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ORIGINAL ARTICLE

Late Jurassic facies architecture of the Złoczew Graben: implications for evolution of the tectonic-controlled northern peri-Tethyan shelf (Upper Oxfordian–Lower Kimmeridgian, Poland)

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Abstract In recent years, numerous wells have been completed in the area of the Złoczew Graben. Drill cores and data collected from wells have led to the recognition of an Upper Oxfordian–Lowermost Kimmeridgian sequence and to the construction of a 3D model of the graben with distribution of facies. Six facies types were distinguished, composed of numerous microfacies representing outer-, middle-, and inner-ramp depositional systems. The boundary of the Planula/Platynota zones is indicated by the transition from mid-inner carbonate ramp facies to mixed, carbonate–siliciclastic outer-ramp facies, as well as by appearance of debrites and calciturbidites. The distribution of gravity-flow deposits reflects the pattern of fault zones of the Złoczew Graben and their Late Jurassic activity. Comparison of Oxfordian–Lowermost Kimmeridgian facies types from central and southern Poland enabled the reconstruction of the general facies architecture in the Polish part of the northern peri-Tethyan shelf belonging to the Małopolska Block. The distribution of Upper Oxfordian–Lowermost Kimmeridgian facies follows the block structure of the basement and was controlled by reactivation of Paleozoic tectonic blocks in the Late Jurassic. The results of studies in the Polish basin correspond well to Upper Oxfordian–Lower Kimmeridgian sequences known from the ramp systems of western Europe where the basic change in deposition, from a carbonate ramp towards mixed, carbonate–siliciclastic sedimentation, was related to both North Atlantic and western European tectonics.

Keywords Ramp facies and microfacies · Stromatactis · Synsedimentary tectonism · Late Jurassic grabens · Oxfordian–Kimmeridgian · Poland

Introduction

The Złoczew Graben (central Poland) is located at the boundary of the Złoczew High and the Wieluń Upland (Fig. 1). During the Late Jurassic Oxfordian–Lower Kimmeridgian, the Polish part of the shelf bordered a vast, epicontinental sea that rimmed the Tethys Ocean from the north (e.g., Ziegler 1990; Matyszkiewicz 1997b; Golonka 2004). Reconstruction of the Late Jurassic facies architecture of this broad, epeiric carbonate shelf located in central and southern Poland is difficult and controversial due to insufficient knowledge of microfacies development and facies distribution. The concepts of depositional system development are based mostly on data from Upper Jurassic outcrops located in the northeastern and southwestern margins of the Holy Cross Mountains and Kraków-Częstochowa, and Wieluń uplands (Fig. 1) (e.g., Kutek et al. 1977; Matyja et al. 1989; Matyszkiewicz et al. 2006a and references therein). The knowledge of facies development of Upper Jurassic sediments in the remaining areas of central and southern Poland is based on rarely published data from wells (e.g., Gutowski et al. 2005; Złonkiewicz 2009; Krajewski et al. 2011a and references therein). In the Oxfordian, the study area formed the eastern part of an epicontinental ramp system that developed in western and central Europe (e.g., Leinfelder et al. 1996; Matyszkiewicz 1997b; Bádenas and Aurell 2001; Olóriz et al. 2003; Reolid et al. 2005; Olivier et al. 2008). The Upper Oxfordian deposits from central and southern Poland were assigned to the deep-water open shelf, so-called sponge megafacies

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(Matyja et al. 1989; Gutowski et al. 2005). To the northeast, this megafacies passes into sediments of a shallow-water platform prograding from the Lublin area located some 200 km to the east. In the Late Oxfordian, the front of that platform approached the southwestern margin of the Holy Cross Mountains (Fig. 1).

The most important factors controlling deposition in these areas were: sea-level changes, diverse basement structures, and synsedimentary tectonics (e.g., Kutek 1994; Gutowski et al. 2005; Matyszkiewicz et al. 2006a, b, 2012; Krajewski et al. 2011a, 2014). In the Late Jurassic depositional system of both central and southern Poland, the Oxfordian/Kimmeridgian boundary was one of the most important and best-marked stages in the sedimentation history of the Polish Basin. This stage included the extinction of reefs and the intensive development of deep-water, lime mudstone and marly facies (e.g., Kutek 1994; Matyszkiewicz 1996, 1997b; Gutowski et al. 2005; Krajewski et al. 2014).

In the area of the Złoczew Graben and its vicinity, covering about a 15 × 3-km strip of land, nearly 200 wells have reached the Upper Jurassic succession in the exploration for a lignite deposit (Borowicz et al. 2007). Such a dense grid along with the precise location and depths of the wells, and full-depth coring, has enabled the study of facies and microfacies development of Upper Jurassic sediments in the area and the visualization of facies distribution in a 3D model of the Złoczew Graben. The aim of this paper is to document the Upper Jurassic facies and microfacies from the Złoczew Graben and to make comparisons to equivalent sediments from the adjacent areas in southern and central Poland.

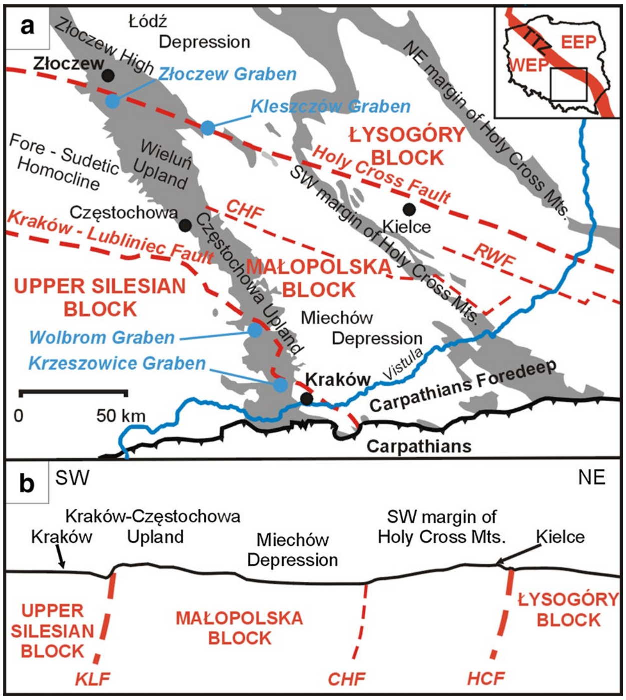


Fig. 1 **a** Location map of the study areas with Upper Jurassic outcrops and sub-Cenozoic Jurassic subcrops (*grey*) in southern and central Poland (after Pożaryski et al. 1979, modified and simplified). Tectonic structures (in *red*) after Buła and Habryn (2011) and Krzywiec (2006). *KLF* Kraków-Lubliniec Fault, *HCF* Holy Cross Fault, *CHF* Chmielnik Fault, *RWF* Ryszkowa Wola Fault, *TTZ* Teisseyre-Tornquist Zone, *EEP* East European Platform, *WEP* West European Platform. **b** Sketch of main geographical units and main tectonic units in the Paleozoic basement

Geological setting

The Złoczew Graben is located at the boundary of two trans-regional tectonic units of Poland: the Fore-Sudetic Homocline and the Łódź Depression (Fig. 1). The Złoczew Graben occurs within the northeast border of the Małopolska Block, which forms the margin of the West European Platform (e.g., Gutowski and Koyi 2007; Żelaźniewicz et al. 2011; Buła and Habryn 2011). The Małopolska Block occupies a large part of central and southern Poland (Fig. 1). In its southwestern part, both the Middle and Upper Jurassic strata commonly rest directly upon Cambrian, Ordovician, and Silurian deposits (Buła and Habryn 2010, 2011; Żelaźniewicz et al. 2011). In its central and northeastern parts, Jurassic strata cover Devonian, Carboniferous, and Triassic deposits as a result of uplift of the southwestern part of the block.

The Upper Jurassic deposits of the Złoczew High comprise limestone and marl dated as Oxfordian–Lower Kimmeridgian (Deczkowski 1977; Deczkowski and Gajewska 1983). The oldest sediments are Lower Oxfordian nodular limestone with stromatolites, which grade up into alternating marl and limestone with sponges and ammonites (Deczkowski 1977; Deczkowski and Gajewska 1983), followed by Middle and Upper Oxfordian, thin-bedded, platy limestone as well as massive and bedded sponge limestone with chert and marl interbeds. The youngest marl and limestone belong to the Lower Kimmeridgian (Deczkowski 1977; Deczkowski and Gajewska 1983). The thickness of the Upper Jurassic succession in the Złoczew Graben reaches 290 m (Biesiec 1 and 2 wells).

The Złoczew Graben is 13 km long, up to 1.5 km wide, and from 200 to 350 m deep. The recent geometry of the graben originated in the Miocene. The dislocations parallel to the graben axis are steep faults with throws from 25 to 200 m. These are accompanied by transverse faults (Deczkowski and Gajewska 1983; Borowicz et al. 2007; Dukacz 2013). The graben is filled with Paleogene and Neogene sediments, and the whole area is covered by Pleistocene sand and boulder clay.

Materials and methods

Preliminary data on Jurassic sediments from the Złoczew Graben can be found in unpublished reports on 110 wells completed before 2011 and in geological assessment reports of the Złoczew Graben. The principal research tool was microscopic examination of sections from 125 full-cored wells completed in the years 2011–2012, arranged in a grid shown in Fig. 2. From samples collected in drill cores, both polished slabs (Fig. 5) and thin-sections (Figs. 6, 7, 8) were made, and these were the basis for sedimentological studies. Upper Jurassic sediments, up to 130 m thick, were encountered in all studied cores. Lithology and thickness of the older Oxfordian sediments are known from previous wells (see e.g., Deczkowski 1977; Deczkowski and Gajewska 1983).

Fieldwork provided the lithological columns and samples for microfacies studies. Generally, six facies types were distinguished (FT 1–6) in which numerous microfacies were identified (Fig. 2). The analysis of facies distribution was based upon lithological columns and structural maps, and visualized as a 3D model of the Złoczew Graben (Dukacz 2013). Modeling utilized the Triangular Irregular Networks (TIN) numerical model for the top surface of the Jurassic strata, using the ArcGis software. The model presents the locations of wells, top surface of Upper Jurassic deposits and distribution of the distinguished facies (Figs. 2, 3). In marly limestone and marl, the $CaCO_3$ contents were analyzed.

