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Experimental method for estimation of compaction in the Oxfordian bedded limestones of the southern Kraków-Częstochowa Upland, Southern Poland

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ABSTRACT:

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The Upper Jurassic carbonates exposed in the southern part of the Kraków-Częstochowa Upland are well known for their significant facies diversity related to the presence of microbial and microbial-sponge carbonate buildups and bedded detrital limestone in between. Both the buildups and detrital limestones revealed differential susceptibility to compaction which, apart from differential subsidence of the Palaeozoic basement and synsedimentary faulting, was one of the factors controlling seafloor palaeorelief in the Late Jurassic sedimentary basin.

The compaction of the detrital limestones has been estimated with an experimental oedometric method in which specially prepared mixtures made of ground limestones from a quarry in the village of Żary were subjected to oedometer tests. The diameters of the detrital grains and their percentages in the limestones were determined by microscopic examinations of thin sections. The diameters were assigned to predetermined classes corresponding to the Udden-Wentworth scale. The rock samples were then ground down to the grain sizes observed in thin sections. From such materials, mixtures were prepared of grain size distributions corresponding to those observed in thin sections. After adding water the mixtures were subjected to oedometer tests.

Analysis of the compression of such mixtures under specific loads enabled preparation of a mathematical formula suitable for the estimation of mechanical compaction of the limestone. The obtained values varied from 27.52 to 55.53% for a load corresponding to 300 metres burial depth. The most significant effect of mechanical compaction was observed for loads representing only 2 metres burial depth. Further loading resulted in a much smaller reduction in sample height.

The results of the oedometer tests cannot be used directly to determine compaction of the detrital limestones. Mainly because microscopic observations of thin sections of the experimental material show that chemical compaction was also an important factor influencing thickness reduction of the limestones.

Key words: Differential compaction; Oedometer tests; Basin analysis; Microfacies; Upper Jurassic; Kraków-Częstochowa Upland.

INTRODUCTION

Estimations of compaction of carbonate facies allow us to determine the sedimentation rate and conditions, palaeorelief and accommodation space, thereby enabling reconstruction of the depositional environment. Compaction is one of the principal processes reducing the thickness of carbonate sediments (see e.g., Coogan

1970; Bathurst 1975, 1987; Flügel 2004; Tucker and Wright 2004; Bjørlykke 2010). Compaction results from the pressure exerted by the water column in a sedimentary basin, partly reduced by buoyancy, and by the load of continuously accumulating sediments (see e.g., Dunnington 1967; Bathurst 1975; Moore 2001).

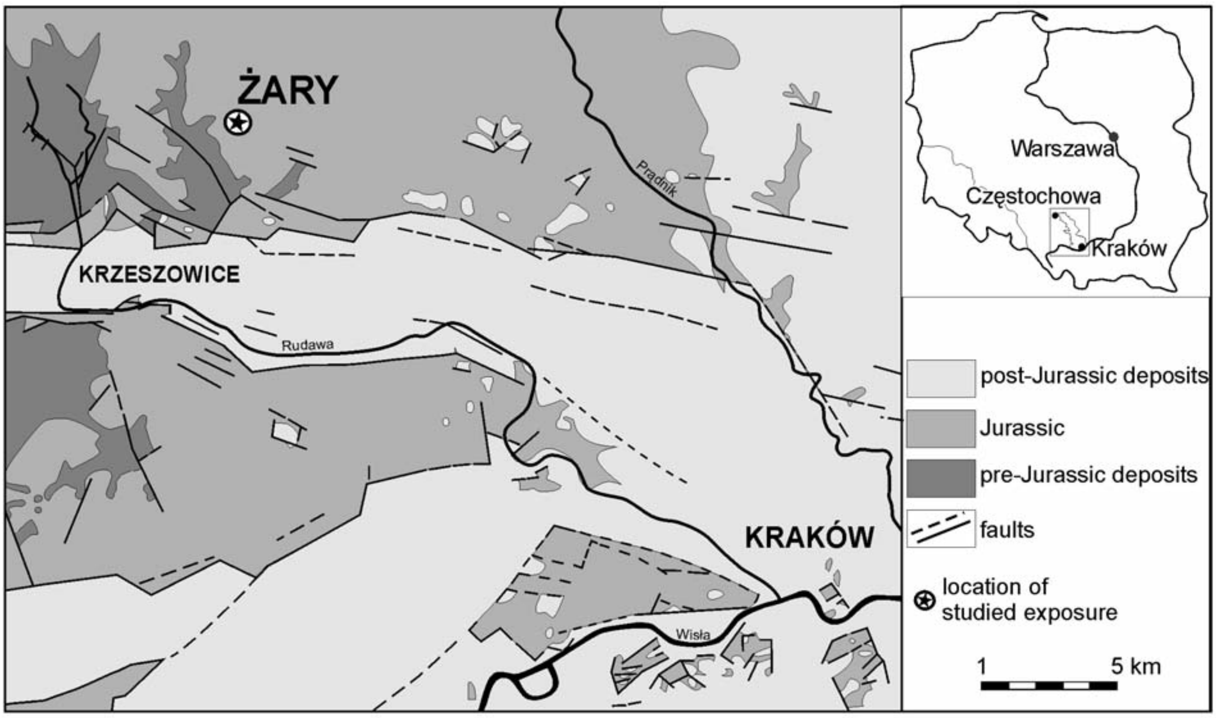
Mechanical compaction affects sediments during early diagenesis. It starts during deposition and continues until lithification of the sediment is completed (Moore 2001), thereby defining the boundary between early and late diagenesis. Mechanical compaction can be moderated by early cementation i.e., sediments already cemented are free of or only insignificantly transformed by compaction (Moore 2001; Croizé *et al*. 2010). Both compaction and cementation decisively control reduction of sediment porosity. Mechanical compaction of a sediment results primarily in the rearrangement of its components, i.e., rotation of grains and denser packing of the framework grains.

Chemical compaction (pressure dissolution) operates during late diagenesis and requires pressures corresponding to the load imposed by overburden several hundreds of metres thick (Bathurst 1975; Wanless 1979; Buxton and Sibley 1981). This process commences at the end of early diagenesis. Pressure dissolution starts when a range of critical burial depths is achieved, estimated as about 200–300 metres (Schlanger and Douglas 1974; Garrison 1981; Czerniakowski *et al*. 1984). Beneath 300 metres burial depth pressure dissolution becomes an important factor influencing reduction in sediment thickness (Bathurst 1991). The intensity of thickness reduction is controlled by the "diagenetic potential" of a sediment (Schlanger and Douglas 1974), defined as the content of metastable calcite varieties: aragonite and high-Mg calcite. Depending on the primary structure of the sediment and the intensity of early cementation, pressure dissolution results in the formation of stylolites, dissolution seams and fitted fabrics (e.g., Logan and Semeniuk 1976; Buxton and Sibley 1981; Railsback 1993). In extreme cases, intensive pressure dissolution in limestones may lead to the formation of marl layers due to the removal of high amounts of calcium carbonate (Huber 1987).

