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LOWER JURASSIC SPICULITE SERIES FROM THE KRIŽNA UNIT IN THE WESTERN TATRA MTS, WESTERN CARPATHIANS, POLAND

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Abstract: Lower Jurassic spiculite series was studied in the Polish part of the Križna Unit in the Western Tatra Mts. This series consists of interbedded spiculites and crinoidal limestones. The spiculites are built almost entirely of siliceous sponge spicules belonging to Hexactinellida and Demospongiae classes. The prolific growth of siliceous sponge community was caused by favourable topographic and bathymetric conditions and by increased content of dissolved silica in the seawater. The spicules were not transported. Crinoidal limestones intercalating with spiculites are composed predominantly of crinoidal ossicles redeposited from shallower parts of the basin by gravity currents generated by storm events. The deposits of the studied series reveal a shallowing upward trend, marked by upward gradual replacement of hexactinellids by demosponges and by thickening and coarsening of the crinoidal limestone layers.

Key words: spiculites, crinoidal limestones, siliceous sponges, depositional environments, Lower Jurassic, Tatra Mts.

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INTRODUCTION

Deposits containing abundant siliceous sponge spicules are common in the Lower Jurassic, especially in Pliensbachian deposits of the Tethys margins (e.g., Bernoulli & Jenkyns, 1974; Wiedenmayer, 1980a; Böhm, 1986). Some of them are composed almost exclusively of sponge spicules, but commonly they contain minor intercalations of crinoidal limestones. Despite the relatively common presence, these specific deposits have been rarely a subject of detailed studies, so conditions favouring their formation and the processes of their deposition have not been sufficiently explained.

A good example of such deposits are the Lower Jurassic spiculites of the Križna Unit in the western part of the Polish Tatra Mts (Sujkowski, 1933; Lefeld *et al.*, 1985; Godlewski, 1996), however, they have not been a subject of detailed sedimentological research. The main purpose of this paper is to reconstruct conditions and environment of the spiculite sedimentation, and to describe in detail the evolution of the studied part of the Križna Unit during their deposition.

GEOLOGICAL SETTING

The studied spiculites crop out in the Polish part of the Križna Unit (Lower Sub-Tatric Succession) in the Western Tatra Mountains (Fig. 1). The Križna Unit, which represents the main nappe element of the Fatricum (Häusler *et al.*, 1993), forms in the studied area a large tectonic unit (the so-called partial nappe) distinguished as the Bobrowiec Unit (Andrusov, 1959). It is a faulted element, dipping monoclinally to the north (Bac, 1971; Bac-Moszaszwili *et al.*, 1979), which extends from the Osobita mountain on the west to the Dolina Kościeliska valley on the east. The Bobrowiec Unit comprises almost complete sequence of the Lower Triassic to the Lower Cretaceous deposits (Bac, 1971).

The upper part of the Lower Jurassic of the Križna Unit is built of various carbonate and siliceous deposits. They belong to the Huciska Limestone Formation, in the formal lithostratigraphy (Lefeld *et al.*, 1985), and the studied spiculites represent the Świńska Turnia Spongolite Member (Fig. 2).

Spiculites from the studied area form a series, which is up to 16 m thick (Fig. 3). Their age is determined as Domerian (late Pliensbachian) on the ground of their position in

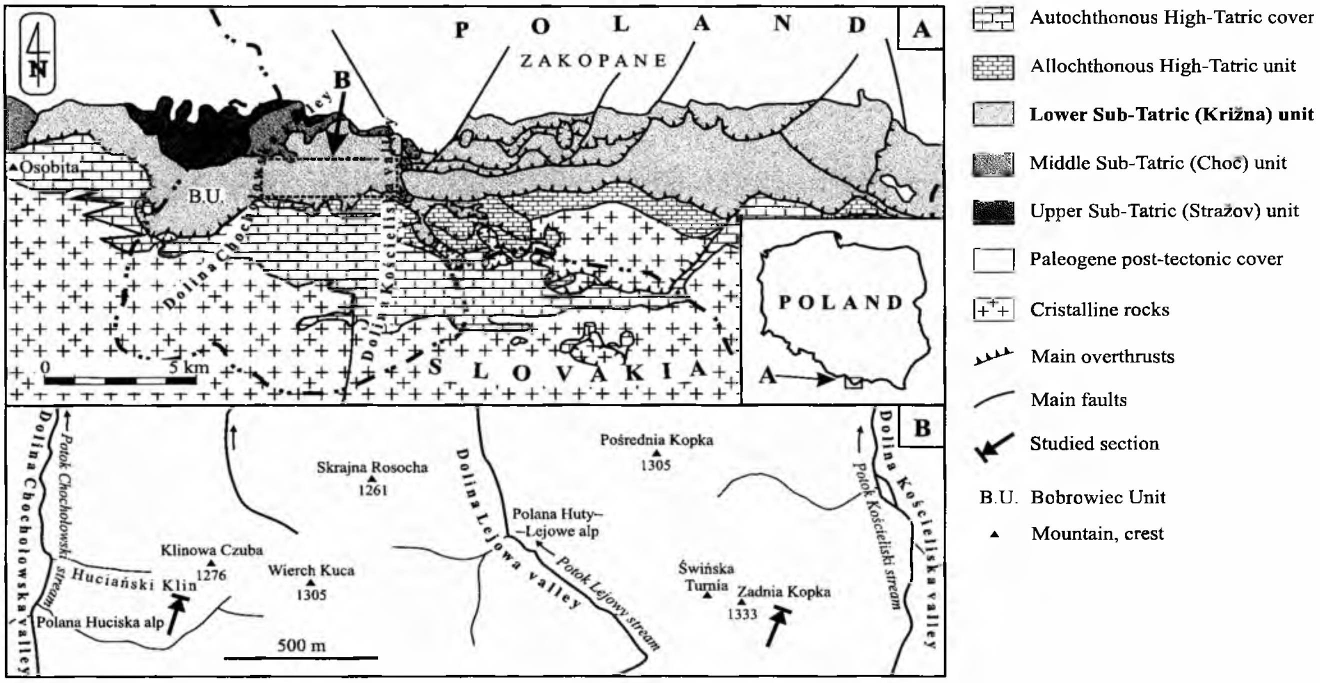

Fig. 1. Geological sketch map of the Polish Tatra Mountains showing location of the studied sections (after Bac-Moszaszwili *et al.*, 1979; simplified)

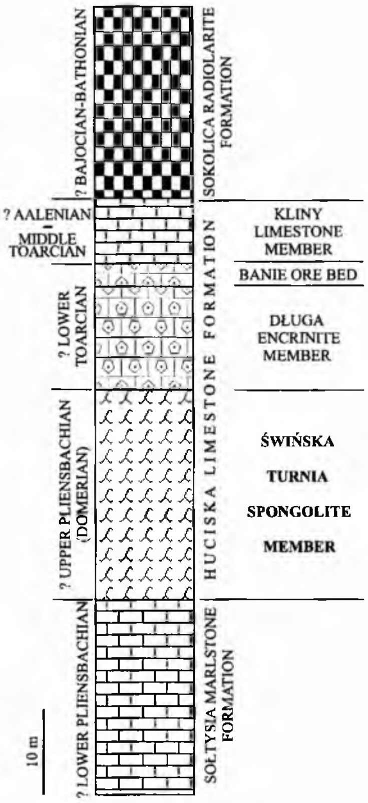

Fig. 2. Lithostratigrafic log of the Lower-Middle Jurassic deposits of the Križna Unit in the Western Tatra Mts (after Lefeld *et al.*, 1985)

the succession (Lefeld *et al.*, 1985). They overlie spotty limestones belonging to the Sołtysia Marlstone Formation (lower Pliensbachian) and are covered by the Długa Encrinite Member of the early Toarcian age (Lefeld *et al.*, 1985; Krajewski *et al.*, 2001). The Lower Jurassic deposits of the Križna Unit show distinct facies variation (Sokołowski, 1925; Guzik, 1959). Among others, the variation is manifested by locally present dark marls and limestones above the spiculites, of the lower-middle Toarcian (Jach, 2001; Jach & Tyszka, 2001). In the eastern part of the Tatra Mts, the spiculites are laterally replaced by locally silicified spotty limestones containing subordinate spiculite layers (Krzywań Limestone Member; Lefeld *et al.*, 1985; cf. Iwanow, 1973; Brud, 1986).

