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INJECTION DYKES AS EVIDENCE OF CAMPANIAN SYNSEDIMENTARY TECTONICS ON THE KRAKÓW SWELL, SOUTHERN POLAND

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Abstract: The topmost part of the Oxfordian limestones, building the Zakrzówek Horst in Kraków, is featured by a network of minute fissures, filled with Upper Cretaceous limestones. The fissures are dominantly subhorizontal, anastomosing and polygonal in plane. They are filled with white limestones representing mostly foraminiferal-calcisphere wackestones, with subordinate amount of quartz pebbles and fragments of stromatolite coming from the latest Turonian–?Early Coniacian conglomerate overlying Oxfordian basement. The fissures are seismically-induced injection dykes. In contrast to gravitationally-filled neptunian dykes, the recognised injection dykes were filled by overpressured soft sediments. Foraminifera within some dykes are abundant, and dominated by planktonic forms, which indicate the Early/Late Campanian age (Globotruncana ventricosa and Globotruncanita calcarata zones) of the filling, and hence date also the synsedimentary tectonics. Abundant and diversified keeled globotruncanids in the Campanian of the Kraków region are recognised for the first time. Other important findings at the studied section include karstic cavities featuring the surface of the Oxfordian bedrock filled with conglomerates of the latest Turonian–?Early Coniacian age based on foraminifera and nannoplankton, and lack of Santonian deposits, which elsewhere are common in the Upper Cretaceous sequences in the Kraków region. The discovered Campanian dykes provide new evidence for the Late Cretaceous tectonic activity on the Kraków Swell related to the Subhercynian tectonism, which resulted among others in stratigraphic hiatuses and unconformities characteristic of the Turonian–Santonian interval of this area.

Key words: injection dykes, synsedimentary tectonics, biostratigraphy, Late Cretaceous, Campanian, Kraków Swell, Poland.

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INTRODUCTION

Late Cretaceous tectonics is commonly accepted as an important factor controlling sedimentation during the Turonian–Santonian on the Kraków Swell. The Subhercynian movements are well marked there by multiple stratigraphic hiatuses and unconformities (Marcinowski, 1974; Walaszczyk, 1992; Olszewska-Nejbert, 2004; Olszewska-Nejbert & Świerczewska-Gładysz, 2009). Direct effects of synsedimentary tectonics like seismically-induced fabrics are, however, poorly known. The vertical fissures filled with green marls at the Bonarka Horst in Kraków, interpreted as Santonian neptunian dykes (Wieczorek *et al.*, 1994, 1995a, b; Wieczorek & Olszewska, 2001), were not commonly accepted (Dżułyński, 1995; Felisiak, 1995).

New evidence of Cretaceous tectonic mobility in the Kraków region, discussed herein, come from temporary outcrops which appeared during construction works carried out in 2008 at the Zakrzówek Horst in Kraków (Pychowicka Street).

GEOLOGICAL SETTING

The southern part of the Kraków Upland is characterised by horst and graben structures, which originated in the Miocene as the Outer Carpathian nappes were thrust to the north. The horsts are composed mainly of the Upper Jurassic limestones and Upper Cretaceous limestones and marls. The grabens are filled with Miocene molasse deposits with dominant fine-grained siliciclastics. The studied area belongs to the Zakrzówek Horst (Fig. 1A, B; Gradziński, 1993).

Upper Cretaceous rocks are preserved locally as a discontinuous cover (up to 25 metres thick) overlying the Oxfordian limestones (Alexandrowicz, 1954; Gradziński,

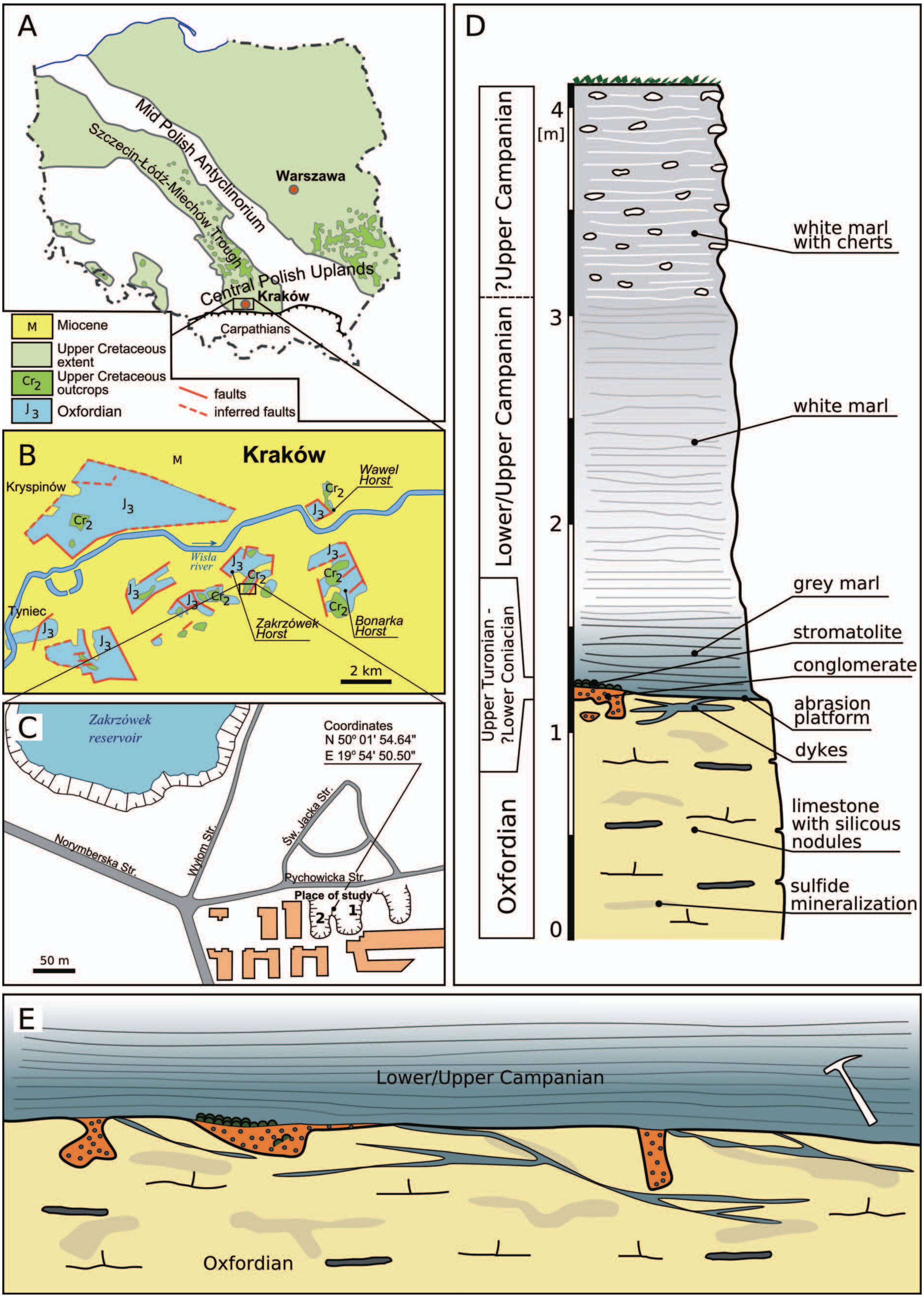

Fig. 1. **A, B** – Location of the study area on the general geological map of Poland (A; based on Sokołowski *et al.*, 1976, fig. 128) and Kraków region (B; based on Gradziński, 1993), **C** – Location of the studied pits 1 and 2 (based on Google Earth), **D** – Generalized section of the Upper Jurassic and Upper Cretaceous sequence at the Pychowicka street in Kraków, **E** – Schematic diagram showing spatial relation of injection dykes, karstic cavities filled with conglomerates, overlying marls and Oxfordian basement truncated by the Late Cretaceous abrasion platform; for symbol explanation see Fig. 1D

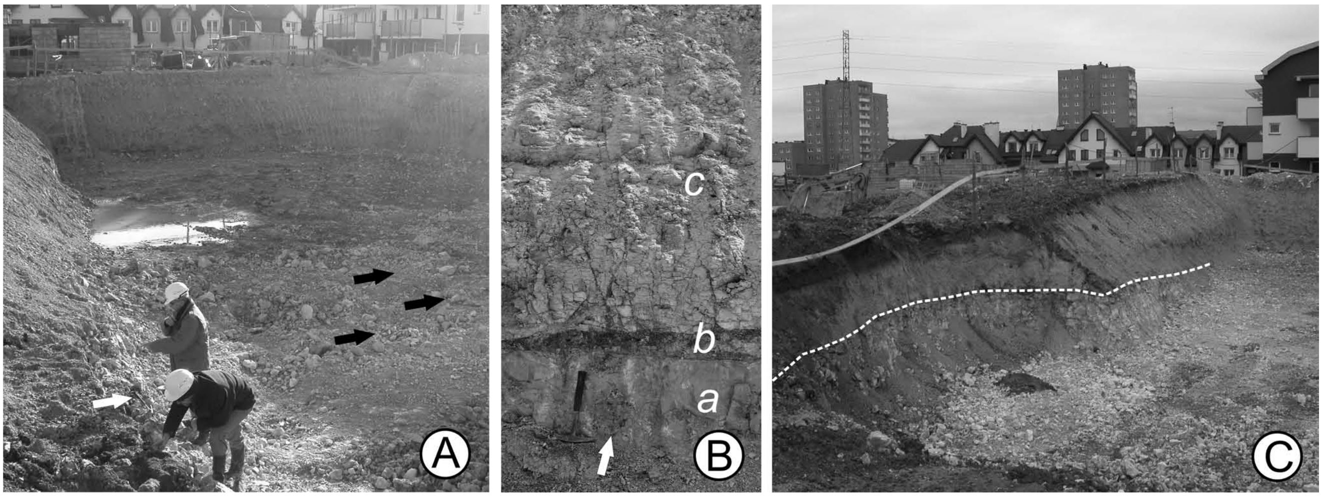

Fig. 2. **A** – General view of pit 1. On the left (eastern) side of the pit (white arrow) injection dykes occur within outcropped Oxfordian limestones (see Fig. 5A). At the pit basement, apart from loose blocks of Oxfordian limestones cut by dykes, upward endings of dykes were observed (black arrows), **B** – Oxfordian limestones (*a*) at pit 1 cut by abrasion platform and covered by weathered uppermost Turonian–?Lower Coniacian conglomerates and ferruginous stromatolites (*b*), and Campanian marls (*c*); note oval karstic cavity filled with conglomerates (arrow; see also Fig. 5D), **C** – General view of pit 2. Late Cretaceous abrasion platform truncating Oxfordian limestones is marked by dotted line. The pit 1 is partly visible in the left, upper part of the picture

1961; see also overview by Bromley *et al.*, 2009). To the north-east of Kraków, in the Miechów Trough, the thickness of the Upper Cretaceous succession increases and attains about 600 m.

