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Biostratigraphy and palaeoenvironment of the Kimmeridgian–Lower Tithonian pelagic deposits of the Krížna Nappe, Lejowa Valley, Tatra Mts. (southern Poland)

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The Upper Jurassic strata of the Krížna Unit in the Tatra Mts. comprises pelagic, fine-grained and well-oxygenated deposits. They are represented by red radiolarites and radiolarian limestones (Czajakowa Radiolarites Formation), red nodular limestones (Czorsztyn Limestones Formation) and wavy, platy or nodular light grey and reddish limestones and marlstones (Jasenina Formation). These deposits are mainly wackestones characterized by a succession of the following microfacies: radiolarian, filament-*Saccocoma*, *Saccocoma* and *Globochaete*–*Saccocoma*. The section comprises four calcareous dinoflagellate zones, i.e. the Late Kimmeridgian Moluccana Zone, and the Early Tithonian Borzai, Pulla and Malmica zones. In the uppermost part of the studied section, the Early Tithonian Dobeni Subzone of the Chitinoidella Zone has been identified. Using these biostratigraphic data, the sedimentation rate for the Late Kimmeridgian (Borzai Zone) and Early Tithonian (Dobeni Subzone of the Chitinoidella Zone) interval is estimated as 3.7 m/my. This is in accordance with the general trend of increasing sedimentation rate through the Tithonian and Berriasian. The increased supply of clastic material in the Jasenina Formation may have been caused by climate changes and continental weathering. The sedimentation was controlled mainly by eustatic changes and fluctuations in ACD and CCD levels.

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Key words: microfacies, biostratigraphy, calcareous dinoflagellates, calpionellids, Upper Jurassic, Western Carpathians.

INTRODUCTION

The biostratigraphy of the Upper Jurassic pelagic deposits of the Krížna Nappe (Fatricum Domain) in the Tatra Mountains is poorly constrained, mainly because of a scarcity of index fossils. The ages of long sections are only roughly ascribed to stages, often on the basis of problematic or controversial evidence. Some data come from radiolaria which date the radiolarian limestones and radiolarites (Ždiar Formation) to the Middle Bathonian–Lower Kimmeridgian (Polák et al., 1998; Bąk, 2001). More precise dating refers to the uppermost Jurassic, where chitinoidellids and calpionellids (Lefeld, 1974; Pszczółkowski, 1996) combined with magnetostratigraphy (Pszczółkowski, 2003a, b; Grabowski and Pszczółkowski, 2006) helped to distinguish discrete zones and levels within the Jasenina Formation from the uppermost Early Tithonian (the Saccocoma Zone and the Magnetozone CM 20r; see also Grabowski and Pszczółkowski, 2004) through the Jurassic–Cretaceous boundary. The most stratigraphically problematic deposits include red radiolarites and radiolarian limestones, nodular and grey platy limestones up to the first occurrences of chitinoidellids (Figs. 1–3).

New stratigraphic information comes from the distribution of calcareous dinoflagellates, which have been successfully used in the stratigraphy of similar deposits in the Pieniny Klippen Belt and other parts of the Western Carpathians in Slovakia (Borza, 1984; Reháková, 2000), but only occasionally in the Tatra Mountains (Grabowski and Pszczółkowski, 2006). With the help of this tool, combined with microfacies analysis, we described the stratigraphy of red radiolarites, radiolarian limestones, and nodular and grey platy limestones of the Krížna Nappe on the eastern slopes of the Lejowa Valley in the Western Tatra Mountains (Figs. 1, 2 and 4). They belong to the top-

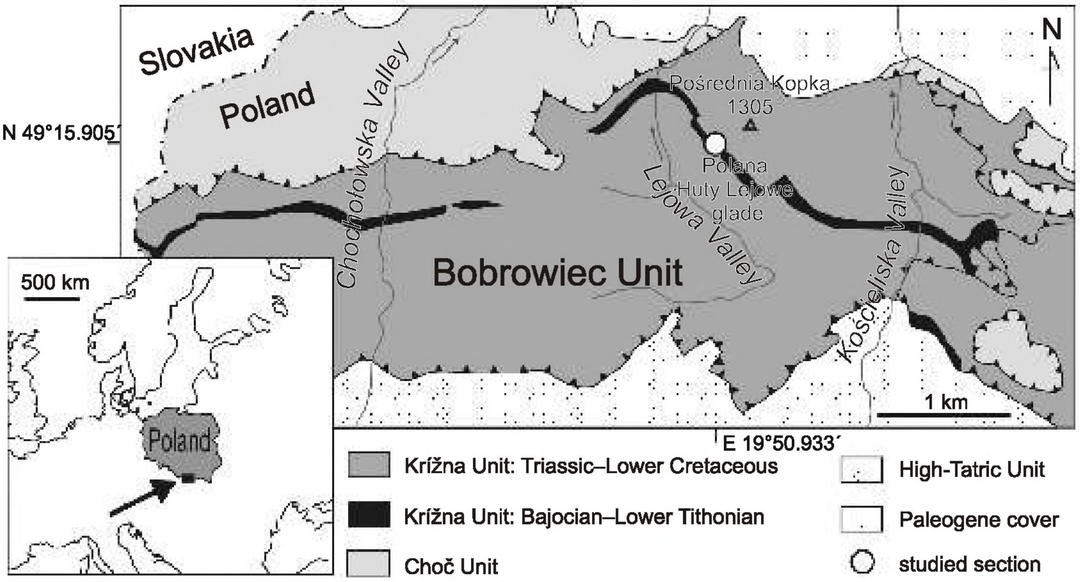

Fig. 1. Geological sketch map of the Polish part of the Western Tatra Mountains (after Bac-Moszaszwili et al., 1979, simplified) showing the location of the Lejowa Valley sections

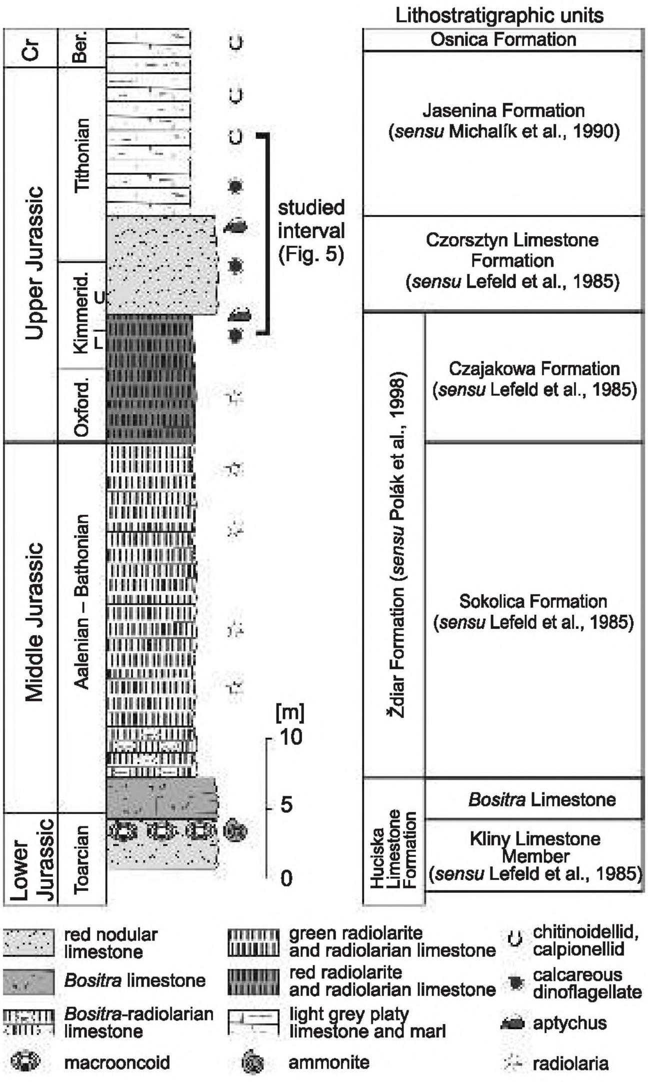

Fig. 2. Lithostratigraphic log of the Upper Jurassic rocks of the Križna Unit in the Western Tatra Mountains (after Lefeld et al., 1985)

most part of the Ždiar Formation, the Czorsztyn Limestone Formation (Lefeld et al., 1985) and to the lowest part of the Jasenina Formation (Fig. 2; Grabowski and Pszczółkowski, 2006). The Czorsztyn Limestone Formation has been ascribed to the Kimmeridgian and partly to the Tithonian on the basis of isolated occurrences of aptychi (Gąsiorowski, 1959, 1962; see also Lefeld et al., 1985), but their imprecise location in the sections limits the value of these findings. The lower (but not the lowest) part of the Jasenina Formation in the Pośrednie III section (3.6 km to the west from the section investigated) is dated to the Lower Tithonian (Grabowski and Pszczółkowski, 2006).

GEOLOGICAL SETTING

The study area belongs to the Križna Unit represented by the partial nappe of the Bobrowiec Unit (Fig. 1). This unit contains about 2000 m of Middle Triassic through to Lower Cretaceous strata of the Fatricum Domain, the beds of dip homoclinally to the north. The Upper Jurassic deposits are developed as typical Tethyan, basinal, pelagic facies, such as radiolarites, radiolarian limestones, red nodular limestones and light platy limestones (Fig. 2).

The red radiolarites and radiolarian limestones, 4–15 m thick, are ascribed to the Czajakowa Radiolarite Formation (Lefeld et al., 1985) or to the uppermost part of the Ždiar Formation (Polák et al., 1998). They have been dated to the Oxfordian–Lower Kimmeridgian on the basis of aptychi (Gąsiorowski, 1959). Their Lower Kimmeridgian upper limit was also based on radiolarians (Polák et al., 1998; Fig. 3).

