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Fossil karst in the Jurassic of the Kościuszko Mound in Kraków (southern Poland)

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Study of four boreholes (each 100 m deep) drilled in St. Bronisława Hill (part of the horst of the Wolski Forest, Kraków) indicates that the Oxfordian limestone is interbedded by claystones with calcareous rubble (detritus) filling fossil karst forms. The claystones, locally showing planar stratification, contain assemblages of Late Cretaceous (Campanian–Maastrichtian) foraminifers. Middle Miocene planar laminated limestones have also been found in cavities formed in the Middle Oxfordian limestones. Miocene deposits of this type, filling the fossil karst, were not previously known from the area of Kraków. Both the Upper Cretaceous and Middle Miocene deposits document probably marine sedimentation that resulted in the filling of the karst system. This type of karst was probably formed before the transgression of the Late Cretaceous sea, and before the transgression of the Middle Miocene sea on the area of the present-day horst of the Wolski Forest.

Key words: southern Poland, Kraków Upland, karst, calcareous nannofossils.

INTRODUCTION

The Kościuszko Mound is located in the southern part of the Kraków Upland (southern Poland), in the western part of Kraków. It consists of Upper Jurassic limestones and is characterized by the occurrence of horsts and grabens (Gradziński, 1962, 1972) reflected in the contemporary relief. Horsts appear as isolated hills, and grabens as depressions. The example of an elevation is the horst of the Wolski Forest (Fig. 1), also referred to as the Sowiniec Horst (Tyczyńska, 1968). Its eastern element is St. Bronisława Hill where the Kościuszko Mound is situated. A set of boreholes were drilled in the immediate vicinity of mound, of which four were 100 m deep (Figs. 2 and 3). The purpose of the boreholes was to recognize the base of the Kościuszko Mound and the geological structure of the area before designation of a tunnel on the so-called “Zwierzyniecka route” (Kos et al., 2013). The aim of this study was to investigate sediments filling fossil karst forms in this area. Results of the boreholes provided new interesting data concerning the karst development and the geological structure of the area, as well as pointed out to alternative options of interpretations of issues associated with the occurrence of younger sediments among Jurassic carbonate rocks in the area of Kraków.

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GEOLOGICAL SETTING

The dominant role in the geological structure of the southern part of the Kraków Upland is played by Upper Jurassic limestones (up to 200 m thick; Rutkowski, 1993). During the Cretaceous, Paleogene and Miocene, they were repeatedly emerged and eroded. This is documented by unconformably lying Albian, Cenomanian, Turonian, Maastrichtian and Neogene sediments (Gradziński, 1962). The sequence was described, among others, from the Bonarka Quarry (Bromley et al., 2009). Karst formations occur within the Jurassic limestones, some of them are filled with younger deposits (Gradziński, 1962; Głazek, 1989; Felisiak, 1992). In the area of Kraków, Upper Jurassic limestones form characteristic horsts. Depressions between the horsts are filled with thick Miocene sediments (Fig. 4).

So far, there are only few geological data concerning the nearest area to the Kościuszko Mound. The most important information was given by Gradziński (1972); it is also included in publications related to the geological maps of the area (Rutkowski, 1993; Felisiak et al., 2005; Gradziński, 2009). Deposits of the Miocene transgression were found closest to St. Bronisława Hill, and described by Gradziński (1962) Felisiak (1992) and Gradziński et al. (1995). The oldest of them are considered to be marine oyster limestones occurring under the Norbertine Monastery (Gradziński, 1962), and caliche-type deposits found both above and below the oyster limestone (Gradziński et al., 1995). Quaternary sediments, mainly loess from the “Spadzista street” site, were described by Łanczot et al. (2013). In the study area, two caves have been discovered so far NW of the Kościuszko Mound (Słobodzian, 2011): “Schronisko pod Klasztorem Norbertanek” (Baryła and Szelerewicz, 2011) and “Kawerna pod Fortem Kościuszko”,

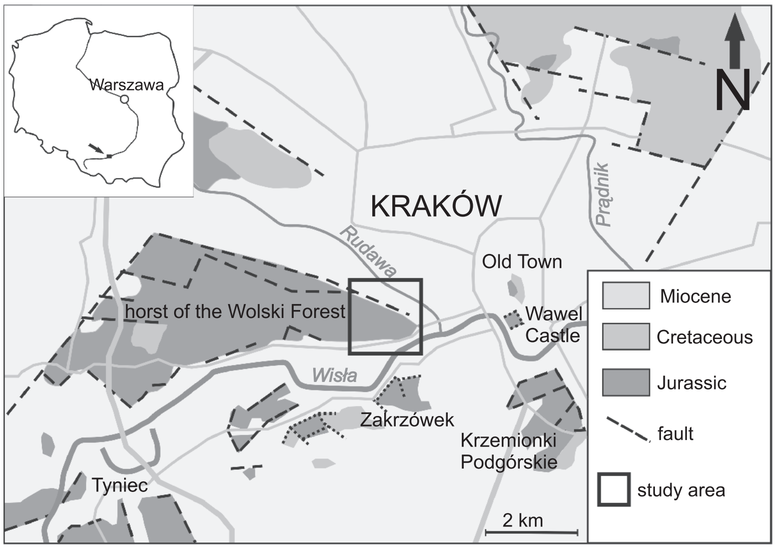

Fig. 1. Location of the study area on the map of main horst elements (after Gradziński, 2009)