The oldest Upper Cretaceous rocks in the Kraków region are Cenomanian sands and quartzose conglomerates, which overlie locally an abrasion surface truncating the Oxfordian limestones. The overlying Turonian carbonate deposits do not exceed 10 m in thickness (Walaszczyk, 1992). The Coniacian, well recognised northwards from Kraków (Walaszczyk, 1992; Olszewska-Nejbert & Świerczewska-Gładysz, 2009), used to be considered absent or not documented palaeontologically at Kraków, the view that should be revised (see discussion in the section ‘Biostratigraphic data’). The Santonian is usually present in the Kraków region, although stratigraphic gaps still exist. The Upper Cretaceous rocks in this region are composed mostly of Campanian marls, marly limestones and siliceous chalky facies.

SECTION DESCRIPTION AND METHODS

The studied sections represented by two pits, each *ca.* 50 × 30 m in size, were exposed in the Pychowicka Street, during construction works, and were accessible from January to April 2008 (Figs 1C, D, 2).

In pit 1 (Figs 1E, 2A, B), the inclined, karstified and abraded Oxfordian limestones are covered locally by conglomerates (uppermost Turonian–?Lower Coniacian) and/or by weathered ferruginous stromatolites. Conglomerates usually fill the karstic cavities developed in the Oxfordian bedrock (see Fig. 5). The palaeokarst surface was partly truncated during the Late Cretaceous transgression and is pierced by *Entobia cracoviensis* Bromley et Uchman, sponge borings which are abundant on the abrasion platform at the Bonarka Horst (Bromley *et al.*, 2009). Mostly, however, the Jurassic bedrock, particularly in pit 2, is covered directly by the Lower/Upper Campanian grey marls followed by the ?Upper Campanian white marls and marls with chert nodules (Figs 1D, 2). The Santonian marls, occurring commonly in most sections in the Kraków region, were not found in the studied outcrops.

45 rock samples and 21 thin sections of Oxfordian limestones with dykes or dyke filling limestones, and 10 samples from conglomerates (8 thin sections) were studied. Most of the samples were collected as loose blocks from the bottom of pit 1. The stratigraphy is based on foraminifers and nannoplankton.

Foraminifers from the dyke fillings were analysed in thin sections by means of optical microscopy. From the overlying marls, the samples were dried and disintegrated by repeated heating up and drying in a solution of sodium carbonate. Residues were dried and washed through sieves with 63 μm mesh diameter.

The slides for calcareous nannoplankton were prepared using the standard smear-slide technique and then investigated at ×1000 magnification under the light microscope with bright and cross-polarised light. The average abundance of assemblages is estimated as less than 1 specimen per 10 fields of views. The studied samples are rich in carbonates, thus the main reason of poor preservation seems to be the secondary calcite overgrowth, then the state of preservation were established as O-2 or O-3 using Roth’s (1983) scale of coccolith preservation.

Rock samples, thin sections and other micropalaeontological samples are deposited at the Institute of Geological Sciences, Jagiellonian University.

DESCRIPTION OF DYKES

The characteristic feature of the studied rocks, in particular in pit 1, is a fissure network which pierces the topmost, several centimetres thick Jurassic bedrock (Fig. 5A, and schematic diagram in Fig. 1E). The cracks are polygonal in plane, commonly anastomosing, with widths ranging between 1 mm and several centimetres (Figs 3, 4). Some of the fissures display upward endings. It is intriguing that most of the cracks are (sub)horizontal, while the vertical or oblique ones (those not related with karstification) are short, thin and quite rare (Fig. 4B). The opposite walls of the cracks display good fitting (Fig. 3A). Slightly displaced clasts of Oxfordian limestone from dyke wall were also observed (Fig. 3F).

The fissures are filled with hard, pelitic limestones representing mostly foraminiferal-calcisphere wackestones (Figs 4C–F, 9, 10), with rare small gastropods (Fig. 3A),

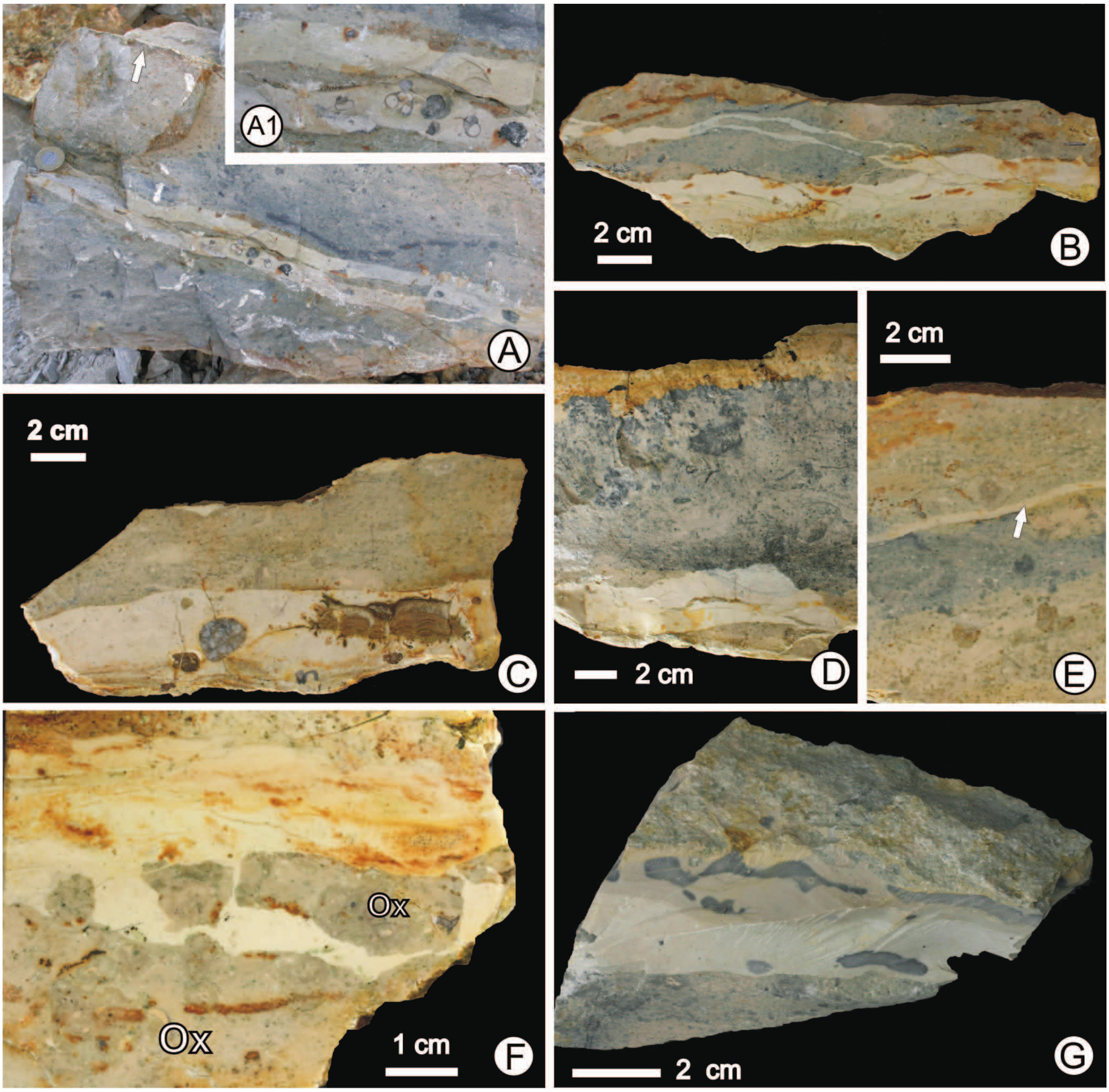

Fig. 3. Samples of Oxfordian limestones cut by injection dykes. All sections are approximately perpendicular to the topmost part of Oxfordian limestones. **A** – Oxfordian limestones truncated by abrasion surface (arrow) and cut by horizontal injection dykes filled with foraminiferal-calcisphere limestones with quartz pebbles and gastropod shells. Coin for scale is 2 cm in diameter, **A1** – Close-up of the dyke from the figure A showing gastropod shells and quartz pebbles, **B** – Polished slab showing fragment of larger dyke and thin outgrowth dykes, **C** – Dyke (lower part) filled with limestones containing fragment of stromatolite and quartz pebbles, **D** – Dyke (lower part) within Oxfordian limestones, dark colour due to sulphide mineralization, **E** – Thin dyke (arrow) cutting Oxfordian limestones (pit 2), **F** – Clasts of Oxfordian (Ox) limestone slightly displaced from the wall of dyke filled with white-reddish limestone, **G** – Oxfordian limestones cut by injection dyke filled by Campanian silicified limestones

rare quartz pebbles (Fig. 3A, C) and debris of phosphatic and ferruginous stromatolites (Fig. 3C). The limestones are white, locally with reddish, green and black spots. Several generations of dykes and fissure fillings (microstratification) were recognised (Fig. 4). They differ in abundance of foraminifera and calcispheres and subtly in sediment colour. The dyke fillings usually show lining parallel to the fissure walls.