The radiolarites and radiolarian limestones are overlain by nodular and partly marly red limestones, which are 6–10 thick, and are ascribed to the Czorsztyn Limestone Formation (Lefeld et al., 1985). They are less marly in the eastern part of the Tatra Mts. (Belianske Tatry). They were dated to the Kimmeridgian–Lower Tithonian on the basis of aptychi (Gąsiorowski, 1959).

The overlying 15 m thick succession of partly siliceous limestones and marly limestones belongs to the Jasenina Formation

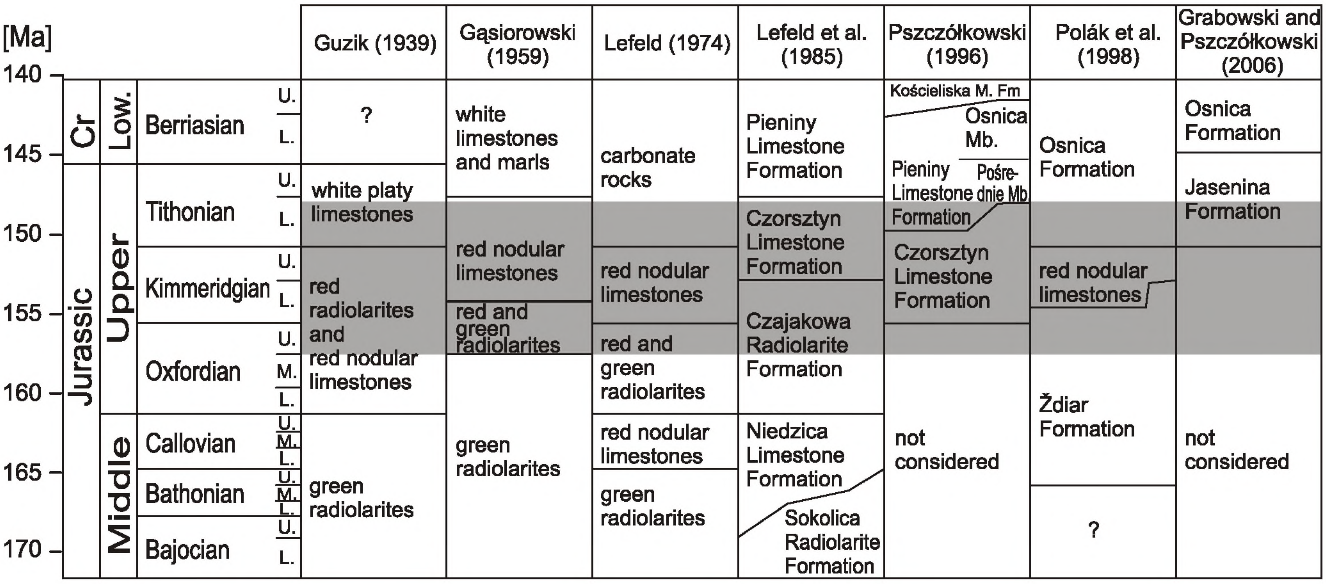

Fig. 3. Literature data on the stratigraphical position of the section studied

The time interval studied is shaded

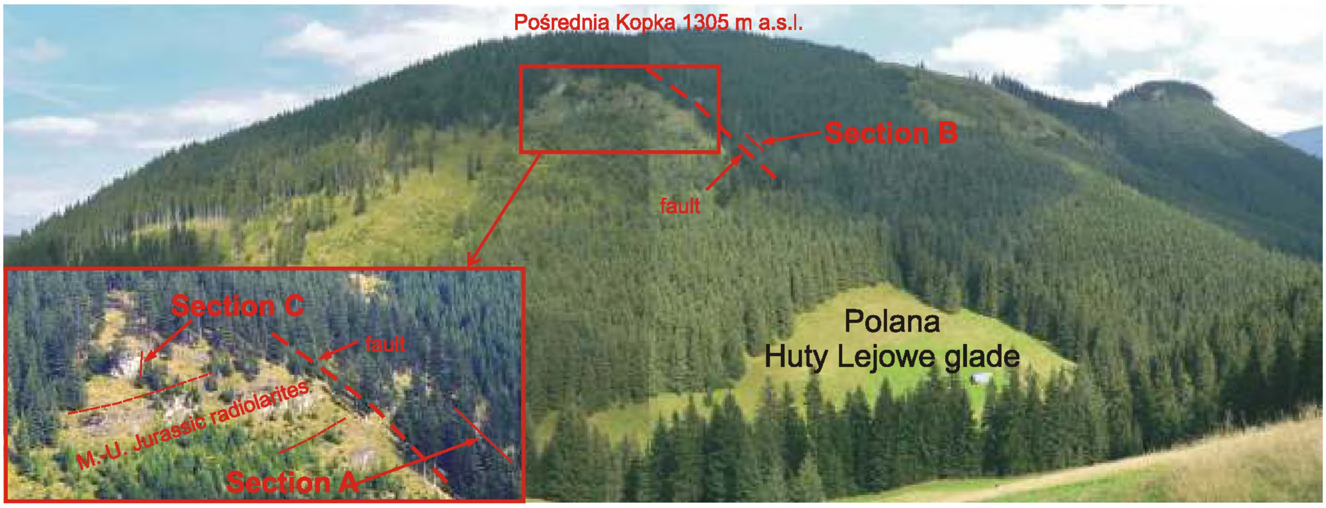

Fig. 4. View of the eastern slopes of the Lejowa Valley showing the location of the partial sections studied

(Michalík et al., 1990; Grabowski and Pszczółkowski, 2006), which has been previously ascribed to the Pieniny Limestone Formation (Lefeld et al., 1985; Pszczółkowski, 1996) of the Maiolica facies (Wieczorek, 1988). Their beds are 8–10 cm thick. These deposits are light grey; however, in some packages of beds in the lower part of the formation they are red. The lower, but not the lowest part of the Jasenina Formation in the Pośrednie III section is dated to the Lower Tithonian on the basis of calcareous dinoflagellates, while the higher part is dated precisely by a combination of calpionellid biostratigraphy and magnetostratigraphy (Grabowski and Pszczółkowski, 2006).

The section studied of Kimmeridgian–Tithonian deposits is located on the eastern slopes of the Lejowa Valley in the Western Tatra Mts., on the slope of Pośrednia Kopka Mt. and in a forested gully running towards the Polana Huty Lejowe glade (Figs. 1 and 4). This is a composite section that contains three parts: A, B, and C (Figs. 4 and 5). Part A, located on the southern margin of the gully (GPS coordinates: N49°15.905'; E19°50.933'), includes red radiolarites of the topmost part of the Ždiar Formation, red nodular limestones of the Czorsztyn Limestone Formation, and grey platy limestones with packages of red marly limestones, which belong to the lowest part of the Jasenina Formation. Part B that includes red radiolarites of the topmost part of the Ždiar Formation and red nodular limestones of the Czorsztyn Limestone Formation, is located in a rocky step in the axis of the gully (GPS coordinates: N49°15.916'; E19°51.086'). Parts A and B are separated by a fault from part C (Fig. 4). Part C is correlated with the uppermost part of section A. It is exposed in a rocky cliff (GPS coordinates: N49°15.978'; E19°50.981') and it contains grey, olive-grey wavy or platy limestones with packages of red slightly nodular limestone, which belong to the lowest part of the Jasenina Formation.

