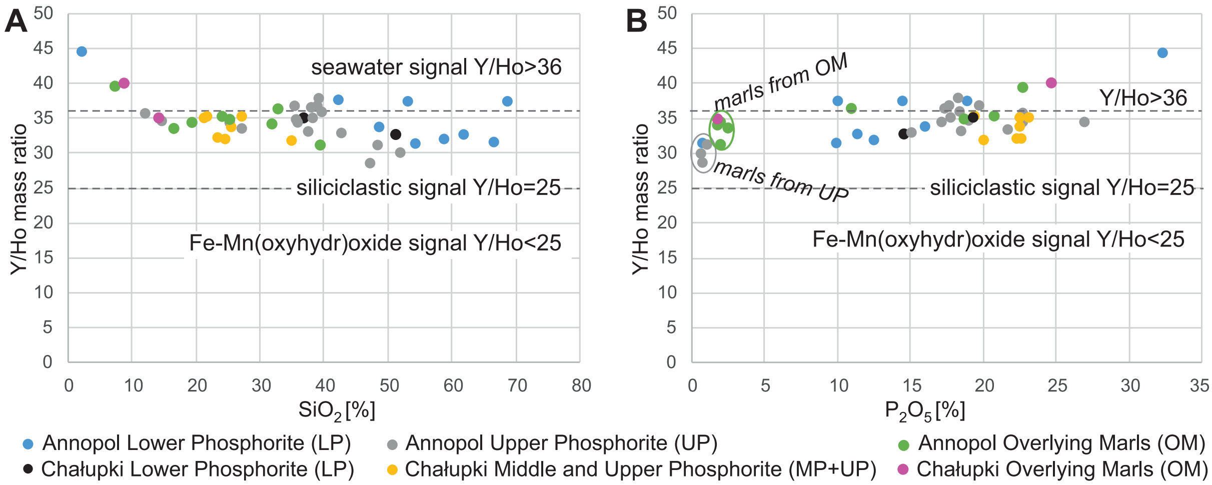
The concentration of REE+Y is higher in phosphates than in marls (Table 3 and Appendix 1).

At Annopol, the concentration of REE+Y (Text-fig. 4C) displays a pattern with a clear negative Ce anomaly (quite deep ‘v’), a slight MREE-enrichment and a slight HREE-depletion (Text-fig. 4A). The La_N/Nd_N ratio oscillates around 1 (Text-fig. 5B, D, F), which means lack of enrichment in La. All samples have a clear positive Y anomaly, expressed by a value above 1.20 (Text-fig. 5A, F; Appendix 1),



Text-fig. 5. REE composition of studied samples expressed as a combination of parameters. A – Y anomaly *vs* Ce anomaly. B – La_N/Nd_N ratio *vs* Ce anomaly. C – Sum REEs *vs* Ce anomaly. D – Sum REEs *vs* La_N/Nd_N ratio. E – Sum REEs *vs* Y anomaly. F – La_N/Nd_N ratio *vs* Y anomaly.

such as in the underlying phosphorite. The values of the Ce anomaly are in range 0.40–0.61 (Text-fig. 5A–C), differing this lot from the samples from the underlying phosphorites. Two samples from black phosphoclasts (Ann-17 and Ann-20) display a slight MREE-enrichment with weak Ce-anomaly (shallow 'v' in Text-fig. 4A) which is more characteristic of the Upper Phosphorite. The values of the Ce anomaly of



Text-fig. 6. Y/Ho mass ratio for the studied phosphorites, and the Overlying Marls plotted against 'allogenic' SiO_2 component (A) and 'authigenic' P_2O_5 component (B). Note that dashed lines indicate key threshold values (see Tostvin *et al.* 2016): 25 is the Y/Ho mass ratio for shale, and Y/Ho > 36 is a threshold value for carbonate REE+Y signals from seawater.

these samples (0.77 and 0.79) match well the samples from the Upper Phosphorite, suggesting that these clasts are derived from that unit.

At Chałupki, the concentrations of REE+Y (Text-fig. 4D) from the Overlying Marls display patterns similar to those from Annopol. The Ce and Y anomalies, La_N/Nd_N ratio (Text-fig. 5), and the Y/Ho mass ratio (Text-fig. 6) match well into the corresponding Annopol sample lot. A black phosphoclast (Ch-6-1) yields the slightly MREE-enriched pattern with a weak Ce anomaly (shallow 'v' in Text-fig. 4D and value 0.71). These data are more characteristic for the Middle and Upper Phosphorites, suggesting reworking of the black clast from the Upper Phosphorite, in analogy to the clasts from Annopol mentioned above.