The fractured Oxfordian limestones from pit 1 are irregularly stained with sulphide minerals (*e.g.*, Fig. 3A, D), while the non-fractured limestones are sparsely mineralized. Moreover, microscopic observations revealed that Oxfordian limestones are partly dolomitized, but spatial distribution of dolomitization was not studied. The sulphide mineralization and silicification were also observed within the dyke fillings, however less intensively than in the host Oxfordian limestones. It is also noteworthy that while in pit 1 the fissures are common (mostly in the eastern part), in pit 2, located some 100 m apart, the Jurassic bedrock was fractured very sparsely (Fig. 3E).

Additionally, rare vertical karstic cavities filled with conglomerates were identified (Fig. 5C). They are rounded in cross sections (Figs 2B, 5D) what indicates that they represent vertical dips of karstic cavities. They are, however, developed mostly as superficial depressions exposed on the abraded Oxfordian limestones (Fig. 5A, B). Vertical cavities are maximum *ca*. 50 cm deep, however, their definite vertical extension is not recognised because of poor exposure of the Oxfordian bedrock. Figure 1E shows spatial relation of injection dykes, karstic cavities, overlying marls and Oxfordian basement truncated by the Late Cretaceous abrasion platform.

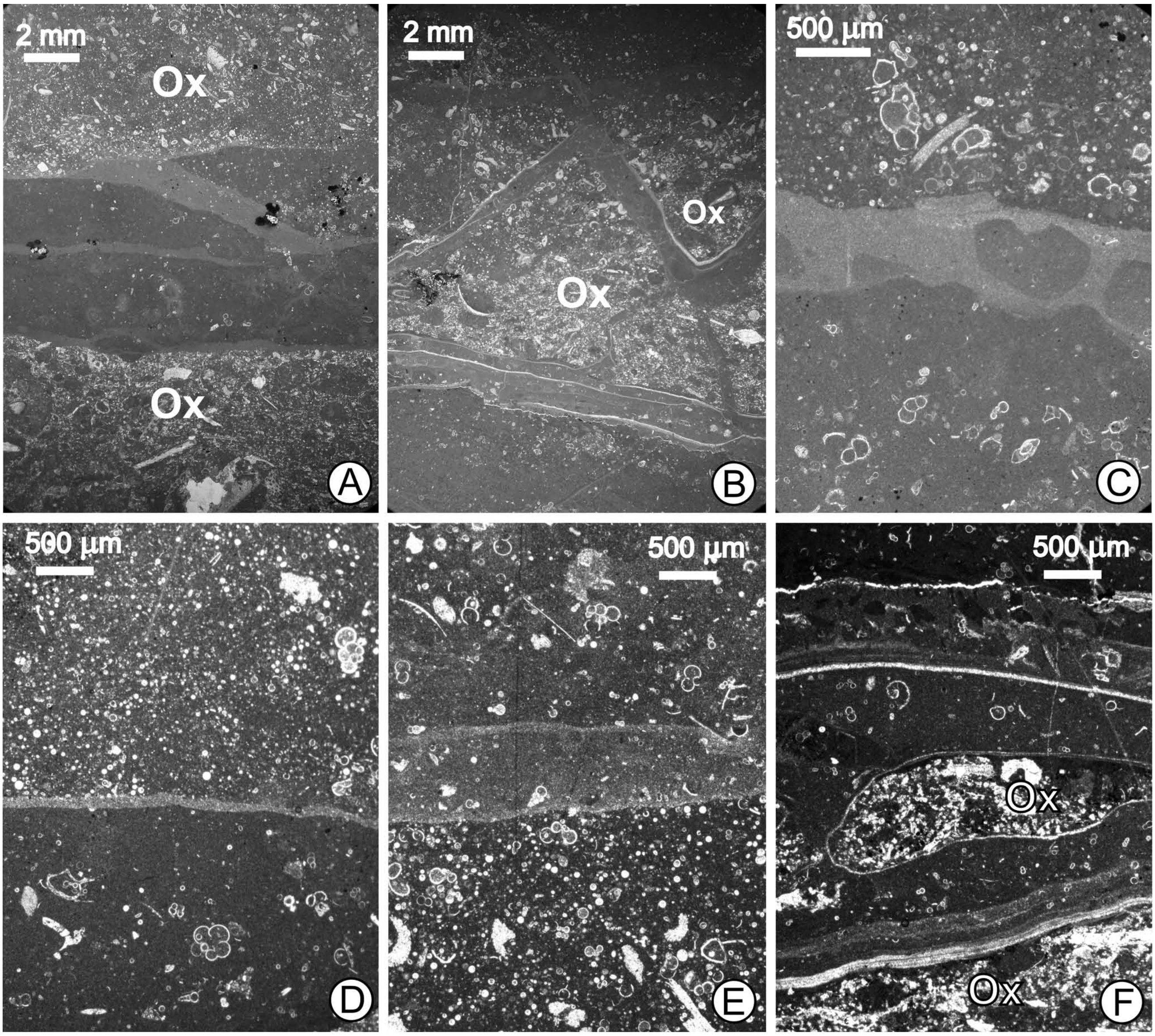

Fig. 4. **A–F** – Microphotographs of Campanian injection dykes and Oxfordian basement (Ox). Different generations of dykes are reflected in differences of filling sediments as result of various content of foraminifera, calcispheres (calcareous dinocysts) and micritic matrix. Note fissure network (**B**), dyke containing injected fragments of consolidated micritic limestone (**C**) and subtle lamination (**F**)

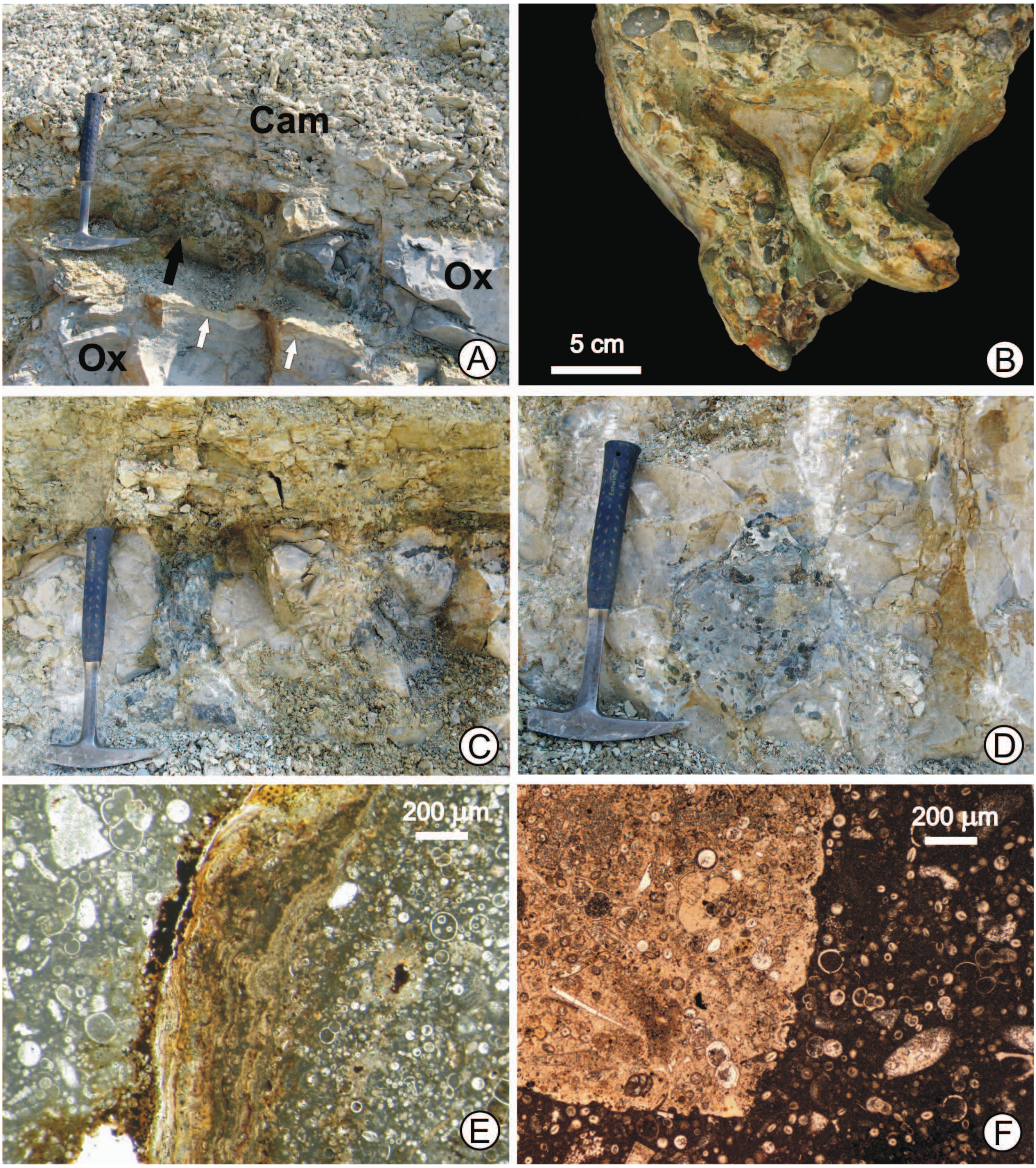

Fig. 5. **A** – Uneven abrasion platform truncating Oxfordian limestones (Ox); uppermost Turonian–?Lower Coniacian conglomerate fills cavity of karstic origin (black arrow) and is covered by Campanian marls (Cam); note subhorizontal injection dykes (white arrows; see also Fig. 2A), **B** – Late Cretaceous conglomerate filling karstic cavities (“cast”), **C** – Vertical karstic cavity filled by conglomerate, **D** – Transverse section through channel-like karstic cavity within Oxfordian limestones (compare Fig. 2B), **E, F** – Microphotographs of the uppermost Turonian–?Lower Coniacian conglomerate filling karstic cavities; note differences in microfacies of carbonate clasts and encrustation of ferruginous stromatolite

BIOSTRATIGRAPHICAL DATA

The age of conglomerates

Micropalaeontological examination was done both for the limestone clasts and carbonate matrix of the conglomerates.