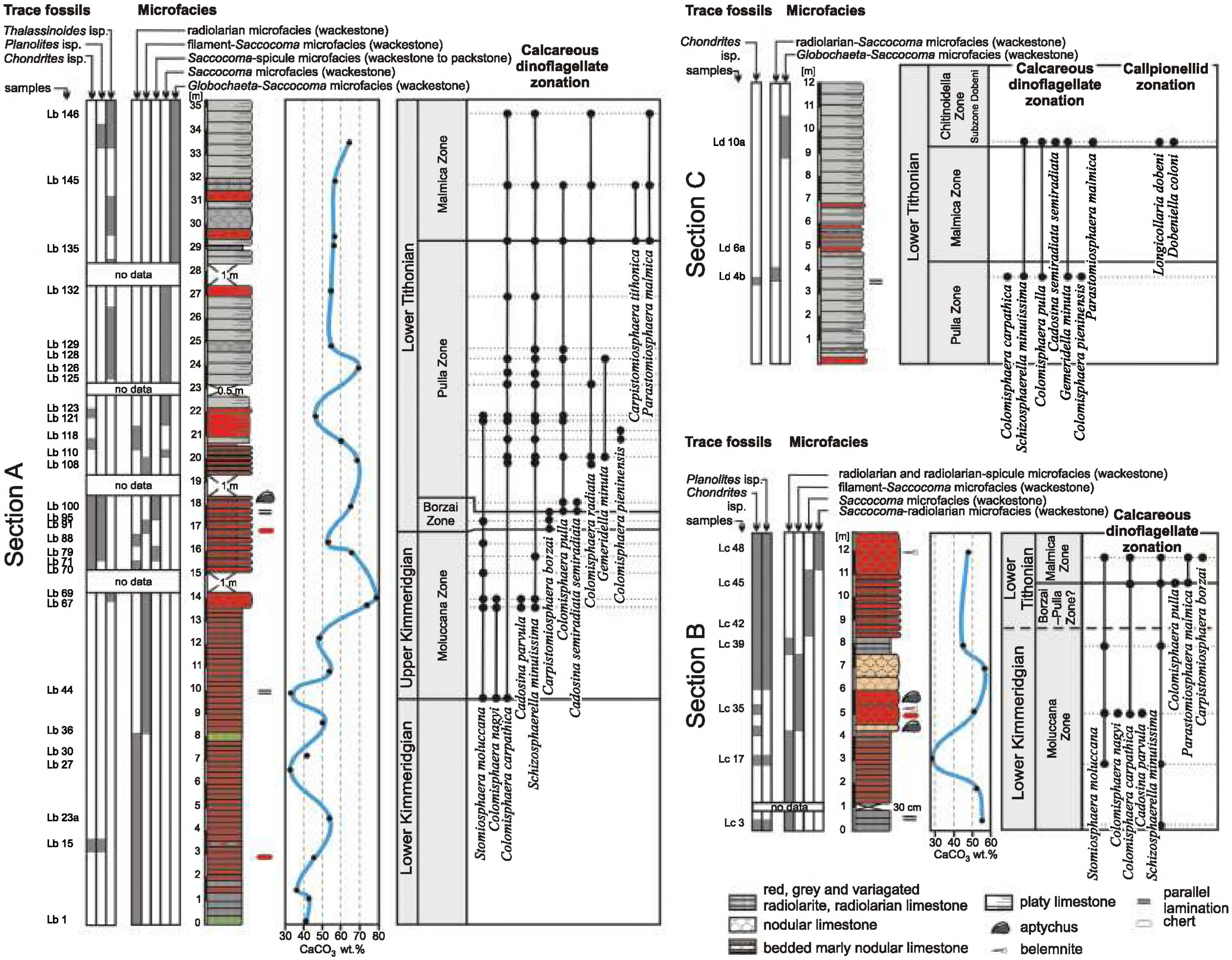

Fig. 5. Detailed lithological sections A, B and C of the Upper Jurassic deposits in the Lejowa Valley

MATERIAL AND METHODS

The succession analysed, exposed in the partial sections A, B, C, is in total 59 m thick. The sections were analysed bed-by-bed with detailed sampling. Microfacies have been analysed in 47 thin sections. Allochems and micrite have been evaluated in thin sections under a *LEICA DM 2500P* optical microscope. Rock samples and the thin sections are stored in the collection of the Institute of Geological Sciences, Jagiellonian University in Kraków.

The calcium carbonate content of the rock samples was estimated with a calcimeter made by Eijkelkamp (model 08.53) in the Institute of Geological Sciences, Jagiellonian University in Kraków. This calcimeter works in accordance with the method of Scheibler which involves a determination of calcium carbonate content in the rock using a volumetric method. The content of $CaCO_3$ was analysed in 32 samples.

Radiolarites and radiolarian limestones, named as such because of a common to abundant content of radiolarian tests, are fine-grained pelagic deposits (Flügel, 2010). Radiolarites contain more than 50% of SiO_2 (Hallsworth and Knox, 1999); if sediment contains more than 50% $CaCO_3$ it should be classified as radiolarian limestone. Dunham's (1962) classification of microfacies is applied in this paper to radiolarites and radiolarian limestones.

FACIES AND MICROFACIES

The Upper Jurassic studied contains three different facies: red radiolarites (which include radiolarites and radiolarian limestones), red nodular limestones and mostly grey, platy limestones (Figs. 6–9).

RED RADIOLARITES

The red radiolarites of the uppermost part of the Czajakowa Radiolarite Formation are red or rarely variegated. Their $CaCO_3$ average content is about 45 wt.%, ranging from 31 up to 55 wt.% (Fig. 5), therefore they are classified as radiolarites. Some of these rocks are radiolarian limestones; however, for sake of simplicity, they will be termed hereafter radiolarites. In some beds red or grey cherts occur.

The red radiolarites are homogeneous and distinctly bedded, with bed thickness from 5 to 30 cm, locally with thin marly intercalations (Fig. 6A). Some beds display centimetre-thick partings more or less parallel to the bedding. Locally, primary lamination is visible, especially in thin sections (Fig. 7A). The lamination is manifested by fluctuations in abundance of radiolarian tests (compare Lefeld et al., 1985). Scarce trace fossils such as *Chondrites*, rarely *Planolites*, are present.

The red radiolarites (samples Lb 1–44; Lc 3–17) contain indistinctly laminated radiolarian biomicrites (wackestone passing locally into mudstone; Fig. 7A) and filamentous-*Saccocoma* biomicrites (wackestone; Fig. 7B). Cryptocrystalline silica occurs mainly in the matrix. These deposits contain radiolarian tests or filaments that dominate over fragments of the planktonic crinoid *Saccocoma* sp. Moreover, other fragments of crinoids, ophiuroids, filaments, foraminifers and aptychi are present. They are accompanied by cysts of the calcareous dinoflagellates *Stomiosphaera moluccana* Wanner (mainly silicified), *Colomisphaera nagyi* (Borza), and *Colomisphaera carpathica* Borza. Some of the bioclasts are phosphatized. The matrix is stylolitized and cut by differently oriented calcite veins. Stylolites are impregnated by Fe-minerals. Clastic grains are represented by silt-sized grains of quartz and muscovite flakes. Scattered pyrite aggregates are present.

RED NODULAR LIMESTONES

The Czorsztyn Limestone Formation shows three subfacies: (1) nodular limestones, (2) thin bedded limestones and (3) grey siliceous deposits.

1) The first subfacies is a massive limestone which shows a distinct nodularity, with micritic light grey, pink or reddish, commonly cherty nodules, whereas the clay-rich matrix is cherry-red or dark reddish to brownish (Fig. 6C, E). Nodules vary in size; however, most of them are 8–10 cm long and 2–3 cm thick. Nodules are surrounded by stylolites and dissolution seams, which in places form horse-tail bunches (Fig. 6E). Nodules and matrix are differently weathered at exposure (Fig. 6C).

2) The second subfacies constitutes the thinner, regularly bedded limestones with less developed nodularity in beds that are 4–5 cm thick and interbedded with 1–2 cm thick marly layers.

3) Within red nodular limestones, 40 cm thick, grey siliceous, platy deposits (radiolarian-spicule wackestone) occur (sample Lc 39). They contain beds, which are 2–7 cm thick (Fig. 6B).

Belemnites and aptychi occur sporadically (Fig. 6E). The $CaCO_3$ content of the red nodular limestones is about 63 wt.%; ranging from 50 up to 80 wt.% (Fig. 5). The trace fossils *Chondrites*, *Planolites* and rarely *Zoophycos* and *Thalassinoides* are common, mainly in the nodules (Fig. 6D, F, G). Primary lamination is visible in some layers (Fig. 6G).

The nodular limestones (samples Lb 67–110; Lc 35–48a) contain filamentous-*Saccocoma* biomicrites (wackestone to packstone), *Saccocoma*-spicule biomicrites (wackestone to packstone), *Saccocoma*-radiolarian biomicrites (wackestone), *Saccocoma* biomicrites (wackestone to packstone) and less frequently radiolarian biomicrites (Figs. 7C–F and 9A). Nodules are bordered by dense systems of stylolites and dissolution seams (Fig. 7C, D). The limestones contain rare aptychi (Figs. 7C and 9A), crinoids (formed by twinned lamellar calcite), cysts of the calcareous dinoflagellates *Cadosina parvula* Nagy (Fig. 10B), *Colomisphaera nagyi* (Borza) (Fig. 10A), *Stomiosphaera moluccana* Wanner (Figs. 10C, D and 11A, B), *Carpistomiosphaera borzai* (Nagy) (Figs. 10F, G and 11D, G, H), *Colomisphaera pulla* (Borza), *Colomisphaera radiata* (Vogler) (Fig. 10H), *Colomisphaera carpathica* (Borza) (Figs. 10I and 11F), *Schizosphaerella minutissima* (Colom) (Figs. 10E and 11C), *Parastomiosphaera malmica* (Borza) (Fig. 11E, I), the problematicum *Gemeridella minuta* Borza et Mišík, the spores *Globochaete alpina* Lombard, foraminifera fragments, calcified sponge spicules and radiolarian tests (Fig. 7C–F). Some of the bioclasts are phosphatized. In some layers the matrix is slightly silicified and contains also small silicified ?cysts (samples Lb 88, Lc 39). Silt-sized muscovite flakes and quartz