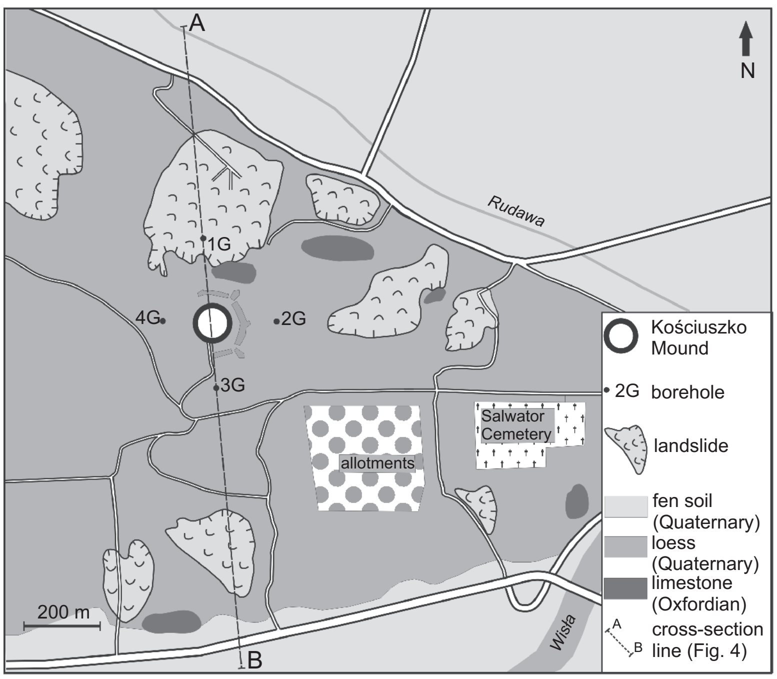

Fig. 2. Location of boreholes in the Kościuszko Mound area

probably of anthropogenic origin. On the Sowiniec Horst, Tynieckie Hills and Twardowski Rocks, situated south of the Vistula River valley, about twenty caves and shelters have been identified. Kowalski (1951) and Gradziński (1962) discussed the earlier views on karst processes in the southern part of the Kraków Upland. There are two views that suggest that the intense karst development took place during the Paleogene (Różycki, 1960) or Neogene, and Quaternary (Klimaszewski, 1958). The underground karst forms from the southern part of the Kraków Upland were studied by Gradziński (1962). He adopted the view that majority of the fossil karst channels were formed in the Early Paleogene and Late Neogene, during erosion of Upper Cretaceous sediments – therefore sediments of this age are found in the karst forms developed of the Upper Jurassic limestone. Younger sediments filling karst forms in older rocks according to Gradziński (1962) were earlier eroded and transported from land. The caves, which are now accessible, are related to the cutting of the limestone massif by deep valleys in the Late Miocene and Pliocene (Gradziński, 1962).

The existence of Cretaceous fillings in the Jurassic limestone in the Bonarka region (Kraków) was discussed by Wieczorek et al. (1995a, b), Dżułyński (1995) and Felisiak (1995). Wieczorek et al. (1995a, b) assumed that the fillings occurred in the submarine conditions, and they are neptunian dykes due to Late Cretaceous tectonics. Dżułyński (1995) and Felisiak (1995) concluded that the faults are of Paleogene age. Felisiak (1995) regarded the fill as a kind of clastic dykes formed by pressing of the overlying plastic Santonian marls into the widening tectonic crevices. Similar forms, described as injection dykes, have been found in anthropogenic outcrops near Pychowicka Street in Kraków (Kołodziej et al., 2010). Krobicki et al. (2008) suggested also earlier stages of origin of the neptunian dykes around Kraków, in the Oxfordian.

MATERIAL AND METHODS

The studied material came from four fully cored boreholes (each 100 m deep): 1G–4G (Fig. 3). Their location is shown in Figure 2. Cores were transferred to the municipal office of Kraków.

In all cases, white, creamy and creamy-greyish thick-bedded and massive limestones occur at a depth from 10 to 100 m under Quaternary sediments represented by loess or loess-like clay. Ten samples were taken for micropalaeontological investigation. Most of them came from the fillings of karst cavities in limestones. Two samples were collected from host limestones. Sampling depths are shown in Figure 3. Seven samples were taken for foraminiferal studies, and three samples for calcareous nannofossil investigations. Foraminiferal studies were performed on samples treated with water, washed and dried on an oven. Smear slides for nannofossil investigations were prepared according to the standard method described by Báldi-Beke (1984). Fine water suspension of the rock is spread out on the microscope slide after stirring and a short period of settling. After drying, the microscope slide is covered with Canada balsam and a cover glass. The slides were inspected with a *Nikon Eclipse E400Pol* light microscope at 1000x magnification, and photographed using a *DS-Fi1 Nikon* camera.

RESULTS

The upper parts of the sections studied are strongly karstificated and cavernous. Caverns are frequently filled with