Foraminifera distinguished in thin sections include planktonic index species. The presence of *Dicarinella primitiva* (Dalbiez) (Fig. 6E, F), which is the index species of Marginotruncana sigali–Dicarinella primitiva Zone (Premoli-Silva & Sliter, 1999), and the presence of *Dicarinella concavata* (Brotzen) (Fig. 6D), which is the index species of Dicarinella concavata Zone (zonation according to Robaszynski *et al.*, 1984; Caron, 1985; Robaszynski & Caron, 1995; Premoli-Silva & Rettori, 2002; Premoli-Silva & Verga, 2004) indicate an age within the latest Turonian–Coniacian interval (sample Pych 40; Fig. 7).

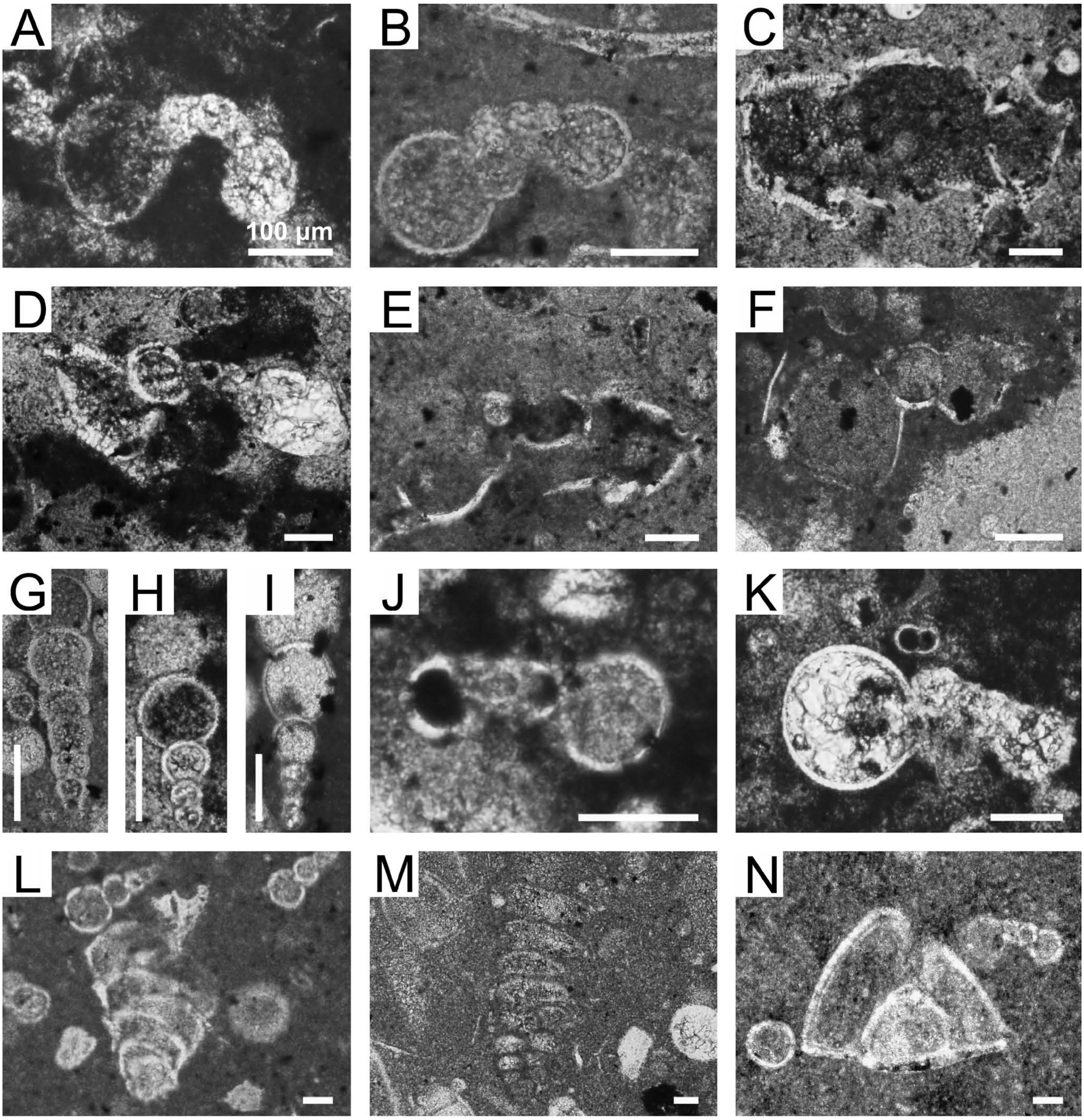

Fig. 6. **A–K** – The planktonic foraminiferids from conglomerate filling karstic cavities (Pych 40), axial sections. **A** – *Archaeoglobigerina bosquensis* (Pessagno), **B** – *Archaeoglobigerina* cf. *bosquensis* (Pessagno), **C** – *Dicarinella* sp., **D** – *Dicarinella concavata* (Brotzen), **E, F** – *Dicarinella primitiva* (Dalbiez), **G** – *Heterohelix moremani* (Cushman), **H, I** – *Heterohelix* sp., **J** – *Muricohedbergella planispira* (Tappan), **K** – *Whiteinella baltica* Douglas et Rankin, **L–N** – Benthic foraminiferids from Campanian injection dykes, axial section. **L**– *Eouvigerina aculeata* (Ehrenberg), **M** – *Gaudryina* sp., **N** – *Globorotalites* cf. *michelinianus* (d'Orbigny). Scale bar indicates 100 µm

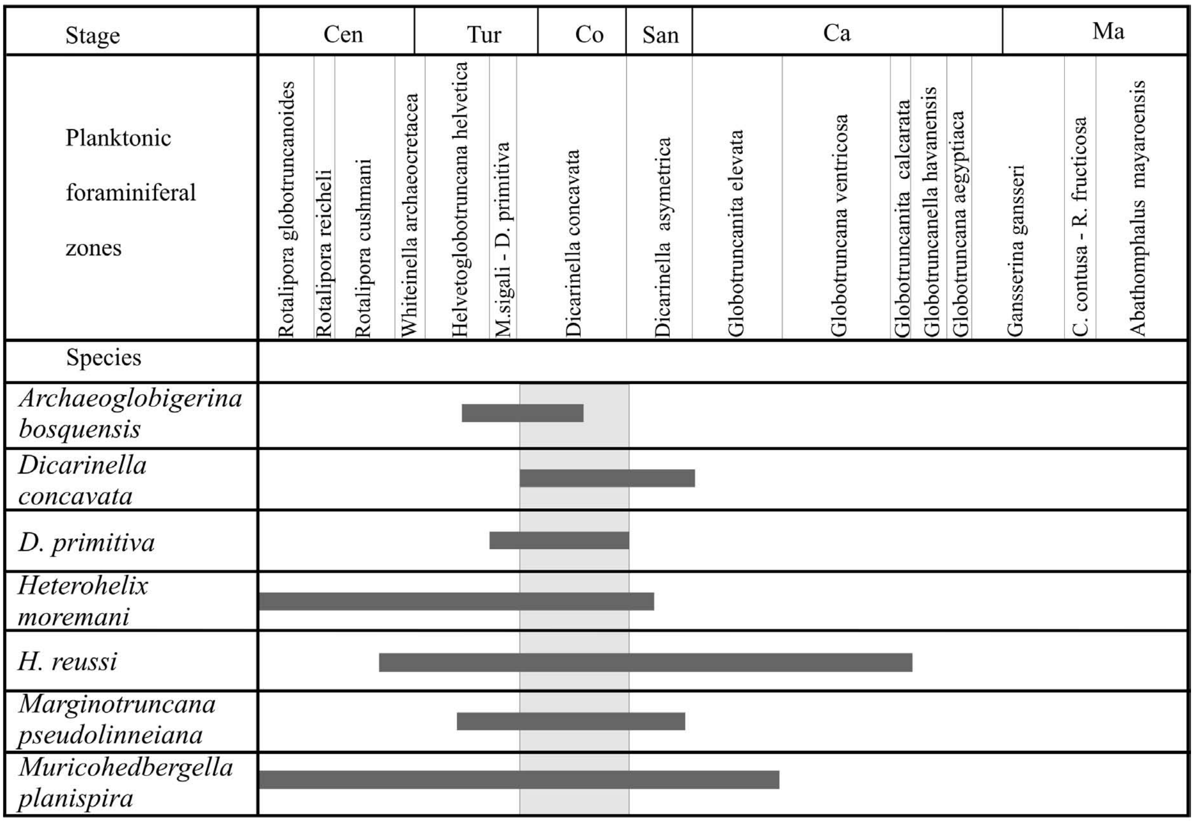

Fig. 7. Biostratigraphical ranges of the studied planktonic index foraminiferids from conglomerate. Ranges of species and biozones combined after Robaszynski *et al.* (1984), Caron (1985), Robaszynski and Caron (1995), Premoli-Silva and Rettori (2002), and Premoli-Silva and Verga (2004). The grey area indicates biozones recognised in the studied material