Biostratigraphy

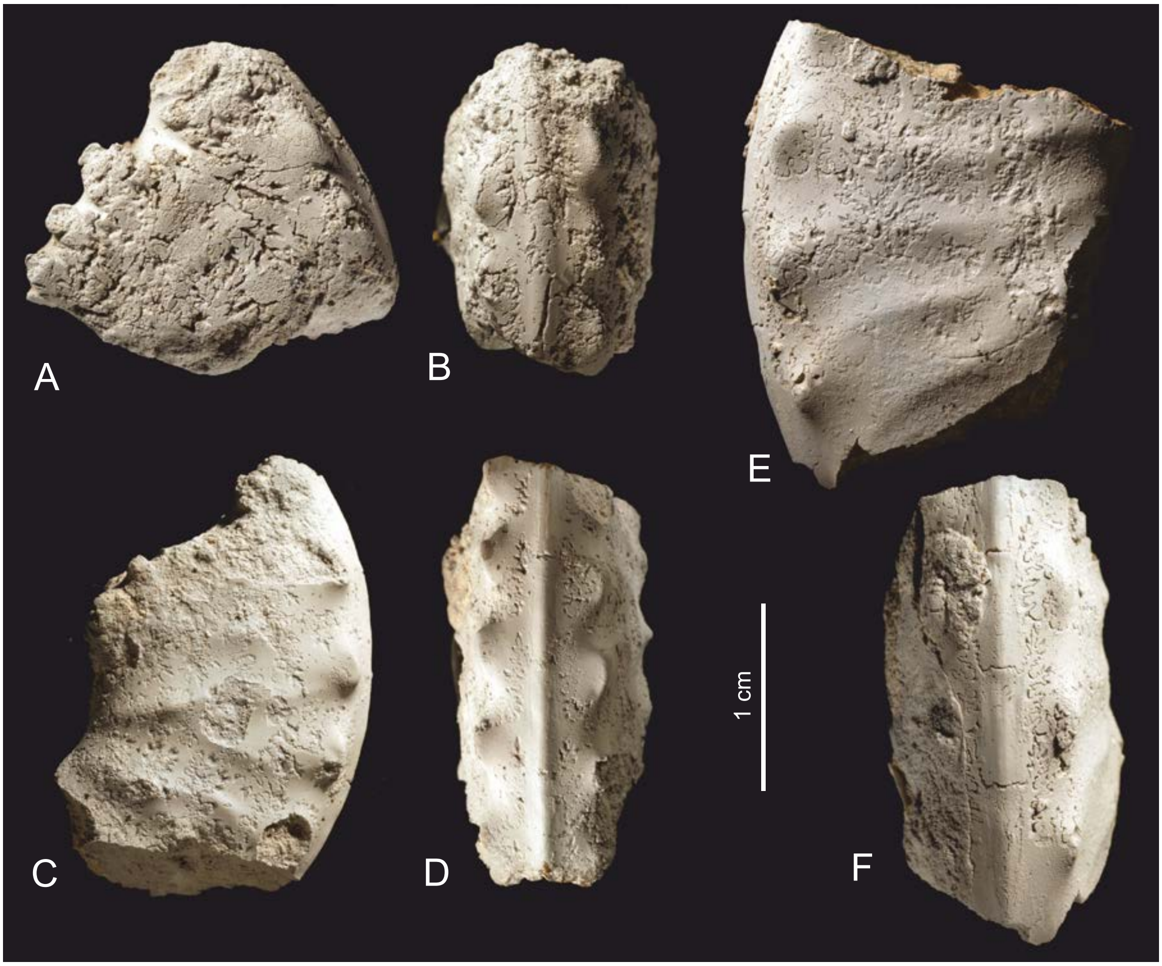
Ammonites

These cephalopods from Annopol were described and illustrated by Cieśliński (1959), Marcinowski and Wiedmann (1985, 1990), Marcinowski and Radwański (1983, 1989), Marcinowski and Walaszczyk (1985), Machalski and Kennedy (2013), Kennedy and Machalski (2015), and Machalski and Olszewska-Nejbert (2016). Ammonite lists were provided by Samsonowicz (1925, 1934). In contrast, ammonites from Chałupki have only been listed in a single note (Samsonowicz 1937). Remarkably, all ammonites illustrated so far from the Annopol phosphorites are decisively Albian taxa, although Samsonowicz (1925, 1934) mentioned rare occurrences of the Cenomanian *Schloenbachia varians*. On the other hand, Samsonowicz (1937, p. 28) listed Cenomanian taxa ('*S. varians*, *Baculites baculoides*') and '*Turrilites*' from the Chałupki phosphorites. We had no possibility of checking these identifications as the specimens are lost. However, we are able to confirm the presence of undoubted Cenomanian ammonites in the phosphorite interval at Chałupki based on our finds of three specimens of *Schloenbachia varians*. These are: ZPAL V. 53/69 (Text-fig. 7A, B) from the middle part of the Middle Phosphorite, ZPAL V. 53/70 (Text-fig. 7C, D) from a level below the Upper Phosphorite, and ZPAL V. 53/71 (Text-fig. 7E, F) from the Upper Phosphorite.

All these specimens are fragments of septate inner whorls and are preserved as phosphatic internal moulds, clearly derived as demonstrated by their worn appearance and the presence of minute oyster spat on the surface of specimens 69 and 71 (preserved on the unfigured sides of the specimens). Despite their fragmentary preservation these individuals reveal ornament and proportions typical of the lower Cenomanian ammonite *Schloenbachia varians* (Wilmsen and Mosavina 2011; Kennedy 2013; Wright and Kennedy 2015; Machalski 2018). This is a very common and morphologically variable species in Europe (*lit. cit*). There are no unequivocal records of *S. varians* from the Albian (Wright and Kennedy 2015).

Bivalves

Representatives of the genus *Aucellina* and inoceramids are of primary importance for stratigraphical interpretation of the phosphorite interval. In

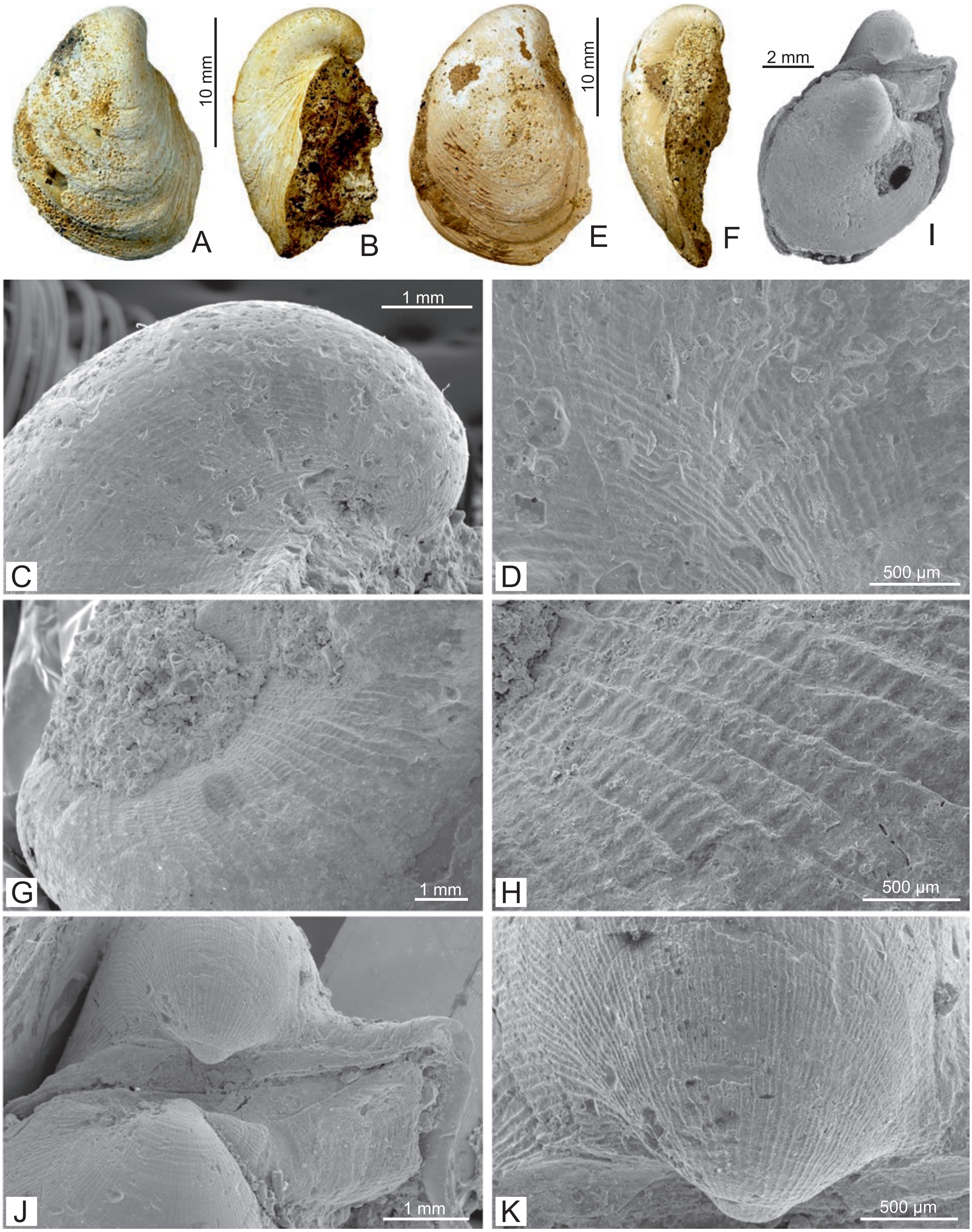


Text-fig. 7. *Schloenbachia varians* (J. Sowerby, 1817) from the phosphorite interval at Chałupki. A, B – Specimen ZPAL V. 53/69 from the middle part of the Middle Phosphorite. C, D – ZPAL V. 53/70 from a level below the Upper Phosphorite. E, F – ZPAL V. 53/71 from the Upper Phosphorite.

addition to poorly preserved specimens assigned to *Aucellina* spp, we identified two species of this genus in the phosphorite interval. These are *Aucellina gryphaeoides* (Text-fig. 8A–H), which is common, and *A. uerpmanni* Polutoff, 1933 (Text-fig. 8I–K), which is extremely rare. According to Morter and Wood (1983, p. 520), the name *A. gryphaeoides* is relevant to 'large, relatively thin-shelled, non -or weakly sulcate elongate oblique forms', and the name *A. uerpmanni* to 'small, thicker shelled sulcate, equidimensional forms' with prominent horizontal anterior ear. Morter and Wood (1983) thoroughly discussed the taxonomy of European representatives of *Aucellina*, stressing the provisonal character of their taxonomic assignments, but, for the purposes of this paper, we treat both names as valid.