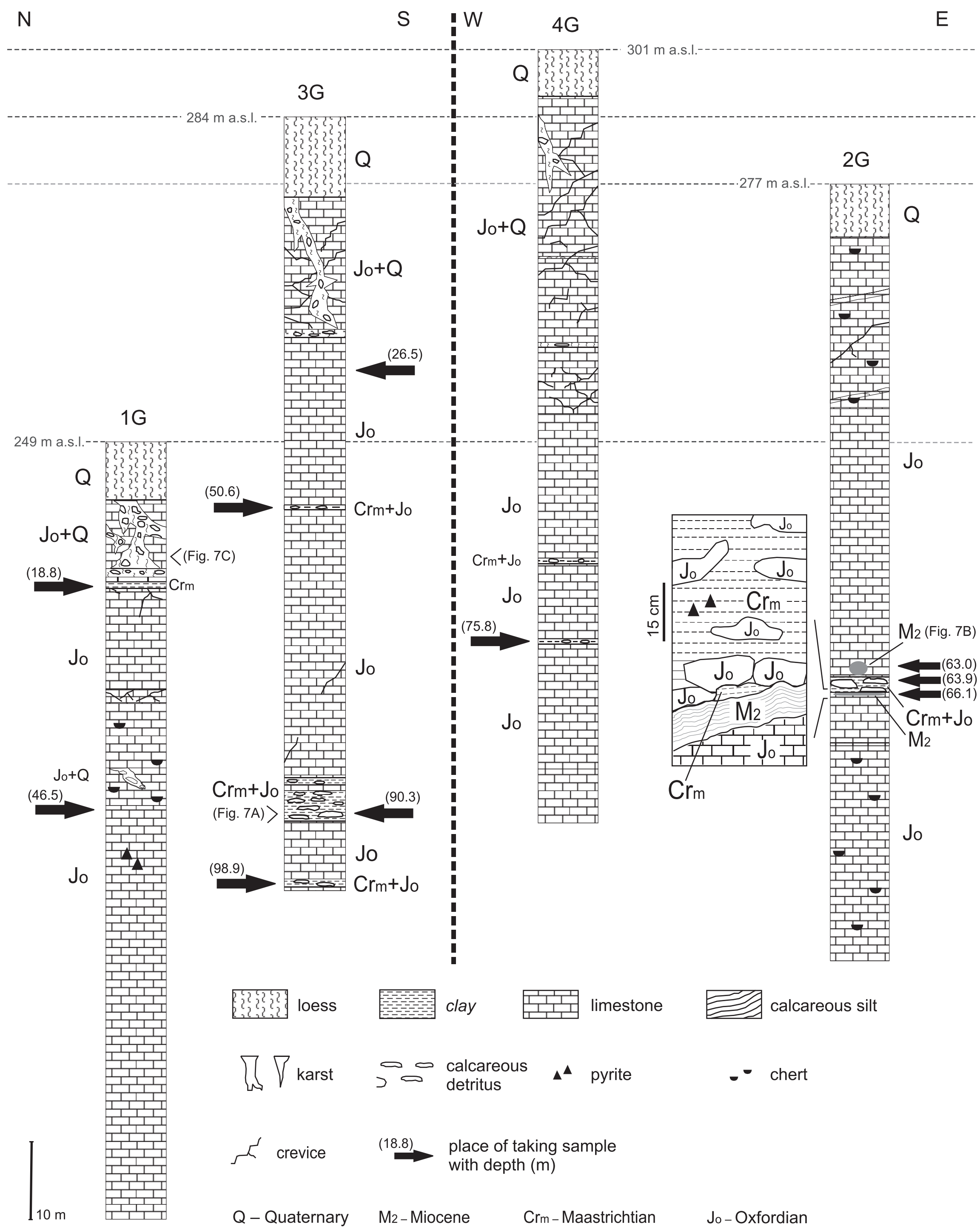

Fig. 3. Lithostratigraphic sections of the 1G–4G boreholes

calcite crystals. Light beige marly silt fills rare interlayer spaces. The limestones from the lower part of the boreholes are darker, creamy-grey and less weathered. Their specific colour is probably caused by admixture of pyrite (Dżułyński and Żabiński, 1954). Piryte crystals were found in a cavern at a depth of 55 m. Numerous point precipitations or dendrites of manganese hydroxides and sutural joints (stylolites) occur locally within the limestones. Chert concretions coated by a white porous crust are randomly distributed in the limestone (Fig. 3). No distinct boundaries between the layers (with or without cherts) have been observed in the boreholes.

The results of micropalaeontological analysis (foraminifera, calcareous nannofossils) are presented in Table 1 and in Figures 5 and 6. The 46.5 m depth sample from the 1G borehole contained only isolated specimens of the long-ranging foraminifer genera *Rumanolina seiboldi.* The Oxfordian foraminifera assemblage was found in the 3G borehole at a depth of 26.5 m. Three different types of deposits have been recog-