The index taxa are accompanied by other planktonic forams including *Archaeoglobigerina bosquensis* (Pessagno) (Fig. 6A, B), *Dicarinella* sp. (Fig. 6C), *Heterohelix moremani* (Cushman) (Fig. 6G), *Heterohelix reussi* (Cushman), *Marginotruncana praelinneiana* Pessagno, *Marginotruncana* sp., *Muricohedbergella planispira* (Tappan) (Fig. 6J), and *Whiteinella baltica* Douglas et Rankin (Fig. 6K). The Dicarinella concavata Zone contains *A. bosquensis*, the last occurrence of which is known from the Middle Coniacian and characterizes the middle part of this zone (Fig. 7). However, in the case of the studied conglomerates, the possible redeposition of the older faunas does not allow us to define the precise age. Dicarinella concavata Zone remains indicative, thus the age of the conglomerate based on foraminifera points to the latest Turonian–Coniacian interval.

The nannofossil assemblage, represented by sample Pych 41, is moderately diversified and abundant. State of preservation of the nannofossils is the best among the studied samples, though it is still estimated as O-2. This assemblage, dominated by *W. barnesiae*, contains 24 taxa, including among others such taxa as *Arkhangelskiella cymbiformis* (Fig. 8H), *Broinsonia parca expansa* (Fig. 8F), *Quadrum gartneri* (Fig. 8Oa) or *Micula* spp. (Fig. 8M). Moreover, it contains also two index species of Burnett's (1998) stratigraphic nannoplankton zonation for the Upper Cretaceous (UC zones): *Quadrum gartneri* (Fig. 8Oa), which defines the base of the middle Turonian UC 7 Zone; and *Broinsonia parca expansa* (Fig. 8F), which defines the base of the UC9c Subzone, lately correlated with the Upper Turonian (Lees, 2008). Furthermore, the assemblage also includes *Micula* spp. (Fig. 8M). Taxonomy of the found specimens was determined at the genus level due to poor preservation and scarce occurrence, but they may represent either *M. adumbrata* or *M. staurophora*. The first occurrence (FO) of *M. adumbrata* (probable ancestor of *M. staurophora*) is diachronous through the UC9a to UC9c zones, which embraces the interval from the middle Middle Turonian to the lower Middle Coniacian (Lees, 2008). Lees (2008) noted the FO of *M. adumbrata* in Słupia Nadbrzeżna section (Poland) within the UC9c Zone (Lower Coniacian), but in the Czech Republic (Březno section) this species was found within the UC9b Zone (Upper Turonian). On the other hand, Kędzierski (2008) studied the Turonian/Coniacian boundary interval in the Opole Trough (Poland) and did not find any *Micula* species up to upper Lower Coniacian. In contrast, *M. staurophora* has the certain stratigraphic position of the FO, that is the index species of the base of the UC10 Zone, correlated with the lower Middle Conia- cian. Therefore, in the case of *M. adumbrata* occurrence, that is *Micula* genus in general, the age of the studied assemblage is not older than the Late Turonian (UC9c Zone), but its Late Turonian/Early Coniacian age seems probable.

To conclude: based on foraminifera and nannoplankton, the age of conglomerates is established as the latest Turonian–?Early Coniacian.

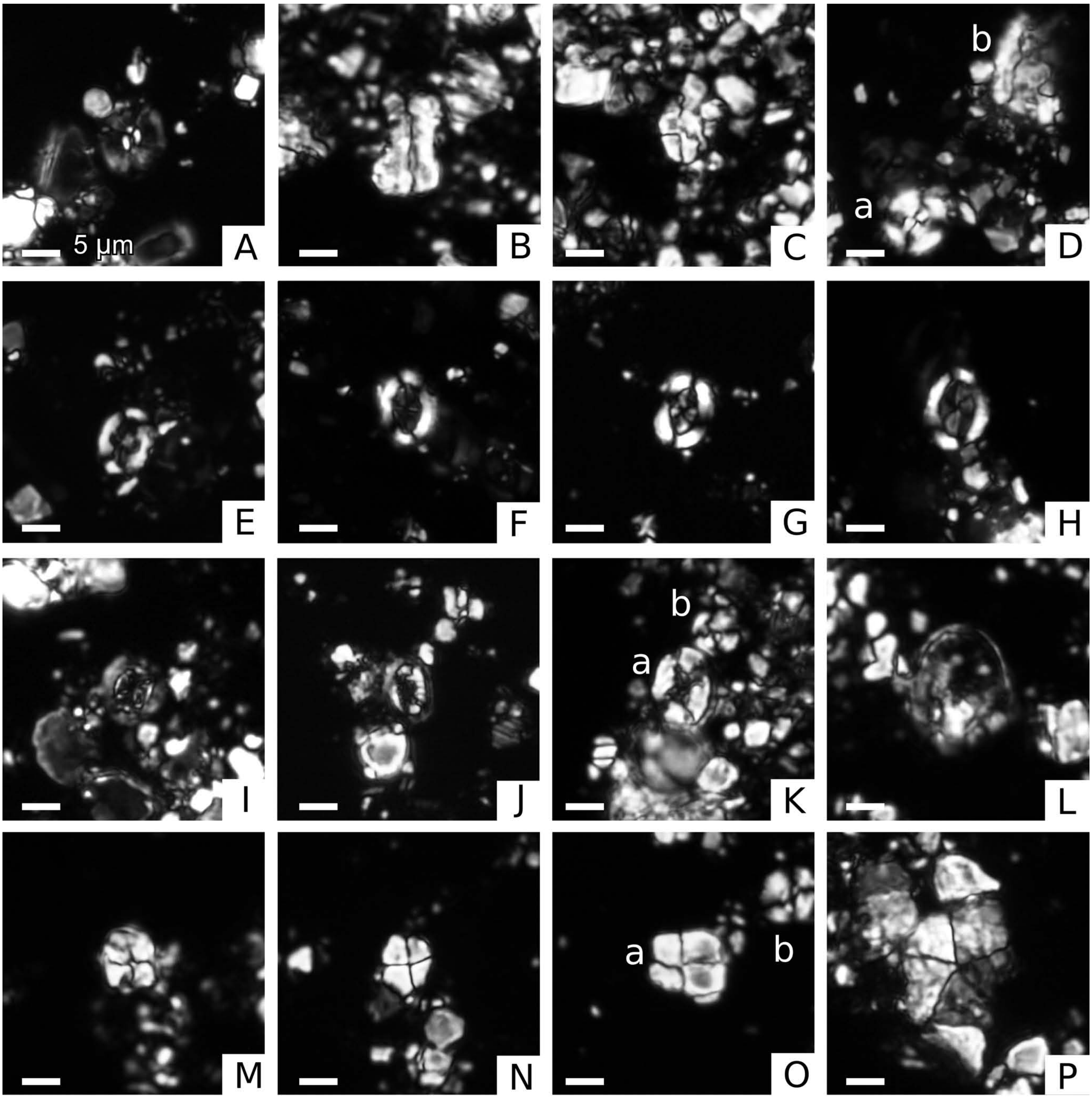

Fig. 8. Calcareous nannoplankton under the light microscope in cross-polarised light. **A** – *Bisctum constans* (Pych 41), **B** – *Lucianorhabdus cayeuxii* (Pych 50), **C** – *Calculites ovalis* (Pych 50), **D** – a. *Watznaueria barnesiae*, b. *Lucianorhabdus* cf. *L. cayeuxii* (Pych 50), **E** – *Broinsonia signata* (Pych 41), **F** – *Broinsonia parca expansa* (Pych 41), **G** – *Broinsonia matalosa* (Pych 41), **H** – *Arkhangelskiella cymbiformis* (Pych 41), **I** – *Prediscosphaera cretacea* (Pych 41), **J** – *Cribrosphaerella ehrenbergii* (Pych 41), **K** – a. *Eiffellithus eximius*, b. *Watznaueria barnesiae* (Pych 41), **L** – *Kamptnerius magnificus* (Pych 41), **M** – *Micula* sp. (Pych 41), **N** – ?*Quadrum* sp. (Pych 41), **O** – a. *Quadrum gartneri*, b. *Watznaueria barnesiae* (Pych 41), **P** – *Braarudosphaera bigelowii* (Pych 41). Scale bar indicates 5 µm

Coniacian deposits are well documented by Walaszczyk (1992) and Olszewska-Nejbert and Świerczewska-Gładysz (2009) *ca*. 30 km northwards of Kraków, and possibly they may also be expected in the Kraków region. There are also some older reports that may point to the presence of the Coniacian in Kraków vicinity in the light of the modern stratigraphic scheme. For instance, Zaręczny (1878), Smoleński (1906), Panow (1934) and Alexandrowicz (1954) described fossils which first appear within the traditional Inoceramus schloenbachi Zone. Lately, *I. schloenbachi* fell into synonymy with the *Cremnoceramus crassus*, the index species for C. crassus Zone correlated with the Lower Coniacian (Walaszczyk, 1992; Kauffman *et al.*, 1996; Walaszczyk & Wood, 1998). Hence, the mentioned findings may be ascribed as the Lower Coniacian. Nevertheless, these older findings need current studies to indubitably confirm them.

