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Deep vs shallow – two contrasting theories? A tectonically activated Late Cretaceous deltaic system in the axial part of the Danish-Polish Trough; a case study from SE Poland

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Abstract:

The Danish-Polish Trough – a large Trans-European sedimentary basin stretching from Denmark, through Germany, to south-eastern Poland and even further to the south into Ukraine, had undergone an uplift during the Late Cretaceous, which in consequence resulted in its inversion and development into the Mid-Polish Anticlinorium. In many existing paleotectonic interpretations, SE Poland, i.e. the subsurface San Anticlinorium and the recent-day Roztocze Hills area was included during the Late Cretaceous into the Danish-Polish Trough, representing its axial and most subsiding part. Such a paleotectonic model was the basis for facies and bathymetric interpretations, assuming that upper Cretaceous sediments deposited close to the axial part of the Danish-Polish Trough (e.g. Roztocze) were represented by the deepest facies. Several studies performed in recent years contradict this concept. The growing amount of data indicates that already from the Coniacian-Santonian times, this area was a land-mass rather than the deepest part of the basin - the same is true for the Campanian and Maastrichtian times.

Additionally, recent discoveries of cyclic middle Campanian deposits of shallow deltaic origin, along with a decreasing contribution of terrigenous material towards the NE, have led to the adoption of new facies and bathymetric models, being all in opposite to most of the previous interpretations. The new interpretation implies the presence of a land-mass area in the place where formerly the deepest and most subsiding part of the Danish-Polish Trough was located.

Here we document in detail the Late Cretaceous deltaic system, i.e. the Szozdy delta developed in the axial part of the Danish-Polish Trough. The middle Campanian deposits which crop out extensively in the middle Roztocze Hills region, close to the village of the Szozdy, exhibits coarsening-upward tripartite cyclothems. The sequence was deposited in a shallow-water, delta front platform setting. Three facies associations have been distinguished: (1) dark grey calcareous mudstone, deposited in prodelta environment, (2) yellow calcareous sandstone unit, interpreted as prograding delta front lobe deposits of fluvially-dominated though wave/tidally influenced setting, and (3) calcareous gaize unit deposited in areas cut-off from the material supply. The sequence as a whole was accumulated by repeated progradation and abandonment of deltaic complexes.

This interpretation is supported by the new sedimentological, palynofacies, and heavy mineral data. The latter is also discussed in the context of their possible source rock provenance, which might suggest a different burial history than thought so far.

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The development of the Szozdy delta system is placed next to dynamic tectonic processes operating at that time in SE Poland, i.e. the inversion on the one hand, and the generation of new accommodation space for the deltaic deposits by enhanced subsidence. This discovery shed new light on our understanding of facies distribution, bathymetry, paleogeography, and paleotectonic evolution of the south-easternmost part of the inverting Danish-Polish Trough into the Mid-Polish Anticlinorium during the Late Cretaceous times.

Key words: Late Cretaceous, inversion tectonics, Szozdy delta, sedimentology, palynofacies, heavy mineral, provenance

1. Introduction

The Danish-Polish Trough – a large Trans-European because of Late Cretaceous inversion tectonics had undergone an uplift and transformation into a prominent structural unit - the Mid-Polish Anticlinorium. Similar deformations are observed in the whole Central European Basin (Voigt et al., 2021, *this issue,* for a recent review).

For more than a hundred years, the late Cretaceous paleotectonic evolution of SE Poland has intrigued geologists. The tectonic evolution of the Danish-Polish Trough (Danish-Polish Basin), especially its SE segment (Figs 1 and 2), until the time of its final tectonic inversion, is still a matter of debate and so far no consensus has been reached (see reviews in Walaszczyk and Remin 2015; Krzywiec et al., 2009, 2018). The most important conclusion is that the existing interpretations developed in the last 50 years do not explain the entire geological history of this fragment of Poland (a part of the supposed Danish-Polish Trough), during the Mesozoic and especially Late Cretaceous times.

In the last decades, two concepts were developed independently by different authors. They focused mainly on the onset of the inversion movements (uplift) of the Danish-Polish Trough (including SE Poland) as well as facies and bathymetric (environmental) interpretations. The inversion-related uplift and subsequent erosion of the former axial part of the basin, in consequence, led to the formation of a prominent structural unit - the Mid-Polish Anticlinorium (Figs 1B and 2AB) (for recent reviews see Krzywiec et al. 2009; Walaszczyk and Remin, 2015; Krzywiec et al., 2018).

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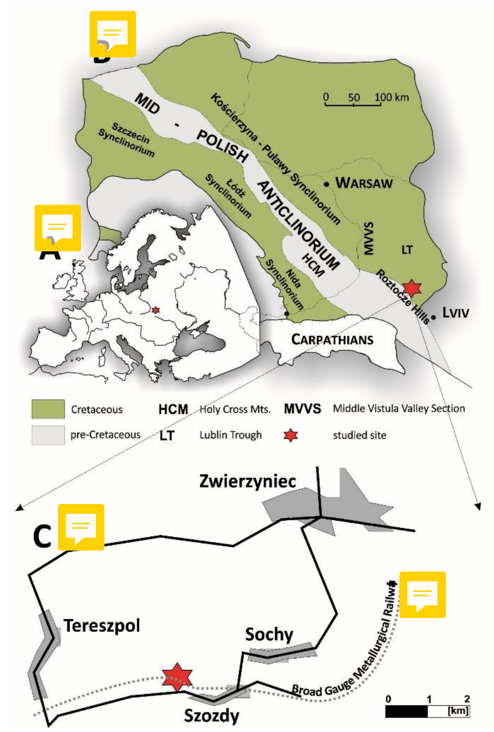

Fig. 1. A, location of the studied site in Europe; **B** ,simplified geological sketch-map of extra-Carpathian Poland, without the Cenozoic cover (adopted form Pożaryski, 1974); tectonic units after Żelaźniewicz et al. (2011); **C)** detailed localization of the studied section.

According to many so far interpretations, the SE edge of the Danish-Polish Trough, i.e. the subsurface San Anticlinorium (Fig. 2A-C), currently almost devoid of the Mesozoic overburden (Fig. 2A-C), represented during the Late Cretaceous times its axial part and deepest, most subsiding sedimentary environments (e.g. Kutek and Głazek, 1972; Hakenberg and Świdrowska, 1998, 2001; Świdrowska 2007; Świdrowska et al., 2008; Leszczyński 2010, 2012). The assumed palaeotectonic model become the basis for facies and bathymetric interpretations, which points that sediments deposited close to the axial part of the Danish-Polish Trough (e.g. Roztocze Hills, SE Poland) would be represented by the deepest facies (Fig. 2C).

A series of studies performed over the past few years have supplied contrary data to the above interpretation, showing that just from the Coniacian/Santonian (possibly even from the late Turonian) times the axial part of the Danish-Polish Trough should rather be considered as a land-mass instead of the deepest part of the basin (e.g. Krzywiec et al. 2009; Remin et al., 2015a; Walaszczyk and Remin 2015; Remin et al., 2016; Krzywiec et al. 2018; Remin, 2018). This view is supported by the presence of some clearly shallow-water facies located along the north-eastern edge of the present-day Mid-Polish Anticlinorium (discussion in: Walaszczyk and Remin, 2015). Additionally, seismic data show progradational bodies from SW toward NE (Krzywiec et al., 2009, 2018), thus toward the north-eastern direction from the supposed axial part of the basin. However, still the existing data did not provide

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hard proof for the existence of an emerged landmass in SE Poland during the Late Cretaceous times, and when treated separately, their value might be undermined.

In 2015, Remin et al. provided conceptual interpretation of the middle Campanian and ?Maastrichtian siliciclastics deposits of the Roztocze Hills, as being of deltaic origin. Thus in a place where according to the widely accepted paleotectonic model of Kutek and Głazek (1972) and several later authors, the axial and the deepest part of the Danish-Polish Trough was located (compare Fig. 2D-E). The implementation of the new concept imposed the need for revision of the existing paleotectonic model of this part of Poland and forced the adoption of a new facies and bathymetric model for several Late Cretaceous facies, which stay opposite compared to most previous interpretations (compare Fig. 2D and 2E; Remin et al., 2015a; Walaszczyk and Remin 2015). Since this conceptual interpretation lacks precise argumentation, the present paper fulfills this gap to show the proofs to a wider audience for the development of the Szozdy deltaic system induced by active inversion tectonics.

The pioneering nature of this paper is about reversing thinking about paleogeography, tectonics, and structural position of SE Poland, particularly the subsurface San Anticlinorium (part of Małopolska Massif), during the Late Cretaceous times. The study area gives direct insight into the unique Campanian and Maastrichtian sedimentary successions, thus allowing for precise bio- and chronostratigraphic dating, essential for detailed sedimentological, facies, and paleotectonic interpretations.

The new data sets provided the foundation for first direct sedimentological, petrographic, and palynofacies data proving the presence of an emerged landmass in the area now devoid of the Mesozoic cover, i.e. the subsurface San Anticlinorium – an area considered to be deeply submerged during the Late Cretaceous times (Fig. 2E). The objective of this paper is to show how dynamic tectonic regime, including inversion processes (uplift) on the one hand and rapid subsidence on the other, coupled with a possible wave or bottom currents transport processes and significant terrigenous sediment input, activated the development of a well-defined Szozdy deltaic system. The remnants of its subaquatic part, originally developed in the axial part of the supposed Danish-Polish Trough, are actually preserved in the rock record of the Roztocze Hills (SE Poland).

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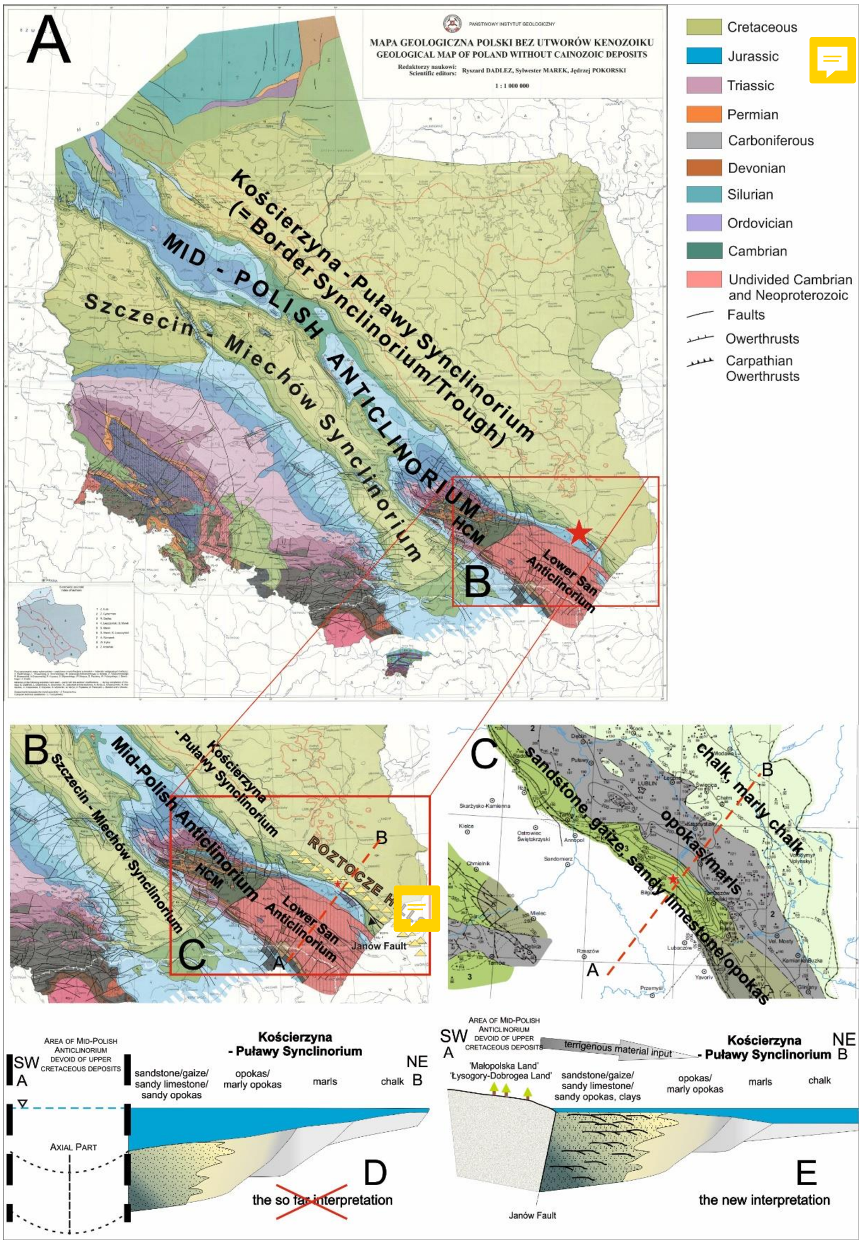

