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Lithology of the Upper Jurassic–Lower Cretaceous (Tithonian-Lower Berriasian) Aj-Petri reef complex (southern Ukraine, the Crimea Mountains)

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With 10 figures

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Abstract: The following paper presents a lithological characterization of Tithonian-Lower Berriasian limestones from the southern Crimea Mountains. Both the massive and bedded limestones forming the Aj-Petri reef-complex comprise four main lithofacies groups: stromatoporoid-microbial framestone-bindstone, bioclastic wackestone-floatstone, oncoidal packstone and oolitic and intraclastic grainstone-rudstone. Due to strong cementation, the specific lithofacies groups appear as macroscopically homogenic, massive Aj-Petri limestones. The rocks were deposited in shallow, subtidal and intertidal environments related to the shallowing sea level trends. The principal reef-builders were stromatoporoids (demosponges), microbialites and microencrusters, which produced numerous stromatoporoid-microbial patch-reefs and biostromes. These rocks, along with detrital sediments form the main part of the Aj-Petri reef. A dominance of stromatoporoid bioconstructions may reflect the restricted environmental conditions, which limited or even precluded the growth of other reef-building organisms, particularly the corals. Among the most important factors facilitating the vigorous growth of stromatoporoid bioconstructions in such environments could have been their high tolerance for changing depositional conditions resulting in dense packing of skeletons. Such packing, in turn, might have facilitated the intensive growth of microencrusters in the interskeletal spaces, particularly *Bacinella* and *Thaumatoporella*, enabling rapid lithification of the initial, stromatoporoidal reef frame supporting the development of a rigid framework, resistive to intensive erosion. During periods of more stable environmental conditions, intensive microbialites growth took place which enabled the binding of specific patch-reefs and peri-reefal deposits, resulting in the formation of the massive Aj-Petri limestone monolith as it appears today.

Key words: microbialites, microencrusters, stromatoporoids, reef facies, Upper Jurassic-Lower Cretaceous, Crimea Mountains.

1. Introduction

The development, stratigraphy and sedimentary environment of Upper Jurassic and Lower Cretaceous strata of the Crimea Mountains has had the attention of geologists since the 19th century, as shown by an abundance of mainly Russian literature. Nevertheless, stratigraphic position and development of Upper Jurassic sediments still raise numerous doubts and controversies. Until recently, most of the interpretations and conclusions have been based on rather outdated publications, usually containing poor illustrative material and lacking detailed site locations, precluding data revision and comparative studies. More

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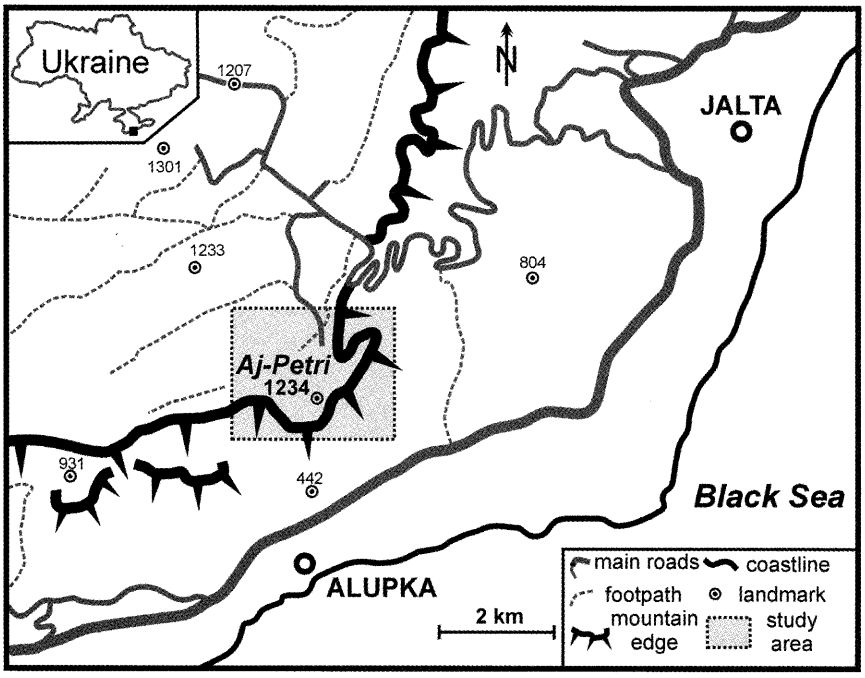

Fig. 1. Location of the study area.

recent publications provided only minor modifications or were compilations of previous concepts (e.g., LESHUKH et al. 1999). Recently published detailed studies revealed, in turn, new data pertaining to the development and stratigraphy of the Upper Jurassic and Lower Cretaceous rocks of the Crimea Mountains (e.g., GORBATCHIK & MOHAMAD 1997; MILEEV & BARABOSHKIN 1999; ARKAD'EV & ROGOV 2006; MILEEV et al. 2006; ARKAD'EV 2007; and references therein).

The main part of the Crimea Mts. is mostly composed of thick complexes of bedded limestones showing variable bed thicknesses, from finely laminated to thick-bedded. Thin-bedded, marly limestones are ubiquitous. Massive limestones facies of carbonate build-ups rarely occur within carbonates of the Crimea Mts. Such limestones usually form small, lens-like bodies, from a few to a dozen metres across, enclosed within bedded limestones. Larger complexes, a few tens to – exceptionally – a few hundreds of metres across, are rare. Notwithstanding their rare occurrence, the massive limestones are easy to identify among other rocks due to their increased resistance to erosion. The best known and most spectacular example is the Aj-Petri Mountain, the central part of which is composed of massive limestones laterally grading into bedded limestones (Figs. 1, 3).

The microfacies development and the origin of the massive limestones from the Crimea Mts. have been only occasionally studied in detail. A frequently quoted opinion relates these limestones to coral reefs (e.g., LESHUKH et al. 1999). The existing descriptions of the massive limestones are based mostly on examinations of exposures containing common corals. It is likely that assigning the carbonate buildups to coral structures results from the fact that corals belong to a few macroscopically well-recognizable components within a relatively homogeneous mass of strongly cemented limestones. Recent, detailed microfacies studies of massive limestones from the Aj-Petri Mountain allow us to conclude that the coral reef assumption is an oversimplified generic interpretation, which cannot be referred to all occurrences of massive limestones in the Crimea Mts. (KRAJEWSKI & OLSZEWSKA 2006, 2007).