The age of the dyke filling limestones

In the foraminiferal assemblages (analysed in the thin sections) from dyke filling limestones, abundant planktonic non-keeled and keeled taxa occur, such as: *Archaeoglobigerina cretacea* (d'Orbigny) (Fig. 9A, 10K), *Archaeoglobigerina blowi* (Bolli), *Contusotruncana* cf. *plummerae* (Gandolfi) (Fig. 9B), *Globotruncana arca* (Cushman) (Fig. 9C), *Globotruncana bulloides* Vogler (Fig. 9D, E), *Globotruncana hilli* Pessagno (Fig. 9F, G), *Globotruncana* ex gr. *lapparenti* Brotzen (Fig. 9H), *Globotruncana linneiana* (d'Orbigny) (Fig. 9I), *Globotruncana* cf. *rosetta* (Carsey) (Fig. 9J), *Heterohelix globulosa* (Ehrenberg) (Fig. 9K), *Heterohelix* cf. *reussi* (Cushman) (Fig. 9M), *Muricohedber-*

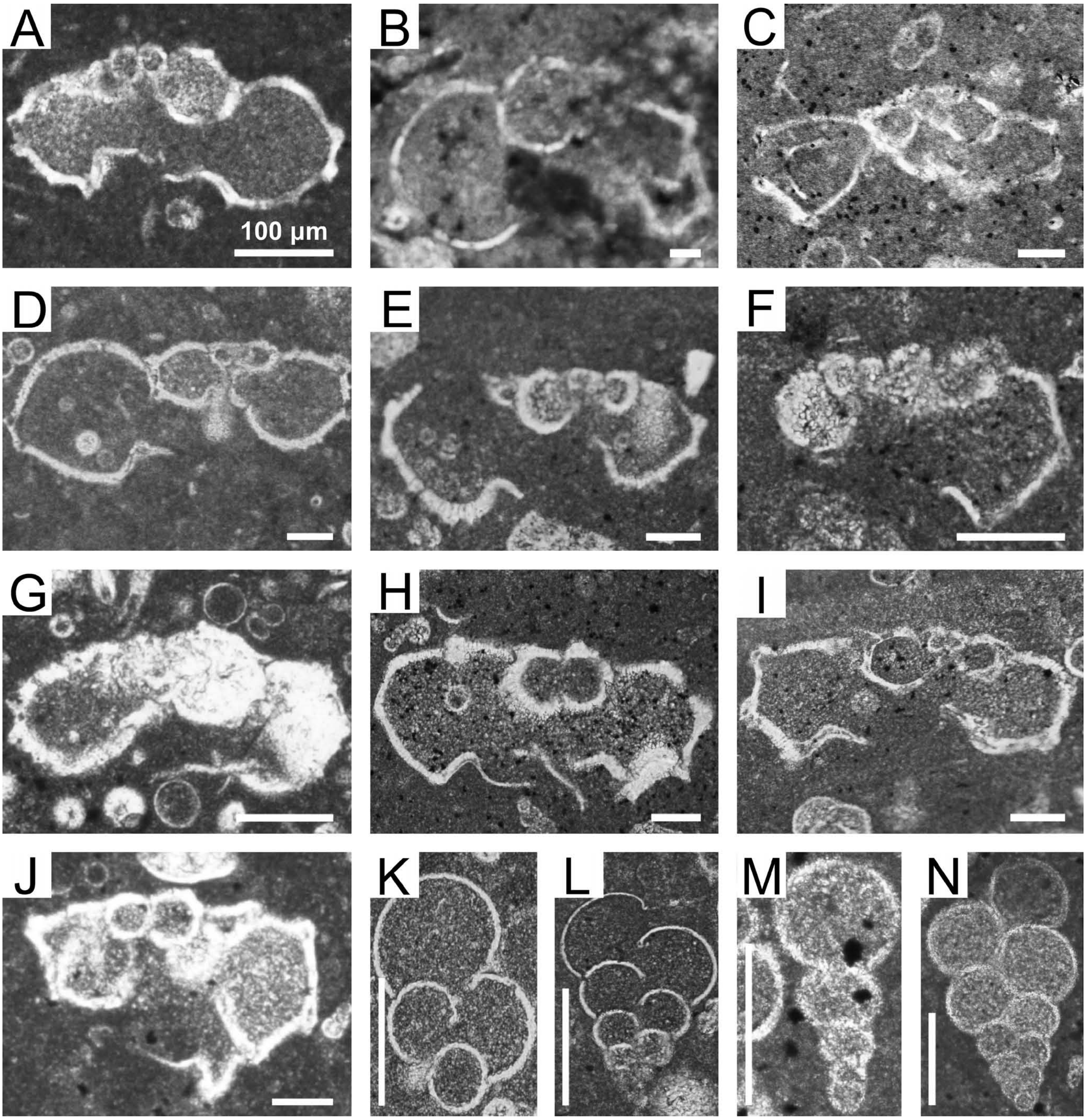

Fig. 9. Campanian planktonic foraminiferids from injection dykes. **A** – *Archaeoglobigerina cretacea* (d'Orbigny), axial section (Pych 5), **B** – *Contusotruncana* cf. *plummerae* (Gandolfi), axial section (Pych 4), **C** – *Globotruncana arca* (Cushman) (Pych 5), **D** – *Globotruncana bulloides* Vogler, axial section (Pych 5), **E** – *Globotruncana bulloides* Vogler, axial section (Pych 27), **F** – *Globotruncana hilli* Pessagno, axial section (Pych 5), **G** – *Globotruncana* cf. *hilli* Pessagno, axial section (Pych 4), **H** – *Globotruncana* ex. gr. *lapparenti* Brotzen, axial section (Pych 5), **I** – *Globotruncana linneiana* Brotzen, axial section (Pych 5), **J** – *Globotruncana* cf. *rosetta* (Carsey), axial section (Pych 5), **K** – *Heterohelix globulosa* (Ehrenberg), axial section (Pych 27), **L** – *Heterohelix* sp., perpendicular to axial section (Pych 4), **M** – *Heterohelix* cf. *reussi* (Cushman), perpendicular to axial section (Pych 27), **N** – *Heterohelix* sp., axial section (Pych 27). Scale bar indicates 100 µm

gella holmdelensis (Olsson) (Fig. 10D), *Muricohedbergella monmouthensis* (Olsson) (Fig. 10E–G), and *Rugoglobigerina rugosa* (Plummer) (Fig. 10H–J).

Benthic foraminiferids are relatively rare and dominated by calcareous specimens: *Eouvigerina aculeata* (Ehrenberg) (Fig. 6L), *Globorotalites* cf. *michelianus* (d'Orbigny) (Fig. 6N), *Reussella* sp., and *Stensioeina* sp. Agglutinated benthic forms are represented by *Arenobulimina* sp. and *Gaudryina* sp. (Fig. 6M).

The planktonic foraminiferal assemblages represent Globotruncana ventricosa and Globotruncanita calcarata zones *sensu* Robaszynski *et al.* (1984), Caron (1985), Robaszynski and Caron (1995), Premoli-Silva and Rettori (2002), and Premoli-Silva and Verga (2004) and indicate the Early/Late Campanian age (Fig. 11), not older than the latest Early Campanian. All the diagnostic species as well as some taxa which are typical of the studied foraminiferal assemblages are illustrated in Figs 9 and 10. Among foraminiferal assem-