Fig. 2. A) General position of Roztocze Hills and San Anticlinorium against the geological map of Poland by Dadlez et al. (2000) without Cenozoic deposits; **B)** closer view on Roztocze Hills area relative to the position of Holy Cross Mountains and Lower San Anticlinorium; red dashed line – the interpreted cross-section; **C)** The general distribution of lithofacies during the Campanian in the SE Poland (adopted from Świdrowska, 2007) together with the so far assumed paleobathymetric interpretation: sandy limestone = deep; chalk = shallow; **D)** The so far accepted facies and bathymetric model of

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sedimentation assuming a deep-water character of deposits close to the axial part of the Danish-Polish Trough; vertical dashed-lines indicate an area recently devoid of Cretaceous deposits; **E)** Depositional, structural and environmental interpretation of facies and bathymetry in a cross-section perpendicular to the axis of the Mid-Polish Anticlinorium (adopted from Remin et al., 2015; Walaszczyk and Remin, 2015); HCM = Holy Cross Mountains.

2. State of the art – a short story of the two contrasting theories

The current literature offers two concepts concerning the onset of the inversion tectonics and the beginning of the rise of the Mid Polish-Anticlinorium. These concepts can be grouped into two lines of thought (for current review see: Krzywiec et al., 2009; Walaszczyk and Remin, 2015; Krzywiec et al., 2018).

The first concept assumed the beginning of inversion of the Danish-Polish Trough during the late Maastrichtian and Paleogene times (e.g. Kutek i Głazek, 1972; Hakenberg and Świdrowska, 1998, 2001; Świdrowska and Hakenberg, 1999; Świdrowska 2007; Świdrowska et al., 2008 Leszczyński 2010, 2012).

The concurrent concept argued for the much earlier onset of the inversion tectonics of the Danish-Polish Trough, which might started already in the Coniacian/Santonian times or even earlier (e.g. Pożaryski, 1960; Jaskowiak-Schoeneichowa and Krassowska, 1988; Walaszczyk, 1992; Krzywiec et al., 2009; Walaszczyk and Remin, 2015; Remin et al., 2016; Krzywiec et al. 2018; Remin, 2018; Łuszczak et al., 2020).

Noteworthy is the fact that these two concepts were based on the same geological data set, especially the geometry and thickness pattern of sedimentary successions in the cross-section perpendicular to the Mid-Polish Anticlinorium (Fig. 2) (see review in Walaszczyk and Remin, 2015).

Undisputedly, Kutek and Głazek's (1972) paper was a benchmark for the interpretation of the Late Cretaceous palaeogeographic and palaeotectonic evolution of south-eastern Poland. The thickness increase of the Mesozoic sedimentary successions toward the present-day Mid-Polish Anticlinorium, especially the Holy Cross Mountains area (Fig. 2) was their key argument in favor of the presence of a depocentre in the axial part of the Danish-Polish Trough, at least until the early Maastrichtian.

The concept of Kutek and Głazek (1972) became widely accepted and for decades dominated thinking about Mesozoic paleotectonic evolution of extra-Carpathian Poland. Accordingly, the south-eastern part of Poland during Late Cretaceous times would represent the axial, most subsiding part of the Danish-Polish Trough (compare Hakenberg and Świdrowska, 1998; Świdrowska and Hakenberg, 1999; Świdrowska 2007, Leszczyński 2010, 2012). The acceptance of such a paleotectonic model has some basic interpretational consequences, i.e. it was assumed that facies located in the axial part of the Danish-Polish Trough would represent the deepest sedimentary environment (e.g. Kutek and Głazek, 1972; Hakenberg and Świdrowska, 1998; Świdrowska 2007, Leszczyński 2010, 2012). In this case, the facies and bathymetric interpretation was evidently fitted to the assumed paleotectonic model (see discussion in: Walaszczyk and Remin, 2015). It is noteworthy, however, that Upper Cretaceous mixed carbonate siliceous facies elude easy environmental interpretations, and the adopted paleobathymetric model, as well as the spatial distribution of particular facies (Fig. 2D), were not supported by any relevant sedimentological indicators.

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Based on new sedimentological and chronostratigraphic data, Remin et al. (2015a) and Walaszczyk i Remin (2015) proposed an exactly opposite sedimentological model (Fig. 2E). This interpretation implies the presence of a land area in the place, where according to the model of Kutek and Głazek (1972), the deepest part of the Danish-Polish Trough was located. The proposed model (Fig. 2E) assumes that deposits adjacent to the area of epigenetic erosion represent the shallowest facies and pass into deeper facies towards the NE (Fig. 2D) (Remin et al., 2015; Walaszczyk and Remin, 2015).

It is worthy of note that sandy facies in the Roztocze Hills area has been mentioned by several authors (e.g. Świdrowska et al., 2007; Leszczyński, 2010, 2012, and literature therein) but this prominent terrigenous input has never been explored by means of sedimentology to reveal possible paleobathymetry and environment.

Confirmation of this model is the presence of deltaically influenced sedimentation in the area of the Roztocze Hills during the Campanian and Maastrichtian, clearly indicating shallow-water environments (Fig. 2). Such interpretation is forced by new sedimentological and biotic data (Remin et al 2015a; Cyglicki and Remin, 2016, 2018; Niechwedowicz et al., 2016; Remin et al., 2016; Remin, 2018). Additionally, perfectly preserved plant debris, including complete leaves (Halamski, 2013) as well as palynofacies characteristic (this paper and Niechwedowicz et al. in prep) indicate the proximity of land areas.

Interestingly, this is not a new interpretation. At the beginning of the 20th century, up to c. 1960-ties (e.g. Rogala, 1909; Nowak, 1907, 1908; Kamieński, 1925; Samsonowicz, 1925; Pożaryski, 1960, 1962), the area of SE Poland was interpreted as an emerged area, constituting a landmass during the Late Cretaceous times. For this landmass different names were adopted i.e. the "Łysogóry-Dobrogea Land" of Samsonowicz (1925), Jurkowska et al. (2019); the "Krukienic Island" of Pasternak (1959) and Pasternak et al. (1968, 1987); Walaszczyk, 1992; Dubicka et al., 2014; Jurkowska and Barski, 2017; the "Świętokrzyski Land" or "Małopolska Land" of Pożaryski (1960, 1962) and Jaskowiak-Schoeneichowa and Krassowska (1988), among others.

3. Regional setting

Roztocze Hills forms a prominent geographic unit (approximately 185 x 25 km) made up of a range of hills, which extends from the city of Kraśnik in the Lublin Uplands (SE Poland) to the city of Lwów in western Ukraine (Figs 1 and 2). Geologically, these hills form a prominent range along the southwesterly margin of the Kościerzyna–Puławy Synclinorium in SE Poland (Figs 1B and 2B). To the south-west, it borders the Carpathian Foredeep filled with the Miocene deposits. The sub-Miocene sedimentary cover of the San Anticlinorium is almost entirely devoid of the Mesozoic remnants (besides few exceptions) (Fig. 2) and is represented mainly by the fine-grained sedimentary rocks in addition to anchimetamorphic rocks of the Cambrian and Neoproterozoic age (e.g. Dziadzio and Jachowicz, 1996; Żelaźniewicz et al., 2009) of the Łysogóry Block and northern edge of the Małopolska Block (e.g. Żelaźniewicz et al 2009; Narkiewicz et al., 2015 for the recent overview).

The boundary of the Roztocze Hills and the Carpathian Foredeep is sharp and is rooted on a prominent fault zone - a possible continuation of the Holy Cross Fault (e.g. Kutek and Głazek, 1972) or Janów Fault (e.g. Narkiewicz et al., 2015). In the field, this boundary is manifested by a prominent escarpment, up

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to 50–80 m in height, excellently visible from the almost flat surface of the Carpathian Foredeep towards the NE direction.

In the Polish part of the Roztocze, the hills are made up of the Campanian (up to 550 meters in thickness) and Maastrichtian (c. 250 m but not complete) deposits unconformably overlain by the Miocene sediments (e.g. Pożaryski, 1956). The Upper Cretaceous deposits of the Roztocze Hills (depending on the place) are represented by various types of opoka facies (siliceous limestone with a various admixture of biogenic silica), gaizes, marls, calcareous sandstones, calcareous mudstones in addition to argillaceous mudstone or clays, sometimes devoid of $CaCO_3$ admixture. The whole succession dips gently to the northeast in most of the area studied.

The Szozdy section is situated within the railroad cutting of the Broad Gauge Metallurgical Railway Line, about 4 km southwest of Zwierzyniec, close to the small village of Szozdy in the SE Poland (Fig. 1BC). The studied interval has yielded rich fossil assemblage, comprising ammonites, belemnites, inoceramid bivalves, echinoids as well as diverse gastropods, and non-inoceramid bivalves as well as a suite of microfossils (Remin et al., 2015a, b).

This fossil assemblage assigns a middle Campanian date to the Szozdy section, particularly, the lower/middle portion of the *Didymoceras donezianum* ammonite Zone (*sensu* Błaszkiewicz, 1980) and middle portion of the "*Inoceramus*" *tenuilineatus* inoceramid Zone (Walaszczyk, 2004). The interval available at Szozdy, in addition to other sections available in the Roztocze Hills area, is easily correlatable with the equivalent interval in the Middle Vistula River Valley section (compare Fig. 3), a reference section for the Upper Cretaceous of the extra-Carpathian Poland.