The Aj-Petri massif is one of the largest and best exposed Upper Jurassic massive limestone complexes in the Crimea Mts. (Figs. 2-3). Besides corals, stromatoporoids (demosponges) usually associated with microencrusters and microbialites are common constituents (KRAJEWSKI & OLSZEWSKA 2006). The massive limestones together with detrital sediments compose the bulk of the massif's carbonate sediments. The occurrence and the environmental preferences of stromatoporoids have rarely been studied in details

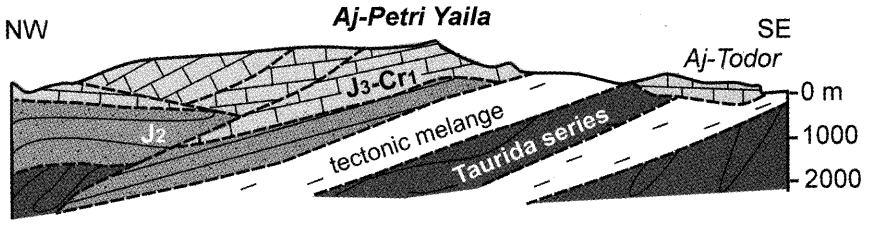

Fig. 2. Geological cross-section through the Aj-Petri Yaila; after YUDIN (2001), simplified.

despite their frequent appearance in Upper Jurassic strata (e.g., WOOD 1999; LEINFELDER et al. 2002, 2005 and references therein).

2. Geological setting

The Crimea Mountains are situated at the margin of the Scythian plate (e.g., NIKISHIN et al. 1998; YUDIN 1999, 2001; GOLONKA 2004). The mountains occupy the southern, maritime part of the Crimea Peninsula and form a narrow, roughly W-E-trending belt which extends over a distance of more than 150 km. The sub-Upper Jurassic bedrock shows a complicated structure, including a number of intrusive bodies, thrusts of chaotic complexes, faults, and tectonic melanges (NIKISHIN et al. 1998; YUDIN 1999, 2001; MILEEV et al. 2006; Fig. 2).

The bulk of the Crimea Mts. main ridge comprises an allochthonous complex composed of thrusts of Upper Jurassic and Lower Cretaceous rocks. This complex unconformably covers Late Triassic-Early Jurassic, folded flysch of the Tauride series (Fig. 2). The age of thrusts within the allochthonous series was determined as the end of the Early Cretaceous.

Rocks building the main part of the Crimea Mts. were deposited in a time interval from Callovian to Berriasian, although the stratigraphic sequence is sometimes disturbed due to complicated tectonic deformations (cf. MILEEV & BARABOSHKIN 1999) and in certain regions stratigraphic gaps occur. Deposition in the Crimea Mts. area proceeded in a back-arc basin, which became filled with shallow- to relatively deep-water marine sediments that were deposited close to the land, along the margins of an epicontinental basin bordering the Tethys Ocean from the north (GOLONKA 2004).

The Crimea Mts. are subdivided into several smaller massifs, the highest parts of which are karst plateaus (Yaila), up to 1,500 m a.s.l. Individual massifs, although adjacent, frequently represent tectonically isolated fragments of different morphology, lithology, and stratigraphic position of Upper Jurassic strata. The Aj-Petri-Yaila massif is composed mainly of Tithonian and Berriasian rocks (e.g., MILEEV & BARABOSHKIN 1999; KRAJEWSKI & OLSZEWSKA 2006, 2007; ARKAD'EV 2007).

3. Methods

Based upon reconnaissance observations and casual sampling run in various parts of the massif, five sites were selected for detailed descriptions and sampling (University collection, sections No. KA, KB, KC, KE, KR; Fig. 3). Due to inaccessible terrain, mountaineering techniques had to be occasionally applied. Classification of limestones was based upon macroscopic field examinations and laboratory microfacial analysis. Samples for microfacies studies were collected in spacings from dozens of centimeters to dozens of meters, depending on sediments variability. Such methods enabled identification of the main rock components and recognition of the large-scale sedimentary sequences, reflecting main trends in Aj-Petri reef depositional history. In some selected sites the sampling density allowed for more detailed analyses presented in the stromatoporoid-microbial patch-reef section.

4. Microfacies analysis

The KA and KB sequences exemplify the development of the central parts of massive limestones, whereas the KC, KR and KE sequences represent the marginal parts of the buildups, in the transition zone from massive to bedded limestones (Fig. 3). Although rather monotonous if examined macroscopically in the field, the Aj-Petri limestones reveal high diversity under the microscope. Several complexes were distin-