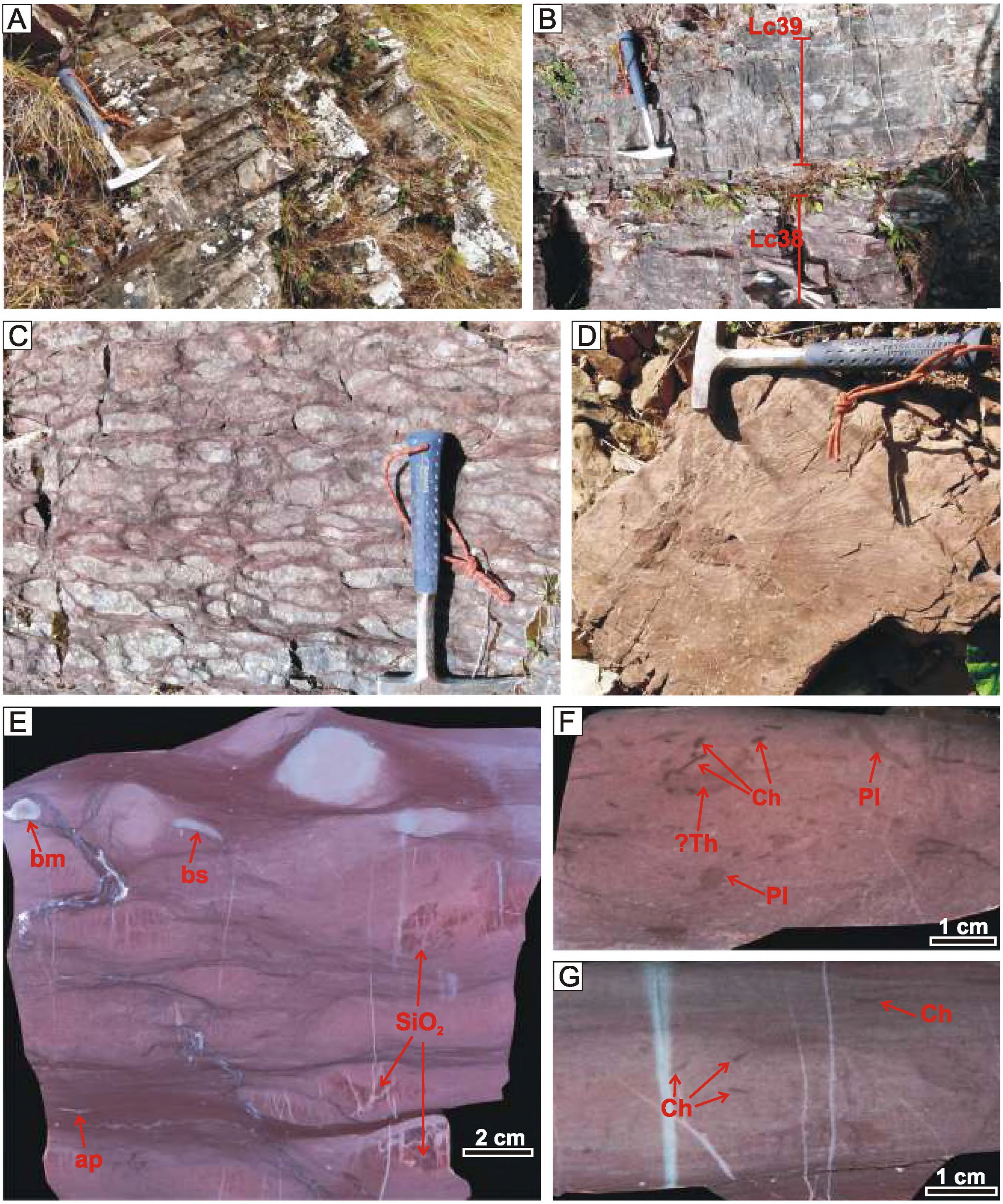

Fig. 6. Red radiolarian limestones and red nodular limestones – facies characteristics

A – distinctly bedded red radiolarites; **B** – massive red nodular limestone (sample Lc 38) and overlying 40 cm thick, grey siliceous, platy deposits (sample Lc 39); **C** – detail of the red nodular limestone (sample Lc 36), exposure surface; **D** – *Zoophycos* in red nodular limestone, loose block; **E** – internal structure of the red nodular limestones, light pink, red and cherty (SiO_2) nodules surrounded by cherry-red matrix with dark dissolution seams, individual bioclasts of aptychus (ap), belemnite (bm) and a bivalve shall (bs) occur, sample Lc 35, polished slab; **F** – *Planolites* (Pl), *Chondrites* (Ch) and *Thalassinoides* (Th) in vertical section, sample Lc 42, polished slab; **G** – *Chondrites* in vertical section, sample Lb 71, polished slab; sample location is indicated in Figure 5

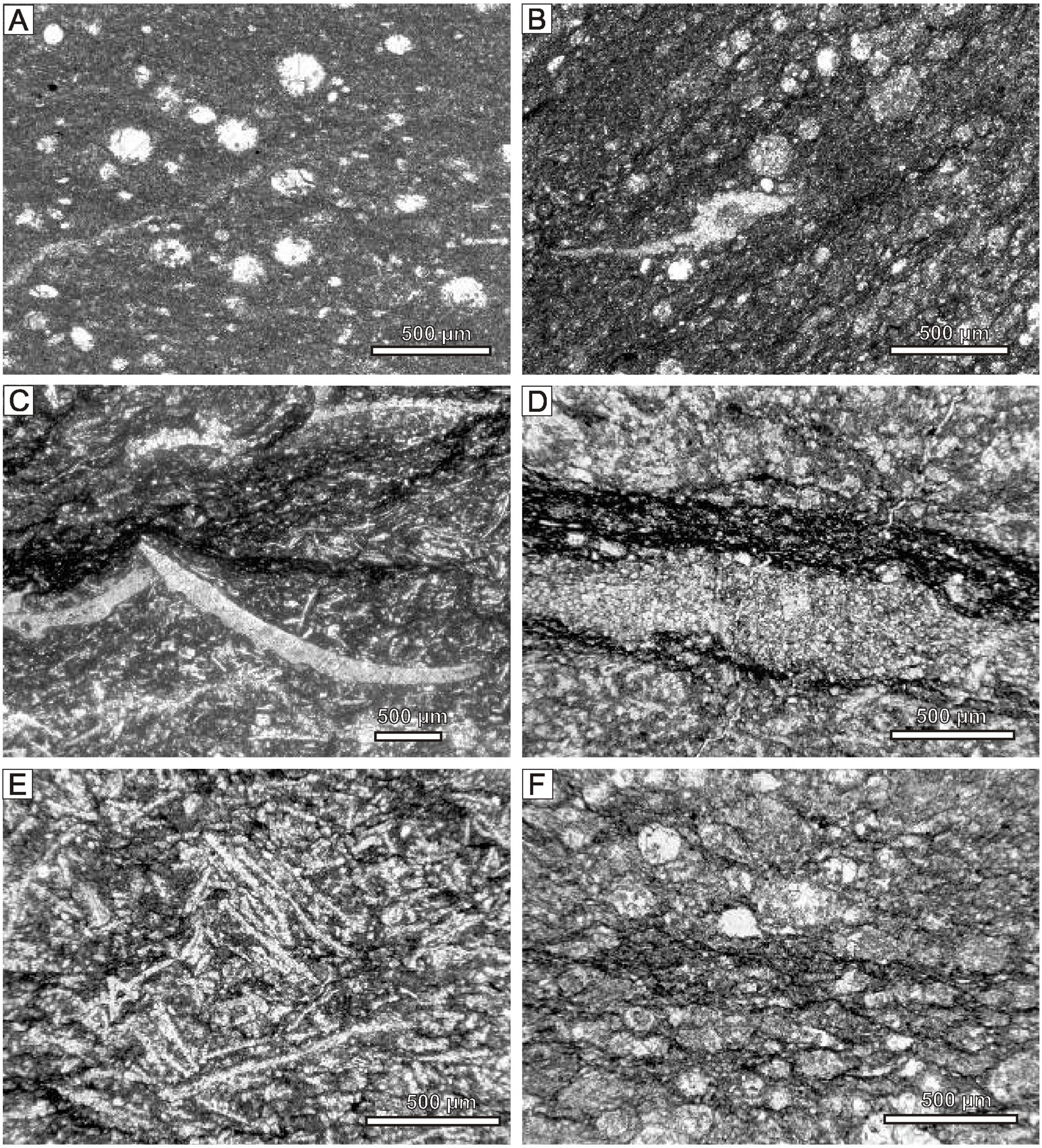

Fig. 7. Kimmeridgian microfacies and microfossils. Lejowa Valley, section A

A – radiolarian biomicritic, slightly laminated limestone (wackestone), Lower Kimmeridgian, sample Lb 1; **B** – *Saccocoma* sp. in laminated radiolarian biomicrite with graded bioclasts (packstone passing upwards to wackestone), Lower Kimmeridgian, sample Lb 23a; **C** – aptychi fragments in filamentous-*Saccocoma* biomicrite (wackestone to packstone) rich in stylolites, Upper Kimmeridgian, sample Lb 67; **D** – slightly dolomitized matrix in filamentous-*Saccocoma* biomicrite (packstone) rich in stylolites, Upper Kimmeridgian, sample Lb 69; **E** – filamentous-*Saccocoma* biomicrite (packstone), Upper Kimmeridgian, sample Lb 69; **F** – slightly recrystallized and laminated radiolarian-spicule biomicrosparite (wackestone), Upper Kimmeridgian, sample Lb 88; sample location is indicated in Figure 5

