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PRESSURE-SOLUTION AND CHEMICAL COMPACTION OF CONDENSED MIDDLE JURASSIC DEPOSITS, HIGH-TATRIC SERIES, TATRA MOUNTAINS

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Abstract: Condensed Middle Jurassic deposits (Dunajec Group), outcropping in the High-Tatric tectonic units of the Tatra Mountains, were subjected to intensive pressure dissolution resulting in great thickness reduction. Crinoidal limestones of the Smolegowa Formation (Bajocian) lost about 20 % of their thickness. The Krupianka Formation (Bathonian) occurs in three lithofacies, differing in the intensity of pressure-solution phenomena. Chemical compaction of the Krupianka crinoidal limestones equalled >30 %, of stylonodular limestones — ~50 %, and of ferruginous limestones even — ~70 %. It differed in various tectonic units, probably due to different tectonic history. The ferruginous and stylonodular limestones owe their modern development to pressure-solution processes. The ferruginous limestones are highly enriched in elements resistant to dissolution. The stylonodular structure formed by selective dissolution of nodular limestones. Pre-compactional differences between the Krupianka Formation lithofacies were less evident than they are today.

Key words: Central Western Carpathians, Tatra Mountains, condensed Middle Jurassic deposits, crinoidal limestones, compaction, pressure-solution.

Introduction

The present-day development, texture and structure of sedimentary rocks are highly influenced by diagenetic phenomena. Diagenetic compaction embraces a range of mechanical and chemical processes. The present paper is an attempt to describe and evaluate the late diagenetic processes of chemical compaction caused by pressure-solution, which took place after the rock lithification. The obtained values concerning the so-called pre-compactional attributes of the rocks are therefore to be treated as referring to lithified deposits, which have already undergone mechanical compaction, undoubtedly also causing substantial thickness reduction.

The intensity and type of pressure-solution depends on the rock's structure, and particularly on such attributes as: occurrence of early cements, size of crystals and clasts, carbonate content, insoluble components' admixture, and rock homogeneity (e.g. Wanless 1979; Buxton & Sibley 1981). Pressure-solution phenomena display a wide range of types, from sutured stylolites to non-sutured dissolution seams. Apart from the rock's structural attributes, the range of chemical compaction processes is a function of cap-rock pressure, and may to some extend depend also on regional compressive tectonics (Railsback 1993; Mišík et al. 1994).

Pressure-solution had great influence on the modern attributes of the High-Tatric condensed Middle Jurassic deposits. Their occurrence in three tectonic units, representing different tectonic histories, on the one hand, and development in a range of facies essentially differing in structural attributes, on the other, enables us to evaluate the influence of various factors on the intensity and type of late diagenetic phenomena.

Geological setting

The High Tatras are the northernmost of the so-called "core mountains" of the Central Western Carpathians (Kotański 1979). On their northern slopes the Variscan crystalline massif is covered by Permo-Mesozoic sedimentary rocks, lying in autochthonous and allochthonous positions. The sedimentary cover represents two major successions (or series) that substantially differ in their facies development. The High-Tatric succession, resting on the crystalline massif, is represented generally by relatively shallow-water facies, marked by numerous stratigraphic gaps. The Sub-Tatric series, covering the High-Tatric succession, is composed generally of deeper-water facies and is more complete.

The High-Tatric series consists of both autochthonous and allochthonous rocks. They belong to three major tectonic units (Fig. 1) — Kominy Tylkowe Unit (autochthonous), and Czerwone Wierchy and Giewont units (allochthonous). The allochthonous units have been detached from their basement and overthrust northwards during the Alpine Orogeny, and paleogeographically represent areas situated south of the autochthonous series.

A condensed Middle Jurassic sequence forms the Dunajec Group, which consists of the Smolegowa Limestone Formation and the Krupianka Limestone Formation (Fig. 2). In the allochthonous units a major stratigraphic gap occurs above Middle Triassic (Anisian) limestones and dolomites, which are covered penecordantly by Middle Jurassic deposits of the Smolegowa (Bajocian), Krupianka (Bathonian) or even Raptawicka Turnia formations (Callovian-Hauterivian). The Smolegowa Formation and particularly the Krupianka Formation are laterally discontinuous, lenticular bodies of thick-