As demonstrated by Morter and Wood (1983), Mitchell (1995) and Underwood and Mitchell (1999), the progressive changes in microsculptures of the successive samples of *Aucellina* left valves may be used for stratigraphic subdivision of the Albian/lower lower Cenomanian interval. We therefore examined over a hundred *Aucellina* specimens from both localities studied. Unfortunately, most of these are preserved as internal phosphatic moulds with no shell material adhered; many other preserve the shell, the surface of which is, however, in most cases heavily worn or obliterated by pressure-dissolution pits (*sensu* Radwański 1965; Lescinsky and Benninger 1994). The microstructures are well preserved only in 18 individuals of *A. gryphaeoides* and in a single specimen of *A. uerpmanni* from Kopiec in the Annopol anticline. The identifiable microsculptures are absent in specimens collected at Chałupki.

Two types of shell microsculpture distinguished by Morter and Wood (1983) are discernible in the studied



Text-fig. 8. General morphology and shell microsculptures of *Aucellina gryphaeoides* (J.de C. Sowerby, 1836) (A–F, C, D, G, H) and *A. uerpmanni* Polutoff, 1933 (I–K) from Annopol preserved on umbonal parts of their left valves. A–D – Specimen ZPAL V. 53/72 from Upper Phosphorite, striate sculpture. I–K – ZPAL V. 53/83 from the lower portion of Upper Phosphorite, striate sculpture. E–H – ZPAL V. 53/84 from the lower portion of Overlying Marls, elongate reticulate sculpture. Specimens in A–F are isolated left valves. Specimen in I is a double-valved specimen photographed in the right valve view.

lot from Annopol: 1) **Striate** microsculpture, discernible on the near-umbonal shell surface of the left valves in 11 individuals (ZPAL V. 53/72–82) of *A. gryphaeoides* from Upper Phosphorite (e.g. Text-fig. 8A–D) and a single specimen of *A. uerpmanni* (ZPAL V. 53/83) from the lower part of Upper Phosphorite (Text-fig. 8I–K); 2) **Elongate reticulate** microsculpture found in 7 specimens (ZPAL V. 53/84–90) of *A. gryphaeoides* from Overlying Marls (e.g. Text-fig. 8E–H).

According to Morter and Wood (1983, figs 1 and 2 and pp. 519, 522–523), the striate microsculpture is characteristic of the *Aucellina* samples from the lower, phosphate-rich portion of the Cambridge Greensand Member and from the Glauconitic Marl Member, both in the West Melbury Marly Chalk Formation of eastern and southern England, respectively (the lithostratigraphic terminology based on Hopson 2005). As for the Cambridge Greensand, which contains mixed late Albian and early Cenomanian fossils (e.g. Morter and Wood 1983; Machalski 2018), the age of the striate *Aucellina* may be either late Albian or the early Cenomanian (*Neostlingoceras carcitanense* Subzone of the *Mantelliceras mantelli* Zone, see Morter and Wood 1983; Table 1). In contrast, the striate *Auccellina* from the Glauconitic Marl may be firmly placed in the eponymous subzone of the lower Cenomanian (Morter and Wood 1983). The 'advanced' *Aucellina*, that is those with the elongate reticulate sculpture, are reported by Morter and Wood (1983, p. 523) from several higher *carcitanense*-age chalk units across England, and also from 'the basal Cenomanian Tourtia of Lüneburg, Germany'. A smilar succesion of microsculptures has been also documented by Mitchell (1995) from the Albian Hunstanton Red Chalk Formation and the lowermost portion of the overlying Cenomanian Ferriby Chalk Formation at Speeton, North Yorkshire, England (lithostratigraphy from Hopson 2005). There, striate-ornamented *Aucellina* specimens cross the Albian–Cenomanian boundary (which is defined by carbon isotope signatures in view of the absence of ammonites) and are replaced by *Aucellina* with reticulate elongate microsculpture at a level within the Crowe's Shoot Member, which is correlatable with *N. carcitanense* Subzone (Mitchell 1995, fig. 11). *Aucellina* does not range higher than the lower lower Cenomanian *N. carcitanense* Subzone of the *Mantelliceras mantelli* Zone (Morter and Wood 1983). In view of this, and taking into account the above described patterns in microsculpture development, one may state that the occurrences of striate *Aucellina gryphaeoides* are of late Albian or early Cenomanian age, and the elongate reticulate *Aucellina gryphaeoides* is restricted to the early Cenomanian.

As for the inoceramid bivalves (compare Cieśliński 1987), no identifiable specimens have been found in the middle and upper phosphorite levels at Annopol and Chalupki, except for a derived individual of the Albian species *Birostrina concentrica* from Annopol (see above). Just at the bottom of the Overlying Marls, individuals of *Gnesioceramus crippsi* appear, which are abundant at Annopol and less common at Chałupki. There are 33 mostly phosphatic moulds of this species from the basal metre of the Overlying Marls at Annopol (ZPAL V. 53/36–68) and 4 from Chałupki (ZPAL V. 53/91–94) in our collections. *G. crippsi* is a typical lower Cenomanian species widely distributed in Europe, which forms a distinctive bioevent (epibole) in the middle of the *M. mantelli* Zone (in the upper *Sharpeiceras schlueteri* Subzone, see e.g. Robaszynski *et al.* 1998; Wilmsen 2012; Wilmsen *et al.* 2021; Table 1). In the expanded successions around Hannover the first specimens appear 3–5 m above the Cenomanian onlap surface represented by a condensed glauconite- and phosphate-rich basal Cenomanian transgressive lag (the *Neohibolites ultimus*/*Aucellina* Bioevent of Ernst *et al.* 1983; see also Wilmsen 2012). In British sections, *G. crippsi* first appears some distance above the last appearance of *Aucellina* (Morter and Wood 1983; Mitchell 1995). In contrast, the interval of co-occurrence of *Aucellina* and *G. crippsi* is reportedly a typical feature of the Polish sections (the *Inoceramus crippsi* and *Aucellina gryphaeoides* Zone, or C_1 Zone in Cieśliński 1987, see also Cieśliński and Pożaryski 1970 and Cieśliński 1976). This interval was regarded as the basalmost Cenomanian by the quoted authors, but this interpretation is not supported by our data from Annopol and Chałupki.

Belemnites

Samsonowicz (1925, 1934) mentioned *Belemnites ultimus* d'Orbigny, 1845 from the phosphorite interval of Annopol, reportedly rare in the middle and common in the upper portion of the unit (Upper Phosphorite in the present paper); he also noted common specimens of this species from the Overlying Marls. Samsonowicz (1937) mentioned this taxon from the middle and upper phosphorite beds (MP and UP herein) exposed at Chałupki. According to Pożaryski (1947), abundant *B. ultimus* co-occur with *Aucellina gryphaeoides* in the upper portion of the phosphorite interval of the whole northeastern margin of the Holy Cross Mts. Cieśliński (1959) presented descriptions and illustrations of the belemnites from this area, identifying two taxa from the phosphorite interval and overlying strata: *Neohibolites ultimus* and *Parahibolites tourtiae*.