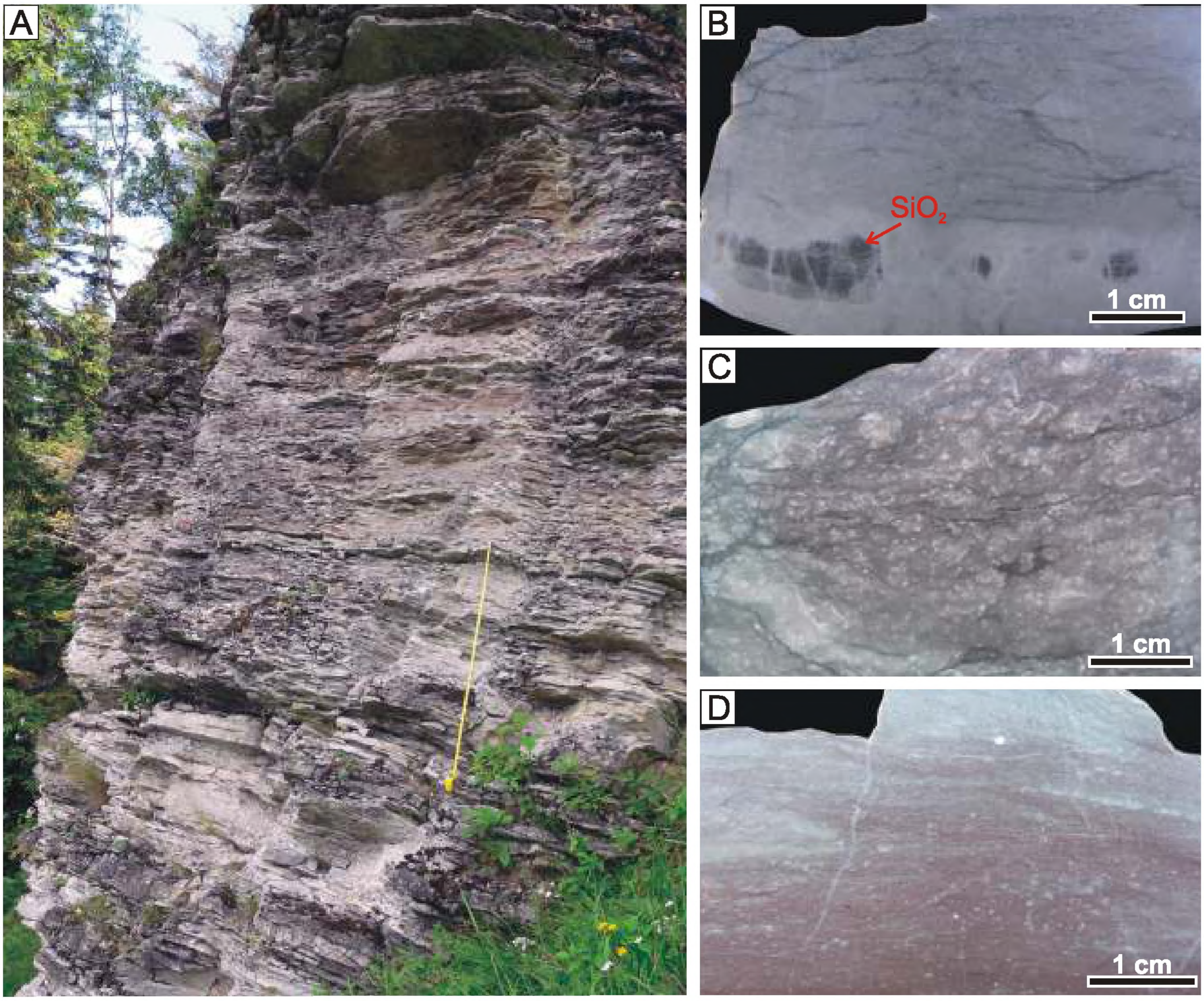

Fig. 8. Grey, platy limestones – facies characteristics

A – grey, platy limestones with six reddish nodular packages, section C, the measuring stick is 1 m long; **B** – grey micritic limestone with common dissolution seams and grey chertifications (SiO$_2$), vertical section, polished slab, sample Ld 6a; **C** – bioclasts, most probably of *Saccocoma*, in the gray limestone, vertical section, polished slab, sample Lb 125; **D** – variegated limestone with dissolution seams, vertical section, polished slab, sample Lb 132; sample location is indicated in Figure 5

grains are common, mostly in parts rich in stylolites. The matrix contains also scattered pyrite aggregates. Some layers are cut by dense calcite veins.

GREY PLATY LIMESTONES

The transition from red nodular limestones to the overlying grey platy limestones of the Jasenina Fomation is abrupt. The lower part of the Jasenina Formation is composed of light grey, olive-grey or in places reddish, partly wavy, siliceous micritic limestone (Fig. 8A–C), with thin (up to 3 cm thick) marly intercalations (Fig. 8A–D). The limestone beds are 2–10 cm thick. Locally, packages of reddish, pinkish or variegated, slightly nodular limestone beds occur (Fig. 8A, D). They are 15–95 cm thick. The upper part of the Jasenina Formation is composed of thinly bedded, platy micritic limestones. Trace fossils are rare; only *Chondrites* occurs in some beds. The average CaCO$_3$ content is 58 wt.% (ranging from 46 up to 70 wt.%; Fig. 5).

These deposits contain laminated radiolarian biomicrites (wackestone to packstone), *Saccocoma* biomicrites, crinoid-*Saccocoma* biomicrites, *Saccocoma*-radiolarian biomicrites and *Globochaete*-*Saccocoma* biomicrites (all are wackestone; Fig. 9B–F). Bioclasts include radiolarian tests, sponge spicules, fragments of *Saccocoma*, filaments, aptychi (some of them are bored by microorganisms; Fig. 9D–F), ostracod and foraminifera tests, and fragments of crinoids and bivalves. Moreover, the spore *Globochaete alpina* Lombard (Figs. 11J and 12J, K), the microproblematicum *Gemeridella minuta* Borza et Mišík (Fig. 11K, L), and the cysts *Colomisphaera pulla* (Borza) (Figs. 10K and 12A), *Carpistomiosphaera borzai* (Nagy), *Colomisphaera radiata* (Vogler) (Fig. 12B, C), *Parastomiosphaera malmica* (Borza) (Figs. 10L and 12F, G), *Colomisphaera carpathica* (Borza), *Colomisphaera pienin-*

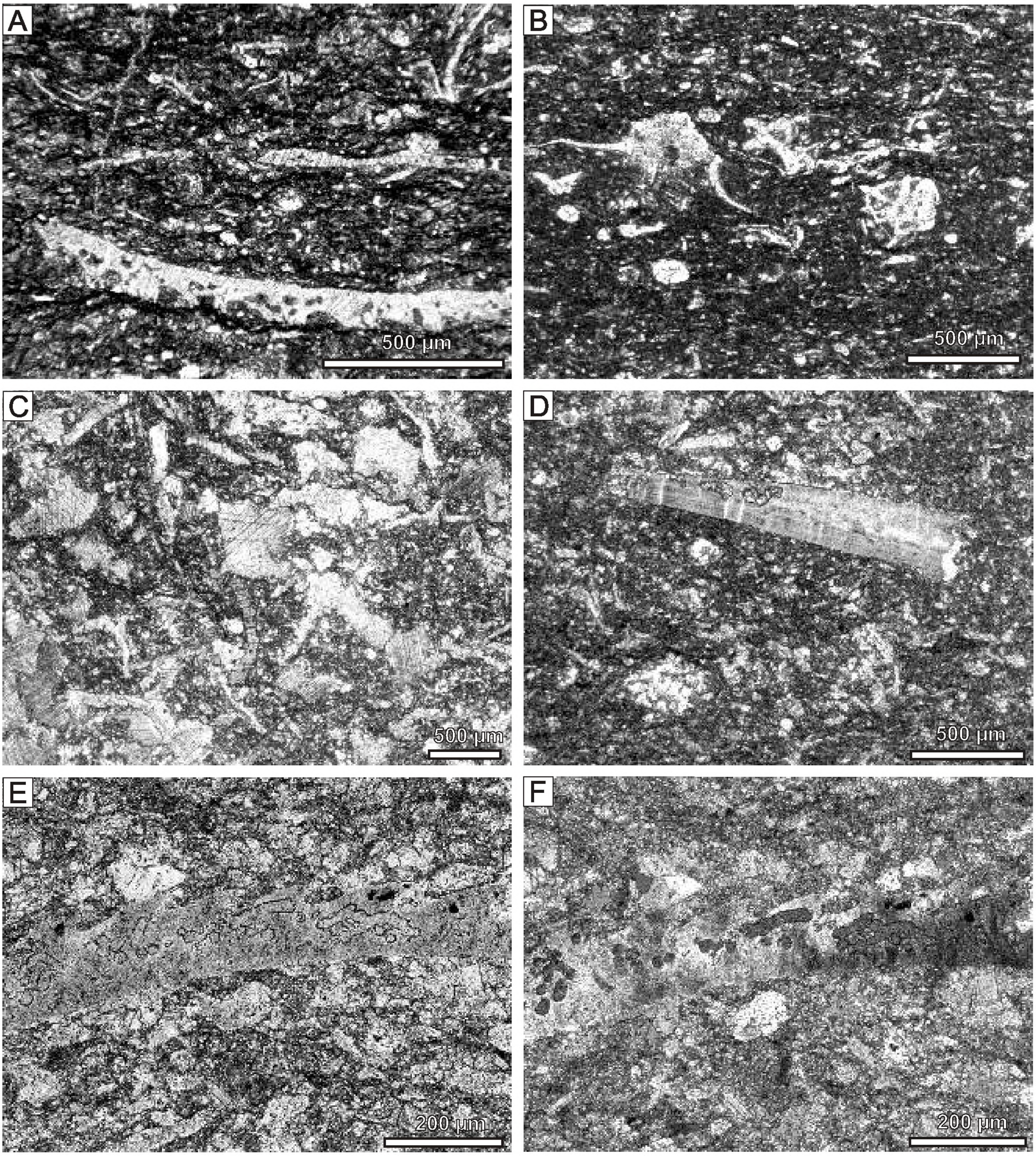

Fig. 9. Lower Tithonian microfacies and microfossils, Lejowa Valley, section B

A – filamentous-*Saccocoma* biomicrite (wackestone) with aptychi affected by borings, lowermost Tithonian, sample Lb 91; **B** – laminated *Saccocoma* biomicrite (wackestone), lowermost Tithonian, sample Lb 123; **C** – crinoid-*Saccocoma* biomicrite, *Saccocoma* fragments dominate over common crinoids (formed by twinned lamellar calcite), lowermost Tithonian, sample Lb 125; **D**, **E**, **F** – bivalve (in D) and aptychi (in E, F; XPL in F) affected by borings in laminated *Saccocoma*-radiolarian biomicrite (wackestone), lowermost Tithonian, sample Lb 126; sample location is indicated in Figure 5