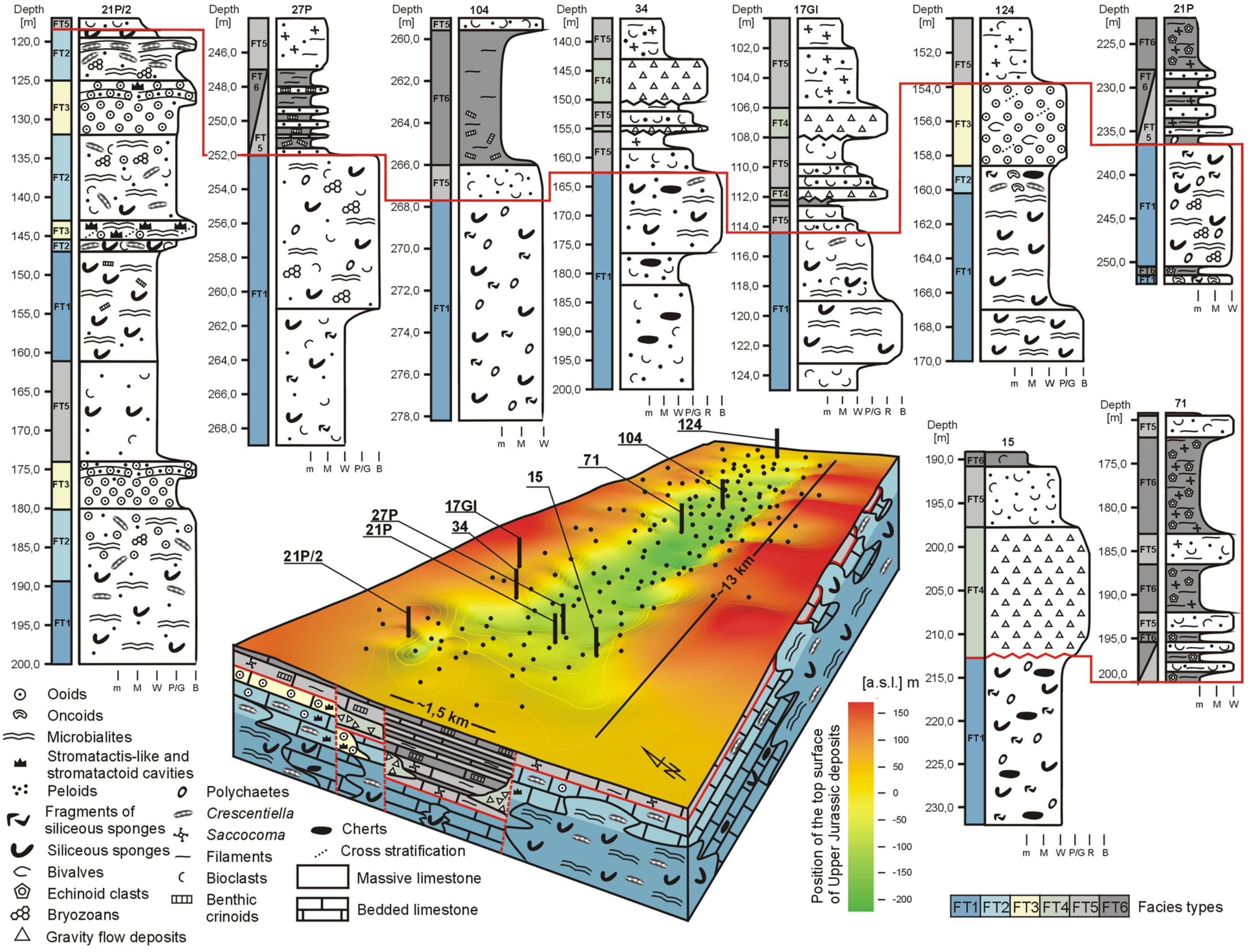


Fig. 2 3D model of the Złoczew Graben with location of wells (*dark dots*), distribution of facies and examples of lithological columns with facies types 1–6. *Black vertical lines* indicate location of lithological columns. *Red dotted lines* on the 3D model indicate main faults bordering the Złoczew Graben. The *red lines* on the lithological columns and 3D model of Złoczew Graben indicate the correlation horizon, which represents the transition from the mid-ramp to the outer-ramp system. The width of the graben is ca. 1.5 km. *m* marl, *M* mudstone, *W* wackestone, *P* packstone, *G* grainstone, *B* boundstone, *R* rudstone

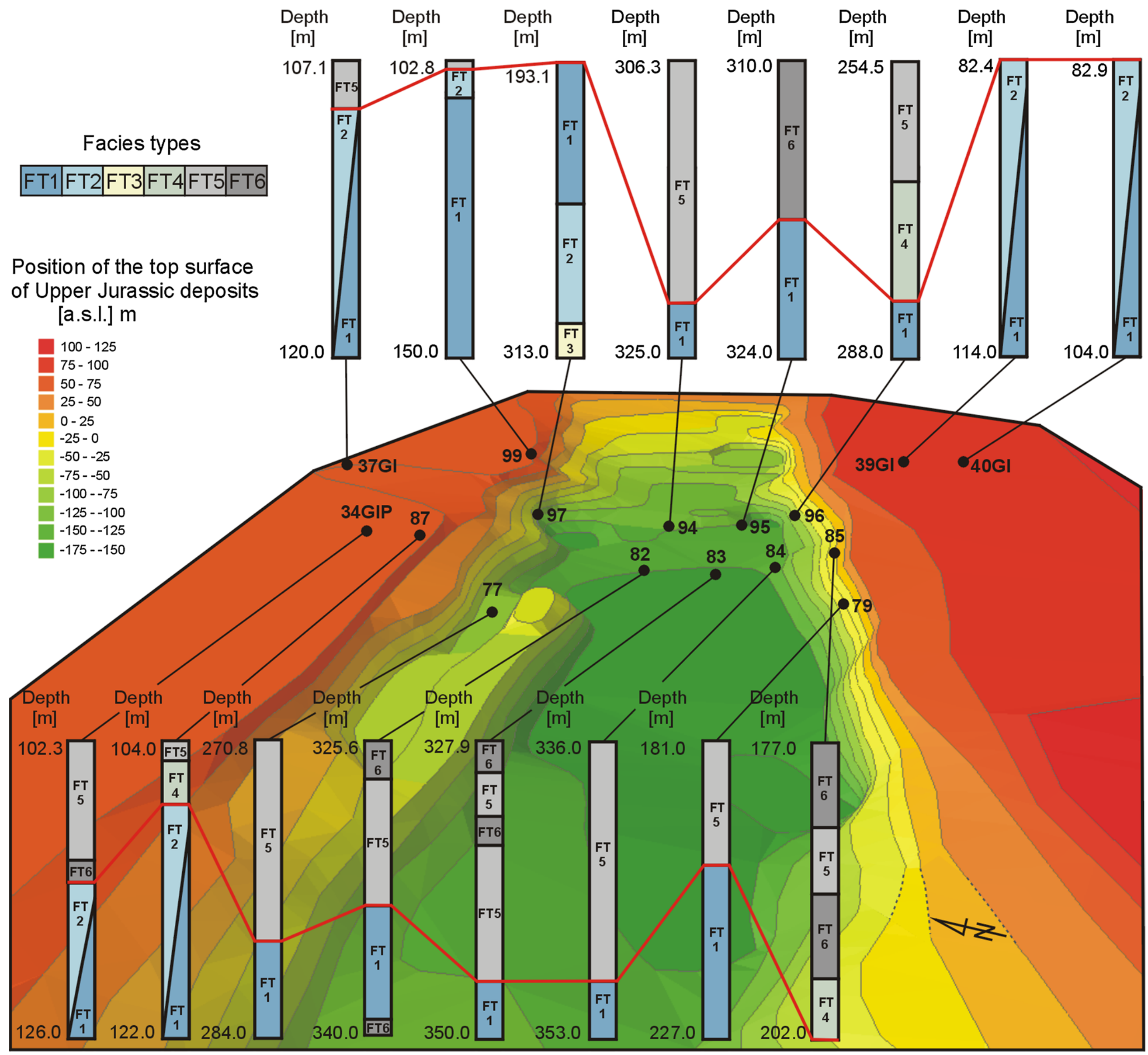


Fig. 3 The northeastern part of the Złoczew Graben with distribution of facies types in the wells oriented in transverse lines. The *red line* on the columns with distribution of facies types and 3D model of the Złoczew Graben area indicate the correlation horizon, which represents the transition from the mid-ramp to the outer-ramp system

Results

Stratigraphy

Microfossil studies support the earlier stratigraphic subdivisions (Deczkowski 1977; Deczkowski and Gajewska 1983) indicating the Upper Oxfordian and Lowermost Kimmeridgian ages (e.g., Olszewska et al. 2012). The foraminifer assemblage includes, among others: *Sievoides kocyigti*, *Reophax Helvetius*, *Protomarssonella jurassica*, *Paalzowella turbinella*, *Rumanolina feifeli*, *Gaudryina* sp., *Mohlerina basiliensis*, *Haghimashella arcuata*, *Protopeneroplis strata*, and *Nautiloculina* cf. *Bronnimanni*. Moreover, calcareous dinocysts were identified: *Colomisphaera lapidosa*, *Stomiosphaera moluccana*, *Colomispharea* af. *heliosphaera*, *Colomisphaera* aff. *Radiata* (Vogler), *Colomisphaera misolensis* Vogler, *Stomiosphaera minutissima* and *Colomisphaera* cf. *Peniniensis* (Borza). The presence of Lower Kimmeridgian (Platynota zone) deposits is confirmed by the marker horizon with hiatus concretions observed in the Złoczew Graben, which is of regional correlative importance in central Poland (Krajewski et al. 2014). Additionally, the observed sedimentary sequences (Fig. 4) correspond well to Upper Jurassic sequences from

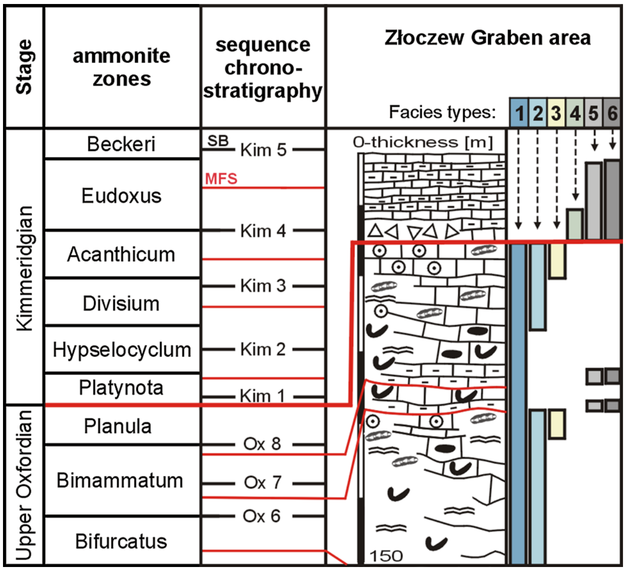


Fig. 4 Stratigraphic position of the Upper Jurassic deposits from the Złoczew Graben area. *SB* sequence boundary, *MFS* maximum flooding surface. Ages of ammonite subzone boundaries and of sequence boundaries according to Hardenbol et al. (1998). Description as on Fig. 2

adjacent areas (e.g., Wierzbowski et al. 1983; Matyszkiewicz 1997b; Matyszkiewicz et al. 2006a, 2015; Krajewski et al. 2011a) and the Ox–Kim sequence boundaries identified by Hardenbol et al. (1998).

