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MULTI-PHASE KARST SINKHOLE DEPOSITS IN THE OWADÓW-BRZEZINKI QUARRY, CENTRAL POLAND: SEDIMENTOLOGY, PALYNOLOGY AND STRATIGRAPHY

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Abstract: A multi-phase succession of karst sinkhole deposits in the tectonic zone of the Owadów-Brzezinki limestone quarry at the north-western margin of the Holy Cross Mts. was studied in detail, using petrographic, palynological and other palaeontological methods. Upper Jurassic limestones are covered by a residual reddish brown clay layer of *terra rossa* type and a yellow-brown, loose calcareous deposit of a silt fraction. The yellow-brown calcareous silt consists of rhombohedral calcite grains, which may have been formed by the disaggregation of speleothems. The colouration of both deposits and clay mineral admixtures point to intensive weathering under a subtropical climate. The successive deposits of the sinkholes include coaly clay and a layer of whitish, microcrystalline, siliceous sinter. The coaly clay yielded a rich Middle Miocene palynofloral assemblage, indicative of a warm temperate and humid climate, as well as freshwater algae, which inhabited surface-water pools. The origin of the siliceous sinter probably is related to the activity of a hot spring. The youngest, massive infillings of the sinkholes consist of grey silty clays, which yielded marine bivalves, gastropods and *Dichotomites* ammonites, diagnostic for the Upper Valanginian as well as white yellow quartz sands of Upper Hauterivian? – Middle Albian age. The massive siliciclastic deposits probably slumped into the sinkholes during their final collapse. The sinkhole infillings document the development and timing of karst processes, Middle Miocene climatic conditions and the original succession of Lower Cretaceous–Neogene strata of the study area, which were removed from the surface by erosion.

Key words: Palaeokarst infillings, Miocene coal and palynoflora, siliceous sinter, Lower Cretaceous marine deposits, Valanginian ammonite fauna.

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INTRODUCTION

The Owadów-Brzezinki Quarry, on the north-western margin of the Holy Cross Mts., is a unique outcrop of the Tithonian in the territory of extra-Carpathian Poland (Fig. 1). It is a famous palaeontological site, rich in exceptionally well-preserved terrestrial and marine fossils, which are important for palaeontology, stratigraphic correlation and palaeoenvironmental reconstruction (e.g., Błażejowski *et al*., 2016, 2023; Wierzbowski *et al*., 2019). The Owadów-Brzezinki Quarry is located on the south-eastern part of the Laramide-age Tomaszów Mazowiecki Syncline,

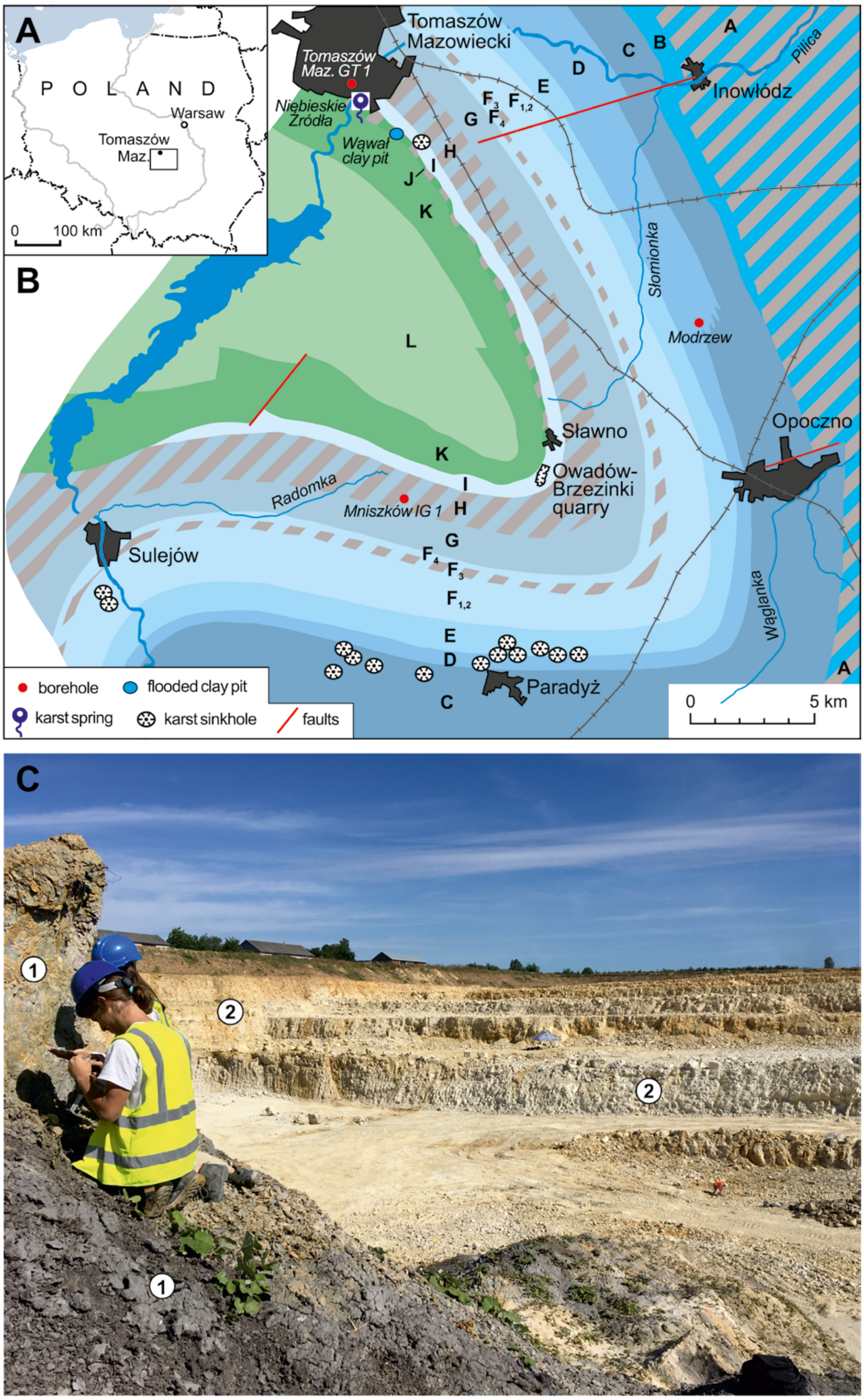

Fig. 1. Location of the study site. **A.** Location of the study area in Poland. **B**. Geological map of the Tomaszów Mazowiecki Syncline with reported karst phenomena and the location of the Owadów-Brzezinki Quarry (after Matyja and Wierzbowski, 2014; modified). Lithological divisions: A – siltstones, calcareous mudstones and claystones (Middle Jurassic); B – “chalcedonies” (Middle Callovian–Middle Oxfordian?); C – Częstochowa Sponge Limestone Formation (Oxfordian–Lower Kimmeridgian); D – Pilica Formation (Lower Kimmeridgian); E – Coral Limestone Formation (Lower Kimmeridgian); F – “Oolite” formation (Lower Kimmeridgian) including F1,2 – Lower and Upper Kurnędz Limestone Member, F3 – Middle Marly association, and F4 – Oolite-Platy Limestone Member; G – Stobnica Lumachelle Formation (Lower–Upper Kimmeridgian); H – Pałuki Formation (Upper Kimmeridgian–Lower Tithonian); I – Kcynia Formation (Upper Tithonian); J – Wąwał Formation, an equivalent of the combined Opoczki Member of the Rogoźno Formation, the Bodzanowo Formation and the Wierzchosławice Member of the Włocławek Formation (Valanginian) as well as younger Hauterivian deposits; K – Biała Góra Formation (Upper Hauterivian?–Middle Albian); L – mudstones and gaizes (mid-Upper Cretaceous). Location of Mniszków IG 1 and Tomaszów Mazowiecki GT 1 boreholes is marked with red dots. **C.** An upper part of the main karst sinkhole section in the Owadów-Brzezinki Quarry with 1 – re-deposited Cretaceous silty clays, surrounded by 2 – uppermost Jurassic limestones.

close to its axis. There are exposed Lower–Upper Tithonian boundary strata, consisting of marls of the uppermost part of the Pałuki Formation and limestones of the lower part of the Kcynia Formation, which dip slightly to the north-west and are covered by Quaternary deposits (Kin *et al*., 2013; Matyja and Wierzbowski, 2016; Wierzbowski *et al*., 2016).

Although the Tithonian limestones underwent Paleogene–Neogene weathering and karstification processes, which were widespread in the south Polish Uplands (cf. Głazek, 1989; Liszkowski, 1996), only isolated karst phenomena have been reported, so far, from the Tomaszów Mazowiecki Syncline and its vicinity. This is probably due to the thick Cretaceous and Quaternary cover of siliciclastic deposits. The known karst phenomena on the north-eastern limb of the syncline include a few karst sinkholes and the "Niebieskie Źródła" springs at Tomaszów Mazowiecki, which are developed in Tithonian limestones and fed by waters circulating in these deposits (Lencewicz, 1913; Małecka, 1997). Karst sinkholes and small karst valleys, developed in the Oxfordian–Lower Kimmeridgian limestones, are also known from the south-western limb of the Tomaszów Mazowiecki Syncline, in the areas around Sulejów and Paradyż (Różycki, 1946; Barczyk, 1961; Głazek and Szynkiewicz, 1980a; Fig. 1). In addition, a presumed karst sinkhole, filled with Miocene deposits, was observed in a similar geological position in the Modrzew borehole on the north-eastern limb of the Tomaszów Mazowiecki Syncline (Szałamacha, 1992).

Easily detectable karst sinkholes have been observed in the Owadów-Brzezinki Quarry, beginning in 2016. Since that time, the quarry has expanded by a few hundred metres to the north, revealing the presence of numerous partly exposed sinkholes, filled with siliciclastic, siliceous and coaly deposits. The sinkholes preserve Lower Cretaceous and Neogene deposits, eroded from the surface, and constitute a window into their lithology and depositional settings.

Reconstruction of the evolution of the newly discovered karst sinkholes in the Owadów-Brzezinki Quarry and sedimentological analysis of their infillings are the main goals of the present study. It also aims at dating and deciphering the regional depositional and palaeoenvironmental settings of previously unknown karst forms, developed in Tithonian limestones in the southern part of the Tomaszów Mazowiecki syncline. The analysis of sinkhole coaly deposits is particularly useful for the reconstructions of ancient floristic assemblages (e.g., Ochoa *et al*., 2016). It is worth noting that palynological studies of karst sediments rarely have been conducted in Poland. Examples include: the palynological analysis of Miocene and Oligocene palynofloras, found in karst sinkholes developed in the Middle Triassic limestones in the Upper Silesian-Kraków Upland (Rogala and Sadowska, 2003; Worobiec and Szulc, 2010a, b, 2020; Worobiec, 2011, 2014b; Szulc and Worobiec, 2012; Szulc *et al*., 2015) and the Middle Miocene palynoflora of the Nowy Waliszów karst site in the Eastern Sudetes (Sobczyk *et al*., 2024), all of which were used for dating and palaeoenvironmental reconstruction. The same applies to the Quaternary fossil plant assemblages in the karstic deposits of the Nida Trough (Szczepanek, 1971) and the Neogene plant macroremains in the karst sinkholes of the Upper Silesia Upland in southern Poland (Baranowska-Zarzycka, 1980).

GEOLOGICAL SETTING

The karst sinkholes of the Owadów-Brzezinki Quarry occur along a 60-m-wide zone of strongly weathered Tithonian limestones of the Kcynia Formation, extending downwards to the top of the light grey marls of the Pałuki Formation (Fig. 2). This zone corresponds to the prominent subvertical fault, stretching in a WNW–ESE direction (110°–120° azimuth), the southern block of which was moved downward by a few metres. Field measurements indicate that some karst sinkholes attain a few tens of metres in diameter. They contain displaced dark silty clays and white-yellow sands of Early Cretaceous age as well as coaly deposits and a siliceous sinter band of presumed Miocene age.

The lithological succession of the Owadów-Brzezinki Quarry comprises the ~2-m-thick uppermost part of the clayey

Fig. 2. A general view of the Owadów-Brzezinki Quarry, showing the tectonic fault zone with a WNW–ESE trend and karst phenomena. The location of a main karst sinkhole is indicated by an arrow.

Pałuki Formation and locally karstified limestones of the Kcynia Formation ~25 m in thickness. The latter deposits are divided into the Sławno Limestone Member (units I and II), which consists of chalky/micritic limestones with marly limestone intercalations and organo-detrital limestones as well as the informal *Corbulomima* limestones (unit III) and serpulite beds (unit IV; cf. Matyja and Wierzbowski, 2016; Wierzbowski *et al.*, 2016). The Tithonian section is overlain by a stratigraphic unconformity and a cover of Quaternary sands and gravels, a few metres thick.

The topmost part of the Pałuki Formation and the lower part (unit I) of the Sławno Limestone Member are dated to the Scythicus–Virgatus zone boundary of the "Middle Volgian" and the Fittoni–Albani zone boundary of the English "Upper Kimmeridgian" and the "Portlandian" (Matyja and Wierzbowski, 2016). The exact position of the Lower/Upper Tithonian boundary, which may occur at the base of the Owadów-Brzezinki section, is not known; the limestone strata of the Kcynia Formation are, however, correlated with the lowermost Upper Tithonian (Błażejowski *et al.*, 2023).

The Lower Cretaceous beds are not present in the Owadów-Brzezinki Quarry but occur close to it in the internal parts of the Tomaszów Mazowiecki Syncline (Fig. 1). A so-called "Infravalanginian", currently assigned to the lower part of the Rogoźno Formation, consists of a basal conglomerate, overlying an erosion surface, and claystone-mudstone-sandstone deposits with iron oolites and siderite concretions (Witkowski, 1969; Marek, 1997). The sedimentology and stratigraphy of Valanginian–Hauterivian deposits of the predominant mudstone-claystone lithology were studied in detail in the Wąwał clay pit on the north-eastern limb of the Tomaszów Mazowiecki Syncline and documented in a few boreholes (cf. Witkowski, 1969; Raczyńska, 1979; Kutek *et al.*, 1989; Dziadzio *et al.*, 2004; Morales *et al.*, 2015). The Valanginian deposits, previously assigned to the Wąwał Formation, are nowadays included in: (1) the Opoczki Member of the Rogoźno Formation, (2) the Bodzanowo Formation and (3) the Wierzchosławice Member of the Włocławek Formation (cf. Poręba, 1987; Marek, 1997; Dziadzio *et al.*, 2004). The youngest, Hauterivian part of the Włocławek Formation of the Tomaszów Mazowiecki Syncline, consisting of sandy claystones and mudstones, is overlain by kaolinite sandy, silty and sandstone deposits of the Biała Góra Formation, which are dated ambiguously to the Middle Albian or to a longer Upper Hauterivian–Middle Albian interval (Raczyńska and Cieśliński, 1960; Raczyńska, 1979; Marcinowski and Rudowski, 1980; Poręba, 1987; Szałamacha, 1992; Poręba *et al.*, 2018). They probably correspond to the Kruszwica Member of the Mogilno Formation, which is widespread in the central part of the Polish Lowlands (Marcinowski and Rudowski, 1980).

A general lack of Lower Cretaceous deposits near Owadów-Brzezinki is probably a result of their low original thickness in the southern part of the Tomaszów Mazowiecki Syncline and wide-scale erosion (e.g., Witkowski, 1969; Poręba, 1987; Kutek *et al.*, 1989). It is, however, worth noting that presumed clasts of lowermost Cretaceous mudstones have been found recently in the rubble breccia at the erosional surface, developed on the topmost part of the Jurassic limestones in the northernmost part of the Owadów-Brzezinki Quarry. This breccia locally may contain material, younger than the rocks in the central part of the quarry (cf. Witkowski, 1969).