The amount of reduction in sediment thickness, due mostly to compaction, can be estimated with various methods, usually referred to the effects of mechanical compaction. The first group of methods is based upon various compaction indicators: crushed fragments of shells or already lithified laminae and on deformation analysis of ooids, initially cylindrical sections of ichnofossils, microfenestral pores and palynomorphs. Such indicators enable us to determine compaction of the whole sediment in which the indicators are embedded (e.g., Coogan 1970; Lasemi *et al*. 1990; Westphal 1997; Westphal and Munnecke 1997; Broichhausen *et al*. 2005; Katsman and Aharonov 2006; Ziółkowski 2005; Chanda *et al*. 2011). The second group of methods includes: models which simulate the compaction under laboratory conditions (e.g., Shinn and Robin 1983; Holcomb *et al*. 2007; Kochman 2010), numerical models (e.g., Perrier and Quiblier 1974; Aplin *et al*. 1995; Suetnova and Vasseur 2000), as well as comprehensive analysis of geological conditions including microfacies analysis supported by one or several other methods such as chemical analyses of limestones and their insoluble residuum, and porosity/permeability measurements (e.g., Ricken 1986, 1987; Doglioni and Goldhammer 1988; Martire and Clari 1994; Clari and Martire 1996; Martire 1996; Goldhammer 1997; Matyszkiewicz 1999; Łuczyński 2001; Rusciadelli and Di Simone 2007).

Correct estimation of the amount of compaction is particularly important for determination of sea floor relief in basins of significant facies diversity, where uncompactable or low-compactable sediments are accompanied by highly compactable deposits (cf. Aagaard and Jahren 2010). The effects of differential compaction are vital for reconstructions of the depositional architectures of the basins and the determination of sedimentation rates (cf. Hunt *et al*. 1995; Saller 1996; Kenter *et al*. 1997; Rusciadelli and Di Simone 2007). However, the true sedimentation rate does not correspond to the rate calculated as the quotient of the recent thickness of sediments representing a given stratigraphic interval and the duration of this interval, because it does not include the reduction in thickness induced by compaction. Hence, the true sedimentation rate is represented by the accumulation rate, which is the quotient of reconstructed, pre-compaction thickness and sedimentation time (Gómez and Fernández-López 1994).

The area of the Kraków-Częstochowa Upland is an excellent site for studies on compaction because the Upper Jurassic shelf facies are perfectly exposed (Matyszkiewicz 1999; Ziółkowski 2005; Kochman 2010). The following studies were carried out in a small quarry located in the village of Żary, near Krzeszowice, in the southern part of the upland (Text-figs 1, 2). In the quarry walls we can observe an Upper Jurassic succession of massive and bedded carbonates representing the intrabiohermal facies developed within the carbonate buildup complex and deposited contemporaneously with the intensive growth of the buildups (Krajewski 2000; Krajewski and Matyszkiewicz 2004; Matyszkiewicz and Krajewski 2007). The principal study method was the oedometer test of consolidation, which seems to ap-



Text-fig. 1. Location of study area on geological bedrock map of the southern part of Kraków-Częstochowa Upland (after Gradziński 2009, simplified)

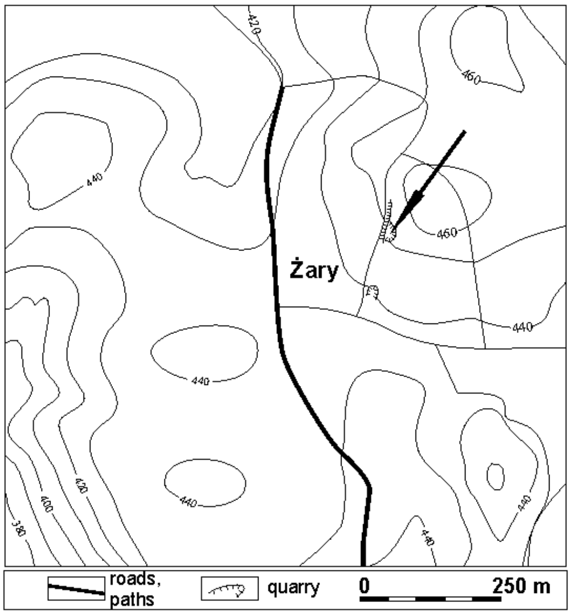
proximate the compactional reduction in thickness operating within sediment up to its cementation.

GEOLOGICAL SETTING

The Upper Jurassic sediments from the Kraków-Częstochowa Upland reveal high facies diversity. The sediments were deposited on an epicontinental shelf located in the northern periphery of the Tethys Ocean, in a well-oxygenated sea of alkalinity close to that of the Recent world ocean (Matyszkiewicz *et al*. 2012). Some sediments show bedding (so-called "normal facies"; cf. Gwinner 1976) but the most spectacular landforms typical of the upland landscape are built of massive facies. A special category consists of submarine gravity flow deposits, which can be encountered in almost the entire Upper Jurassic succession (Marcinowski 1970; Matyszkiewicz 1996).

The Upper Jurassic bedded sediments of the Kraków-Częstochowa Upland include: (i) marls; (ii) numerous varieties of bedded pelitic limestones (so-called "platy limestones") of the Solnhofen type; (iii) detrital limestones (wackestones-packstones-grainstones); and (iv) microbial-sponge and microbial biostromes, the facies development of which is similar to the massive facies. The first three types, deposited mostly in intrabiohermal depressions, were highly susceptible to mechanical compaction due to poor early cementation (Matyszkiewicz 1999). In contrast, the biostromes that grew on the slopes of the carbonate buildups revealed only a small susceptibility to compaction, due to the formation of a rigid framework and intensive early diagenetic cementation.

The massive facies, defined traditionally as unbedded, chert-free limestones (Dżułyński 1952), show high microfacies diversity. The massive limestones represent preserved fragments of the microbial and microbial-sponge carbonate buildups which, after the initial aggradational growth, showed a tendency to lateral expansion and to the formation of vast complexes of diverse facies. Presumably, one of the important factors determining the local initiation of growth, development and size of carbonate buildup complexes was decreased subsidence of sea floor fragments related to Permian intrusions into the basement of the Late Jurassic shelf (Kutek 1994; Matyszkiewicz *et al.* 2006). It is possible that some carbonate buildups developed in the vicinity of Late Jurassic fault zones locally transferring low-temperature hydrothermal solutions (Gołębiowska *et al.* 2010; Kochman and Matyszkiewicz 2012). Both the early-diagenetic cementation and the presence of a rigid framework in the Upper Jurassic massive limestones from the southern part of the Kraków-Częstochowa Upland have already been well-documented in the literature (Matyszkiewicz and Krajewski 1996; Matysz-



Text-fig. 2. Sketch map of the Żary quarry (arrow)

kiewicz 1997; Matyszkiewicz *et al.* 2012). Hence, it can be suggested that these sediments were only insignificantly affected by mechanical compaction. The growth of carbonate buildups, forming highs in the seafloor relief of the Late Jurassic shelf, combined with active synsedimentary tectonics, gave rise to submarine gravity flows represented by the typical sediments of grain flows, debris flows and calciturbidites.