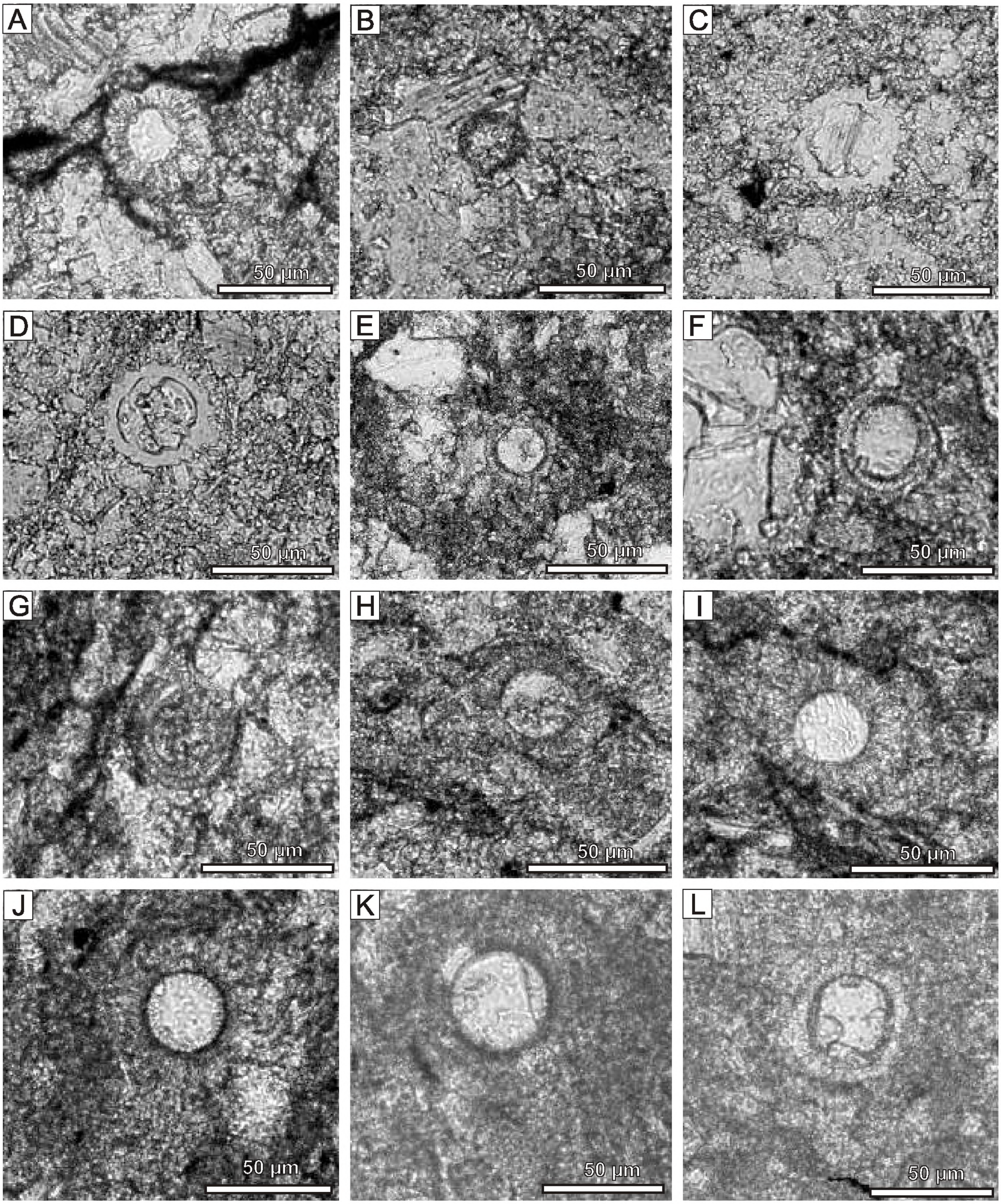

Fig. 10. Upper Kimmeridgian – upper part of Lower Tithonian calcareous dinoflagellates, Lejowa Valley, section B

A – *Colomisphaera nagyi* (Borza), Upper Kimmeridgian, sample Lb 67; **B** – *Cadosina parvula* Nagy, Upper Kimmeridgian, sample Lb 67; **C**, **D** – *Stomiosphaera moluccana* Wanner, Upper Kimmeridgian, sample Lb 67, Lb 110; **E** – *Schizosphaerella minutissima* (Colom), Upper Kimmeridgian, sample Lb 79; **F**, **G** – *Carpistomiosphaera borzai* (Nagy), Lower Tithonian, sample Lb 100; **H** – *Colomisphaera radiata* (Vogler), Lower Tithonian, sample Lb 108; **I** – *Colomisphaera carpathica* (Borza), Lower Tithonian, sample Lb 108; **J** – *Carpistomiosphaera* cf. *tithonica* Nowak, Lower Tithonian, sample Lb 12; **K** – *Colomisphaera pulla* (Borza), Lower Tithonian, sample Lb 135; **L** – *Parastomiosphaera malmica* (Borza), uppermost part of Lower Tithonian, sample Lb 145; sample location is indicated in Figure 5

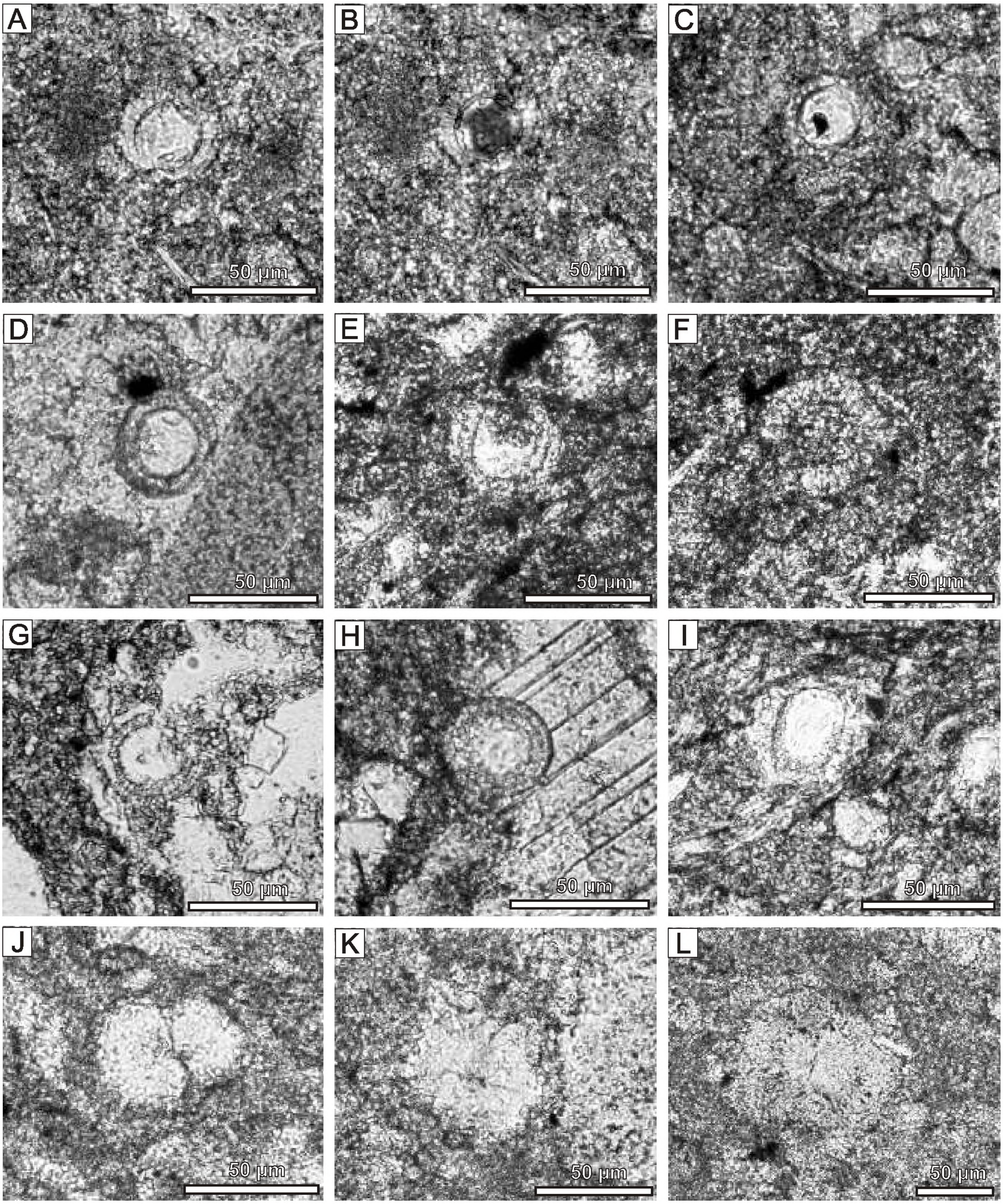

Fig. 11. Upper Kimmeridgian – upper part of Lower Tithonian calcareous dinoflagellates, Lejowa Valley, section A

A, **B** – *Stomiosphaera moluccana* Wanner (XPL in B), sample Lc 48; **C** – *Schizosphaerella minutissima* (Colom), sample Lc 48; **D** – *Carpistomiosphaera borzai* (Nagy), sample Lc 48; **E** – *Parastomiosphaera malmica* (Borza), sample Lc 48; **F** – *Colomisphaera carpathica* (Borza), sample Lc 48; **G**, **H** – *Carpistomiosphaera borzai* (Nagy), sample Lc 46; **I** – *Parastomiosphaera malmica* (Borza), sample Lc 46; **J** – *Globochaete alpina* Lombard, sample Lb 123; **K**, **L** – *Gemeridella minuta* Borza et Mišík, sample Lb 128, Lb 135; sample Lc 48 and Lc 46 belong to the Malmica Zone (upper part of Lower Tithonian); sample location is indicated in Figure 5