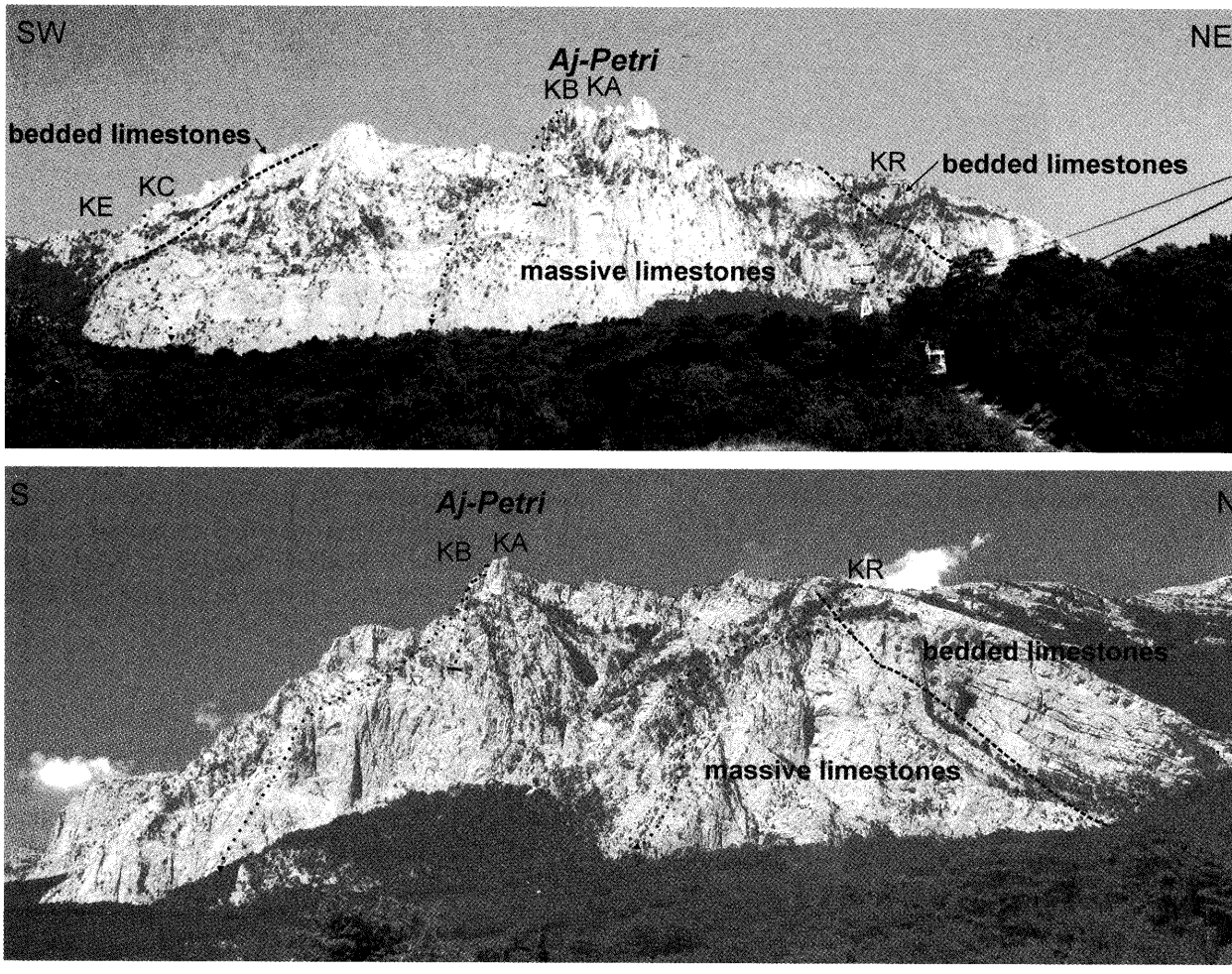

Fig. 3. Southern scarp of the Aj-Petri Mountain. The core of the mountain is formed by unbedded, massive limestones which grade into medium-bedded limestones. Five vertical sequences KA, KB, KC, KE and KR were sampled. Rock walls are up to 600 m high.

guished based upon dominance of particular microfacies (Figs. 4-5). Four main microfacies groups were distinguished:

I. Stromatoporoid-microbial framestone-bindstone (facies I). Main components are stromatoporoids, rarely corals, that together with microbialites and microencrusters, form small patch-reefs and biostroms. This facies is common in the KB sequence and in the lower part of the KR section.

II. Bioclastic wackestone and floatstone (facies II). Main components are various bioclasts, mainly fragments of stromatoporoids, corals, algae, bivalves and brachiopods. Microencrusters and microbialites are common, often showing fenestral structures. This group is most widespread in the Aj-Petri massif and was found in all studied sequences. Together with the stromatoporoid-microbial framestone-bindstone group (facies I) it composes the bulk of the Aj-Petri massive limestones.

III. Oncoidal packstone (facies III). Main components are various micrite-dominated and *Bacinella* oncoids, redeposited fragments of stromatoporoids and corals as well as foraminifers, algae and peloids. Common are microbialites, stabilizing the packstones. This group is most common in the KC, KB and KR sections.

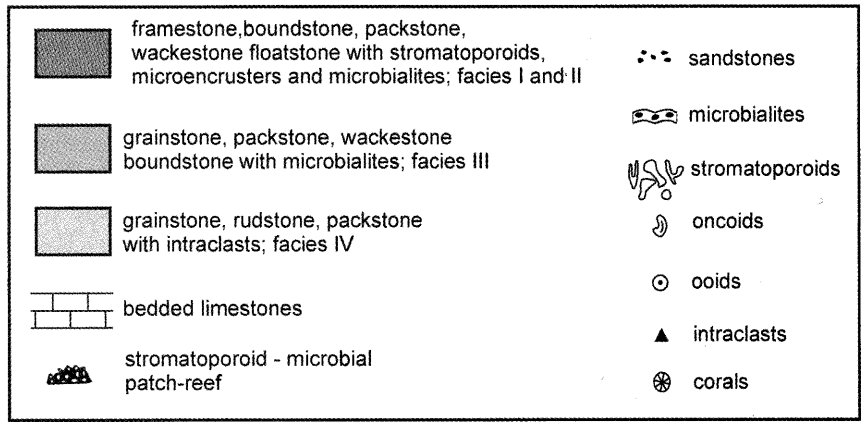

Fig. 4. Explanations for Fig. 5.

IV. Oolitic and intraclastic grainstone and rudstone (facies IV). Main components are intraclasts, ooliths, bioclasts (usually echinoderms, foraminifers and molluscs as well as algal fragments). This group occurs mostly in the KC and KB sections.

Specific complexes dominated by particular microfacies groups show variable thicknesses and successions. In these complexes, several lower-rank sedimentary sequences can be distinguished but their precise characterization cannot be accomplished without more detailed studies.

The central part of massive limestones represented by the KA and KB sequences are mostly lithologically and paleontologically diversified (Figs. 5-6, 9-10). In the whole sequences biolithites predominate over detritus. In the lower and middle parts most common are framestones-bindstones comprising stromatoporoids, microencrusters and microbialites (Figs. 5, 6f-h, 9-10) whereas in the uppermost parts wackestones, packstones and microbial bindstones prevail (Fig. 6a, b). Moreover, micro-frameworks formed by *Tubiphytes* or *Bacinella* (Fig. 6b) as well as wackestones and floatstones are frequent containing abundant fragments of stromatoporoids, corals and algae.

In the KA and KB sequences detrital limestones are commonplace, represented by packstones composed of various bioclasts and oncoids (Fig. 6a), especially *Bacinella*. Grainstones and rudstones containing bioclasts, intraclasts and ooids forming several oncolithic horizons (Fig. 6d) are rarer. Both the grainstones and packstones are often stabilized by microbial crusts (Fig. 6e). Moreover, borings are frequent, fenestral packstones-bindstones and sedimentary breaks (Fig. 6c, f). In the lower part of the KB sequence horizons of siliciclastic sandstones and sandy limestones were found (Fig. 5).