The village of Żary is located in the southern part of the Kraków-Częstochowa Upland, about 8 km northeast of the town of Krzeszowice (Text-fig. 1). In the northeastern part of the village there is a small, abandoned quarry (Text-fig. 2) in which we can observe different facies of Upper Jurassic sediments. This site has not been described in detail but the stratigraphic position of the facies exposed is close to that of Upper Jurassic sediments known from the adjacent Będkowska and Szklarka valleys, which were comprehensively described and identified as belonging to the Oxfordian interval from the Transversarium to Bifurcatus zones (Krajewski 2000; Krajewski and Matyszkiewicz 2004; Matyszkiewicz and Krajewski 2007).

The Upper Jurassic sediments from Żary show diverse facies resulting from the relief of the sedimentary basin floor shaped by Permian intrusions into the Palaeozoic basement, as well as by Late Jurassic movements along the extended Kraków-Lubliniec Fault Zone (Krajewski and Matyszkiewicz 2004). It can be assumed that in the Late Jurassic the Żary area formed a distinct submarine high in the basin floor on which carbonate buildup complexes developed, in which both the massive and bedded facies are observed. The individual carbonate buildups were separated by depressions in which the bedded facies of detrital limestones were deposited. The presence of neptunian dykes cutting through the Jurassic strata indicates the activity of Late Jurassic synsedimentary tectonics in the study area (Matyszkiewicz and Krajewski 2007).

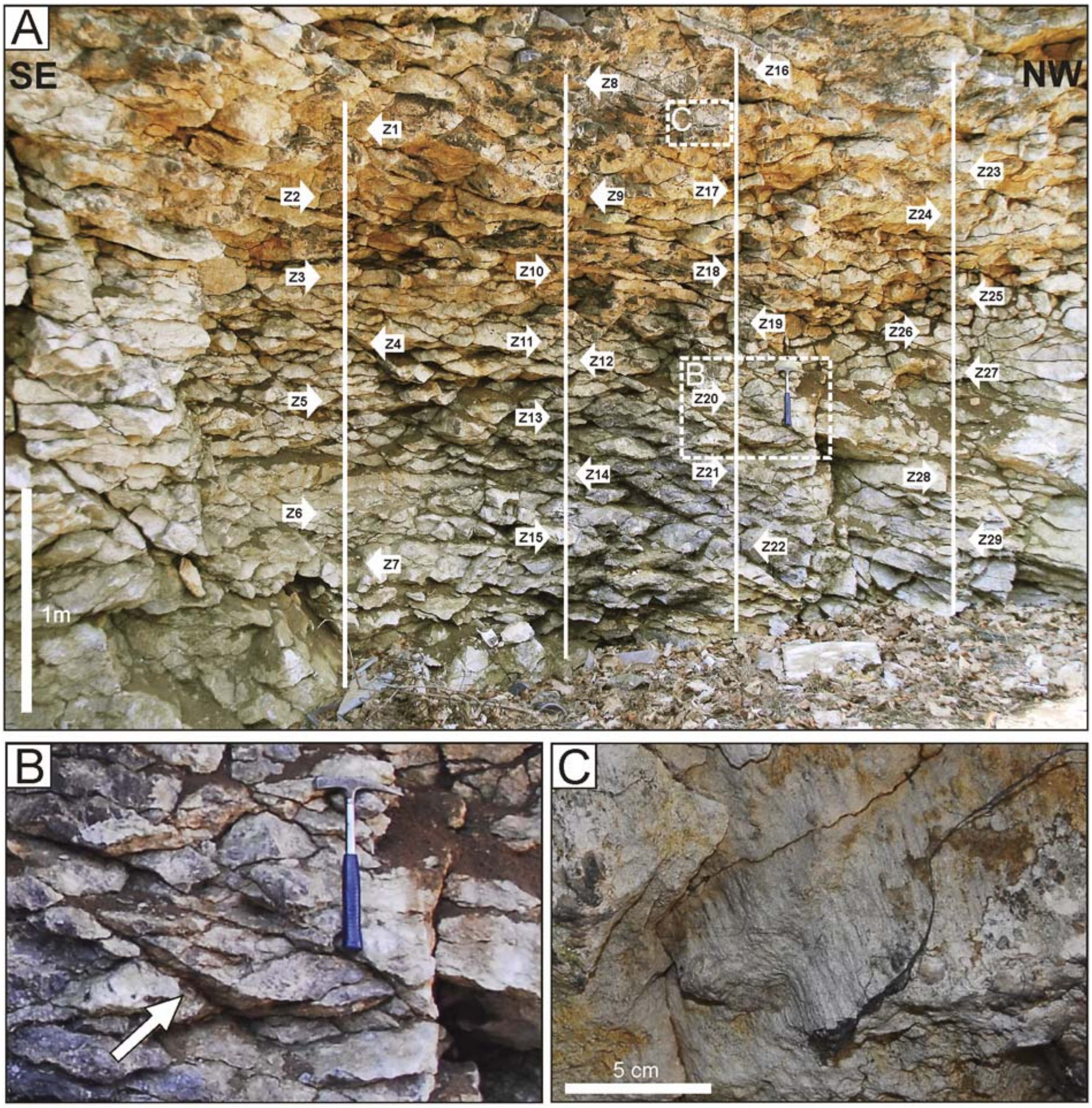
METHODOLOGY

The Upper Jurassic limestones were sampled in a wall of the Żary quarry in which only the bedded limestones facies are exposed. In that wall, four 3 metres long sampling lines were established (Text-fig. 3A). In total, 29 oriented samples were collected, each on average weighing about 1.5 kg. From all the collected samples oriented thin sections were prepared (without cover slip) and studied for microfacies analysis under the OLYMPUS SZX9 microscope. For description of the microfacies the Dunham classification was applied (Dunham 1962). The remaining part samples were prepared for oedometer tests.

In thin section cut from detrital limestones (wackestones-packstones-grainstones) grain diameters were measured under the microscope using the AnalySIS FIVE DOCU software and assigned to classes corresponding to the Udden-Wentworth system (Wentworth 1922): below 0.063 mm; 0.063–0.125 mm; 0.125–0.25 mm; 0.25–0.5 mm; 0.5–1 mm and over 1 mm. Percentages of grain diameters in the various classes were then calculated. It was found that grain diameters below 0.063 mm constituted 80 vol.% of average grain-size composition observed in the thin sections. Other diameters were less frequent: 0.063–0.125 mm – 4 vol.%; 0.125–0.25 mm – 8 vol.%; 0.25–0.5 mm – 5 vol.%; 0.5–1 mm − 2 vol.% and over 1 mm – 1 vol.%.