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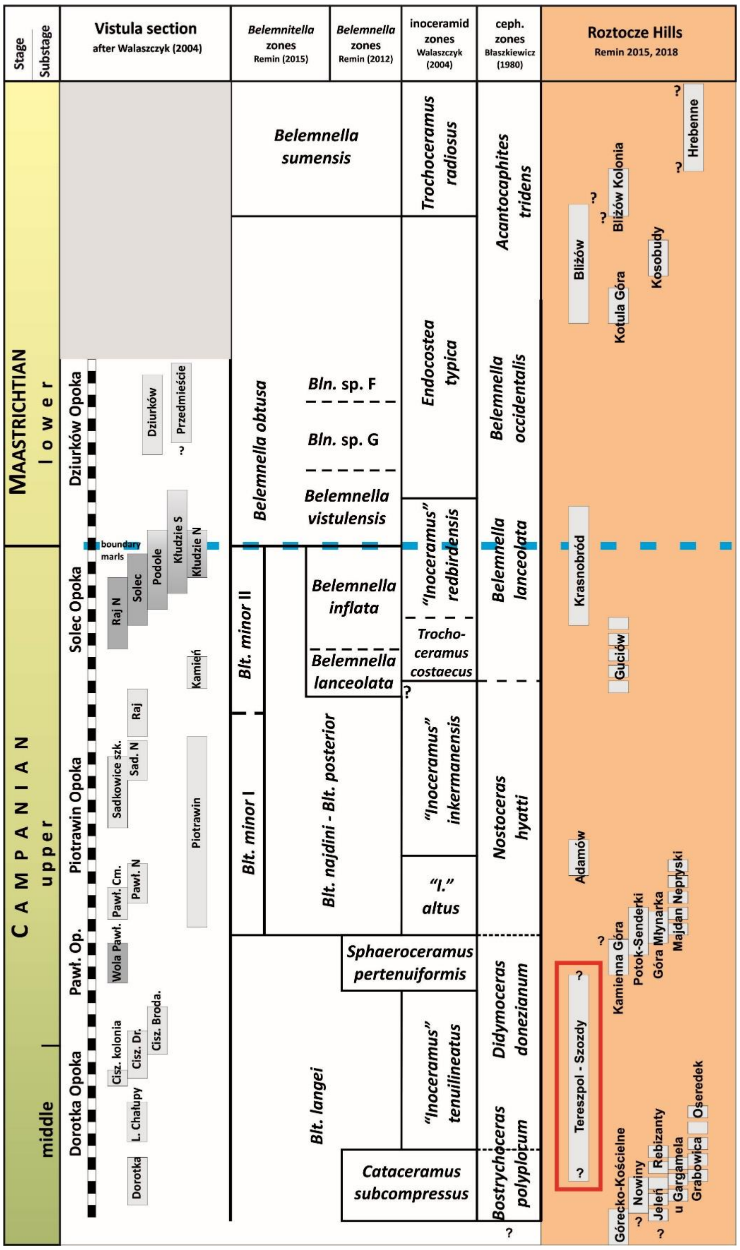

230 Fig. 3. The stratigraphic position of the Szozdy section (right column; meters scale not included) in relation to Vistula section (left column; scale bar = 2m); the full account of other sections of the Roztocze Hills area and their stratigraphic position will be provided elsewhere; biostratigraphic subdivision according to Błaszkiewicz (1980), Walaszczyk (2004), Remin (2012), Remin (2015), Remin et al. (2015a, b), Remin (2018).

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4. Material and Methods

The study section at Szozdy has been sampled for the following purposes: 1) sedimentology, including macro-and microscopic observations; 2) heavy minerals, and 3) palynofacies analysis; the two latter mainly for the hydrodynamic properties and paleoenvironmental context.

Out of 22 samples in total, seventeen samples (1-17) have been subjected to detailed analyses and were collected from the lower portion of the studied section (Fig. 4). Three complete cycles and one incomplete in between (Fig. 4) have been chosen in order to find the differences or regularities governing the distribution pattern of heavy minerals and palynofacies indicators and their complementarity to sedimentological observations. The full account concerning the heavy mineral (including provenance analysis) and palynofacies analysis will be provided elsewhere.

For the present study, the Szozdy section is placed in a wider context of the distribution pattern of $CaCO_3$, quartz sand and clay content, the distribution of plant debris, and the thickness pattern for the Campanian strata of the Middle and Eastern Roztocze Hills.

Sedimentology: standard macro-and microscopic observations.

Heavy minerals analysis: It includes qualitative and quantitative analyses of heavy minerals assemblages (density > 2.9 g/cm^3). In our studies, the combination of optical microscopy, SEM, EDS, and microprobe analyses were applied for different purposes (Garzanti and Andò, 2019; Mange and Maurer, 1992, Velbel, 1999, Velbel et al., 1996, Velbel, 2007, Velbel et al., 2007 Turner and Morton, 2007). Electron micro-probe analyses included geochemistry of tourmaline and garnet (e.g. Henry and Guidotti, 1985; Mange and Morton, 2007; Preston et al., 2002; Wright, 1938; Meres, 2008; Aubrecht et al., 2009).

General palynofacies analysis: Following Tyson (1993, 1995), kerogen particles were subdivided into: phytoclasts (opaque phytoclasts, translucent phytoclasts, cuticle), palynomorphs (terrestrial and marine), and amorphous organic matter (AOM). At least 300 kerogen particles per sample were counted for palynofacies analysis. A preliminary analysis of palynomorph assemblages is focused on both, sporomorphs (spores, pollen, saccate pollen), and aquatic palynomorphs (dinoflagellate cysts, foraminiferal test linings, acritarchs, algae, and freshwater algae), and it was based on at least 250 counts per sample. Additionally, the terrestrial to marine (T/M) palynomorph index, and peridinioid to gonyaulacoid (P/G) dinoflagellate cysts ratio (see e.g., Olde et al., 2015) were also applied.

5. Results

5.1 Sedimentology – macro-and microscopic observations at Szozdy section

The most prominent macroscopic feature of the study section is the presence of tripartite cyclothems. From bottom to top, if complete, the cyclothem consists of three units: calcareous mudstone, calcareous sandstone, and calcareous gaize (Fig. 4). Within the study section, not every cyclothem is complete, and e.g. cyclothem II lacks the calcareous sandstone unit (Fig. 4).

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The **calcareous mudstone unit** (Fig. 4) is dark grey and is poorly indurated. The color most likely came from disseminated carbonized organic matter. The clay and silt content is highest amongst the distinguished units and varies in the range 31 – 44% (mean = 38%). The sand fraction, composed mainly of quartz is in the range of 16 – 26% (mean = 22%) and is the lowest within the whole section; the quartz is a fine grain, with a mean value of c. 100µm; the quartz grains are sub-angular to angular – the sub-rounded grains are less common. The $CaCO_3$ content of this unit varies in succeeding cyclothems in a relatively narrow interval being c. 34 – 46% (mean = 38%) and is ascribed mainly on the broken biocomponents. In macroscale, small bioturbations are visible; other sedimentary structures are absent. In this unit the macrofauna is rare and only some bivalves and badly preserved echinoids were found.

The **calcareous sandstone unit** (Fig. 4) is yellow to yellow-brownish and is poorly indurated. The clay and silt content is c. 10% lower than in the underlying calcareous mudstone unit, being in the range of 24 – 36% (mean = 29%). The sand fraction, represented by quartz and subordinate glauconite, varies in a narrow interval – 36 – 43% (mean = 40%), and these values are highest out of units recognized in the succeeding cyclothems; the quartz sand is still fine-grained, however, the grains could be as twice as large in comparison to the underlying unit and are up to 200µm or so; the quartz grains are sub-angular to angular – the sub-rounded grains are less common. The $CaCO_3$ content is c. 10% lower in comparison to calcareous mudstone and is in the range of 26 – 38% (mean = 31%). On a macroscale, this unit seems to be bioturbated at least to some degree. In consequence sedimentary structures are absent. In this unit, the macrofauna is extremely rare, and similarly to underlying mudstone only some badly preserved bivalves and echinoids were found.

The **calcareous gaize unit** (Fig. 4) is white-gray, fully indurated, and might be extremely hard; in the field, it is expressed as protruding horizons between deposits more prone to erosion (Fig. 4). This unit is composed of a small amount of clay and silt fraction with an amount of 8 – 18% (mean = 13%) – these are the lowest values out of units recognized in the succeeding cyclothems. The content of quartz sand with subordinated glauconite is in the range 21 – 35% (mean = 24%) and the sand fraction is similar to that recognized in the underlying unit but is fully cemented by a calcareous matrix with the only subordinated siliceous matrix. The $CaCO_3$ content is highest out of recognized units – 60 – 75% with a mean value of 64%. Out of three units of the full cyclothem, only this unit provided well preserved fully marine fauna, i.e. relatively frequent ammonites including baculites as well as inocerams and extremely rare belemnites. Other fauna is also frequent and consists of non-inoceramid bivalves, different species of snails, and occasionally solitary corals. It is worth mentioning that ammonites and other aragonitic shell animals retain remnants of original shell structure including iridescence. This unit also provided large amounts of macroscopic plant debris including tree boughs, tree branches, and relatively well-preserved compound leaves or their fragments.

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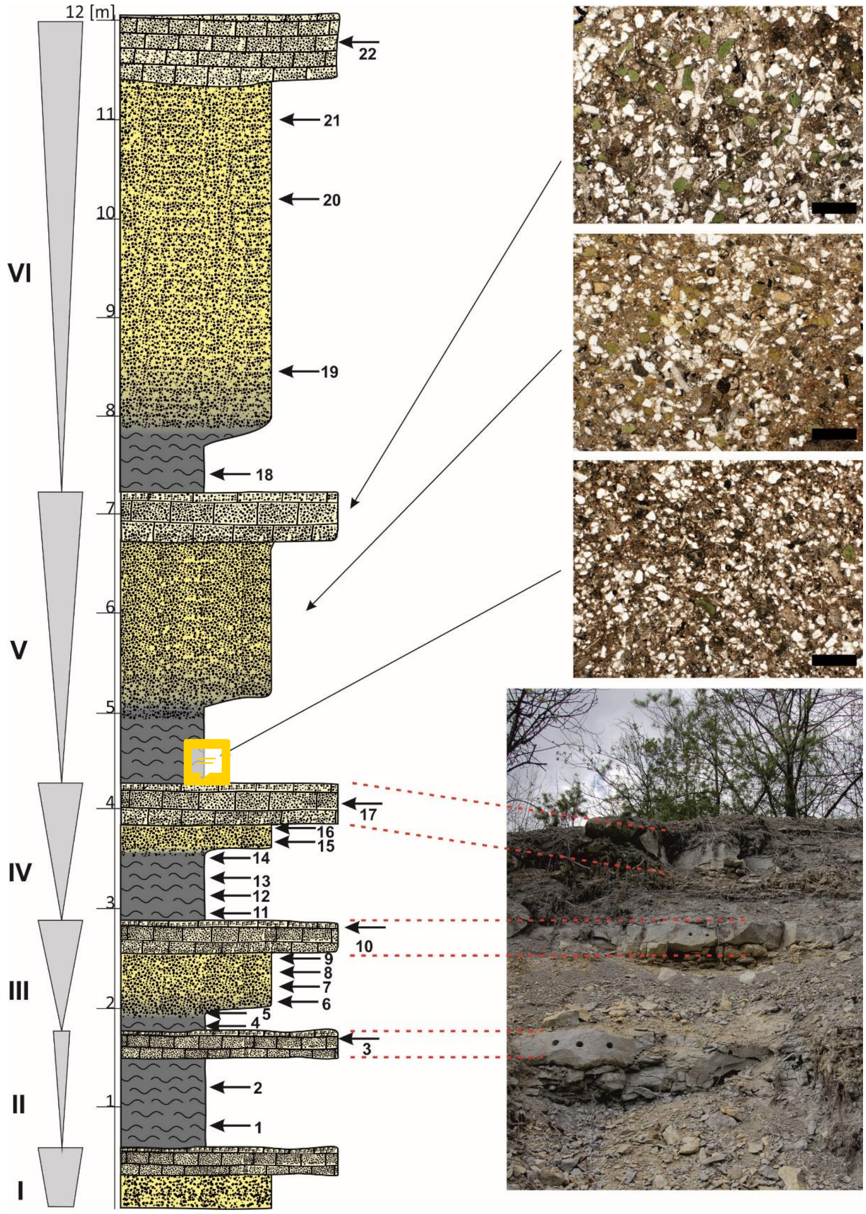

Fig. 4. Lithological column of the Szozdy section. Dark grey – calcareous mudstone; yellow - calcareous sandstone; light gray - calcareous gaize. Triangles on the left side of the column indicate coarsening-upward cyclothems. Field photo of the part of the secession with prominent layers of calcareous gaize indicated by red dashed lines. Typical thin sections from succeeding units of the cycle; scale bar = 500µm.