TERMINOLOGY, MATERIALS AND METHODS

The discussed deposits have been hitherto called spongolites (e.g., Sujkowski, 1933; Lefeld *et al.*, 1985) but in fact these deposits built of sponge spicules should be called spiculites. The term spongolite is used for deposits formed of "rigid-bodied sponge skeletons" (Gammon & James, 2001, p. 560). Accordingly, the term spiculite is consistently used in this paper to describe the studied deposits. The whole series, together with the interbedded crinoidal limestones is called spiculite series, and the deposits made entirely of sponge spicules are called spiculites.

The sampled sections are situated between the Dolina Kościeliska valley in the east and the Dolina Chochołowska valley in the west (Fig. 1). The first section, which is the stratotype of the Świńska Turnia Member, lies on the southern slopes of the Zadnia Kopka hill above the Dolina Le-

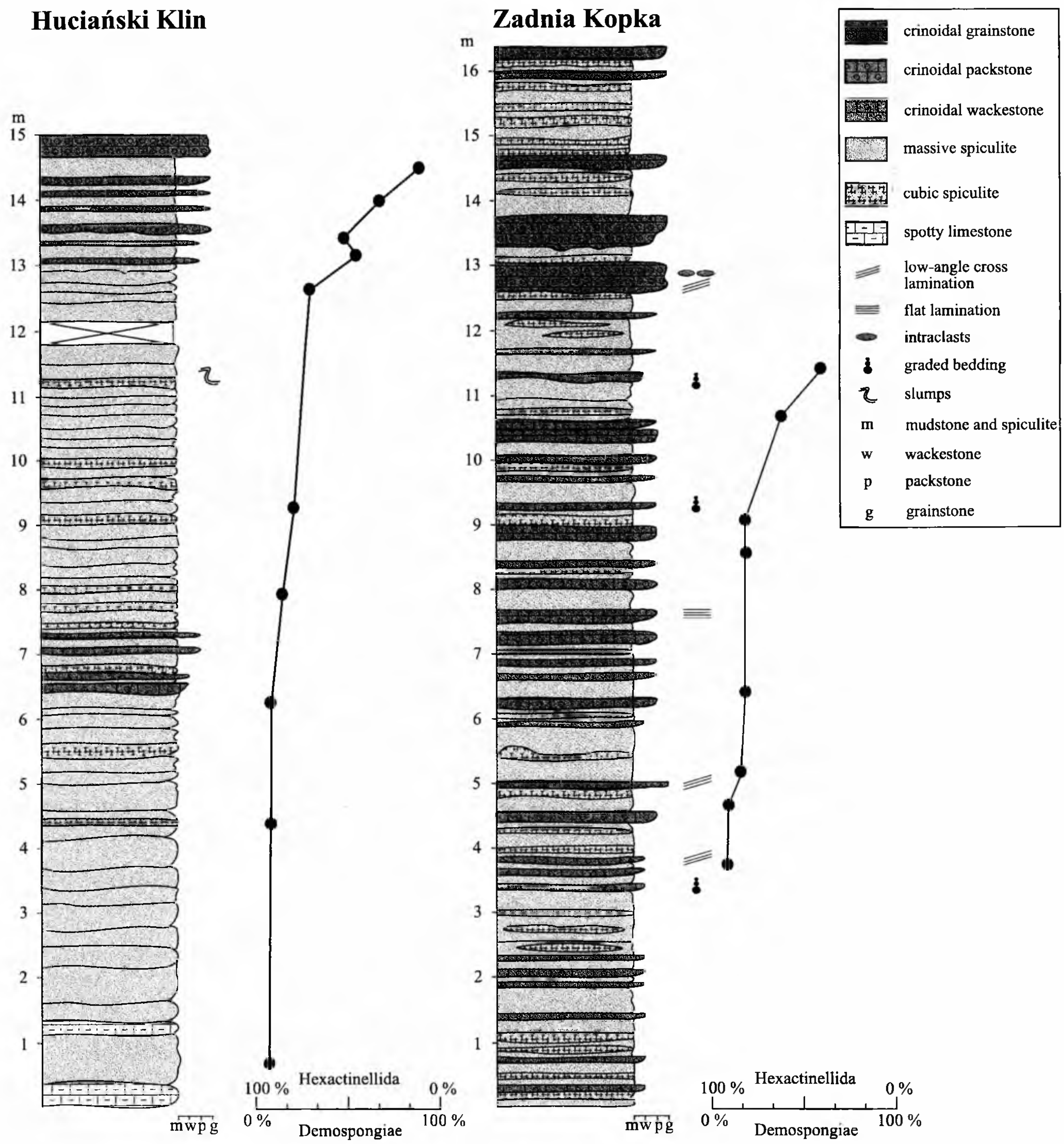

Fig. 3. Lithological sections of the spiculite series at the Huciański Klin crest and Zadnia Kopka hill, with changes in proportions of Hexactinellida and Demospongiae spicules

jowa valley. A belt of south-facing cliffs lies there at an altitude of 1315 metres. The cliffs are built mainly of spiculite series (Fig. 4) and of the overlying encrinites (the Długa Encrinite Member). The second section is situated at the Huciański Klin crest, on the southern slopes of the Klinowa Czuba hill above the Polana Huciska alp. At an altitude of about 1200 metres, there is a group of crags, facing towards the south. They are built mainly of the spiculite series and the lower part of the encrinites (the Długa Encrinite Member).

The two sections were examined bed by bed. One hundred twenty samples were taken and used to make polished slabs and 30 thin sections. Samples collected by Piotr Godlewski during his work on the Master thesis (Godlewski, 1996) have been also used. Based on field observation and, first of all, on observation of the polished sections, several facies were distinguished in the studied deposits. The observations were then extended using microfacies analysis.

Various methods of etching were applied to isolate siliceous sponge spicules. The most effective way was etching in 3–4% hydrofluoric acid for about twelve hours. This method was successfully applied by Sujkowski (1933) to the spiculites from the Tatra Mts. It is based on the difference in dissolving time of silica containing various size of crystals. The applied method enabled identification of spicule geometry in the studied samples and observation of qualitative variation of the spicules. Variation in the quantitative proportion of spicules in each group of sponges have been identified accepting the spicules gained after etching each sample as 100%.

Observations of the etched spiculite surfaces and photographs of isolated spicules were made using a scanning electron microscope JEOL 5410, while chemical composition of the samples was determined using an analyser Voyager 3100 connected to the microscope.

FACIES DESCRIPTION

The studied series consists of two different kinds of facies (see Fig. 13). The first one is spiculites built mainly of sponge spicules. The second one is crinoidal limestones.

SPICULITES

The studied spiculites are dark, hard and bedded, with bed thickness varying from a few to 30 cm (Fig. 4). In the upper part of the studied sections, there are packages with disordered bedding. Their thickness varies from 0.5 m to 2 m. Within the packages, the beds are displaced and locally rotated, so they have a character of breccia at some places. Bottom surfaces in these packages are uneven (Fig. 5). The discussed packages are covered with non-deformed beds of spiculites.