MATERIAL AND METHODS

Sinkhole deposits of the Owadów-Brzezinki Quarry were successively examined and sampled in the years 2016–2023 for palynological, macrofaunal and sedimentological studies.

Thin sections prepared from karstified uppermost Jurassic limestones as well as the siliceous and silty clay deposits of the karst sinkholes were studied, using the petrographic optical microscope (Zeiss, Axio Scope A1) with a digital camera, and the scanning electron microscope (SEM) Zeiss Leo 1430, equipped with energy-dispersive X-ray spectroscopy (EDS) elemental detectors. Fragments of the loose and clayey deposits of the sinkholes were studied, using the SEM Zeiss Leo 1430 and Thermo Fisher Quattro S microscopes, with EDS detectors, to document the original fabric and composition of the rocks.

Two palynological samples, taken from the coaly clay deposits of the main sinkhole, were processed in the Laboratory of the W. Szafer Institute of Botany, Polish Academy of Sciences, Kraków, using successively 10% hydrochloric acid (HCl), 10% potassium hydroxide (KOH), 40% hydrofluoric acid (HF), and 10% hydrochloric acid (HCl; cf. Moore *et al.*, 1991; Worobiec *et al.*, 2021). The residuum was sieved at 5 µm on a nylon mesh. Microscope slides were made, using glycerine jelly as the mounting medium. Spore-pollen, algae and fungal remains analysis was conducted on the basis of ten slides. The identified fossil taxa of pollen and spores of plants were classified and divided into "Palaeotropical" (P), including "tropical" (P1) and "subtropical" (P2), "Arctotertiary" (A), including "warm-temperate" (A1) and "temperate" (A2), as well as cosmopolitan (P/A) elements, based on the *Atlas of Pollen and Spores of the Polish Neogene* (Stuchlik *et al.*, 2001, 2002, 2009, 2014). Microphotographs of selected pollen grains and algae were taken, using a Nikon Eclipse E400 microscope, fitted with a Canon A640 digital camera.

Three samples, taken from the coaly clay layer outcropping in the same sinkhole, were examined for the presence of macroscopic plant remains. They were prepared in the Museum of the Earth in Warsaw, Polish Academy of Sciences. The samples were disaggregated in boiling water, with added laundry detergent. The resulting suspension was washed through a sieve with a 0.2-mm mesh diameter.

A piece of coalified and partially pyritised wood (5 x 3 cm), which was found in a debris pile at the base of the main sinkhole, also was studied. For identification purposes, the wood fragment was impregnated with epoxy resin and cut into transversal, tangential and radial thin sections. Its thin sections were examined with a Nikon optical microscope, equipped with a digital camera.

Several specimens of marine macrofauna, including ammonites, bivalves and gastropods, were collected from the grey clays in the central part of the main sinkhole, occurring in the tectonic zone. The same applies to the microfossils studied by Chrząstowska *et al.* (2025), whose results are reported in the present paper. The most valuable macrofossil specimens are stored in the palaeontological pavilion of the Owadów-Brzezinki Geosite (Geopark) or housed at the Institute of Palaeobiology, Polish Academy of Sciences in Warsaw.

RESULTS

Sinkhole sections

Infillings of the studied sinkholes show original layering, consisting of various generations of clayey-silty to sandy deposits, which rest on the surface of the highly weathered and karstified Tithonian limestones.

The weathered, yellow-brownish-coloured, Tithonian limestones in the main sinkhole, ~30 m in diameter (coordinates: 51°22′46″ N; 020°8′10″ E), are covered by residual debris and a ~15-cm-thick, continuous layer of reddish brown clay residuum with limonite coatings (Fig. 3). Between the karstified limestones and the clay residuum, in the upper part of the sinkhole section, there is a large pocket, filled with yellow-brown, loose calcareous deposits of the silt fraction. The reddish brown clay layer is overlain by a ~10-cm-thick layer of black coaly clay, laterally mixed with grey clay, and a ~5-cm-thick bed of brittle, white to whitish grey, siliceous sinter, disaggregating into separate pebbles. The sinter bed occurs only in the middle part of the section (visible *in-situ* in a 1.5-m section). Large, displaced pebbles (up to 9 cm in diameter) of brittle, white to whitish grey, siliceous sinter, also were found in the pile of grey clay around the main sinkhole and ~10 m from it (coordinates: 51°22′46″ N; 020°8′9″ E).

A central part of the sinkhole is filled with mostly massive clayey deposits, consisting of light grey and light brown, silty clays with a sand admixture up to 1.5 m in thickness and ~1 m-thick, dark bluish grey, partially silty clays (Fig. 3). The upper part of the clays is dark grey and relatively pure. It is devoid of distinct bedding and contains marine macrofossils, including ammonite fragments. The massive clayey deposits partly transect the older deposits of the sinkholes and contain coaly clay intraclasts; they are also strongly deformed and folded, showing, where visible, mixed subvertical to semihorizontal layering. The youngest deposits of the sinkhole are white yellow quartz sands.

The light to dark grey clays and white yellow sands are observed on the surface throughout the whole tectonic zone, with the karstified Jurassic limestones probably covering small sinkholes that are not visible in detail.

In the easternmost part of the Owadów-Brzezinki Quarry, in the continuation of the wide zone of karstified Jurassic limestones, a small karst cavity recently was discovered (coordinates: 51° 22′ 48″ N; 20° 8′ 15″ E). Inside the cavity, on the surface of Jurassic limestones, there is a bed of white, micritic calcite (~5 cm thick), which is covered by redeposited grey clays and yellow Quaternary sands (Fig. 4).

Sedimentology and lithofacies

Microfacies analysis of the Jurassic karstified limestones and debris, derived from the walls of the main sinkhole (deposit no. 1), has revealed a predominantly wackestone microstructure. The studied rocks contain fragments of oyster shells and serpulid worm tubes (Fig. 5A), which are typical

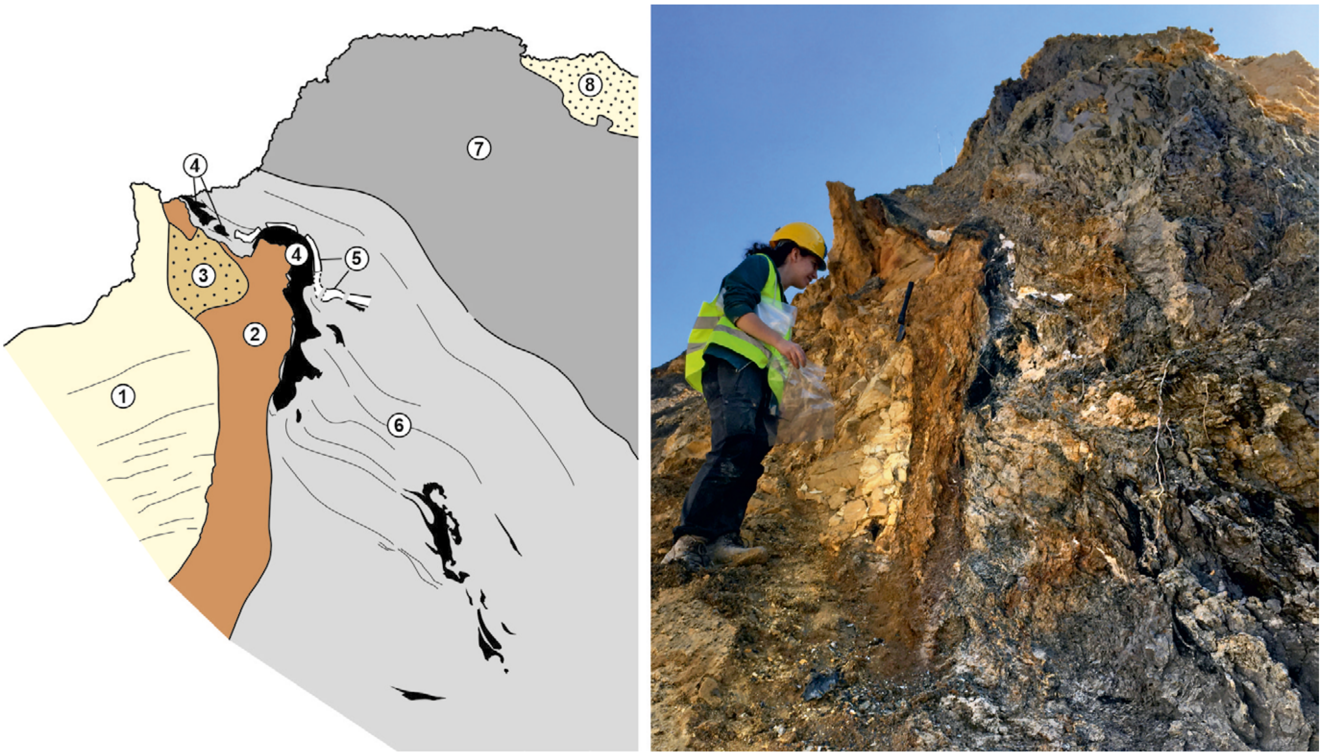

Fig. 3. A photograph and the drawn section of the main karst sinkhole in the Owadów-Brzezinki Quarry. The deposits of the sinkhole are: 1 – karstified, yellow-brownish, uppermost Jurassic limestones; 2 – reddish brown residual clay layer; 3 – a pocket, filled with yellow-brown, calcareous deposits of silty fraction; 4 – coaly clay layer; 5 – brittle white to white grey, microcrystalline siliceous sinter; 6 – light grey and light brown silty clays with sand admixture; 7 – dark grey, partially silty clays; 8 – white yellow quartz sands.

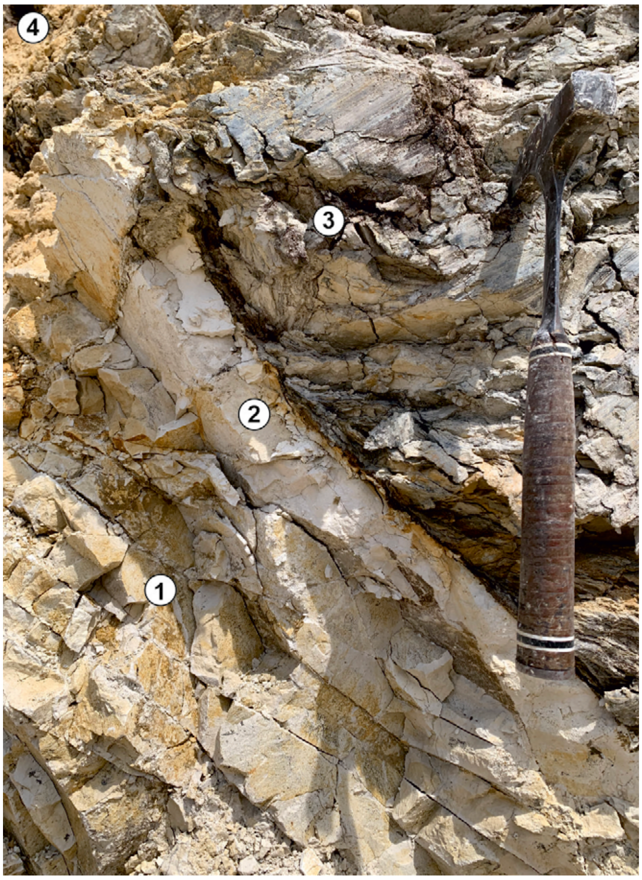

Fig. 4. A photo of the small karst cavity. The deposits of the sinkhole are: 1 – karstified uppermost Jurassic limestones; 2 – white, micritic calcite deposit; 3 – redeposited grey clays; 4 – yellow Quaternary sands.

of the lithology of the uppermost unit IV (serpulite) of the Owadów-Brzezinki section of the Kcynia Formation (cf. Matyja and Wierzbowski, 2016; Wierzbowski *et al*., 2016).

SEM analysis showed that the reddish brown residual clay layer (deposit no. 2) consists of a dense clay mineral matrix, mixed with various proportions of iron hydroxides/oxides and individual quartz grains. In places, individual clay mineral grains show a foliated, plate morphology (Fig. 5B). The reddish brown colours of the clay are linked to variable amounts of iron compounds.

The unstructured, yellow-brown, loose calcareous deposit of the silt fraction (deposit no. 3), which occurs in a pocket between the karstified Jurassic limestones and the reddish brown clay, is composed of rhombohedral calcite crystals, a few tens of micrometres in diameter, as revealed by SEM studies (Fig. 5C). The crystals show euhedral or subhedral forms or form aggregates. Their crystal faces are slightly corroded and/or possess secondary calcite and clay mineral overgrowths and coatings (Fig. 5D).

SEM studies of the dark and opaque, coaly clay deposits (deposit no. 4) have revealed their compact clay fabric; organic matter particles are not visible on broken surfaces, probably because of the clay mineral coating (Fig. 5E). Chemical analyses of selected spot areas have shown variable non-carbonate carbon content, ranging from 3.3 to 45.8 wt.% (mean 15.1 wt.%). Elemental mapping revealed some areas, enriched in carbon and sulphur, which may represent organic particles embedded in clay.

The brittle, white-whitish grey siliceous sinter (deposit no. 5) consists of almost pure silica with traces of Al in the external parts, as revealed by EDS analyses, and has a porous internal structure (Fig. 5F). Particular quartz microcrystals of the rock are barely discernible in thin sections. However, its microcrystalline texture can be easily observed on the broken surfaces of the rock particles, using the SEM technique. The siliceous sinter consists of a mosaic of bladed, euhedral quartz microcrystals with sharp edges, forming a kind of net with regular empty spaces between them (Fig. 6A, B). Spherical chalcedony/silica agglomerates are visible in some places in thin sections (Fig. 6C). Some quartz crystals are partially etched or show irregular surfaces. The entire porosity and brittleness of the studied rock are related to specific microcrystal alignments with empty spaces between them. Investigation of a thick pebble of the siliceous sinter (Fig. 7), derived from the proximity of the main sinkhole, revealed similar microstructure and chemical composition. Its external parts consist, however, of a mosaic of bladed quartz microcrystals overgrown by spherical agglomerates of fine, granular chalcedony/silica (Fig. 6D).

The massive, light-grey to light brown, silty clays (deposit no. 6) in the central parts of the karst sinkholes consist of microscopic layers and lenses of silty deposits with minor sandy admixtures, which are embedded in finely layered zones of clay minerals, as revealed in the microscopic analysis of thin sections (Fig. 6E). The detrital rock components, including quartz grains and a subordinate admixture of feldspars, muscovite, foliated clay minerals and heavy minerals (rutile, ilmenite, galena), can be easily observed in the back scattered electron mode of SEM (Fig. 6F). Fine-grained clay parts are unstructured and contain small detrital grains. A small lens of opaque, coaly deposits was observed in one thin section, prepared from the silty clays. The massive, light-grey, silty clays (deposits no. 6) and especially the overlying dark bluish grey silty clays (deposit no. 7) yielded marine micro- and macrofossils. These deposits show strong lithological affinities to the marine dark clays of the Wierzchosławice Member of the Włocławek Formation, known in the Tomaszów Mazowiecki Syncline (Witkowski, 1969; Raczyńska, 1979; Marek, 1997).