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5.2 Heavy minerals

Heavy-mineral assemblages coming from the middle Campanian mixed calcareous siliciclastic deposits of the Szozdy section are characterized by little differentiation and stable composition. Analyzed associations included ultrastable and stable phases like rutile, zircon, tourmaline, sillimanite, kyanite, staurolite, garnet (presented in order of decreasing resistance to weathering in surface conditions), authigenic glauconite, pyrite, and other subordinate species like chlorite, Cr-spinel, epidote, and single apatite grains.

A zircon-tourmaline-rutile (ZTR) maturity index (Hubert, 1962) ranges between 55-85% (mean value 67%). The highest ZTR values are associated with the calcareous mudstone unit of the cyclothems, which are ascribed mainly on tourmaline abundance (dravite to shorl ratio, 4:1). In general, out of three index mineral species, tourmaline dominates in all studied samples. Amongst the ZTR minerals, subrounded and rounded crystals dominate (> 65%); other crystals of this group are angular or even euhedral (c. 4%). On the other hand, garnets, kyanites, and staurolites almost exclusively consist of angular-shape crystals (> 70-80%) with almost no oval/rounded ones.

Within the lower part of the Szozdy section, chosen for detailed studies, a distinct pattern can be observed for rutile and tourmaline abundance. These two mineral phases are reversely correlated. This is best seen in cyclothems III and IV (Fig. 5) which are most densely sampled. In the calcareous mudstone unit of the cyclothem III, the abundance of rutile is markedly reduced whereas the tourmaline content is significantly higher than the average. An opposite pattern is observed for the calcareous sandstone, that overlies dark mudstone. Within this unit, the occurrence of rutile is highly promoted whereas the tourmaline content is lower than the average. A similar pattern, as in the sandstone unit, for the content of rutile and tourmaline (Fig. 5) is observed within the calcareous gaize unit. The only case that does not support this rule is the calcareous gaize unit at the top of incomplete cyclothem II in which the sandstone does not occur. In this case the rutile – tourmaline content follows the pattern recognized in the underlying mudstone.

To emphasize the relative changes in abundance of these two mineral species within the section, i.e. rutile and tourmaline, the standardized Z-scores statistic was calculated (Fig. 5). This statistic, in terms of standard deviation, reveals how far the values for each sample are from the mean value of the whole group (the whole Szozdy section) (Ryan et al., 2007).

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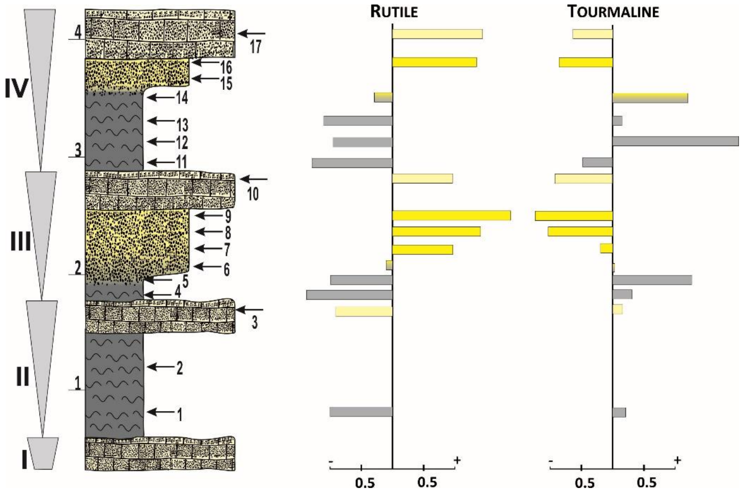

Fig. 5 Vertical bar chart of percentage standardized to z-score for two mineral species (rutile and tourmaline) in the Szozdy section. The vertical line indicates the mean value for analyzed minerals based on counts from the whole section. Bars are directly linked to succeeding samples shown on the litholog on the left. Gray bars correspond to the mudstones; yellow bars – sandstones; yellow-beige bars – gaizes.

5.3 Geochemistry of tourmalines and garnets

Electron microprobe analyses of tourmalines and garnets are summarized on ternary diagrams (Figs. 6, 7AB). The vast majority of tourmalines occupy fields 4 and 5 on the Henry's and Guidotti's (1985) diagram (Fig. 6).

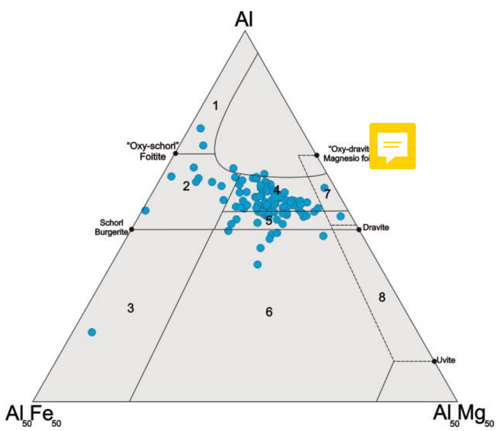

Fig. 6. Al – Fe(tot)50 – Mg50 ternary diagrams for tourmaline from various types of rock (after Henry and Guidotti, 1985). 1 = Li-rich granitoid pegmatites and aplites; 2 = Li-poor granitoids and their associated pegmatites and aplites; 3 = ferric iron-rich quartz-tourmaline rocks (hydrothermally altered granites); 4 = metapelites and metapsammites coexisting with an Al-saturating phase; 5 = metapelites

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and metapsammites not coexisting with an Al-saturating phase; 6 = ferric iron-rich quartz-tourmaline rocks, calc-silicate rocks, and metapelites; 7 = low-Ca metaultramafics and Cr, V-rich metasediments; 8 = metacarbonates and meta-pyroxenites. Blue dots indicate the geochemistry of tourmalines from the Szozdy section.

The results of the EPMA analysis allowed us to divide garnet grains due to their compositions into four genetic groups. The largest group consists of grains containing in their composition a higher content of almandine (60-70%), lower content of pyrope (20-30%), low content of spessartine (<2%) and grossular (<5%). The second group consists of grains with the almandine composition (> 70%), pyrope (<20%), spessartine (2-10%) and grossular (<7%) (Figs 7AB). The third group is characterized by an increased grossular content (about 30%) and a reduced content of almandine (50-60%). The last group in relation to the previous one is distinguished by the increased spessartine content (> 8%) (Figs 7AB).

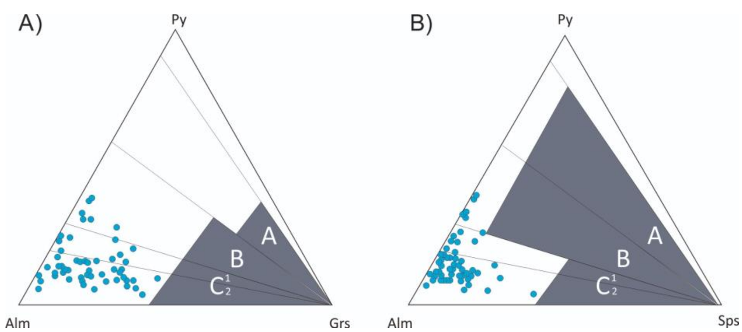

Fig. 7. Composition of garnets from the Szozdy section (blue dots) on the Pyrope-Almandine-Grossular and Pyrope-Almandine-Spessartine ternary diagrams of Meres (2008).

5.4 Palynofacies

Terrestrially sourced organic matter represented by the phytoclast group (opaque phytoclasts, translucent phytoclasts, cuticle) is dominant palynofacies component throughout the studied succession. The content of AOM is generally low. Among the land-derived palynomorphs, sporomorphs (spores, pollen, saccate pollen) are well-represented, while freshwater algae are rare. Marine palynomorphs are represented by dinoflagellate cysts, foraminiferal test linings, acritarchs, and algae. Dinoflagellate cysts and foraminiferal linings are the most common among the marine palynomorphs, though their abundances fluctuate throughout the succession, while acritarchs, and algae are less common, but relatively constant in abundance. The dinoflagellate cyst assemblages are rich and diverse; gonyaulacoid dinoflagellate cysts generally are more common than the peridinioid ones.

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Calcareous mudstone. Palynofacies of this unit are dominated by phytoclasts (c. 85–93% of total kerogen), basically by translucent phytoclasts (c. 33–44% of total kerogen), and cuticle (c. 22–42% of total kerogen). The concentration of cuticle in calcareous mudstones is visibly higher than in other distinguished units; cuticle debris is mostly degraded. The content of AOM fluctuates at low values (0.5–5% of total kerogen). Terrestrial/marine ratio is relatively high, ranging between 25% and 41%, and is ascribed mainly on non-saccate pollen abundance (up to 82% of sporomorphs). Foraminiferal linings (c. 44–64%) visibly dominate over the marine palynomorphs. P/G ratio is variable (11–39%), and its values indicate that peridinioid dinoflagellate cysts are relatively less common in calcareous mudstones, as compared, e.g., with calcareous sandstones.

Calcareous sandstone. This unit is characterized by the dominance of phytoclasts (up to 81% of total kerogen), represented mainly by translucent phytoclasts (c. 40–64% of total kerogen). Of note is a very low concentration of cuticle, which counts only up to 3% of total kerogen. The content of AOM oscillates at extremely low values (c. 0.5%). Calcareous sandstones are characterized by the highest T/M ratio (up to 49%) of the whole section; raised concentrations of saccate pollen (up to 51% of sporomorphs) are notable. Marine palynomorphs are dominated by dinoflagellate cysts; peridinioids are visibly more common (P/G = 28–49%) in calcareous sandstones, as compared with other distinguished units. An almost complete lack of foraminiferal linings is conspicuous.

Calcareous gaize. The concentration of phytoclasts, although still relatively high (c. 62–65% of total kerogen), and also dominated by translucent phytoclasts (c. 24–36% of total kerogen), is visibly lower, as compared with other units. The content of the cuticle is low to moderate (7–30% of total kerogen) and the cuticle debris is mostly degraded. The content of AOM is generally moderate (c. 23–25% of total kerogen), but these are the highest values recorded throughout the succession. T/M ratio (27–32%) is visibly lower, as compared with other distinguished units, with sporomorphs being dominated by non-saccate pollen. Dinoflagellate cysts predominate over the other marine palynomorphs, and P/G ratio exhibit a moderate values (19–32%).