Facies types

FT 1: Microbial-sponge limestone

This facies type includes massive carbonate buildups and bedded limestone. In the hanging-wall blocks of the Złoczew Graben, the FT 1 facies grades up into the FT 2 facies, whereas in the central parts of the graben, the FT 1 passes upwards into the FT 5 and FT 6 facies (Fig. 2).

The massive limestone observed in the hanging walls of the graben reach thicknesses up several tens of meters. These are mostly microbial-sponge boundstone and bioclastic wackestone/packstone (Fig. 2; Table 1). Dish-like siliceous sponges (Lithistida and Hexactinellida) overgrown by microbialites form the frameworks of that limestone (Fig. 6a). Microbialites are dominated by fine crusts of dense micrite, clotted thrombolites, and peloidal stromatolites (sensu Schmid 1996) (Fig. 6b, c). The bioclastic wackestone/packstone is composed mostly of peloids, fragments of siliceous sponges, and numerous fine bioclasts. Abundant are microencrusting organisms, usually bryozoans, benthic foraminifers (*Nubecularia*, *Bullopora*), and serpulids. The agglutinating annelid *Terebella lapilloides* is common. In the upper parts of the FT 1 sequence, *Crescentiella* microencrusters are common (*Tubiphytes* in older literature) (Fig. 6c).

Massive limestone in the Złoczew Graben does not occur in all studied wells, which indicates its rather limited lateral extent (Fig. 2). The thickness does not exceed several meters. The main builders are siliceous sponges whereas microbialites (layered thrombolites and leiolites) are less common. Other fossils are bryozoans, serpulids, and echinoderms. The massive limestone contains thin (up to 0.5 cm) laminae of marly limestone and lime mudstone.

The bedded limestone can be thick- or thin-bedded. The thick-bedded variety with chert resembles the massive limestone in hand specimen. The essential differences are microfacies features: bedded limestone contains fewer benthic organisms but more bioclastic wackestone/packstone. The thin-bedded limestone occurs in the graben (Fig. 2). The microfacies is mainly peloidal–bioclastic wackestone and packstone with fragments of siliceous sponges, fragments of ammonites, and bioturbation (*Thalassinoides* and *Chondrites*). Similar to the massive facies, the bedded limestone of the down-thrown central part of the graben is in some cases intercalated with marly limestone and marl.

Facies interpretation The FT 1 is a typical microbial-sponge facies widely distributed over the whole northern shelf of the Tethys Ocean (see e.g., Keupp et al. 1990; Leinfelder et al. 1996; Matyszkiewicz 1997b; Schmid et al. 2001; Olóriz et al. 2003; Olivier et al. 2004; Reolid et al. 2005). Both the massive and the thick-bedded limestone represent microbial-sponge reefs or biostromes. The massive limestone seen in the graben forms a low-relief space cluster reef sensu Riding (2002) and shows a close relationship to the initial 'loose' bioherms described from the Kraków-Częstochowa Upland (Trammer 1989; Matyszkiewicz et al. 2012). The intercalations of marly limestone and lime mudstone are products of deep-water deposition in local depressions between the reef complexes. Similar, deep-water sponge-microbial reefs were described from the Swabian and Franconian Alps (Keupp et al. 1990; Schmid et al. 2001; Olivier et al. 2004).

The FT 1 facies was deposited in a distal, mid-ramp setting, mostly a low-energy, nutrient-rich environment (e.g., Keupp et al. 1993; Olóriz et al. 2003; Olivier et al. 2004). The growth of microbialites and their diversity were controlled mainly by sedimentation rate and energy level (e.g., Keupp et al. 1993; Leinfelder et al. 1996; Matyszkiewicz et al. 2012), which reflect local conditions unaffected by significant changes in sea-water chemistry (Matyszkiewicz et al. 2012). Common microencrusters, mostly benthic microbial communities, serpulids, bryozoans, and foraminifers, indicate a low-energy environment, low sedimentation rate and low terrigenous influx (e.g., Reolid and Gaillard 2007). *Terebella lapilloides* is commonly observed in Upper Jurassic reefs and represents a low-energy setting

Table 1 Facies types and microfacies with main features and depositional environments from the Złoczew Graben

Facies types	Microfacies	Main features	Depositional environment
FT 1: microbial-sponge limestone	Microbial-sponge boundstone Bioclastic wackestone–packstone Peloidal–bioclastic wackestone–packstone	Siliceous sponges, micritic and clotted thrombolites, peloidal stromatolites, spicules, bryozoans, serpulids, *Crescentiella*	Low- to moderate-energy mid ramp
FT 2: microbial-*Crescentiella* limestone	Microbial boundstone *Crescentiella*-bioclastic packstone–grainstone	*Crescentiella*, bryozoans, agglutinating and peloidal stromatolites, intraclasts, ooids, carbonate sponges, stromatactis-like and stromatactoid cavities	Moderate-energy transition zone between mid and inner ramp
FT 3: oolitic–bioclastic limestone	Micritic–oolitic grainstone–packstone Agglutinated stromatolite ooid-bearing boundstone Oolitic grainstone Oolitic–oncolitic–bioclastic grainstone	ooids, micritic ooids, bivalves, oncoids, aggregate grains, *Crescentiella*, *Bacinella*, stromatactis-like and stromatactoid cavities	Moderate- to high-energy inner ramp
FT 4: gravity flow deposits	Rudstone–grainstone Packstone–wackestone Mudstone	Breccias and debris flow eroded from FT 1 and FT 2, calciturbidites, Bouma division	Tectonically triggered erosion and redeposition along horsts and grabens, mid to outer ramp
FT 5: fine-grained detrital limestone and lime mudstone	Fine-bioclastic wackestone–packstone Mudstone	Planktonic and benthic Crinoids, spicules, echinoids, filaments	Low-energy outer ramp
FT 6: marly limestone and marl	Oncolitic-bivalve wackestone–floatstone Mudstone Bioclastic wackestone–packstone	Planktonic and benthic crinoids, oncoids, ammonites, trace fossils	Mixed carbonate–siliciclastic setting of low energy outer ramp

under dysoxic conditions (e.g., Reolid et al. 2005; Kaya and Altiner 2014). The presence of phototrophic microbialites and *Crescentiella* in thick, massive and bedded limestone, indicates paleodepths above storm-wave base, i.e., around 40–60 m (e.g., Keupp et al. 1993; Aurell et al. 1995; Leinfelder et al. 1996; Matyszkiewicz 1997b; Krajewski 2000).

FT 2: Microbial-Crescentiella limestone

This facies type occurs in both the massive and bedded limestone located along the margins of the Złoczew Graben (Fig. 2). The FT 2 grades up into the FT 3 and/or FT 5 (Fig. 2). Dominating components of FT 2 are: very abundant *Crescentiella morronensis* (Crescenti) and bryozoans (Table 1; Fig. 6c, d). *Crescentiella* occurs as individuals or colonial assemblages in which the individual forms are commonly connected with cyanophycean crusts (Fig. 6d). Thickness of colonies may reach some tens of centimeters and their lateral extensions are presumably much larger (cf. Matyszkiewicz and Felisiak 1992; Krajewski 2000). This association includes two microfacies varieties: (1) microbial boundstone and (2) *Crescentiella*-bioclastic packstone–grainstone (Fig. 6d, e). Apart from *Crescentiella*, agglutinated and peloidal stromatolites are present. Detrital components in stromatolites comprise fine bioclasts, peloids, and ooids. In *Crescentiella*-bioclastic packstone–grainstone, *Crescentiella* is usually accompanied by numerous, crushed bioclasts dominated by randomly distributed bivalve shells, calcareous sponges, intraclasts, and, less common, fragments of siliceous sponges. In the lower portions of FT 2, *Crescentiella* coexists with siliceous sponges and thrombolites, which gradually disappear upwards with the increasing amounts of non-skeletal coated grains, including oncoids and ooids (Fig. 6e, f). Close to the graben margin, FT 2 contains stromatactis-like cavities (sensu Matyszkiewicz 1997a) and stromatactoid cavities (cf. Neuweiler et al. 2001) (Figs. 5b, 6f). Their characterization is presented below, in the description of FT 3.

Facies interpretation Limestone with numerous *Crescentiella* was included in the *Tubiphytes–Terebella* association (Leinfelder et al. 1996). *Crescentiella* represents symbiosis between nubecularid foraminifers and cyanophyceans (e.g., Senowbari-Daryan et al. 2008; Pleş et al. 2013). Commonly, the individual specimens in life position are connected with cyanophycean crusts, forming a kind of colony, which builds micro-constructions (e.g., Schlagintweit and Gawlick 2008; Krajewski 2008; Senowbari-Daryan et al. 2008). Such an association is common in a mid-ramp setting (e.g., Leinfelder et al. 1996). Such sediments were common in many parts of Late Jurassic, open-marine, shallow-water, epicontinental environments of the Tethyan Realm (e.g., Leinfelder et al. 1996; Matyszkiewicz 1997b; Krajewski and Olszewska 2006; Senowbari-Daryan et al. 2008; Pleş et al. 2013; Chatalov et al. 2015; Kaya and Altiner 2015 and references therein). FT 2 is a transitional facies between mid-ramp and inner-ramp facies. Common grainstone in this association indicates reworking of material close to the wave base. A common feature of FT 2 as well as FT 1 and FT 3 is the presence of *Crescentiella* in transition zones between the facies. Both the skeletal and non-skeletal components of FT 2, including thick-shelled bivalves, oncoids, and ooids indicate an environment close to the fair-weather wave base (e.g., Matyszkiewicz and Felisiak 1992; Krajewski 2000; Matyszkiewicz et al. 2006a).