Field observations lead to distinction of two kinds of spiculites (Fig. 6): the dominant massive spiculites and subordinate cubic spiculites (Godlewski, 1996). The first ones have uneven fracture and variable colour, from dark-grey to greyish yellow. The cubic spiculites are found locally, usually in central part of layers. They form dark-grey lenses, a few centimetres thick, which extend up to 2 m in length. They are characterised by a network of cracks parallel or oblique to the layer, that creates an impression of a single cubic structure. The cracks are usually filled with sparry calcite cement.

The spiculites are built almost entirely of sponge spicules which constitute up to 60% of the rock (Fig. 7). Spicules belong to sponges with loose skeletons. The sponges represent Hexactinellida and Demospongiae (mostly Tetractinellida). The former sponges are represented by hexactines (Fig. 8A-G). Spicules of demosponges consist mainly of triaenes with dichotraenes dominating; there are also anatriaenes, strongyles, tetractines, oxeas and selenasters (Fig. 8H–Z). "Lithistida" (now believed as informal group) have not been found and microscleres occur only sporadically. Spicules are mostly unbroken and unabraded. They are commonly arranged with the longest axis parallel to bedding and locally the longest axes are orientated parallel to one another. This is particularly well visible in relation to elongated spicules, espacially of the oxeas type (Fig. 9).

The fabric of the spiculites is grain-supported, with fine-grained carbonate material between the spicules. The carbonates are partially or completely silicified. Crinoidal ossicles and undetermined foraminifers occur rarely in the fabric. Rare grains of detrital quartz (up to 300 μm) have been also found in the spiculites.

Spicules of hexactinellids predominate in the lower parts of the studied sections whereas spicules of demosponges are found only locally. Upwards, the proportion of spicules of demosponges to those of hexactinellids increases, so that in the highest layers the demosponges spicules significantly outnumber those of hexactinellids.

The spicules are commonly bound with chalcedony or blocky microquartz cement (Fig. 10). Chalcedony cement is formed into long-fast fibres. In some places calcite rhombohedra, 20–100 μm in size, appear within the cubic spiculites (Figs 1 & 12).

Interpretation

The studied spicules are characteristic of siliceous sponges representing these groups of hexactinellids and demosponges, whose loose skeletons disintegrated quickly after their death. The loose spicules accumulated then as mats on the basin bottom. Similar modern mats composed of siliceous sponge spicules have been found, among others, on the shelves of the Ellesmere Island (Van Wagoner *et al.*, 1989) and Greenland (Henrich *et al.*, 1992), while their fossil equivalents are known, among others, from the Pennsylvanian carbonates of western central Indiana (Lane, 1980). The quantitative and qualitative variation among the spicules in individual beds and their good preservation prove that the spicules were not transported over longer distances and may be regarded as autochthonous bioclasts.

Although the spicules were not transported, they were sorted by weak currents, as is suggested by their parallel arrangement in some beds. Similarly, a parallel orientation of spicule long axes was found in the Lower Jurassic spiculites from the Northern Calcareous Alps, where Lackschewitz *et al.* (1991) interpreted this as the effect of weak bottom currents. In case of the studied deposits, the currents caused only winnowing of the microscleres which were not found in the examined material. The lack of microscleres, however, could also be due to their low fossilisation potential (Gruber, 1993). Moreover, it cannot be excluded that the microscleres were dissolved during sample etching.

Sponges, especially hexactinellids, are considered as an ultraconservative group of organisms (Mehl, 1992). Based on their present occurrence one can reconstruct environmental preferences of the corresponding fossil forms. Currently, hexactinellids are the deepest living group of sponges (Tabachnick, 1994). They occur mostly in bathyal or even hadal zones, being most frequent between the depths of 100 and 200 m (Reid, 1968; Mehl, 1992). Demosponges occupy a somewhat shallower bathymetric zone. They now live in environments from the littoral, down to the upper continental slope, that is to about 200 metres (Vacelet, 1988; Lidell & Ohlhorst, 1988). Both groups of sponges can coexist at depths not exceeding 200 metres (Krautter, 1997). In specific environmental conditions, especially non-actualistic ones, both groups can occupy shallower ba-

Fig. 4. Outcrop of spiculite series at the Zadnia Kopka hill (photo by A. Uchman)

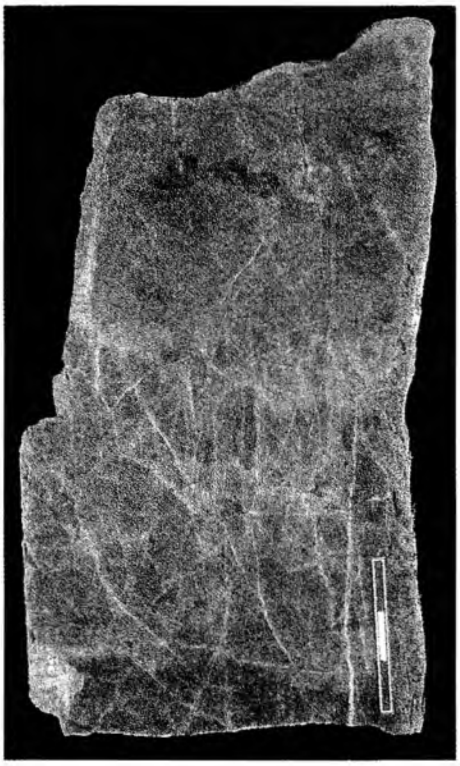

Fig. 6. Cross section of a spiculite bed. Note cubic spiculites at the bottom, and massive spiculites at the top of bed; polished slab; scale bar – 3 cm; Zadnia Kopka hill

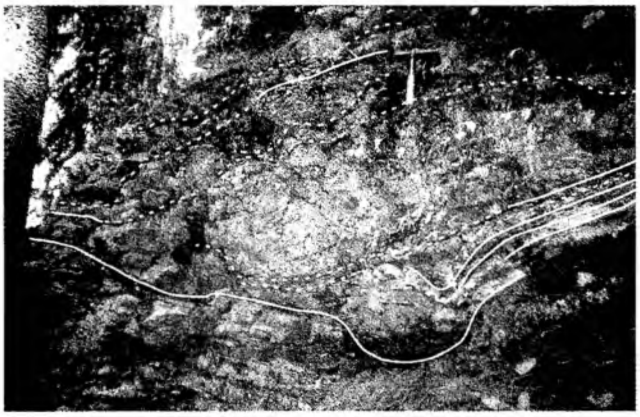

Fig. 5. Submarine slump within the studied spiculites; note uneven base of the slumped beds; Huciański Klin crest

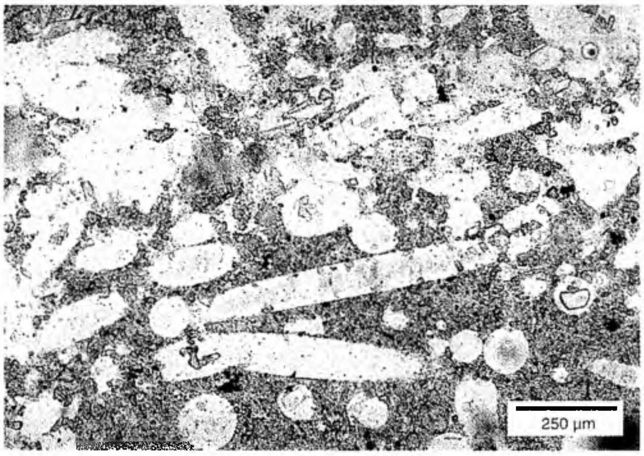

Fig. 7. Spiculites in thin section; parallel nicoles; Huciański Klin crest

thymetric sites (e.g., Gammon *et al.*, 2000). It can be thus accepted that the sponges inhabited the bottom to a depth of 200 metres or less. This idea can be indirectly supported by the lack of radiolarians, which are abundant in Jurassic sediments of upper slope and deeper zones (Kiessling, 1996). This interpretation agrees with the data of Broglio Loriga *et al.* (1991) who describe similar groups of sponges from the Upper Sinemurian of the Trento Plateau and estimate the depth of their origin at about 100 metres. It can be also accepted that sponges inhabited calm hydrodynamic settings, below the normal, and probably also storm, wave base. This area had to be protected, by topographic conditions, from inflow of fine-grained clastics, which would inhibit prolific development of the sponge community.