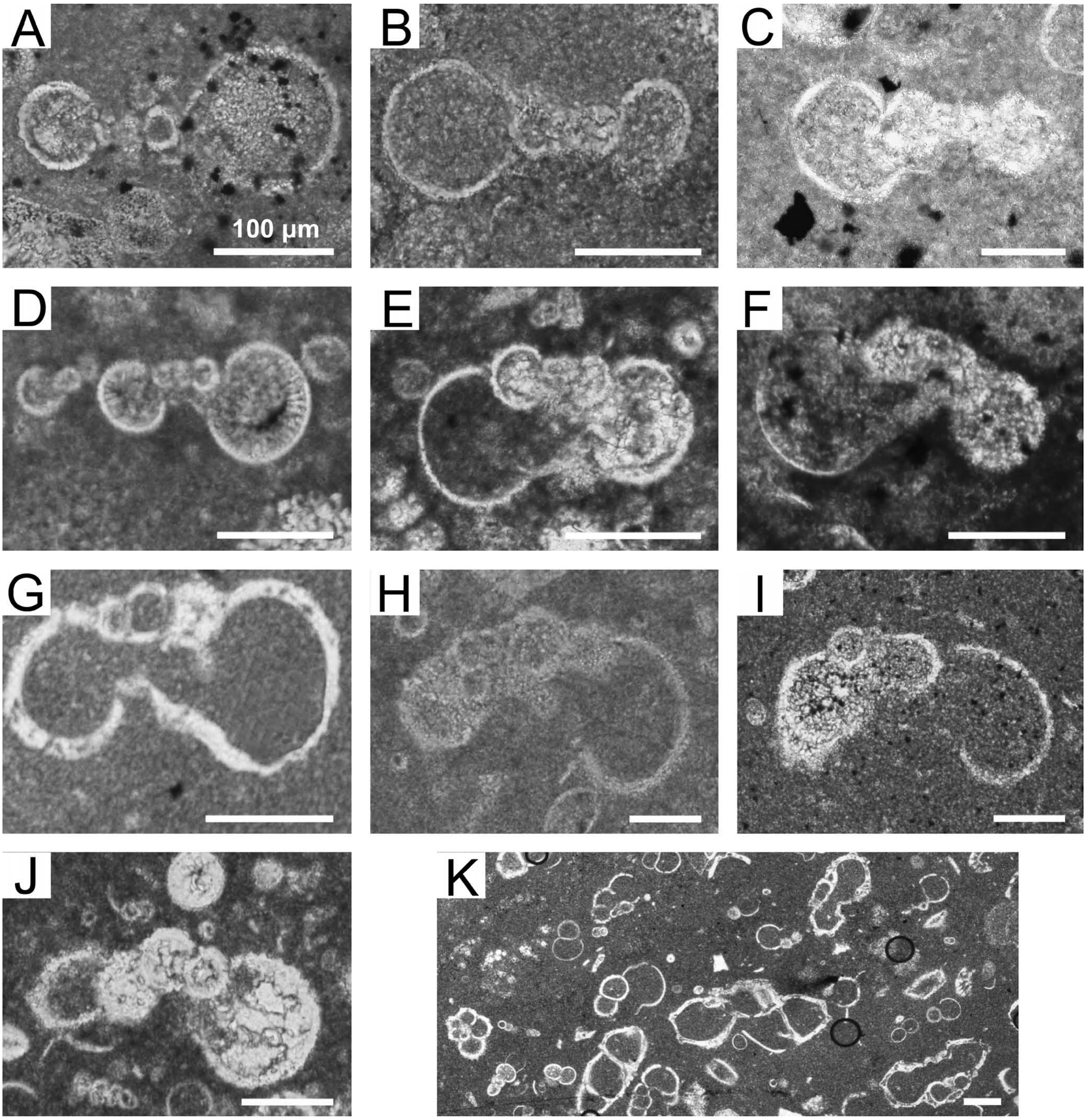

Fig. 10. Campanian planktonic foraminiferids from injection dykes; axial sections. **A** – *Macroglobigerinelloides bollii* (Pessagno) (Pych 5), **B** – *Macroglobigerinelloides bollii* (Pessagno) (Pych 27), **C** – *Macroglobigerinelloides* cf. *prairiehillensis* Possagno (Pych 5), **D** – *Muricohedbergella holmdelensis* (Olsson) (Pych 5), **E, F** – *Muricohedbergella monmouthensis* (Olsson) (Pych 5), **G** – *Muricohedbergella monmouthensis* (Olsson) (Pych 5), **H**–**J** – *Rugoglobigerina rugosa* (Plummer) (Pych 5), **K** – Foraminiferal assemblages dominated by *Archaeoglobigerina cretacea* (d'Orbigny) (Pych 4). Scale bar indicates 100 µm

Table 1

Distribution of calcareous nannofossils and state of preservation of the studied assemblages

	Pych 5	Pych 20	Pych 24	Pych 31	Pych 41	Pych 50
State of preservation	O-3	O-3	O-2	O-3	O-2	O-2
Arkhangelskiella sp.					x	
A. cymbiformis					x	
Biscutum constans					x	
B. melaniae					x	
Braarudosphaera sp.						x
B. bigelowii					x	
Broinsonia matalosa					x	
B. signata					x	
B. parca expansa					x	
Calculites sp.			x			
C. cf. *ovalis*						x
Chiastozygus litterarius					x	
Cribrosphaerella ehrenbergii					x	
Eiffellithus sp.					x	x
E. eximius					x	
Gartnerago obliquum					x	
Kamptnerius magnificus					x	
Lucianorhabdus sp.			x			x
Lucianorhabdus cayeuxii						x
Micula sp.					x	
Prediscosphaera sp.					x	
P. cretacea					x	
?Quadrum sp.					x	
Quadrum gartneri					x	
Reinhardtites sp.					x	
Retecapsa crenulata					x	
Watznaueria barnesiae	x	x	x	x	x	x
Zeugrhabdotus bicrescenticus					x	
Z. diplogrammus					x	
Z. embergeri					x	
Z. gabalus					x	

x – presence; blank – absence

blages only the range of *Heterohelix reussi* is an exception; its last occurrence (LO) is characteristic for the middle part of Globotruncanita elevata Zone (Fig. 11), which represents the Early Campanian. However, according to Peryt (1980), the LO of this species in Central Poland is noted from the Upper Campanian (Globotruncanita calcarata Zone). In the current Cretaceous Time Scale (Ogg *et al.*, 2008) Globotruncanita calcarata Zone is situated in the lower part of the Upper Campanian (Fig. 11).

The nannofossil assemblage from dykes (samples Pych 5, 20, 24, 31, 50) contains poorly preserved and scarce calcareous nannofossils (Fig. 8B–D). Only five taxa were recognised within this assemblage dominated by *Watznaueria barnesiae* (Fig. 8Da), which constitutes about 90% of total abundance. Furthermore, *Calculites ovalis* (Fig. 8C), *Lucianorhabdus cayeuxii* (Fig. 8B, Db), *Eiffellithus* sp., and *Braarudosphaera* sp. were ascertained as well. Complete list of the calcareous nannoplankton is given in Table 1.

Although only few index species occur within the dyke fillings, the presence of *L. cayeuxii*, whose FO defines the base of UC11c subzone embracing the uppermost Coniacian and the Lower Santonian, allows one to define the age of the fillings as not older than the latest Coniacian.

Concluding, the age of limestone filling injection dykes is Early/Late Campanian (Globotruncana ventricosa and Globotruncanita calcarata zones), and not older than the latest Early Campanian.

The age of the overlying marls

The grey marls overlying Oxfordian limestones are lithologically very similar to the Santonian–Lower Campanian marls described from other sites in the Kraków region; therefore, they were previously believed to represent the Santonian (Kołodziej *et al.*, 2008), an assumption which is here revised. The marls contain abundant non-keeled planktonic foraminifera with dominating *Archeoglobigerina cretacea* (d'Orbigny), *Heterohelix navarroensis* Loeblich, *Heterohelix striata* Ehrenberg, *Muricohedbergella monmouthensis* (Olsson), and rare *Rugoglobigerina rugosa* (Plummer). Planktonic keeled forams are rare and represented by *Globotruncana arca* (Cushman) and *Globotruncana bulloides* Vogler. The first occurrence of *M. monmouthensis* (zonation according to Robaszynski *et al.*, 1984; Caron, 1985; Robaszynski & Caron, 1995; Premoli-Silva & Rettori, 2002; Premoli-Silva & Verga, 2004) indicates the Early/Late Campanian age, not older than the latest Early Campanian. Numerous benthic species from the marls, including *Cibicides beaumontianus* (d'Orbigny), *Gavelinella costulata* (Marie), *Globorotalites michelinianus* (d'Orbigny), *Praebulimina* div. sp., *Stensioeina* div. sp. (*Stensioeina exsculpta* (Reuss), and *Stensioeina gracilis* Brotzen) are characteristic for the Campanian (Zapałowicz-Bilan, 1982, *cf.* Gawor-Biedowa, 1992).

DISCUSSION

Recently, Montenat *et al.* (2007) reviewed the main types of seismites and proposed their modified classification. Among principally brittle deformations, neptunian dykes and injection dykes are the best known seismites. Neptunian dykes are formed by infilling pre-existing fissures exposed on the sea bottom, and which may be open for a long time. Injection dykes are filled by material through hydrostatically controlled pressure, and are combination of hydrofracturing of hard substrate and filling by overpressured (fluidized) soft sediments (Flügel, 2004; Montenat *et al.*, 2007). Fissure networks developed nearby the fault zone commonly produce a jigsaw-puzzle pattern (autoclastic breccias; Montenat *et al.*, 2007). Well developed jigsaw-puzzle pattern of cracks does not occur in the studied case, what can suggests that the region was not situated close to an active fault.