FT 3: Oolitic-bioclastic limestone

This facies type is encountered in wells located along the northwestern and western margins of the Złoczew Graben where it overlies the FT 2 facies (Fig. 2). In places, it occurs as redeposited sediment within the graben (e.g., No. 97 well) (Fig. 3). The FT 2–FT 3 transition is gradual over ~20 cm where the percentage of *Crescentiella* decreases and that of ooids increases. Four types of microfacies were distinguished (Table 1; Fig. 7): (1) micritic-oolitic grainstone–packstone, (2) agglutinated stromatolite ooid-bearing boundstone, (3) oolitic grainstone, and (4) oolitic–oncolitic–bioclastic grainstone. The micritic-oolitic grainstone–packstone and the agglutinated stromatolite ooid-bearing boundstone can be observed in the lower part of the FT 3 succession. Up the succession, these are replaced by oolitic grainstone and oolitic–oncolitic–bioclastic grainstone.

Micritic-oolitic grainstone–packstone is composed of small (<0.5 mm) ooids, small intraclasts, and oncoids accompanied by abundant bioclasts, brachiopods, gastropods, bivalves, and echinoids (Fig. 7a). Commonly, the sediment is stabilized by microbial crusts.

Agglutinated stromatolite ooid-bearing boundstone is composed of ooids bounded by microbialites in which stromatactis-like and stromatactoid cavities are observed (Fig. 7b, c). This microfacies occurs only close to the margins of the Złoczew Graben, in its hanging-wall blocks (Fig. 2). Stromatolites are commonly discontinuous and laminae are deformed (Fig. 7b). Dominating components are radial ooids, up to 1 mm across, micritic ooids, fine bioclasts, and peloids. Thickness of detrital sediments enclosed between microbial laminae may reach up to 1 cm but is usually <2 mm (Fig. 7c).

In this microfacies, stromatactis-like and stromatactoid cavities are common (Fig. 2). Cavities reach 2 cm in length and are up to 0.5 cm high (Fig. 5b). Stromatactoid cavities are smaller, up to about 0.5 cm wide, and 3 mm high. Both types of cavity occur as individuals or locally they

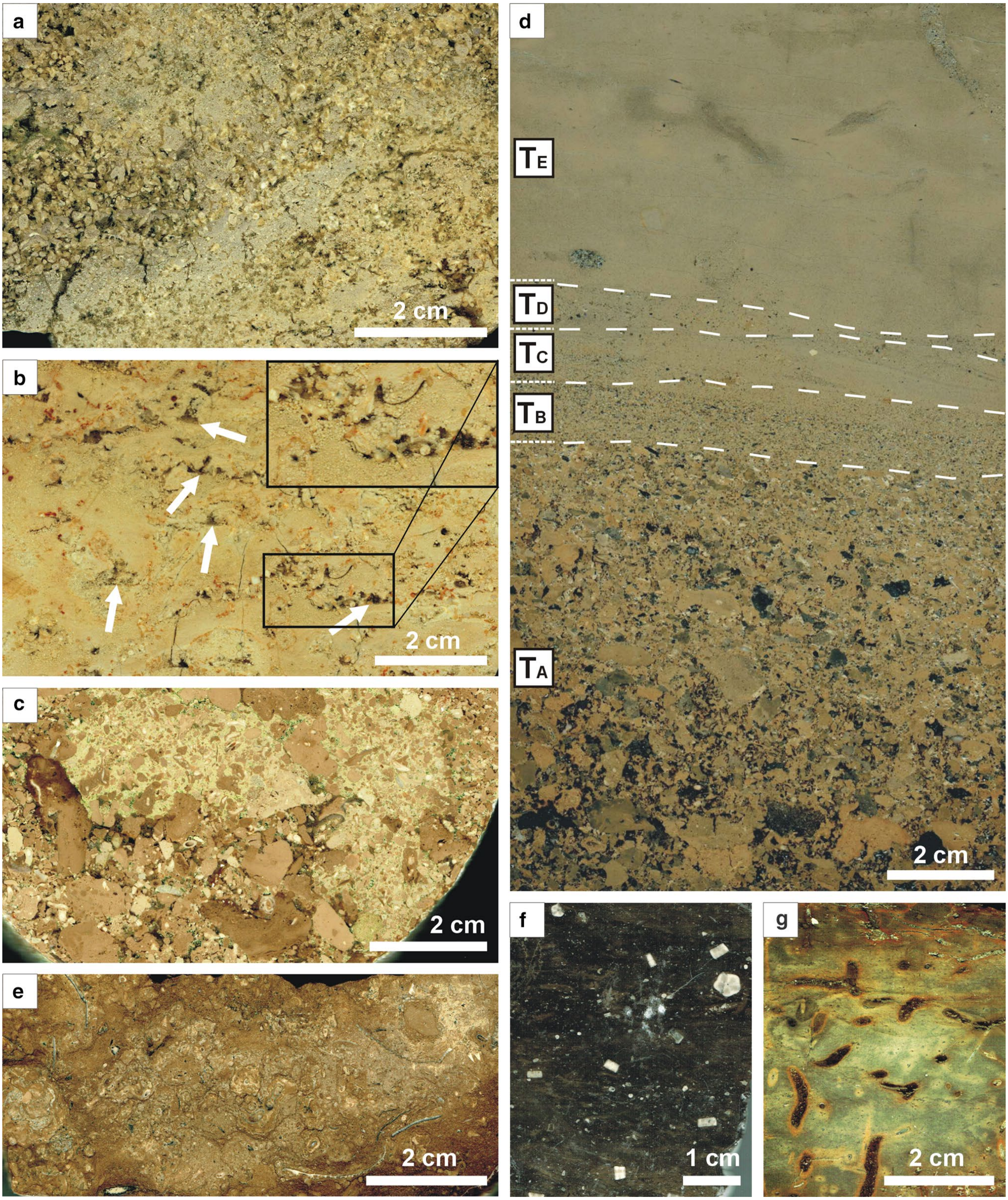


Fig. 5 Polished slabs from Upper Jurassic deposits. **a** Detrital limestone with numerous *Crescentiella* and bioclasts (FT 2). 116 well, depth 188.0 m. **b** Microbial-*Crescentiella* limestone with numerous stromatactis-like and stromatactoid cavities (*white arrows*) (FT 2). 21P/2 well, depth 143.6 m. **c** Gravity-flow deposits (synsedimentary breccia) with numerous irregular clasts of different facies types (FT 4). 17GI well, depth 112.0 m. **d** Gravity-flow deposits with visible Bouma divisions (FT 4). N43 well, depth 262.0 m. **e** Marly limestone with numerous irregular oncoids and bivalves (FT 6). 86P well, depth 328.0 m. **f** Marl with numerous fragments of benthic crinoids (FT 6). 53 well, depth 307.0 m. **g** Marly limestone with numerous burrows (FT 6). P(H-1/1) well, depth 238.6 m