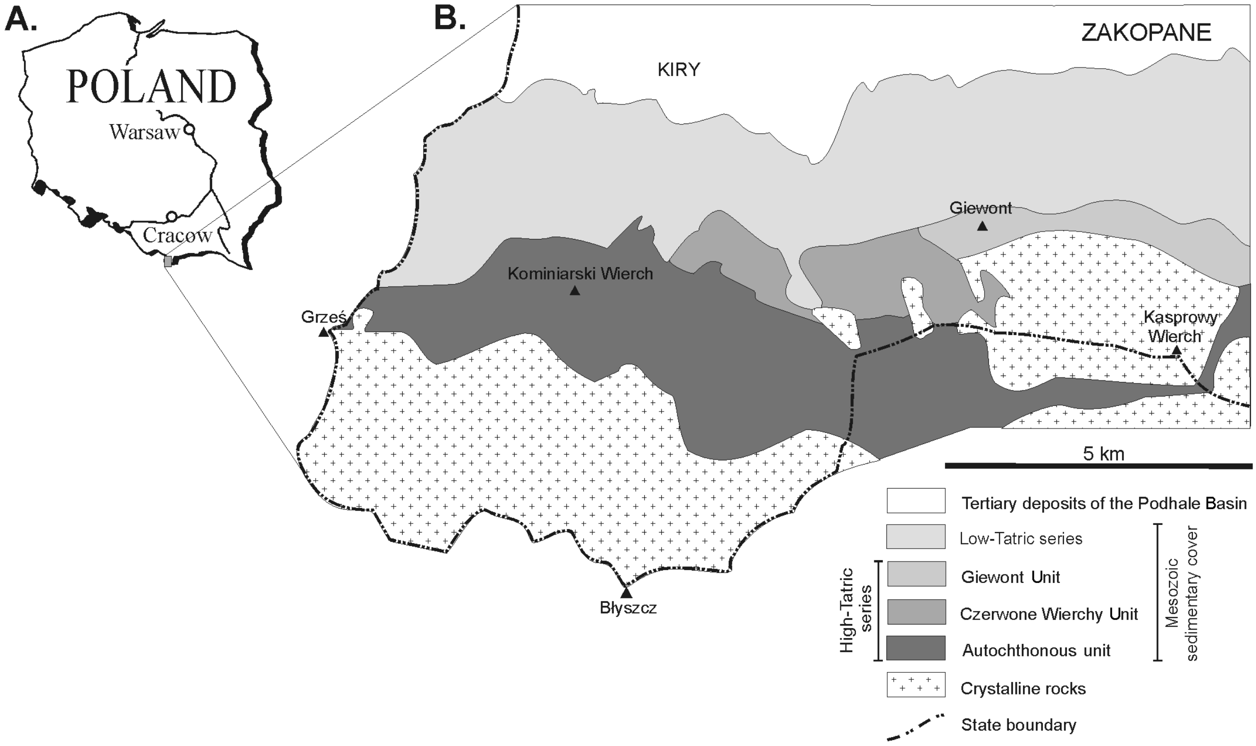

Fig. 1. Structural map of the western part of the Polish section of the High Tatra Massif (B), and its geographical location (A).

Stage(s)	Formation	Group
Callovian – Tithonian	Raptawicka Turnia	Kominy Tylkowe
Bathonian	Krupianka	Dunajec
Bajocian	Smolegowa	
Hettangian – Aalenian	Dudziniec	-

Fig. 2. Lithostratigraphy of the High-Tatric Jurassic (after Lefeld et al. 1985).

ness ranging usually from a few dozen centimetres to about 2 metres (Fig. 3). The same formations exposed in the autochthonous unit, where they overlay the Lower Jurassic to Aalenian Dudziniec Formation, are usually more continuous, and are up to a dozen or so metres thick.

The Smolegowa Formation is uniformly developed as unbedded white, light grey and pinkish coarse-grained crinoidal limestones. It is considered to be of Bajocian age, although this ascription is based only on doubtful brachiopod fauna (Horwitz & Rabowski 1922; Lefeld et al. 1985).

The Krupianka Formation of Bathonian age (Passendorfer 1936, 1938; Lefeld et al. 1985) occurs in three major lithofacies: crinoidal, ferruginous and nodular limestones (Łuczyński 1999). Common features of all three lithofacies are: intensive red colour, occurrence of more or less rich pelmatozoan debris and a relatively abundant and coarse terrigenous admixture of quartz, limestones, dolomites (and dedolomitized secondary limestones), commonly with ferruginous envelopes. Red crinoidal limestones are exposed mainly in the Giewont Unit. In the Czerwone Wierchy Unit the crinoidal limestones pass laterally into ferruginous limestones, with thickness usually not exceeding 30 cm. Stromatolites are common in both crinoidal and ferruginous limestones (Szulczewski 1963, 1968). In most sections of the Kominy Tylkowe Unit the Krupianka limestones exhibit a well-developed nodular structure.

Methods of study

Data concerning types of pressure-solution structures (PSS) and intensity of their occurrence come from field observations, examinations of thin sections and studies of the so-called "insoluble component" — a residuum obtained by dissolving the rocks in 10 % acetic acid. In limestones the proportion of insoluble components content is considered a good measure of the pressure-solution intensity (e.g. Ogg 1981; Braithwaite 1989). The compaction rate has been expressed as a proportional loss of the rock's original thickness.

Residuum received after dissolving the rocks of the Dunajec Group consists mainly of clay minerals, hematite and quartz grains. However, the insoluble components content is a function of three main variables — intensity of pressure-solution, ferruginous mineralization and influx of clastic admixture. Moreover, it depends on the deposition rate. Identification of these factors is crucial in all attempts to evaluate the chemical compaction rate that are based on the insoluble components content. In this context, special attention was paid to:

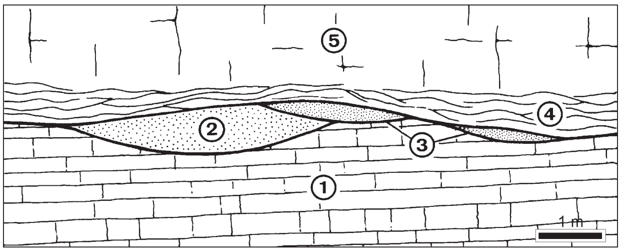

Fig. 3. Idealized spatial relations between the Middle Jurassic lithosomes in the High-Tatric foldic units; **1** — Middle Triassic limestones and dolomites, **2** — white coarse crinoidal limestones of the Smolegowa Formation (Bajocian), **3** — red ferruginous and crinoidal limestones of the Krupianka Formation (Bathonian), **4** — Wavy bedded limestones of the Raptawicka Turnia Formation (Callovian), **5** — Massive limestones of the Raptawicka Turnia Formation (Oxfordian).

— frequency and sizes of PSS,

— variations in insoluble components content between the rocks of the same facies, and differing in PSS frequency,

— variations in the total quartz content in the rocks,

— differences in quartz contribution in the terrigenous admixture,

— proportion of insoluble component derived from the concentrations of PSS in its total volume.

Various rocks or their elements were considered resistant to pressure-solution and thus could be used as reference points in determining original, pre-compactional insoluble component volume. Stromatolites are one of them (Wanless 1979). However, residuum content in the stromatolites strongly depends on their growth rate. More reliable indicators are: terrigenous admixture content, and contribution of insoluble quartz in it. Clari & Martire (1996) stated that deposits accumulated in neptunian dykes represent a rock environment, which is not subjected to any pressure-solution processes. However, the Smolegowa and the Krupianka limestones filling numerous neptunian dykes cannot be used as reference points, as they are commonly penetrated by PSS (Łuczyński 2000).