5.5 Distribution of the CaCO3 and the thickness pattern of the Campanian deposits

To place the middle Campanian succession of the Szozd section in a wider sedimentological context, two maps were constructed. The first one (Fig. 8) shows the distribution pattern of $CaCO_3$ content coupled with terrigenous material (quartz sand and clay) content and is based on more than 50 observations in outcrops (green triangles on Fig. 8). The $CaCO_3$ content is more or less reversely correlated to the quartz-sand and clay content. Additionally, the distribution pattern of macroscopic plant debris is provided (Fig. 8), including imprints of tree boughs, tree branches, and leaves. The frequency of plant debris is expressed in two subjective classes i.e. rare and common, that are based on field observations in particular outcrops (Fig. 8).

The lowest values of $CaCO_3$ are concentrated in a relatively narrow belt bordering to the SW the recent-day Carpathian Foredeep (subsurface NE edge of the Małopolska Massif represented by the San Anticlinorium) (Fig. 2A, 8), being simultaneously the area with the highest amount of terrigenous material (quartz sand and clay). In the SW-NE directed transect, the $CaCO_3$ content is progressively higher whereas the quartz sand and clay content tend to be less and less common in the north-east

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direction. It is worthy of note that in the SE part of the studied area i.e. Horyniec Zdrój area (Fig. 8) pure clay intervals may also occur in couplets with clayly opokas.

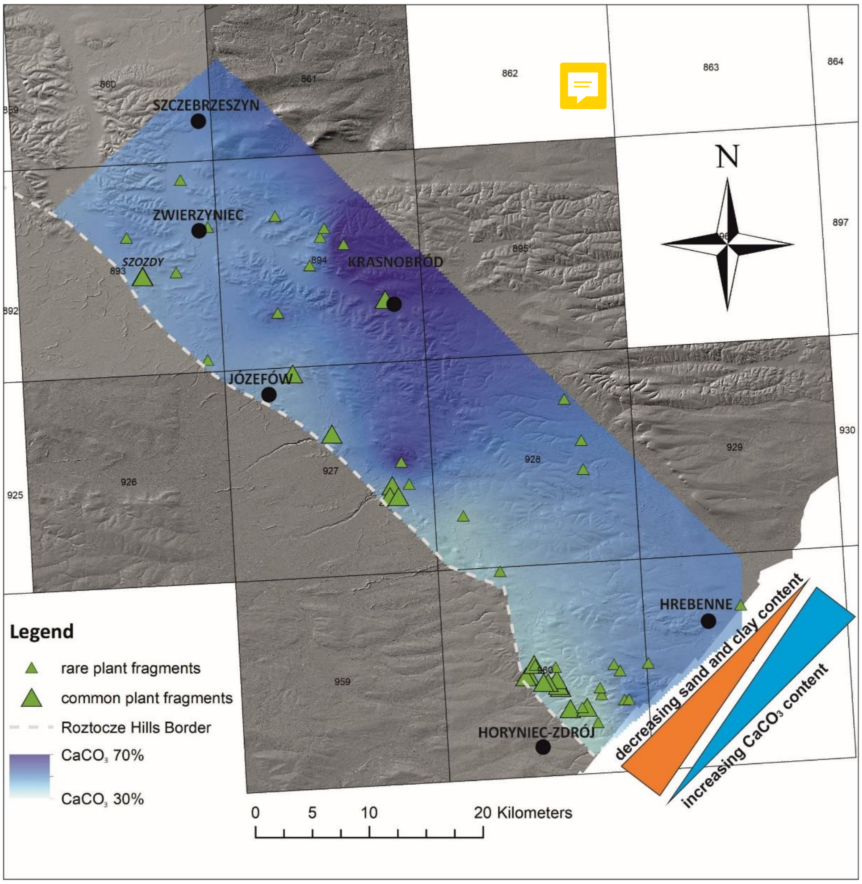

Fig. 8. Distribution of $CaCO_3$ in the Roztocze Hills area between the town of Zwierzyniec and the Polish/Ukrainian State border to the east. Note that $CaCO_3$ is consistently lowest at the edge of the Roztocze Hills, at the border with the Carpathian Foredeep. Green triangles indicate the finds of macroscopic plant fragments; the Szozdy section is located SW from Zwierzyniec.

The thickness pattern of the Campanian deposits in the Roztocze Hills area are based on 16 chosen boreholes where the Campanian deposits were documented, i.e.: Chrzanów IG-1, Dyle IG-1, Izbica IG-1, Jarczów IG-2, Jarczów IG-4 Komarów IG-1 – IG4, Narol PIG-1, Narol PIG-2, Rachanie IG-1, Stróża IG-1, Tarnawatka IG-1, Tomaszów Lubelski IG-1 and Ulhówek IG-1 (Fig. 9). The well-data are stored in the CBDG database of the Polish Geological Institute. It is worth mentioning that the original thickness, especially in the most SW part, which borders the Carpathian Foredeep (subsurface NE edge of the Łysogóry Block/Małopolska Block), could be even higher since not the whole Campanian is preserved. The highest values are located in the area of Narol boreholes (Fig. 9) where the Campanian reaches c.

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500 m. In the NE direction, the thickness of the Campanian deposits is progressively lower, being c. 150-200 m in the Komarów and Ulhówek boreholes (Fig. 9).

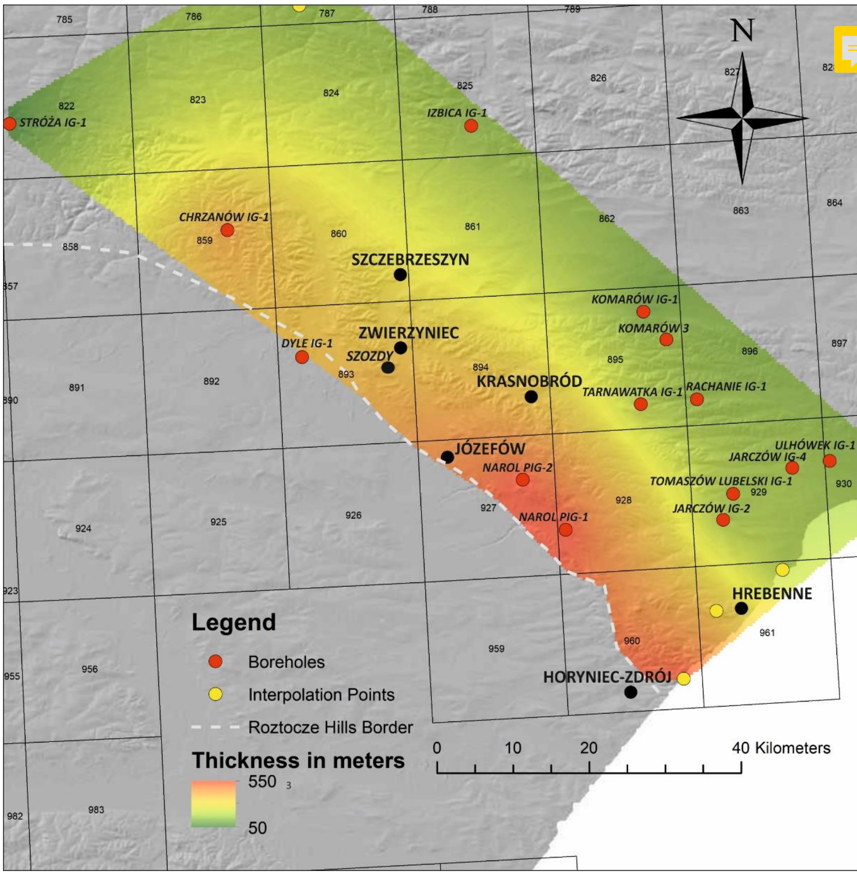

Fig. 9. Thickness pattern of the Campanian deposits in the Roztocze Hills area.

6. Interpretation and discussion

6.1 Hydrodynamics properties derived from heavy minerals

The strong reverse dependence between tourmaline and rutile can be recognized at first glance within the whole section (Figs 5 and 10) indicating changes in hydrodynamic power in the sedimentary environment.

The Z-score calculations, performed for the whole study section underline the changes in the proportion of respective minerals in succeeding samples, enabling a better understanding of the roles governing their distribution pattern within the section (Fig. 5) (e.g. Ryan et al. 2007). Both minerals are of similar shape and durability, however of markedly different densities, i.e. 3.03-3.18 g/cm^3 and 4.23

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g/cm[3] for tourmaline (dravite) and rutile respectively. Since the weight of the two analyzed minerals is high it might be expected that these two mineral phases will be strongly dependent both vertically and spatially by the actual sedimentary environment and in consequence the hydrodynamic power that actually existed during the deposition of subsequent units of the cyclothem. The recurring increase in the abundance of tourmaline with a simultaneous decrease in rutile in muddy units most likely resulted from a decrease in hydrodynamic power in the depositional environment what might be translated to the environment more distal from the main river discharge, thus complementary to prodelta (compare Figs 10 and 11)(Komar, 2007; Omran, 2007). Contrary, the increase in the share of rutile with simultaneous decrease of tourmalines in the sandy units can be associated with an increase in the flow rate which might be translated to an environment closer to the river discharge, thus representing the main delta lobe/slope setting (compare Figs 10 and 11). Simply, the tourmaline as lighter will be transported further to the prodelta environment making the prodelta facies overrepresented in this mineral phase, whereas the rutile as markedly heavier will fall out from the suspension close to river discharge.

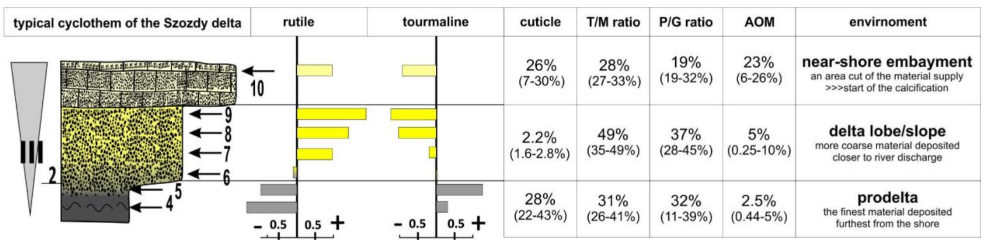

Fig. 10. The proposed environment for the succeeding units within the cyclothem deposited in the Szozdy delta coupled with the vertical distribution of selected heavy minerals and selected palynofacies indicators (for abbreviation compare the text); cyclothem III adopted from the Fig. 4. The values in brackets show the range for the whole studied section in all cyclothems.

6.2 Palynofacies analysis

The present analysis, although based on selected features and therefore preliminary (a more comprehensive palynological analysis is in preparation), provides valuable data on the palaeoenvironmental conditions prevailing in the study area. The characteristic palynofacies features of the succession are expressed by abundances of phytoclasts (particularly the translucent ones, and cuticle), sporomorphs, peridinioid dinoflagellate cysts, and foraminiferal linings; each of these indicates a relative proximity to land. The abundances of translucent phytoclasts, that are fresh, unoxidized particles, suggest a very short transportation (Tyson, 1993). The same may be inferred from abundances of cuticle, that can easily be degraded and thus may serve as an indicator of not prolonged transportation (e.g., Tyson, 1993). The relatively high concentrations of sporomorphs, but particularly the presence of spores and non-saccate pollen, support the interpretation, as these sporomorphs are preferentially deposited in a close proximity to land (Tyson, 1993). The increased percentages of peridinioid dinoflagellate cysts and foraminiferal linings have been suggested to be related to the availability of nutrients, that may originate from upwellings (e.g., Wall et al., 1977; Lewis et al., 1990;

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Powell et al., 1990, 1992; Eshet et al., 1994), or river discharge (e.g., Downie et al., 1971; Wall et al., 1977; Powell et al., 1990, 1992; Hardy and Wrenn, 2009). In the case studied herein, the latter source of nutrients seems more probable.