Similarly to other Lower Jurassic spiculites (cf. Wiedenmayer, 1980a; Galácz & Vörös, 1989; Böhm, 1986; Lackschewitz *et al.*, 1991; Cobianchi & Picotti, 2001) it can be presumed that the studied group of sponges inhabited submarine slopes. The facies distribution in the Tatra part of the Križna Unit confirms the above conclusion. The occurrence of the spiculite series is limited only to some parts of the Tatra Mts (Lefeld *et al.*, 1985) namely to the Western Tatra Mts and Holica Mt area. In other parts of the Križna Unit in the Tatra Mts., equivalents of the spiculites are

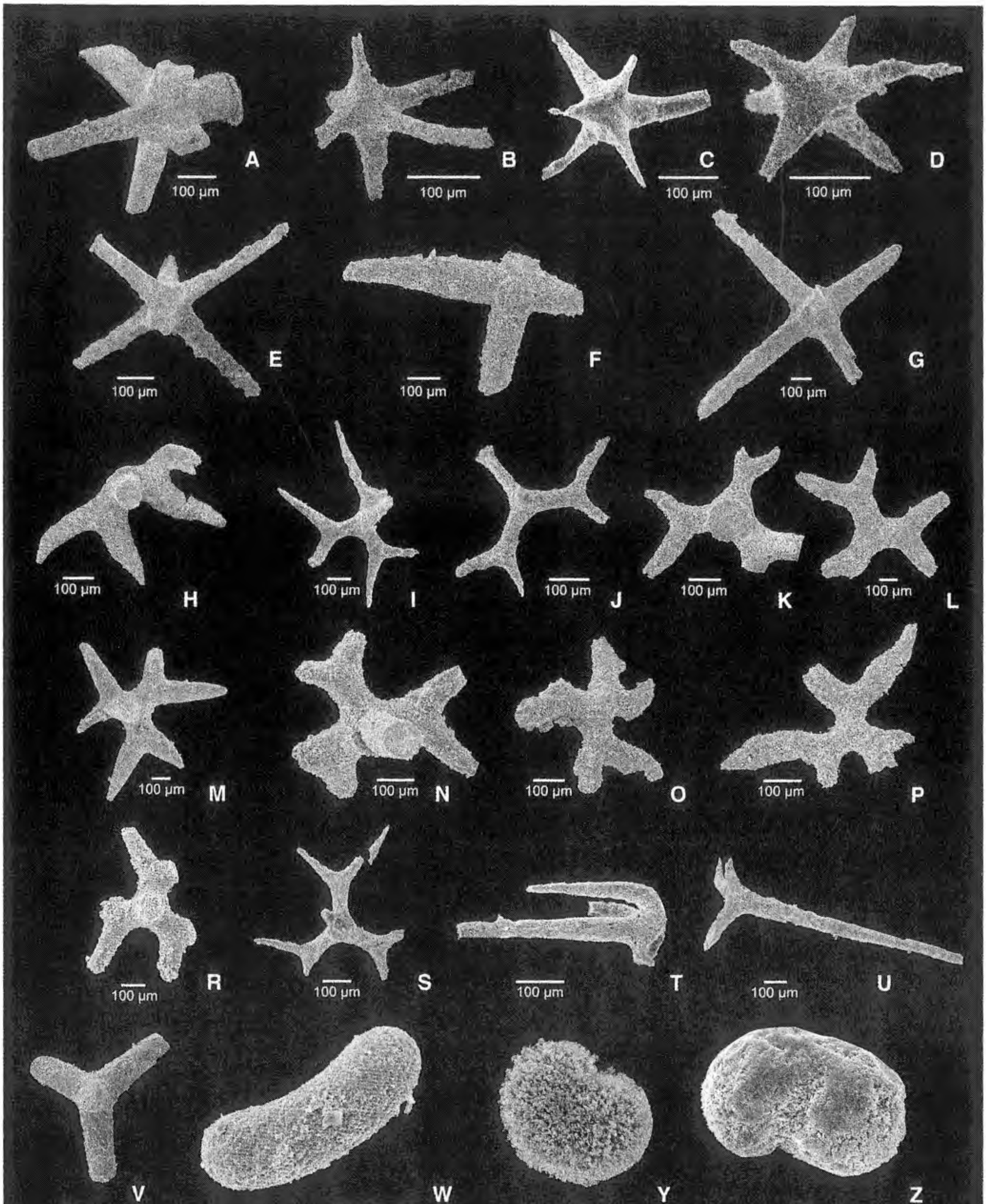

Fig. 8. Selected spicules isolated by etching in HF. Hexactinellid spicules: **A–G.** hexactines; Demosponge spicules: **H–S.** dichotriaenes; **T.** anatriaene; **U.** triaene; **V.** tetractine; **W.** strongyle; **Y–Z.** selenasters

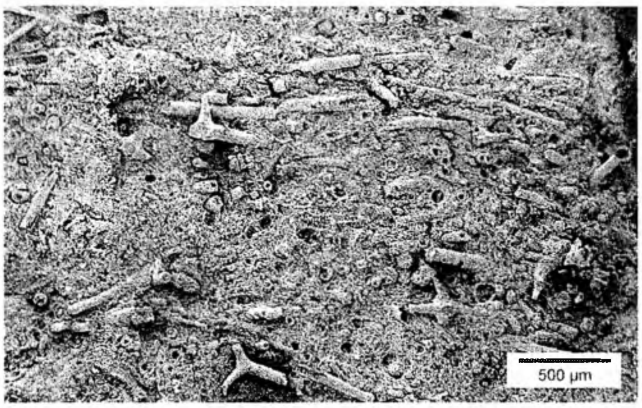

Fig. 9. A distinctive accumulation of siliceous sponge spicules. Parallel arrangement of spicules is visible. SEM image of HF etched surface; Huciański Klin crest

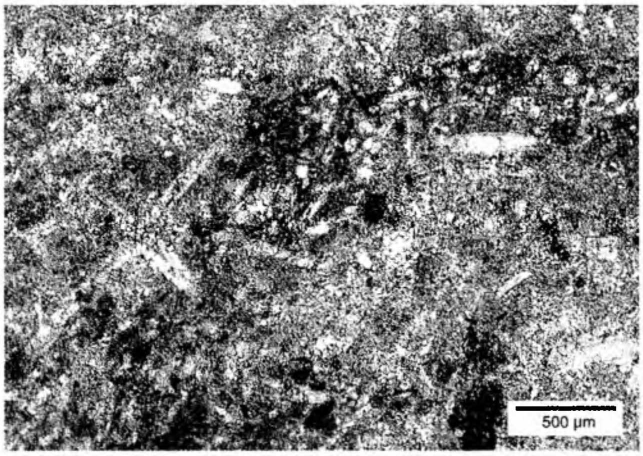

Fig. 10. Sponge spicules filled with chalcedony, with a sheal of length-fast fibres; crossed nicoles; Zadnia Kopka hill