Distribution of pressure-solution structures

Basic PSS types occur in a continuous range of variations. Probably most common are the *stylolites*, having a form of sutured boundaries between the rock units (e.g. Böer 1977; Braithwaite 1989). Stylolites are thin and concentrate relatively little residuum. At the other end of the spectrum lie the non-sutured *dissolution (clay) seams*, characterized by gentle course, relatively big thickness, and abundant residuum (e.g. Buxton & Sibley 1981). Between thin, sutured stylolites and thick, non-sutured dissolution seams lie a range of intermediate structures, usually called *stylolite seams* (e.g. Clari & Martire 1996) or *sutured dissolution seams* (e.g. Cronan et al. 1991). Clay and stylolite seams often pass laterally into parallel sets of thin *microstylolites* or into rapidly fading away *horsetail stylolites* (Wanless 1979).

Sometimes, the PSS do not have a linear character, but the dissolution effects are evenly distributed within the rocks. Sutured crystal and/or grain boundaries, occurring in the whole rock's volume are referred to as *fitted fabric* (Railsback 1993), while homogeneous rock dissolution, without any characteristic structures, is called *pervasive solution* (Wanless 1979). Moreover, intensive PSS occurrence leads to formation of a number of characteristic varieties of nodular limestones, such as flaser limestones (e.g. Kaldi 1980), or stylonodular limestones (Logan & Semeniuk 1976; Braithwaite & Heath 1992; Demicco & Hardie 1994). Appart from these, the most frequent manifestations of pressure dissolution are:

— disappearance of voids and porosity (Railsback 1993),

— rotation of resistant grains perpendicularly to the stress direction (Braithwaite 1989; Demicco & Hardie 1994),

— bioclast truncation (Schlager 1974; Comas et al. 1981),

— micritization of spar grains (Neugebauer 1978),

— grain overlap (Mc Bride et al. 1991),

— re-precipitation of dissolved calcium carbonate as cements (Logan & Semeniuk 1976),

— dolomitization (Wanless 1979),

— undulations of younger vertical veinlets (Mišík 1998).

Most of the above listed structures and phenomena occur in the Dunajec Group.

Smolegowa Limestone Formation

The Smolegowa crinoidal limestones are almost exclusively composed of syntaxial crystals, only locally accompanied by micrite enclaves (Fig. 4). Their similar development in all the High-Tatric tectonic units implies that eventual variations in PSS occurrence and intensity are caused by differences of tectono-diastrophic history.

Among the PSS of the Smolegowa limestones sutured varieties distinctly predominate (Table 1). They are represented mainly by thin stylolites, with little residuum and high amplitude of sutures. Contacts of syntaxial crystals are commonly sutured, which can be treated as a specific type of fitted fabric (Fig. 5). Stylolite seams with little residuum occur locally in more micritic zones. Resistant grains — mostly quartz, concentrate on some of the PSS. The intensity of pressure-solution effects is relatively low, with some parts of the profiles devoid of them.

High resistance of sparry, coarse-grained crinoidal Smolegowa limestones to pressure-solution caused a very distinct domination or even exclusiveness of sutured PSS. Sutured structures with little residuum form mainly in pure limestones with prevalence of spar over micrite (Buxton & Sibley 1981). High amplitude of sutures is characteristic for rocks composed of large and resistant elements (Braithwaite 1989). Fitted fabric is typical for sparry limestones subjected to high pressures (Railsback 1993). Paucity of the residuum was caused by low insoluble material content.

Krupianka Limestone Formation

The three facies of the Krupianka Formation were treated separately, as were the stromatolites.

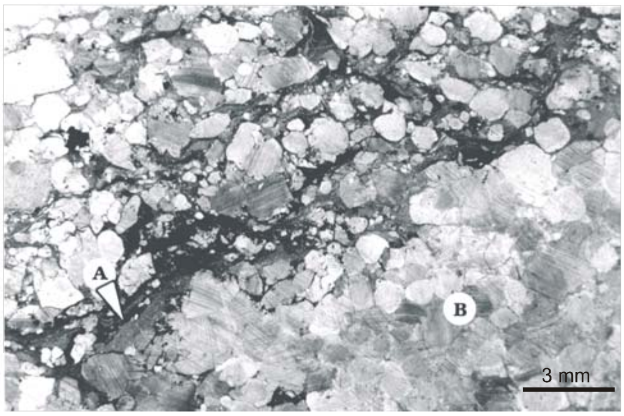

Fig. 4. Micritic enclaves (A) with concentrations of insoluble material within coarse crinoidal Smolegowa limestones (B).

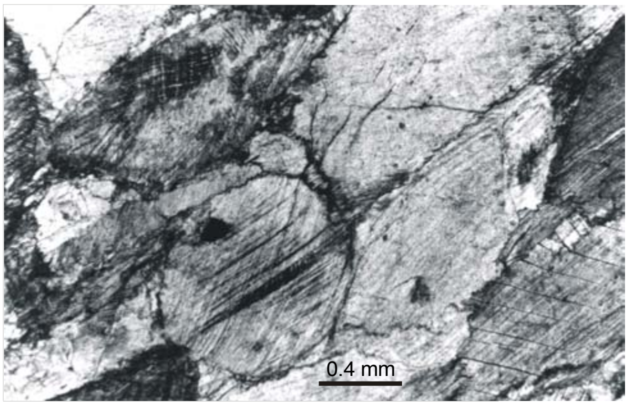

Fig. 5. Fitted fabric structure in coarse-crinoidal limestones of the Smolegowa Formation. Syntaxial crystals have sutured boundaries.

Crinoidal limestones

The Krupianka crinoidal limestones (outcropping in the Giewont Unit and in the eastern part of the autochthonous unit) in many aspects distinctly differ from the Smolegowa limestones. These differences have found their reflection in PSS development. Special attention had to be paid to:

— spar/micrite ratio (corresponding generally with the content of pelmatozoan elements),

— size of syntaxial crystals,

— original — pre-compactional content of ferruginous minerals,

— content of terrigenous admixture (particularly of insoluble quartz grains).

The most frequent pressure-solution effects in the Krupianka crinoidal limestones are stylolite seams (Table 1). They are accompanied by sutured stylolites and non-sutured dissolution seams. Laterally thick clay seams pass locally into sets of microstylolites and horsetail stylolites (Fig. 6). The residuum volume of the PSS is distinctly higher than in the Smolegowa Formation, and concentrations of resistant quartz grains and hematite are also much more frequent (Fig. 7), while fitted fabric occurs very rarely. The PSS are widespread, and with various intensities occur in all outcrops.