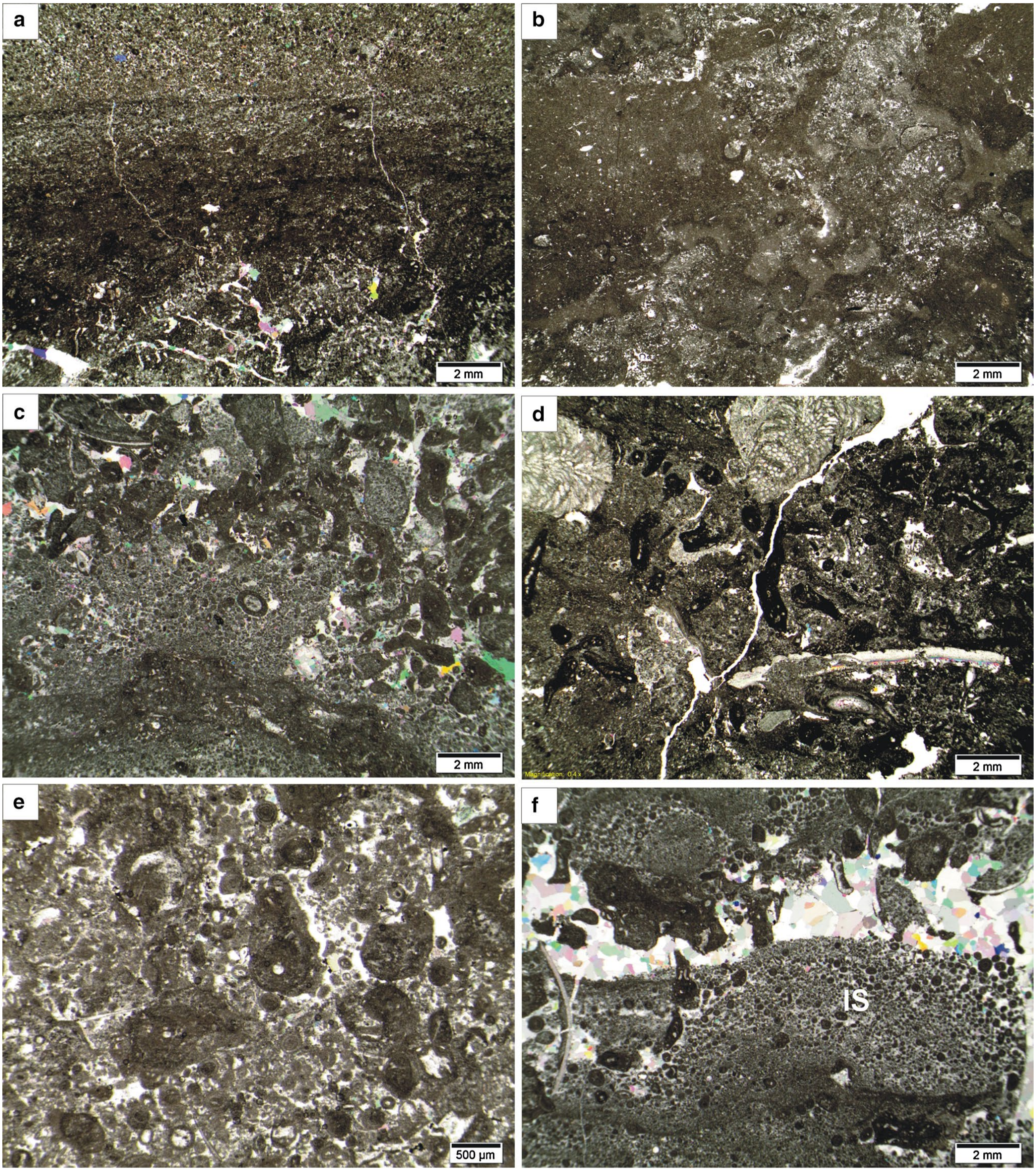


Fig. 6 Microfacies from Upper Jurassic deposits (FT 1–2). **a** Microbial sponge boundstone (FT 1). In the *lower part* of the photo, siliceous sponge with microbialites are visible. In the *upper part*, peloidal wackestone is present. 21P/2 well, depth 163.7 m. **b** Microbial sponge boundstone with thrombolite. 21P well, depth 241.8 m. **c** Microbial boundstone, which passes upward into the microbial-*Crescentiella* boundstone. 116 well, depth 188.0 m. **d** Microbial-*Crescentiella* boundstone with numerous bryozoans. 21P/2 well, depth 120.2 m. **e** Microbial-*Crescentiella* packstone with coated grains. 116 well, depth 196.0 m. **f** Stromatactis-like cavity within microbial-*Crescentiella* limestone. *Lower part* of cavity is filled with internal sediment (IS), whereas the *upper part* is filled with blocky cement. In the *lower part* of internal sediment, microbial crusts are visible. 21P/2 well, depth 143.6 m

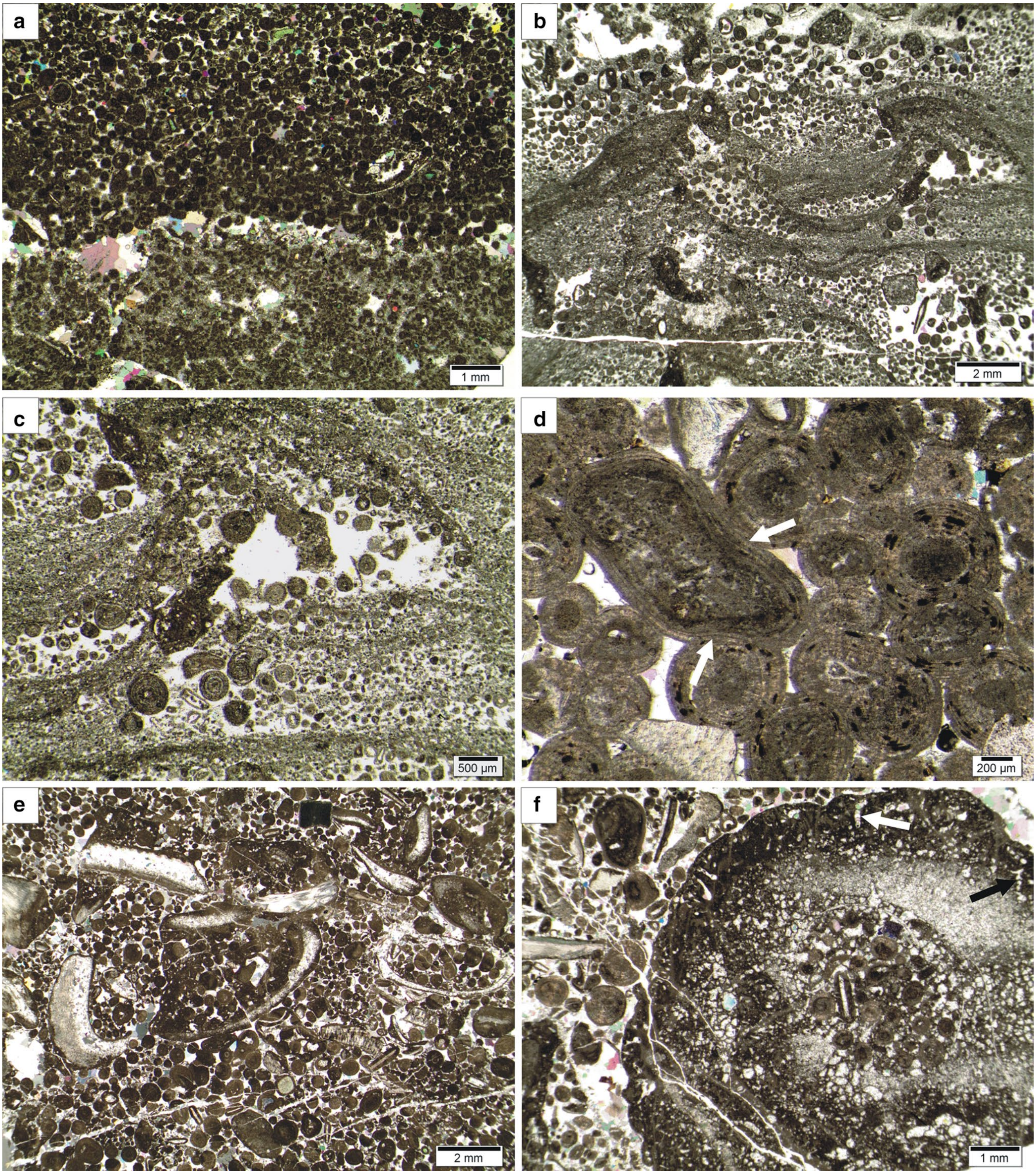


Fig. 7 Microfacies from Upper Jurassic deposits (FT 3). **a** Peloid packstone, which passes upward into the micritic-fine ooid-peloid packstone/grainstone. 124 well, depth 154.0 m. **b** Micritic-fine-ooid grainstone–packstone with agglutinating stromatolite (central part of photo). 21P/2 well, depth 127.8 m. **c** Ooid-bearing boundstone with ooids stabilized by microbial crusts. 21P/2, depth 127.8 m. **d** Ooid grainstone with compactional deformation (*arrows*) of the ooids. 124 well, depth 157.0 m. **e** Ooid-bioclastic grainstone with numerous bivalve shells. 97 well, depth 312.5 m. **f** Ooid–oncoid–bioclastic grainstone with *Bacinella irregularis* and *Trogrotella incrustants* (*arrows*). 124 well, depth 155.0 m

form clusters. In their lower parts, cavities contain internal sediments, followed by calcite cement (Fig. 6f). The upper interfaces with the host sediment are irregular and follow the shapes of oncoids, ooids, *Crescentiella* and bivalve shells. In the last case, the roofs are smooth and convex downward. Internal sediment is grainstone with ooids up to 0.5 mm across and single oncoids, *Crescentiella* and bioclasts. Macroscopically, it is difficult to identify the boundaries between the internal sediment and the host sediment. Under the microscope, the boundaries are often the microbial crusts (Figs. 6f, 7b, c). In such cases, the internal sediment is a light-colored grainstone containing darker microbial crusts and the boundaries are somewhat wavy. In some cavities, the internal sediment is a grainstone grading into enclosing packstone.

Two types of calcite cement are present. The walls of cavities are covered with isopachous cement, up to 0.03 mm thick, whereas the central parts are filled with blocky cement of crystals up to 1.2 mm. Within such blocky cements are oncoids, ooids, bioclasts, and irregular fragments of sediment composed of particles of enclosing rock (Fig. 6f).

The oolitic grainstone comprises aggregate grains, less commonly bioclasts and peloids. Dominating components are radial ooids with thin-laminated, fine-radial cortices, up to 1 mm across. Compactional deformation of ooids (Fig. 7d) and aggregate grains has taken place locally.

The oolitic–oncolitic–bioclastic grainstone contains numerous bivalve shells, echinoderms, gastropods, *Crescentiella* and aggregate grains (Fig. 7e). Moreover, oncoids also occur, with the microproblematica ulvophycean green alga *Bacinella irregularis* Radoičić 1959 (Schlagintweit et al. 2010) and characteristic, boring foraminifera *Troglotella incrustans* (Fig. 7f).

Facies interpretation The FT 3 microfacies represents the succession from fore shoal through shoal to back shoal of an oolitic-dominated inner-ramp setting, in which non-skeletal components prevailed (e.g., Bádenas and Aurell 2010). The oolitic grainstone is interpreted as normal-marine shallow water within the range of normal wave base (e.g., Flügel 2004). The oolitic–bioclastic grainstone was deposited in a moderate- to low-energy back-shoal or lagoonal environment. The presence of *Bacinella irregularis* Radoičić, 1959 suggests a shallow, subtidal, back-shoal environment. The *Bacinella* oncoids are genetically linked to low-energy, oligotrophic interior lagoons (e.g., Dupraz and Strasser 1999; Védrine et al. 2007; Bádenas and Aurell 2010), although, in the Złoczew area, these occur in a higher-energy back shoal with ooid-dominated grainstone.

The sedimentary environment of agglutinated stromatolites with numerous ooids and stromatactis-like and stromatactoid cavities was the slope on which ooids were temporarily deposited. The origin of stromatactis cavities, in general, is still controversial despite numerous investigations (see for review and references, e.g., Matyszkiewicz 1997a; Hladil et al. 2007; Aubrecht et al. 2009; Lazăr et al. 2011). Stromatactis-like cavities and stromatactoid cavities described in this paper differ from true stromatactis in terms of size, shape, and occurrence. The origin of the cavities here is related to remodeling of initial open spaces in an inhomogeneous, partly lithified sediment (cf. Matyszkiewicz 1997a; Neuweiler et al. 2001; Olchowy 2011). Such open spaces might have formed at the contacts of loose particles (ooids, oncoids, bioclasts, or intraclasts) and partly lithified microbial crusts during sedimentation (cf. Hladil et al. 2006). According to Schmid et al. (2001), the presence of small-scale discontinuities within sediment together with an unstable shelf position may led to gravitational slumping. The factor disturbing the stability of sediment with initial open spaces might have been synsedimentary tectonics responsible for generation of stress within the rocks (Matyszkiewicz 1997a; Olchowy 2011).