The remaining parts of the samples were crushed in jaw and roll crushers, then ground in a Bond ball mill and screened in order to obtain the desired grain-size fractions. These fractions were subsequently mixed in proportions corresponding to the average grain-size distribution observed in thin sections. Finally, water was added 1:1 to the dry mixtures and the resultant material was used for oedometer tests. The oedometer was equipped with a special steel frame.

In order to estimate the compaction of the detrital limestones, a modified oedometer compressibility test was applied. Despite some limitations, compressibility (cf. Myślińska 1998) can be compared to the compaction of carbonate sediments, particularly to mechanical compaction, which affects a loose sediment during early diagenesis. Similarly to mechanical com-



Text-fig. 3. Upper Jurassic detrital bedded limestones at the Żary quarry: A – fractured layers of detrital limestones showing platy fissibility surfaces dipping to the NW at 10–15°. Sampling sites marked along the selected lines. Fragments of quarry wall (rectangles) are expanded in the inserts (Text-fig. 3B–C); B – example of sediment displacement along arcuate, concave surface (arrow), presumably a submarine slump initiated at the slope of carbonate buildup inclined towards the intra-biohermal depression. The displaced limestone fragment is cut by several fractures inclined gently to the left. Such form are typical of sediment fragments sliding on an unstable slope of a carbonate buildups complex or a single buildup (cf. Gwinner 1976); C – stylolite lineation on limestone surface at 10–12º from the vertical, indicating the presence of lithostatic stylolites

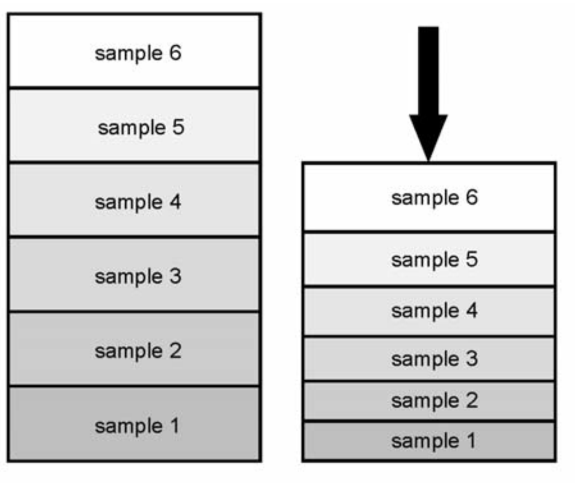
paction, compressibility leads to reduction of sediment volume under load due to denser packing of the grains and to transformation of the framework towards a more rigid one. Deformation resulting from imposed load depends on both the grain-size distribution and the value of the load. Studies were carried out under triaxial stress and uniaxial strain conditions. The sample was placed in a metal cylinder and incrementally loaded until stabilization of the sample was achieved (cf. Glazer and Malinowski 1991; Myślińska 1998).

In our research, the oedometer tests included a series of experiments in which samples were loaded according to a predefined schedule (Table 1). For the purpose of the project it was presumed that six samples would represent a model stratigraphic sequence (Text-fig. 4). The experiments included six oedometer tests. For each

time to consecutive change of imposed load [24 h]	sample 1 load [kPa]	sample 2 load [kPa]	sample 3 load [kPa]	sample 4 load [kPa]	sample 5 load [kPa]	sample 6 load [kPa]
1	2.78	2.55	2.78	2.55	2.78	2.55
2	20.42	33.73	21.15	42.30	83.70	167.90
3	41.57	33.73	21.15	42.30	83.70	167.90
4	41.57	76.03	63.45	126.00	251.90	
5	83.87	76.03	63.45	126.00	251.90	
6	83.87	155.55	147.15	293.90		
7	168.45	155.55	147.15	293.90		
8	168.45	323.45	315.05			
9	336.35	323.45	315.05			
10	336.35					

Table 1. Loading schedule of samples for oedometer tests applied to studies on mechanical compaction

sample from the model sequence an individual schedule was applied (Table 1) with specific loading time and specific maximum load. The sequence of loads was predefined according to the principle that a sample representing a layer located higher in the stratigraphic sequence was subjected to lower compaction than one lower in the sequence. Therefore, sample 1, representing the lowest layer in the model sequence, was subjected to the highest compaction (=highest load) whereas sample 6, representing the highest layer in the model sequence, was subjected to lower compaction (=lower load) than all other underlying samples. Specific loads were selected according to the methodology applied in typical oedometer tests, i.e., the load increment ratio was close to 1/2.



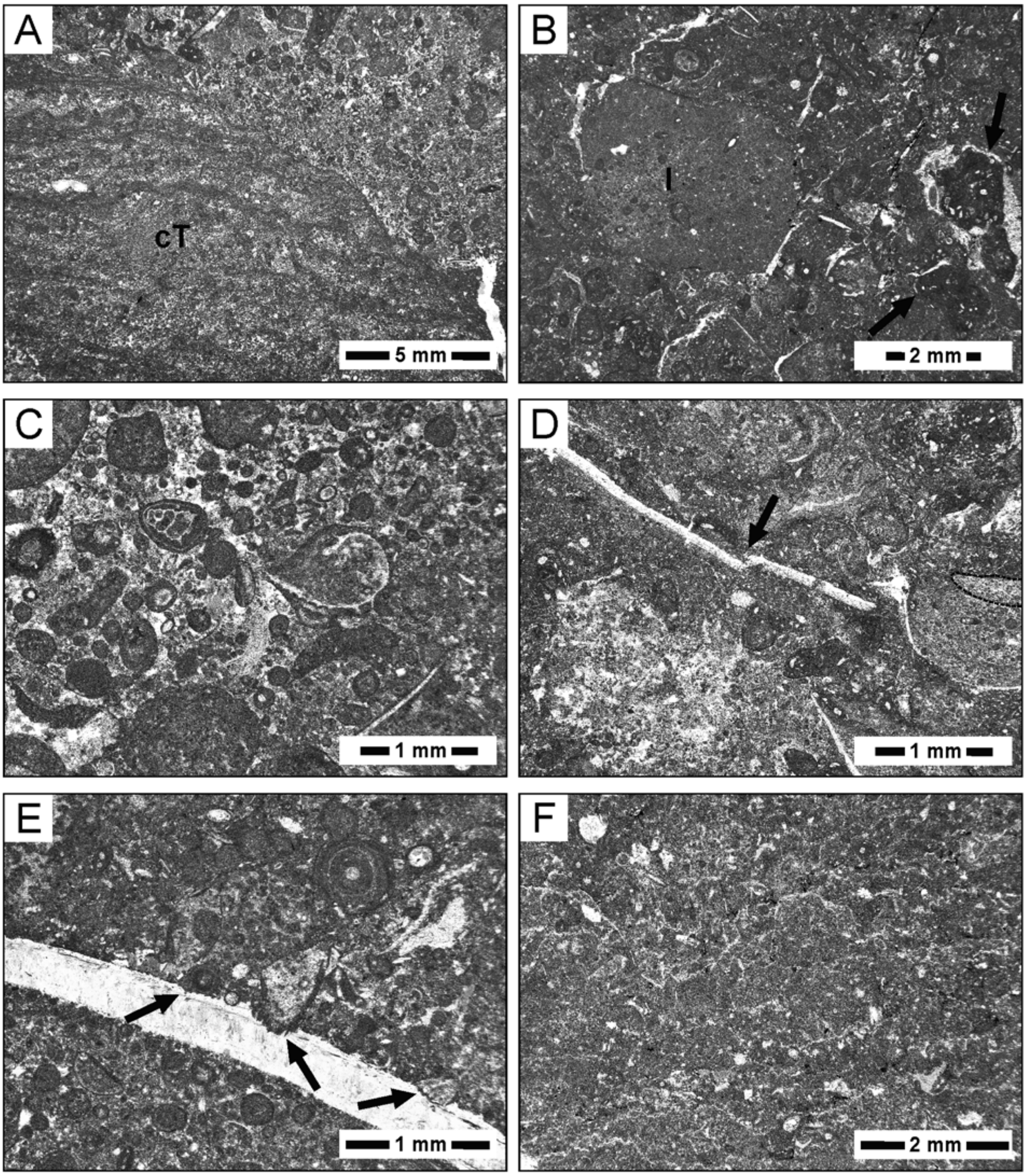
Text-fig. 4. Schematic presentation of changes in thickness of model stratigraphic sequence subjected to load before and after oedometer test (arrow). Sample 1 represents the lowest layer in the sequence, in which compaction was highest. Thicknesses of consecutive samples representing overlying layers increase upward due to decreasing load

