Upper Jurassic Bedded Limestones and Early Diagenetic Dolomitized Limestones in the Light of Mineralogical, Geochemical and Sedimentological Studies; Kraków Area, Poland

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Abstract: This paper describes and analyzes the Upper Jurassic (Lower Kimmeridgian) succession exposed in the Zakrzówek Horst, located in the Kraków area. Three distinguished facies types FT 1-FT 3 comprise several limestone varieties: sponge-microbial, pelitic-bioclastic, and partly dolomitized detrital-bioclastic. Their sedimentary environments varied from relatively deeper, attaining storm-wave base, to more shallower, probably close to normal-wave base. Characteristic features of limestones are changes in contents of CaCO₃ and insoluble residuum as well as porosity values in vertical transitional zones between facies types. The investigated facies types differ in sediment porosity dependent on development of limestones and its susceptibility to mechanical compaction during the early diagenesis. The studied limestones show high CaCO₃ contents and minor insoluble residuum contents comprising quartz, chalcedony and clay minerals. No distinct variability occurs in contents of magnesium, silica, alumina and iron accumulated in clay minerals, iron oxides and oxyhydroxides, as well as in the amounts of amorphous silica. Early diagenetic dolomites, which occur locally within the limestones, were unrelated to fracture systems as possible pathways responsible for transfer of solutions rich in Mg²⁺ ions. The possible source of Mg²⁺ ions might have been the pore solutions, which migrated from compacted basinal bedded facies towards reef facies or the grain-supported bedded facies developed in the adjacent areas. Microscopic studies revealed dedolomitization at the surfaces and in the inner parts of dolomite crystals. In many cases, dolomite crystals were replaced by calcite forming pseudomorphs.

Keywords: Upper Jurassic limestone facies; mineralogy; geochemistry; dolomitization; dedolomitization; porosity

1. Introduction

The most characteristic features of the Kraków area (Southern Poland) are isolated hills built of the Upper Jurassic (Oxfordian-Lower Kimmeridgian) white rocks, which represent bedded and massive reefal facies deposited onto the Mesozoic northern shelf of the Tethys Ocean [1,2]. In Europe, exposures of these rocks form an extended belt, which stretches from Portugal to the Caucasus Mts. In the Kraków area (Figure 1), research of the Upper Jurassic deposits has been focused mainly on sedimentological analysis of the massive facies, which comprises various types of Oxfordian reefs [2-5]. The Lower Kimmeridgian sediments are dominated by thick-bedded facies with cherts (Figure 2A), which can be observed in numerous quarries in the Kraków area. In the southern and central Poland, Upper Jurassic bedded facies provide mineral raw materials appreciated by various industry branches and architecture. When categorized by the age of carbonate deposits in Poland, Upper Jurassic limestones constitute nearly 60% of the resources [6].
In the research area, only preliminary mineralogical and geochemical data on the Upper Jurassic limestones have been presented so far and have not been discussed in detail, on the contrary to extended facies and microfacies analyses of these sediments [7,8]. The main aim of this article is to present the new data on Lower Kimmeridgian bedded facies from the Zakrzówek Horst (Figure 2B) and their mineralogical and geochemical characterization. For this purpose, the already published preliminary results [8] were supplemented with the latest data and discussed in relation to the newly distinguished facies types of bedded limestones. Another aim of this study is to characterize dolomitic limestones, in relation to the described limestone facies. The enigmatic genesis of dolomitization of Upper Jurassic limestones is still one of the key and unsolved geological problems of the Kraków area. The described examples of facies types are also representative of other locations of similar Lower Kimmeridgian deposits in the southern margin of the Kraków-Częstochowa Upland.

2. Geological Setting

The studied quarries are located in the Zakrzówek Horst, situated in the Carpathian Foredip [9], which borders from the north the Kraków-Częstochowa Upland (Figure 1). In the Kraków area, numerous tectonic horsts are present as isolated hills built mainly of Upper Jurassic deposits and separated by tectonic grabens filled with Miocene clays. The uppermost part of Upper Jurassic limestones succession is cut by the Upper Cretaceous abrasion surfaces covered locally by Turonian calcareous sandstones and Santonian marls with cherts [10–13].