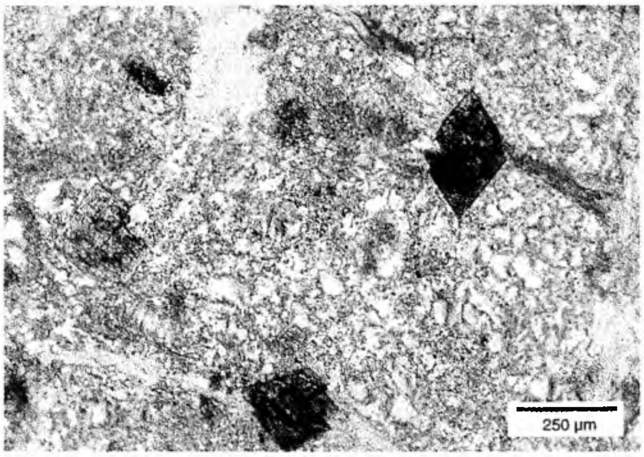

Fig. 11. Calcite rhombohedra in the cubic spiculites; thin section; crossed nicoles; Zadnia Kopka hill

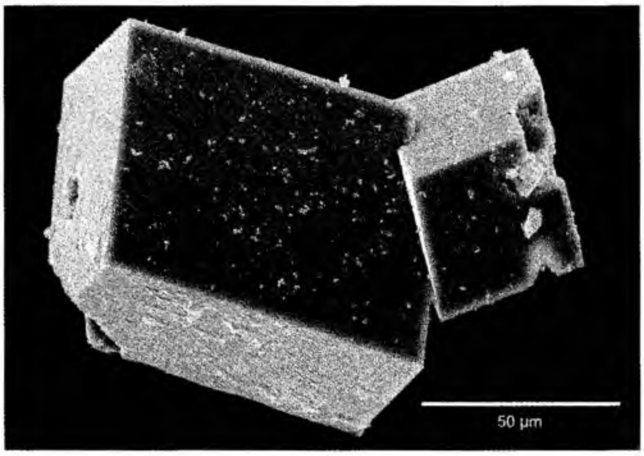

Fig. 12. Calcite rhombohedra isolated by HF etching; SEM image; Zadnia Kopka hill

spotty limestones and marls containing subordinate spiculite layers (Lefeld *et al.*, 1985) interpreted as basinal deposits (Iwanow, 1973).

Apart from the above mentioned conditions concerning hydrodynamic energy and bathymetry, other conditions were required for abundant development of siliceous sponges, resulting in their absolute predominance within benthos (e.g., Gammon *et al.*, 2000).

Extremely important among these factors was elevated silica content in seawater. Sponges are able to assimilate silica only as dissolved $Si(OH)_4$ and its insufficiency limits their occurrence (Maldonado *et al.*, 1999; Gammon *et al.*, 2000). Modern siliceous deposits occur mainly in regions with elevated contents of dissolved silicon in seawater (Decker, 1991). Although Vacelet (1988) maintains that currently increased silica content in seawater does not affect the distribution of siliceous sponges, it seems highly probable, however, that this concerns only post-Cretaceous times. Up to the Cretaceous period, in contrast to the later periods, siliceous sponges belonged to the main groups of organisms taking part in the silica cycle (Maliva *et al.*, 1989). Mass occurrence of siliceous sponges is correlated with increased supplies of silica (Wiedenmayer, 1980a; Zimmerle, 1991), which could be of terrigenous or endogenous origin. The first one is connected with extensive weathering on land (e.g., Gammon & James, 2001), the second is, among others, a result of volcanic activity and extensive tectonics (e.g., Wiedenmayer, 1980a; Zimmerle, 1991; Rosales *et al.*, 1995).

In the discussed case of the Lower Jurassic spiculites, the supply of terrigenous silica should be excluded, because of the long distance of the area inhabited by the sponge community from any continental area that could supply significant quantity of silica of weathering origin. A serious argument for endogenous origin of the silica is the common mass occurrence of siliceous sponges in various Lower Jurassic deposits of the Tethys margins (cf. Wiedenmayer, 1980a; Zimmerle, 1991), preserved as both, spiculites and spongolites. The first ones are known, among others, from the Liassic deposits of the Northern Calcareous Alps (Böhm, 1986; Lackschewitz *et al.*, 1991), Sinemurian and Pliensbachian deposits of the Southern Alps (Beccarelli

Bauck, 1988; Cobianchi & Picotti, 2001), and Sinemurian and Pliensbachian deposits of the Bakony Mts (Galácz & Vörös, 1989). Spiculites are noted also in other tectonic units of the Tatra Mts Wójcik (1981) described some spiculites from Pliensbachian deposits of the autochthonous High-Tatric Units, and Uchman (1994) from Carixian–Domerian deposits of the Choč Unit. Silicified limestones with aboundant sponge spicules were noted from the Slovak part of the Križna Unit (Mišík, 1966), especially from the Veľka Fatra Mts (Mišík & Rakús, 1964; Polák *et al.*, 1997). Siliceous sponge reefs are rare and are known from the southern margin of the Tethys. They are noted from the Sinemurian–Carixian deposits of the Atlas Mountains in Morocco (Neuweiler *et al.*, 2001), Pliensbachian deposits of the Southern Alps (Krautter, 1996), and Toarcian–Aalenian deposits of the Lusitanian Basin in Portugal (Krautter *et al.*, 2001).

The above examples prove that mass occurrence of siliceous sponges in Early Jurassic was of supraregional character. It may thus reflect increased silica content in seawater over a large area. Chemical changes on such a scale can be attributed to the supplies of endogenic silica, connected with a supraregional event such as intensive rifting in the Western Tethys.

CRINOIDAL LIMESTONES

Crinoidal wackestones, packstones and grainstones make an important part of the studied series. They form beds of various thickness intercalating with the beds of spiculites. The wackestones and packstones are light-grey and the grainstones vary from grey to red in colour. Crinoidal limestones occur in various proportions in both profiles. Their intercalations are more numerous and generally thicker in the Zadnia Kopka hill section.

The thickness of the crinoidal wackestones ranges from 3 to 12 cm, of the packstones from 5 to 20 cm, and of the grainstones from 5 to 37 cm. The packstones and grainstones can also appear as beds of variable thickness, or as lenses. The width of the lenses is difficult to measure because of the small outcrops, but it can be estimated as exceeding 10 metres. The lower surfaces of the limestone layers are uneven, gently wavy, while the upper surfaces are usually flat. A part of the bottom surfaces look like dissolution seams. Above the limestone beds, there is often a thin horizon of dark grey marls (1–3 mm) accentuating bedding in the whole series of spiculites (Fig. 13).

Besides abundant crinoid ossicles of various size (commonly from 250 to 500 µm, rarely up to 3 mm) the beds of crinoidal wackestone/packstone bear isolated echinoid spines, bivalve shells, rarely foraminifers, including *Lenticulina* sp., *Ichtyolaria* sp., *Nodosaria* sp., *Ophthalmidium* sp. (determined by D. Ivanova), ostracods and peloids. Bioclasts in the wackestones are rounded and often crushed. Space between the grains is filled with micrite and rare enclaves of sparite. Crinoidal packstones consist of slightly rounded bioclasts and the enclaves of sparite often appear there. Solution seams are common both in, wackestones and packstones.