One of the changeable elements in the Krupianka crinoidal limestones is the pelmatozoan fragments versus micrite ratio. Sutured PSS types predominate in parts with more abundant spar crystals. However, the stylolites' amplitude is relatively low, which is caused by the limited dimensions of individual crystals. Fitted fabric could not develop, as the syntaxial crystals are not in contact with each other. In more micritic zones

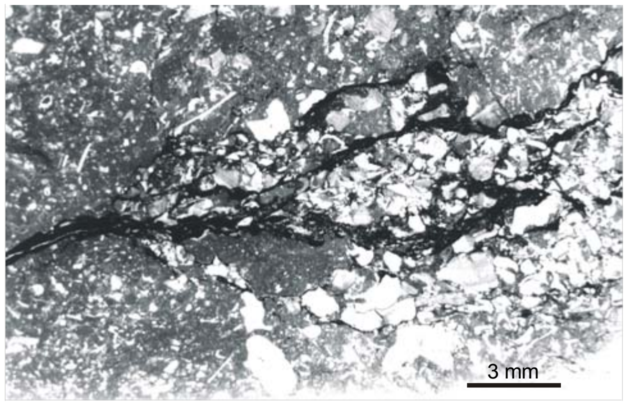

Fig. 6. Clay seam laterally passing into microstylolites in the crinoidal limestones of the Krupianka Formation.

Table 1: Occurrence of pressure solution structures in condensed Middle Jurassic sediments of the High-Tatric series.

Lithostratigraphic units	Lithological varieties	Stylolites with high sutures	Stylolites with low sutures	Stylolite seams	Thin clay seams	Thick clay seams	Microstylolites & horsetail stylolites	Fitted fabric	Pervasisive solution	Concentrations of resistant grains
Smolegowa Formation	Crinoidal limestones	Numerous	Rare	Very rare	-	-	-	Very rare	-	Very rare
Krupianka Formation	Crinoidal limestones	Rare	Numerous	Common	Numerous	Rare	Rare	Sporadic	-	Rare
	Ferruginous limestones	Very rare	Numerous	Common	Common	Common	Common	-	Common	Rare
	Nodular limestones – matrix	-	-	Rare	Numerous	Common	Common	-	-	Rare
	Nodular limestones – nodules	Rare	Numerous	Rare	Rare	-	Numerous	-	-	-
	Stromatolites	Rare	Numerous	Very rare	-	-	Numerous	-	-	Numerous

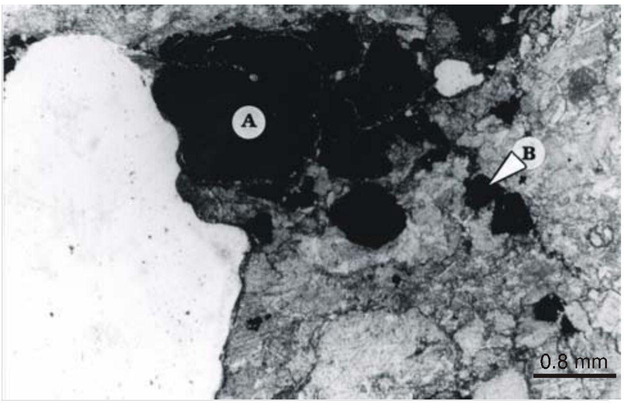

Fig. 7. Amorphous concentrations (A) and authigenic crystals of hematite (B) in the Krupianka crinoidal limestones.

Fig. 8. Concentration of grains resistant to pressure dissolution on a stylolite seam (arrows) in the ferruginous limestones of the Krupianka Formation.

mainly thin clay seams occur. A dominance of non-sutured structures is typical for micritic limestones devoid of elements resistant to pressure-solution (Braithwaite 1989).

The residuum is much richer in the PSS of the Krupianka crinoidal limestones than in that of the Smolegowa limestones. More intensive dissolution of the Krupianka limestones was caused by their higher susceptibility to pressure-solution processes. The abundance and size of resistant pelmatozoan elements were decisive factors. Higher insoluble material content did not restrict the dissolution, as postulated by Wanless (1979) and Zydorowicz (1991).

Ferruginous limestones

The Krupianka ferruginous limestones (outcropping in the Czerwone Wierchy Unit) form a continuous spectrum with the crinoidal limestones, from which they differ mainly by gradual (but rarely total) elimination of pelmatozoan elements, and by a greater abundance of ferruginous minerals, terrigenous admixture and PSS.

Non-sutured varieties predominate among the PSS of the ferruginous limestones (Table 1). Thick dissolution seams are most frequent. In some sections, clay seams concentrate so much insoluble material, and occur so densely, that practically the whole formation (with a thickness of dozen or so centimetres) has the character of pressure-solution residuum. In such cases a pervasive solution took place. Laterally thick clay seams pass into parallel systems of thinner dissolution seams, microstylolites and horsetail stylolites. Dominating non-sutured dissolution seams are accompanied by stylolite seams with relatively low sutures and rich residuum, concentrating in zones with more abundant pelmatozoan fragments and terrigenous admixture (Fig. 8).

The set of PSS that occurs in the Krupianka ferruginous limestones is characteristic for rocks that are: very susceptible to pressure-solution (Buxton & Sibley 1981), devoid of (or with very few) larger resistant elements influencing the course of the PSS (Railsback 1993), and abundant in clay and/or dispersed ferruginous minerals passing into the residuum (Braithwaite 1989).

Micritic ferruginous limestones, with limited admixture of pelmatozoan fragments were very susceptible to pressure-solution. General paucity of resistant elements is responsible for a non-sutured course of the PSS, while thickness of the clay seams, and the richness of the residuum are an effect of precompactional abundance of clay and ferruginous minerals.

Nodular limestones

Nodular limestones of the Krupianka Formation outcrop in the western part of the Polish section of the autochthonous unit. Szulczewski (1965) interpreted their formation by redeposition processes. They display a structure, which is commonly referred to as stylonodular (e.g. Braithwaite & Heath 1992; Demicco & Hardie 1994; Clari & Martire 1996).

In the Krupianka nodular limestones distinctly different dissolution phenomena are characteristic for the nodules and for the matrix that surrounds them.