Our collection from Annopol contains 20 specimens of *Parahibolites tourtiae* (ZPAL V. 53/95–114), and 22 of *Neohibolites ultimus* (ZPAL V. 53/115–136) from Upper Phosphorite and 65 specimens of *N. ultimus* from Overlying Marls (ZPAL V. 53/29–31 and V. 53/137–98). At Chałupki, only *N. ultimus* is present: 2 specimens (ZPAL V. 53/199–200) from Middle Phosphorite, 11 specimens (ZPAL V. 53/201–211) from Upper Phosphorite (some may come from a level just below), and 22 specimens (ZPAL V. 53/212–233) from Overlying Marls. The belemnite distribution matches the data of Cieśliński (1959), who reported that *P. tourtiae* is restricted to the Upper Phosphorite at Annopol, but *N. ultimus* ranges from this level to the overlying marls (OM). Cieśliński (1959) ascribed a late Albian age to the specimens of both species from the Upper Phosphorite. However, all reliable records of *N. ultimus* elsewhere are restricted to the lower and lower part of the middle Cenomanian (Spaeth 1971; Naidin 1952; Pasternak *et al.* 1968; Combémorel *et al.* 1981; Wilmsen 1999; Wilmsen *et al.* 2010; Mitchell 2005). Only a few authors still extend the range of this taxon down into upper Albian, apparently based on – doubtful as it appears now – dating of the Polish phosphorite strata and belemnite specimens by Cieśliński (e.g. Khevpa 2014).

As far as *P. tourtiae* is concerned, this is an eastern taxon, described from the lower lower Cenomanian strata of western Ukraine (its stratum typicum is the section at Nizhniov, Niżniów in Polish literature, on the banks of the Dniestr River, see Weigner 1909). *P. tourtiae* occurs there with *N. ultimus* and *Aucellina gryphaeoides* (Bujalski 1911; Naidin 1952; Pasternak *et al.* 1968) which points to the early Cenomanian age of these specimens (compare Morter and Wood 1983 and Mitchell 1995). The westernmost occurrence of *P. tourtiae* has been reported so far from the lower Cenomanian of the Münster Basin (Mitchell 2005). In summary, both belemnite species are early Cenomanian taxa.

Shark teeth

A comment is relevant here on the results of a paper by Siversson and Machalski (2017) who described selachian teeth from the phosphorite interval at Annopol. These authors proposed a late Albian (‘Vraconnian’) age for the shark teeth assemblage from the Upper Phosphorite, based on evolutionary trends and presence of some taxa. However, they noted that ‘There are no demonstrably Cenomanian taxa in the studied material [from the phosphorite interval], but we recognize the lack of described elasmobranch faunas with biostratigraphically significant taxa, firmly dated as earliest Cenomanian’ (Siversson and Machalski 2017, p. 439).

DISCUSSION

Lithological correlation

Both sections at Annopol and Chałupki show a smilar lithological development, with several thin units separated by hiatal surfaces in approximately the same position in both sites (Fig. 1A, B). For the purposes of lithological correlation, two distinctive levels, which bracket the phosphorite interval in both sections, are crucial. These are the lower boundary of sandy phosphorites at the bottom (Lower Phosphorite), and the sharp boundary between the Upper Phosphorite and Overlying Marls. These are pivotal boundaries, reflecting major changes of the depositional regime in both successions. The intervening deposits, developed as phosphate-poor and phosphate rich intervals (Upper Phosphorite at Annopol; Middle Phosphorite and Upper Phosphorite at Chałupki) may be interpreted as the results of minor lateral variation in development of the studied interval (Text-fig. 1A, B). As far as the middle and upper phosphorites are concerned, the lithology of phosphates is similar in both sections (Table 2) which strengthens the correlations presented in Text-fig. 1A, B.

Rare Earth Elements and Yttrium (REE+Y)

These elements are supplied to seas and oceans mainly through rivers which give a ‘flat’ or ‘continental’ type shale-normalization distribution pattern (Tostevin *et al.* 2016). The carbonate fluorapatite (francolite in marine environment) is more prone to incorporate REEs (Jarvis *et al.* 1994; Trappe 1998; Emsbo *et al.* 2015) than e.g. calcite, thus the sums of REE in samples from marls surrounding the phosphates are usually lower than in the phosphates themselves (Table 3 and Appendix 1). The primary composition of REE+Y incorporated into deposits may be changed by subsequent diagenetic processes (Reynard *et al.* 1999; Shield and Stille 2001; Kidder *et al.* 2003) and weathering (Kidder and Eddy-Dilek 1994). The SEM study of samples from Annopol shows that the phosphate minerals did not undergo any dissolution or recrystallization (study in progress; Machalski and Olszewska-Nejbert 2016). We have also found the same REE+Y patterns in the Annopol samples from the subsurface mine and the opencast locality Kopiec (Text-fig. 4A–C; Table 3 and Appendix 1). Therefore, weathering and late diagenesis should be excluded as important factors influencing the REE+Y compositions of the studied samples. Consequently, we believe that these compositions reflect the primary content of these elements in pore waters, which in turn reflects the original composition of mid-Cretaceous sea waters. With this assumption, we use REE+Y data for correlations and interpretations of the geochemical environment during the phosphogenetic phases (Trappe 1998) of the development of the phosphorite beds.

The typical seawater REE+Y pattern shows a negative Ce anomaly, positive Y anomaly and progressive enrichment in heavier REE (Jarvis *et al.* 1994; Alibo and Nozaki 1999, Dubinin 2004; Tostevin *et al.* 2016; Tostevin 2021). The modern coastal and ocean surface waters generally provide little or no negative Ce anomaly and little HREE enrichment (Elderfield and Greaves 1982; Jarvis *et al.* 1994; Alibo and Nozaki 1999; Crocket *et al.* 2018), but both signals increase progressively with depth (Alibo and Nozaki 1999) to form more typical seawater patterns. The flat patterns characterizing the lower phosporite beds at Annopol and Chałupki depart from typical seawater ones. The lack of the Ce anomaly may indicate suboxic/anoxic conditions in the sediment during the incorporation of REE+Y (Tostevin *et al.* 2016). However, the large supply of siliciclastic components can also suppress the Ce anomaly in conditions of normal oxygenation (Tostevin *et al.* 2016). The content of SiO_2 is similar in the Lower Phosphorite beds at Annopol and Chałupki (Text-fig. 6A) and is definitively higher than in higher phosphorite beds at both locations. The Y/Ho ratio, oscillating near 36 in some samples (Tet-fig. 6; Table 3 and Appendix 1), may partly indicate an unaltered seawater signal. In the majority of the samples, however, a clear siliciclastic signal is observed (Y/Ho ratio decidedly less than 36, compare Tostevin *et al.* 2016**)**. We therefore do not exclude suboxic/anoxic conditions during the incorporation of REE+Y, but favour a scenario in which the large supply of siliciclastic material to the studied sites reduced the Ce anomaly under quite normal oxygenation conditions.