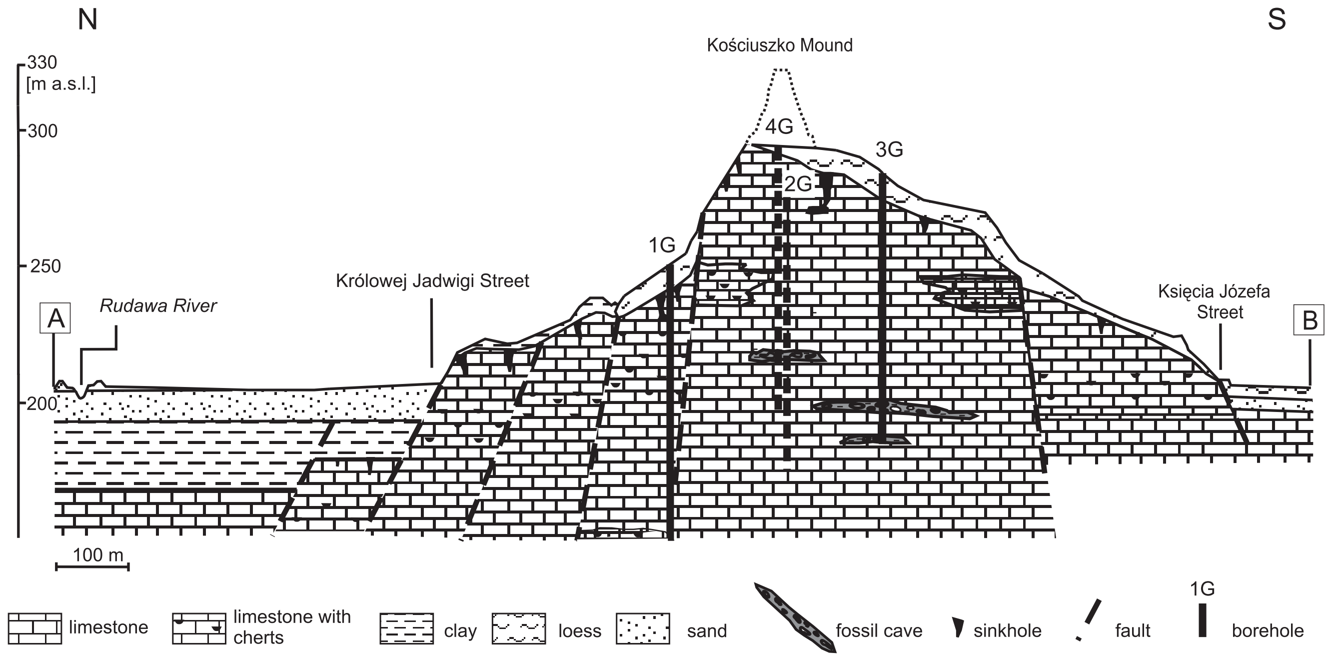

Fig. 4. Cross-section of the St. Bronisława Hill

nized: greenish-grey clays with calcareous, locally stratified, debris (Late Cretaceous in age), grey calcareous silts with planar lamination (Middle Miocene), and loess-like grey and tan-coloured silts with calcareous debris (Quaternary).

GREENISH-GREY CLAYS
WITH CALCAREOUS DEBRIS

Greenish-grey clays with calcareous debris were found within the limestones in the 2G, 3G and 4G boreholes (Fig. 3). In the 1G borehole (depth 18.8–18.9 m), similar clays do not contain calcareous debris, which may be due to their small thickness. Clays enclosed in Jurassic rocks, recognized in the boreholes from the middle part of St. Bronisława Hill, contained traces of planar bedding. Clays usually comprised weakly rounded or sharp-edged calcareous pebbles (from a few milimetres to10 cm long), elongated and irregular in shape (Fig. 7A). The longer axes of the pebbles are parallel to the bedding. The clays attain the greatest thickness in the 3G borehole, where an almost 4 m thick layer of greenish clay with calcareous debris (Fig. 3) occurs below a depth of 87.7 m. In the sample from this borehole, a diversified Maastrichtian foraminifer assemblage was found. Furthermore, numerous sponge elements, ostracods and calcareous concretions were found in the assemblage. The same age is concluded for the assemblage obtained from the pyrite-rich clays in the 2G borehole, at the depth 63.9 m. In the 3G borehole, only poorly preserved, long-ranging foraminifers were identified at a depth of 90.3 m in light grey clays. Deeper in this borehole section, in the sample from a depth of 98.9 m, the identified foraminiferal species and characteristic numerous sponge elements indicate Campanian-Maastrichtian age (Fig. 6 and Table 1). The same age is concluded for a foraminiferal assemblage found in the 4G borehole at a depth of 75.8 m. The sample from 50.6 m depth in the 3G borehole contains residual, poorly preserved (due to mechanical deformation, dissolution and secondary calcitization) and rare calcareous nannofossils that indicate Late Cretaceous (Campanian–Maastrichtian) age.

GREY CALCAREOUS SILTS
WITH PLANAR LAMINATION

An oval structure, differing from the surrounding light Jurassic limestones, filled with distinctly laminated calcareous silt, was observed in the 2G borehole at a depth of 62.8 m (Fig. 3). This structure is 25 cm high and its width exceeds that of the core diameter (i.e. 10 cm). The thickness of the light and dark grey laminae is 1–8 mm (Fig. 7B). They have a horizontal and slightly sinuous arrangement. Particular laminae are bent upwards, suggesting a greater size of the structure filled by smaller channels. One of the channels (~2 cm across) can be observed on the side of the structure.

The sample of laminated mudstones from a depth of 63.0 m and the sample from grey laminated deposits situated between the Cretaceous clays and Jurassic limestones, from a depth of 66.1 m, yielded an Early Badenian calcareous nannofossil association. It is dominated by long-ranging placoliths (*Coccolithus*, small *Reticulofenestra*), tolerant to adverse environmental conditions, and less common shallow-water, nearly near-shore helicoliths (*Helicosphaera*) and cribriliths (*Pontosphaera*). According to Švabenicka (2002) and Báldi-Beke (1982), *Helicosphaera* prefers unstable environments that can be associated with the beginning of transgression, whereas *Pontosphaera* requires more stable environmental conditions and only slight fluctuation in salinity (Melinte, 2005). Important for the Middle Miocene stratigraphy, *Sphenolithus heteromorphus* and *Discoaster variabilis* occur only as single specimens. Both *Sphenoliths* and *Discoasters* are the most resistant

Tables 1

Foraminifers, calcareous nannofossils and other characteristic microfossils in the 1G–4G boreholes

Microfossils: foraminifera and others	Borehole						
	1G		2G	3G			4G
	depth [m]						
	18.8	46.5	63.9	26.5	90.3	98.9	75.8
Abathomphalus mayaroensis			x				
Ammobaculites sp.		x					
Arenobulimina sp.	x					x	
Astrorhizidae *family*					x		
Cibicides bembix	x						
Cibicides sp.			x				
Crescentiella morronensis				x			
Gavelinella sp.	x						
Globigerinelloides asperus	x		x				x
Globigerinelloides sp.						x	
Globorotalites michelinianus	x						
Globotruncana arca						x	
Globotruncana linneiana	x						
Globotruncana lapparenti	x						
Glomospira sp.			x		x		
Gyroidinoides nitidus	x					x	x
Hedbergella sp.			x				x
Heterohelix globulosa						x	x
Lenticulina sp.		x					
Rugoglobigerina macrocephala	x						
Rugoglobigerina rugosa						x	
Rugoglobigerina sp.			x				
Spirillina sp.	x			x			x
Spiroplectammina navarroana	x						
Stensioeina aff. *gracilis*							x
Terebella lapilloides (worms)				x			
bivalves				x			
bryozoans		x					
echinoids' spines			x				
calcareous sponges	x	x	x			x	
micromummies of the siliceous sponges	x	x	x			x	
ostracods	x						
radiolarians			x				