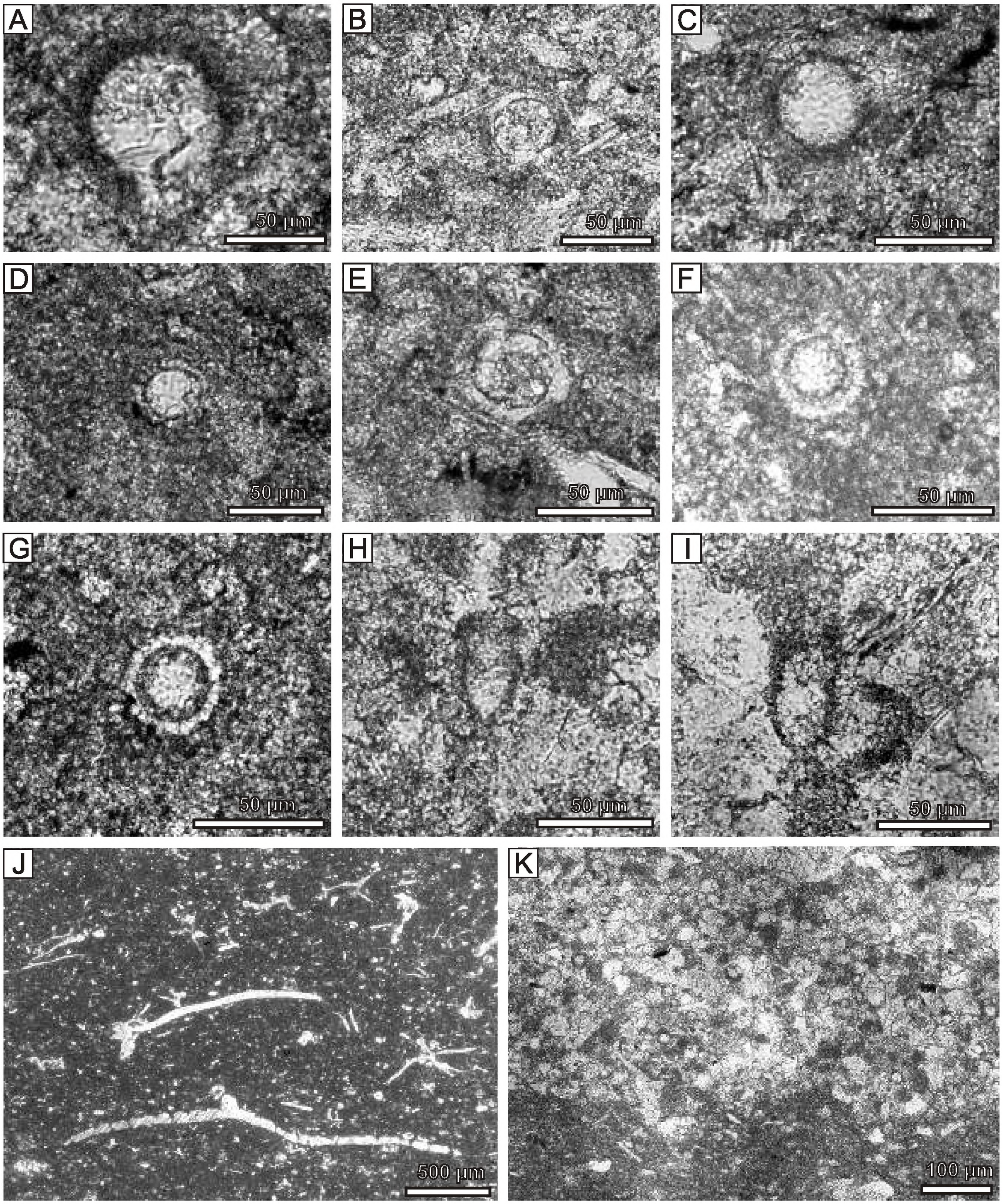

Fig. 12. Lower and Middle Tithonian calcareous dinoflagellates, chitinoidellids and microfacies, Lejowa Valley, section C

A – *Colomisphaera pulla* (Borza), Lower Tithonian, sample Ld 4b; **B**, **C** – *Colomisphaera radiata* (Vogler), Lower Tithonian, sample Ld 4b; **D** – *Schizosphaerella minutissima* (Colom), Lower Tithonian, sample Ld 4b; **E** – slightly silicified dinoflagellate cyst, Lower Tithonian, sample Ld 4b; **F**, **G** – *Parastomiosphaera malmica* (Borza), upper part of Lower Tithonian, sample Ld 10a; **H** – *Dobeniella colomi* (Borza), uppermost part of Lower Tithonian, sample Ld 10a; **I** – *Longicollaria dobeni* (Borza), uppermost part of Lower Tithonian, sample Ld 10a; **J**, **K** – laminated biomicrite limestone of *Saccocoma–Globochaete* microfacies (wackestone), (J) passing upwards to globochaete packestone which contains abundant cysts of *Cadosina semiradiata semiradiata* (Wanner), (K) and rare chitinoidellids (figured above H, I), uppermost part of Lower Tithonian, sample Ld 10a; sample location is indicated in Figure 5 *ensis* (Borza), *Carpistomiosphaera* cf. *tithonica* Nowak (Fig. 10J), *Schizosphaerella minutissima* (Colom) (Fig. 12D), and the chitinoidellids *Longicollaria dobeni* (Borza) (Fig. 12I) and *Dobeniella colomi* (Borza) (Fig. 12H) are abundant. The bioclasts are concentrated in distinct laminae; in some of them large fragments of *Saccocoma* are dominant (Fig. 9C). Some bioclasts are slightly silicified (Fig. 12E) or phosphatized. The matrix locally contains abundant silty muscovite flakes, quartz grains and scattered pyrite aggregates. Stylolites and dissolution seams are abundant and impregnated by Fe-minerals. Beds are cut by calcite veins.

BIOSTRATIGRAPHY

The biostratigraphy of the section studied is based on calcareous dinoflagellates and calpionellids; however, calpionellids are very rare and limited to the upper part of the section. In spite of the locally slightly recrystallized matrix, cysts of the calcareous dinoflagellates are generally well-preserved. The dinoflagellate cyst zonations proposed by Borza (1984) and Borza and Michalík (1986), which was later revised by Reháková (2000), and the chitinoidellid biostratigraphical scheme as proposed by Reháková (2002) were adopted. Four dinocyst zones and one calpionellid zone have been recognized in the section studied (Fig. 5).

The occurrence of the calcareous dinocyst association *Stomiosphaera moluccana* Wanner (Fig. 10C, D), *Cadosina parvula* Nagy (Fig. 10B), *Colomisphaera nagyi* (Borza) (Fig. 10A), *Colomisphaera carpathica* Borza, *Schizosphaerella minutissima* (Colom) (Fig. 10E) was observed in the uppermost part of the red radiolarites of the Czajakowa Radiolarite Formation (sample Lb 44) and in the lower part of the red nodular limestones of the Czorsztyn Limestone Formation (samples Lb 67, 69, 70, 88; Lc 1, 17, 35). This association is typical of the Late Kimmeridgian Moluccana Zone.

Younger deposits (red nodular limestone of the Czorsztyn Limestone Formation: samples Lb 91, 95) yield a cyst association in which *Stomiosphaera moluccana* Wanner is accompanied by *Carpistomiosphaera borzai* (Nagy). The latter cyst is the index marker of the Borzai Zone, which dates the latest part of the Kimmeridgian and the earliest part of the Tithonian.

The overlying biomicrites of the red nodular limestones (Czorsztyn Limestone Formation: samples Lb 100, 108, 110,) and grey platy limestones (Jasenina Formation: samples Lb 121, 123, 125, 126, 129, 132) contain a cyst association with *Colomisphaera pulla* (Borza), *Carpistomiosphaera borzai* (Nagy) (Fig. 10F, G), *Colomisphaera radiata* (Vogler) (Fig. 10H), *Colomisphaera carpathica* (Borza) (Fig. 10I), *Colomisphaera pieninensis* (Borza) and *Schizosphaerella minutissima* (Colom). This association marks the base of the Early Tithonian Pulla Zone. In spite of the fact that one cyst resembles *Carpistomiosphaera tithonica* Nowak, the Tithonica Zone (*sensu* Lakova et al., 1999; Reháková 2000) was not distinguished here. According to Borza (1984), *Carpistomiosphaera tithonica* Nowak and *Colomisphaera pulla* (Borza) occasionally may replace each other and both are suitable for distinguishing the Pulla Zone or the combined Pulla–Tithonica Zone (Early Tithonian).

The highest cyst zone was determined in the uppermost part of the red nodular limestones (samples Lc 46, 48a), in the middle part of the grey platy limestones of the Jasenina Formation (samples Lb 137, 145, 4b) and in grey platy limestones intercalated with red nodular limestones (the same formation). Here the cysts *Parastomiosphaera malmica* (Borza) (Figs. 10L and 11E), *Schizosphaerella minutissima* (Colom) (Figs. 11C and 12D), *Carpistomiosphaera* cf. *tithonica* Nowak (Fig. 10J), *Colomisphaera pulla* (Borza) (Figs. 10K and 12A), *Colomisphaera carpathica* (Borza) (Figs. 10I and 11F), *Colomisphaera radiata* (Vogler) (Fig. 12B, C) are documented. This cyst association is typical of the Malmica Zone that marks the upper part of the Early Tithonian. So far, the last occurrence of *Colomisphaera radiata* (Vogler) has been identified in the Pulla Zone (Borza, 1984; Reháková, 2000). Thus, the stratigraphic range of this taxon should be corrected and shifted to the Malmica Zone.