The crinoidal grainstones consist almost entirely of well preserved crinoid fragments and subordinate echinoid spines (1–3 mm). The components are cemented with syntaxial overgrowths (Fig. 14). Contacts between bioclasts are often stylolitic. Besides fragments of echinoderms, rarely occur shells of bivalves and brachiopods, ostracods, rostra of belemnites and foraminifers, including *Lenticulina* sp., *Nodosaria* sp., *Laevidentalina* sp. and ?*Brisalina* sp. (determined by J. Tyszka). Microborings (10 to 60 µm in diameter) are visible in some crinoid ossicles, echinoderm spines, and molluscan shells. The grainstones are similar to the overlying Długa Encrinite Member (Lefeld *et al.*, 1985; cf. Krajewski *et al.*, 2001).

Besides the bioclasts, extraclasts of dolomites occur in the crinoidal limestones (Fig. 15). They have sharp edges, lack of borings, and are commonly 100 µm, but sporadically up to 2 mm in size. There are also well rounded quartz grains of 100 µm in size. Plastically deformed silicified intraclasts consisting crinoids and spicules are randomly distributed in the crinoidal limestones.

Subtle flat bedding, low-angle cross lamination or graded bedding are visible in some wackestone and packstone layers (Fig. 3). The sedimentary structures are weakly visible or invisible at all in grainstones, apparently because of good sorting of grains.

In the studied profiles there is a clear trend of upward increasing number and thickness of the crinoidal limestone beds. Maturity of the carbonate deposits also increases upwards; crinoidal wackestones and packstones appear mainly in the lowermost and middle parts of the described sections, while the crinoidal grainstones appear only in the uppermost parts.

Interpretation

The sedimentary structures, graded bedding, roundness and larger sizes of bioclasts than those in the spiculites, also the uneven, probably erosional, lower surfaces of the beds, indicate that the crinoidal limestones were deposited in conditions of much higher energy than the spiculites. This fact, coupled with the absolutely different components of both distinguished facies, and the above shown autochthonous nature of the spiculites, prove that the beds of crinoidal limestones are allochthonous, deposited as event beds. Contrary to spiculites the beds are composed of material redeposited by gravity flows to the area of deposition. Thin horizons of marls overlying crinoidal limestones represent tails of gravity flows or background pelagic sediments.

The material of the crinoidal limestones was transported from shallower parts of the basin. The source area for this material were probably elevated parts of the basin floor, overgrown by so-called crinoidal meadows or crinoidal gardens (Fabricius, 1968; Głuchowski, 1987). A characteristic feature of crinoidal ossicles is their primary porous internal structure which determines their hydrodynamic behaviour and makes possible their transport over long distances, even by weak bottom currents (Blyth Cain, 1968; Böhm, 1986; Głuchowski, 1987). Thus the crinoidal ossicles building the studied limestones could have been transported downwards even over long distances.

The dolomite extraclasts found in the crinoidal limestones derive from erosion of older rocks of the basement.

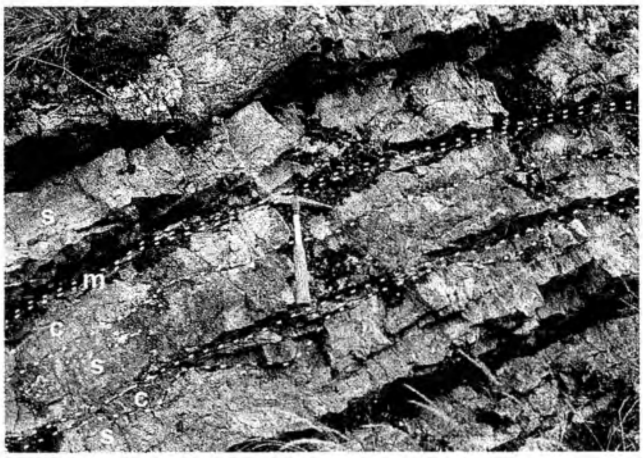

Fig. 13. Spiculites interbedded with crinoidal limestones; s – spiculites, c – crinoidal limestones, m – marls; Zadnia Kopka hill (photo by A. Uchman)

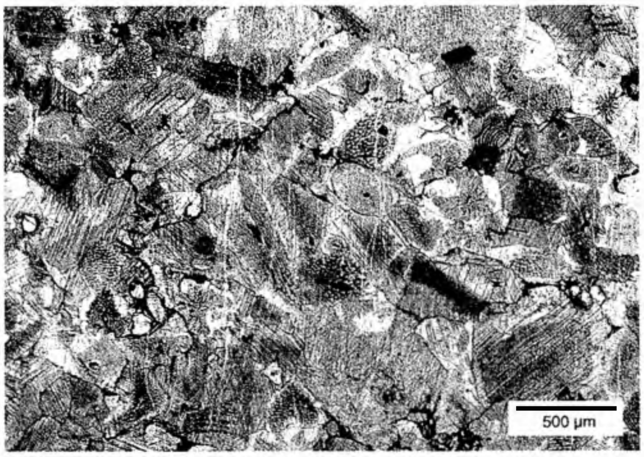

Fig. 14. Thin section of crinoidal grainstone with syntaxial overgrowth; parallel nicoles; Zadnia Kopka hill

Their small size and homogeneous interior structure do not allow to determine the rock series they come from. Radwański (1959) describes similar grains of Triassic dolomites found in the Lower Jurassic deposits of the High-Tatric Unit, and Uchman (1994) from the Lower Jurassic of the Choč Unit. According to these data, and taking into consideration the character of the beds underlying the studied spiculites, it can be assumed that the clasts originated from eroded Triassic deposits. The concentration of extraclasts in the lower parts of beds (Fig. 15) is connected with their higher bulk density compared to that of the co-existing bioclasts (cf. Eberli, 1987).

Precise determination of the nature of transport and deposition mechanisms in the studied limestones seems to be impossible. Solving this problem is difficult because the outcrops are few and small and because the absence of diagnostic sedimentary structures in the studied limestones. Graded bedding, flat lamination and cross-bedding are characteristic of both, gravity flows and tempestites (Einsele & Seilacher, 1991).

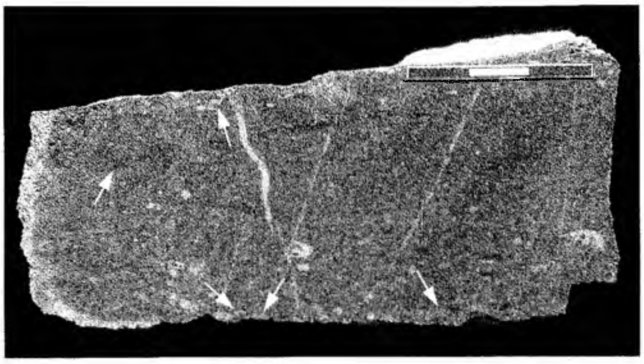

Fig. 15. Vertical cross-section of a crinoidal limestone bed from spiculite series. It shows low angle cross lamination and graded bedding; clasts of dolostones occur locally (arrows); scale bar – 3 cm; Zadnia Kopka hill

Despite these difficulties, the processes leading to deposition of the crinoidal limestones can be evaluated. The limestones were deposited at the depth where siliceous sponge community lived. Taking into account the environmental requirements of the studied sponges, the depth is estimated as no more than 100–200 m. At this depth the material from shallower areas was transported and deposited by density flows that were genetically connected to severe storms operating below normal storm water base (cf. Myrow & Southard, 1996). The differences in number and thickness of the crinoidal limestone beds between the two studied sections are due to diverse basin geometry during the deposition of these sediments (cf. Krajewski *et al.*, 2001).

REMARKS ON DIAGENESIS

The studied spiculites are largely silicified. Both the matrix primarily composed of carbonate micrite, and the sponge spicules are siliceous. In the lower part of the series, up to about four metres above the base, silicification is partial. This part of the series consists of massive spiculites only. Some originally siliceous spicules are now partly or completely calcified. Also the carbonate micrite is silicified only in part. In the upper part of the section, in both the massive and the cubic spiculites, commonly all spicules are silicified. The difference in preservation of the lower and the upper parts of the studied series is probably a result of differences in chemistry of pore water during the early diagenesis.