The white yellow sands, being the youngest sinkhole deposits (deposit no. 8), consist of fine aggregates of clay minerals and quartz grains (Fig. 8A). Their yellow-coloured parts show admixtures of iron compounds. The well-sorted lithology and common pale colours of the sands closely resemble the Upper Hauterivian(?)–Middle Albian deposits of the Biała Góra Formation, particularly the thick Potok Sand Member, belonging to the middle part of formation (Poręba 1987; Poręba *et al*., 2018).

It is noteworthy that dark clays and sandy deposits constitute the dominant part of the Lower Cretaceous sedimentary complex of the internal part of the Tomaszów Mazowiecki Syncline, which presently occurs north-west of the Owadów-Brzezinki Quarry (e.g. Witkowski, 1969; Marcinowski and Rudowski, 1980; Poręba, 1987; Poręba *et al*., 2018). The depositional succession of the studied karst sinkholes, including the coaly clay and overlying

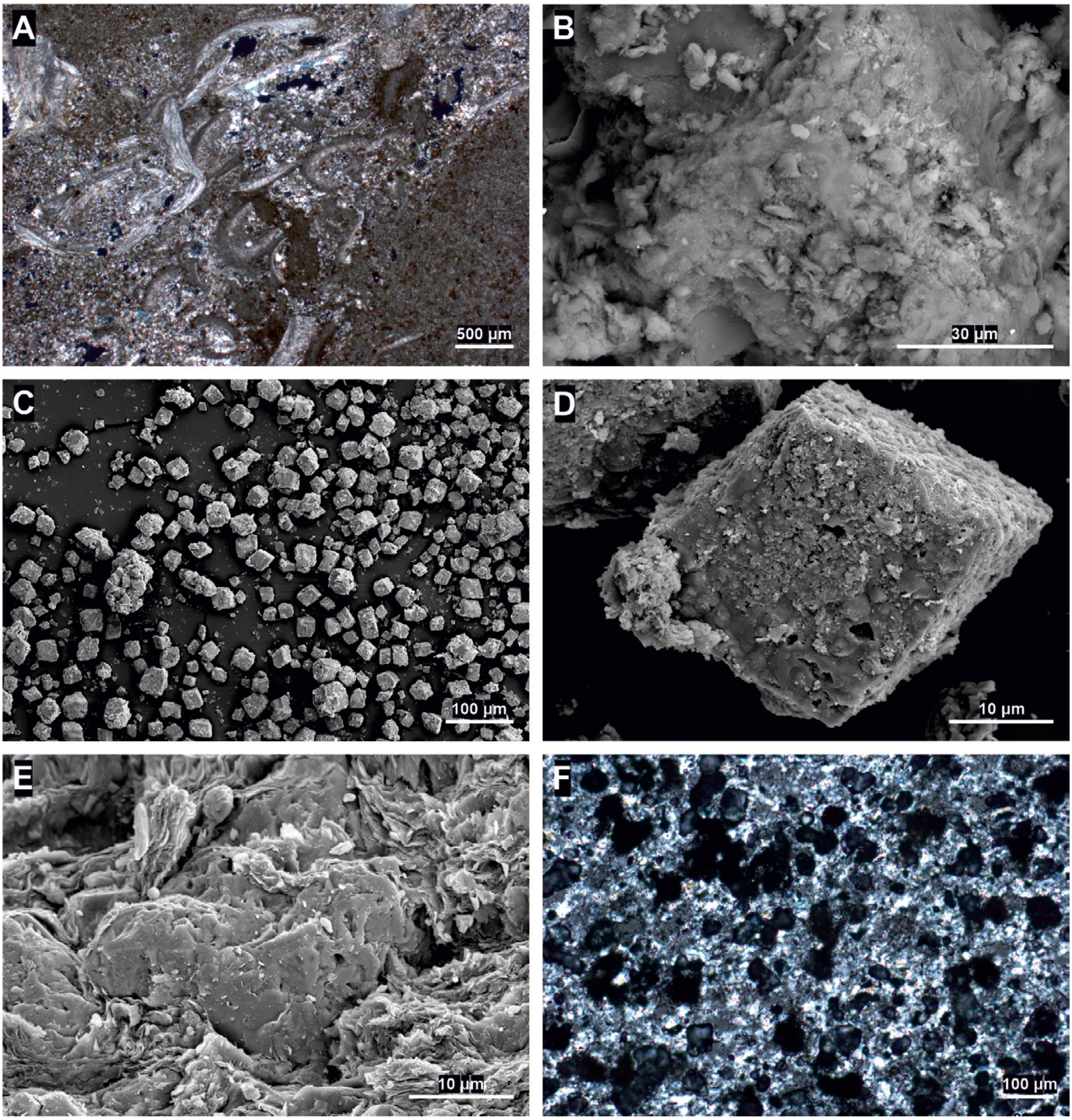

Fig. 5. Microstructure of studied rocks. **A**. Karstified uppermost Jurassic of predominant wackestone rock microfacies, containing detritus of oyster shells and serpulid tubes. Thin section, optical microscope image, polarized light. **B.** Dense clay mineral fabric of the reddish brown residuum. Single foliate clay mineral grains are visible on the surface of the dense clay matrix. SEM image, BSE mode. **C.** Rhombohedral calcite crystals from yellow-brown, loose calcareous deposits. SEM image, mixed BSE/SE mode. **D.** Secondary calcite and clay mineral overgrowths/coating on the surfaces of rhombohedral calcite crystals from the loose calcareous deposits. SEM image, mixed BSE/SE mode. **E.** Black coaly clay of compact internal structure. SEM image, mixed BSE/SE mode. **F.** The brittle white to whitish grey siliceous sinter, showing pure silica mineralogy and a porous internal structure. Thin section, optical microscope image, polarized light.

white yellow sand layers, also resembles the position of white, sand beds, overlying the Miocene coal layer in the karst sinkhole at Sulejów, and the lithological section of presumed karst deposits in the Modrzew borehole, both of which occur in the external parts of the Tomaszów Mazowiecki Syncline (cf. Barczyk, 1961; Głazek and Szynkiewicz, 1980a; Szałamacha, 1992).

Additional SEM studies of white micritic calcite deposit, discovered in a small karst cavity on the continuation of the tectonic zone, have shown its pure calcium carbonate mineralogy and micritic fabric (mean grain size of 1–2 µm; Fig. 8B). The calcite grains in some places form compact, medium-sized aggregates or porous higher-order aggregates (Fig. 8C).

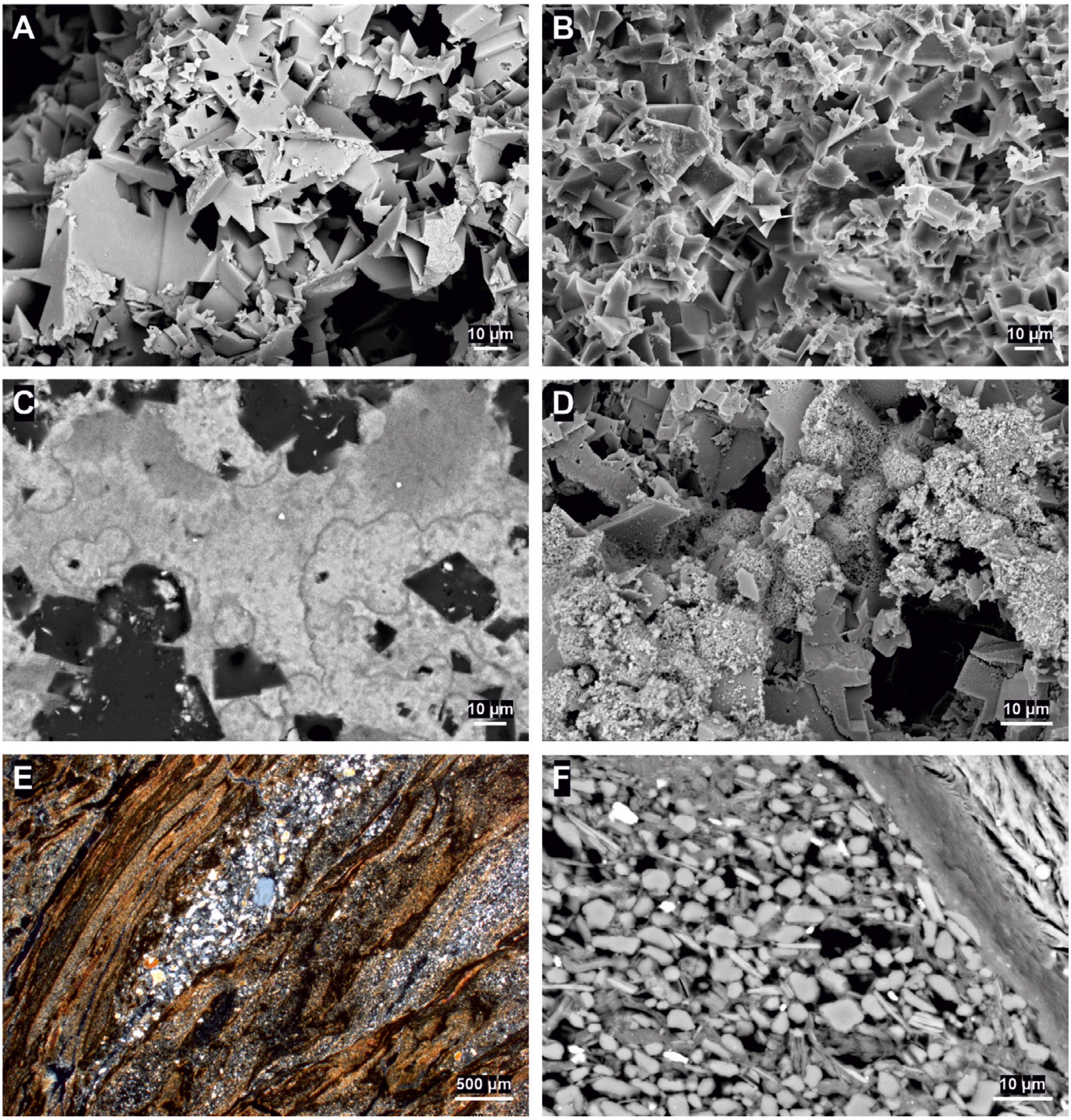

Fig. 6. Microstructure of studied rocks (continued). **A, B.** Euhedral quartz microcrystal fabric of the brittle white-whitish grey siliceous sinter. SEM images, BSE and SE mode, respectively. **C.** Spherical chalcedony/silica agglomerates in the brittle white whitish grey siliceous sinter. Thin section, SEM image, BSE mode. **D**. A mosaic of bladed quartz microcrystals overgrown by spherical aggregates of microgranular chalcedony/silica in a large pebble of the siliceous sinter from the proximity of the main karst sinkhole. SEM image, mixed BSE/SE mode. **E.** Layers and lenses of silty deposits with subordinate sandy admixtures embedded in fine-grained clay zones from light grey to light brown silty clays. Thin section, optical microscope image, polarized light. **F.** Detrital rock components of the light grey and light brown silty clays consisting of quartz grains with subordinate admixture of feldspars, muscovite, foliate clay minerals and heavy minerals. Thin section, SEM image, BSE mode.

Cretaceous faunal assemblage

A few fragmentarily preserved ammonites collected from the massive dark bluish grey silty clay (deposit no. 7) belong to the genus *Dichotomites* (Fig. 9). They show moderate evolute coiling and massive, widely-spaced ribs, possibly with bidichotomous subdivision, which suggests an affinity to *Dichotomites evolutus* Kemper. This species is indicative of the Crassus Zone of the Upper Valanginian (Kemper, 1978). The assemblage of ammonites of the genus *Dichotomites*, including *D. evolutus* and *D.* cf. *krausei*, diagnostic of the Crassus Zone, has been described from the

Fig. 7. A large pebble of the siliceous sinter from the proximity of the main karst sinkhole.

Dichotomites beds at Wąwał, on the north-eastern limb of the Tomaszów Mazowiecki Syncline (Kemper, 1978; Kutek and Marcinowski, 1996; see also Witkowski, 1969).

The other marine molluscs consist of a few highly coiled, but indeterminable gastropod shells and heterodont bivalves.

Miocene palynomorphs

The first coaly clay sample (deposit no. 4) yielded a rich assemblage of well-preserved palynomorphs (Tab. 1; Fig. 10). Within it, over 800 pollen grains, 18 plant spores, and 13 algal remains were identified. In the second sample, the same taxa were found, but the frequency of palynomorphs was distinctly lower. A total of 71 fossil-species of sporomorphs (including 5 species of plant spores, 19 species of gymnosperm pollen, and 47 species of angiosperm pollen) were identified. Corroded, unidentifiable pollen grains average 3%. Non-pollen palynomorphs are represented mainly by the freshwater algae *Pediastrum* and *Botryococcus braunii*; only four fungal spores were recorded.

Rare spores of ferns (fossil-genera *Laevigatosporites*, *Leiotriletes* and *Neogenisporis*) and lycopods (*Retitriletes*) make up about 2% of the spore-pollen spectrum. Gymnosperm pollen grains make up about 40% and among them, pollen of the Cupressaceae family, including *Taxodium/Glyptostrobus*, *Sequoia/Sequoiadendron/Metasequoia* and *Cupressus* (fossil-genera *Inaperturopollenites*, *Sequoiapollenites* and *Cupressacites*) and pollen of the Pinaceae

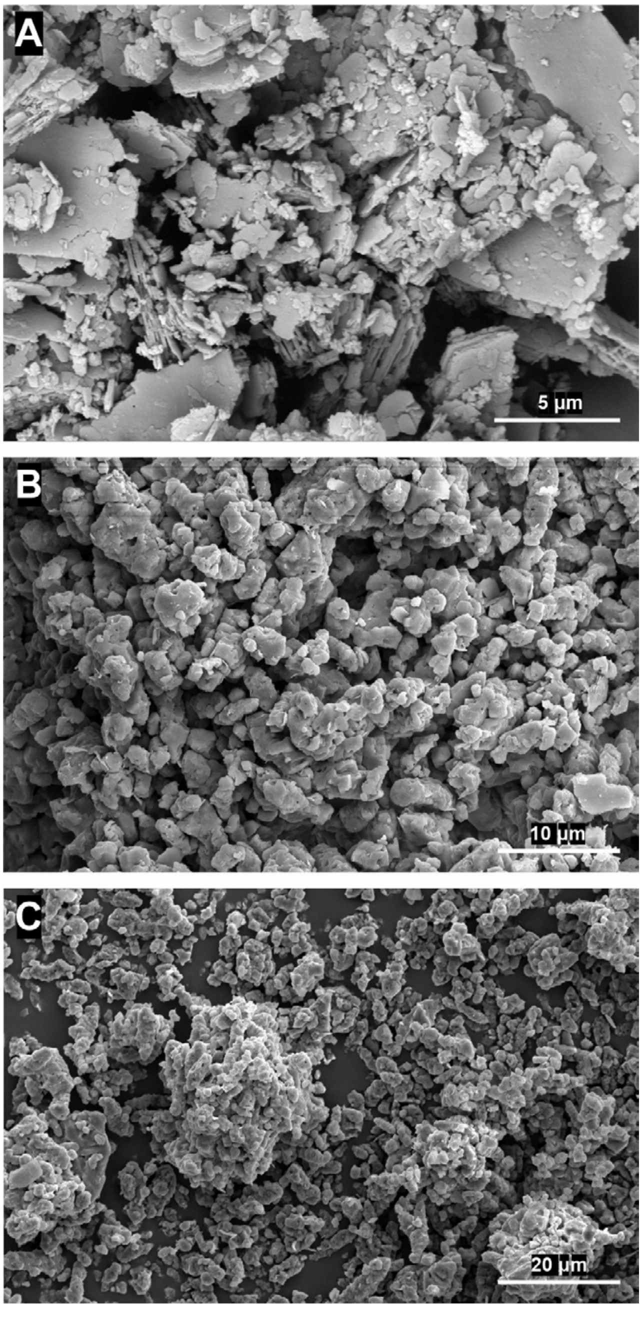

Fig. 8. Microstructure of studied rocks (continued). **A.** Fine clay mineral aggregates of the white yellow sands from the outermost part of the main sinkhole. SEM image, mixed BSE/SE mode. **B.** Micrite fabric of the white, micritic calcite deposit with single calcite grains, predominantly 1–2 µm in size, collected from a small karst cavity, located on the continuation of the zone of karstified Jurassic limestones. SEM image, mixed BSE/SE mode. **C.** The calcite grains of the white, micritic calcite deposit from the small karst cavity, forming compact medium size aggregates and porous higher-order aggregates. SEM image, mixed SE mode.