Microfacial development of strata from the KC sequence is mostly monotonous (Fig. 5). Detrital sediments, mainly packstones, grainstones, rarely rudstones composed of oncoids, ooids, intraclasts and various bioclasts are dominant (Fig. 7a, c, f). Microbial bindstones which cement the detrital sediments are common. *Bacinella* is an abundant component that usually forms large oncoids together with *Tubiphytes* which often build micro-frameworks (Fig. 7h). Similarly to the KB, in the lower parts of the sequence horizons of sandstones, sandy limestones and oncoliths were observed (Fig. 7b, c) whereas in the uppermost part of the sequence redeposited fragments of stromatopoids are abundant.

In the KR sequence facies, succession is similar to that observed in the KA and KB columns (Fig. 5). In the lower parts stromatoporoid-microbial framestone-bindstones forming small patch reefs and biostromes are ubiquitous whereas in the upper parts, in the transition zone to bedded limestones, facies are much less diversified. Wackestones and packstones composed of peloids and bioclasts (especially stromatoporoids, and corals, gastropods and algae) are more common (Fig. 8a-c). Rarer are microbial structures and microencrusters but mudstones with algae and gastropods are numerous.

Microfacial development of the KE sequence is also monotonous (Fig. 5). Bedded limestones are mostly packstones composed of oncoids and peloids as well as wackestones (Fig. 8e). Microbialites are common. In both the packstones and microbial bindstones the fenestral structures are typical components (Fig. 8f, h). Grainstones are often bound by microbial crusts. Gastropods and foraminifers are frequent whereas stromatoporoids and corals are absent. In significant portions of sediments, *Bacinella* is a principal component.

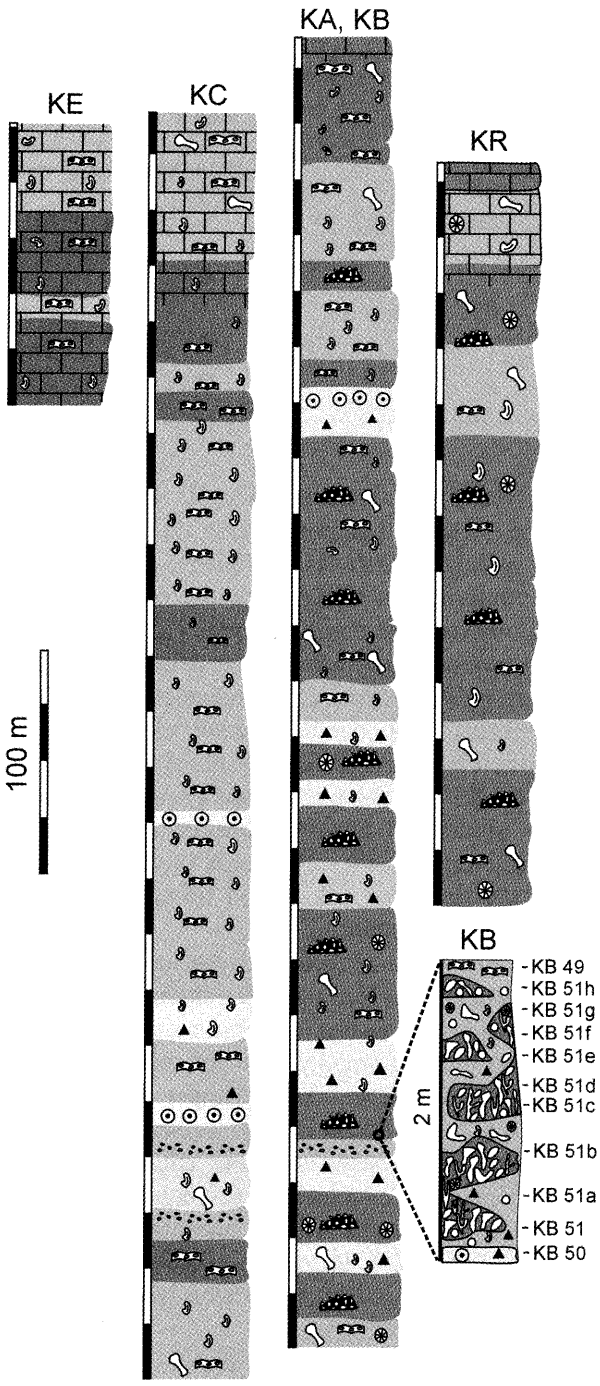

Fig 5. Lithological columns of the Aj-Petri massive and bedded limestones; for explanations see Fig. 4.

5. Characteristics of the main components

In both the massive and bedded limestones from the Aj-Petri massif abundant fossils were encountered: stromatoporoids, algae, corals, gastropods, bivalves, foraminifers and microbialites (Fig. 5-10). Most important components were described below. Of particular interest are biolithites produced by stromatoporoids (see the section Stromatoporoid – microbial patch-reefs).

Corals are relatively rare and were found *in situ* only in the KB sequence and as redeposited fragments in the KR one. These are represented by phaceloid forms of *Calamophylliopsis, Latomeandra, Stylosmilia* and *Microphyllia* (Fig. 6g, h). However, most of these fossils are completely recrystallized, preventing identification. Their morphology is underlined by microbial encrustations and microencrusters. In the studied sediments, corals usually co-exist with stromatoporoids forming small patch-reefs and biostromes (Figs. 6, 9- 10).

The common components of massive limestones are microencrusters (Krajewski & Olszewska 2005; Figs. 6-10). Dominating is the assemblage of *Lithocodium-Bacinella, Tubiphytes morronensis* and *Thaumatoporella*. Environmental preferences and spatial distribution of microencrusters have been studied in detail in recent years by Leinfelder et al. (1996), Schmid (1996), Dupraz & Strasser (1999), Shiraishi & Kano (2004) and others. In the Aj-Petri sediments, *Lithocodium* (Schmid & Leinfelder 1996) usually occurs directly upon the upper outer surfaces and rarely on the side surfaces of stromatoporoids and corals (Fig. 9a). *Lithocodium* is commonly observed on larger bioclasts (Fig. 7g), usually on bivalves and/or brachiopod shells. These forms show low thickness but large lateral exent, practically embracing the entire surfaces of macrofauna specimens. The chambers frequently contain the fora-

Fig. 6. Examples of microfacies from massive Aj-Petri limestones – sequences KB and KA. **a** – Oncoidal packstone-rudstone with *Lithocodium-Bacinella* assemblage; sample KA1a. **b** – Thrombolitic (T) bindstone grading upward to *Tubiphytes* (*Tb*) micro-framework; sample KB7e. **c** – Surface of depositional break with wackestone-packstone, microbial crust (arrow) and breccia (higher in the sequence); sample KB24a. **d** – Cortoid grainstone-rudstone; sample KB15a. **e** – Peri-reefal grainstone stabilized by microbial crust (arrow); sample KB3a. **f** – Bindstone with fenestral structures; sample KB20a. **g** – Coral framestone; in stromatoporoid-coral patch-reef; sample KB7a. **h** – Coral framestone; *Stylosmilia* in stromatoporoid-coral patch-reef; sample KB41a.