In the Kraków area, the Upper Jurassic deposits belong to the so-called microbial-sponge megafacies [2,4] and attain maximum thickness of ~250 m (Figure 2). The Upper Jurassic succession begins with Lower-Middle Oxfordian (Cordatum-Plicatilis zones) thin-bedded marls and marly limestones [2,14]. These strata grade upwards into the strongly differentiated, Middle Oxfordian-Lower Kimmeridgian (Transversarium-Planula zones) massive reef facies and thick-bedded limestones with cherts (Figure 2A). The topmost Lower Kimmeridgian (Platynota Zone) part of the succession comprises thin-bedded limestones, marly limestones and marls (Figure 2A) representing so-called Lowermost Marly Horizon [15].

The Upper Jurassic sedimentary succession from the Zakrzówek Horst represents the Lower Kimmeridgian Planula Zone [16]. Comparison of thicknesses of Upper Jurassic deposits from the Kraków-Pychowice Skotniki 2 borehole (210 m) situated in the western part of the Zakrzówek Horst (Figure 1), and the rocks from other exposures in the horst area, elevated about 15 m above that borehole, showed that total thickness of Upper Jurassic sediments in the Zakrzówek Horst reaches ~225 m (Figure 2A). In addition, until the early 1990s, the older members of Upper Jurassic succession could be observed in the nowadays flooded Zakrzówek quarry, where single, poorly preserved ammonites were found [M. Krobricki, pers. com., 2000]. These specimens enabled the dating of these deposits at the Bimammatum Zone. Today, total thickness of the Upper Jurassic sedimentary succession accessible in quarries of the Zakrzówek Horst attains ~40 m (Figure 2B).
In the study area, four types of bedded limestones are distinguished: micritic, chalky, nodular and detrital [16]. These limestones were partly dolomitized but the genesis of dolomitization remains unclear [7,17–19]. Additionally, epigenetic silicification is observed [7,20], probably of hydrothermal provenance, related to the Cenozoic faulting of Upper Jurassic deposits.

3. Materials and Methods

Detailed research of Upper Jurassic deposits was carried out in several quarries of the Zakrzówek Horst, which is located in Kraków urban area. The research material was collected from six locations in the Kapelanka and the Zakrzówek quarries, the Twardowski Rocks and the Księza Hill (Figure 1). Totally, 165 rock samples were collected from bedded limestones, dolomitic limestones and dolomites.

The basic research method was microfacies analysis (Figure 3), which included lithofacies descriptions based on 155 thin sections. Geochemical and mineralogical studies were carried out on 42 samples representing all facies types of limestones and dolomites. Additionally, seven samples were studied under the FEI Quanta 200 FEG scanning electron microscope (SEM). Quantitative chemical analyses were performed for most of the samples. The X-ray diffraction (XRD) method was applied for identification of minerals using the Rigaku MiniFlex X-ray diffractometer supported by the XRayan software [21] with the implemented PDF-2 database. Both the chemical and mineralogical data of some
samples have already been presented in preliminary studies [8]. Here, these are supplemented and referred for the first time to the newly distinguished facies types (Table 1).

Porosity of studied limestones, determined as the percentage of pore spaces in a given volume of the sample, was calculated from the ratio of difference between the density of solid particles and the bulk density to density of solid particles, measured with the pycnometer method [8]. Moreover, the insoluble residuum was studied as well. For this purpose, calcium carbonate was dissolved with the acetic acid in order to eliminate the chemical alteration of both the clay minerals and the silt fraction components. In the insoluble residuum, two fractions were separated: >2 and <2 μm. Mineral composition of >2 μm fraction was recognized under the transmitted-light microscope whereas the composition of <2 μm fraction was analyzed with the XRD.

4. Results
4.1. Limestone Facies and Microfacies Analyses

In the Upper Jurassic sedimentary succession from the Zakrzówek Horst, three facies types (FT) (Figure 2) were distinguished: sponge-microbial limestones (FT 1), pelitic-bioclastic limestones (FT 2) and detrital-bioclastic, partly dolomitized limestones (FT 3). These facies form characteristic lithologic horizons described earlier by Krajewski [16] as: (i) nodular limestones (=FT 1), (ii) micritic and chalky limestones (=FT 2) and (iii) partly dolomitized granular limestones (=FT 3). Due to the faults, particular facies types can be observed at various elevations in several quarries of the Zakrzówek Horst [16].

![Figure 2](image-url)
Lithostratigraphic log of the Zakrzówek Horst with Upper Jurassic facies and microfacies types. Value of the CaCO₃, insoluble residuum and sediment porosity after Krajewski and Bajda [8] (modified and supplemented). Microfacies types: W—wackestone; F—floatstone; P—packstone; G—grainstone; B—boundstone.