Matrix. The matrix of nodular limestones has a high PSS concentration, with predominance of relatively thin clay and stylolite seams (Table 1). Laterally the seams pass into parallel sets of microstylolites and stylolites, locally penetrating the nodule boundaries (Fig. 9).

Nodules. The PSS are much more rarer in the nodules than in the matrix. Stylolites with relatively low sutures and little residuum are most frequent (Table 1). They are the only

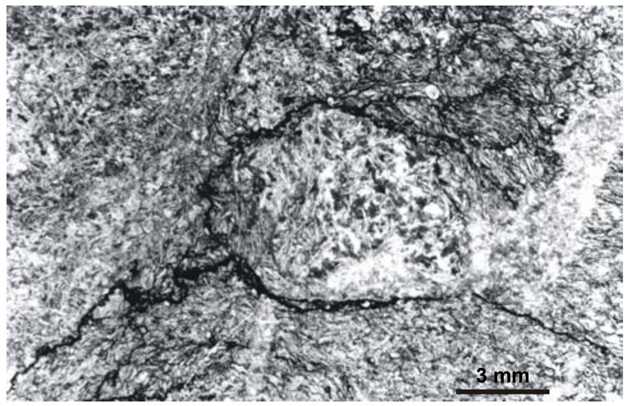

Fig. 9. Stylolite seams passing laterally into sets of microstylolites and horsetail stylolites, forming a stylonodular structure in the nodular limestones of the Krupianka Formation.

types of PSS that penetrate the central parts of the nodules, while all the others concentrate on their rims (Fig. 9). Microstylolites penetrating the nodule/matrix boundary are common in peripheral parts of the lenticular nodules.

Pressure-solution phenomena that took place in the nodules and in the matrix, are characteristic for different rock environments. Structures from the matrix resemble those from the ferruginous limestones. The abundance of their occurrence, and distinct domination of non-sutured forms, point to the rocks' susceptibility to dissolution and lack of resistant elements (Wanless 1979; Buxton & Sibley 1981). However, the process was not so strong as in the ferruginous limestones, and the pre-compactional insoluble clay and/or ferruginous minerals content was lower. On the other hand, pressure-solution intensity in the nodules is relatively low. Stylolites with low sutures are characteristic for competent rocks, composed of equally resistant elements. As the nodules are poor in resistant elements, the only factor that could cause their resistance, is heterogeneous early cementation (Jurgan 1969; Zydorowicz 1991; Clari & Martire 1996).

Stromatolites

Stromatolites occur within the profiles of crinoidal and ferruginous Krupianka limestones in all the High-Tatric tectonic units (Szulczewski 1963). As they co-exist in the same sections with other types of rocks, and therefore have undergone the same history of overload pressure and regional stress, they may act as reference points in attempts to assess the influence of the rock structure on pressure-solution.

The following features of PSS are characteristic of the High-Tatric Middle Jurassic stromatolites (Table 1):

— thin stylolites with low sutures inside the stromatolite domes,

— common capping of upper surfaces of stromatolites by thick clay seams,

— relatively common concentrations of fine resistant elements (mainly quartz and ferruginous grains) in the stylolites and clay seams.

Intensity of dissolution phenomena in the stromatolites is usually much lower than in the neighbouring rocks, which is an effect of their higher resistance, caused by early cementation of the stromatolite domes (Wanless 1979). The relatively most frequent, thin stylolites followed the original internal structure of the stromatolites. On the other hand, because of their low rate of growth (Szulczewski 1966, 1968; Pentecost 1990), the stromatolites comprised a lot of fine terrigenous material, concentrating in the PSS. Clay seams capping the stromatolites are an effect of dissolution of the overlying rocks, and residuum concentration on top of rigid domes.

Assessment of compaction rate

One of main effects of pressure-solution is the rock's thickness reduction. The first stage of the rock's volume decrease is the mechanical compaction — mainly disappearance of porous spaces. It is followed by chemical compaction, being an effect of the overload pressure.

Attempts to assess the rate of the rock's chemical compaction have been based on various features. Ogg (1981) estimated that in the Ammonitico Rosso Formation one stylolite seam corresponds to about 4 cm of deposits. Braithwaite (1989) determined the quantity of dissolution residuum concentrated on the stylolites. Railsback (1993) assessed the compaction of clastic rocks by the rate of grain overlap. In the present paper in every possible case the compaction of the High-Tatric Middle Jurassic was independently determined on the basis of various available data, in order to confirm the obtained results.

Smolegowa Limestone Formation

In the Czerwone Wierchy Unit the Smolegowa limestones are devoid of any indications of pressure-solution. Therefore, the rocks outcropping there were treated as a reference point in attempts to assess rock compaction in other tectonic units (Table 2a). The second method used consisted in determination of the average PSS content (Table 2b), and calculation of the corresponding thickness reduction.

The two methods gave close results, especially for the Giewont Unit. Somewhat bigger differences occur for the autochthonous unit, where the result obtained from the weight analysis of insoluble components is distinctly higher than that coming from the calculations of the PSS quantity. It has probably been caused by two main factors: relatively higher intensity of ferruginous mineralization, which has increased the insoluble component content, and small thickness of the Smolegowa limestones in some sections of the autochthonous unit. This effected the concentration of insoluble material on lithological boundaries, which is a typical phenomenon (Buxton & Sibley 1981; Bathurst 1987; Braithwaite & Heath 1992).

Thickness reduction of the Smolegowa Formation in the autochthonous and Giewont units, caused by pressure-solution, was in the range of ~15 up to >20 %.

Krupianka Limestone Formation

Crinoidal limestones

Thickness reduction of the Bathonian crinoidal limestones, calculated on the basis of insoluble components content, is >30 % (Table 3a). The pre-compactional insoluble components content was calculated by comparing the residuum weights of similarly facially developed samples, with different PSS abundance.