The plastic, locally even brittle, behaviour of the studied spiculites in slumps provides evidence for quick lithification of the deposits. Wiedenmayer (1980b) maintains that good preservation of siliceous spicules should be associated with a high silica content in the interstitial water. Moreover, the absence of clay minerals in sediment enhanced relatively fast transformation of the unstable opal A building the sponge spicules, into the more stable opal CT (cf. Kastner *et al.*, 1977).

The zones now built of cubic spiculites underwent faster lithification than the surrounding deposit, now present in form of massive spiculites. In such zones the transformation of opal A into opal CT was faster. Redistribution of silica consisted in its import by cubic spiculites at the cost of the surrounding deposit (Tada, 1991). In an early stage of diagenesis calcite rhombohedra developed in the cubic spiculites. Mišík (1993) considers that such rhombohedra develop when siliceous gel has still a high water content.

DEPOSITIONAL TRENDS

Distinctive upward trends are noticeable in the studied series. They consist in a change of the autochtonous fauna, i.e. gradual replacement of hexactinellids by demosponges, and grain coarsening and bed thickening in the crinoidal limestones (Fig. 3).

GRADUAL REPLACEMENT OF HEXACTINELLIDS BY DEMOSPONGES

The gradual changes in the sponge assemblages, shown by gradual replacement of hexactinellids by demosponges upwards in the studied series, may have resulted from different, though interrelated factors (cf. Pisera, 1997). This results from different ecological adaptations in these two groups of sponges, such as trophic requirements, ability to settle on soft substrata and tolerance to fine clastics suspended in the water.

The studied sponges settled on unconsolidated substrata devoid of a larger amount of clasts. Hexactinellids are better adapted to such conditions than demosponges (Tabachnick, 1991). The deficiency of hard substratum eliminated "Lithistida", which were not found in the studied sections (cf. Gammon *et al.*, 2000). Hexactinellids adapted to these conditions by developing long basal prostalia which fixed the organisms in the soft substratum (Tabachnick, 1991). This was probably the case of the studied spiculite series, while mats of loose sponge spicules could facilitate settling of demosponges which are less tolerant to soft substrata. Modern similar mats are settled by demosponges larvae (Henrich *et al.*, 1992). It does not explain, however, the upward increase in the number of demosponges. Also the more and more numerous layers with crinoidal detritus towards the top of the sections did not provide a sufficiently stable substratum for the population of sponges, therefore, it seems that the character of substratum did not have a crucial influence on the observed gradual replacement of hexactinellids by demosponges.

Another factor influencing the changes in sponge populations are the kinds of available nutrients. Hexactinellids are ineffective filter feeders (Leinfelder *et al.*, 1996) and are dependent on a constant supply of nutrients. Osmotrophy is their main feeding strategy. They absorb colloidal organic matter and dissolved amino acids (Tabachnick, 1991; Leinfelder *et al.*, 1996; Krautter, 1997). Contrarily, demosponges use mainly cellular organic matter, such as nannoplankton and bacteria (Leinfelder *et al.*, 1996). A change in available nutrients could thus have bring about the observed gradual replacement of hexactinellids by demosponges. There could be various reasons for the change (cf. Pisera, 1997). It could results from shallowing as colloidal organic matter and dissolved amino acids dominate in deep-sea water, below the zone of the highest biomass productivity, and cellular organic matter is available mainly at depths of a few dozen meters (Krautter, 1997; Ehrlich, 1996).

The increased supply of suspended fine clastics should be also considered as a reason for the gradual replacement. Hexactinellids, dominating in the lower parts of the sections, require strongly limited amount of suspended fine clastics. In contrast to hexactinellids, demosponges tolerate increased content of suspended fine clastics in water. They developed a system which protects their circulation pathway from clogging (Leinfelder *et al.*, 1996; Krautter, 1997). Thus, the discussed gradual replacement may be a result of systematic increase in supply of fine clastics suspended in water. This possibility is indirectly confirmed by the gradual increase upsection in the number of crinoidal limestone layers deposited by density flows. This points to a general tendency to increased supplies of sand-sized carbonate grains. This material was probably accompanied by increased amounts of fine clastics, diluted within the spiculites and now undetectable because of the later diagenetic silicification. Taking the above data into consideration, the observed gradual replacement of hexactinellids by demosponges may be explained by progressive shallowing of the examined part of the Križna basin during the spiculite deposition. This shallowing might determine, among others, a change in available nutrients, and it would result in a systematic increase in the amount of supplied mineral suspension. Similar changes in groups of sponges were described by Rosales *et al.* (1995) from the Albian of Northern Spain, and interpreted as bathymetric changes. Also Leinfelder *et al.* (1996) consider progressive shallowing as the main reason for outnumbering of hexactinellids by "Lithistida" in the Kimmeridgian deposits of Southern Germany. However, it cannot be excluded that the discussed change in environmental parameters, and the resulting gradual replacement of sponge groups, were independent of sea-level changes, and can be related to other factors such as changes in the circulation pattern in the basin (cf. Pisera, 1997).

THICKENING AND COARSENING UPWARD TRENDS IN CRINOIDAL LIMESTONES

The studied crinoidal limestones interbedded with the spiculites display a change in general thickening of beds and coarsening of grains up the section (Fig. 3). The observed trend proves a systematic change in depositional conditions of the limestone beds.

As it was shown above, the crinoidal limestones are most probably the result of gravity flows related to storm events. If so, the coarsening and thickening upward trend is a record of shallowing (e.g., Aigner, 1985; Einsele, 1992). Sponges covered gentle slopes of the outer ramp area (*sensu* Burchette & Wright, 1992). Initially, this area was not far below the storm wave base and was affected only by very strong storms (cf. Vera & Molina, 1998). During the progressive shallowing, the flows induced by storms more and more often reached the area covered with sponge communities and their deposits gradually became thicker and coarser-grained. Deposition of every single flow probably buried and annihilated the living sponge community, which then regenerated slowly in subsequent non-turbulent conditions (Zimmerle, 1991). At last, the more and more frequent flows made this impossible and caused decline of spiculite sedimentation. The crinoidal limestones present above the spiculite series prove further subsequent shallowing in the studied area (Wieczorek, 1990). This scenario is strongly supported by the interpretation presented above based on gradual replacement of hexactinellids by demosponges.

EUSTATIC VERSUS TECTONIC CONTROLS ON DEPOSITIONAL TRENDS

Lack of detailed sedimentological studies of the Lower Jurassic deposits in other parts of the Križna basin, imprecise stratigraphy of the examined deposits and the occurrence of the Križna basin deposits in many isolate tectonic units, make it impossible to find whether the shallowing-upward sequence is of local importance, or is recorded in the deposits of the whole Križna basin. Neither is it possible to precisely compare this series with those of the other Liassic shelves of the Tethys. It can be noted, however, that this event coincided with the late Domerian regression described, among others, by Graciansky *et al.* (1998) and given local rather than global importance by Hallam (2001).

It cannot be excluded, that the regional trends overlapped with local events caused by synsedimentary tectonics. Submarine slumps found within the spiculites (Fig. 5) may be considered an indirect evidence of tectonic activity during the spiculite sedimentation. The occurrence of dolomitic extraclasts with crinoidal detritus proves that older substratum rocks were exposed and eroded during the deposition of the spiculite series discussed here. This could be due to synsedimentary tectonic movements which resulted in a change in topography of the Križna basin (cf. Häusler *et al.*, 1993; Plašienka & Prokešová, 1996).