Before the oedometer test each sample was loaded for 24 hours with a perforated cap of weight corresponding to 2.55 kPa or 2.78 kPa loads in order to drain part of water which flowed out over the cap. Such a procedure prevented the squeezing of the water-saturated mixture from the cylinder during the test. Compression of samples was recorded each 24 hours or before each change of imposed load (Table 1). After the tests, thin sections were prepared from each sample tested in the oedometer and subjected to microscopic observations.

MACROSCOPIC OBSERVATIONS AND MICROFACIES DEVELOPMENT OF LIMESTONES FROM THE ŻARY QUARRY

Macroscopic observations

The abandoned Żary quarry is elliptical, about 18 metres across by about 10 metres long. The quarry walls are up to 8 metres high. In the two parallel, NW-SE-trending walls various limestones of diverse facies are exposed. In the northeastern wall, massive limestones in the bottom and middle parts of the sequence are overlain by platy limestones. In the southwestern wall only bedded, platy limestones were exposed (Text-fig. 3A) dipping at 10–15° to the NW. Limestone beds, 5–10 centimetres thick, show so-called wave bedding (cf. Gwinner 1976) and are strongly fractured. Locally, mostly in the lower part of the wall, cleavage accompanied by displacements of sediment along arcuate, concave surfaces was observed (Text-fig. 3B). Stylolite lineations on limestone surface at 10–12° from the vertical were commonly visible (Text-fig. 3C).



Text-fig. 5. Microfacies of Upper Jurassic limestones from the Żary quarry; localization of oriented samples of detrital bedded limestones as in Text-fig. 3A. A – left and bottom: clotted thrombolites (cT), right and top: packstones with numerous tuberoids, *Tubiphytes* sp., benthic foraminifers and microoncoids. Massive limestones. B – packstones with numerous tuberoids and abundant detritus originated from erosion of microbial-sponge carbonate buildup. Centre-left – poorly rounded intraclast (I), over 2 mm across. Right: irregular clasts of microbialites (arrows) with numerous benthic foraminifers, serpulids and bryozoans growing on their outer surfaces; sample Z5. C – packstones, locally grainstone with common tuberoids and oncoids with bioclasts in the nuclei (gastropods, fragments of thin-shelled bivalves and ossicles of echinoderms); sample Z10. D – packstones-wackestones with common tuberoids, *Tubiphytes* sp. and boring (contoured with dashed line) filled with packstone with numerous peloids and microoncoids. Centre: shell fragment of a thin-shelled bivalve broken due to mechanical compaction (arrow); sample Z18. E – packstones, locally wackestones with numerous microoncoids and fossil fragments. Centre: microstylolites developed at the contact of a shell of thin-shelled bivalve with larger detrital grains (arrows) documenting the action of chemical compaction; sample Z28. F – wackestones with abundant bioclasts (fragments of echinoderms ossicles, ophiuroids and calcified spicules of siliceous sponges) and very common, horizontal lithostatic stylolites; sample Z23

Microfacies analysis of the massive limestones

From the massive limestones a single sample was collected for microfacies analysis. The massive limestones are developed as boundstones with local intercalations of packstones (Text-fig. 5A). The main components are microbialites developed as clotted thrombolites, locally also as micropeloidal stromatolites and calcified, siliceous hexactinellid sponges. The detrital components in the packstones include both tuberoids and *Tubiphytes* sp.

Microfacies analysis of the bedded detrital limestones

The bedded limestones are developed mostly as packstones, locally also as wackestones and grainstones (Text-fig. 5B–F). The main recognizable detrital components are tuberoids, microoncoids and intraclasts. Among the fossils we observed skeletal fragments and single calcified spicules of siliceous sponges, bryozoans, *Terebella* sp., *Tubiphytes* sp., fragments of thin-shelled bivalves, holothurian sclerites, ophiuroids, ossicles and spines of echinoids, aptychi, small gastropods, shells of juvenile ammonites, rostra of belemnites, calcispheres, and planktonic and benthic foraminifers. Some of the larger bioclasts are covered with microbial crusts (Text-fig. 5C). Locally, in the wackestones we observed irregular borings, up to 1–2 millimetres in diameter, filled with packstone with numerous peloids and spheroidal microoncoids (Text-fig. 5D).

The farther from the massive limestones the detrital limestones show reduction in grain size and poor grain rounding. Also, the dominant components become microoncoids, tuberoids and echinoid ossicles with syntaxial calcite (Text-fig. 5C), whereas close to the mas-

sample 6

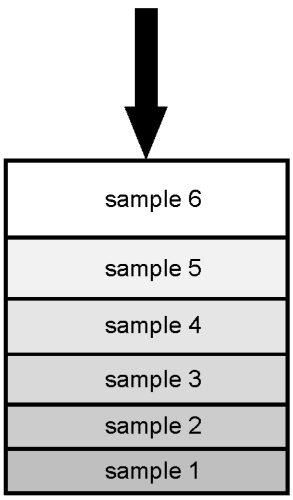
load [kPa]	height [mm]	C [%]
0	41.37	0
2.55	34.69	16.15
167.90	29.94	27.63
167.90	29.93	27.65

sample 5

load [kPa]	height [mm]	C [%]
0	41.42	0
2.78	34.90	15.74
83.70	29.75	28.17
83.70	29.71	28.27
251.90	29.16	29.60
251.90	29.15	29.62

sample 4

load [kPa]	height [mm]	C [%]
0	35.22	0
2.55	29.64	15.84
42.30	24.21	31.26
42.30	24.20	31.29
126.00	23.45	33.42
126.00	23.42	33.49
293.90	22.61	35.80
293.90	22.56	35.94



sample 3

load [kPa]	height [mm]	C [%]
0	45.15	0
2.78	38.64	14.42
21.15	32.96	26.99
21.15	32.95	27.01
63.45	31.97	29.19
63.45	31.96	29.20
147.15	31.25	30.77
147.15	31.25	30.79
315.05	30.69	32.03
315.05	30.64	32.14