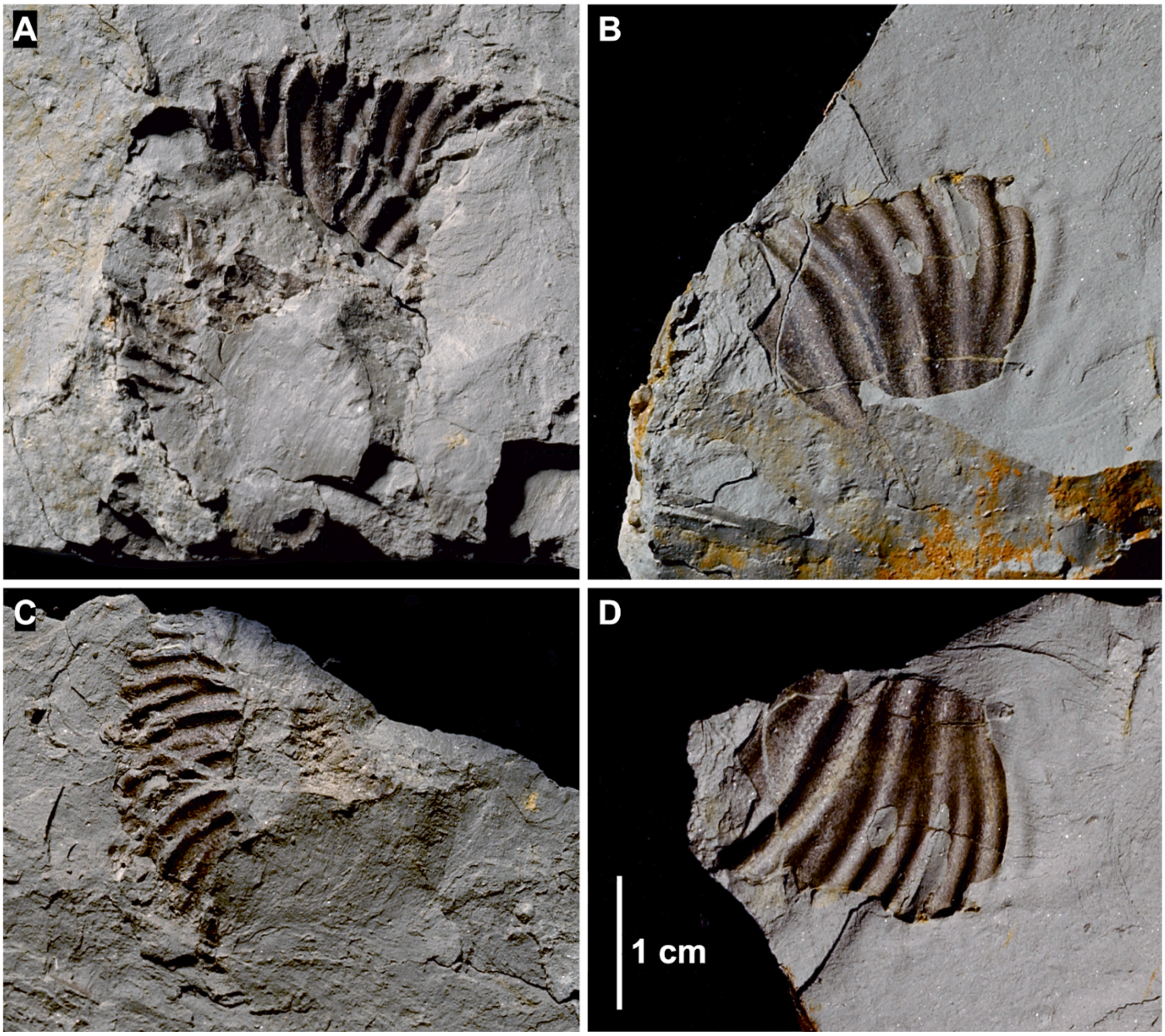

Fig. 9. Ammonite fauna collected. **A–D**. *Dichotomites* sp. ammonites distinctive for the Crassus Zone of the Upper Valanginian, collected from the grey clay in the middle part of the main sinkhole section. One scale bar refers to all photographs.

family (mainly *Pinuspollenites*) are the most common. Other conifers are represented by rare pollen grains of *Sciadopitys*. Angiosperms are more numerous (almost 60% of the spore-pollen spectrum) and taxonomically more diverse (Tab. 1). Among the pollen grains of angiosperms, the most common are *Quercus* (*Quercoidites henricii* and *Quercopollenites*), fossil-species *Tricolporopollenites pseudocingulum*, *Ulmus*, *Myrica*, *Fagus*, *Fraxinus*, *Alnus*, Tilioideae, *Acer*, *Zelkova*, *Carya*, *Betula*, and *Cercidiphyllum*. Pollen grains of Engelhardioideae (*Momipites*), fossil-species *Tricolporopollenites dolium*, *Nyssa* (*Nyssapollenites*), Mastixiaceae (*Cornaceaepollis satzveyensis*), Oleaceae, Vitaceae (mainly *Vitispollenites*), *Arceuthobium*, Cyrillaceae/Clethraceae, *Ilex*, *Salix*, *Celtis*, and *Liquidambar* are less common. In addition, single pollen grains of *Carpinus*, Ericaceae, *Hedera*, *Platanus*, *Pterocarya*, Sapotaceae, and *Symplocos*, were recorded. Herbs are represented only by single specimens of the pollen of Cyperaceae.

The composition of the studied sporomorph association shows an apparent predominance of "Arctotertiary" and "Palaeotropical/warm-temperate" palaeofloristic elements. "Palaeotropical" (including "tropical" and "subtropical") taxa are represented by *Leiotriletes* sp., *Neogenisporis* sp., *Cornaceaepollis satzveyensis*, *Cyrillaceaepollenites megaexactus*, *Ilexpollenites margaritatus*, *Momipites* sp., *Sapotaceoidaepollenites* sp., and *Symplocoipollenites miocaenicus* (Tab. 1).

Macroscopic plant remains

Articulated plant organs, especially disseminules, are good indicators of the local environment, but are rarely described from sinkhole infills (Mai, 2008). However, the coaly clay examined (deposit no. 4) did not yield macroscopic fossil plant remains. A small fossil wood fragment, found in the debris pile, suggests that the sinkhole infills

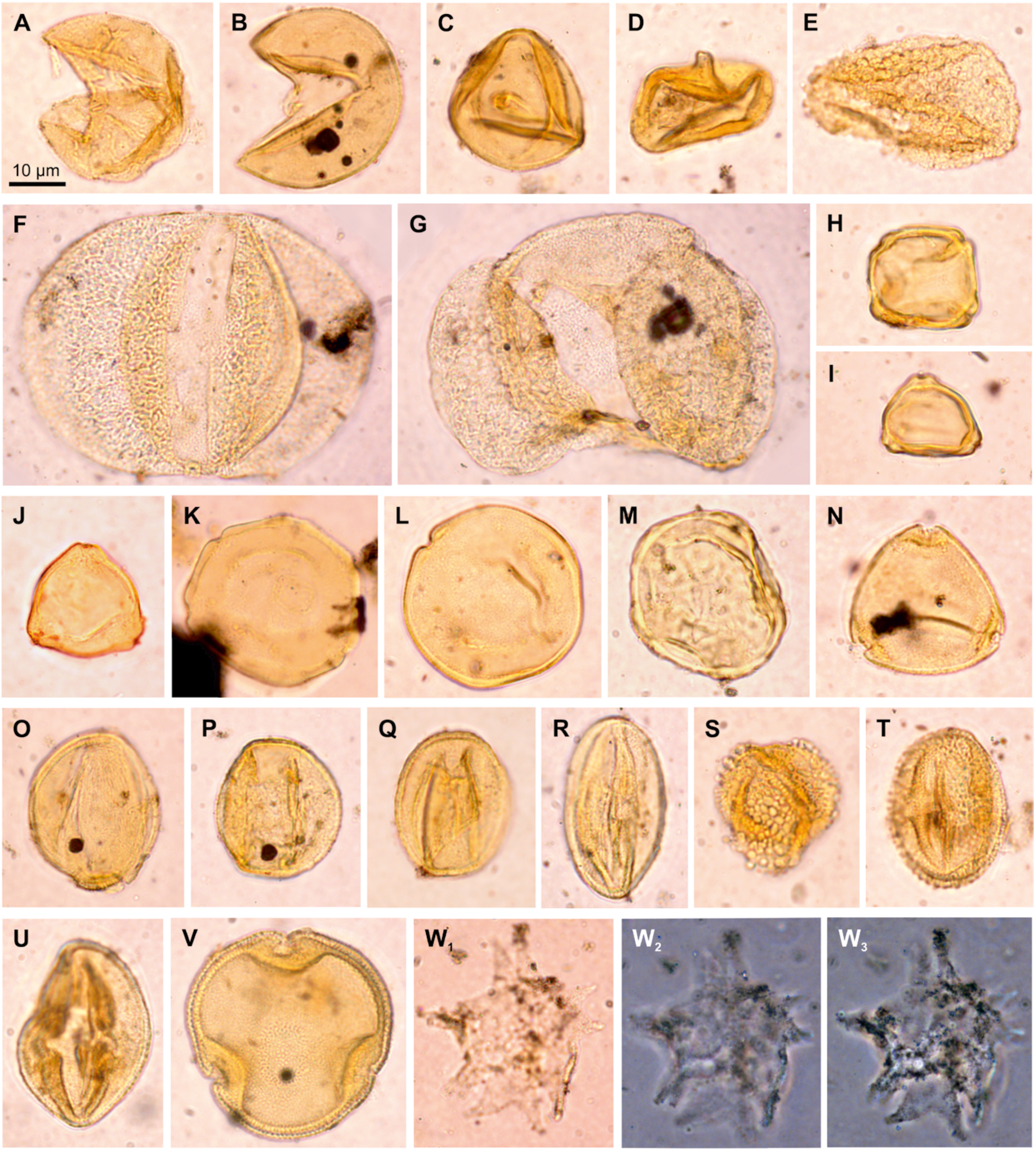

Fig. 10. Pollen grains and freshwater algae from Middle Miocene coal deposits; **A–G.** Pollen grains of gymnosperms; A – *Inaperturopollenites concedipites* (Wodehouse) Krutzsch; B – *Inaperturopollenites verrupapillatus* Trevisan; C – *Sequoiapollenites rotundus* Krutzsch; D – *Sequoiapollenites* sp.; E – *Sciadopityspollenites verticillatiformis* (Zauer) Krutzsch; F – *Cathayapollis erdtmanii* (Sivak) Ziembińska-Tworzydło; G – *Pinuspollenites labdacus* (Potonié) Raatz. **H–V.** Pollen grains of angiosperms; H – *Alnipollenites verus* (Potonié) Potonié; I – *Trivestibulopollenites betuloides* Pflug; J – *Myricipites* sp.; K – *Polyatriopollenites stellatus* (Potonié) Pflug; L – *Caryapollenites simplex* (Potonié) Raatz; M – *Ulmipollenites maculosus* Nagy; N – *Symplocoipollenites miocaenicus* Grabowska; O – *Aceripollenites striatus* (Pflug) Thiele-Pfeiffer; P, Q – *Quercopollenites rubroides* Kohlman-Adamska & Ziembińska-Tworzydło; R – *Quercoidites henricii* (Potonié) Potonié, Thomson & Thiergart; S – *Ilexpollenites margaritatus* (Potonié) Thiergart; T – *Araliaceoipollenites reticuloides* Thiele-Pfeiffer; U – *Tricolporopollenites pseudocingulum* (Potonié) Thomson & Pflug; V – *Intratriporopollenites parainstructus* Krutzsch. **W1–W3**. Alga, *Pediastrum* sp., with different contrast. One scale bar refers to all photographs.

Table 1

Spores, pollen grains, and non-pollen palynomorphs recorded in the palynological sample from Middle Miocene coal deposits of the sinkhole in the Owadów-Brzezinki Quarry. The taxonomy and botanical affinity of the specimens were determined according to Stuchlik *et al*. (2001, 2002, 2009, 2014). The following palaeofloristic elements have been distinguished: "Palaeotropical" (P), including "tropical" (P1) and "subtropical" (P2); "Arctotertiary" (A), including "warm-temperate" (A1) and "temperate" (A2); and cosmopolitan (P/A). X – palaeofloristic element unassigned.

Fossil taxon	Botanical affinity	Element	Number of specimens
Spores of plants			
Laevigatosporites sp.	Polypodiaceae, Davalliaceae, and other ferns	P/A	9
Leiotriletes sp.	Lygodiaceae and other ferns	P	2
Neogenisporis sp.	Gleicheniaceae, Cyatheaceae	P1	1
Retitriletes pseudoclavatus Krutzsch + *Retitriletes* sp.	Lycopodiaceae: *Lycopodium*	A	6
Pollen grains of gymnosperms			
Abiespollenites sp.	Pinaceae: *Abies*	A	3
Cathayapollis erdtmanii (Sivak) Ziembińska-Tworzydło + *Cathayapollis* sp.	Pinaceae: *Cathaya*	A1	2
Cupressacites bockwitzensis Krutzsch + *Cupressacites* sp. + *Inaperturopollenites concedipites* (Wodehouse) Krutzsch + *I. verrupapillatus* Trevisan	Cupressaceae: incl. *Cupressus*, *Taxodium*, *Glyptostrobus*	A1, P2/A1	126
Keteleeriapollenites dubius (Khlonova) Słodkowska	Pinaceae: *Keteleeria*	A1	2
Piceapollenites alatus Potonié + *Piceapollis praemarianus* Krutzsch + *Piceapollis* sp.	Pinaceae: *Picea*	A	17
Pinuspollenites labdacus (Potonié) Raatz + *Pinuspollenites* sp.	Pinaceae: *Pinus sylvestris* type	A	101
Sciadopityspollenites verticillatiformis (Zauer) Krutzsch + *Sciadopityspollenites* sp.	Sciadopityaceae: *Sciadopitys*	A1	3
Sequoiapollenites polyformosus Thiergart + *S. rotundus* Krutzsch + *S. rugulus* Krutzsch + *Sequoiapollenites* sp.	Cupressaceae: incl. *Sequoia*, *Sequoiadendron*, *Metasequoia*	A1	79
Pollen grains of angiosperms			
Aceripollenites striatus (Pflug) Thiele-Pfeiffer + *Aceripollenites* sp.	Sapindaceae: *Acer*	A1	18
Alnipollenites verus (Potonié) Potonié	Betulaceae: *Alnus*	P2/A	20
Araliaceoipollenites reticuloides Thiele-Pfeiffer	Araliaceae: *Hedera*	A1	1
Carpinipites carpinoides (Pflug) Nagy	Betulaceae: *Carpinus*	P2/A1	1
Caryapollenites simplex (Potonié) Raatz	Juglandaceae: *Carya*	A1	15
Celtipollenites sp.	Ulmaceae: *Celtis*	P/A1	2
Cercidiphyllites minimireticulatus (Trevisan) Ziembińska-Tworzydło	Cercidiphyllaceae: *Cercidiphyllum*	A1	11
Cornaceaepollis satzveyensis (Pflug) Ziembińska-Tworzydło	Mastixiaceae	P1	7
Cyperaceaepollis neogenicus Krutzsch	Cyperaceae	P/A	5
Cyrillaceaepollenites megaexactus (Potonié) Potonié	Cyrillaceae, Clethraceae	P	3
Ericipites sp.	Ericaceae	A	1
Faguspollenites sp.	Fagaceae: *Fagus*	A	21