CONCLUSIONS

The studied series consists of spiculites interbedded with crinoidal limestones. The spiculites are composed of siliceous sponge spicules typical for hexactinellids and demosponges. Spicules were not transported but only sorted by weak bottom currents. Deposition of spiculites had taken place on an outer ramp below the storm wave base. The overwhelming predominance of sponges in the benthic community was the result of favourable trophic conditions, low hydrodynamic energy and increased content of silica in seawater. Silica came from endogenic supply, connected with intense Early Jurassic rifting in the Western Tethys.

The crinoidal limestones interbedded with spiculites are deposits of gravity flows related to storm events. Their grain coarsening and bed thickening upward prove gradual shallowing, evidenced also by the gradual replacement of hexactinellids by demosponges.

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Streszczenie

DOLNOJURAJSKIE SPIKULITY JEDNOSTKI KRIŻNIAŃSKIEJ W TATRACH ZACHODNICH, KARPATY ZACHODNIE, POLSKA

Renata Jach

W utworach jury dolnej jednostki kriżniańskiej w zachodniej części Tatr Polskich występuje seria spikulitów (Fig. 1). W niniejszej pracy opisano i zinterpretowano warunki sedymentacji tych skał w oparciu o odsłonięcia w zachodniej części jednostki kriżniańskiej, należące do tzw. jednostki Bobrowca. Seria spikulitów w tej jednostce tworzy kompleks o maksymalnej miąższości 16 m. W ujęciu formalnej litostratygrafii utwory te należą do formacji wapieni z Hucisk (fm) stanowiąc jedno z jej ogniw, wydzielone pod nazwą ogniwa spongiolitów ze Świńskiej Turni (og). Wiek tej serii skał został określany na domer na podstawie jej superpozycji (Fig. 2; Lefeld *et al.*, 1985). Badania autorki dotyczyły profili zlokalizowanych pomiędzy Doliną Kościeliską a Doliną Chochołowską, w szczytowych partiach Klinowej Czuby na Huciańskim Klinie oraz na Zadniej Kopce (Fig. 3, 4).

W badanym kompleksie osadów występują dwie różniące się facje: spikulity oraz wapienie krynoidowe. Badane spikulity są wykształcone jako ciemne, twarde i uławicone skały. Miąższość ławic waha się od kilku do 30 cm. Wyróżniono dwa typy spikulitów: dominujące masywne oraz kostkowe (Fig. 6). Spikulity są zbudowane prawie wyłącznie z igieł gąbek krzemionkowych, stanowiących do 60% objętości skały i tworzących zwarty szkielet ziarnowy (Fig. 7). Igły należą do gąbek krzemionkowych z gromad Hexactinellida i Demospongiae; wśród tych ostatnich dominują Tetractinellida (Fig. 8). Igły te tworzyły luźne szkielety gąbek. Są one zazwyczaj niepołamane, często ułożone najdłuższą osią równolegle do uławicenia (Fig. 9). Dowodzi to, że nie były one transportowane lecz co najwyżej sortowane przez słabe prądy, są to zatem autochtoniczne bioklasty. Igły tworzyły nagromadzenia na dnie zbiornika w formie mat. Pomiędzy igłami występuje drobnoziarnisty materiał węglanowy, częściowo lub całkowicie skrzemionkowany (Fig. 10) oraz nieliczne fragmenty krynoidów i otwornice. Igły gąbek spojone są głównie cementem krzemionkowym wykształconym jako chalcedon lub blokowy mikrokwarc. Miejscami w obrębie kostkowych spikulitów występują romboedry kalcytowe (do 100 µm) (Fig. 11, 12).

Gąbki zasiedlały nachylone podmorskie skłony basenu (wewnętrzna rampa *sensu* Burchette & Wright, 1992), gdzie panowały warunki niskiej energii, tj. poniżej normalnej, a zapewne także sztormowej podstawy falowania. Całkowita dominacja bentosu przez gąbki była związana z dogodnymi warunkami troficznymi, stosunkowo niską energią środowiska i podwyższoną zawartością krzemionki w wodzie morskiej (Zimmerle, 1991; Rosales *et al.*, 1995; Maldonado *et al.*, 1999; Gammon *et al.*, 2000).

Wapienie krynoidowe przeławicające się z warstwami spikulitów stanowią istotną część badanych profili. Wapienie te są zbudowane głównie z fragmentów krynoidów, podrzędnie z kolców jeżowców, skorup ramienionogów i małży, otwornic, małżoraczków i peloidów oraz ekstraklastów dolomitów (Fig. 14, 15). W górę profili rośnie ilość ławic wapieni krynoidowych, przy równoczesnym wzroście ich miąższości (Fig. 3). W ławicach tych w górę badanych profili wzrasta konsekwentnie ilość ziarnitów krynoidowych.

Warstwowanie przekątne, laminacja pozioma, uziarnienie frakcjonalne normalne i zdecydowanie większe rozmiary bioklastów w wapieniach krynoidowych w porównaniu do spikulitów, a także nierówny, zapewne erozyjny charakter dolnych powierzchni ławic wskazują, że wapienie krynoidowe deponowane były w warunkach wyższej energii niż spikulity (Fig. 13, 15). Ten fakt w połączeniu z zupełnie innymi komponentami obu wydzielonych facji i autochtoniczną naturą spikulitów dowodzą, że ławice wapieni krynoidowych reprezentują tak zwane "*event beds*". Ławice te są zbudowane z materiału przytransportowanego z płytszych części basenu przez spływy grawitacyjne zapewne genetycznie związane ze sztormami. Cienkie horyzonty margli (1–3 mm) występujące ponad ławicami wapieni reprezentują najdrobniejszą frakcję spływów grawitacyjnych lub autochtoniczny osad pelagiczny. Depozycja wapieni krynoidowych zachodziła na głębokości, gdzie skłon zbiornika zasiedlany był przez gąbki.

Od dołu ku górze badanego kompleksu osadów zaznaczają się dwa wyraźne trendy. Pierwszy z nich wyraża się zastępowaniem Hexactinellida przez Demospongiae w górę badanego kompleksu osadów (Fig. 3). Stwierdzone zastępowanie można tłumaczyć postępującym spłycaniem badanego fragmentu basenu kriżniańskiego w trakcie depozycji spikulitów, które decydowało o zmianie warunków ekologicznych na dnie (por. Tabachnick, 1991; Leinfelder *et al.*, 1996; Krautter, 1997; Pisera, 1997). Drugi trend wyrażający się wzrostem miąższości ławic oraz wielkości ziarn w wapieniach krynoidowych w górę profili, również świadczy o spłycaniu basenu (por. Einsele, 1992).

Stwierdzone spłycanie jest zapisem zjawisk regionalnych, takich jak regresja w późnym domerze w Zachodniej Tetydzie (Graciansky *et al.*, 1998; Hallam, 2001), na które nałożyły się zjawiska lokalne spowodowane synsedymentacyjną tektoniką (Häusler *et al.*, 1993). Za pośredni przejaw tektonicznej aktywności w trakcie sedymentacji spikulitów można uznać stwierdzone w obrębie spikulitów osuwiska podmorskie (Fig. 5). Obecność ekstraklastów dolomitów w obrębie detrytusu krynoidowego, świadczy o odsłanianiu skał podłoża w obszarze położonym powyżej depozycji spikulitów, co także może być efektem tektonicznego przemodelowania niektórych fragmentów basenu kriżniańskiego. Różnice w ilości i miąższości ławic wapieni krynoidowych pomiędzy dwoma badanymi profilami są spowodowane zróżnicowaną geometrią dna basenu w trakcie depozycji tych osadów (por. Krajewski *et al.*, 2001).