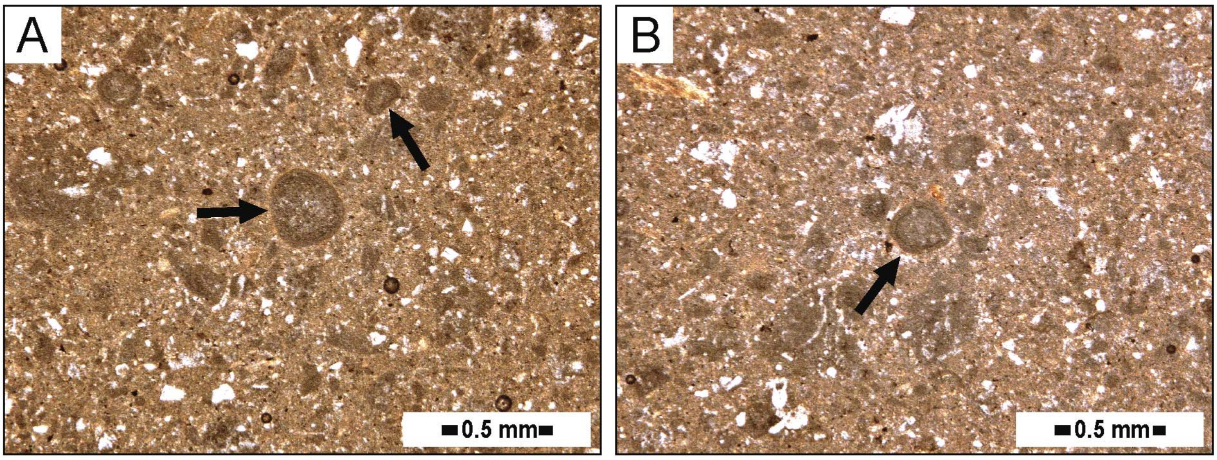
sample 2

load [kPa]	height [mm]	C [%]
0	32.08	0
2.55	26.92	16.08
33.73	24.16	24.69
33.73	24.14	24.75
76.03	23.72	26.06
76.03	23.70	26.11
155.55	23.19	27.71
155.55	23.16	27.79
323.45	22.66	29.35
323.45	22.63	29.46

sample 1

load [kPa]	height [mm]	C [%]
0	33.64	0
2.78	27.74	17.54
41.57	25.64	23.78
41.57	25.64	23.78
83.87	23.90	28.97
83.87	23.89	28.98
168.45	23.35	30.59
168.45	23.34	30.62
336.35	22.83	32.12
336.35	22.81	32.18

Text-fig. 6. Height reduction of samples obtained from oedometer tests and calculated mechanical compaction



Text-fig. 7. Examples of microscopic images of compacted sample 1 subjected to 336.35 kPa load. Grain size distribution corresponds to wackestones from Upper Jurassic detrital limestones at the Żary quarry (oriented sample, top surface upward). A – tuberoids among coarser grains with common brownish rims (arrows). B – centre: brownish rim (arrow) seen at the bottom surface of microoncoid. Small pores result from washout of sediment during preparation of thin section

sive facies the detrital limestones contain poorly rounded intraclasts, over 2 millimetres in diameter, together with microbialite fragments incrusted with foraminifers, serpulids and bryozoans (Text-fig. 5B). In the packstones and wackestones crushed shell fragments of thin-shelled bivalves are common (Text-fig. 5D). Locally, the wackestones and packstones contain horizontal microstylolites (Text-fig. 5E), sometimes very common (Text-fig. 5F).

RESULTS OF THE OEDOMETER TESTS

The reductions in height of samples prepared from mixtures of grain size distribution corresponding to that observed in the limestones, as well as the amount of mechanical compaction calculated for each sample from the model stratigraphic sequence, are presented in Text-fig. 6. Thin sections were cut from the oedometer-compacted mixtures. Microscopic observations of these thin sections demonstrated a lack of porosity (Text-fig. 7A, B), presumably caused by the dominance of the finest fraction (below 0.063 mm). This dominance, roughly corresponding to the grain size of the matrix in pelitic limestones, is responsible for significant cohesiveness of the sediment. The composition of the compacted mixtures is comparable with the microfacies observed in thin sections cut from the bedded facies of the detrital limestones. In all of the thin sections, some larger grains show rusty-brown rims less than 0.02 millimetres thick (Text-fig. 7A, B). This is probably an effect of dissolution of some of the finest grains containing Fe hydroxides formed during the grinding of the limestone samples.

DISCUSSION

Constraints of the methodology

The reduction in height of the samples resulting from the oedometer tests can be interpreted (under certain assumptions) as representing the compaction-induced reduction in thickness of the carbonate sediments. Unfortunately, there are several factors that cannot be taken into account in such tests. These include early diagenetic cementation and changes in pore solution chemistry when the carbonate sediment enters various zones of diagenesis, as well as when temperature rises during the burial (see e.g., Sandberg 1983, 1985; Sellwood 1992). Moreover, during the oedometer test any sample is compressed for only several days whereas the time of true compaction is incomparably longer. The short time of the tests eliminates the cementation, neomorphism, replacement and recrystallization processes that are typically active during the diagenesis of carbonate sediments. Hence, the tested carbonate sediment cannot be fully lithified and its cohesiveness results only from denser packing of the grains.

The compaction cannot be regarded as a single event proceeding under a constant load. Instead, it is a continuous process in which both the load and the thickness of compacting sediment increase with the progressing deposition. Although the continuity of compaction was simulated by increments of load in scheduled, constant time intervals, such an operation cannot fully imitate the compaction in the sedimentary basin. Finally, during the oedometer test the sample is placed within a cylinder and cannot expand horizontally, which does not correspond to the true conditions of compaction of the Upper Jurassic carbonates. If the basin floor is irregular the compacting sediment can migrate horizontally.

Mathematical model illustrating the mechanical compaction

Based on the reduction in height of samples of grain size distribution corresponding to that of the limestones from the Żary quarry obtained during the oedometer tests (Text-fig. 6), a mathematical model has been developed, which illustrates this process (Kochman 2010). The relationship between the reduction in height of a sample and the imposed load can be expressed as a power formula:

$$Y = aX^b \qquad (1)$$

where:

Y – height (=thickness),

X – load,

a, b – estimators.