Fossil taxon	Botanical affinity	Element	Number of specimens
Fraxinipollis oblatus Słodkowska + *Fraxinipollis* sp.	Oleaceae: *Fraxinus*	P/A	21
Ilexpollenites iliacus (Potonié) Thiergart	Aquifoliaceae: *Ilex*	P/A1	1
Ilexpollenites margaritatus (Potonié) Thiergart	Aquifoliaceae: *Ilex*	P2	2
Intratriporopollenites parainstructus Krutzsch + *Intratriporopollenites* sp.	Malvaceae: Tilioideae	P/A1	20
Momipites sp.	Juglandaceae: *Engelhardia*, *Alfaroa*, *Oreomunnea*	P2	9
Myricipites bituitus (Potonié) Nagy + *M. coryphaeus* (Potonié) Potonié + *Myricipites* sp.	Myricaceae: *Myrica*	P2/A1	39
Nyssapollenites contortus (Pflug & Thompson) Nagy + *Nyssapollenites* sp.	Nyssaceae: *Nyssa*	P2/A1	8
Oleoidearumpollenites sp.	Oleaceae	P2/A1	6
Parthenopollenites marcodurensis (Pflug & Thomson) Traverse	Vitaceae	P/A1	1
Periporopollenites sp.	Altingiaceae: *Liquidambar*	A1	2
Platanipollis ipelensis (Pacltová) Grabowska	Platanaceae: *Platanus*	P/A1	1
Polyatriopollenites stellatus (Potonié) Pflug	Juglandaceae: *Pterocarya*	A1	1
Quercoidites henricii (Potonié) Potonié, Thomson & Thiergart	Fagaceae: *Quercus*	P2/A1	31
Quercopollenites asper (Pflug & Thomson) Kohlman-Adamska & Ziembińska-Tworzydło + *Q. rubroides* Kohlman-Adamska & Ziembińska-Tworzydło + *Quercopollenites* sp.	Fagaceae: *Quercus*	A1	56
Salixipollenites sp.	Salicaceae: *Salix*	A	3
Sapotaceoidaepollenites sp.	Sapotaceae	P	1
Spinulaepollis arceuthobioides Krutzsch	Santalaceae: *Arceuthobium*	P2/A1	3
Symplocoipollenites miocaenicus Grabowska	Symplocaceae: *Symplocos*	P	1
Tricolporopollenites dolium (Potonié) Thomson & Pflug	Fagaceae?	unknown	9
Tricolporopollenites pseudocingulum (Potonié) Thomson & Pflug	Fagaceae?, Styracaceae?	P/A1	54
Trivestibulopollenites betuloides Pflug	Betulaceae: *Betula*	A	14
Ulmipollenites stillatus Nagy	Ulmaceae: *Ulmus*	A	1
Ulmipollenites maculosus Nagy + *Ulmipollenites* sp.	Ulmaceae: *Ulmus*	A2	56
Vitispollenites tener Thiele-Pfeiffer	Vitaceae: *Vitis*	P2/A1	4
Zelkovaepollenites potoniei Nagy + *Zelkovaepollenites* sp.	Ulmaceae: *Zelkova*	A1	16
corroded pollen grains	unknown	unknown	26
Total			**842**
Selected non-pollen palynomorphs			
Botryococcus braunii Kützing	Dictyosphaeriaceae: *Botryococcus braunii* Kützing	X	2
Pediastrum sp.	Chlorophyta: *Pediastrum* sp.	X	11
Spores of fungi	Fungi	X	4
Total			**859**

contain some plant macrofossils. This fossil wood was identified tentatively as Coniferae (?*Juniperoxylon* sp.). It may represent the autochthonous flora of the study area. The level of taxonomic identification of the wood fragment cannot provide important stratigraphical or palaeobotanical data. It should be noted only that the fossil wood reveals growth rings, indicating climate seasonality.

DISCUSSION

Late Valanginian biostratigraphy and palaeobiogeography

The ammonite assemblages, collected from the grey clays, point to their assignment to the Upper Valanginian Crassus Zone. The ammonite fauna shows strict similarity to the *Dichotomites* beds of the upper part of the Wąwał section of the north-eastern limb of the Tomaszów Mazowiecki Syncline (see Kutek *et al*., 1989). All the ammonites are of Boreal affinity.

The lack of the older *Dichotomites* fauna in the dark clays of the sinkhole infill suggests the presence of an original stratigraphic discontinuity, similar to that observed at the base of the *Dichotomites* beds at Wąwał (Kutek and Marcinowski, 1996). It may be related to the early Late Valanginian marine transgression, described from the Wąwał section, which brought a north-western European assemblage of *Dichotomites* ammonites, replacing an older one of the Tethyan origin, typical of the verrucosum horizon of the Verrucosum Zone of the earliest Late Valanginian. The older Tethyan assemblage possibly also was absent in the Owadów-Brzezinki area. This may point to tectonic control of Valanginian sedimentation in the Tomaszów Mazowiecki Syncline, which resulted in the periodical uplift of its lateral parts and the presence of stratigraphic gaps (cf. Witkowski, 1969; Poręba, 1987).

It is noteworthy that the results of micropalaeontological studies of the dark clays in the same sinkhole showed the presence of a diversified dinocyst assemblage in the light grey to dark grey clays, including *Muderongia extensa*, *Pseudoceratium pelliferum*, *Spiniferites ramusus, Dichadogonyaulax bensonii* and *Kleithriasphaeridium fasciatum*, taxa diagnostic of the Valanginian as well as a relatively poorly differentiated assemblage of benthic foraminifera, represented by nine genera (*Haplophragmoides, Verneuilinoides, Bulbobaculites, Ammobaculites, Kutsevella, Ammodiscus, Glomospirella, Trochammina, Patellovalvulina*), which are typical of the Valanginian–Hauterivian interval (Chrząstowska *et al*., 2025). The dinoflagellate cyst assemblage contains both Boreal and Tethyan forms, which points to water exchange between both oceanic domains.

Miocene vegetation and palaeoenvironment

The taxonomic composition of the palynological assemblage from the coaly deposits (Fig. 10) and the good state of preservation of most sporomorphs and algae suggest that their occurrence is *in situ*. The presence of freshwater planktonic algae (*Pediastrum* and *Botryococcus*) indicates the existence of an open freshwater pool. *Pediastrum* is found, nowadays, in a variety of habitats, including lakes, ponds, oxbow lakes, rivers, peat bogs and lagoons (Komárek and Jankovská, 2001). *Botryococcus* is one of the most common algae in freshwater bogs, temporary water pools, ponds, and lakes (Batten and Grenfell, 1996). Both algae previously were found in the Miocene sediments, filling karst palaeosinkholes in the Opole region, SW Poland (Worobiec, 2011, 2014a, b).

The water body (pond?) was surrounded by wetland and mesophytic vegetation. Cyperaceae probably grew on the shores of this water body. Swamp forests, composed of *Taxodium* and/or *Glyptostrobus*, *Nyssa*, and presumably *Alnus*, *Acer* and others, might have overgrown the neighbouring area with a higher groundwater level or the marginal zone of the water body. Nowadays, swamp forests with *Taxodium ascendens*, *Nyssa sylvatica* var. *biflora* and *Acer rubrum* occur in the South Atlantic coastal plain of the USA (Christensen, 2000). In wetlands, probably periodically flooded, grew *Ulmus*, *Myrica*, *Fraxinus*, *Acer*, *Zelkova*, *Carya*, *Betula*, *Vitis*, Cyrillaceae and/or Clethraceae, *Ilex*, *Salix*, *Liquidambar*, *Pterocarya*, and others. *Sequoia* might also have occurred in these wetlands (Kovar-Eder *et al.*, 2001; Worobiec *et al*., 2021). In the vicinity, there were mesophytic forests, composed of *Quercus* (also thermophilous trees, producing pollen of the fossil-species *Quercoidites henricii*), *Fagus*, *Cercidiphyllum*, Engelhardioideae, Mastixiaceae, Tilioideae as well as *Carpinus*, Sapotaceae, *Symplocos*, and conifers. The parasitic *Arceuthobium* probably grew on *Pinus* trees.

The climate during sedimentation of the coaly clay was warm temperate and humid. This is indicated by a significant proportion of taxa, representing "warm temperate" and "Palaeotropical/warm-temperate" palaeofloristical elements of the palynoflora. "Palaeotropical" plants with higher climatic requirements, such as Mastixiaceae, Sapotaceae, Symplocaceae and thermophilous ferns, constitute a small proportion of the plant communities.

Age of palynoflora

The palynoflora studied is similar to well-known Miocene spore-pollen assemblages. Numerous Miocene palynofloras were described from the Polish Lowlands, with a particularly large number of data coming from lignite deposits (Stuchlik *et al*., 2001, 2002, 2009, 2014). Miocene spore-pollen spectra are rich in *Quercoidites henricii*, *Tricolporopollenites pseudocingulum*, *Sequoiapollenites* and other taxa that are present in the material studied (Piwocki and Ziembińska-Tworzydło, 1997; Kasiński and Słodkowska, 2016). In particular, the *Taxodium/Glyptostrobus–Nyssa* swamp forests were widespread in Europe during the Oligocene–Pliocene period, being typical of peat-forming vegetation (Mai, 1981). In the Polish Lowlands, these forests had the most favourable conditions in the Early and Middle Miocene (Piwocki and Ziembińska-Tworzydło, 1997).

The absence of small tricolporate pollen grains of Fagaceae (i.e. *Fususpollenites fusus*, *Quercoidites microhenricii* and others) and palms indicates that the examined sediments are not older than Middle Miocene. On the other hand, the composition of the palynoflora, almost devoid of the pollen of herbaceous plants, rather excludes a Late Miocene or lesser age of the examined sediments. This allows definition, with a high probability, of the age of the examined deposits as Middle Miocene.

The climate of the Middle Miocene favoured the development of peat-forming vegetation (Mosbrugger *et al*., 2005; Bruch *et al*., 2007; Ivanov and Worobiec, 2017). In the Polish Lowlands, there are common Middle Miocene lignites of the 2nd Lusatian and 1st Mid-Polish seam groups (Piwocki and Ziembińska-Tworzydło, 1997; Kasiński and Słodkowska, 2016), comprising a thick coal series of the nearby Kleszczów Graben, which are exploited in the Bełchatów open-pit mine (Ciuk and Piwocki, 1980; Stuchlik *et al*., 1990; Widera, 2024a, b). The discovered palynoflora is similar to spore-pollen spectra from the seam groups, described from various localities in Poland (Kasiński *et al*., 2010; Worobiec *et al*., 2022), including the Middle Miocene palynofloras of the Kleszczów Graben (Stuchlik *et al*., 1990) and that found in a palaeosinkhole at Tarnów Opolski, in the Opole region of southern Poland (Worobiec and Szulc, 2010a; Worobiec, 2011).

Karstification processes

The erosion of the uppermost Jurassic–lowermost Cretaceous deposits during the Early Cretaceous Neo-Cimmerian tectonic event resulted in the formation of a peneplain with outcropping Upper Jurassic limestones (Głazek and Szynkiewicz, 1980b). Minor limestone karstification at that time might have been manifested in karst breccias and a reddish brown residue, filling fissures and forming a thin limestone cover (Głazek and Szynkiewicz, 1980b; Głazek, 1989; Głazek *et al*., 1992). The Neo-Cimmerian tectonic event is reflected in the hiatus, developed at the Jurassic–Cretaceous boundary in the Tomaszów Mazowiecki Syncline, and by the presence of a basal conglomerate with pebbles of lowermost Cretaceous rocks, which began the deposition of a new package of Lower Cretaceous deposits (Witkowski, 1969). Redeposited fragments of the Lower Cretaceous deposits, devoid of distinct karst features, are recognized in rubble breccia only in the northernmost part of the Owadów-Brzezinki Quarry. However, these deposits may have been displaced during the Paleogene–Neogene.

Karstification of the Jurassic limestones and the formation of karst sinkholes in the Owadów-Brzezinki Quarry should be related to a multi-phase process, which occurred after the post-Laramide inversion of the former Mid-Polish Trough and uplift of the area of the south Polish Uplands (Głazek and Szynkiewicz, 1980b; Głazek *et al*., 1992). The karstification culminated during the Oligocene–Early Miocene in the formation of abundant caves and sinkholes in south-central Poland, some of which are documented on the north-eastern and southern margins of the Tomaszów Mazowiecki Syncline or their immediate vicinity (Lewinski, 1922; Różycki, 1946; Barczyk, 1961; Głazek and Szynkiewicz 1980a; Głazek, 1989; Szałamacha, 1992).

The development of the studied sinkholes in the Owadów-Brzezinki Quarry was probably affected by tectonic phenomena. The latest Oligocene–Early Miocene tectonic processes resulted in the extensional deformation of the Mesozoic cover of south-central Poland, formation or the re-activation of faults with an E–W trend, and tectonic grabens, including the nearby Kleszczów Graben (e.g., Ciuk, 1980; Jarosiński *et al*., 2009). A fault, developed in the central part of the Owadów-Brzezinki Quarry, likely belongs to the tectonic zone, which stretches in a WNW–ESE direction in the southern part of the Laramide Tomaszów Mazowiecki Syncline, obliquely to its axis (see a map of Szałamacha, 1989, 1992, where a narrow valley, filled with clays, is seen in a cross-section of this area). Similar WNW–ESE arrangements of karst forms, corresponding to fault zones, are documented from the vicinity of Paradyż, located a few kilometres south of the Owadów-Brzezinki Quarry (cf. Różycki, 1946).

The tectonic zone, recognized at Owadów-Brzezinki, possibly developed during the Oligocene–Early Miocene. It may have become a place of infiltration of meteoric waters, which resulted in strong karstification of the Upper Jurassic limestones of the Kcynia Formation, overlain and underlain by impermeable deposits of the Lower Cretaceous Włocławek Fm. (Upper Valanginian) and the Upper Jurassic Pałuki Fm. (Late Kimmeridgian to Early Tithonian), respectively (Fig. 11).

Formation of the sinkhole deposits

The reddish brown clay residuum that covers the karstified Upper Jurassic limestones resembles *terra rossa* palaeosols, which are widely developed on the Upper Jurassic limestones of the south Polish Uplands. They are interpreted as being a result of intensive chemical weathering under conditions of a seasonally wet subtropical climate during the Late Oligocene–Miocene (Liszkowski, 1996).