FT 4: Gravity flow deposits

This facies type is represented by debrites and calciturbidites. In the Złoczew Graben, the FT 4 sediments are observed only in narrow zones close to faults where they grade vertically and horizontally into FT 5 (Fig. 2). Debrites reach a thickness up to 15 m (Fig. 2). The boundaries between gravity-flow deposits and overlying (FT 5) and underlying sediments are distinct and their basal surfaces are erosional. The sediments are poorly sorted, have a variable clast size, a chaotic clast fabric, and a lack of stratification. The clasts are angular or subangular, polymictic, randomly distributed, and include: microbial-*Crescentiella* boundstone (FT 2), microbial-sponge boundstone, bioclastic wackestone–packstone (FT 1), lime mudstone (FT 5), and less commonly micritic–oolitic grainstone–packstone (FT 3) (Table 1). Clasts have created umbrella cavities with geopetal sediment below. The size of clasts varies from several mm to more than 10 cm. The matrix between the clasts usually comprises Upper Jurassic rudstone–grainstone, packstone–wackestone, mudstone, and blocky cement (Figs. 5c, 8a). Upwards, breccias grade into calciturbidites with Bouma-type divisions T_A to T_E, excluding convolute lamination (Figs. 5d, 8a, b).

Facies interpretation The FT 4 represents debrites and calciturbidites (e.g., Flügel 2004). The presence of debrites in narrow zones following the boundaries of the Złoczew Graben indicates synsedimentary tectonic activity along steep, tectonically controlled scarps (e.g., Drzewiecki and Simó 2002). Such sediments could not be transported for long distances due to the lack of buoyancy (e.g., Drzewiecki and Simó 2002). Tectonic activity in the graben was the main trigger for the sediment-gravity flows (e.g.,

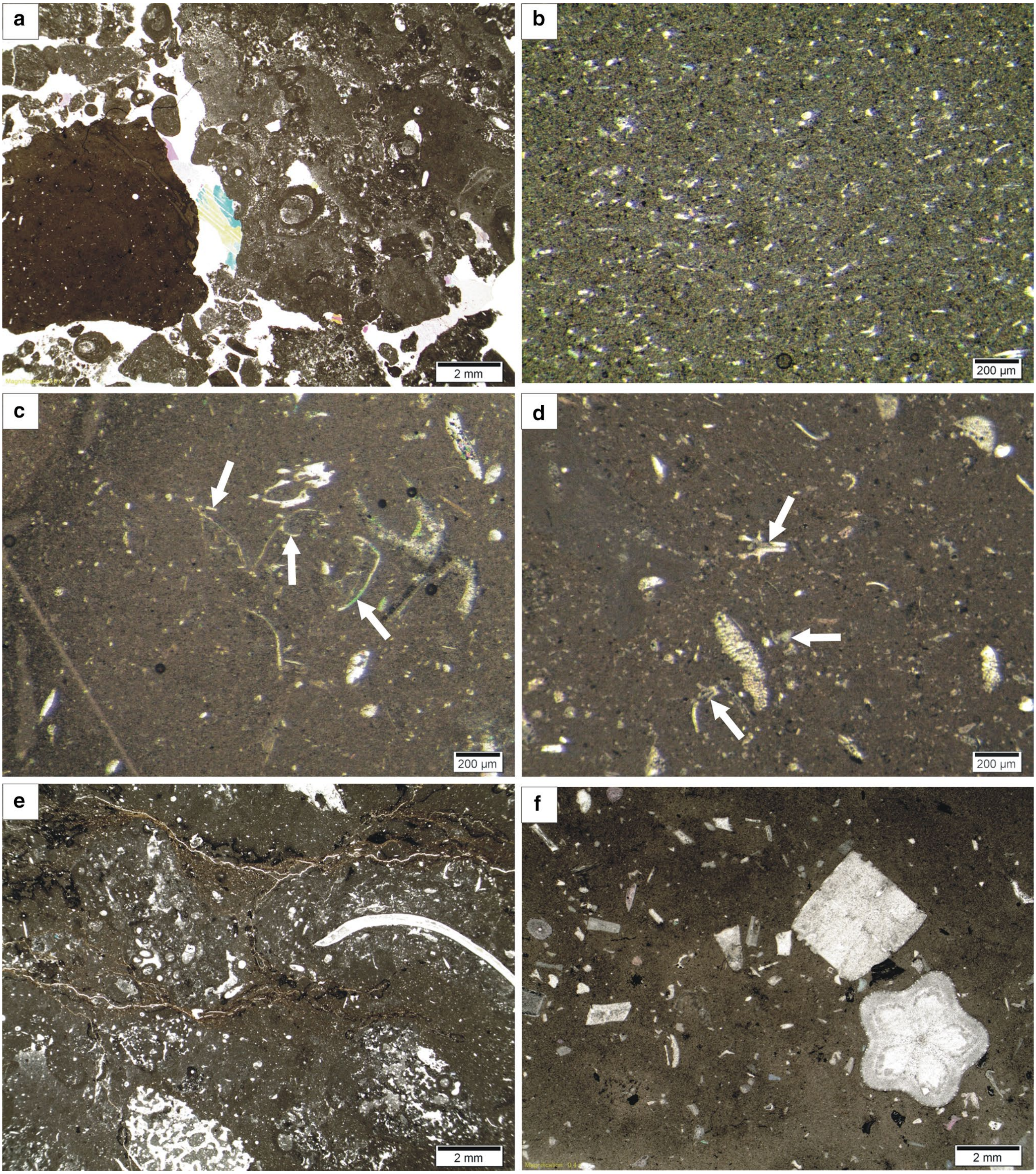


Fig. 8 Microfacies from the Upper Jurassic deposits (FT 4–6). **a** Rudstone with angular clasts. In the *left* part of the photo, a clast composed of mudstone/wackestone is present. In the *right* part of the photo, a clast composed of microbial boundstone with *Terebella lapilloides*. *Lower part* of Bouma division (T_A). 17GI well, depth 112.0 m. **b** Fine bioclastic wackestone. *Upper part* with Bouma divisions. 17GI well, depth 114.0 m. **c, d** Fine bioclastic wackestone with numerous planktonic remains of *Saccocoma* secundibranchials (*arrows*). 64 well, **c** depth 333.0 m, **d** depth 332.5 m. **e** Marly oncoid bivalve floatstone. 21P well, depth 251.8 m. **f** Marl with fragments of benthic crinoids. 53 well, depth 307.0 m

Matyszkiewicz 1996; Montenat et al. 2007; Krajewski et al. 2014).

FT 5: Fine-grained detrital limestone and lime mudstone

FT 5 was found in both the basement and the margins of the Złoczew Graben (Fig. 2). Its thickness does not exceed several meters and reaches a maximum in the marginal parts of the graben (Figs. 2, 3). FT 5 rests upon FT 1 in the basement of the graben and upon FT 2 and 3 along its margins. Up the sequence, FT 5 most commonly grades into marly limestone and marl of the FT 6 facies, in some cases forming limestone-marl alternations with a total thickness up to 40 m. The FT 5 sediments are usually fine-bioclastic wackestone–packstone and mudstone (Table 1; Fig. 8c, d). The latter contain trace fossils including *Thalassinoides* and *Chondrites*. The FT 5 facies comprises common fragments of planktonic rovecrinoids *Saccocoma* sp., echinoids, spicules, benthic crinoids, filaments, and some fragments of siliceous sponges.

Facies interpretation The FT 5 sediments were deposited in an outer ramp setting (e.g., RMF 3–5; Flügel 2004). The transition from mid-inner ramp facies to outer-ramp facies indicates the essential change in sedimentary conditions related to submergence of the carbonate platform.

FT 6: Marly limestone and marl

This facies variety occurs above the FT 5 facies (Figs. 2, 3). It commonly forms limestone-marl alternations with FT 5 sediments, with rare clay intercalations up to several centimeters thick. Thickness of FT 6 may reach 10 m, but usually it does not exceed several meters. The FT 6 sediments are grey, thin-bedded, bioturbated marl and marly limestone, locally with abundant fragments of ammonites, bivalves, crinoids, and oncoids (the latter found in the lowermost part of the FT 6 succession). The marly microfacies comprises: (1) oncolitic-bivalve wackestone–floatstone, (2) mudstone, and (3) bioclastic wackestone–packstone (Table 1). Contents of $CaCO_3$ change from 45 to 98 wt%.

Oncolitic-bivalve wackestone–floatstone occurs in the lowermost parts of the FT 6 section, as beds in marly limestone up to 10 cm thick. Oncoids vary in size from a few mm to 3 cm. Both oval and irregular oncoids with sharp or diffused contours are present. Most oncoids have a bioclastic nucleus (Fig. 8e). Cortexes consist of micrite or, rarely, of organism-bearing lamination. Some oncoids reveal traces of bioerosion.

In marl and marly limestone, numerous trace fossils are common, represented by *Planolites* and *Chondrites*. In bioclastic wackestone–packstone, crinoids are common, particularly the remains of benthic *Isocrinus* sp. and large, abraded pluricolumnals of Millercrinidae (Fig. 8f) (Gorzelak and Salamon 2009), as well as poorly preserved, planktonic Roveacrinidae (*Saccocoma* sp.) (Fig. 8c, d). Fragments of echinoids, foraminifers and filaments also occur. Skeletal elements of crinoids are commonly arranged parallel to each other (Fig. 5f). The sediments contain a moderately preserved but taxonomically poor nannoplankton assemblage dominated by long-lived *Watznaueria* and *Cyclagelosphaera* (Upper Jurassic–Lower Cretaceous) among which were identified *Watznaueria barnesae* (Black) Perch-Nielsen, small *Watznaueria britannica* (Stradner) Reinhardt, *Cyclagelosphaera margerelii* Noe. and *Etthmorhabdus* sp.

Facies interpretation Bioturbated marl and marly limestone represent the deepest facies identified, deposited in a low-energy, outer-ramp setting. Marly facies with oncoids were described from low-energy, mixed, carbonate–siliciclastic mid-ramp setting (e.g., Olivier et al. 2011). The appearance of oncoids in marly sediments along with the traces of bioerosion on their surfaces indicate nutrient-rich and turbid waters. Relatively well-preserved crinoid fragments without clear signs of abrasion indicate short post-mortal transport (Gorzelak and Salamon 2013). Although the parallel arrangement of their skeletons imply transport over some distance, a lack of microencrustations on the crinoid surfaces suggests rapid burial (e.g., Brett et al. 1997; Salamon and Gorzelak 2010). Crinoids settled in deep water (about 200–250 m depths) beneath the storm wave base, under low-energy conditions, and at low sedimentation rates.