Compaction of the Krupianka crinoidal limestones from the Giewont Unit was also determined on the basis of quartz content in the terrigenous admixture (Table 3b). It equals about 15 % in the Bajocian outcropping in this area, and about 20 % in the Bathonian. It can be assumed that, at least predominantly, the difference is caused by change of clastic admixture composition due to selective dissolution of carbonate clasts. It corresponds to about 25 % thickness reduction, as related to the Smolegowa limestones. Total compaction calculated this way is about 40 %. In selected sections an attempt was also

Table 2: Compaction rate assessment of the Smolegowa Formation.

a.

Tectonic unit	Average insoluble component content in 1 kg of rock in a profile devoid of PSS* **(x)**	Average insoluble component content in 1 kg of rock in profiles with PSS* **(y)**	Proportional thickness reduction **(100% • (y - x) / y)**
Czerwone Wierchy	18g		
Giewont		21g	~ 15%
Autochthonous		25.5g	~ 29%

* Average for all the studied samples.

b.

Type of pressure solution structures	Tectonic unit	Density of the occurrence of PSS in the vertical profile **(x)**	Probable thickness reduction connected with a single structure **(y)**	Proportional thickness reduction **(x • y• 100%)**
Stylolites with high sutures and with little residuum	Giewont	~ 10/m	~ 1 cm*	~ 10%
	Autochthonous	~ 15/m		~ 15%
Stylolites with low sutures and stylolite seams	Giewont	~ 3/m	~ 1.5 cm**	~ 4%
	Autochthonous	~ 5/m		~ 8%
Fitted fabric	Autochthonous	Only locally	~ 20%***	Minor importance (<1%)
Concentration of resistant grains	Autochthonous	Only locally	~ 2 - 3cm	Minor importance (<1%)
Total	Giewont			~ 14%
	Autochthonous			~ 24%

* Value approximated by comparing the insoluble component contents of the samples devoid of PSS and samples where their number in a vertical profile has been determined.
** Value approximated by comparing average residuum volume of these structures and of the stylolites with high sutures.
*** Average size reduction of the syntaxial crystals.

made to compare the PSS occurrence in the Smolegowa and Krupianka limestones (Table 3c). The method was based on the stylolites abundance in both formations. It pointed to a compaction rate of 30 %– >50 %.

PSS distribution in the Krupianka crinoidal limestones is very heterogeneous, and therefore the obtained data must be treated only as an approximation. However, confirmation of their creditability comes from the resemblance of the results obtained by various methods.

Stromatolites

Compaction of the stromatolites from the Czerwone Wierchy and Giewont units is distinctly different. In case of stromatolites from the ferruginous limestones of the Czerwone Wierchy Unit, it amounts >30 %, while in stromatolites from the crinoidal limestones of the Giewont Unit, it equals about 10 %. Similar proportions exist between the Krupianka Formation rocks from the two aforementioned tectonic units.

Stromatolites are the only rocks of the Krupianka Formation, in which major PSS could be creditably counted (Table 4a). The results obtained this way, and by evaluation of the insoluble component (Table 4b), are very close to each other.

Ferruginous limestones

Among the Krupianka Formation lithofacies the most intensive dissolution took place in the ferruginous limestones. The determinations of the pre-compactional insoluble components content were based on appropriate values that were calculated for the stromatolites.

Comparison of the terrigenous admixture composition and abundance was made for stromatolites and ferruginous limestones from the same profiles. Two phenomena are characteristic. Firstly, quartz content drastically drops in the stromatolites, being quite stable within a given profile. Most probably, the higher quartz content in the ferruginous limestones is caused by intensive selective dissolution of carbonates. Thickness reduction calculated this way equals about

Table 3: Compaction rate assessment of the Krupianka Formation crinoidal limestones.

a .

Tectonic unit	Probable precompactional insoluble component content in 1 kg of rock* (x)	Average insoluble component content in 1 kg of rock** (y)	Proportional thickness reduction (100% • (y - x) / y)
Giewont	~ 92g	149g	~ 38%
Autochthonous	~ 112g	167g	~ 33%

* Value estimated by comparing the residuum volume of the profiles with a determined content of PSS — the increase of the residuum content connected with doubling the number of PSS in the rocks has been calculated.
** Average for all the studied samples.

b.

Tectonic unit	Quartz content in the terrigenic admixture in the Bajocian* (x)	Quartz content in the terrigenic admixture in the Bathonian* (y)	Proportional compaction of the Bathonian versus the Bajocian (100% • (y - x) / y)	Proportional thickness reduction of the Bajocian** (z)	Proportional thickness reduction (z + (100% • (y - x) / y))
Giewont	~ 15%	~ 20%	~ 25%	~ 15%	~ 40%

* Average of all the studied samples.
** See Table 2a.

c.

Tectonic unit	Proportional thickness reduction of the Bajocian attributed to the stylolites* (x)	Relative proportion of the stylolites occurrence in the Bathonian and the Bajocian (y)	Contribution of the stylolites in the thickness reduction of the Bathonian** (z)	Proportional thickness reduction (100% • x • y / z)
Giewont	~ 10 %	~ 1.5 : 1	~ 40%	~ 37%
Autochthonous	~ 15 %	~ 1.5 : 1	~ 40%	~ 56%

* See Table 2b.
** Approximate value, determined on the basis of the intensity of the occurrence of stylolites and other PSS.

71 % (Table 5a). Secondly, stromatolites differ from ferruginous limestones in the total terrigenous admixture content (Table 5b). The result obtained by calculation of these data (77 %) corresponds well with that emerging from quartz-content analysis. It is, however, strongly dependent on the relation with depositional rates.

The presumed pre-compactional insoluble components content of the ferruginous limestones has been calculated (Table 5c). Results (~ 91 g/kg) are comparable with those obtained for other lithofacies, which confirms the creditability of the presented data.

The present thickness of the Krupianka ferruginous limestones is 4–5 times smaller than prior to the compaction. Therefore, their whole volume can well be treated as a pressure-solution residuum. The rocks probably reached the border value of insoluble components content (between 30 % and 50 %), which froze the dissolution process (Wanless 1979).

Nodular limestones

Compaction of the matrix is incomparably higher than of the nodules, which caused the necessity of their separate treatment.