The yellow-brown, loose calcite silt, which occurs in a pocket between the karstified Jurassic limestones and the reddish brown clay, is probably an autochthonous karst deposit. It is composed of rhombohedral calcite grains, which show secondary dissolution and coatings/overgrowth by carbonate and clay minerals or form grain aggregates of various sizes. This deposit may have been formed as a result of the disaggregation of crystalline calcite speleothems in karst aquifers and the secondary sorting of suspended sediments of the silty fraction by the water flow, induced by periodic heavy rains (cf. Toran *et al*., 2006; Herman *et al*., 2007). In such a case, it may be treated as a genetic analogue of the disintegrated "sandy" limestones, which are a rare product of limestone dissolution by percolating fluids, similar to karst corrasion (cf. Dżułyński and Kubicz, 1971; Dżułyński and Rudnicki, 1986).

It is less likely that the calcite silt was precipitated from an oversaturated calcium carbonate solution in a karst environment, as such precipitates, which include large variety of calcite aggregates and crystallographic forms (cf. Durakiewicz *et al*., 1995), are usually formed, when calcium carbonate-saturated water freezes in ice caves (cf. Žak *et al*., 2004, 2018). In addition, the suspended calcite grains of subtropical or warm-temperate karst systems mostly consist of broken detrital grains of irregular morphologies and rarely contain rhombohedral calcite crystals, precipitated from a water solution (cf. Herman *et al*., 2007; Nannoni

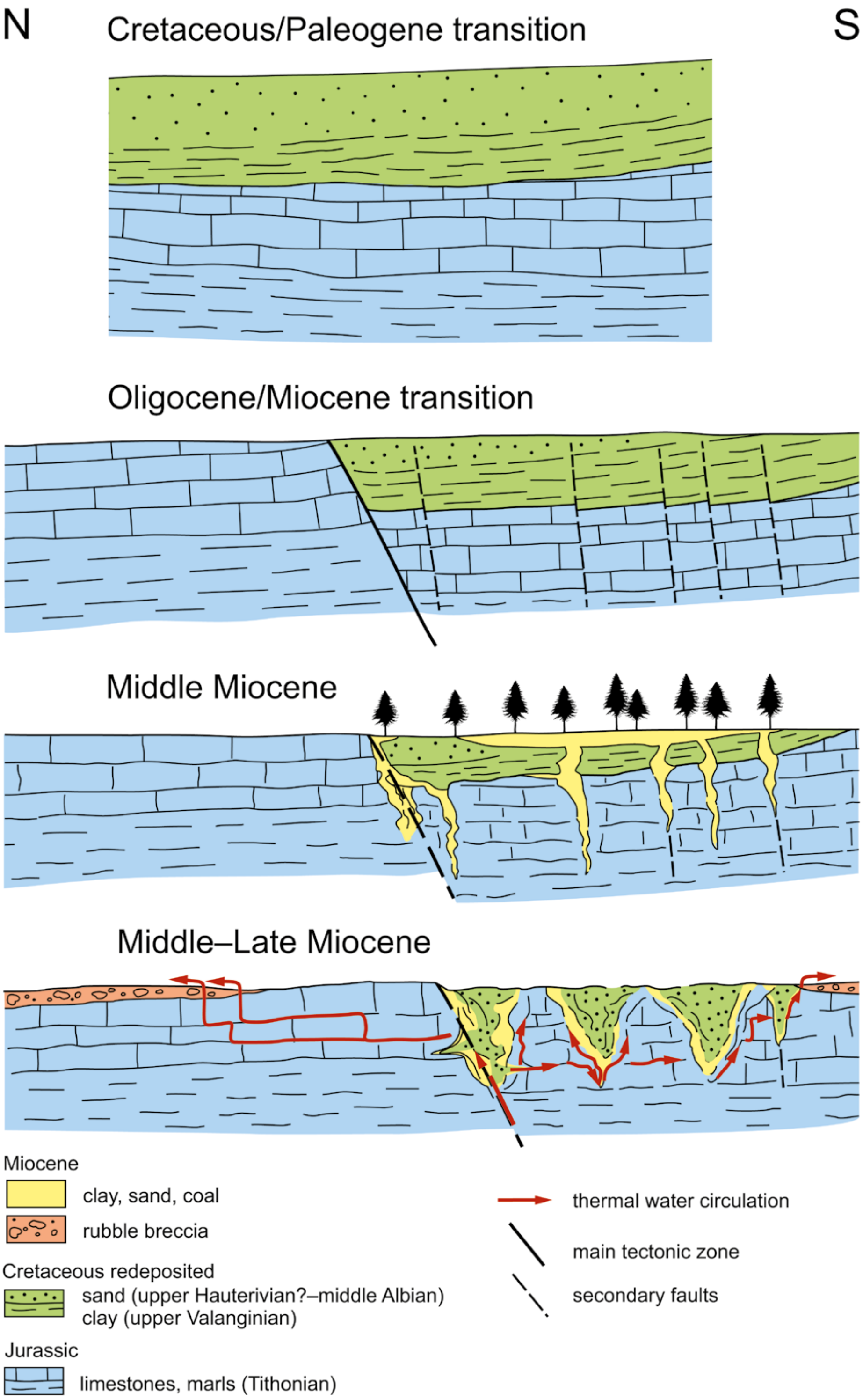

Fig. 11. The development scheme of the karst sinkholes and their infilling deposits in the Owadów-Brzezinki Quarry.

et al., 2021). The diagenetic processes are probably responsible for the yellow-brown colouration of calcite silt, related to the admixture of iron compounds and clay mineral coatings. Such colouration and the presence of clay minerals is often observed in karstic deposits, e.g., in the "moulding sands", widely distributed in karstic forms in the south Polish Uplands (Gradziński, 1977; Bosák *et al*., 1978). It is noteworthy that the predominant yellow-brown colour of the "moulding sands" of presumed Paleogene or Early Oligocene–Early Miocene age was related to weathering processes that occurred under a seasonally wet and hot subtropical climate (Gradziński, 1977; Bosák *et al*., 1978; Liszkowski, 1996).

The Middle Miocene coaly clay yielded diversified sporomorphs and fresh-water algae, which suggests the exis tence of a body of freshwater in the close neighbourhood of the outcrop. It is probable that the water body developed over the karstified tectonic zone on the substrate of Early Cretaceous (Valanginian) silty clays (Fig. 11). The warm temperate and humid climate of the Middle Miocene favoured peat-forming vegetation and the accumulation of brown coal (lignite), forming the large 2nd Lusatian coal seam in the nearby Kleszczów Graben, which is dated as early Middle Miocene (Ciuk and Piwocki, 1980; Stuchlik *et al.*, 1990; Widera, 2024a, b). It also may have been a period of pronounced development of karst processes and enlargement of the sinkhole, which corresponded to the final period of tectonic subsidence of the Kleszczów Graben (Widera, 2024a, b).

The siliceous sinter band cannot be older than the Middle Miocene, as it rests on coal deposits of that age. Laterally, it may have overlain parts of the light grey to light brown silty clays, although its original position in strongly deformed zones of the sinkholes is difficult to reconstruct. The siliceous sinter may have formed as a result of rapid, abiotic silica precipitation from a hot spring, circulating throughout the karst sinkhole. The precipitation from a solution is substantiated by the presence of well-formed, euhedral, often blade-like microcrystals and spherical agglomerates with a porous internal structure, which makes them very susceptible to recrystallization.

The chemical purity and mineralogical characteristics of the siliceous sinter are completely different from those of the silcrete rocks, found in the near-surface environment (cf. Nash and Ullyott, 2007; Thiry and Milnes, 2017). The silcretes are composed mostly of opal, cryptocrystalline silica or microcrystalline quartz grains, which form as a result of silica encrustation or cementation of host rocks and occur in their association. They show massive, nodular, blocky to granular structure and often preserve relicts of the host rocks, detrital grains or impurities. In addition, the pre-Lower Oligocene to Upper Miocene silcrete rocks of the Polish Uplands include pedogenic siliceous crusts as well as siliceous crusts and concretions precipitated from groundwaters, all of which are contaminated with iron hydroxides/oxides and clay minerals (cf. Liszkowski, 1996) They differ markedly, in both form and colour, from the siliceous sinter, found in the Owadów-Brzezinki karst sinkhole.

The precipitation of siliceous sinter may be related to the circulation of waters of elevated temperatures along the deep-rooted tectonic zone with a WNW–ESE trend, developed in the Owadów-Brzezinki Quarry. The precipitation of silica is commonly observed around geysers and hot springs (cf. Campbell *et al.*, 2015; Hamilton *et al.*, 2019; Jones, 2021). The formation of authigenic quartz grains with blade-like microcrystals is, however, unusual and needs conditions of stable precipitation.

To date, no siliceous sinter has been documented from the Tomaszów Mazowiecki Syncline or its vicinity. The thermal karst phenomena, including round forms of caves, specific solution cavities, limestone silicification and siliceous flowstones, were, however, reported from the Wieluń Upland and the northern part of the Kraków-Częstochowa Upland as well as the Lower Silesia area of Poland, being tentatively dated as Palaeogene or Middle–Late Miocene as well as Late Miocene, respectively (Galewski and Głazek, 1973; Głazek *et al.*, 1977; Głazek and Szynkiewicz, 1980b; Gradziński *et al.*, 2011). The epigenetic silicification of Upper Jurassic limestones in the form of late diagenetic crusts on chert nodules, irregular nests within host rocks and void fillings, associated with sulphides, is additionally reported from the Kraków-Częstochowa Upland (Matyszkiewicz, 1987; Matyszkiewicz *et al.*, 2015; Kochman *et al.*, 2020). It is manifested by microcrystalline quartz, silica or rarely euhedral quartz forms. The main process of low-temperature hydrothermal silica precipitation in the Kraków-Częstochowa Upland occurred during the Cenozoic tectonic activity postdating the process of pedogenic silcrete formation (Matyszkiewicz *et al.*, 2015; Kochman *et al.*, 2020).

It should also be noted that a large complex of silicified Middle Callovian – Middle Oxfordian(?) carbonate rocks, referred to as "chalcedonies" in the regional English-language literature, is present on the SE margin of the Inowłódz anticline at its western boundary with the Tomaszów Mazowiecki Syncline (Różycki, 1947; Gągol, 1979; Gągol *et al.*, 1986; Deręgowski, 1988; Matyja, 1991; Feldman-Olszewska and Iwańczuk, 2014; Matyja and Wierzbowski, 2014). The closest "chalcedonies" occurrences are documented at about 8 km northeast of the Owadów-Brzezinki Quarry, near Kraśnica village (Szałamacha, 1989). The origin of "chalcedonies|" is unclear. Although they often are considered as an effect of the late diagenetic silicification of Jurassic limestones under a hot and seasonally dry, possibly Miocene, climate (cf. Różycki, 1947; Matyja, 1991) the mineralogical data do not indicate their epigenetic origin (Gągol, 1979; Gągol *et al.*, 1986; Deręgowski, 1988). Dissolution of the skeletons of siliceous sponges, which are common in the Upper Callovian–Middle Oxfordian, usually is thought to have been a primary silica source. However, the specific geostructural position of "chalcedonies" above the deep-rooted Grójec (also called Tomaszów Mazowiecki-Grójec) Fault Zone, passing through the SE part of the Tomaszów Mazowiecki Syncline and the Inowłódz Anticline (cf. Dadlez, 1998; Matyja and Wierzbowski, 2014), may suggest their link to deep fluid circulation, which resulted in secondary re-distribution of silica. To that scenario also points the presence of deeply-buried, partially silicified, Oxfordian–Callovian limestone-dolomitic rocks or Callovian marly-dolomitic rocks, which were found in the southern limb (Mniszków IG 1 borehole) and the north-eastern limb (Tomaszów GT 1 borehole) of the Tomaszów Mazowiecki Syncline (Wagner *et al.*, 2020; Złonkiewicz, 2021) respectively. This may substantiate widespread circulation of hydrothermal fluids in the study area.

A white, micritic calcite deposit, discovered in a small karst cavity, located on the continuation of the zone of karstified Jurassic limestones, may have been formed at a similar time as the calcite silt or the siliceous sinter. It is probably composed of endogenetic micrite that formed through the destruction of older carbonate deposits in a karst environment, but calcification by microbes or its direct precipitation in lateral parts of the karstified zone cannot be excluded (cf. Jones and Kahle, 1995). It is worth noting that some modern calcareous tufas are composed of calcite micrograins of similar fabric (Gruszczyński and Mastella, 1986; Pedley, 1990).

Deposition of the bedded, light grey to light brown silty clays from the central part of the sinkhole should be related to the periodic delivery of large amounts of argillaceous Lower Cretaceous material (Fig. 11). The clays are slightly contaminated with coal and sand from the ancient deposit cover. They probably represent the marine Upper Valanginian dark clays of the Wierzchosławice Member of the Włocławek Formation. The massive white yellow quartz sands from the outermost parts of karst forms probably fell into the sinkholes during their final collapse. They likely represent Upper Hauterivian(?) – Middle Albian sands of the Biała Góra Formation. A similar infill of karst forms was encountered in the fault zones of the nearby Miocene Kleszczów Graben (e.g. Biernat, 1971; Ciuk, 1980). Multi-generation, fine-grained uppermost Oligocene–Miocene infillings of karst forms, containing loose blocks of Santonian marls in reversed stratigraphic position, are also documented from the southernmost part of the Kraków-Częstochowa Upland (Gradziński, 1962; Felisiak, 1992). They may be linked to the similar, multi-phase process of karstification.

The final infilling of the studied karst sinkholes, consisting of older Cretaceous deposits, may have been formed as a result of the rapid progress of karstification, followed by general subsidence of the study area, which is documented in southern Poland by the mid-late Middle Miocene marine transgression (Głazek and Szynkiewicz, 1980b, 1987; Głazek, 1989; Głazek *et al.*, 1992; Górka, 2019). It is remarkable that no younger deposits are found in the sinkholes of the Owadów-Brzezinki Quarry. Such deposits, if originally present in the Tomaszów Mazowiecki Syncline, might have been removed by subsequent erosion, for example, related to the Late Miocene regression and Pliocene uplift, which resulted in the exhumation of older karst structures in the south Polish Uplands, and the inversion of major tectonic grabens (cf. Głazek, 1989; Głazek *et al.*, 1992; Jarosiński *et al.*, 2009).

Although the Lower Cretaceous deposits are known only from the sinkholes at Owadów-Brzezinki, they provide important information on the poorly studied Early Cretaceous succession of the south-eastern part of the Tomaszów Mazowiecki Syncline (cf. Witkowski, 1969). Silty clays, yielding *Dichotomites* ammonites, indicate the presence of the Upper Valanginian *Dichotomites* beds of the Wierzchosławice Member. Younger, white yellow quartz sands of the shallow-marine Biała Góra Formation mark the beginning of a new sedimentary cycle. The partial record of the Lower Cretaceous deposits in the sinkholes points to their incomplete development in the south-eastern part of the Tomaszów Mazowiecki Syncline, which is in agreement with available geological data (cf. Witkowski, 1969; Poręba, 1987). The incomplete Lower Cretaceous succession of the south-eastern part of the Tomaszów Mazowiecki Syncline and the thickness reduction of the Upper Jurassic in this area are interpreted as a result of synsedimentary tectonic activity of the Grójec fault zone (Matyja and Wierzbowski, 2014).

CONCLUSIONS

Detailed, palaeontological, stratigraphical and sedimentological studies of sinkhole deposits of the Owadów-Brzezinki Quarry, which accumulated on the substrate of Upper Jurassic limestones on the south-eastern part of the Tomaszów Mazowiecki syncline, have revealed a multiphase lithological succession. It consists of:

Karstified lowermost Upper Tithonian limestones of “serpulite” type, covered by a reddish brown clay residuum of *terra rossa* type.