Calcareous nannofossils	Borehole		
	2G		3G
	depth [m]		
	63.0	66.1	50.6
Arkhangelskiella sp.			x
Braarudosphaera cf. *bigelowii*	x	x	
Braarudosphaera bigelowii	x	x	x
Calculites obscurus			x
Coccolithus pelagicus	x	x	
Cyclicargolithus floridanus		x	
Dictyococcites aff. *bisectus*		x	
Discoaster cf. *variabilis*		x	
Eiffellithus eximius	x		x
Ericsonia formosa	x		
Helicosphaera carteri	x	x	
Helicosphaera walbersdorfensis	x		
Helicosphaera sp.	x	x	
Lucianorhabdus cayeuxii			x
Lucianorhabdus maleformis			x
Micula decussata	x	x	x
Micula swastica			x
Micula sp.		x	x
Pontosphaera multipora	x	x	
Prediscosphaera aff. *cretacea*			x
Prediscosphaera cretacea	x		x
Reticulofenestra hillae		x	
Reticulofenestra sp. (small forms)	x	x	
Sphenolithus heteromorphus	x	x	
Umbilicosphaera rotula	x		
Uniplanarius gothicus			x
Uniplanarius sissinghii			x
Watznaueria barnesae	x		
Watznaueria sp.		x	x

to dissolution (Bukry, 1981), but sensitive to high fluctuation in salinity. The scarcity of these species in the analysed samples may be due to the generally poor state of preservation of most of the identified forms or unfavourable (especially for discoasters) environmental conditions. In both samples, poorly preserved, destroyed and scarce redeposited Eocene-Oligocene (*Dictyococcites* aff. *bisectus*, *Ericsonia formosa*, *Reticulofenestra hillae*) and Upper Cretaceous species were identified, but due to the poor preservation, their quantity is impossible to estimate.

GREY AND TAN-COLOURED LOESS-LIKE SILTS WITH THE CALCAREOUS DEBRIS

The deposits occur in the top part of the cored section (Fig. 3) and are the most frequent in the 1G borehole down to a depth of 20.0 m. This borehole was drilled about 200 m north of the Kościuszko Mound, probably through a karst sinkhole. Fragments of the limestone (from a few centimetres to more than 10 cm across) are distributed randomly in loam of the upper part

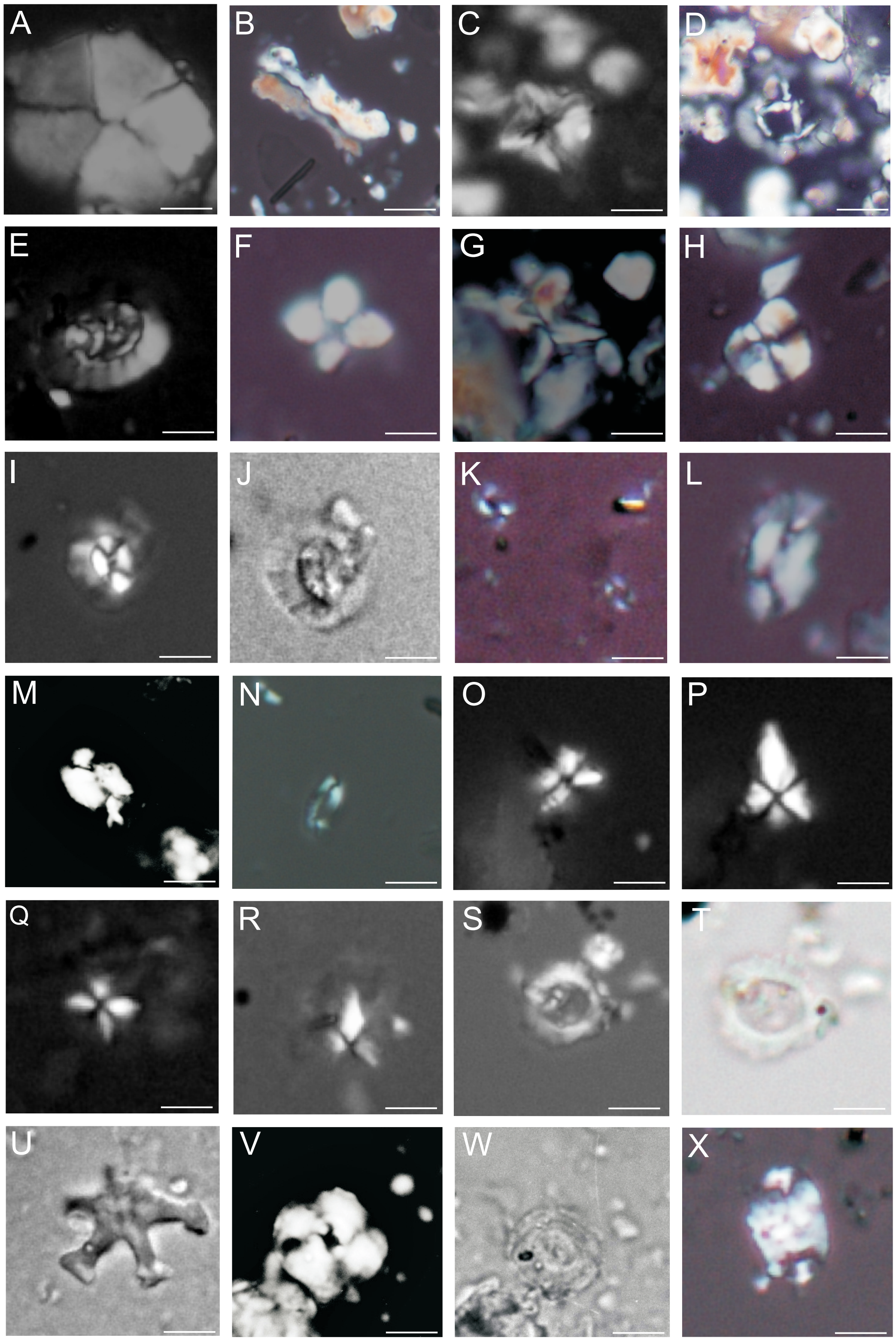

Fig. 5. Calcareous nannoplankton in the boreholes: 2G (depth 63.0 m: I–T and 66.1 m: U–X) and 3G (depth 50.6 m: A–H)