Small specimens of *Watznueria britannica* indicate mesotrophic to eutrophic conditions (e.g., Pittet and Mattioli 2002; Olivier et al. 2004). Their common occurrence together with the low-diversity nannoplankton assemblage may be related to higher trophic conditions and a stratified water column. The more common occurrence of *Watznueria barnesiae* points out to somewhat better-oxygenated but still highly trophic conditions.

Discussion

Facies development

The dense grid of exploration wells together with the facies analysis enabled the determination of spatial relationships of facies in the Złoczew Graben (Figs. 2, 3). Facies relations observed across faults separating the marginal hanging-wall blocks from the down-thrown central part of the graben indicate synsedimentary movements during the Late Jurassic stage of its evolution. A rapid vertical facies change observed in all sections distributed across the graben and the bounding shoulders occurs between FT 1–3 and FT 4–6 (Figs. 2, 3). This boundary documents an important depositional change and is used as datum in correlation of the lithological columns shown in Figs. 2 and 3. Based on the analysis of archival and new data on facies relationships, two developmental stages in the depositional system were identified: Upper Oxfordian (sensu Bifurcatus–Planula zones sequence) and Lowermost Kimmeridgian (sensu Platynota zone) (Fig. 4).

Upper Oxfordian stage

The sedimentary succession in the Złoczew area begins with the microbial-sponge facies (FT 1). Several transitions of FT 1 and FT 2–3 (Figs. 2, 4) probably correspond to cyclic sea-level changes. The regressive trends during the Late Oxfordian are visible at the end of the Bifurcatus and Planula zones (e.g., Hardenbol et al. 1998). Hence, the oldest sediments encountered in this research may represent the Bifurcatus zone.

FT 1 represents typical Upper Oxfordian facies, widely distributed in Europe (e.g., Aurell et al. 1995; Leinfelder et al. 1996; Matyszkiewicz 1997b; Olóriz et al. 2003; Olivier et al. 2004, 2011; Reolid et al. 2005). The development of FT 1 can be related to a more distal mid-ramp setting. Such sediments represent matrix-supported and skeleton-supported, microbial-sponge reefs (sensu Riding 2002) and contemporaneous bedded limestone deposited in inter-reef depressions. The microbial-sponge reef facies were found mostly in hanging-wall blocks of the Złoczew Graben whereas at the graben center the equivalent thin-bedded facies were deposited with small, meter-scale sponge bioherms interbedded with marly limestone. Thus, it can be suggested that the course of the Złoczew Graben followed the morphology of the sea floor during the Late Oxfordian (Fig. 2).

FT 1 was gradually replaced by microbial-*Crescentiella*-dominated FT 2. Development of these facies in the study area is referred to the regressive trend in the Late Oxfordian (Planula Zone; Matyszkiewicz and Felisiak 1992; Matyszkiewicz 1997b; Krajewski et al. 2011a) (Fig. 4). In successions with FT 2, a distinct decrease in the number of sponges and thrombolites was recorded, and an increase in agglutinated stromatolites, coated grains, and detrital material. These sediments were not encountered in the central part of the graben, still occupied by FT 1. The FT 2 sediments grade up into oolitic FT 3 (Fig. 2) to form a succession from mid-ramp microbial-*Crescentiella* reefs to shallow-water, inner-ramp oolitic fore-shoal, shoal, and back-shoal facies (cf. Bádenas and Aurell 2010). These sediments occur exclusively in the western and northwestern blocks of the graben (Fig. 2). Hence, it is suggested that during the Upper Oxfordian, the Złoczew area formed a transition area between the inner ramp extending northward and/or westward, and the mid ramp extending to the southeast and south.

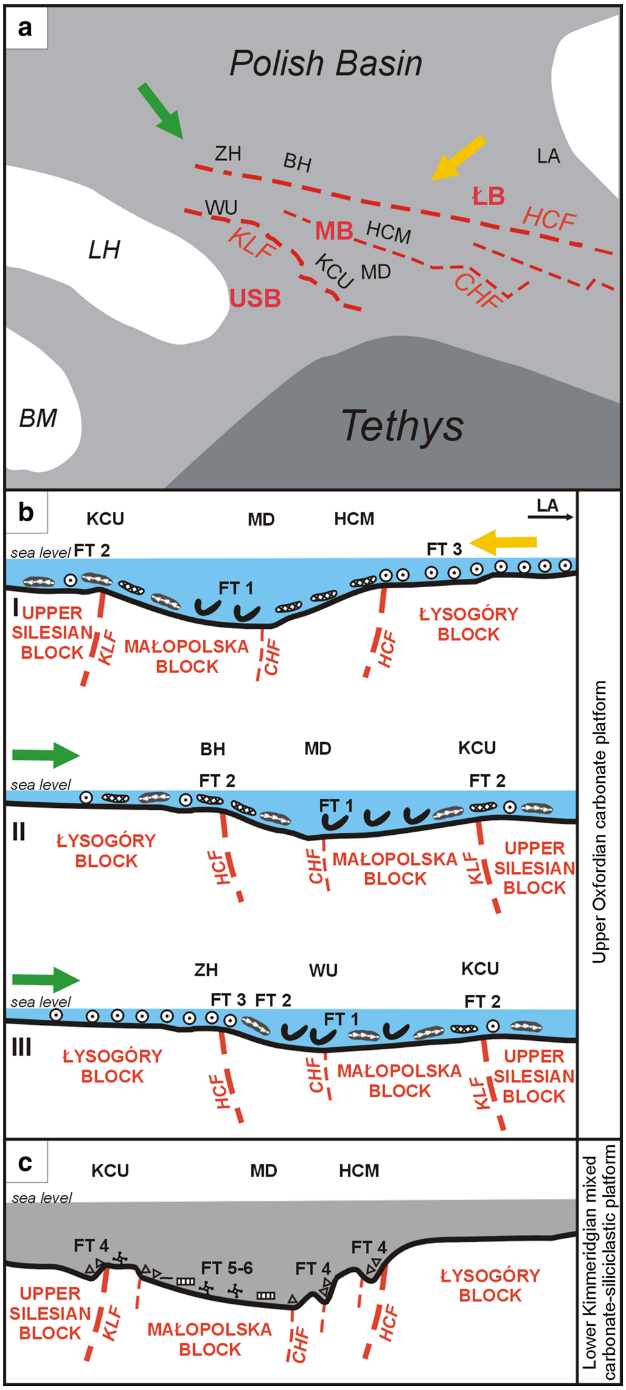
The Lowermost Kimmeridgian stage

At the Oxfordian/Kimmeridgian boundary, an important change in sedimentary environment took place, from mid-inner carbonate ramp to mixed, carbonate–siliciclastic outer ramp (Figs. 2, 3, 4, 9c). The debrites and calciturbidites (FT 4) deposited in the marginal zone of the Złoczew Graben reflect its tectonic activity. This suggestion is supported by the presence of stromatactis-like cavities, which were interpreted as products of synsedimentary tectonic movements by Matyszkiewicz (1997a) and Olchowy (2011). Material laid down as the gravity flow deposits were derived mostly from areas of FT 1–3, whereas fine-grained calciturbidites were derived from FT 5. The lack of reef complexes well-marked in sea-floor relief along with the dominance of detrital deposition strongly limited the formation of steep slopes in the Late Oxfordian, along which redeposition could have taken place. However, steep slopes might have formed due to syndepositional faulting. Seismic activity and normal faulting at the horst/graben margin were the main triggers of gravity-flow deposits (e.g., Kutek 1994; Matyszkiewicz 1996; Montenat et al. 2007; Krajewski et al. 2014).

Both the FT 4 sediments in the graben and the FT 1–3 deposits along its margin grade upward and laterally into FT 5 and/or FT 6 facies (Figs. 2, 3). Such a transition from benthic to pelagic sedimentation documents the submergence of the ramp. This event can be observed in successions from the Kraków-Częstochowa and the Wieluń uplands as well as from the southwestern margin of the Holy Cross Mountains and from the Miechów Depression (e.g., Kutek 1994; Matyszkiewicz 1996; Matyja and Wierzbowski 2006; Złonkiewicz 2009; Krajewski et al. 2014). Initially, oncolitic-marly facies appeared, related to a more distal setting of the mid ramp (e.g., Olivier et al. 2011). These were followed by the marly-limestone alternations representing a deep-water, mixed carbonate–siliciclastic outer-ramp facies (Fig. 9c).

The results obtained in the area of the Złoczew High and those reported from the Kraków-Częstochowa Upland correspond well to successions described from the Lower Kimmeridgian ramp of western Europe (e.g., Bádenas and Aurell 2001, 2010; Olóriz et al. 2003; Olivier et al. 2008). Transition from carbonate ramp to mixed, carbonate–siliciclastic ramp systems observed in the Lower Kimmeridgian can be related to third-order sea-level oscillations and is indicated by the increasing content of terrigenous material (Fig. 4) (e.g., Olivier et al. 2008; Colombié et al. 2014), supplied as a result of tectonic activity close to the Oxfordian–Kimmeridgian boundary.