FT 1: sponge-microbial limestones

This facies dominates in two stratigraphic intervals: the lower, about 5.0 m thick (interval 13.0–18.0 m) (Figure 2B) and the upper, 3 m thick (interval ~ 37.0–40.0 m). In the upper interval, observed in the Księża Hill, local lateral transition was encountered of FT 1 into FT 3 facies. The FT 1 sponge-microbial limestones are built of strongly lithified nodules, from some centimeters up to 20 cm in size. Boundaries of individual nodules often correspond to sponge contours. The FT 1 includes two microfacies types: sponge-microbial floatstones and boundstones (Figure 3A). The FT 1 comprises calcified siliceous sponges (mainly Lithistida and Hexactinellida) encrusted by other epifauna species and microbialites (Figure 3A). Bryozoans, benthic foraminifers (Nubecularia, Bullopora), serpulids and agglutinating annelids Terebella lapilloides are abundant. The intraframework spaces, up to some centimeters across, are filled with fine-grained bioclastic wackestones or floatstones (Figure 3A), both composed mostly of tuberoids, sponge spicules, peloids, brachiopods (mostly terebratulids), microencrusters Crescentiella morroensis and numerous, small, hardly identifiable bioclasts. In the upper interval, larger quantities of bioclasts, microbialites (mainly agglutinating stromatolites) as well as growth cavities are observed while the number of sponges is lower. Additionally, porosity of the upper interval is higher, up to 17.98%, whilst in the lower one it varies from 3.55 to ~6% (Figure 2B).

FT 2: pelitic-bioclastic limestones

This facies, up to 13 m thick (interval 0–13.0 m; Figure 2B), dominates in the lowermost part of studied sedimentary sequence. Higher in the profile, the FT 2 is observed in two levels (18.0–19.0 and 35.2–37.0 m) but its thickness distinctly decreases. In the lower and middle parts of the lowermost FT 2 succession (interval 0–11.0 m), the limestones are strongly lithified whereas in its upper part (interval 11.0–13.0 m), lithification is less advanced. These features are reflected in limestone porosity (Figure 2B). In the strongly lithified, lower and middle parts of the lowermost FT 2 succession, porosity reaches several percent, while in the upper part, it increases to ~15% (Figure 2B). In the lower and middle parts of the FT 2 succession (interval 0–11.0 m), bioclastic wackestones dominate along with numerous cherts (up to 10 cm in diameters) and single, calcified, dish-shaped, siliceous sponges as well as bioclasts and tuberoids (Figure 3B). The matrix of these limestones is dominated by micrite with dispersed sparite crystals, up to 50 μm across (usually up to 10 μm) (Figure 3B; 4A). Sometimes, empty voids are observed, up to 80 μm long and 15 μm high, completely or partly filled with sparite and some admixture of micrite (Figure 4A). In the upper part of the lowermost FT 2 succession (interval 11.0–13.0 m), quantities of tuberoids and sponges increase, such that the sediment becomes the sponge-tuberoid floatstone (Figure 3B), and, locally, the sponge-microbial boundstone. In the upper part of the lowermost FT 2 succession (interval 11.0–13.0 m), in a narrow horizon (some centimeters to a dozen of centimeters thick) accumulation of ammonites was found pointing to the Planula Zone, Planula Subzone, Proteron Horizon (Figure 2B). Upward, these deposits grade into the FT 1.
Figure 3. Microfacies of the Lower Kimmeridgian bedded facies from Zakrzówek Horst. (A) FT 1; Sp — calcified siliceous sponge, Mc — microbialites developed on sponges; sample As1. (B) FT 2; wackestone with tuberoids (arrows) and numerous bioclasts; sample M6. (C) FT 3; grainstone/packstone with numerous bioclasts, Crescentiella (C), oncoids (white arrows), ooids (black arrows) and intraclasts (In); sample A6. (D) FT 3; spotty structure with partly dolomitized matrix and not dolomitized grains; sample Z1. (E) FT 3; dolomitized and partly dedolomitized limestones; arrows indicate styololite which cuts dolomitized matrix and calcite pseudomorphs; sample C2. (F) FT 3; partly dedolomitized limestones with dolomoldic porosity (black voids after dolomite crystals); C — Crescentiella microencrusters; sample A12.