A – *Braarudosphaera bigelowii* (Gran et Braarud) Deflandre – CN; **B** – *Lucianorhabdus cayeuxii* Deflandre – CN; **C** – *Micula decussata* Vekshina – CN; **D** – *Prediscosphaera* aff. *ponticula* (Bukry) Perch-Nielsen – CN; **E** – *Prediscosphaera* cf. *cretacea* (Arkhangelsky) Gartner – CN; **F** – *Uniplanarius gothicus* (Deflandre) Hattner et Wise – CN; **G** – *Uniplanarius sissinghii* Perch-Nielsen – CN; **H** – *Watznaueria* sp. – CN; **I** – *Coccolithus pelagicus* (Wallich) Schiller – CN; **J** – *Coccolithus pelagicus* (Wallich) Schiller – NL; **K** – small *Reticulofenestrids* – CN; **L** – *Helicosphaera carteri* (Wallich) Kamptner – CN; **M** – *Helicosphaera carteri* (Wallich) Kamptner – CN; **N** – *Helicosphaera walbersdorfensis* Müller – CN; **O** – *Sphenolithus heteromorphus* Deflandre – CN 0°; **P** – *Sphenolithus heteromorphus* Deflandre – CN 45°; **Q** – *Sphenolithus heteromorphus* Deflandre – CN 0°; **R** – *Sphenolithus heteromorphus* Deflandre – CN 45°; **S** – *Umbilicosphaera rotula* (Kamptner) Varol – CN; **T** – *Umbilicosphaera rotula* (Kamptner) Varol – NL; **U** – *Discoaster* cf. *variabilis* Martini et Bramlette – NL; **V** – *Cyclicargolithus floridanus* (Roth et Hay) Bukry – CN; **W** – *Cyclicargolithus floridanus* (Roth et Hay) Bukry – NL; **X** – *Pontosphaera* cf. *multipora* (Kamptner) Roth – CN; CN – crossed polars, NL – normal light, scale bar is 5 μm

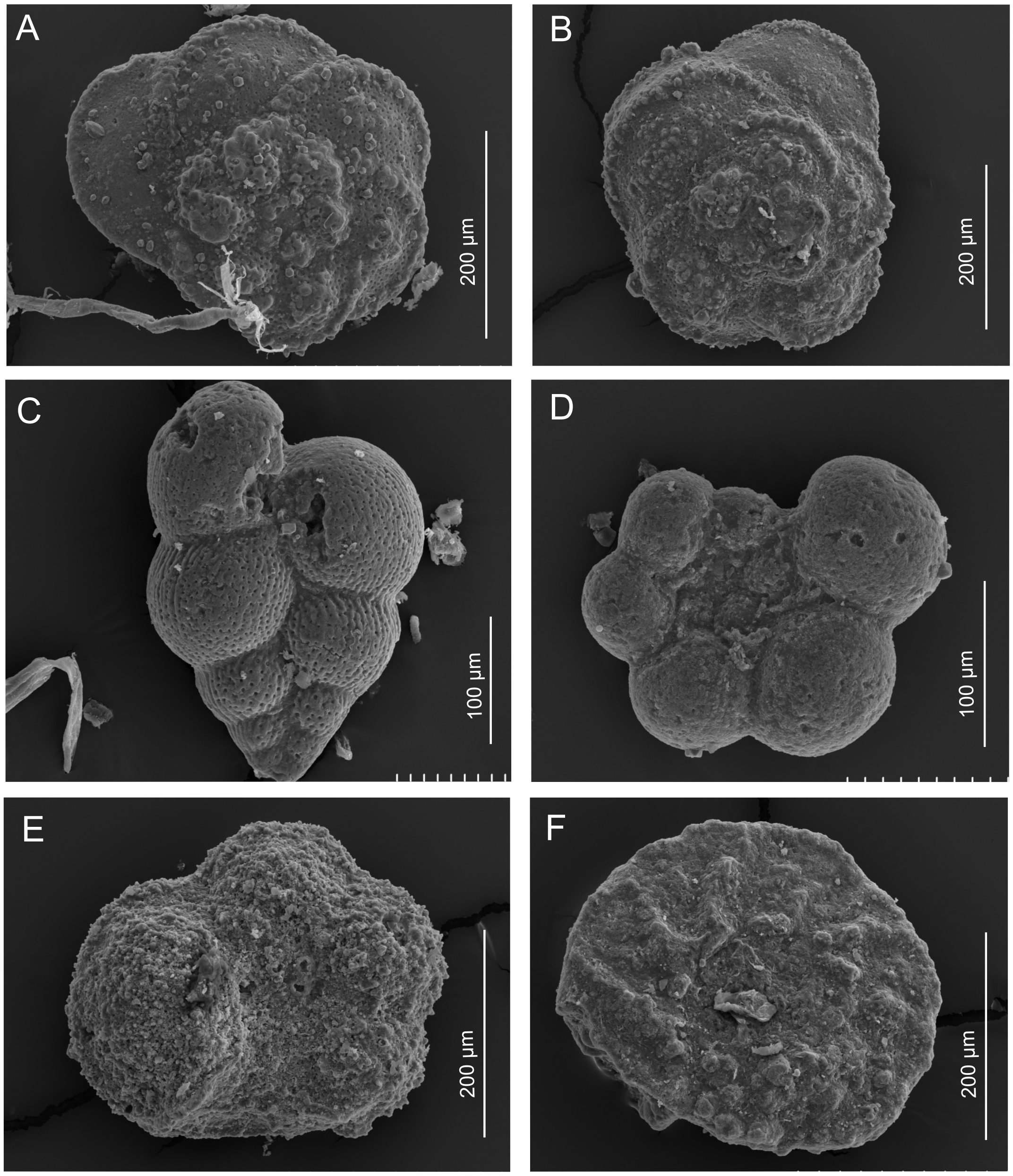

Fig. 6. Some Late Cretaceous foraminifers from the boreholes in the Kościuszko Mound area