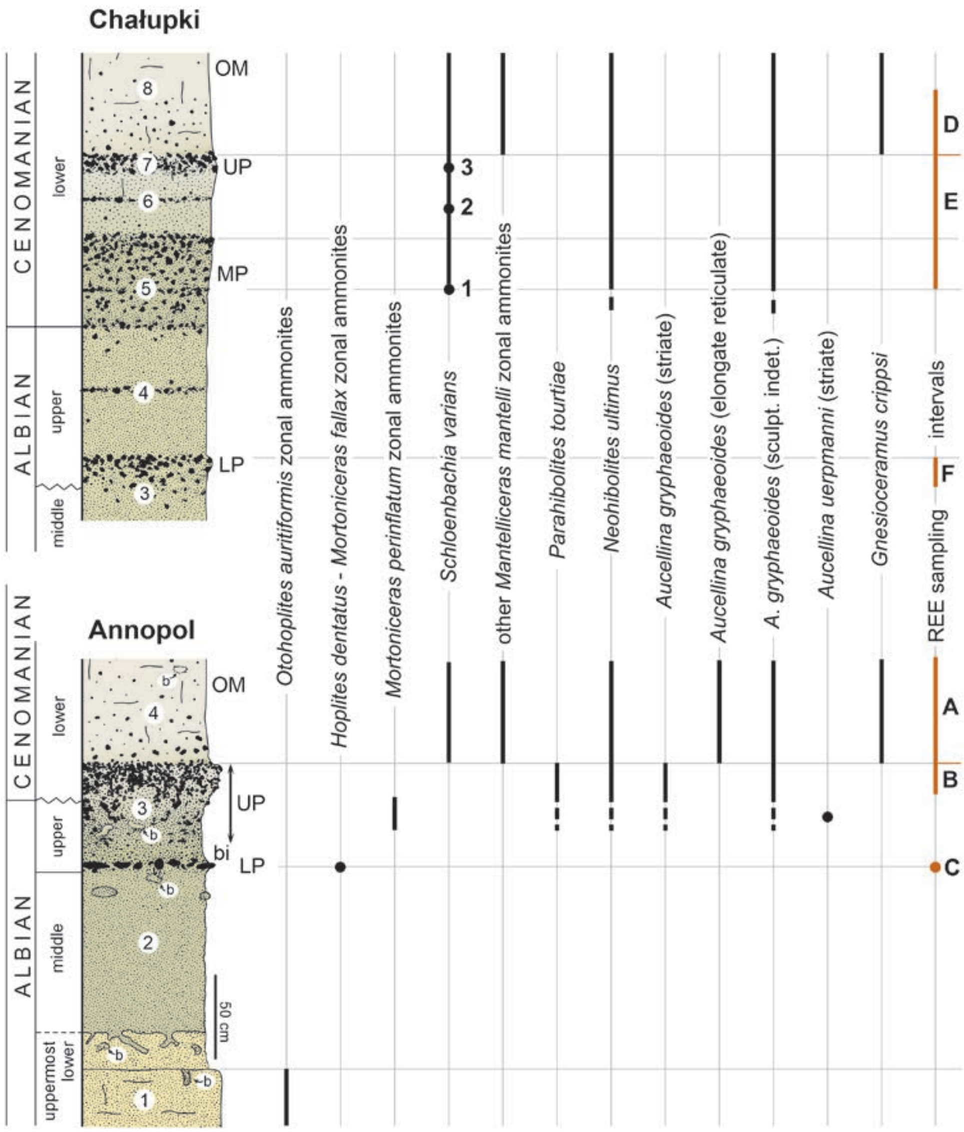
The REE composition expressed as a combination of various parameters ($Ce_{anom.}$,$Y_{anom.}$, La_N/Nd_N, sumREE) shows that samples from the Lower Phosphorite of Chałupki fit well into the Lower Phosphorite fields from Annopol (Text-fig. 5). This allows for correlation of both phosphorite beds and suggests a similar geochemical environment during REE incorporation to these deposits.

The REE+Y patterns from the Middle and Upper Phosphorite at Annopol and Chałupki do not display the typical seawater shape, because the Ce anomaly is weak, and there is only a slight MREE enrichment. The weak expression of the Ce anomaly may indicate better oxygenation of the sediment during the incorporation of REE+Y (Tostevin *et al.* 2016) and/or a lower supply of siliciclastic components than during the formation of the Lower Phosphorite, a possibility we prefer here. We note that the content of 'allogenic' SiO_2 (mainly quartz grains) is higher in the Upper Phosphorite at Annopol than in Middle and Upper Phosphorites at Chałupki whereas the content of 'authigenic' P_2O_5 is lower at Annopol than at Chałupki (Text-fig. 6). The siliceous component dilutes the REE and Y signals, hence the sum REE + Y in Annopol is lower than in Chałupki (compare Tostevin *et al.* 2016).

The combination of the parameters $Ce_{anom.}$,$Y_{anom.}$, and La_N/Nd_N shows that samples from Middle and Upper Phosphorite of Chałupki fit well into the field of the Upper Phosphorite at Annopol (Text-fig. 5A, B). In addition to similar REE+Y patterns, this points to a similar geochemical environment during incorporation of REE+Y and supports correlation of these beds.

The REE+Y patterns obtained from the Overlying Marls at Annopol and Chałupki are close to typical seawater patterns. The Ce anomaly is clear, but slight enrichment in MREE is not a typical feature. The presence of a well-expressed Ce anomaly may indicate good oxygenation of the subsurface sediments during incorporation of REE+Y (Tostevin *et al.* 2016). On the other hand, the supply of siliciclastic components expressed as 'allogenic' SiO_2 is much lower than in the Upper Phosphorite at Annopol and similar to the Middle and Upper Phosphorite at Chałupki (Text-fig. 6A). This could have also amplified the Ce anomaly. The Y/Ho ratio oscillates around 36, a value marking the boundary between siliciclastically influenced and unaltered seawater signals (Text-fig. 6; Table 3 and Appendix 1). The marls with a very low amount of P_2O_5 have a Y/Ho ratio clearly lower than 36 but it is interesting to note that the marl samples from the Overlying Marls have higher values than those from the Upper Phosphorite (Text-fig. 6B). This may reflect the weakening of siliciclastic input due to the increasing distance from source areas and transfer of the study site to a more open marine setting.

In summary, the REE+Y results support the lithological correlations (Text-figs 1, 9) and are consistent with interpretations of the phosphorite interval as a transitional unit formed during the overall progression of the mid-Cretaceous transgression.



Text-fig. 9. Vertical distribution of age-diagnostic fossils and REE sampling intervals A–D (compare Text-fig. 4) in the Annopol and Chałupki sections. Abbreviations: b – burrow; LP – Lower Phosphorite; bi – 'barren' interval; MP – Middle Phosphorite; UP – Upper Phosphorite; OM – Overlying Marls. 1–3 – Location of specimens of *Schloenbachia varians* in the Chałupki section (ZPAL V. 53/69, 70, and 71, respectively). Dotted portions of the range bars denote intervals of rare occurrences of taxa, potentially resulting from the down-piping by burrowing organisms. For further explanations see text.

Biostratigraphy versus taphonomy

The Annopol and Chałupki successions, including the phosphorite interval, are characterised by depositional units of reduced thickness, gaps accentuated by hardgrounds and burrowed surfaces, layers of phosphatic nodules and clasts, occurrence of reworked fossils and abundant glauconite (e.g. Samsonowicz 1925, 1934; Walaszczyk 1987; Marcinowski and Radwański 1989; Machalski and Kennedy 2013; Dubicka and Machalski 2017). Additionally, both successions are demonstrably thinner than the correlative successions north-west of the study area (Cieśliński 1959, fig. 2). Therefore, these are typical condensed successions (see Kidwell 1991 and Föllmi 2016 for definitions).

Taphonomic analysis of fossil assemblages is a necessary prerequisite to draw correct biostratigraphic interpretations of condensed successions; the most important issue is whether the fossils are derived or indigenous (Kennedy 1969; Fürsich *et al.* 1981; Hairapetian *et al.* 2018; Machalski and Jagt 2018). More specifically, a possibility of their redeposition into younger strata or, alternatively, their piping by burrowers down to older strata should be adressed (e.g. Kennedy and Garisson 1975; Fürsich *et al.* 1981; Walaszczyk 1987; Dubicka and Machalski 2017; Machalski and Jagt 2018). Particularly, the microfossil record can be distorted by the latter process. In the case of the Annopol section, this has resulted in difficulties in the interpretation of the lowest occurrence of the planktonic foraminifer *Thalmanninella globotruncanoides* (Sigal, 1977), which defines the global Boundary Stratotype Section and Point (GSSP) for the base of the Cenomanian Stage (Dubicka and Machalski 2017, pp. 407–409).