FT 3: detrital-bioclastic, partly dolomitized limestones

This facies dominates in the upper part of sedimentary sequence (interval ~19.5-35 m; Figure 2B). The dominant microfacies are bioclastic packstones-grainstones, and wackestones with numerous microencrusters Crescentiella morrisonensis, foraminifers, brachiopods, bivalve shells, peloids, oncoids, micritic ooids, echinoids, siliceous and calcareous sponges, bryozoans (Figure 3C), and single scleractinian corals [16]. Common are dolomite crystals or their calcitic pseudomorphs (Figures 3D,E; 4B) scattered in limestone matrix and built of micrite with common sparite crystals, up to 15 μm in size. Pseudomorphs of calcite after dolomite crystals commonly reveal distinct rhomboidal habits and are partly or completely filled with micrite and calcite crystals, up to 50 μm across (Figure
The FT 3 succession contains lenses of brown-yellowish dolomitic limestones and rare dolomites (Figure 2B). Thickness of such lenses ranges from several dozen centimeters to ~2 m and maximum observed length is 30 m [18]. Locally, in the uppermost part of FT 3 succession, lenses of dolomitic limestones and dolomites are cut and eroded by Upper Cretaceous abrasive surface [18]. The boundaries between limestones and dolomitic limestones are macroscopically diffused but are marked by increasing porosity, from 7.00% in limestones up to 16.62% in dolomitic limestones (Figure 2B). Locally, the presence of caverns, from a few to several centimeters in diameter, increases the porosity up to several dozen percent. Often the rock surface is spotty, which is an effect of light grey, undolomitized, skeletal and nonskeletal grains embedded within grey-brownish matrix of dolomitic limestones (Figure 3D, E). The matrix of dolomitic limestones contains mainly the mosaics of densely packed subhedral to anhedral and, subordinately, euhedral dolomite crystals, from 0.03 mm to ~1 mm in size. Sometimes, completely recrystallized zones are present in dolomitic limestones, which form dolosparstone with sporadically preserved calcite relics. Dolomites are built of euhehedral or subhedral crystals, up to 160 μm in diameter. Common is intercrystalline porosity (Figure 4D). Crystal surfaces are generally rough, with numerous, fine pores. All rock varieties mentioned above contain numerous joints and stylolites (Figure 3E). However, no dolomitized zones were observed along these joints and along the bedding surfaces.

The results of dedolomitization processes are observed in dolomitic limestones and dolomites [19, 22]. Common are euhedral-anhedral dolomite crystals with rough, porous surfaces, partly replaced by calcisparite. Replacement features are visible mostly on surfaces of dolomite crystals but appear also in their inner parts (Figure 4E). Frequent are dolomite crystals, in which the outer parts are already replaced by calcite but the inner ones are still built of dolomite. Dedolomitization affects single dolomite crystals as well as their aggregates giving rise to calcite pseudomorphs after dolomite (Figure 4F). Such pseudomorphs are completely or partly built of calcisparite, which retains the primary, rhombohedral habit of dolomite crystals. Dedolomitization of dolomite aggregates is seen as a mosaic of calcite crystals with locally preserved, almost obliterated contours of dolomite crystals. In such mosaics, single, unreplaced dolomite crystals or their aggregates can still be preserved (Figure 4E). Additionally, common are rhombohedral voids forming dolomoldic porosity (Figure 3F).

4.2. Geochemical and Mineralogical Analyses of Limestones and Dolomitic Limestones

In general, limestones from all locations contain high amounts of CaCO₃ (Figure 2B), although changes are observed between facies types: 94.08–97.31 wt.% CaCO₃ (locally ~100 wt.%) in sponge-microbial limestones (FT 1), 97.00–98.31 wt.% in pelitic-bioclastic limestones (FT 2) and 96.00–98.32 wt.% in detrital-bioclastic, partly dolomitized limestones (FT 3). Only in the top part of the lowermost FT 2 interval, significant decrease in CaCO₃ content was observed in a narrow interval (12.0–13.0 m) (Figure 2B). Some differentiation of mineral composition is visible in pelitic-bioclastic limestones (FT 2) from the Twardowski Rock. The XRD patterns indicate the peaks of calcite and quartz (Figure 5C, D). Quantitative XRD analysis reveals quartz admixtures, from 0.4 to 0.6 wt.% (Table 2). Differences in magnesium contents in these limestones are insignificant. In the facies types, small differences were found in the contents of silica (apart from FT 2 succession in the Twardowski Rock), alumina (Al₂O₃ = 0.02 – 0.11 wt.%), iron hosted in clay minerals, iron oxides and oxyhydroxides (Fe₂O₃ = 0.05 – 0.12 wt.%), as well as amorphous silica (SiO₂ = 0.02 – 0.11 wt.%)(Table 1).