The dramatic and cyclic fluctuations in the palynofacies and palynomorph assemblages characteristic for particular lithological units suggest highly dynamic conditions. The most evident differences are evidenced between the calcareous mudstones and sandstones (Fig. 10), as expressed by changing relative percentages of phytoclasts (basically cuticle), pollen, peridinioid dinoflagellate cysts, and foraminiferal linings. Such a sharp transition between the palynofacies patterns could be explained by either varying salinity level, or by different hydrodynamic properties of palynofacies components, or a mix of both. Dinoflagellate cysts and foraminiferal linings are indicative of rather normal salinity conditions, although some dinoflagellates might have been tolerant to abnormal salinities in nearshore settings (Tyson, 1993). Hence, the rarity of foraminiferal linings in calcareous sandstone units could possibly be explained by influence of brackish conditions. The almost complete lack of cuticle in calcareous sandstones (Fig. 10) may also indicate a higher water energy, resulting in bypassing by flotation and suspension of the most buoyant particles, such as cuticle (see Tyson, 1993), and its deposition in a more distal, lower-energy settings (calcareous mudstones and gaizes) (Fig. 11). On the other hand, the raised percentages of saccate pollen documented in calcareous sandstones may suggest the opposite – a decrease in water energy, since saccate pollen are preferentially concentrated in low-energy environments (see Tyson, 1995). Nevertheless, a slightly higher T/M and P/G ratios recorded in calcareous sandstones (Fig. 10) suggests that this unit apparently has been deposited more proximally, as compared with calcareous mudstones and gaizes (Fig. 11).

The shift in the palynofacies patterns and palynomorph assemblages documented from calcareous mudstones and gaizes (Fig. 10) are less spectacular. In both units the content of phytoclasts (including cuticle) is comparable, and relatively high. Dinoflagellate cysts and foraminiferal linings are also well represented in both units, although the percentages of the latter are visibly lower in calcareous gaizes. Gaizes are also characterized by a raised concentration of AOM (the highest values recorded throughout the succession), suggesting a more distal setting for this unit (see Tyson, 1993, 1995). Considering the above, the most proximal setting is suggested for calcareous sandstones, while gaizes apparently were deposited in a more offshore environment or in areas cut-off from the material supply; mudstones occupied an intermediate position (compare Fig. 11).

6.3 Sedimentary environment

The study section is unique and similar lithologies have never been previously described neither from the Roztocze Hills area nor from the Polish Uplands. Although the prominent input of the quartz sand material has been mentioned previously by several authors (e.g. Pożaryski, 1956, 1960, 1962; Hakenberg and Świdrowska, 2001; Świdrowska 2007; Świdrowska et al., 2008, Leszczyński, 2010, 2012), these quartz/clay-rich deposits have never been explored by means of sedimentology to reveal paleobathymetry or possible environment.

The investigated section of the middle Campanian deposits, characterized by tri-partite mixed carbonate siliciclastic sediment is best interpreted if the deltaic origin for those tri-partite cyclothems is accepted. Besides the macro and microscopic characteristics, such an interpretation is

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independently confirmed by palynofacies analyses and hydrodynamic properties derived from heavy minerals as well as distribution patterns of terrigenous material and $CaCO_3$ (Fig. 8).

A modern Mahkanam deltaic system (Indonesia) might serve as a good recent-day counterpart for the interpretation of the sedimentary environment of the Szozdy Delta. The similarities are of course general – the Mahakam delta is huge in comparison to the Szozdy deltaic system (although the spatial and vertical distribution is unknown), however, besides differences, several analogies can be found in the sedimentary environments at both sides.

Various physical processes (e.g. water flow, sediment input, ocean currents, wind, waves, tides) and their relative importance regulate the morphology and internal geometry of deltas. Accordingly, three main classes are commonly distinguished, i.e. i) tide-dominated; ii) wave-dominated, and iii) river-dominated deltas (e.g. Coleman and Wright, 1975; Galloway, 1975).

The modern Mahakam delta is considered to be a text-book example of a fluvial-tide-dominated delta system built across a narrow shelf (Galloway, 1975; Allen et al., 1977). The shelf, and deltaic deposits, itself borders the N-S oriented Makassar Trough that acts as a through-flow pathway for Pacific waters to the Indian Ocean (Wyrtki, 1987), that also must regulate, at least in part, redistribution of suspended sediments. The Mahakam River discharge is characterized by the absence of flood surges, therefore avulsion of distributary channels don't take place (e.g. Allen et al., 1977; Storms et al., 2005). Additionally, an extremely wide, submerged delta front platform, which extends to 5-meters isobaths up to 15-20 km offshore, works as a perfect platform that dissipates wave energy (Robert and Sydow, 2003). In consequence, the fluvial distributaries push the suspended sediment basinward, resulting in extremely fast progradation (Storms et al., 2005 and references therein).

For the Szozdy Delta, an easy definition of which process was dominant in the development of this deltaic system (fluvial-, tide-, wave-dominated), is markedly hindered and at least speculative. Although relatively large, the exposure at Szozdy, an 800 m long railroad cutting, that gives access to approximately 30-35 meters of the succession, still represents a single locality with such unique sedimentation that can be ascribed to be deltaic in origin.

On the other hand, taking into account that succeeding cyclothems are consequently very regular and particular units can be traced over dozens to a few hundred meters, a strong wave or tide action would rather result in more chaotic development of the succeeding units and the whole cyclothems. Accordingly, at the current stage, we might only speculate that fluvially-dominated processes privilege with possibly some additional wave and/or tide action.

The small thickness of the repeatedly occurring cyclothems i.e. 1 – 5 m (Fig. 4) with grain-size coarsening upsection in each cyclothem, indicate that progradation of succeeding facies – i.e. more muddy and more sandy units of the cyclothems (Figs 4 and 10) proceeded relatively fast. This might also suggest that the accommodation space was highly limited (Fig. 11). Since there is no evidence for the presence of delta plain deposits, the whole sedimentation acted in the subaquatic part of the Szozdy deltaic system as exemplified in figures 11 and 12.

This implies, that at least in this respect, the deposition of the submerged deltaic facies of the Szozdy delta took place at relatively flat, wide, shallow to extremely shallow delta front platform (Fig. 11), similar to the delta front platform of modern Mahakam delta, where progradation is fastest. Platform

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wide enough to dissipate most of the strong wave-energy action keeping it at moderate to low strength.

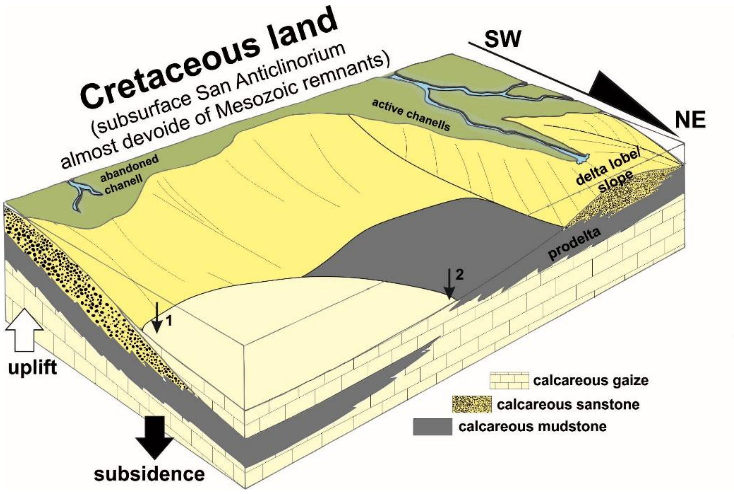

Fig. 11. Block diagram illustrating relationships between subaerial (not available in the study area) and subaqueous deltaic environments of the Szozdy delta in relation to active and abundant distributary channels. Arrows 1 and 2 indicate two different situations i.e. 1) – full tripartite cyclothem and 2) incomplete cyclothem; compare to Fig. 4. Not is scale.

Different thickness of succeeding units of the cyclothems (Fig. 4) indicate that specific environmental conditions had different time-longevity before the change in material input regime from prodelta to delta lobe/slope facies. This suggests rather dynamic tectonic conditions resulting in changes of the delta architecture, migration and avulsion of distributary channels, and simultaneous change in the sedimentary environment at particular places, which resulted in repetition of cyclothems.

Accordingly, to the above proposed environmental interpretation, the lowest unit of each cyclothem, i.e. the calcareous mudstone would represent the so-called prodelta environment (Figs 11 and 12), deposited on the submerged delta front platform in a more distal area from the river discharge (Figs 11 and 12). This unit is composed of the highest amount of clay and the finest fraction of sand. Upsection, the calcareous mudstone passes quickly into yellowish calcareous sandstone with markedly less amount of disseminated organic matter of fitogenic origin. Additional confirmation of such environmental interpretation is scarcity of macroscopic full-marine fauna - only some bivalves and echinoids were recognized within the mudstone unit whereas in the sandstone unit such fauna is almost absent.

The origin of the calcareous gaize is more problematic. This unit is considered to originate in an area cut off from the sediment supply. Once it happened, e.g. by tectonic activity and changes in delta architecture (e.g. an avulsion of distributary channels), a relatively quick calcification process just "freeze" the upper portion of the sediment. Three observations might support such an interpretation.

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Firstly, in all studied cases, the grain size always repeats the grain size observed in the underlying unit. In complete cyclothems, the gaize are characterized by the grain size similar to the sandy unit which is proved in cyclothems I and III-VI (Fig. 4). The same is true for the cyclothem II where gaize directly overlies the muddy unit, however, in this case, the grain size is smaller and follows those observed in the mudstone. Secondly, in this unit, the fully marine fauna is common which indicates that the main fresh-water input was retreat. Additionally, the terrestrial components are also abundant. This concern mainly to macroscopic plant debris including tree boughs, tree branches, and leaves – these as buoyant, were transported, sunk, and "frozen" by calcification. Thirdly, ammonites and other aragonitic shell animals still retain remnants of the original shell structure including iridescence. This indicates that they were cut off from the surrounding environment aggressive for aragonite – in another way the original aragonite would have no chance to be preserved.