Fig. 9 Upper Jurassic paleogeographical position and facies distribution on the Małopolska Block (central and southern Poland). **a** Paleogeographical position of the study areas (after Ziegler 1990, modified) with the position of main tectonic structures (in *red*): Małopolska Block (MB), Łysogóry Block (ŁB), Upper Silesian Block (USB). *Red lines* indicate main faults bordering the Małopolska Block: Holy Cross Fault (HCF) and Kraków-Lubliniec Fault (KLF), Chmielnik Fault (CHF). Abbreviations in *black* indicate areas with discussed Upper Jurassic deposits: Złoczew High (ZH), Bełchatów High (BH), SW margin Holy Cross Mt., (HCM), Lublin area (LA), Wieluń Upland (WU), Miechów Depression (MD) and Kraków-Częstochowa Upland (KCU). *Yellow arrow* indicates direction of progradation of oolitic platform suggested so far. *Green arrow* indicates direction of progradation of oolitic platform in the Złoczew High area suggested by the authors. *LH* Lusatian High, *BM* Bohemian Massif. **b** Schematic cross sections between KCU-HCM, KCU-BH, and KCU-ZH showing distribution of Upper Oxfordian (Planula Zone) facies on the main tectonic blocks in the basement. On the SW marginal parts of the tectonic blocks, microbial-*Crescentiella*, coral, and oolitic facies were deposited. In the central part of the MB, microbial-sponge facies were deposited. I—cross section between KCU a HCM oriented transversally to the MB. *Yellow arrow* indicates direction of shallow-water platform progradation suggested so far. II—cross section between KCU and BH oblique to the MB. *Green arrow* indicates direction of shallow-water platform progradation. III—cross section between KCU and ZH oblique to the MB. *Green arrow* indicates direction of shallow-water platform progradation suggested by the authors. **c** Cross section oriented transversally to the MB, which shows distribution of deep-water outer platform lime mudstone and marly facies on the MB during the Lowermost Kimmeridgian (Platynota Zone). On the tectonically active edges of the MB, gravity-flow deposits were deposited ▸



Regional implications

It is widely accepted in the Polish literature (e.g., Matyja et al. 1989; Gutowski et al. 2005 and references therein) that in the Upper Oxfordian the Złoczew High, Kraków-Częstochowa and Wieluń uplands belonged to a southward-sloping, deep-water open shelf occupied by a sponge megafacies. This megafacies developed on the foreland of a shallow-water carbonate platform prograding from the east, from the Lublin area (Fig. 9a, b). In the Planula Zone, the platform front reached the southwestern margin of the Holy Cross Mountains (e.g., Matyja et al. 1989; Gutowski et al. 2005) where shallow-water, oolitic facies graded through coral facies to deep-water sponge facies. The argument in favor of deep-water, open-shelf deposition west and south from the Holy Cross Mountains was the development of Upper Oxfordian strata as lime mudstone and sponge facies described from both the Miechów Depression and the Wieluń Upland (e.g., Deczkowski 1977; Kutek et al. 1977; Wierzbowski et al. 1983; Złonkiewicz 2009). In accordance with the ramp model, facies encountered southwest from these areas, in the Kraków-Częstochowa Upland, should occupy more distal and deeper-water settings. However, sediments known from the southern part of the Kraków-Częstochowa Upland, dominated by microbial-*Crescentiella* facies with numerous coated grains, are similar to those from the Złoczew area (e.g., Matyszkiewicz and Felisiak 1992; Krajewski 2000; Matyszkiewicz et al. 2006a). Such facies are typical of more shallow-water settings within the ramp, which is in obvious contradiction to theoretically shallower successions of the Miechów Depression and the Wieluń Upland (Fig. 9b). The problem of ramp system interpretation has been already discussed by Matyszkiewicz (1997b) who based his opinion on the more shallow-water character of Upper Oxfordian facies seen in the southern part of the Kraków-Częstochowa Upland, in comparison with those described from areas located in the north. The sedimentological features together with the tectonic controls (Kutek 1994) led to the interpretation of the southern part of the Kraków-Częstochowa Upland as an elevation of the shelf margin (Matyszkiewicz 1997b). In the following years, the origin of this elevation was linked to a structure in the Paleozoic basement (Matyszkiewicz et al. 2006a, b).

The sedimentary successions described from the Złoczew area document a continuous facies transition from mid-ramp, microbial-sponge through microbial-*Crescentiella* to inner-ramp oolitic facies but without the coral-dominated facies, as in the southwestern margin of the Holy Cross Mountains. It is suggested that in the Złoczew area as well as in the southern part of the Kraków-Częstochowa Upland the equivalents of coral facies are the microbial-*Crescentiella* (FT 2) facies deposited in a mid-ramp setting. Indirect support of this concept is provided by the results of studies on Upper Oxfordian coral facies from central and southern Poland (Roniewicz and Roniewicz 1971; Roniewicz 2004), where coral facies are dominated by platy coral colonies of *Microsolena*, which grew in a mid-ramp, low-light and low-energy setting, below fair-weather wave base (Insalaco 1996; Leinfelder et al. 1996; Olivier et al. 2011). Corals described from the sites in the Kraków-Częstochowa Upland most commonly occur together with the *Crescentiella*-dominated facies (e.g., Olchowy 2011).

An important aspect of Upper Oxfordian facies distribution in central and southern Poland is the earlier appearance of oolitic facies in the Złoczew area, in comparison with the areas where, according to recent interpretations, more shallow-water settings were developed. In fact, the oolitic facies corresponding to the inner-ramp shoal and backshoal environments appeared in the Złoczew area as early as at the end of the Oxfordian. Considering the interpretation of Złoczew area, the accepted model of open-shelf deposition and progradation of the shallow-water platform from the Lublin area (Fig. 9a, b) needs further consideration. During the Planula Zone, the progradation of shallow-water oolitic facies might have proceeded not only from the east (from the Lublin area) but also from the north-west, from the Złoczew High (cf. Niemczycka and Brochwicz-Lewiński 1988) (Fig. 9a, b). During the Planula Zone, the Złoczew area was located in the marginal part of the inner ramp, prograding to the southeast and south.

The Late Oxfordian facies distribution in central and southern Poland reflects the trends of the main, trans-regional tectonic zones that border the Małopolska Block (Fig. 9b). In the Upper Oxfordian, at the margin of the main tectonic blocks (Fig. 9a, b), the microbial-*Crescentiella*, oolitic and coral facies were deposited in the areas of the Złoczew and Bełchatów highs, and along the southwestern margin of the Holy Cross Mountains. On the other hand, in the southwest, in the central part of the Małopolska Block (Miechów Depression, Wieluń Upland), the deeper, microbial-sponge and lime mudstone facies were deposited (Fig. 9b). However, on the southwestern, uplifted margin of the Małopolska Block (recent area of the Kraków-Częstochowa Upland), the microbial-*Crescentiella* facies with numerous coated grains and rare corals was deposited (Fig. 9b). The uplifted, marginal parts of such blocks were occupied by shallow-water FT 2 and FT 3 locally accompanied by coral facies, whereas the deeper-water FT 1 and lime mudstone were widely distributed in the central part of the Małopolska Block (Fig. 9a, b).

One of the most important factors controlling sedimentation in the Złoczew area in the Late Jurassic, near the Planula/Platynota boundary, was synsedimentary tectonics, particularly intensive in the Platynota Zone (e.g., Matyszkiewicz 1996; Krajewski et al. 2014). Most probably, the Late Jurassic tectonic movements along the eastern margin of the West European Platform resulted in reactivation of the main dislocation zones cutting the tectonic blocks in the Paleozoic basement (Bednarek et al. 1985; Żaba 1999; Krzywiec 2006; Matyszkiewicz et al. 2006a; Gutowski and Koyi 2007; Buła and Habryn 2010, 2011; Krajewski et al. 2014) (Fig. 1). The synsedimentary tectonics active in this zone influenced the development of gravity-flow deposits. The Lowermost Kimmeridgian (Platynota Zone) gravity-flow deposits (Fig. 9c) deposited along regional dislocations bounding the Małopolska Block are known from: (1) the southern Kraków-Częstochowa Upland (e.g., Kutek 1994; Matyszkiewicz 1996, 1997a, b), (2) the southwestern margin of the Holy Cross Mountains (e.g., Migaszewski et al. 2006; Krajewski et al. 2014), (3) the Ukrainian part of the Carpathian Foredeep overprinting the Małopolska Block (Krajewski et al. 2011b) and (4) the Łódź Depression (Krajewski et al. 2014) (Fig. 1a).

The best analogue of the Złoczew Graben is the Krzeszowice Graben located at the southwestern margin of the Małopolska Block (Fig. 1). The most important similarities of the Złoczew and the Krzeszowice grabens are: (1) their structural position along the marginal part of the Małopolska Block which was tectonically active in the Mesozoic (Fig. 1a), (2) the similar thickness of Oxfordian sediments (cf. Matyszkiewicz et al. 2012), (3) the stratigraphic position (cf. Matyszkiewicz 1996; Ziółkowski 2007), (4) the transition from benthic to planktonic sedimentation at the boundary of the Planula and Platynota zones and (Matyszkiewicz 1996; Krajewski et al. 2014) (5) the presence of calciturbidites and debrites in the marginal parts of both grabens (e.g., Matyszkiewicz 1996; Krajewski et al. 2014). Other examples are the Kleszczów Graben in which Lower Kimmeridgian, synsedimentary gravity-flow deposits with calciturbidites and pelagic sediments (Fig. 5d) were observed along the margins (e.g., Krajewski et al. 2014) as well as Wolbrom Graben (Fig. 1a) (Bednarek et al. 1985; Matyszkiewicz et al. 2006a). These examples demonstrate that the facies development of the ramp system in the Polish part of the peri-Tethys shelf was periodically strongly modified by synsedimentary tectonics active in the marginal parts of trans-regional tectonic blocks developed in the eastern part of the West European Platform, particularly along the margins of the Małopolska Block.

The intensive development of gravity-flow deposits in the Lower Kimmeridgian and the change of deposition towards the clay-rich environment in the Małopolska Block (Fig. 9c) correspond well to the features of Lower Kimmeridgian ramp systems described in western Europe (e.g., Bádenas and Aurell 2001, 2010; Olivier et al. 2008) where such changes were related to both North Atlantic and west European tectonics.

Conclusions

1. Upper Oxfordian–Lower Kimmeridgian sediments from the Złoczew Graben include six facies types. The mid-ramp facies comprises microbial-sponge and microbial-*Crescentiella* limestone; the inner-ramp facies includes oolitic–bioclastic limestone; the outer-ramp facies has fine-grained, detrital limestone, lime mudstone, marly limestone, and marl. The Planula/Platynota boundary in the Złoczew Graben area shows a transition from shallow-water, inner-ramp facies to deep-water, outer-ramp facies with simultaneous development of gravity-flow deposits, calciturbidites, and debrites.
2. The presence of calciturbidites and debrites in the marginal zone of the Złoczew Graben reflects Late Jurassic activity of boundary faults of the graben.
3. The transition from inner- and mid-ramp facies to mixed, carbonate–siliciclastic outer-ramp facies resulted from tectonic movements of the Małopolska Block, from increasing supply of siliciclastic material and from the sea-level rise in the Early Kimmeridgian (Platynota zone).
4. The selected facies types and their distribution visualized in a 3D model of the Złoczew Graben enabled a reconstruction of the facies architecture during the Late Jurassic stage of graben evolution. The Złoczew Graben can be presented as a model of similar grabens cutting through the Upper Jurassic formations in central and southern Poland, in the marginal zone of the Małopolska Block.
5. Sedimentation in the Polish part of the peri-Tethys ramp system characterized by the sea-level rise and transition from mid-inner carbonate ramp to outer, mixed, carbonate–siliciclastic ramp at the Planula/Platynota boundary corresponds well to the Lowermost Kimmeridgian ramp system known from elsewhere in western Europe.

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