A pocket, filled with a yellow-brown loose calcareous deposits, consisting of calcite crystals of silt size. Although these deposits are interpreted as having been derived from disaggregation of speleothems, they underwent partial dissolution and impregnation by iron hydroxides/oxides and clay minerals, possibly in a seasonally wet climate.

A black coaly clay layer, which yielded an abundant Middle Miocene palynoflora, freshwater algae and fossil wood debris, indicative of the humid warm temperate climate. This points to peat formation in bogs or temporary water bodies.

White-whitish grey crystalline siliceous sinter, which probably precipitated rapidly from the waters of a hot spring. The hot springs may have been associated with a local tectonic zone, developed in the central part of the Owadów-Brzezinki Quarry. A white, micritic calcite deposit, observed in the continuation of the tectonic zone, probably formed through the destruction of limestones in a karst environment.

Massive infillings of the sinkhole that consist of light to dark grey partly silty clays and white yellow quartz sands of Early Cretaceous age. The former yielded marine micro- and macrofossils, including Upper Valanginian ammonites; the latter are assigned to sandy deposits of the Upper Hauterivian(?)–Middle Albian age. Both infillings are regarded as an effect of the final collapse of the cave and the sudden displacement of the overlying Early Cretaceous deposits into the open karst sinkhole. This probably occurred as a result of the acceleration of karstification of the Tithonian limestones during the Middle–Late Miocene.

The results of the current study are important for deciphering of the poorly-known karstification processes, which developed in the north-western margin of the Holy Cross Mts. (central Poland), the reconstruction of the Middle Miocene vegetation and climate, the documentation of the presumed circulation of thermal water through the karst aquifers, the dating and description of palaeontological assemblages of the Upper Valanginian deposits, as well as the reconstruction of the original sedimentary cover of the south-eastern part of the Tomaszów Mazowiecki Syncline, which had been removed by erosion.

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REFERENCES

Baranowska-Zarzycka, Z., 1980. Sarmatian mosses, fruits and seeds from Nowa Królewska Wieś near Opole. *Prace Muzeum Ziemi*, 33: 31–37. [In Polish, with English summary.]

Barczyk, W., 1961. Le Jurassique de Sulejów. *Acta Geologica Polonica*, 11: 3–102. [In Polish, with French abridged version.]

Batten, D. J. & Grenfell, H. R., 1996. *Botryococcus*. In: Jansonius, J. & McGregor, D. C. (eds), *Palynology: Principles and Applications, Volume 1.* American Association of Stratigraphic Palynologists Foundation, Dallas, pp. 205–214.

Biernat, S., 1971. Geological structure and shape of the Cainozoic substrate in the Bełchatów area. *Biuletyn Instytutu Geologicznego*, 254: 37–48. [In Polish, with English summary.]

Błażejowski, B., Gieszcz, P. & Tyborowski, D., 2016. New finds of well-preserved Tithonian (Late Jurassic) fossils from Owadów-Brzezinki quarry, central Poland: a review and perspectives. *Volumina Jurassica*, 14: 123–132.

Błażejowski, B., Pszczółkowski, A., Grabowski, J., Wierzbowski, H., Deconinck, J.-F., Olempska, E., Teodorski, A. & Nawrocki, J., 2023. Integrated stratigraphy and clay mineralogy of the Owadów-Brzezinki section (Lower–Upper Tithonian transition, Central Poland): implications for correlations between the Boreal and the Tethyan domains and palaeoclimate. *Journal of the Geological Society, London*, 180: jgs2022-073.

Bosák, P., Głazek, J., Gradziński, R. & Wójcik, Z., 1978. Origin and age of the Rudice type of pocket deposits. *Kras i Speleologia*, 2: 11–16. [In Polish, with English summary.]

Bruch, A. A., Uhl, D. & Mosbrugger, V., 2007. Miocene climate in Europe – patterns and evolution. A first synthesis of NECLIME. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 253: 1–7.

Campbell, K. A., Guido, D. M., Gautret, P., Foucher, F., Ramboz, C. & Westall, F., 2015. Geyserite in hot-spring siliceous sinter: Window on Earth's hottest terrestrial (paleo)environment and its extreme life. *Earth-Science Reviews*, 148: 44–64.

Christensen, N. L., 2000. Vegetation of the Southeastern Coastal Plain. In: Barbour, M. G. & Billings, W. D. (eds), *North American Terrestrial Vegetation*. Cambridge University Press, Cambridge, New York, pp. 397–448.

Chrząstowska, J., Dubicka, Z., Barski, M., Worobiec, E., Błażejowski, B. & Todes, J., 2025. A micropaleontological record of the Early Cretaceous marine-terrestrial interface in central Europe. *Lethaia*, 58: 1–17. https://doi.org/10.18261/let.58.3.6

Ciuk, E., 1980. Tektonika rowu Kleszczowa i jej wpływ na warunki powstania złoża węgla brunatnego. In: Barczyk, W. (ed.), *Przewodnik 52 Zjazdu Polskiego Towarzystwa Geologicznego, Bełchatów, 11–14.09.1980*. Wydawnictwa Geologiczne, Warszawa, pp. 38–56. [In Polish.]

Ciuk, E. & Piwocki, M., 1980. Geologia trzeciorzędu w rowie Kleszczowa i jego otoczeniu. In: Barczyk, W. (ed.), *Przewodnik 52 Zjazdu Polskiego Towarzystwa Geologicznego, Bełchatów, 11–14.09.1980*, Wydawnictwa Geologiczne, Warszawa, pp. 56–70. [In Polish.]

Dadlez, R., 1998. *Tectonic Map of the Zechstein-Mesozoic complex in the Polish Lowlands, 1:500 000*. Państwowy Instytut Geologiczny, Warszawa.

Deręgowski, Z., 1988. Geochemiczne, mineralogiczne i petrograficzne badania oksfordzkich chalcedonitów z okolic Inowłodza. *Geological Quarterly*, 32: 231–232. [In Polish.]

Durakiewicz, T., Hałas, S., Migaszewski, Z. M. & Urban, J., 1995. Origin of the "calcite groats" in the Chelosiowa Cave near Kielce (Holy Cross Mts.) inferred from petrographic and isotopic investigations. *Geological Quarterly*, 39: 75–94.

Dziadzio, P. S., Gaździcka, E., Ploch, I. & Smoleń, J., 2004. Biostratigraphy and sequence stratigraphy of the Lower Cretaceous in Central and SE Poland. *Annales Societatis Geologorum Poloniae*, 74: 125–196.

Dżułyński, S. & Kubicz, A., 1971. Recrystallized and disaggregated limestones in the Triassic of Silesia. *Rocznik Polskiego Towarzystwa Geologicznego*, 41: 519–530.

Dżułyński, S. & Rudnicki, J., 1986. Karst-corrasion features of disaggregated limestones controlled by diffusion bands. *Annales Societatis Geologorum Poloniae*, 56: 109–115.

Feldman-Olszewska, A. & Iwańczuk, J., 2014. Chalcedonite quarry in Inowłódz. In: Feldman-Olszewska, A. & Wierzbowski, A. (eds), *Jurassica XI, Jurajskie Utwory Synkliny Tomaszowskiej. Przewodnik wycieczek terenowych, abstrakty i artykuły. Spała 9-11.10.2014*. Państwowy Instytut Geologiczny-Państwowy Instytut Badawczy, Warszawa, pp. 27–32. [In Polish.]

Felisiak, I., 1992. Oligocene – Early Miocene karst deposits and their importance for recognition of the development of tectonics and relief in the Carpathian Foreland, Kraków region, southern Poland. *Annales Societatis Geologorum Poloniae*, 62: 173–207. [In Polish, with English summary.]

Gągol, J., 1979. Chalcedonity górnojurajskie w antyklinie inowłodzkiej (północne obrzeżenie Gór Świętokrzyskich). *Geological Quarterly*, 23: 509–510. [In Polish.]

Gągol, J., Deręgowski, Z. & Kuleta, M., 1986. *Chalcedonity górnojurajskie w północnym obrzeżeniu Gór Świętokrzyskich*. Poz. Planu 76.00.02/8.2.29/. Unpublished report, Central Geological Archive of the Polish Geological Institute National Research Institute, inventory no. 7191/2024, Warszawa, 146 pp. [In Polish.]

Galewski, K. & Głazek, J., 1973. An unusual occurrence of the Dytiscidae (Coleoptera) in the siliceous flowstone of the Upper Miocene cave at Przeworno, Lower Silesia, Poland. *Acta Geologica Polonica*, 23: 445–461.

Głazek, J., 1989. Paleokarst of Poland. In: Bosák, P., Ford, D., Głazek, J. & Horáček, I. (eds), *Paleokarst: A Systematic and Regional Review*. Elsevier, Academia, Amsterdam, Prague, pp. 77–105.

Głazek, J., Galewski, K. & Wysoczański-Minkowicz, T., 1977. New data on fossil karst at Przeworno. *Kras i Speleologia*, 1: 81–88. [In Polish, with English summary.]

Głazek, J., Pacholewski, A. & Rozkowski, A., 1992. Karst aquifer of the Cracow-Wielun Upland, Poland. In: Back, W., Herman, J. S. & Paloc, H. (eds), *Hydrogeology of Selected Karst Regions, International Contributions to Hydrogeology, Volume 13.* International Association of Hydrogeologists, Heinz Heise GmbH & Co KG, Hannover, pp. 289–306.

Głazek, J. & Szynkiewicz, A., 1980a. Formy krasowe wypełnione węglonośnymi osadami miocenu w Sulejowie. In: Barczyk, W. (ed.), *Przewodnik 52 Zjazdu Polskiego Towarzystwa*

Geologicznego, Bełchatów, 11–14.09.1980. Wydawnictwa Geologiczne, Warszawa, pp. 231–233. [In Polish.]

Głazek, J. & Szynkiewicz, A., 1980b. Kras między Pilicą a Wartą i jego praktyczne znaczenie. In: Barczyk, W. (ed.), *Przewodnik 52 Zjazdu Polskiego Towarzystwa Geologicznego, Bełchatów, 11–14.09.1980*. Wydawnictwa Geologiczne, Warszawa, pp. 84–99. [In Polish.]

Głazek, J. & Szynkiewicz, A., 1987. Stratigraphy of the Late Tertiary and Early Quaternary karst deposits and their paleogeographic importance. In: Jahn, A. & Dyjor, S. (eds), *Problemy młodszego neogenu i eoplejstocenu w Polsce*. Ossolineum, Wrocław, pp. 113–130. [In Polish, with English summary.]

Górka, M., 2019. An overview of the Badenian and Sarmatian succession in the northern margin of the Carpathian Foredeep Basin. In: Studencka, B. (ed.), *8th International Workshop on Neogene of Central and South-Eastern Europe, 27th–31st May 2019, Chęciny, Poland*. University of Warsaw, Faculty of Geology, Warsaw, pp. 90–97.

Gradziński, M., Hercman, H., Kicińska, D., Pura, D. & Urban, J., 2011. Ascending speleogenesis of Sokola Hill: a step towards a speleogenetic model of the Polish Jura. *Acta Geologica Polonica*, 61: 341–365.

Gradziński, R., 1962. Origin and development of subterranean karst in the southern part of the Cracow Upland. *Rocznik Polskiego Towarzystwa Geologicznego*, 32: 429–492. [In Polish, with English summary.]

Gradziński, R., 1977. Sedimentation of „moulding sands" on karstified limestone surface in the middle part of Kraków-Wieluń Upland. *Kras i Speleologia*, 1: 59–69. [In Polish, with English summary.]

Gruszczyński, M. & Mastella, L., 1986. Calcareous tufas in the area of the Mszana Dolna tectonic window. *Annales Societatis Geologorum Poloniae,* 56: 117–131. [In Polish, with English summary.]

Hamilton, A. R., Campbell, K. A. & Guido, D. M., 2019. *Atlas of Siliceous Hot Spring Deposits (Sinter) and Other Silicified Surface Manifestations in Epithermal Environments*. GNS Science, Lower Hutt (NZ), 56 pp.

Herman, E. K., Tancredi, J. H., Toran, L. & White, W. B., 2007. Mineralogy of suspended sediment in three karst springs. *Hydrogeology Journal*, 15: 255–266.

Ivanov, D. & Worobiec, E., 2017. Middle Miocene (Badenian) vegetation and climate dynamics in Bulgaria and Poland based on pollen data. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 467: 83–94.

Jarosiński, M., Poprawa, P. & Ziegler, P. A., 2009. Cenozoic dynamic evolution of the Polish Platform. *Geological Quarterly*, 53: 3–26.

Jones, B., 2021. Siliceous sinters in thermal spring systems: Review of their mineralogy, diagenesis, and fabrics. *Sedimentary Geology*, 413: 105820.

Jones, B. & Kahle, C. F., 1995. Origin of endogenetic micrite in karst terrains: a case study from Cayman Islands. *Journal of Sedimentary Research*, A65: 283–293.

Kasiński, J. R., Piwocki, M., Swadowska, E. & Ziembińska-Tworzydło, M., 2010. Lignite of the Polish Lowlands Miocene: characteristics on a base of selected profiles. *Biuletyn Państwowego Instytutu Geologicznego*, 439: 99–153. [In Polish, with English summary.]

Kasiński, J. R. & Słodkowska, B., 2016. Factors controlling Cenozoic anthracogenesis in the Polish Lowlands. *Geological Quarterly*, 60: 959–974.

Kemper, E., 1978. Einige neue biostratigraphisch bedeutsame Arten der Ammoniten-Gattung *Dichotomites* (NW-Deutschland, Obervalangin). *Geologisches Jahrbuch*, A45: 183–251.

Kin, A., Gruszczyński, M., Martill, D., Marshall, J. & Błażejowski, B., 2013. The paleoenvironment and taphonomy of a Late Jurassic (Late Tithonian) Lagerstätte from central Poland. *Lethaia*, 46: 71–81.

Kochman, A., Kozłowski, A. & Matyszkiewicz, J., 2020. Epigenetic siliceous rocks from the southern part of the Kraków-Częstochowa Upland (Southern Poland) and their relation to Upper Jurassic early diagenetic chert concretions. *Sedimentary Geology*, 401: 105636.

Komárek, J. & Jankovská, V., 2001. Review of the green algal genus *Pediastrum*; implication for pollen-analytical research. *Bibliotheca Phycologica*, 108: 1–127.

Kovar-Eder, J., Kvaček, Z. & Meller, B., 2001. Comparing Early to Middle Miocene floras and probable vegetation types of Oberdorf N Voitsberg (Austria), Bohemia (Czech Republic), and Wackersdorf (Germany). *Review of Palaeobotany and Palynology*, 114: 83–125.

Kutek, J. & Marcinowski, R., 1996. Faunal changes in the Valanginian of Poland: tectonic or eustatic control? *Mitteilungen aus dem Geologisch-Paläontologischen Institut der Universität Hamburg*, 77: 83–88.

Kutek, J., Marcinowski, R. & Wiedmann, J., 1989. The Wąwał section, Central Poland – an important link between Boreal and Tethyan Valanginian. In: Wiedmann, J. (ed.), *Cretaceous of the Western Tethys. Proceedings 3rd International Symposium, Tübingen, 1987.* E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, pp. 717–754.

Lencewicz, S., 1913. Contribution à la connaissance des dépôts quaternaires et de l'hydrographie des environs de Tomaszów Rawski. *Pamiętnik Fizjograficzny*, 21: 11–25. [In Polish, with French summary.]

Lewiński, J., 1922, Monographie géologique et paléontologique du Bononien de la Pologne. *Mémoires de la Société Géologique de France*, 56: 1–108.