A – *Globotruncana arca* (Cushman), dorsal side, 2G borehole, depth 63.0 m; **B** – *Abathomphalus mayaroensis* (Bolli), dorsal side, 2G borehole, depth 63.9 m; **C** – *Heterohelix globulosa* (Ehrenberg), side view, 3G borehole, depth 98.9 m; **D** – *Globigerinelloides asperus* (Ehrenberg), side view, 2G borehole, depth 63.9 m; **E** – *Rugoglobigerina* sp., ventral side, 2G borehole, depths 63.9 m; **F** – *Stensioeina* cf. *exculpta* (Reuss), dorsal side, 2G borehole, depths 63.0 m

of the 1G borehole (Fig. 7C). They are weakly rounded and sharp-edged. Below a depth of 16.5 m, the light brown loam is replaced by grey silt. In the other borehole (2G–4G), the karst fissures have various sizes and are frequently funnel-like. The smallest fissures are a few centimetres across while the largest ones may attain a few metres. The size of calcareous debris varies from a few to more than ten centimetres. No microfaunal study was performed on the grey and tan-coloured loess.

INTERPRETATION AND DISCUSSION

The Upper Jurassic limestones from the area of the Kościuszko Mound were deposited in a shallow, warm sea on the northern shelf of the Tethys Ocean (Trammer, 1982). These were good conditions for developing cyanobacteria-sponge bioherms (Dżułyński, 1952; Matyszkiewicz, 1989; Heliasz, 1996)

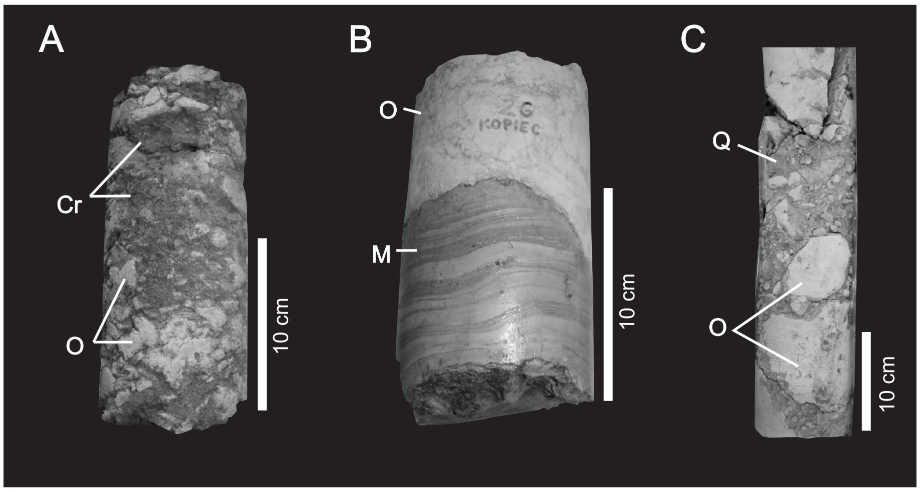

Fig. 7. Sediments filling fossil karst forms

A – greenish-grey clays with calcareous debris in the 3G borehole (depth 90.4–90.6 m); Cr – Upper Cretaceous clays, O – Oxfordian limestone debris; **B** – Miocene calcareous silts filling the cavity within Oxfordian limestones; 2G borehole (depth 62.8–62.95 m); O – Oxfordian limestone, M – Middle Miocene calcareous silts; **C** – tan loess with calcareous debris; 1G borehole (depth 14.5–14.9 m); Q – Quaternary loess, O – Oxfordian limestone debris

resulting in the formation of massive limestones that make up the major part of the borehole sections. Irregular distribution of cherts in the non-bedded limestone from some sections of drill cores may be due to drilling through the transition zone between the bedded limestone with cherts and the massive limestone. Such transitions are visible in many places of the Kraków Upland (e.g., Piekary Quarry and Jeziorzany). The Upper Jurassic limestones underwent repeated emergence from the water and were subjected to karstification. The Upper Cretaceous greenish grey clays, Middle Miocene laminated limestones, and Quaternary loess with calcareous debris fill the fossil karst structures.

Gradziński (1962) considered that the clays, containing Late Cretaceous fossils that occur within the limestones in the area of Kraków, come from erosion of marls and are redeposited to different forms of karst. They usually fill karst pits, near which there are exposures of Cretaceous marls. Similar green clays filling fossil caves are included by Felisiak (1992) in the "category of Oligocene-Early Miocene karst deposits". Upper Cretaceous sediments within the Jurassic limestones in the Kraków area were also considered as clastic dykes (Dżułyński, 1995; Felisiak, 1995), neptunian dykes (Wieczorek et al., 1995a, b; Krobicki et al., 2008) or injection dykes (Kołodziej et al., 2010). Cretaceous sediments within the Jurassic limestone were also found in the Gdów area, about 25 km E of Kraków (Połtowicz, 1962), where they are at a depth of about 200 m from the top of limestone. Połtowicz (1962) interpreted them as a result of reverse faults.