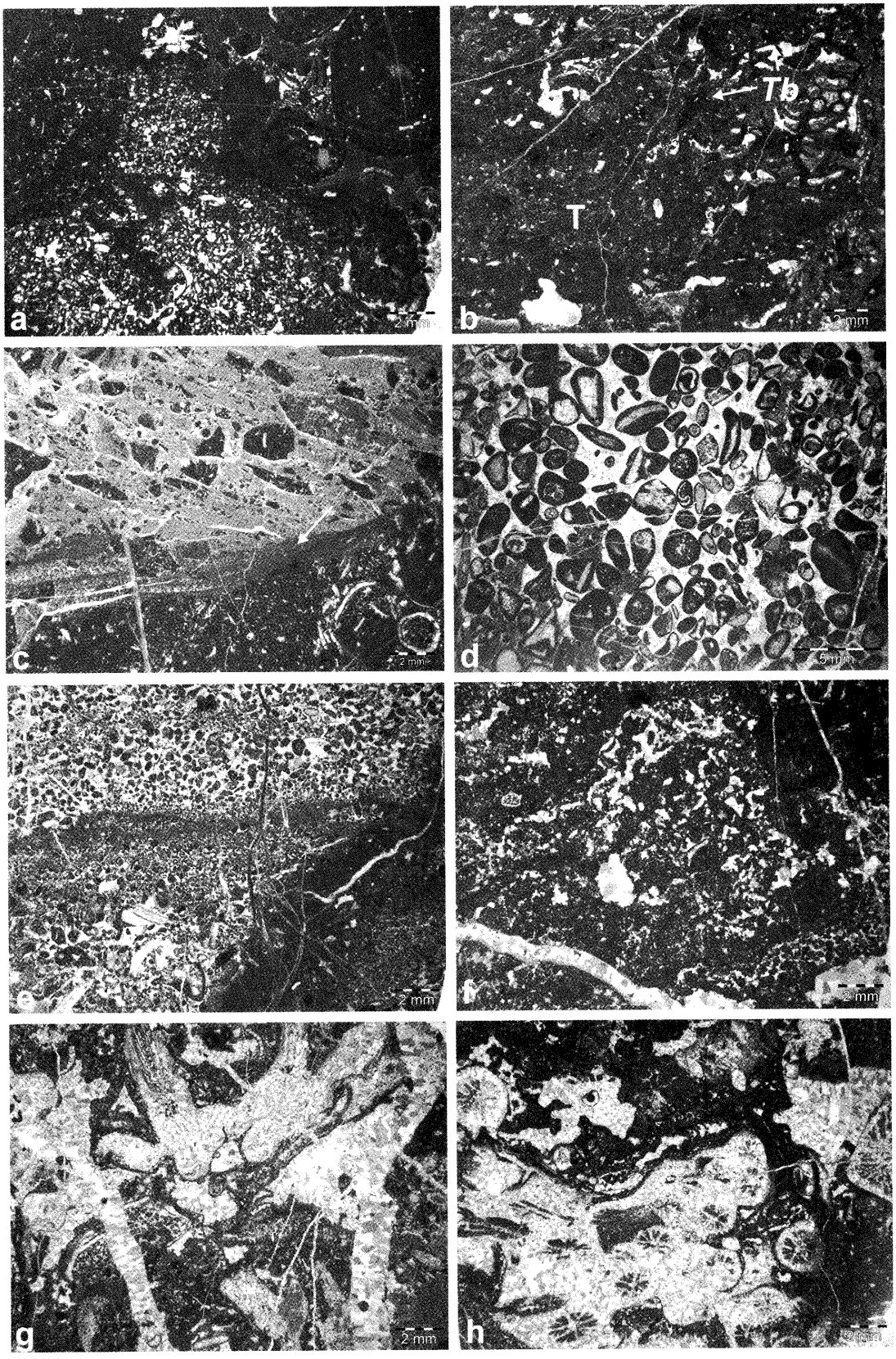

Fig. 6 (Legend see p. 244)