On the basis of the occurrence of stylolites with high sutures, the compaction rate of the nodules was estimated as about 15 % (Table 6a). The residuum weight was used to determine compaction of the whole rock. The Krupianka Formation from the Kominy Tylkowe massif, devoid of nodularity, and lithologically corresponding to the nodules, was used as a reference point. A correction due to their thickness reduction was assessed at 10 % (Table 6a'). Nodular limestones compaction, calculated on the basis of insoluble component content, equals about 50 % (Table 6b).

Determination of the thickness reduction that took place within the matrix was made indirectly. The rock's volume occupied by the nodules and by the matrix was assessed. Knowing the compaction of the nodules and of the whole rock, the thickness reduction of the matrix was determined. It was estimated at about 73 % (Table 6c), which is comparable to results obtained for the ferruginous limestones. The whole matrix can therefore be treated as a pressure-solution residuum.

Regional differentiation of pressure-solution phenomena

Pressure-solution intensity depends mainly on the rock's structure. However, similar rocks of the Dunajec Group, from various tectonic units, distinctly differ in this matter. The differences are most obvious in two cases. In the Smolegowa limestones, strongest compaction took place in the autochthonous unit, distinctly lower in the Giewont Unit (Table 2), while in the Czerwone Wierchy Unit the rocks are devoid of

Table 4: Compaction rate assessment of the Krupianka Formation stromatolites.

a.

Tectonic unit	Occurrence of the stylolites in a vertical profile **(x)**	Probable thickness reduction connected with a single stylolite* **(y)**	Thickness reduction connected with stylolites **(100% • x • y)**	Contribution of stylolites in the total thickness reduction** **(z)**	Proportional thickness reduction **100% • (100% • x • y / z)**
Czerwone Wierchy	40/m	~ 0.005 m	~ 20%	~ 60%	~ 33%
Giewont	10/m		~ 5%	~ 50%	~ 10%

* Value estimated by comparing the residuum volume of the stylolites from the stromatolites and from other rocks and by evaluating the concentrations of fine quartz grains.
** Approximate value determined on the base of the intensity of occurrence of the stromatolites and other PSS (mainly microstylolites and horsetail stylolites).

b.

Tectonic unit	Probable precompactional content of insoluble components in 1 kg of rock* **(x)**	Insoluble component content in 1 kg of rock **(y)**	Proportional thickness reduction **(100% • (y - x) / y)**
Czerwone Wierchy	~ 104 g	163 g	~ 36%
Giewont		119 g	~ 13%

* Value estimated by comparing the residuum volume of the profiles with a determined content of PSS — the increase of the residuum content connected with doubling the number of PSS in the rocks has been calculated.

Table 5: Compaction rate assessment of the Krupianka Formation ferruginous limestones.

a.

Tectonic unit	Content of quartz in the terrigenic admixture in the stromatolites **(x)**	Proportional thickness reduction of the stromatolites* **(y)**	Probable original quartz content in the terrigenic admixture in the stromatolites **(x • (100% - y))**	Average quartz content in the terrigenic admixture in the ferruginous limestones **(z)**	Proportional thickness reduction **(100% • (100% - (x • 100% - y) / z))**
Czerwone Wierchy	1.2%	~ 36%	~ 0.8%	2.8%	~ 71%

*See Table 4b.

b.

Tectonic unit	Terrigenic admixture content in the stromatolites **(x)**	Proportional thickness reduction of the stromatolites* **(y)**	Probable original terrigenic admixture content in the stromatolites **(x • 100% - y)**	Average terrigenic admixture content in the ferruginous limestones **(z)**	Proportional thickness reduction **100% • (100% - (x • 100% - y) / z)**
Czerwone Wierchy	5.5%	~ 36%	~ 3.5%	~ 15%	~ 77%

* See Table 4b.

c.

Tectonic unit	Proportional thickness reduction **(100% • (y - x) / y)**	Average insoluble components content in 1 kg of rock* **(y)**	Probable precompactional insoluble components content in 1 kg of rock* **(x)**
Czerwone Wierchy	77%**	395g	91g

* Average for all the samples.
** Value taken from Table 5a.

PSS. A thickness reduction more than three times higher took place in stromatolites of the Krupianka Formation from the Czerwone Wierchy Unit than in those, from the Giewont Unit (Table 4). Intensive stromatolite dissolution in the Czerwone Wierchy Unit is accompanied by strongest compaction of the Krupianka Formation. Distinctly smaller thickness reduction took place in the autochthonous unit and relatively the smallest in the Giewont Unit. Yet another expression of dissolution intensity in the Czerwone Wierchy Unit comes from common occurrence of neptunian dykes with walls running along stylolites and clay seams (Łuczyński in prep.).

Different overload pressure is the most common cause of varied PSS development in uniformly developed rocks. However, in the Tatra Mountains, the thickness of rocks overlying the Middle Jurassic is similar in various tectonic units (Lefeld et al. 1985). Regional tectonics can be an alter-

Table 6: Compaction rate assessment of the Krupianka Formation nodular limestones.

a. Nodules

PSS type	Tectonic unit	PSS occurrence in the vertical profile **(x)**	Probable thickness reduction connected with a single structure** **(y)**	Proportional thickness reduction **(x • y •100%)**
Stylolites with low sutures and little residuum	Autochthonous*	10/m	1.5cm	~ 15%

a'. Rock without a distinct nodular structure

Stylolites with low sutures and little residuum	Autochthonous***	10/m	1cm	~ 10%

* Only parts of the profiles with a distinct nodular structure.
** Determined by comparing the residuum contents with the structures from other tectonic units.
*** Data for parts of the profiles without distinct nodular structure.

b. The whole rock

Tectonic unit	Average insoluble component content in 1 kg of rock without a distinct nodular structure* **(x)**	Average insoluble component content in 1 kg of rock with a distinct nodular structure** **(y)**	Proportional thickness reduction **(100% • (y - x) / y)**
Autochthonous	~ 66g***	132g	~ 50%

* Average for all the samples.
** Average of all the samples from the profiles with a distinct nodular structures.
*** After taking into account the probable thickness reduction calculated in Table 6a'.

c . Matrix

Tectonic unit	Proportion of the rock occupied by the nodules* **(x)**	Proportion of the rock occupied by the matrix **(100% - x)**	Proportional thickness reduction of the nodules** **(y)**	Proportional thickness reduction of the whole rock*** **(z)**	Proportional thickness reduction of the matrix **[100% - {(100% - z) – 100% • (100% - y) x • 100%} / (100% - x)]**
Autochthonous	~ 40%	~ 60%	~ 15%	~ 50%	~ 73%

* Approximate value.
* See Table 6a.
* See Table 6b.

native cause of such differences (Railsback 1993; Clari & Martire 1996; Mišík et al. 1994).