Comparing all facies types, the most differentiated mineral composition is observed in detrital-bioclastic, partly dolomitized limestones (FT 3) where XRD patterns show calcite, quartz and dolomite peaks (Figure 5). Dolomitic limestones and dolomites from the
Twardowski Rock are dominated by dolomite (up to 98.6 wt.%) whereas calcite and quartz are minor (1.4 and 0.1 wt.%, respectively) (Table 2). Positions of dolomite peaks in XRD patterns of FT 2 samples from the Twardowski Rock are somewhat shifted in relation to standard positions taken from the PDF-2 database. The semiquantitative SEM-EDS analysis revealed the excessive Ca contents of about 10 wt.%. Moreover, the accessory minerals are present, containing the increased iron amounts (Figure 4D). In contrast, dolomitic limestones and dolomites from the Księga Hill consist of dolomite (up to 52.4 wt.%) and calcite (47.4 wt.%) with subordinate quartz (0.1 wt.%). However, the FT 3 detrital-bioclastic limestones may locally consist of pure calcite (100 wt.% CaCO₃) (Table 2).

Table 1. Chemical composition of limestones and insoluble residuum from Zakrzówek Horst; partly based on Krajewski and Bajda [8] (modified and supplemented).

| Sample | Chemical composition of limestones—wt. % | Chemical composition of insoluble residuum—wt.% |
|--------|----------------------------------------|-----------------------------------------------|
|        | FT 1 D2 | FT 2 G3 | A1 F2 | B2 C2 | FT 3 E4 | Sample | FT 1 D2 | FT 2 G3 | A1 F2 | B2 C2 | FT 3 E4 |
| SiO₂   | 0.02    | 0.11   | 0.04 | 0.09 | 0.04 | 0.09   | 0.03 | SiO₂   | 84.14  | 70.35  | 84.65 | 75.02 | 86.42 | 88.97 |
| Al₂O₃  | 0.02    | 0.11   | 0.03 | 0.03 | 0.02 | 0.04   | 0.03 | Al₂O₃  | 8.69   | 19.89  | 8.39  | 15.41 | 8.53  | 5.98  |
| Fe₂O₃  | 0.06    | 0.12   | 0.06 | 0.05 | 0.05 | 0.06   | 0.05 | Fe₂O₃  | 2.41   | 3.57   | 1.29  | 2.6   | 0.91  | 0.88  |
| CaO    | 54.15   | 52.71  | 55.08| 54.7 | 54.69 | 53.07  | 54.92 | CaO    | 0.26   | 0.41   | 0.41  | 0.35  | 0.26  | 0.14  |
| MgO    | 0.13    | 0.2    | 0.01 | 0.27 | 0.27 | 0.27   | 0.27 | MgO    | 1.16   | 0.62   | 1.73  | 2.2   | 0.86  | 0.67  |
| H₂O⁺   | 0.21    | 0.01   | 0.12 | 0.02 | 0.01 | 0.01   | 0.01 | H₂O⁺   | 0.38   | 0.53   | 0.45  | 0.71  | 0.35  | 0.22  |
| H₂O⁻   | 0.36    | 0.9    | 0.28 | 0.4  | 0.35 | 0.38   | 0.31 | H₂O⁻   | 0.01   | 0.01   | 0.01  | 0.01  | 0.01  | 0.01  |
| LOI    | 43.13   | 42.27  | 43.39| 43.38| 42.91 | 42.03  | 43.58 | LOI    | 0.15   | 0.63   | 0.58  | 0.22  | 0.1   | 0.16  |
| Residuum | 1.59   | 2.79   | 0.93 | 1.35 | 1.67 | 4.79   | 1.62 | Residuum | 1.8    | 2.25   | 1.65  | 2.97  | 2.11  | 1.39  |
| Total  | 99.6    | 99.22  | 99.94| 100.29| 99.94 | 100.73  | 100.82| Total  | 99     | 98.26  | 99.17 | 99.5  | 99.55 | 98.42 |

In the intervals where decrease in CaCO₃ is observed, a significant increase (up to 4.79 wt.%) of insoluble residuum content is found (Figure 2B). It is confirmed by the strong, negative correlation coefficient (r = −0.82) between insoluble residuum and CaCO₃ calculated for 22 samples. Geochemical analyses indicate that insoluble residuum includes mainly quartz, chalcedony and clay minerals. The highest contents of SiO₂ (up to 88.97 wt.%) were found in the FT 2 pelitic-bioclastic limestones (Table 1) whereas the lowest ones (up to 68.67 wt.%) were analyzed in the FT 3 detrital-bioclastic limestones (Table 1). Clay fraction < 2 μm is dominated by smectite, illite and mixed-layer illite/smectite minerals. Quartz, apatite and kaolinite are present in lesser amounts. Mineralogical composition of clay fraction >2 μm includes quartz, chalcedony, iron oxides and oxyhydroxides. Feldspars and muscovite are rarely observed [8].