There may be also significant age differences between particular assemblages of fossils of different preservation on the one hand, and between macrofossils and the surrounding matrix on the other (see Kennedy 1969 and subsequent Discussion, p. 558). Generally, the age of a bed is defined by its biostratigraphically youngest fossils, unless they are demonstrably piped down by burrowers. Dating of the processes of phosphatization (and glauconitization) in condensed deposits is still another problem (e.g. Kennedy and Garisson 1975; Krajewski 1984; Machalski and Olszewska-Nejbert 2016). In view of the above, it is necessary to calibrate the available biostratigraphic information provided by fossils from the interval studied against their taphonomic signatures and inferred depositional scenarios.

The Annopol succession

Large-scale interformational reworking and redeposition of fossils is evident for the Lower Phosphorite. It contains a mixture of derived ammonites representing a wide range of biostratigraphical zones and preservational states (Marcinowski and Wiedmann 1990; Kennedy and Machalski 2015). Also the diversity of clasts and nodules as well as the presence of various types of burrows (including shallow-water *Ophiomorpha*) point to a variety of environments and biotic communities which have been merged into this *remanié* assemblage. The oldest datable elements in the Lower Phosphorite are ammonites of the *H. dentatus* Zone, which define the maximum age of the fossils reworked into this bed. The youngest ones are the ammonites of the *M. fallax* Zone, which define the age of the Lower Phosphorite (Kennedy and Machalski 2015). Mixing of all these fossils in a single horizon (Text-fig. 9) points to their derivation from several depositional units now gone, and to the formation of the bed *via* repeated cycles of sedimentation, phosphogenesis, and erosional reworking, leading to the concentration of multiple generations of nodules and fossils by winnowing away of their softer matrix (the ‘Baturin Cycles’, see Föllmi 1990; Trappe 1998; Dickinson and Wallace 2009; Pufahl and Groat 2017).

At the opposite end of the spectrum is the phosphate-poor (‘barren’) interval just above the Lower Phosphorite (Text-figs 1A, 2A) which yields an indigenous fossil assemblage, including abundant and well perserved vertebrate remains. This is indicated by the taphonomic signatures of the fossils, which unfortunately are not age-diagnostic. However, the underlying and overlying assemblages constrain the age of this assemblage – including the vertebrates – as having been no older than the *M. fallax* and no younger than *M. perinflatum* zones.

The resolution of the nature and age of the fossil assemblages from the Upper Phosphorite at Annopol is more complicated. In the lower portion of the bed there are upper upper Albian *M. perinflatum* zonal ammonites (Text-fig. 9), preserved as oyster bioimmurations or phosphatic pseudo-steinkerns (Machalski and Kennedy 2013; Machalski and Olszewska-Nejbert 2016). These fossils are fragmentary which suggests their physical reworking (Machalski and Olszewska-Nejbert 2016, fig. 7D). On the other hand, they are associated with the early Cenomanian belemnites *Neohibolites ultimus* and *Parahibolites tourtiae* (Text-fig. 9), which might have been pushed down by bioturbating organisms from their originally higher positions, or not. In view of the fragile nature of the ammonite-replicating oyster specimens and pseudosteinkerns *vs.* solid nature of the belemnite rostra, we favour the first scenario. This would mean that the lower portion of the Upper Phosphorite is of late Albian age (see Table 1).

Higher up, in the upper part of the Upper Phosphorite, there are no Albian ammonites, and the Cenomanian belemnites are much more abundant. Co-occuring *Aucellina gryphaeoides* with striate microsculpture ranges into the lower Cenomanian elsewhere (see above). Most importantly, the unequivocally Cenomanian ammonite *Schloenbachia varians* occurs in the correlative Middle and Upper Phosphorites at Chałupki (see above). All this strongly points to the early Cenomanian age of the upper portion of the Upper Phosphorite.

The fossil preservation diminishes upwards in the Upper Phosphorite, and the fossils reveal signatures typical of a reworked assemblage. Exotic fossils are extremely rare in the Upper Phosphorite (the black-sandy-nodule *Birostrina*, and the *Schloenbachia* in a burrow). The phosphatic clasts and moulds are broadly of the same lithology as their surrounding matrix, and yield uniform REE signals; all these sediments are typified by high glauconite content. Therefore, the available evidence suggests that the upper portion of the Upper Phosphorite at Annopol originated during the early early Cenomanian, in conditions of low net sedimentation rate, by attrition of successive cohorts of reworked fossils and phosphatic bodies.

In accordance with the existing models of phospho- and phosphorite genesis (Trappe 1998), we envisage the following depositional scenario for the Upper Phosphorite. There were periods of calm conditions favouring interstitial precipitation of phosphatic cements within and around biotic remains in the near-surface bottom sediment. The calm periods were punctuated by several high-energy events (storms?) leading to the winnowing away of fine sediment and intraformational reworking and concentration of phosphatic fossils and clasts (the Baturin Cycling, see e.g, Föllmi 1990; Trappe 1998; Pufahl and Groat 2017). However, the Baturin Cycling at Annopol come to a halt some time prior to the deposition of the overlying marls. Its upper part contains filigree phosphatic aggregates bound by pristine phosphatized matrix, which surely could not have survived redeposition (Machalski and Olszewska-Nejbert 2016).

The phosphates overgrowing Cenomanian belemnites in the upper part of the Upper Phosphorite point to a Cenomanian dating of phosphogenesis. Whether the phosphates from the lower portion of the unit, especially those casting shapes of the Albian ammonites, also precipitated during the early Cenomanian, is not clear. Nevertheless, we favour this latter interpretation in view of the total absence of genuine phosphatic internal moulds of ammonites at this level. A possibility that the phosphatic pseudosteinkerns from Annopol may be younger than the original ammonites was put forward by Machalski and Olszewska-Nejbert (2016).