Liszkowski, J., 1996. The succession of climates and energetics of erosion processes during the Tertiary based on studies of palaeoalterite formations from the south Polish Uplands. *Acta Geographica Lodziensis*, 71: 165–179. [In Polish, with English summary.]

Mai, D. H., 1981. Entwicklung und klimatische Differenzierung der Laubwaldflora Mitteleuropas im Tertiär. *Flora*, 171: 525–582.

Mai, D. H., 2008. Paläokarpologische Untersuchungen im Ober-Oligozän von Oberleichtersbach bei Bad Brückenau (Unterfranken). *Courier Forschungsinstitut Senckenberg*, 260: 31–77.

Małecka, D., 1997. Yield changes of the Niebieskie Źródła springs their reasons and effects. *Acta Universitatis Lodziensis, Folia Geographica Physica*, 2: 95–114. [In Polish, with English summary.]

Marcinowski, R. & Rudowski, S., 1980. Biała Góra II – Kopalnia piasków szklarskich – alb środkowy i górny. In: Barczyk, W. (ed.), *Przewodnik 52 Zjazdu Polskiego Towarzystwa Geologicznego, Bełchatów, 11–14.09.1980*. Wydawnictwa Geologiczne, Warszawa, pp. 221–226. [In Polish.]

Marek, S., 1997. Litostratygrafia i litofacje – Formalne i nieformalne jednostki litostratygraficzne. Kreda dolna (berias–alb górny). In: Marek, S. & Pajchlowa, M. (eds), *The Epicontinental Permian and Mesozoic in Poland. Prace Państwowego Instytutu Geologicznego*, 153: 351–360. [In Polish.]

Matyja, B. A., 1991. O wieku chalcedonitów z Inowłodza. *Przegląd Geologiczny*, 39: 508–510. [In Polish, with English summary.]

Matyja, B. A. & Wierzbowski, A., 2014. Upper Jurassic of the Tomaszów Mazowiecki syncline, NW margin of the Holy Cross Mts. In: Feldman-Olszewska A. & Wierzbowski A. (eds), *Jurassica XI, Jurajskie Utwory Synkliny Tomaszowskiej. Przewodnik wycieczek terenowych, abstrakty i artykuły. Spała 9–11.10.2014*, Państwowy Instytut Geologiczny – Państwowy Instytut Badawczy, Warszawa, pp. 9–20. [In Polish, with English summary.]

Matyja, B. A. & Wierzbowski, A., 2016. Ammonites and ammonite stratigraphy of the uppermost Jurassic (Tithonian) of the Owadów-Brzezinki quarry (central Poland). *Volumina Jurassica,* 14: 65–122.

Matyszkiewicz, J., 1987. Epigenetic silicification of the Upper Oxfordian limestones in the vicinity of Kraków. *Annales Societatis Geologorum Poloniae*, 57: 59–87. [In Polish, with English summary.]

Matyszkiewicz, J., Kochman, A., Rzepa, G., Gołębiowska, B., Krajewski, M., Gaidzik, K. & Żaba, J., 2015. Epigenetic silicification of the Upper Oxfordian limestones in the Sokole Hills (Kraków-Częstochowa Upland): relationship to facies development and tectonics. *Acta Geologica Polonica*, 65: 181–203.

Moore, P. D., Webb, J. A. & Collinson, M. E., 1991. *Pollen Analysis.* Blackwell, Oxford, 216 pp.

Morales, C., Kujau, A., Heimhofer, U., Mutterlose, J., Spangenberg, J. E., Adatte, T., Ploch, I. & Föllmi, K. B., 2015. Palaeoclimate and palaeoenvironmental changes through the onset of the Valanginian carbon-isotope excursion: Evidence from the Polish Basin. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 426: 183–198.

Mosbrugger, V., Utescher, T. & Dilcher, D. L., 2005. Cenozoic continental climatic evolution of Central Europe. *Proceedings of the National Academy of Sciences*, 102: 14964–14969.

Nannoni, A., Piccini, L., Costagliola, P., Batistoni, N., Gabellini, P., Cioni, R., Pratesi, G., Bucci, S., 2021. Innovative approaches for the sedimentological characterization of fine natural and anthropogenic sediments in karst systems: the case of the Apuan Alps (Central Italy). *Frontiers in Earth Science*, 9: 672962.

Nash, D. J. & Ullyott, J. S., 2007. Silcrete. In: Nash, D. J. & McLaren, S. J. (eds), *Geochemical Sediments and Landscapes*. Blackwell Publishing, Oxford, pp. 95–143.

Ochoa, D., Zavada, M. S., Liu, Y. & Farlow, J. O., 2016. Floristic implications of two contemporaneous inland upper Neogene sites in the eastern US: Pipe Creek Sinkhole, Indiana, and the Gray Fossil Site, Tennessee (USA). *Palaeobiodiversity and Palaeoenvironment*, 96: 239–254.

Pedley, H. M., 1990. Classification and environmental models of cool freshwater tufas. *Sedimentary Geology*, 68: 143–154.

Piwocki, M. & Ziembińska-Tworzydło, M., 1997. Neogene of the Polish Lowlands – litostratigraphy and pollen-spore zones. *Geological Quarterly*, 41: 21–40.

Poręba, E., 1987. Litostratygrafia kredy dolnej w synklinie tomaszowskiej. In: Mróz, J., Hammer, J. & Poręba, E. (eds), *Synklina tomaszowska i jej znaczenie surowcowe, Sympozjum Biała Góra, XI 1987.* Przedsiębiorstwo Geologiczne, Tomaszowskie Kopalnie Surowców Mineralnych „Biała Góra", Kraków, pp. 14–26. [In Polish.]

Poręba, E., Nieć, M. & Dróżdż, S., 2018. Quartz (glass) sands deposits in Tomaszów Syncline and their resources reporting problems. *Górnictwo Odkrywkowe*, 3/2018: 84–99. [In Polish, with English summary.]

Raczyńska, A., 1979. The stratigraphy and lithofacies development of the younger Lower Cretaceous in the Polish Lowlands. *Prace Instytutu Geologicznego*, 89: 1–78. [In Polish, with English summary.]

Raczyńska, A. & Cieśliński, S., 1960. The Lower Cretaceous terrestrial strata NW from Święty Krzyż Mts. *Przegląd Geologiczny*, 8: 521–524. [In Polish, with English summary.]

Rogala, W. & Sadowska, A., 2003. Wiek mułów węglistych wypełniających leje krasowe Garbu Chełma (zachodnia część Wyżyny Śląskiej) w świetle analizy palinologicznej. In: Gradziński, M. & Szelerewicz, M. (eds), *Materiały 37. Sympozjum Speleologicznego, Wojcieszów, 24–26.10.2003.* Sekcja Speleologiczna Polskiego Towarzystwa Przyrodników im. Kopernika, Kraków, pp. 54–55. [In Polish.]

Różycki, S. Z., 1946. Contributions à la connaissance des phénomenés karstiques en Pologne. I. Kras opoczyński. *Przegląd Geograficzny*, 20: 107–127. [In Polish, with French summary.]

Różycki, S. Z., 1947. Jurajskie skały krzemionkowe nad Pilicą i ich znaczenie praktyczne. *Biuletyn Instytutu Geologicznego*, 29: 3–15. [In Polish.]

Sobczyk, A., Worobiec, E., Olkowicz, M. & Szczygieł, J., 2024. Mid-Miocene onset of the NE Bohemian Massif (SW Poland, Europe) growth, landscape evolution, and paleoenvironmental changes unraveled using paleokarst sediment palynology. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 640: 112107.

Stuchlik, L., Szynkiewicz, A., Łańcucka-Środoniowa, M. & Zastawniak, E., 1990. Results of the hitherto palaeobotanical investigations of the Tertiary brown coal bed "Bełchatów", Central Poland. *Acta Palaeobotanica*, 30: 259–305. [In Polish, with English summary.]

Stuchlik, L., Ziembińska-Tworzydło, M., Kohlman-Adamska, A., Grabowska, I., Słodkowska, B., Ważyńska, H. & Sadowska, A., 2009. *Atlas of Pollen and Spores of the Polish Neogene. Volume 3 – Angiosperms (1)*. W. Szafer Institute of Botany, Polish Academy of Sciences, Kraków, 233 pp.

Stuchlik, L., Ziembińska-Tworzydło, M., Kohlman-Adamska, A., Grabowska, I., Słodkowska, B., Worobiec, E. & Durska, E., 2014. *Atlas of Pollen and Spores of the Polish Neogene. Volume 4 – Angiosperms (2)*. W. Szafer Institute of Botany, Polish Academy of Sciences, Kraków, 466 pp.

Stuchlik, L., Ziembińska-Tworzydło, M., Kohlman-Adamska, A., Grabowska, I., Ważyńska, H. & Sadowska, A., 2002. *Atlas of Pollen and Spores of the Polish Neogene. Volume 2 – Gymnosperms*. W. Szafer Institute of Botany, Polish Academy of Sciences, Kraków, 237 pp.

Stuchlik, L., Ziembińska-Tworzydło, M., Kohlman-Adamska, A., Grabowska, I., Ważyńska, H., Słodkowska, B. & Sadowska, A., 2001. *Atlas of Pollen and Spores of the Polish*

Neogene. Volume 1 – Spores. W. Szafer Institute of Botany, Polish Academy of Sciences, Kraków, 158 pp.

Szałamacha, G., 1989. *Szczegółowa mapa geologiczna Polski 1:50 000, arkusz 703, Sławno*. Państwowy Instytut Geologiczny, Warszawa. [In Polish.]

Szałamacha, G., 1992. *Objaśnienia do szczegółowej mapy geologicznej Polski 1:50 000, arkusz Sławno (703)*. Państwowy Instytut Geologiczny, Warszawa, 39 pp. [In Polish.]

Szczepanek, K., 1971. The Staszów karst in the light of palaeobotanical studies (South Poland). *Acta Palaeobotanica*, 12: 63–140. [In Polish, with English summary.]

Szulc, J. & Worobiec, E., 2012. Neogene karst sinkhole and its deposits from Górażdże Quarry, Upper Silesia – archive for palaeoenvironmental reconstructions. *Annales Societatis Geologorum Poloniae*, 82: 371–385.

Szulc, J., Worobiec, E. & Ziaja, J., 2015. Multiphase paleokarst of the Silesian-Cracow Upland. In: Kicińska, D., Stefaniak K. & Szynkiewicz, A. (eds), *Materiały 49. Sympozjum Speleologicznego, Załęcze Wielkie 22–25.10.2015 r.* Sekcja Speleologiczna Polskiego Towarzystwa Przyrodników im. Kopernika, Kraków, p. 118. [In Polish.]

Thiry, M. & Milnes, A., 2017. Silcretes: Insights into the occurrences and formation of materials for stone tool making. *Journal of Archaeological Science: Reports*, 15: 500–513.

Toran, L., Tancredi, J. H., Herman, E. K. & White, W. B., 2006. Conductivity and sediment variation during storms as evidence of pathways of karst spring. In: Harmon, R. S. & Wicks, C. (eds), *Perspectives on Karst Geomorphology, Hydrology, and Geochemistry – A Tribute Volume to Derek C. Ford and William B. White. Geological Society of America, Special Papers*, 404: 169–176.

Wagner, J., Kapuściński, J., Bielecki, P., Noga, B., Gajowczyk, P., Mazur, M., Wichowska, A. & Łaski, P., 2020. *Dokumentacja otworowa otworu badawczo-eksploatacyjnego Tomaszów Mazowiecki GT 1, miejsc. Tomaszów Mazowiecki, gm. Tomaszów Mazowiecki, pow. tomaszowski, woj. łódzkie*. Unpublished report, Central Geological Archive of the Polish Geological Institute National Research Institute, inventory no. 6813/2020, Warszawa, 1177 pp. [In Polish.]

Widera, M., 2024a. Cenozoic tectonic evolution of the main lignite-rich grabens in Poland. Part 1. Tectonic stages. *Acta Geologica Polonica*, 74: e2.

Widera, M., 2024b. Cenozoic tectonic evolution of the main lignite-rich grabens in Poland. Part 2. Tectonics versus autocompaction and compaction. *Acta Geologica Polonica*, 74: e7.

Wierzbowski, H., Błażejowski, B. & Tyborowski, D., 2019. Oxygen isotope profiles of uppermost Jurassic vertebrate teeth and oyster shells: a record of paleoenvironmental changes and animal habitats. *Palaios*, 34: 585–599.

Wierzbowski, H., Dubicka, Z., Rychliński, T., Durska, E., Olempska, E. & Błażejowski, B., 2016. Depositional environment of the Owadów-Brzezinki conservation Lagerstätte (uppermost Jurassic, central Poland): evidence from microfacies analysis, microfossils and geochemical proxies. *Neues Jahrbuch für Geologie und Paläontologie-Abhandlungen*, 282: 81–108.

Witkowski, A., 1969. Geological structure of the Tomaszów Syncline. *Prace Instytutu Geologicznego*, 53: 1–123. [In Polish, with English summary.]

Worobiec, E., 2011. Middle Miocene aquatic and wetland vegetation of the paleosinkhole at Tarnów Opolski, SW Poland. *Journal of Paleolimnology,* 45: 311–322.

Worobiec, E., 2014a. Fossil zygospores of Zygnemataceae and other microremains of freshwater algae from two Miocene palaeosinkholes in the Opole region, SW Poland. *Acta Palaeobotanica*, 54: 113–157.

Worobiec, E., 2014b. The palynology of late Miocene sinkhole deposits from Upper Silesia, Poland. *Review of Palaeobotany and Palynology*, 211: 66–77.

Worobiec, E. & Szulc, J., 2010a. A Middle Miocene palynoflora from sinkhole deposits from Upper Silesia, Poland and its palaeoenvironmental context. *Review of Palaeobotany and Palynology*, 163: 1–10.

Worobiec, E. & Szulc, J., 2010b. Palynological analysis of Miocene infill of karst sinkholes at Tarnów Opolski, Upper Silesian Upland – a preliminary report. *Przegląd Geologiczny*, 58: 1176–1181. [In Polish, with English summary.]

Worobiec, E. & Szulc, J., 2020. Palynology of Oligocene lignites in two karst palaeosinkholes at Górażdże, Upper Silesia, Poland. *Annales Societatis Geologorum Poloniae*, 90: 495–504.

Worobiec, E., Widera, M., Worobiec, G. & Kurdziel, B., 2021. Middle Miocene palynoflora from the Adamów lignite deposit, central Poland. *Palynology*, 45: 59–71.

Worobiec, E., Worobiec, G. & Kasiński, J. R., 2022. Decline of Neogene lignite formation as a result of vegetation and climate changes reflected in the middle Miocene palynoflora from the Ruja lignite deposit, SW Poland. *Review of Palaeobotany and Palynology*, 298: 104593.

Žak, K., Onac, B. P., Kadebskaya, O. I., Filippi, M., Dublyansky, Y. & Luetscher, M., 2018. Cryogenic mineral formation in caves. In: Perşoiu, A. & Lauritzen, S.-E. (eds), *Ice Caves*. Elsevier, Amsterdam, pp. 123–162.

Žak, K., Urban, J., Cilek, V. & Hercman, H., 2004. Cryogenic cave calcite from several Central European caves: age, carbon and oxygen isotopes and a genetic model. *Chemical Geology*, 206: 119–136.

Złonkiewicz, Z., 2021. Szczegółowy profil litologiczno-stratygraficzny. In: Fijałkowska-Mader, A., Złonkiewicz, Z. & Waśkiewicz, K. (eds), *Mniszków IG 1, Profile Głębokich Otworów Wiertniczych PIG*, 158: 21–40. [In Polish.]