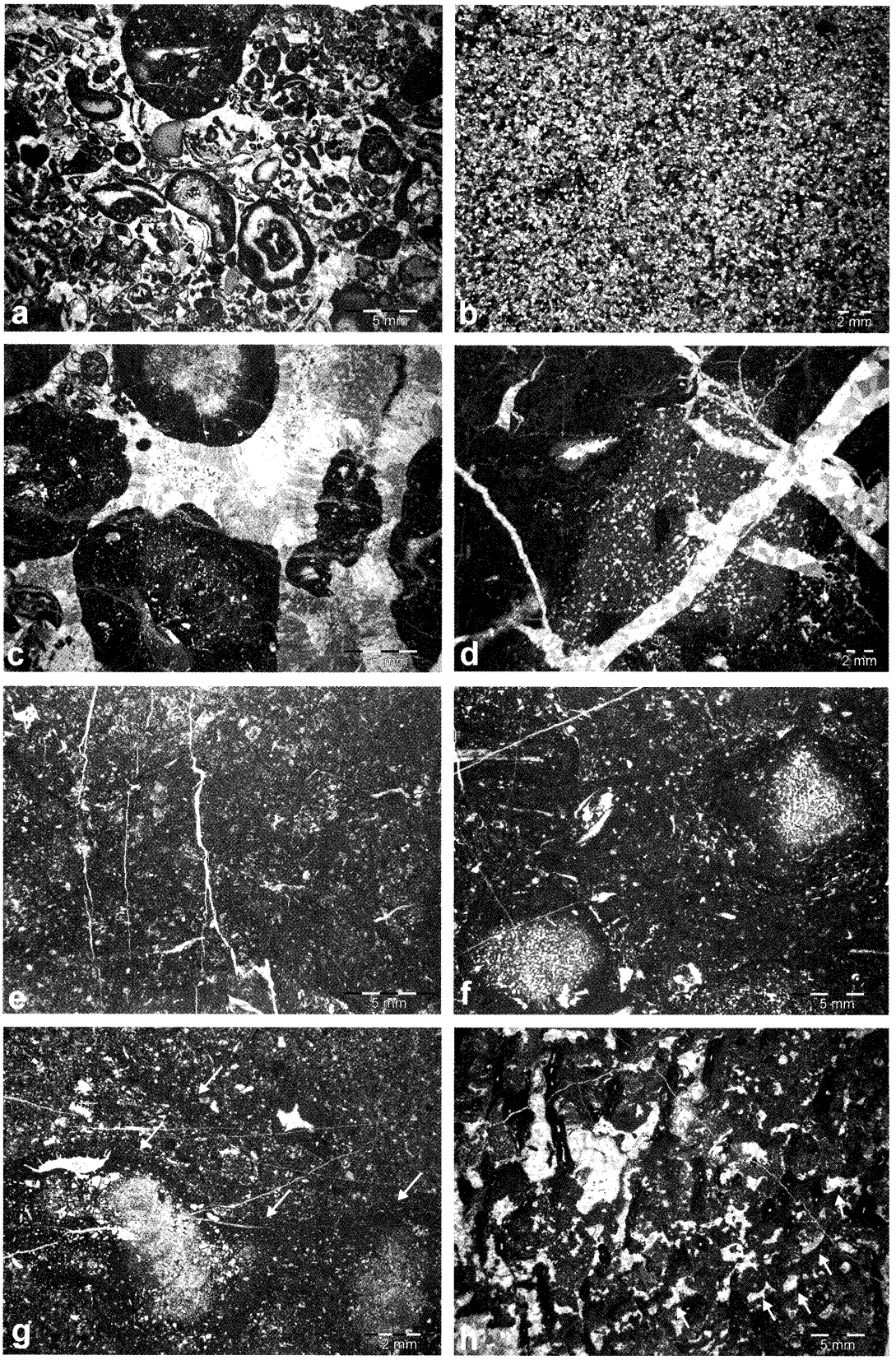

Fig. 7 (Legend see p. 247)

minifer *Troglotella*. Moreover, *Lithocodium* frequently builds dome-like forms embedded within detrital sediments, leading to their binding. Up to now, *Lithocodium* was observed in large numbers in the KA and KB sequences.

Among the microencrusters *Bacinella*, is the most abudant form. It was found in all sequences and in some portions it was one of the main components. The only exception is the bedded limestone from the uppermost part of the KR sequence where *Bacinella* is rather rare. In the KA and KB sequences, and in the lower part of the KR one *Bacinella* usually fills the interskeletal spaces in patch-reefs and biostromes (Figs. 9-10). In the sediments filling the depressions between the patch-reefs it forms *Bacinella* oncoids or fills intergranular spaces. In the KC and KF sequences, *Bacinella* mainly forms oncoids or fills the spaces in bioclasts.

Thaumatoporella is common in stromatoporoid patch-reefs encountered in the KA and KB sequences. In the KC sequence it was sporadically observed on displaced fragments of stromatoporoids. *Thaumatoporella* forms characteristic bonds between various framework components, contributing to cementation and stabilization of the rigid reef framework. Below *Thaumatoporella*, are open spaces partly filled geopetally or by *Bacinella* (Fig. 10c, e).

Tubiphytes morronensis is frequent in the KA, KB and KC sequences. In the KE sequence it is rare and absent in KR. In stromatoporoid-microbial patch-reefs *Tubiphytes morronensis* grows onto the skeleton surfaces or fills the interskeletal spaces (Fig. 10d). It is common in both the packstones and wackestones. In the KB and KC sequences sediments portions were observed exclusively composed of *Tubiphytes* forming the micro-framework (Figs. 6b, 7h). Spaces between *Tubiphytes* were filled with fine peloid packstone and microbialites. In micro-framework, geopetally filled cavities were common (Fig. 7h). Moreover, transitions were observed from thrombolitic bindstones to *Tubiphytes* micro-frameworks (Fig. 6b).

Microbialites commonly occur in the studied deposits as the main reef builders, showing different forms and playing a binding role. Thin microbial films were ubiquitous, developing directly upon stromatoporoids, corals or other skeletal elements for example bivalve or gastropod shells. One can also observe sediments in which macrofauna became dissolved and free spaces became partially or completely filled with blocky calcite cement. The morphology of dissolved fauna remains is preserved in the form of microbial encrustations that developed upon fauna and escaped degradation. Microbial encrustations and microencrusters frequently grade upwards and laterally into microbialites, usually representing peloidal and agglutinated thrombolites (cf. Schmid 1996; Figs. 6b, 7e). Microbial peloids are ubiquitous, whereas thrombolites usually form domes embracing the large parts of patch reefs and biostromes. Typically, thrombolites grade upwards and laterally into either peloidal wackestones or grainstones, or into another generation of stromatoporoids, initiating another sequence in the development of patch reefs and biostromes (Figs. 9a, 10a). In all the sequences, in the upper parts of sediments common features are peloidal microbialites and bindstones with fenestral structures (Figs. 6f, 8f, h).

Foraminifers are common fossils here (Krajewski & Olszewska 2006, 2007). The identified foraminiferal assemblage shows a relatively uniform species composition, including large, thick-shelled representatives of the Loftusiina sub-order of more or less labyrinthic interior (*Pseudocyclammina, Rectocyclammina, Everticyclammina, Neokilianina, Labyrinthina*). Other genera are also present characteristic of shallow-water carbonate environment: *Mohlerina, Nautiloculina, Protopeneroplis, Siphovalvulina, Subbdelloidina, Troglotella*, "trocholinids" and "textulariids".

Fig. 7. Examples of microfacies from massive, bedded Aj-Petri limestones – sequence KC. **a** – Grainstone-rudstone; reef debris; sample KC11a. **b** – Sandstone; sample KC12 a. **c** – Rudstone with *Bacinella* oncoids; isopachous cement seen in intergranular spaces; sample KC17b. **d** – Packstone with *Milleporidium*; sample KC42a. **e** – Thrombolitic bindstone; sample KC18b. **f** – Microbial bindstone with oncoids which cores are stromatoporoid and coral fragments; sample KC26a. **g** – Wackestone-bindstone; *Lithocodium* grows on bioclasts surface and on microbialites (arrows); sample KC14a. **h** – *Tubiphytes* micro-framework with numerous, geopetally filled cavities (arrows); spaces between *Tubiphytes* mostly filled with fine peloids, cements and rarely with microbialites; sample KC7b.