The estimators of parameters a and b were determined by means of regression analysis for a power model (Kochman 2010).

The proposed model enables us to estimate an approximate value of mechanical compaction. According to the model, the amount of compaction depends on the minimum load and the successively imposed load on the compacting layer. Specific loads imposed during the compaction can be represented by the thickness of overburden of the layer studied. Precisely, about 100 kPa of load correspond to a 20-metres-thick overburden (cf. Audet 1995). It was assumed that the accumulating layer is subjected to a minimum load X_{min}= 0.01 kPa (X_{min}>0) which gradually increases with the weight of accreting overburden.

Taking into account the above-mentioned assumptions, the amount of mechanical compaction can be approximated from the formula:

$$C = \left(1 - \frac{Y}{Y_{min}}\right) \cdot 100 \qquad (2)$$

where:

C − compaction [%],

$Y = aX^b$ – thickness of sediment corresponding to gradually increasing load [m],

$Y_{min} = aX^b_{min}$ – initial thickness of sediment corresponding to 0.01 kPa load [m],

X – load of compacting layer corresponding to given thickness of the overburden [kPa],

a ∈ (27.09; 41.16) – estimator determined with the regression analysis of a power model,

b ∈ (-0.068; -0.027) – estimator determined with the regression analysis of a power model.

overburden [m]	**load [kPa]**	**mechanical compaction [%]**	
		a = 27.09 b = -0.068	**a = 41.16 b = -0.027**
beginning of sedimentation	0.01	~ 0	~ 0
0.002	1	26.88	11.69
2	10	37.48	17.02
4	20	40.36	18.55
10	50	43.96	20.54
20	100	46.54	22.02
40	200	49.00	23.46
100	500	52.08	25.33
200	1000	54.29	26.72
300	1500	55.53	27.52

Table 2. Amount of mechanical compaction of Upper Jurassic detrital limestones from the Żary quarry calculated for boundary values of a and b estimators

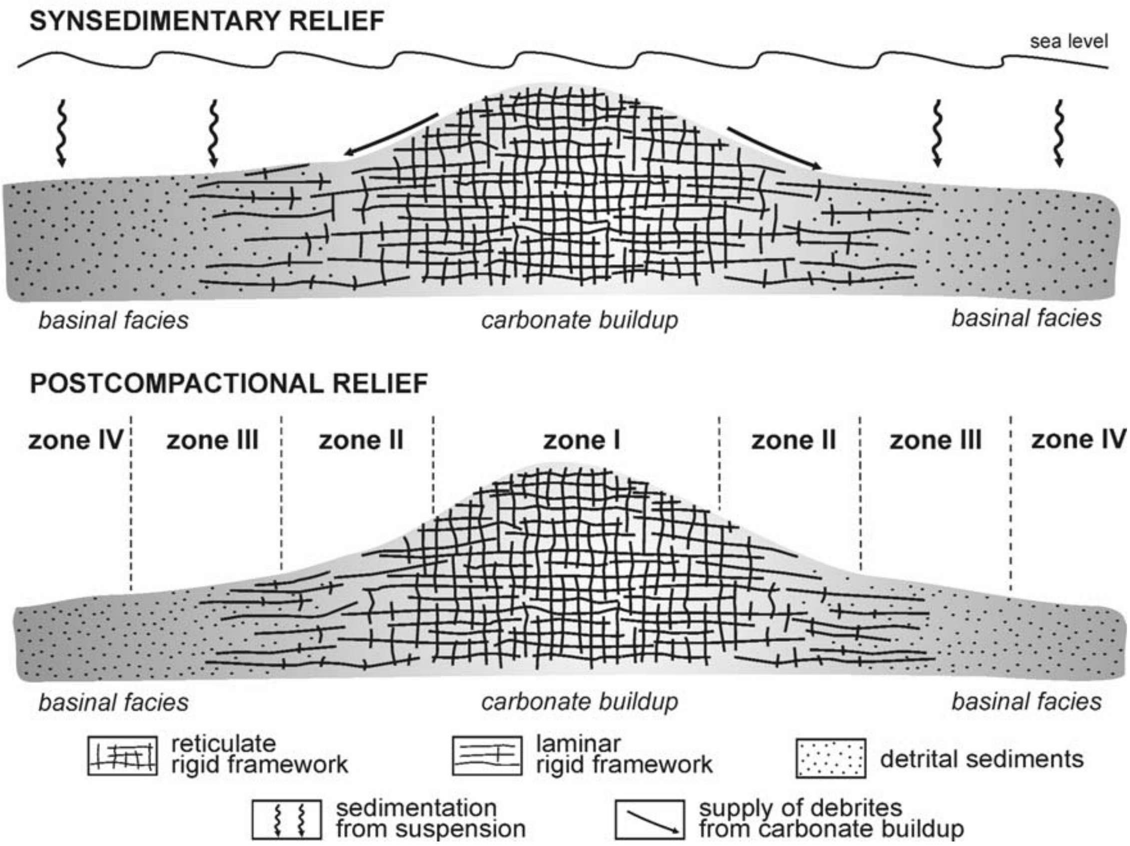
Formula (2) was applied to calculate the amounts of mechanical compaction for parameters a and b, which represent the border values for each interval, placing the compaction of the studied samples within a range of values from 27.52 to 55.53% for 300 metres burial depth (Table 2). For both the lowest and highest calculated amounts of compaction, it can be noticed that the maximum reduction in thickness corresponds to a small overburden load (Table 2). Under a load corresponding to 2 metres burial depth, the amount of compaction lies between 17.02 and 37.48%. Further increase in load results in less compaction, e.g., a load corresponding to 100 metres burial depth causes compaction only 2.19–3.45% less than that equivalent to 300 metres burial depth (Table 2).

CONCLUSIONS

The published results of studies on microfacies development of Upper Jurassic carbonate buildups from the southern part of the Kraków-Częstochowa Upland (Matyszkiewicz 1989, 1994, 1997; Matyszkiewicz and Krajewski 1996; Krajewski, 2000; 2001; Matyszkiewicz *et al*. 2012) enable us to distinguish the following four zones of differential susceptibility to compaction distributed along a transect from the centre of a carbonate buildup to the centre of an intrabiohermal depression (Text-fig. 8).