Time of PSS formation is unknown. Probably the PSS developed not long after deposition of rocks, in which they occur. This is indicated by the influence of early diagenetic cements on their distribution in the stylonodular limestones. Moreover, easier dissolution of micritic matrix than of calcareous extraclasts in the crinoidal and ferruginous limestones points to distinct lithification differences. The PSS probably started to develop during sedimentation of thick deposits of the Raptawicka Turnia Formation. Such an interpretation excludes eventual connection of pressure-solution with otherthrusting of the Tatric nappes.

The influence of pressure-solution on the development of selected lithofacies

Intensive and differentiated pressure-solution had great influence on the composition and structure of the High-Tatric Middle Jurassic. Distinct changes concern: thickness, clay minerals and ferruginous compounds content, content and composition of terrigenous admixture and micrite/spar ratio. The above listed features are commonly taken into account in paleogeographic interpretations and therefore, it is important to know their precompactional values.

Krupianka ferruginous limestones

Very intensive dissolution of Bathonian ferruginous limestones had an essential influence on their thickness, structure and composition, and distinctly altered their original, precompactional attributes.

The probable pre-compactional insoluble components content in the ferruginous limestones equalled about 91 g/kg (Table 5c), which is comparable to values obtained for other Krupianka Formation lithofacies. The total weight of ferruginous compounds, clay minerals and non-calcareous extraclasts, constituting together the insoluble component, was then, quite similar in various lithofacies. Only the proportions were different. Abundance of ferruginous minerals in the Bathonian of the Czerwone Wierchy Unit must have been counterbalanced by paucity of other insoluble elements. The terrigenous admixture quantity has been precisely determined (Łuczyński 1999), and shows no depletion, which indicates that the clay minerals content must have been very low. The described phenomena are typical of stratigraphically condensed units, deposited on paleohighs. On the one hand, they are commonly characterized by rich occurrence of ferruginous compounds (Hallam 1967; Jenkyns 1970, 1974; Wendt 1973, 1974; Winterer & Bosellini 1981); and on the other, by high carbonate content (> 95 % — Comas et al. 1981), probably caused by winnowing of clay minerals into neighbouring basins (Jenkyns 1971).

It appears that prior to the compaction, ferruginous and crinoidal limestones of the Krupianka Formation did not differ as much as they do today. Basic differences were related to proportions of some of the components. The rocks of the Czerwone Wierchy Unit had a slightly higher ferruginous compounds content, and a lower content of clay minerals and pelmatozoan skeletal fragments.

Krupianka stylonodular limestones

The stylonodular structure of the Bathonian of the autochthonous unit is an effect of pressure-solution. It formed by transformation of a non-homogeneous rock.

The most frequent differences between nodules and matrix relate to:

— lithification, usually connected with occurrence of early cements (Jurgan 1969; Garrison & Kennedy 1977; Zydorowicz 1991; Braithwaite & Heath 1992; Clari & Martire 1996),

— carbonates and clay minerals content (Hallam 1967; Logan & Semeniuk 1976; Winterer & Bosellini 1981; Zydorowicz 1991; Baumgartner 1995),

— macrofauna occurrence — mainly ammonites (Jenkyns 1974).

The stylonodular structure of the autochthonous Bathonian is very distinct. The rocks contain all characteristic features of the stylonodular limestones, such as:

— different intensity of the PSS occurrence in the nodules and in the matrix, in favour of the matrix (Szulczewski 1965; Comas et al. 1981; Zydorowicz 1991; Clari & Martire 1996),

— domination of non-sutured PSS varieties in the matrix (Wanless 1979; Demicco & Hardie 1994), and of stylolites in the nodules (Braithwaite & Heath 1992; Baumgartner 1995),

— distinctly higher clay minerals content in the matrix (Hallam 1967; Baumgartner 1995),

— microfauna concentration in the matrix (Ogg 1981; Zydorowicz 1991),

— extraclast concentration in the matrix,

— same nodule and matrix microfacies (Braithwaite & Heath 1992),

— elongated, lenticular nodule shape (Szulczewski 1965; Comas et al. 1981),

— similar nodule sizes (Zydorowicz 1991),

— sharp nodule boundaries at the top and the bottom, and gradual at the sides (Kaldi 1980).

A structure similar to stylonodular was also found in the Krupianka limestones infilling the neptunian dykes (Łuczyński 1999), which confirms its diagenetic origin (Hsü 1983; Vera et al. 1987).

Pressure-solution has led to major reconstruction of the nodular limestones' original structure. Pre-compactional differences between the nodules and the matrix were less evident than they are today. They were limited to various carbonate and clay contents, and to occurrence of rigid, early calcite cements in the nodules. The original ferruginous compounds and terrigenous admixture contents were distinctly lower. All this indicates that the nodular limestones did not differ much from the Bathonian lithofacies.

Conclusions

1) The Dunajec Group was subjected to intensive pressure-solution. Thickness reduction of the Smolegowa Formation caused by chemical compaction has been assessed at about 20 %. The chemical compaction of various Krupianka Formation lithofacies is different, and equals: crinoidal limestones — ~ 30 %, nodular limestones — ~ 50 %, and ferruginous limestones — ~70 %.

2) Chemical compaction of rocks outcropping in various High-Tatric tectonic units (Smolegowa crinoidal limestones, stromatolites) varies in different units. The differences were probably caused by various tectonic histories.

3) The present-day development of the Krupianka Formation as three distinct lithofacies is largely a result of pressure-solution. Crinoidal limestones represent the facies least affected by dissolution. Ferruginous limestones were formed by concentration of resistant elements, caused by very strong compaction. The stylonodular structure is an effect of selective matrix dissolution of nodular limestones. Nodule resistance was probably caused by early calcite cements.

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