Data from the boreholes in the Kościuszko Mound area suggest that the Upper Cretaceous clays fill the fossil karst channels and caves. St. Bronisława Hill as well as the entire horst of the Wolski Forest have the character of a wide and flattened hump, where no Upper Cretaceous deposits have been found on the surface. In addition, there are no Maastrichtian deposits in the immediate vicinity of Kraków. Greenish-grey clays in the basement of the Kościuszko Mound occur well below the Rudawa valley level (Fig. 4). The fillings of fossil karst forms from the area of Kraków, described in the literature, are often represented by sandy-clay sediments (Gradziński 1962; Felisiak, 1992), among others clays layered sand (Alexandrowicz, 1969). The presence of sand indicates that the clays could be locally eroded by surface waters and resedimented. The karst forms in the basement of the Kościuszko Mound do not contain sands. Due to the above, another possibility than redeposition of Cretaceous material in these very deep karst forms (Figs. 3 and 4) is also plausible. The position of the material studied is not a result of tectonic movements, especially because the manifestations of tectonic movements are poor in the obtained cores. The faults identified are younger than the sediments filling the karst channel systems. In the case of Cretaceous sediments in the St. Bronisława Hill area, the concept of neptunian dykes (Wieczorek et al., 1995a, b; Krobicki et al., 2008; Kołodziej et al., 2010) cannot be considered due to the depth of the occurrence of Upper Cretaceous sediments within Jurassic rocks. All forms described as neptunian dykes have been observed in the upper part of limestones.

The origin of the karst system and its fill in the basement of the Kościuszko Mound has not been fully explained yet. The authors do not exclude the possibility that the channels developed during intense karst processes in the Paleogene or Neogene, but they could also form in subaerial conditions during the Late Jurassic and Early Cretaceous lowering of the sea level (cf. Haq et al., 1988). Tithonian-Cenomanian times were among the major periods of karstification in southern Poland, however, few forms have been preserved and documented (Głazek, 1989); most of them were destroyed during the subsequent transgression. The channel system may have formed also as a result of elevation of the limestone massifs above the sea level, which enabled development of karst. Karst channel filling might have occurred during the Late Cretaceous submergence (Campanian–Maastrichtian). During the filling process, there was a slow disintegration of the upper part of the karst channels, as indicated by rubble limestone occurring within the clays derived from rockfall from the ceiling of the caves. Another possibility is that the channels originated as a result of submarine karst in the coastal shelf. Drainage of the fresh-water to submarine zones and infiltration of the salt water into the cracks and their penetration into the land causes mixing of waters of different origin, making them more aggressive (Herak, 1972; Ford and Williams, 2007). Today, the development of karst is observed in many submarine karst systems including the Gulf of Mexico, Bermuda, Sardinia and Croatia (Carobenne and Pasini, 1980; Airoldi and Cinelli, 1996; Surić, 2002; Hengstum et al., 2011). In submarine caves occurring near the high sea coasts, sands are also deposited during storms.

The Middle Miocene laminated calcsiltite channel-fills and small karst forms, found at the base of the Kościuszko Mound (Fig. 3), may also be the result of submarine sedimentation. Miocene deposits of this type, filling fossil karst forms, were not previously known from the area of Kraków. Development of channels that are even less than 60 m from the top of the limestone was probably supported by crevices associated with Neogene tectonics. Karst channels could grow along the walls of horsts that were emerged before the Middle Miocene transgression (Dżułyński, 1953). It is unlikely that sedimentation of laminated calcsilite of Miocene age, containing marine fauna, took place in terrestrial conditions as a result of erosion and transport of sediment from the overburden. A channel visible in the 2G borehole at the depth of 66.1 m formed at the boundary of soluble limestone and less soluble Cretaceous clays. It gave the effect of filling of the karst cavity by two different generations. Unclear is the presence of redeposited Paleogene nannoplankton forms in the samples. Today, such sediments are not found within the study area. For this period creation of the Paleogene planation surface is assumed (Alexandrowicz, 1969). It would indicate erosion and transport of marine Paleogene sediments from an area located north of horst of the Wolski Forest, as the transport from the distant Carpathian area seems unlikely.

Quaternary deposits with Jurassic calcareous debris occur mainly to a depth of 10 m below ground level. The absence of rounding of pebbles indicates a short transport and rapid redeposition. Their irregular distribution in the Quaternary loess covering limestones, clearly indicates that they are the filling of sinkholes. They were formed rapidly due to the collapse of the ceiling of caves in strongly karstified limestones. The funnel-shaped structures of smaller size usually developed along the crevices. They are often fuzzy fault crevices filled with karst-derived material and tectonic breccias.

CONCLUSIONS

New data from the region of the Kościuszko Mound enabled a new interpretation of Upper Cretaceous and Miocene deposits filling the karstic systems in the Jurassic limestones of the Kraków region. It is suggested that these sediments are associated with the submarine filling of fossil karst forms. The development of karst in this area began in the Cretaceous and occurred in several stages: before the Late Cretaceous, during the Paleogene-Neogene, and during the Quaternary.

Fossil karst forms filled with Cretaceous sediments have been found within the Jurassic limestone. They occur even 100 m below the present ground surface. These forms may have been created during the emersion of limestones before the Late Cretaceous. Filling of the karst channels may have took place during the Campanian-Maastrichtian.

Within the limestones drilled around the Kościuszko Mound, a few karst forms filled by Middle Miocene laminated limestones have been recognized. Calcsiltites reached the Jurassic limestones through the system of karst channels. They could develop along the horst walls and accumulated deposits of less than 60 metres below the present ground surface. Deposits of this type filling the fossil karst were not previously known from the area of Kraków.

Karst forms situated nearest to the ground surface are the crevices and sinkholes filled by Quaternary deposits.

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