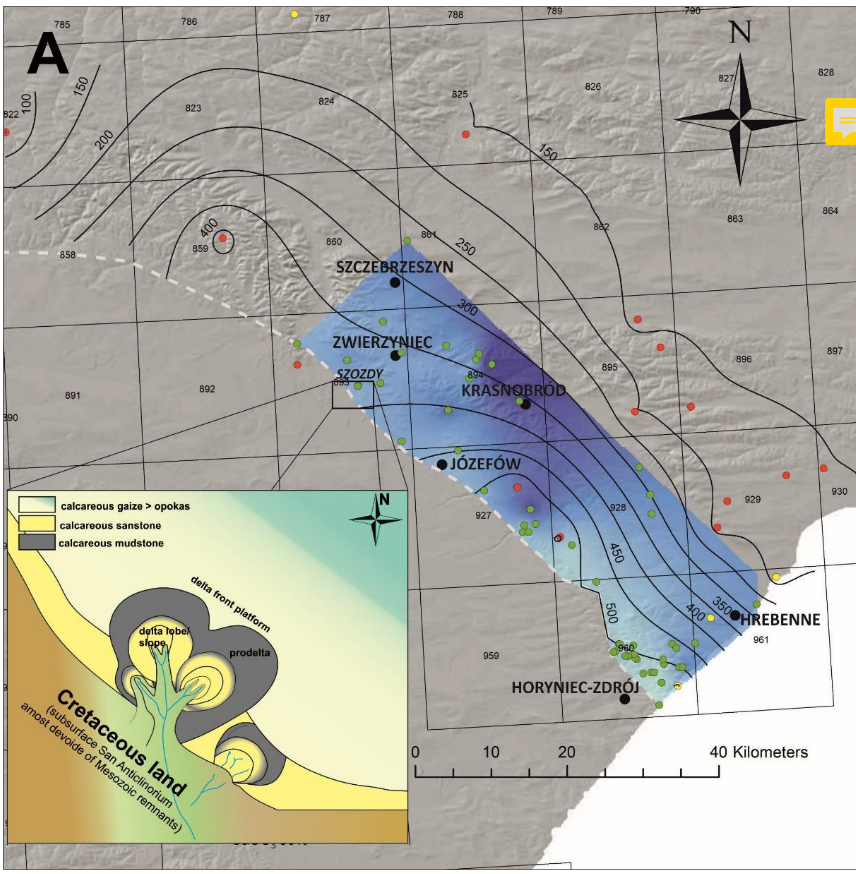

Fig. 12. A) $CaCO_3$ distribution pattern (blue area, compare Fig. 8) against the isolines of the thickness of the Campanian deposits. Red dots = boreholes (compare Fig. 9); green dots = studied outcrops; yellow dots = interpolation points. B) Subaerial view of the discussed deltaic environment of the Szozdy delta in relation to the distribution pattern of selected facies bordering the deltaic environment – not in scale. Squares with numbers represent the succeeding map sheets.

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6.4 Redistribution of terrigenous material

In a wider context, some influence on redistribution of mainly finest material, pushed away to the NE direction from the Szozdy delta, could be preceded by the ocean currents acting parallel with the identified Łysogóry-Dobrogea Land (Fig. 9-13).

The presence of such currents flowing from the north and along with the northern shore of the supposed paleobiogeographic barrier as possible land area (i.e. recent area of the San Anticlinorium), during the Coniacian/Santonian times and its impact on paleocirculation, paleotemperature (based on isotopes), and ammonite distribution fauna has been suggested by Remin et al. (2016). Finally, the further confirmation for the existence of a paleobiogeographic barrier is the distribution pattern of belemnites during the early Maastrichtian (Remin, 2018).

Interestingly, such contourite currents, operating along the landmass during the Campanian times, have been recently confirmed based on nine seismic profiles perpendicular to here postulated landmass (Krzywiec et al., 2018) (compare Fig. 13). This paleogeographic situation is again somewhat similar to the modern Mahakam deltaic system that borders Makassar Trough which is a through-flow pathway for contourite current (Shanmugam, 2017; Brackenridge et al., 2020) which redistributes material from the Mahakam prodelta in the southern direction.

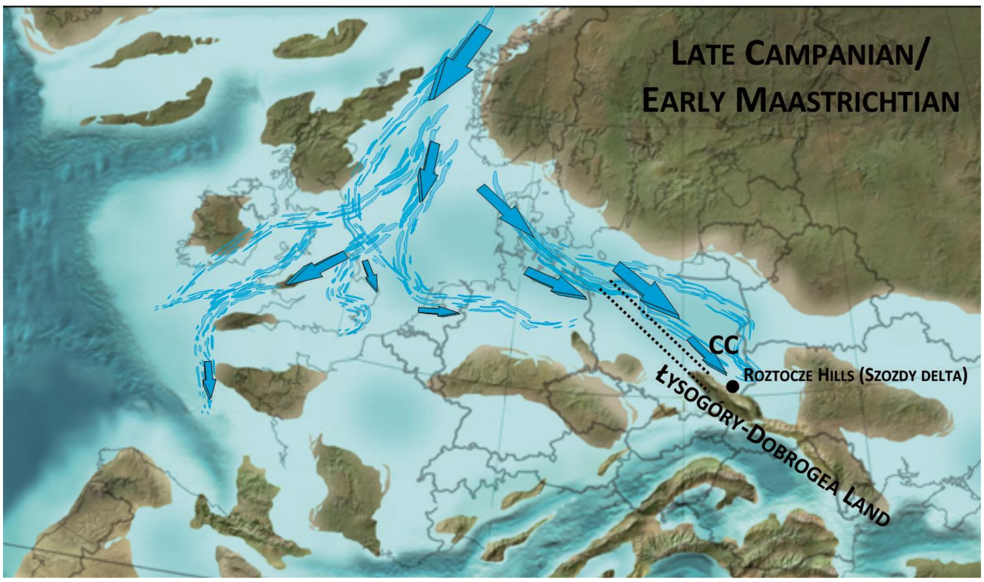

Fig. 13. Palaeogeographic map and location of the Roztocze Hills and the Łysogóry-Dobrogea Land (inserted into the original map). The course of ocean currents is based on Remin et al. (2016) and Remin (2018); the presence of contourite currents (= CC) are according to Krzywiec et al. (2018). Palaeogeographic map by Ron Blakey (2016), used with permission © Ron Blakey Colorado Plateau Geosystems Inc. (http://deeptimemaps.com/wp-content/uploads/2016/05/75_Cret_EurMap.png).

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The presence of contourite currents indicates that the Szozdy deltaic system has been limited to the northeast by a regional slope in the sea-bottom and the currents flowed parallel to the strike redistributing the material in the southeastern direction. The potential manifestation of such redistribution of finest material by the current action might be pure clay deposits of c. the same age, which are located to the southeast from the Szozdy delta, i.e. in the Horyniec Zdrój area (compare Fig. 12). This area is additionally characterized by the smallest amount of $CaCO_3$ and high terrestrial input.

6.5 Driving force for the accommodation space generation

The inversion-related tectonic instability along the deeply rooted Janów Fault Zone (a SW boundary of the Roztocze Hills) (Fig. 2) led to the development of the Szozdy deltaic system. To the SW of the Janów Fault, thus in the are of San Anticlinorium (Fig. 2), there existed a landmass during the Late Cretaceous times, i.e. Łysogóry-Dobrogea Land, which was an alimentation area for the siliciclastics of the Szozdy delta. During the inversion tectonics this area underwent an uplift, which surely resulted in changes of the erosive base. Contrary, on the other side of the Janów Fault (to the NE of it) the Upper Cretaceous strata of recent-day Roztocze Hills were deposited, including the cyclothems of the subaquatic delta front platform of the Szozdy deltaic system. This area, to the NE of Janów Fault, experienced enhanced subsidence what resulted in the deposition of the thick Campanian strata, especially along this active fault zone (compare Figs 9 and 12).

Repeated events of subsidence of the present-day area of the Roztocze Hills during the Late Cretaceous inversion on the one hand and uplift and erosion of the Łysogóry-Dobrogea Land on the other (the area of San Anticlinorium) must pulsating rearrange the delta architecture supplying additional accommodation space for development of succeeding Szozdy delta cyclothems(Figs 11 and 12). Tectonically-induced migration and avulsion of distributary channels led to changes in sedimentary environment at particular places, what resulted in repetition of Szozdy cyclothems.

At the current stage we can not estimate the total thickness of the deltaic deposits of the Szozdy delta since neither the lower nor the upper limit of the cyclic succession is known. The available exposure at Szozdy gives access to approximately 30-35 meters of the succession. Other natural or artificial exposures are not present. In close proximity to the Szozdy section the available well-data are also absent. In the more distal boreholes the Late Cretaceous rocks were cored only in homeopathic amounts, therefore the existing well-data preclude any firm conclusions.

The Campanian deposits of the Roztocze Hills area rich up to 550 meters and the highest values are located along the Roztocze Hill escarpment (Figs 9 and 12) – in the NE direction the thickness is consequently lower. At least part of this thickness has been generated by the active Szozdy deltaic system founded on a prominent and deeply rooted fault zone or redistribution of fine-grain material along the Łysogóry-Dobrogea Land.

The current day Roztocze Hills are delineated from the SW by a prominent escarpment that is a border zone with the subsurface NE edge of the Łysogóry and Małopolska Blocks under the Miocene cover of the recent day Carpathian Foredeep (Fig. 2). This prominent tectonic line has been variously

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interpreted and was considered to be a prolongation of the Holy Cross Mountain Fault (e.g. Kutek and Głazek, 1972). Others (e.g. Narkiewicz et al., 2015, Narkiewicz and Petecki, 2017) synonymized the SW edge of the Roztocze Hills with the Janów Fault (Fig. 2) and placed the prolongation of the Holy Cross Mountain Fault (i.e. Cieszanów Fault) a few kilometers to the SW already within the area of the San Anticlinorium. Both the Cieszanów Fault and the Janów Fault were founded on crustally-rooted fault zones marked as nearly vertical crustal-scale conductive zones (review in Narkiewicz et al., 2015) and were repeatedly reactivated during the inversion tectonics of the Danish-Polish Trough in the Late Cretaceous and during the Carpathian movements during the Miocene times (Kowalska et al., 2000; Buła at al., 2008; compare also Krzywiec, 1999; Buła and Habryń, 2011).

6.6 Comments on burial history and the rate of subsequent erosion

Since the paper of Kutek and Głazek (1972), the Holy Cross Mountains and the San Anticlinorium to the southeast (Fig. 2), were included into the axial part of the former Danish-Polish Trough which undergone subsequent inversion, uplift, and erosion, and transformation into the Mid-Polish Anticlinorium. Apart from the concept of the onset of inversion tectonics, there was a general agreement that the area of the Holy Cross Mountains segment and area of the San Anticlinorium itself has been deeply buried by thick Permian and Mesozoic sediments (e.g. Kutek and Głazek, 1972). Such a line of thought strongly affected the burial and tectonic history of the supposed south-easternmost extension of the Danish-Polish Trough, i.e. the Holy Cross Mountains and San Anticlinorium, especially during the Late Cretaceous times.

Kutek and Głazek (1972) suggested that c. 3000 m of sedimentary rocks have been removed by erosion from the axial part of the Mid-Polish Anticlinorium, especially from the Holy Cross Segment (Fig. 2). Later estimations, like those of Bełka (1990), suggested for the Holy Cross area (to the NW of the San Anticlinorium; Fig. 2), that the thickness of the post-Devonian overburden varies between 1500 and 3800-5500 m depending on the place, being generally higher close to the Holy Cross Fault. Similar values of overburden (1700 – 2300 m) were recently obtained by Łuszczak et al. (2020) for the western slopes of the Holy Cross Mountains.

Those values, however, can not be simply transposed to the San Anticlinorium, because the geological background is different in this region. First of all, to the northeast of the San Anticlinorium there are no Permian, Triassic, and Lower Jurassic deposits (e.g. Świdrowska et al., 2008). The available data starts from the Middle Jurassic strata, thus the stratigraphic record is markedly reduced in comparison to the Holy Cross segment and the Kujawy region to the north-west, where thick Permian, Triassic, and Jurassic deposits are present (Kutek and Głazek, 1972; Świdrowska et al., 2008, Krzywiec et al., 2018 for overview).