6. Stromatoporoid-microbial patch reef

One of the most important reef-builders of the Aj-Petri reef are stromatoporoids (demosponges). These are common in the lower and central parts of massive limestones (KB and KR sequences; Figs. 4-5) as stromatoporoid-microbial framestones-bindstones. In the upper portions of sequences stromatoporoids are rare.

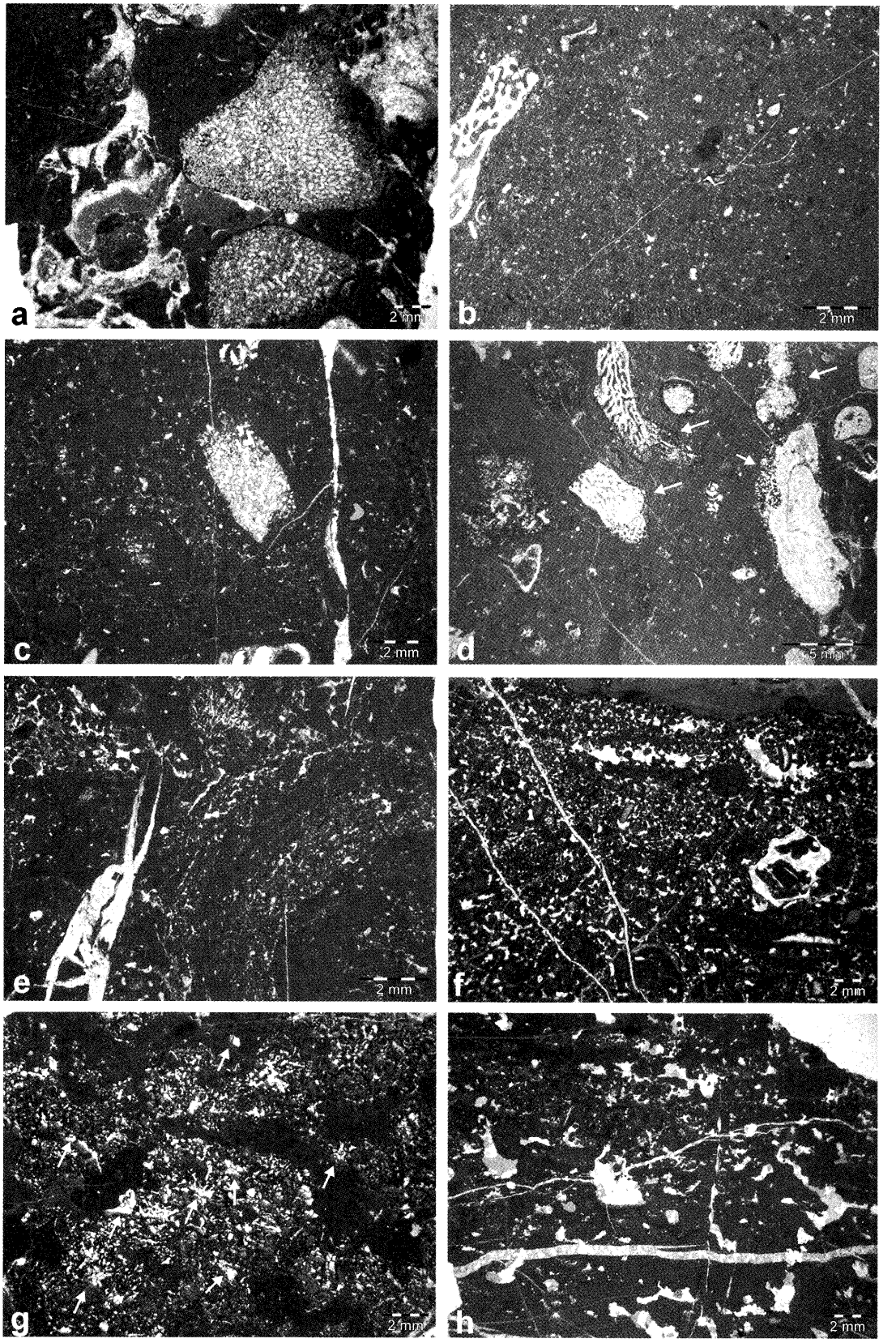

Fig. 8 (Legend see p. 249)

Stromatoporoids usually form numerous but small, monospecific patch-reefs and biostromes whose heights and widths rarely exceed 1 m. Stromatoporoids are mostly small, tightly packed forms, several centimeters across, with an internal structure that is often obliterated or poorly recognizable (Fig. 9a, b). Their skeletons show diversified morphology. Narrow forms of low diameters are frequent (up to about 0.3 cm) but about 10 cm high (Figs. 9b, 10h) and more massive, cylindrical forms up to 2 cm across (Figs. 9a, 10a). Moreover, quite common are branching or wine-glass forms. Preserved fragments of internal structure suggest that most of the skeletons originated from the same genus characterized by diversified morphology (Figs. 9-10). Under the microscope, some stromatoporoids morphologically resemble the branching corals that are also present in studied patch-reefs (Figs. 6g, h, 10g). Sometimes, stromatoporoids and corals are hardly discernible due to obliterated internal structure, although stromatoporoids are usually larger in size (Fig. 10g). In the abundant stromatoporoid assemblage the following species were identified: *Cladocoropsis mirabilis* Felix, *Milleporidium* sp., *Cyclicopsis verticalis* Turnšek and *Actinostromaria* sp., although *Cladocoropsis* was found only as re-deposited fragments in bedded limestones from the upper parts of the KR and KF sequences (Fig. 8a-d).

The patch-reefs were mostly built of tightly packed stromatoporoids in which the interskeletal spaces are filled with microencrusters and microbialites (Figs. 9-10). If the interskeletal spaces exceed several millimeters across, these were filled with bioclastic packstone (Figs. 9b, 10b, h).