Zone I (Text-fig. 8) includes the central part of a carbonate buildup or complex of carbonate buildups connected with biostromes with a fully developed, reticulate rigid framework (cf. Pratt 1982). The main components of these sediments are previously lithified microbial structures and benthic fauna. In this zone, both

Zone	I	II	III	IV
Position in sedimentary basin	central parts of carbonate buildups or carbonate buildup complexes	proximal parts of the slopes of carbonate buildups or carbonate buildup complexes	distal parts of slope of the carbonate buildups or carbonate buildup complexes; proximal parts of intrabiohermal depressions	distal parts of intrabiohermal depressions
Lithology	massive limestones, locally biostromal bedded limestones	biostromal bedded limestones, pseudonodular limestones, bedded limestones with cherts, locally coarse-grained	detrital coarse-grained to fine-grained bedded facies	detrital fine-grained bedded facies, "platy limestones", marls
Microfacies	boundstones	boundstones; packstones to rudstones	packstones to wackestones; locally mudstones and grainstones	wackestones to mudstones
Development of rigid framework	reticulate rigid framework	reticulate to laminar rigid framework	occasionally single microbialite laminae	absent
Microbialites	dominating	common	scarce	absent
Type of compaction	no mechanical compaction, locally possible chemical compaction	locally possible mechanical compaction, significant chemical compaction	significant mechanical and chemical compaction	significant mechanical compaction, poor chemical compaction
Amount of mechanical compaction	$C \cong 0$	$C \in (0 - 27.5\%)$	$C \in (27.5 - 55.5\%)$	$C > 55.5\%$



Text-fig. 8. Schematic cross sections through a fragment of Late Jurassic basin in the southern part of the Kraków-Częstochowa Upland showing facies transition from carbonate buildup into intrabiohermal depression with characterization of sediment development in specific zones and their susceptibility to compaction. Scheme does not include sedimentation of submarine gravity flow deposits. The microfacies of the Upper Jurassic detrital bedded limestones from the Żary quarry enables us to assign these rocks to Zone III mechanical and chemical compaction should be practically lacking. During late diagenesis, local pressure dissolution is possible, particularly in the porous parts of the buildups (see Braithwaite 1989), reflected by development of lithostatic stylolites.

Zone II (Text-fig. 8) comprises the slopes of carbonate buildups or complexes of carbonate buildups, with sediments of a less developed reticulate rigid framework grading into a laminar rigid framework (cf. Pratt 1982). Also occurring in this zone are coarse-detrital sediments derived from the submarine erosion of carbonate buildups. Typical facies varieties are pseudonodular limestones (see Dżułyński 1952; Matyszkiewicz 1994) and bedded limestones with cherts (see Dżułyński 1952; Matyszkiewicz 1989), usually developed as biostromes. The effects of mechanical compaction are insignificant due to the relatively fast early cementation in the boundstones. During late diagenesis these rocks can be subjected to pressure dissolution (especially their most porous portions) due to the low contents of clay minerals.

Zone III (Text-fig. 8) includes the facies in which single, early lithified microbialite laminae are only occasionally observed. The sediments were deposited on the distal slopes of single carbonate buildups or complexes of carbonate buildups, grading into the proximal part of the basin and usually level the relief of the basin floor (see Krajewski 2001). These facies are mostly bedded detrital limestones of highly diverse lithologies and bed thicknesses. Material derived from episodic intensive erosion of carbonate buildups usually includes grainstones and packstones, whereas episodes of low energy deposition from suspension resulted mainly in wackestones and mudstones. In this zone, there is intense mechanical and chemical compaction. The effects of mechanical compaction depend on grain size - coarser-grained sediments are less susceptible that fine-grained ones (cf. Nichols 1999). The effects of chemical compaction are the opposite: coarse-grained sediments are more susceptible to pressure dissolution due to the higher porosity.

Zone IV (Text-fig. 8) includes the deepest parts of intrabiohermal depressions where coarse-detrital material originating from the erosion of carbonate buildups or carbonate buildup complexes is practically lacking and where deposition from suspension prevails. Sediments deposited in this zone most resemble the classic, Solnhofen-type platy limestones or form marl-limestone alternations. The lithification processes in this zone are of the longest duration because the high contents of clay minerals (cf. Bausch 1996) slow down cementation and increase the susceptibility of the sediment to mechanical compaction. At the same time, the increased contents of clay minerals hamper pressure dissolution.

The zones distinguished refer only to the aggradational stage of the carbonate buildups or carbonate buildup complexes. After this stage, intensive lateral growth of the carbonate buildups or carbonate buildup complexes occurs (see Krajewski 2001; Matyszkiewicz *et al*. 2006). Hence, if longer successions are studied, several of the above-distinguished zones can be encountered, representing different degrees of susceptibility to mechanical and chemical compaction.

The microfacies development of the Upper Jurassic detrital limestones from the Żary quarry (Text-fig. 5B–F) indicates their formation from sediments deposited in the proximity of carbonate buildups, as documented by the dominance of coarse-grained sediments (packstones-grainstones) and minor amounts of fine-grained ones (wackestones). The abundant fossil assemblage is redeposited and originates from erosion of microbial-sponge carbonate buildups, whereas the fossils in the wackestones are typical of pelagic, low-energy sedimentary environments. The presence of borings emphasizes the low deposition rates of these rocks.

The microfacies development of the Upper Jurassic detrital limestones from the Żary quarry (Text-fig. 5B–F) suggests their location in Zone III (Text-fig. 8), i.e., at the border of the distal slope of a carbonate buildup and the proximal part of an intrabiohermal depression. Such a position is confirmed by displacements of sediments along arcuate, concave surfaces (Text-fig. 3B) which represent small submarine slides. Hence, the amounts of compaction calculated with the power model based upon laboratory experiments (Kochman 2010) and the assumed 300 metres burial depth fall into the range from 27.5% to over 55.5% (Table 2). However, these values were obtained under the assumption that the compacting sediment had not been subjected to any cementation, which seems to be highly improbable. Inflexible application of these values to the assessment of Late Jurassic palaeorelief will result in an overestimation of mechanical compaction. In fact, reduction in thickness of these sediments was not only the effect of mechanical compaction but also of chemical compaction. The presence of lithostatic stylolites in the bedded facies (Text-figs 3C, 5E, F) indicates that after completion of mechanical compaction these rocks were subjected to intense pressure dissolution, which also contributed to the reduction in their thickness. Therefore, the recent thickness of these strata was produced by the combined actions of mechanical and chemical compactions

The key point seems to be the question of when cementation occurred of the carbonate sediment from which the detrital bedded facies formed. This is a complex issue (cf. Clari and Martire 1996; Westphal and Munnecke 1997; Lucia 1999; Heydari 2000; Budd 2002; Ziółkowski 2005; Rusciadell and Di Simone 2007, and others) and its solution must concern both the lateral and vertical variability of these sediments. Location of the moment of cementation on a time-scale is practically impossible. Undoubtedly, sediments deposited in the areas of the deepest intrabiohermal depressions were much longer free of cementation than those deposited close to the carbonate buildups and buildup complexes. This was caused by the higher contents of clay matter in the depositional environment (Bausch 1996) and by the lack of conditions favourable for the growth of microbialites, which had already been lithified (see Matyszkiewicz and Krajewski 1996; Schmid 1996; Matyszkiewicz *et al*. 2012). Even if we assume roughly contemporaneous lithification, susceptibility to mechanical compaction of the sediments in the distal zones of intrabiohermal depressions was higher than that of those deposited closer to the carbonate buildups due to the finer grain size.

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