5. Discussion

5.1. Geochemical and Mineralogical Characterization of Limestone Facies

Facies and microfacies analyses allowed for distinguishing the three main limestone facies types (FT 1–FT 3) in Lower Kimmeridgian sedimentary succession of the Zakrzówek Horst. Sedimentary environments of similar facies types known from the northern Tethys shelf in Central Europe, are interpreted as mid-ramp carbonate platform [23,24]. The FT 1 consists mainly of synsedimentary, early-cemented framework (supported autobiostromes or autoparabiostromes), in which more than 60% of sponges remain in life positions [3,25]. The FT 2 represents mainly mud-supported sediments, in which benthic fauna created only minor sponge clusters. Both the FT 1 and FT 2 represent sedimentary environment, between normal-wave and storm-wave bases. However, the FT 3 indicates relatively shallower water conditions [2,16,23,24], close to normal storm-wave base. The relatively shallower sedimentary conditions of the grain-supported FT 3, in relation to both the FT 1 and FT 2, are evidenced by numerous coated grains, e.g.,
oncoids and micritic ooids, as well as by skeletal grains (e.g., calcareous sponges and rare Scleractinian corals).

Variability of facies types correlates well with geochemical and mineralogical changes in CaCO₃ and insoluble residuum contents as well as with changes in porosity. Sedimentological, geochemical and mineralogical data of the limestones and their insoluble residuum enable us to distinguish three sedimentary sequences (I–III; Figure 2B) reflecting the sea-level oscillations. These are marked by the changes in facies types and by the decreasing CaCO₃ contents combined with the increasing insoluble residuum amounts in its uppermost parts.

### Table 2. Mineralogical composition of selected samples from FT 1–3.

| Facies Type | Sample | Phase       | wt. % |
|-------------|--------|-------------|-------|
| FT 1        | G4     | Calcite     | 100   |
|             | D4     | Calcite     | 100   |
| FT 2        | C4     | Calcite     | 99.6  |
|             | Quartz | 0.4         |
|             | B4     | Calcite     | 99.4  |
|             | Quartz | 0.6         |
| FT 3        | E7     | Dolomite    | 52.4  |
|             | Calcite| 47.4        |
|             | Quartz | 0.2         |
|             | E5     | Dolomite    | 98.6  |
|             | Calcite| 1.4         |
|             | Quartz | 0.1         |
|             | E6     | Calcite     | 100   |

### 5.2. Porosity Changes of Limestone Facies Types

The Upper Jurassic facies types from the Zakrzówek Horst differ in total sediment porosity. Apart from porosity unrelated to limestone texture (e.g., fracture porosity and/or secondary porosity left after dolomitization, dedolomitization or karstification), we observe porosity variations related to the texture and the genesis of limestones. The current value of limestone (massive reef and bedded facies) porosity appears to be significantly influenced by susceptibility to compaction and by early cementation of the sediments.
Both the mechanical and the chemical compaction belong to the most important processes reducing the thickness of bedded carbonate deposits [26–29]. Reduction of primary porosity of sediments is controlled by both the compaction and the early cementation. Mechanical compaction affects sediments during the early diagenesis whereas chemical compaction (pressure dissolution) operates during the late diagenesis and requires the
The bioclastic, early-cemented, skeleton-supported, sponge-microbial limestones (FT 1), the mud-, and grain-supported, pelitic-bioclastic limestones (FT 2) and the detrital-bioclastic limestones (FT 3) reveal different susceptibility to compaction. In the southern Kraków-Częstochowa Upland, this problem was analyzed by experimental studies on the Upper Jurassic bedded limestones [33]. These authors presented the model showing lateral facies transition from the reefs to the intrareef depressions with characteristic development of sediments in specific “compaction” zones (zones I–IV; see below) due to various susceptibility to compaction. According to Kochman and Matyszkiwicz [33], the most significant effect of mechanical compaction was observed for only a few-meters burial depth. This conclusion may be important in the context of the age of dolomitization processes in the limestones, which are considered as early diagenetic, prior to total lithification (see remarks on dolomitization).