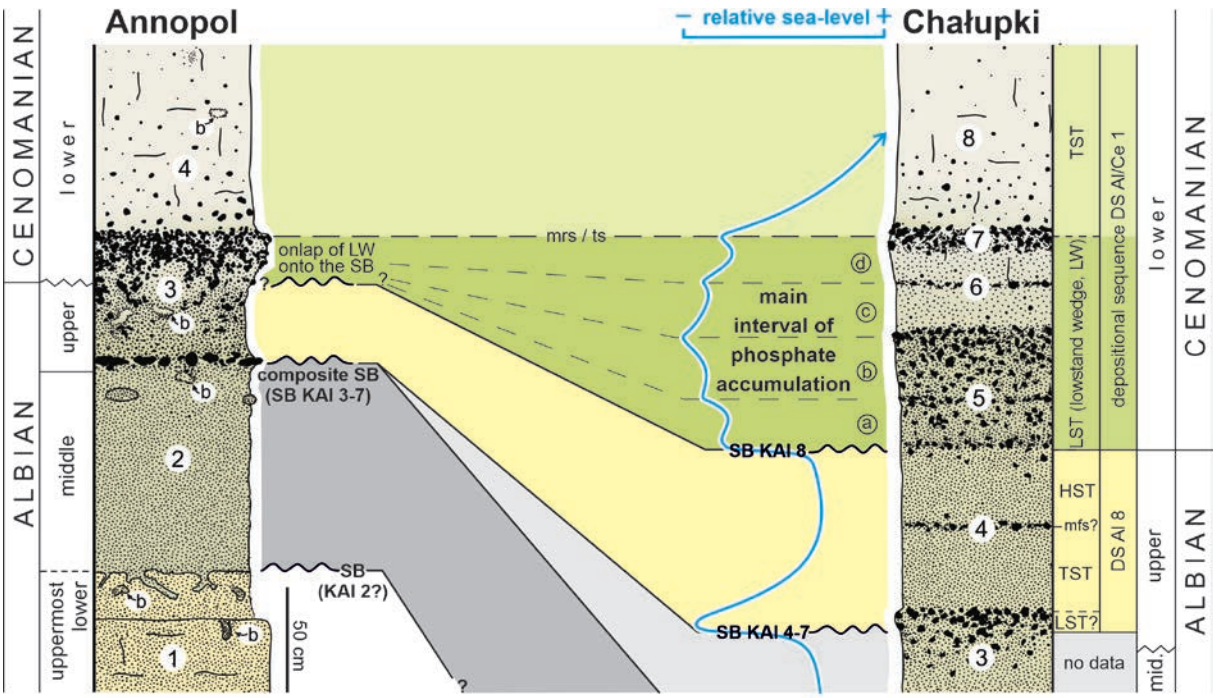
In summary, we propose that the upper portion of the Upper Phosphorite should be assigned an early early Cenomanian age, and the lower part of the bed and the underlying phosphate-poor 'barren' interval (lower part of unit 3) have been deposited in late Albian (Text-figs 1A, B, 9, 10). This means that the Albian–Cenomanian boundary at Annopol does not coincide with the top of the Upper Phosphorite as drawn in papers subsequent to that of Cieśliński (1959), namely in Marcinowski and Wiedmann (1985, 1990), Marcinowski and Walaszczyk (1985), Walaszczyk (1987), Marcinowski and Radwański (1989), Machalski and Kennedy (2013), and Dubicka and Machalski (2017). The Albian–Cenomanian boundary is located below, most likely at the base of the upper portion of the Upper Phosphorite (Text-fig. 1A). In this way we return to the first stratigraphical interpretation of the phosphorite interval at Annopol by Samsonowicz (1925, p. 64) who assigned the upper part of what is here termed the Upper Phosphorite (his unit 5^b) to the 'Tourtia', that is to the lower Cenomanian. The fragmentary, intraformationally reworked oyster shells with Albian ammonite replicas may be the evidence of a 'hidden hiatus' (Voigt 1968) associated with this boundary that additionally may have been obscured by burrowing animals (compare Baird 1978).

Two lines of evidence allow us to estimate the extent of the Albian–Cenomanian hiatus at Annopol. Firstly, the *Praeschloenbachia briacensis* zonal ammonites are missing here. This is essentially the uppermost Albian zone, a minor portion of it ranging into the lowermost Cenomanian (Table 1). Secondly, there are no specimens of *Aucellina gryphaeoides* with quadrate striate microsculpture in the Annopol section. This variety takes an intermediate position between striate and elongate reticulate *Aucellina* in eastern and northern Anglia (Morter and Wood 1983; Mitchell 1995).

The fossil assemblage from the base of the Overlying Marls is of mixed character. Most of the fossils are phosphatic, often fragmentary moulds, suggesting intraformational reworking, but double-valved brachiopods with marly infills and rare marly inoceramid moulds represent remnants of indigenous fauna. This is an early Cenomanian fauna, containing elements of the *N. carcitanense* Subzone of the *Mantelliceras mantelli* Zone (Marcinowski and Walaszczyk 1985). This fauna differs from that from the Upper Phosphorite by the presence of *Gnesioceramus crippsi* and elongate reticulate *Aucellina gryphaeoides*, which replaced striate *Aucellina* known from the Upper Phosphorite, and by the absence of *Parahibolites tourtiae*, which was common in this bed (Text-fig. 9). These differences demonstrate that no significant displacement of fossils from the Upper Phosphorite into the Overlying Marls took place. On the other hand, a few black nodules recovered near the base of the Overlying Marls at Annopol have been derived from the Upper Phosphorite, based on their REE signatures (see above).

The Chałupki succession

The Chałupki section has been studied in much less detail. This is the reason that the section provides much less data on the biostratigraphy and taphonomic history of the fossil assemblages. The taphonomical signatures and taxonomic composition of the



Text-fig. 10. Sequence stratigraphic interpretation of the phosphorite interval at Annopol and Chałupki (sequence boundary nomenclature after Haq 2014). Note that the main interval of phosphate accumulation is related to the sea-level fall and lowstand across the Albian–Cenomanian boundary. Abbreviations: Al – Albian; Ce – Cenomanian; DS – depositional sequence; HST – highstand systems tract; LST – lowstand systems tract; mfs – maximum flooding surface; mrs – maximum regressive surface; SB – sequence boundary; ts – transgressive surface; TST – transgressive systems tract. For other abbreviations see captions to Text-figs 1 and 9.

assemblages from the Middle and Upper Phosphorite and from the basal portion of the Overlying Marls at Chałupki are broadly similar to those from the correlatable units at Annopol (see above). They seem to originate in their mass *via* intraformational reworking of originally indigenous assemblages, which are, therefore, suitable for dating of the beds they are preserved in. This is particularly important with respect to the three specimens of Cenomanian *Schloenbachia varians* recovered from the Middle and Upper Phosphorites (Text-fig. 7A–F). The vertical range of this ammonite in the section approximately matches that of the co-occuring Cenomanian *Neohibolites ultimus* (Text-fig. 9). In view of the lack of any indications of these fossils having been piped down by burrowing animals, they indicate the early Cenomanian age of the Middle and Upper Phosphorite at Chałupki, and based on correlations, also of the upper portion of the Upper Phosphorite at Annopol (see above). It should be noted, however, that the Albian–Cenomanian boundary at Chałupki is only tentatively drawn here at the bottom of the Middle Phosphorite as both *S. varians* and *Neohibolites ultimus* appear slightly above the base of this bed (Text-fig. 9).

A summary of the ranges of age-diagnostic (datable) macrofossil taxa at Annopol and Chałupki is presented in Text-fig. 9, together with the resulting stratigraphic subdivision of the sections.

Sequence stratigraphy

When evaluated from a sequence stratigraphic perspective, conspicuous patterns are evident that allow us to interpret the successions at Annopol and Chałupki in terms of depositional (i.e. 3rd-order) sequences and to identify several key sequence stratigraphic surfaces. The prominent Lower Phosphorite at Annopol is highly condensed and contains middle to mid-late Albian ammonites of the *Hoplites dentatus* to *Mortoniceras fallax* zones (Text-fig. 9). This suggests that its base represents a composite sequence boundary comprising the KAl 3 to KAl 7 unconformities of Haq (2014) and even the lowermost part (LST to early TST) of the following depositional sequence DS Al 8 (Text-fig. 10) that ranges into the *M. fallax* Zone (Amédro 2009). The unconformity at the base of this bed can be correlated to that at the base of the lithologically corresponding Lower Phosphorite at Chałupki (Text-fig. 10), even though ammonites are absent there. The presence of *Hoplites dentatus* to *Mortoniceras fallax* zonal ammonites in the Lower Phosphorite at Annopol indicates the reworking of formerly present sediments into the composite sequence boundary. It may be speculated that the formation of the lag deposit was accompanied by mild uplift of the area that caused the erosion of fine sediment and concentration of phosphoritic material. A similar scenario has been proposed for the upper Cenomanian Tahkte-Sheitan Member of the Kolah-Qazi Formation in Central Iran in which upper Albian to lower middle Cenomanian sediments have been reworked into a conspicuous phosphoritic lag deposit following a late middle to early late Cenomanian uplift event (Hairapetian *et al.* 2018). A series of uplift movements of the study area has already been proposed by Cieśliński (1976) as an explanation for sedimentary discontinuities in this section, and by Marcinowski and Wiedmann (1990, fig. 5), specifically to explain the origin of what is termed the Lower Phosphorite herein. The uplift hypothesis was later discarded in favour of an exclusively eustatic control of deposition (Walaszczyk 1987; Dubicka and Machalski 2017). However, the reworking of upper middle to lower upper Albian sediments that formerly have been deposited cannot solely be related to eustatic sea-level change that was overall strongly rising during that interval (cf. Haq 2014), rather favouring preservation of sedimentary sequences than their erosion due to the overall addition of accommodation space.