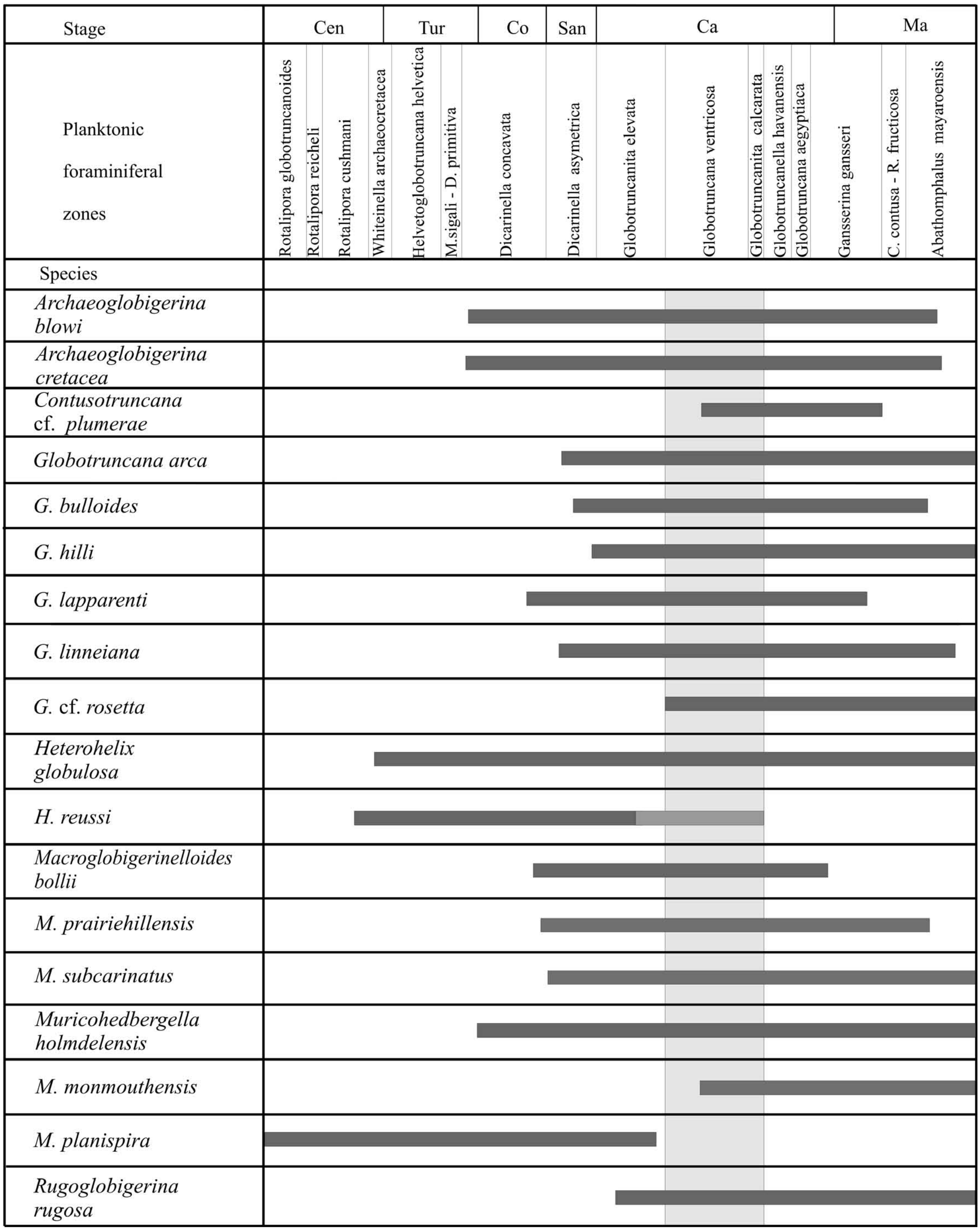

Fig. 11. Biostratigraphical ranges of the planktonic foraminiferids from injection dykes. Ranges of species and biozones combined after Robaszynski *et al.* (1984), Caron (1985), Robaszynski and Caron (1995), Premoli-Silva and Rettori (2002), Premoli-Silva and Verga (2004), and Peryt (1980). The grey area indicates biozones recognised in the studied material

Sediment fillings of the studied dykes display several characteristics, such as microstratification, instant lithification and multiple cross-cutting, which document complex generation of the cracks. Because the dyke fill shows mostly lining parallel to the fissure walls, it evidences an active infilling typical of injection mechanism, that is forceful mode of emplacement initiated as a result of high fluid pressures (Röshoff & Cosgrove, 2002; Montenat *et al.*, 2007). Thus, as previously suggested by Kołodziej *et al.* (2008), the fissures are injection dykes. Seismic shocks induced fluid overpressure, hydraulic fracturing of the Jurassic substrate, and liquefaction of the overlying Lower/Upper Campanian unconsolidated sediments (now recognised only within dykes). The latter, as well as small quartz pebbles and fragments of stromatolite (from the uppermost Turonian–?Lower Coniacian conglomerates) are subordinate components of some injection dykes. They were sucked into the opened fractures, producing the injection dykes.

As mentioned above, the cracks are mostly sub(horizontal) and affected only the topmost several centimetre thick layer of the Jurassic bedrock. This indicates that this system of cracks originated by Love or Rayleigh waves travelling near the ground surface. These surface waves are most effective in ground displacement and disturbance (Bolt, 2004).

The morphological features of the discussed injection dykes differ from the typical, gravitationally-filled neptunian dykes by the dominant role of hydraulic forces. Similar injection dykes are known from other tectonically active settings, both recent (Montenat *et al.*, 1991, 2007) and ancient ones (Füchtbauer & Richter, 1983; Cosgrove, 2001; Aubrecht & Szulc, 2006), where their origin have been also ascribed to the quake tremor. Finally, the seismic origin of such veinlets has been confirmed by quake-simulation experiments (Brothers *et al.*, 1996).

The discussed area was tectonically active in the Late Cretaceous. During that time the Kraków Swell was located on the western margin of the Mid-Polish Trough. According to Krzywiec *et al.* (2009), inversion movements commenced during the Late Turonian?–Coniacian, and lasted until Maastrichtian–post-Maastrichtian times. In the opinion of other authors (Kutek & Głazek, 1972; Świdrowska *et al.*, 2008 and references therein), inversion of the SE part of the Mid-Polish Through could be observed not earlier than in the Maastrichtian. It is noteworthy that the Cretaceous tectonic framework of the studied area was founded as early as in Late Jurassic times, when a complex system of horsts and grabens developed under transcurrent motion of the reactivated Variscan, Kraków–Lubliniec master fault (Złonkiewicz, 2006). Block movements affecting the entire Kraków region during the Turonian–Santonian influenced sedimentary evolution and resulted in unconformities and stratigraphic gaps (Marcinowski, 1974; Walaszczyk, 1992; Olszewska-Nejbert, 2004; Olszewska-Nejbert & Świerczewska-Gładysz, 2009). The lack of Santonian in the studied area and in some other parts of the Kraków region (Zapałowicz-Bilan *et al.*, 2009) might suggest a non-deposition interval.

The Late Cretaceous tectonism in the Kraków region was possibly linked, similarly as in northern Germany and the Anglo-Paris Basin, with compressional stress due to collision of African and European plates (Ziegler, 1990). Tectonic pulses of the Subhercynian tectonism distinguished in both mentioned areas show only some slight age differences, and in opinion of Mortimore *et al.* (1998) can be extended more widely into the northwestern European basins. Following this opinion, the described injection dykes (Early/Late Campanian) could be correlated with the Peine Phase representing the terminal Early Campanian. Campanian tectonics could be related to strike-slip movement of small faults along the NE–SW oriented Kurdwanów– Zawichost Fault Line (Świdrowska *et al.*, 2008).

The injection dykes encompass a foraminiferal assemblage which is unknown from the Kraków region. This indicates that the dykes are hosting sediments eroded before deposition of the overlying grey marls. The foraminiferal assemblage from dykes is characterised by highly diversified planktonic forms with double-keeled species, particularly represented by *Globotruncana* (Fig. 9). Bathypelagic globotruncanids are characteristic of the Tethyan domain. The presence of Tethyan forms in Boreal areas may indicate better communication with the Tethys and/or warming of Boreal waters. The free connection between the Tethyan and Boreal provinces during the Late Cretaceous was already postulated by Hanzlíková (1972), Pożaryska and Peryt (1979), Gasiński (1997, 1998), and Marcinowski and Gasiński (2002). The overlying Lower/Upper Campanian grey marls also differ in their foraminiferal composition from the Santonian–Campanian marls from other places of the Kraków region by dominance of planktonic foraminifera, and not by benthic calcareous forms (Machaniec *et al.*, 2004; Machaniec & Zapałowicz-Bilan, 2005, 2008; Zapałowicz-Bilan *et al.*, 2009).

The recognised karstic cavities filled with conglomerates were interpreted by Krobicki *et al.* (2008a, b) as neptunian dykes, however, their morphological characteristics deny such an interpretation. The latest Turonian–?Early Coniacian age of conglomerates postdates karstification, however, dating of karstification is ambiguous. Unequivocal pre-Cenomanian karst forms are not common in epicratonic Poland (Głazek, 1989). Bukowy (1956) recognised north of Kraków (Korzkiew) palaeokarst structures dated as pre-Turonian.

It is very likely that due to so called seismic pumping, accompanying the quake tremors (Sibson *et al.*, 1975), some ascended hydrothermal fluids resulted in sulphide mineralisation and silicification of the affected rocks. Gaweł (1949) and Dżułyński and Żabiński (1954) recognised that grey Oxfordian limestones, locally occurring in the Kraków region, are caused by finely dispersed pyrite and are associated with Neogene faults. The recent observations suggest that at least part of the sulphide mineralization might be related with the Late Cretaceous tectonic activity. However, its Neogene age due to rejuvenation of Late Cretaceous tectonic structures is an alternative explanation, particularly that this process affected mostly Oxfordian limestones, and not dyke fillings.

CONCLUSIONS

1. The fissures network recognised within the topmost part of Oxfordian bedded limestones of the Zakrzówek Horst represents Early/Late Campanian synsedimentary injection dykes.
2. Abundant planktonic foraminifera in the dyke fillings indicate the Early/Late Campanian Globotruncana ventricosa and Globotruncanita calcarata zones. The presence of numerous and diversified keeled globotruncanids in the Campanian of the Kraków region is recognised for the first time.
3. Injection dykes resulted from seismically induced hydraulic fracturing of the Jurassic substrate, followed by filling of overpressured, fluidised carbonate sediments. Limestones similar to those filling dykes are unknown so far from the Kraków region, and differ in respect to lithology and foraminiferal composition from the overlying grey marls, although they represent the same foraminiferal biozone.

4. The Jurassic bedrock was karstified, and the uppermost Turonian–?Lower Coniacian conglomerates filling of karst cavities postdates the karstification stage.

5. The grey marls overlying the uppermost Turonian–?Lower Coniacian conglomerates or directly Oxfordian limestones represent the Early/Late Campanian Globotruncana ventricosa and Globotruncanita calcarata zones, thus the same as limestones filling injection dykes. These marls contain abundant non-keeled planktonic foraminifera, while keeled forms are rare.

6. The Santonian deposits, which commonly occur in the Late Cretaceous sections in the Kraków region, are absent in the studied section. This indicates differentiated sedimentary or tectonic history of particular tectonic blocks belonging to the Kraków Swell.

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