The compaction zones [33] mentioned above can also be distinguished in vertical facies changes observed in the Zakrzówek Horst. Both the FT 2 and FT 3 sediments represent mud- and grain-supported facies, which are highly susceptible to mechanical compaction during deposition. These can be referred to as zones III (distal slopes of reef complexes) and IV (deepest parts of intrareef depressions) after [33]. Mechanical compaction value was significant—from about 27.5% to over 55% in Oxfordian bedded limestones [29,32]. As a result, the primary sediment porosity was already strongly reduced at the stage of early diagenesis. Undoubtedly, depending on the limestone types, the highest primary porosity characterized the FT 3, which underwent early diagenetic dolomitization prior to complete lithification [18]. The FT 1 sponge-microbial biostromes represent the Zone II (proximal part of the slopes of microbial-sponge reef complexes or bedded limestones) [33]. These sediments were susceptible both to the early cementation during deposition and to the variable degree of mechanical compaction estimated as 0–27.5% [33]. Such variability of compaction degree was controlled by the type of rigid framework, changing from reticulate to laminar, and by the existence of transitional zones between the described facies types. These differences are evident when comparing the lower and the upper intervals of the FT 1. In the lower interval, sponges overgrown by microbialites are embedded within mud-grained sediment. This internal structure probably led to the formation of nodular limestones. However, in the upper FT 1 interval, microbialites are more common, thus, they cement the sediment forming rigid framework together with sponges. It must be noticed that, in comparison to the porosity and the compaction zones, the distinguished facies types do not always fully overlap due to gradual vertical transitions between them.
Figure 5. (A–G) Dyfractograms of selected FT 1-3 samples from Zakrzówek Horst.

The bedded microbial-sponge reefs, which represent the compaction Zone I [33] were not found in the study area. In the Lower Kimmeridgian, they formed extensive, flat biostromes [16]. Additionally, in the upper part of Upper Jurassic succession from the Kraków area, the reefs occurred less frequently (Figure 2), while the low-relief biostromes [3] dominated.

5.3. Remarks on Limestones Dolomitization in the Kraków Area

The mechanism of limestones dolomitization in the study area has not been fully explained so far [3,17–19]. However, our studies add some details to the earlier concepts [3,17–19]. Microfacies studies show that dolomitization affected mainly the FT 3 detrital-bioclastic bedded limestones, in which cherts were generally not observed. The lack of relationships between dolomitized zones and fracture systems indicates early diagenetic dolomitization in incompletely lithified sediment [18,19]. Moreover, the abrasive platforms cut the lenses of dolomites [18], which clearly demonstrates that dolomitization took place before the Late Cretaceous (probably prior to the Turonian).
Based on studies of distinguished facies types, this age can be determined more precisely. Selective replacement of calcite by dolomite in the limestone matrix and simultaneous lack of dolomitization of both the skeletal and non-skeletal grains point out that, at the beginning, dolomitization affected only the incompletely lithified parts of calcareous sediment, probably at the end of the early diagenesis. Experimental studies of Upper Jurassic bedded facies [33] showed that the largest thickness reduction caused by mechanical compaction occurred under a thin overburden. This indicates that conditions favorable for pore solution transfer contributing to dolomitization occurred only during the early diagenesis, i.e., perhaps still during the Kimmeridgian. Today, thickness of the younger Upper Jurassic sediments in the Kraków area is about 25 m (Platynota Zone; Figure 2A). However, the younger Upper Jurassic (Kimmeridgian and Tithonian) sediments have not been observed in the study area, mainly due to Upper Cretaceous erosion. In the adjacent regions (Carpathian Foredeep basement or Mięchów Depression), thickness of younger Upper Jurassic sediments reaches several hundred meters. Moreover, there is no convincing evidence that the younger Upper Jurassic sediments were not deposited in the Krakow area. Therefore, it can be assumed that the essential stage of mechanical compaction was completed before the end of the Kimmeridgian. Additionally, the stylolites cutting both the matrix of dolomitic limestones and the pseudomorphs after dolomite crystals indicate that dolomitization process took place prior to chemical compaction.

Some hints concerning dolomitization may be adopted from analogous Upper Jurassic (Oxfordian-Kimmeridgian) carbonates from the Swabian Alb and the Southern Franconian Alb (Southern Germany) [34,35]. The probable source of Mg2+ ions in these sediments could have been the pore solutions, which migrated from compacted bedded facies towards the sponge-microbial buildups and grain-supported oolitic facies [35]. According to Reinhold [35], transfer of pore waters in deposited carbonate complexes might have taken place even over several dozens of kilometers. Moreover, Reinhold [35] claimed that the initial matrix dolomitization had occurred between the latest Jurassic and the earliest Cretaceous, and was related to pressure dissolution during a very shallow burial, at temperatures of at least 50°C. In the Swabian Alb, the burial compaction provided amounts of fluids sufficient for dolomitization [35]. Additionally, Koch et al. [34] found that distribution of dolomite was closely related to paleogeographical position of dolomitized sediments between relatively shallow-platform carbonate sands and deeper-basin sediments, and that dolomitization was related to Mg2+ ions derived from the more compacted basin sediments. Finally, palaeogeographic position of the Kraków area in the Kimmeridgian also indicates its location adjacent to deeper parts of sedimentary basin [2,36,37].