Since we know nothing about the possible Mesozoic overburden over the San Anticlinorium area (this area is almost devoid of Mesozoic remnants; Fig. 2), we analyzed the heavy mineral assemblages from the Szozdy delta to look for some provenance data. The present heavy minerals analysis, although based on selected mineral phases and therefore preliminary (a more comprehensive analysis is in preparation; Cyglicki and Remin, in prep.), provides valuable data on the potential source rocks for the siliciclastics of the Szozdy deltaic system.

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The tourmalines belong to the alkaline subgroup, in which the ratio of dravite to shorl is 4:1, suggesting that tourmaline grains potentially come from metamorphic rocks. Part of tourmalines correspond to metamorphosed sedimentary rocks rich in aluminum phases like kyanite and staurolite which co-create the studied mineral complexes (Fig. 6). Part of the analyzed grains with their chemical composition corresponds to tourmalines derived from Li - poor granitoids and their vein counterparts. A potential source of two tourmaline grains (Fig. 6) might be ultramafic rocks and metasediments enriched in Cr and V, which is additionally confirmed by the presence of Cr – spinels (Fig. 6).

In the ternary diagrams of Meres (2008), most garnet grains occupy fields C1 and C2 (Figs 7AB). They correspond to garnets originating mainly in transitional granulite/amphibolite and amphibolite facies conditions respectively (Aubrecht et al., 2009; Meres, 2008). Grains that occupy field B (Figs 7AB), might correspond to the garnets from eclogite and granulite facies conditions. Garnets typical for high-pressure to ultra-high-pressure conditions are absent in the analyzed assemblage (Figs 7AB).

The heavy mineral assemblages from the Szozdy section show truly polycyclic nature. On the one hand, a high values of the ZTR index (ascribed on ultrastable mineral phases), in addition to high degree of roundness of mineral grains and the presence of some abrasive structures suggests multiply redeposition (Hubert, 1962; Mange and Wright, 2007; Garzanti, 2017; Garzanti and Andò, 2019). On the other hand, the presence of group of minerals weakly resistant to erosion that consists almost exclusively of angular-shaped crystals (> 70-80%) with almost no oval/rounded ones of garnets, kyanites, and staurolites support the following line of thought concerning the source rocks.

Accordingly, the above data suggest at least two different sources. The first provided multi-recycled mineral phases with the dominance of minerals from the ZTR group, for which the source might be metapelites/metapsamites. The second, "fresh", delivered angular-shaped crystals of garnets, kyanites and staurolites, for which rocks of amphibolite facies were the main source.

This initial data suggest that the source rocks for the heavy mineral assemblages of Szozdy delta are represented on the one hand by multi-recycled sedimentary rocks, on the other hand by fresh weathered metamorphic and igneous rocks. Such characteristics would be rather difficult to obtain from the Mesozoic sedimentary cover of the San Anticlinorium (if present at all) and force us to look for other sources. A tempting hypothesis, although highly speculative, for the potential source rocks would be the comparison of mineral assemblages from the Szozdy delta to the Cambrian and Neoproterozoic rocks subcropping beneath the Miocene deposits of the Carpathian Foredeep, represented by metamorphosed (anchimetamorphic) flysch-type siliciclastics.

6.7 Towards the understanding of late Cretaceous facies distribution

The presence of the middle Campanian deltaic system developed in the axial part of the inverting Danish-Polish Trough (into the Mid-Polish Anticlinorium) has some basic consequences for the overall understanding of some Late Cretaceous facies. This concerns mainly opoka, chalk, and their variants in addition to their mutual spatial and bathymetric relationship in cross transect perpendicular to Łysogóry-Dobrogea Land (Fig. 2E).

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The here presented proofs for shallow water, deltaic origin of mixed carbonate siliciclastic deposits confirm the conceptual proposition of deltaically influenced sedimentation in the Roztocze Hills area during the Campanian times initially proposed by Remin et al. (2015) and Walaszczyk and Remin (2015) and fully confirm the general sedimentological and bathymetrical model they proposed (compare Fig. 2E). In the present study, for the first time, we can directly prove the interfingering of terrigenous-rich deltaic sediments with gaize and variants of opoka facies which are located slightly to the NE from the edge of the Roztocze Hills and Szozdy deltaic system. It clearly shows that this specific facies, i.e. opoka, should rather be considered as a shallow originated type of rock than hitherto thought based on different tectonic and sedimentological models. In the SW-NE transect perpendicular to here defined Szozdy deltaic system and Łysogóry-Dobrogea Land, the more carbonate-rich deposits, including chalk, were deposited in more offshore and deeper zone, which was located to the NE from the main body of Roztocze Hills. The presence of such a deeper zone is confirmed by the last discoveries of contourite currents (Krzywiec et al., 2018) - the latter must operate along a regional slope which was located to the NE of both the Łysogóry-Dobrogea Land and Szozdy deltaic system.

For several decades our understanding of facies distribution was highly influenced by the adopted paleotectonic model developed and proposed by Kutek and Głazek (1972). Those authors *a priori* synonymized the axial part of the Danish-Polish Trough (in recent days represented as the Mid Polish Anticlinorium; Fig. 2) with the most subsiding and deepest part of the basin. As a consequence, it was assumed that the facies deposited close to the axial part of the Danish-Polish Trough (e.g. Roztocze Hills area) would represent the deepest sedimentary environment. Therefore the facies distribution and bathymetric interpretation was fitted to the assumed paleotectonic model (see also discussion in Walaszczyk and Remin, 2015). It is noteworthy, however, that Late Cretaceous mixed carbonate siliceous facies elude easy environmental interpretations, and the adopted paleobathymetric model, as well as the spatial distribution of particular facies (compare Figs 2D and 2E), were not supported by any relevant sedimentological and/or biological indicators. Nevertheless, the concept of deep water origin of opoka (Fig. 2D) has been widely accepted and for decades dominated thinking concerning the spatial distribution of facies and their relation to paleobathymetry (e.g. Leszczyński 1997, 2010, 2012; Hakenberg i Świdrowska, 1998, 2001; Świdrowska and Hakenberg, 1999; Świdrowska 2007; Świdrowska et al., 2008; Świerczewska-Gładysz, 2006; Jurkowska et al., 2019). Accordingly, the Late Cretaceous opoka facies, which is the dominant facies of the Roztocze Hills area, despite a considerable amount of terrigenous material, mainly quartz in a sand fraction as well as clay, were up to now considered as deep-water sediment. In the light of new data presented herein, such a point of view can not be upheld any longer at least for the opoka facies of the Roztocze Hills area.

7. Summary

The presented herein interpretation implies the presence of a landmass area i.e. the Łysogóry-Dobrogea Land, in the place, where according to many previous interpretations, the deepest part of the Danish-Polish Trough was located. For the first time, hard proofs for such paleogeographic and peleobathymetric models are provided based on sedimentological data coupled with heavy mineral and palynofacies analyses. We recommend that this name should be used as it has priority (vide Samsonowicz, 1925).

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The recognition of the Szozdy deltaic system in the supposed axial part of the Danish-Polish Trough gives a fresh look into the sedimentary environment, hydrodynamics, facies architecture, and bathymetric position of several late Cretaceous facies and placed various type of the opoka facies next to deltaic deposits suggesting its shallow-water origin. For the chalk facies, a deeper sedimentary environment is suggested.

Inversion-related tectonic instability along the deeply rooted Janów Fault Zone (a SW boundary of the Roztocze Hills) led to the development of the Szozdy deltaic system. An uplift of the San Anticlinorium during the Late Cretaceous inversion on the one hand and enhanced subsidence of the present-day area of the Roztocze Hills on the other, rearrange the delta architecture, supplying additional accommodation space for the development of Szozdy delta cyclothems.

The Łysogóry-Dobrogea Land, located to the south, south-west to the Roztocze Hills, thus in the area of the recent-day San Anticlinorium, is the only reasonable place that could supply the terrigenous material for the siliciclastics of the Szozdy deltaic system. This area is currently almost completely devoid of the Cretaceous and other Mesozoic remnants and is now hidden under the Miocene cover of the Carpathian Foredeep.

The geochemistry of analyzed tourmaline and garnets (this study; compare also Cyglicki and Remin, 2016, 2018) might indicate that, at least in part, the strata subcropping beneath the Miocene series of the Carpathian Foredeep (to the SW of Roztocze Hills) were already emerged and eroded during the Late Cretaceous.

8. Current challenges and future road map

The results obtained from current research raised several crucial issues that demand to be solved in the near future and allow to formulate a working hypothesis that the recent-day San Anticlinorium has been an elevated structural element during the Late Cretaceous times and ist sedimentary cover subcropping beneath the Carpathian Foredeep have been already eroded supplying terrigenous material for the siliciclastics of the Roztocze Hills. Such a hypothesis, although highly speculative, is supported by initial geochemical data of heavy minerals we obtained, which might suggest that at least part of the material comes from freshly weathered metamorphosed rocks. Positive verification allows for solving the following issues:

1. What was the source for the Late Cretaceous Szozdy deltaic system and siliciclastics of the Roztocze Hills? Was it the Mesozoic cover of the San Anticlinorium? or were the rocks beneath the Miocene cover of the Carpathian Foredeep that underwent erosion already during the Cretaceous times?
2. Accordingly, did or did not, the San Anticlinorium constitute a homogeneous part (structurally and paleogeographically) of the Danish-Polish Trough during Cretaceous times?
3. Accordingly, what was the real south-eastern extension of this trans-European sedimentary basin, i.e. the Danish-Polish Trough during the Cretaceous times?
4. Accordingly, what was the burial history, if at all, of SE Poland during late Cretaceous times?

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Deciphering of these crucial objectives, based on a revised paleofacies and paleobatymetric model, is now of fundamental significance for the overall understanding, at least the Late Cretaceous paleotectonic evolution of the supposed SE edge of the former Danish-Polish Trough.

In turn, the precise recognition of the stratigraphic succession and facies distribution (ongoing) will allow for reliable identification of the main phases of terrigenous material input into the Roztocze Hills area from the nearby land-mass areas along with the estimation of gradients of subsidence, and the identification of these events on high-resolution seismic profiles (ongoing). In consequence, a ceasing of the subsidence rate should lead to the progradation of the siliciclastic facies toward the NE direction, thus from land to offshore zone.

The positive verification of the working hypothesis, i.e. identification of the source rocks for the siliciclastic deposits of the Roztocze Hills, and the scale and rate of uplift (if any) of the San Anticlinorium might be the base for a new model of the Late Cretaceous palaeotectonic evolution of SE Poland, treated so far as the SE part of the trans-European sedimentary basin – the Danish-Polish Trough. Solving all the above issues, especially answering whether or not the San Anticlinorium constitutes structurally part of the Danish-Polish Trough might fundamentally change our understanding of regional geology, burial history as well as paleogeography and paleobiogeography of Central Europe during the Late Cretaceous, with all far-reaching interpretative consequences.

Author contributions. ZR: idea, conceptualization, a compilation of all data, writing of the original draft, funding acquisition (NCN); MC: heavy minerals analyses, conceptualization, discussion and validation, revision, critical review in the pre-publication; MN: palynofacies analyses, conceptualization, discussion and validation, revision, critical review in the pre-publication

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