In the aftermath of the proposed mid-late Albian tectonic uplift, deposition resumed with the transgressive systems tract of DS Al 8 in the latest Albian (Text-fig. 10). The depositional sequence caused a major onlap (cf. Haq 2014) and comprises the lower part of unit 3 (that is the 'barren' interval in Annopol and the lower portion of the Upper Phosphorite), and correlatable unit 4 in Chałupki, yielding *M. perinflatum* zonal ammonites at the former locality (Text-fig. 9). The capping sequence boundary is well expressed at Chałupki, placed at the base of unit 5 (the Middle Phosphorite), where a conspicuous increase in the concentration of phosphoritic material occurred. According to the new biostratigraphic data presented herein, this unit is already of early early Cenomanian age a few decimeters from its base (Text-fig. 9). It, thus, can be correlated to the latest Albian SB KAl 8 of Haq (2014), located within the *Arrhapoceras briacensis* Zone, and possibly to a corresponding surface in the Anglo-Paris Basin (Amédro 2009) that finds its equivalent at the base of the conspicuous phosphorite concentration at the top of unit 3 in Annopol (the Upper Phosphorite), also yielding early Cenomanian belemnites at both sections and ammonites at Chałupki (Text-figs 9, 10). At both sites, the marly chalks with upwards decreasing sand and phosphorite content of the succeding units 4 and 7 (Overlying Marls), respectively, indicate a strong retrogradational facies development that is part of the TST of DS Al/Ce 1 starting with the *ultimus*/*Aucellina* transgression (e.g. Ernst *et al.* 1983; Wilmsen 2003, 2012; Text-fig. 10). The main phosphorite concentrations at both sites, Annopol and Chałupki, are thus a sedimentary product of the sea-level lowstand across the Albian–Cenomanian boundary that is evident from many successions worldwide (e.g. Wilmsen 2003; Amédro 2009; Bornemann *et al.* 2017). This interpretation is not contradicted by the fact that the phosphorite concentration seems to onlap the Annopol swell structure (see Text-fig. 10 and Cieśliński 1976) because deposits of the late lowstand may already show onlap patterns onto the sequence boundary. Correspondingly, in the more expanded section of Chałupki, the lowstand is subdivided into four subcycles (a–d) that seem to merge or to pinch out towards Annopol (Text-fig. 10). The sequence stratigraphic reconstruction of the uppermost Albian to lowermost Cenomanian of the Annopol area shows remarkable correspondence the situation in SE England and East Anglia (Hart and Fox 2020, fig. 7): DS Al 8 is represented by beds XII and XIII of the uppermost Gault Formation, bounded by erosional unconformities comprising SB KAl 7 and KAl 8, respectively, each fused with the succeeding transgressive surface. The overlying lower Cenomanian Cambridge Greensand contains phosphatized *remanié Schloenbachia* (Machalski 2018), possibly derived from the transgressive erosion of only patchily preserved lowermost Cenomanian lowstand deposits (equivalent of 'cycle 6a' in Hart and Fox 2020). Furthermore, SB KAl 7 is also well developed at the margin of the Vocontian Basin in Gard, southeast France where it is represented by a conspicuous erosion surface capping *M. inflatum* zonal sandstones, overlain by a glauconitic condensed lag containing phosphatic nodules and ammonites of the *M. fallax* Zone (Amédro 2008; Jattiot *et al.* 2021). It is also worth noting that the stratigraphic interval of DS Al 8 and the lowstand of DS Al/Ce 1 at Annopol as well as units 5 and 6 at Chałupki, are an equivalent to the 'Vraconnian Stage' of Amédro (2008) which he regards as transitional between the Albian *sensu stricto* below and the Cenomanian Stage above, with identical sequence stratigraphic subdivision (Amédro 2008, fig. 26).

If the above interpretation is correct, our results provide also an interesting addition to the understanding of the formation mode of stratiform phosphate accumulations of economic value. Such beds are thought to have been formed mainly within particular intervals of depositional sequences associated with phenomena of intense syndepositional phosphogenesis, reworking of pristine phosphates and amalgamation of phosphoclasts and phosphatic nodules into relatively thick condensed beds (Trappe 1998; Pufahl and Groat 2017). Specifically, these phenomena are thought to occur preferably in the transgressive and highstand system tracts, commonly along the maximum flooding surfaces (Trappe 1998; Pufahl and Groat 2017). As far as the phosphorite interval at Annopol and Chałupki is concerned, it is also sandwiched between two prominent sequence stratigraphy boundaries, i.e. SB KAl 8 and the succeding transgressive surface, suggesting that the origin of the main exploitable phosphorite beds in this area was linked to a lowstand systems tract (Text-fig. 10).

CONCLUSIONS

New data gained from a recently investigated section at Chałupki and partial reinterpretation of data from the classical section at Annopol are the basis for a reappraisal of the stratigraphy of the phosphorite interval in the overall transgressive mid-Cretaceous succession at the northeastern margin of the Holy Cross Mountains, central Poland. This distinctive lithological unit at the transition between the Albian and Cenomanian has been of considerable stratigraphical, palaeontological, and economic value (phosphate mining in the past, possible source of REE in future). The phosphorite interval has been considered as exclusively Albian in age since the paper by Cieśliński (1959), despite the fact that a Cenomanian age was proposed for higher phosphorite beds at both locations by Samsonowicz (1925, 1937) and Pożaryski (1947). Based on lithological correlation, Rare Earth Elements and Yttrium (REE+Y) signatures of phosphorites, age-diagnostic macrofossils, and sequence stratigraphic patterns we correlate the sections at Annopol and Chałupki and conclude that the higher phosphorite levels at both sites belong to the lower lower Cenomanian. In this way we confirm the first stratigraphical interpretations of the phosphorite interval. In terms of sequence stratigraphy, the phosphorite interval encompasses the depositional sequence DS Al 8 and the Lowstand System Tract of the successive DS Al/Ce 1 sequence. The proposed correlation suggests that lowstand reworking during the Albian–Cenomanian boundary interval played an important role in concentrating the phosphatic clasts and nodules to exploitable stratiform accumulations. Our conclusions are pertinent to regional studies, assessments of natural resources (in view of the recent interest in REE content of phosphorites), and dating of the fossil assemblages preserved in the phosphorite interval (especially at Annopol which has yielded rich vertebrate material, e.g. Bardet *et al.* 2016). On a broader scale, they add to our understanding of the formation of stratiform phosphorite deposits as their accumulation has been usually linked to transgressive and highstand system tracts of depositional sequences with maxima centered around the maximum flooding surfaces (e.g. Pufahl and Groat 2017).

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