Dedolomitization of studied Upper Jurassic sediments can be related to the late diagenesis proceeded under the subaerial conditions [38–40]. Such conditions might have dominated in the Late Cretaceous, when numerous abrasion platforms were formed in Upper Jurassic successions. Varying intensity of dedolomitization might have been an effect of diverse tectonic involvement of Upper Jurassic formation as well as various ranges of fracture systems and stylolites, which were the migration pathways of dedolomitizing solutions. Dedolomitization proceeded mostly from the surfaces of dolomite crystals towards their interiors, as documented by rough, corroded surfaces of many crystals and gradually disappearing zones replaced by calcite towards the crystals’ interiors [22,41]. Dedolomitization was a selective process as it did not affect the full volume of dolostones. Instead, irregular but gradual changes are observed in dolomite/calcite proportions between dolomites and limestones, giving rise to transitional rock varieties.

6. Conclusions

In the study area, three Upper Jurassic limestone facies types were distinguished: (i) sponge-microbial limestones FT 1, (ii) pelitico-bioclastic limestones FT 2 and (iii) detrital-bioclastic, partly dolomitized limestones FT 3. These sediments represent Lower Kimmeridgian mid-ramp carbonate platform facies. The sponge-microbial limestones are
skeletal-supported autabiostromes or autoparabiostromes. In the pelitic-bioclastic limestones, sponges form only minor clusters within mud-supported sediments. Both FT 1 and FT 2 were laid down in a relatively deeper sedimentary environment, between normal and storm-wave base. The grain-supported, detrital-bioclastic, partly dolomitized limestones are products of relatively shallower environment, close to the normal wave base.

The vertical transitional zones between facies types are commonly marked by changes in contents of CaCO₃ and insoluble residuum as well as in porosity values, which reflect three sea-level fluctuations during deposition of sedimentary sequences.

The studied limestones show high CaCO₃ contents, although variability is observed of this component between facies types. The differences in magnesium contents in the limestones are insignificant. In the limestone facies types, no distinct variability occurs in contents of silica, alumina and iron accumulated in clay minerals, iron oxides and oxyhydroxides, as well as in the amounts of amorphous silica. The mostly differentiated mineral composition is observed in the detrital-bioclastic, partly dolomitized limestones.

The decreasing CaCO₃ contents correlate well with the increasing amounts of insoluble residuum in studied limestone facies. Insoluble residuum contains mainly quartz, chaledony and clay minerals. The highest concentrations of SiO₂ were found in pelitic-bioclastic limestones. Clay fraction < 2 μm is dominated by smectite, illite and mixed-layer illite/smectite. Quartz, apatite and kaolinite are present in lesser amounts. Mineral composition of clay fraction > 2 μm includes mainly quartz, chaledony and iron oxides/oxyhydroxides.

Upper Jurassic facies types found in the Zakrzówek Horst differ in total sediment porosity. Porosity differentiation is related to texture and genesis of limestones. The current value of limestone porosity is significantly influenced by susceptibility to mechanical compaction and by early cementation of sediments.

In the study area, dolomitization is mainly observed in the detrital-bioclastic limestones. Dolomitization was a selective process which affected the limestone matrix, however, skeletal and non-skeletal grains were not dolomitized. No relationship has been confirmed between dolomitized zones and fracture systems. It suggests early diagenetic dolomitization. The possible source of Mg²⁺ ions might have been the pore solutions, which migrated from compacted basinal bedded facies towards the sponge-microbial reefs or the grain-supported facies developed in the adjacent areas. Dedolomitization of studied sediments might have commenced in the late diagenesis, under the subaerial conditions prevailing in the Cretaceous. Varying intensity of dedolomitization might have resulted from diverse tectonic involvement of sediments as well as from the range of fracture systems and stylolites, which are common pathways of solution transfer. Dedolomitization was clearly a selective process as it did not affect the full volume of dolomites. Instead, irregular but gradual transitional zones were produced between dolomites and limestones.

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