First calpionellids with microgranular calcite loricas, i.e. *Longicollaria dobeni* (Borza) (Fig. 12I) and *Dobeniella colomi* (Borza) (Fig. 12H), which occur in the uppermost part of the section studied (only in sample Ld 10a) confirm onset of the Middle Tithonian Dobeni Subzone of the Chitinoidella Zone (*sensu* Borza, 1984; Reháková and Michalík, 1997). Since the Middle Tithonian is not generally accepted by ammonite specialists we would propose to put the Chitinoidella Zone in the latest part of the Early Tithonian.

DISCUSSION

STRATIGRAPHY

The crucial complement to stratigraphical study of Kimmeridgian–Lower Tithonian deposits was the occurrence of calcareous dinoflagellates, which allowed application of the calcareous dinoflagellate zonation. Previously, the age of these deposits was determined on the basis of their position in the section and on their aptychi content (Fig. 3). The Lejowa Valley section comprises the upper part of the red radiolarites of the Czajakowa Radiolarite Formation that extends probably up to the Late Kimmeridgian Moluccana Zone; the red nodular limestones of the Czorsztyn Limestone Formation (Late Kimmeridgian Moluccana Zone extented to the Early Tithonian, most probably the Malmica Zone) and grey platy limestones of the Jasenina Formation (Early Tithonian Pulla or Malmica zones to the earliest Berriasian). The age of the Czorsztyn Limestone Formation is determined more precisely, ranging from the Late Kimmeridgian Moluccana Zone to the Early Tithonian Malmica Zone. This determination is more or less consistent with the age based on aptychi (Gąsiorowski, 1959, 1962; Fig. 3), the location of which in the section is unknown.

The zones distinguished allow a precise stratigraphic positioning of the section studied in continuity with the stratigraphic scheme of the Jasenina Formation by Pszczółkowski (1996) and Grabowski and Pszczółkowski (2006), because the lowest zone of the Early Tithonian, i.e. the Pulla Zone, distinguished by the cited authors in the Pośrednie III section (3.6 km to the west from the section investigated), is recognized in the topmost part of the section investigated in the Lejowa Valley (Fig. 5).

PALAEOENVIRONMENT

The differences in lithology and stratigraphic data between sections A and B are difficult to explain. They may be caused by rapid facies changes. It is not excluded that the recent fault separating the sections was reactivated as a palaeofault influencing the morphology of the sea-floor and facies distribution. Another possibility is that the section is incomplete in its middle part due to a tectonic reduction, but even so, the nodular limestone beds from the upper part of the section A are only partly correlated with the section B, suggesting a significant facies change. This is not unusual in deep-pelagic environments. For instance, facies changes are well-documented between two sections of the Cenomanian–Turonian boundary interval in the Gubbio area, Apennines, Italy, over a distance of 2.5 km (Monaco et al., 2012). The morphology of recent deep-sea basins is not smooth, either (e.g., Flood, 1980; Hoi-Soo et al., 2001).

The Upper Jurassic deposits studied represent a pelagic, fine-grained facies. Red nodular limestones were inferred to have a low sedimentation rate (Wieczorek, 1983). This is consistent with the generally low sedimentation rate, which is estimated as 3.7 m/my after compaction for the upper part of the Czorsztyn Limestone Formation (Late Kimmeridgian Borzai Zone) and for the lower part of the Jasenina Formation (Early Tithonian Dobeni Subzone of the Chitinoidella Zone; Fig. 5). This sedimentation rate was estimated using the time scale of Gradstein et al. (2004). The value obtained is a minimum one due to factors such as compaction, dissolution effects, or small sedimentary gaps. The occurrence of microborings in aptychi suggests their long residence on the sea-floor (Fig. 9A, D–F). The value obtained of sedimentation rate is quite similar to that calculated for the Jasenina Formation on the basis of magnetostratigraphic zonation (Grabowski and Pszczółkowski, 2006). According to Grabowski and Pszczółkowski (2006), sedimentation rate increases upwards from 3–7 m/my for the Jasenina Formation to 8–18 m/my for the Osnica Formation.

The facies change from the red nodular limestones (Czorsztyn Limestone Formation) to the grey, platy limestones (Jasenina Formation) is characterized by an increase in clastic input of quartz silt grains and muscovite flakes. Some beds in section A (samples Lb 95, 100, 108, 110, 118, 123, 125, 126, 132) contain siliciclastic material that is easily observed in thin section (no quantitative data), which was supplied by bottom currents or wind. However, no primary sedimentary structures documenting bottom currents were observed. It is possible that such structures have been destroyed by bioturbation. Probably, concentrations of microbioclasts (Fig. 8C) resulted from winnowing by weak currents; however, periods of strong increase in primary productivity combined with low sedimentation rate cannot be excluded.

The Late Kimmeridgian–Tithonian records a regressive episode related to the long term sea level fall in the Tethys (Hallam, 2001). Abundant evidence indicates humid conditions during the Late Jurassic in low-latitude Northern Tethys and intense runoff of clastic sediment from the continent, including kaolinite, as observed worldwide, e.g., southern France, Jura Mountains, England, Greenland (Weissert and Mohr, 1996 with references therein; Danelian and Johnson, 2001). Continental weathering intensification is recorded in the enriched ^{87}Sr values through the Late Jurassic (Jones and Jenkyns, 2001). Increased siliciclastic input in the Late Kimmeridgian–Tithonian deposits studied corresponds well to this trend.

The transition from the Czorsztyn Limestone to the Jasenina formations is manifested by a significant change in microfacies; from radiolarian through filamentous-*Saccocoma* to the more uniform *Saccocoma* and *Globochaete–Saccocoma* dominated microfacies. This trend is consistent with shifting of sedimentation from biosiliceous to carbonatic, as observed in other Tethyan basins (e.g., Bartolini et al., 1999). This Late Kimmeridgian–Tithonian switch was due to climatic and trophic level changes (Danelian and Johnson, 2001). The Late Jurassic is an interval of prevailing eutrophic conditions in the Western Tethys (Danelian and Johnson, 2001).

Sedimentation of red nodular limestones was related to elevated parts of the basin floor and was controlled by bottom currents and early cementation and dissolution. The nodular limestones contain early diagenetic, hard nodules and soft matrix (Clari and Martire, 1996). The compactional effect took place mainly in the soft matrix, where dissolution seams and stylolites are common. Grey platy limestones of the Jasenina Formation, which are more homogeneous, contain abundant dissolution seams. They may correspond to the so-called mud-supported clay-rich carbonates, which refer to deep sea marly carbonates rich in dissolution seams (Clari and Martire, 1996).

The trace fossil assemblage is of low diversity and trace fossils are generally small, poorly preserved, never abundant and present only in some beds (Fig. 5). This is especially true for radiolarites and platy limestones in comparison to the nodular limestones. The presence of *Zoophycos,* the overall low diversity of the trace fossils (*Planolites*, *Thalassinoides*) and pelagic sediments points to the Zoophycos ichnofacies, which displays a wide bathymetric range (Frey and Seilacher, 1980) from the distal range of tempestites to abyssal depths (Uchman, 2007). The generally small sizes, poor preservation, low abundance, but almost exclusive total bioturbation are related to the low content of food in the sediment concentrated in a thin surface layer, which was the main target of burrowing activity.

Concentration of food in a thin layer is caused by poor burial of organic matter conditioned by very low sedimentation rate. The thin, nutritional layer was strongly saturated with water (soft ground to soup ground), therefore burrowing activity caused total sediment churning in the so-called mixed layer (Ekdale and Berger, 1978; Berger et al., 1979; Uchman and Wetzel, 2011), but without preservation of trace fossils. The latter were produced only occasionally in a deeper, more cohesive sediment of the so-called transitional layer. Oligotrophic conditions on the sea-floor do not exclude high productivity in the water column suggested by the abundance of radiolarians, *Saccocoma* and calcareous dinoflagellates. Low oxygenation as a cause of the trace fossil impoverishment is less probable because fine lamination is very rare and its primary origin is doubtful. Moreover, common red colours of sediments caused probably by well-oxygenated iron minerals exclude low oxygen content in pore waters.

The presence of aptychi which are made of calcite and the absence of ammonite shells which are made of aragonite, suggest depths below the aragonite compensation depth and above the calcite compensation depth (Bosellini and Winterer, 1975;

Wieczorek, 1983, 1988). Wieczorek (1983) suggested that deposition of the Maiolica facies (Osnica Formation in this paper) took place at similar or greater depth than the radiolarites due to deepening of the Tethyan calcite compensation depth. This progressive CCD deepening started during the mid-Oxfordian (Weissert and Erba, 2004).

CONCLUSIONS

1. The age of Upper Kimmeridgian–Lower Tithonian deposits of the Krížna Unit was determined on the basis of calcareous dinoflagellates. The upper part of the red radiolarites of the Czajakowa Radiolarite Formation probably extends up to the Late Kimmeridgian Moluccana Zone. Red nodular limestones of the Czorsztyn Limestone Formation include the Late Kimmeridgian Moluccana Zone to the Early Tithonian, most probably Malmica Zone, while grey platy limestones of the lower part of the Jasenina Formation include the Early Tithonian Pulla or Malmica zones.

2. The sedimentation rate for the interval studied is estimated at 3.7 m/my. This value corresponds well with increasing sedimentation rate through the Late Jurassic. This trend is accompanied by increased input of siliciclastic sediment caused by climate change.

3. The deposits studied represent a pelagic, fine-grained facies, the sedimentation of which was considerably controlled by eustatic changes, as well as by fluctuations of the ACD and CCD.

4. The deposits studied contain trace fossils typical of the Zoophycos ichnofacies, including, *Planolites*, *Thalassinoides*, *Chondrites* and *Zoophycos*. Almost all the deposits are totally bioturbated indicating oxygenated pore waters. Burrowing took place in a thin sediment layer due to limited burial of organic matter.

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