The microencrusters are mostly *Lithocodium, Thaumatoporella, Tubiphytes*, and *Bacinella*. *Lithocodium* usually grows onto the upper surfaces of stromatoporoids skeletons (Figs. 9a, 10a), but these are small forms whose thicknesses rarely exceeding 1 mm. A more common microencruster is *Bacinella*. It usually tightly fills the interskeletal spaces in the central parts of patch-reefs (Figs. 9b, 10). One of the most important frame-building microencrusters is *Thaumatoporella* that forms characteristic binds connecting adjacent parts of stromatoporoid skeletons (Fig. 10c, e). A typical feature is the presence of numerous open spaces between *Thaumatoporella* specimens, mostly filled geopetally or by *Bacinella* (Fig. 10c). Also common is *Tubiphytes* which grows onto the stromatoporoid surfaces or in sediment that fills the interskeletal spaces (Fig. 10d). In marginal parts of the patch-reefs, microencrusters developed on the outer surfaces of skeletons grading into microbial structures, mostly thrombolites (Figs. 9a, 10a). These are the final components of patch-reef growth, which grades upward and laterally into peri-reefal deposits, usually wackestones, packstones or grainstones (Figs. 5, 9-10). Detrital components are dominated by peloids, oncoids, fragments of stromatoporoids, echinoderms, algae, foraminifers and small bioclasts. The peri-reefal deposits are commonly stabilized by microbial crusts and by *Bacinella*.

7. Conclusions

The rocks of the Aj-Petri reef complex reveal abundant and diversified microfacies assemblage contrasting their rather monotonous macroscopic view that results from strong cementation, from which one can conclude that limestones are quite uniform. Identification of the massive limestone's coral assemblage traditionally led to a conclusion that the Aj-Petri complex was a coral reef. However, the results of microfacies studies show that corals, although commonly observed, were not the dominating reef-builders (Krajewski & Olszewska 2005, 2006). In studied sequences, stromatoporoids and microbialites are more common, which appear to be the main builders of massive limestones.

Based upon the results of microfacies studies, it was concluded that all sediments forming the Aj-Petri reef complex and bedded limestones in its close neighbourhood were shallow-marine sediments deposited in subtidal and intertidal sedimentary environments. Apart from corals, algae and stromatoporoids,

Fig. 8. Examples of microfacies from the bedded Aj-Petri limestones – sequences KR and KF. **a** – floatstone with numerous fragments of *Milleporidium*; sample KR12a. **b** – Wackestone with fragment of *Caladocoropsis*; sample KR13a. **c** – Peloidal-oncoidal packstone with fragment of stromatoporoid; sample KR15a. **d** – Wackestone-floatstone with numerous fragments of *Caladocoropsis*; microencrusters (arrows) developed on the upper surfaces of fossil fragments; sample KED12a. **e** – Large oncoid in bindstone – packstone; sample KED3a. **f** – Peloidal bindstone with fenestral structures; sample KE1a. **g** – *Bacinella*; cavities commonly geopetally filled (arrows); sample KE7a. **h** – Mudstone grading upward into microbial mats; numerous fenestral structures; sample KE11b.

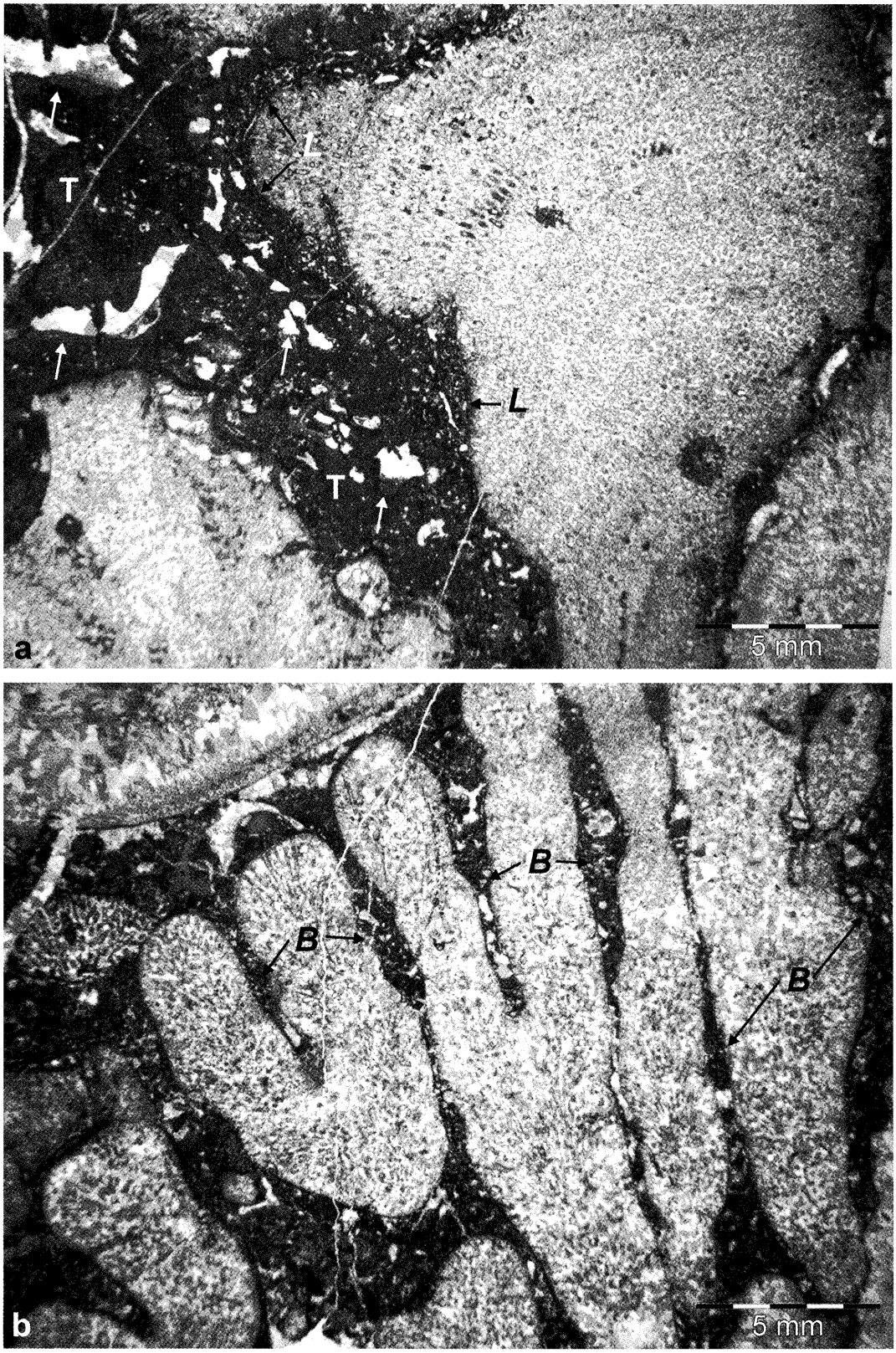

Fig. 9 (Legende s. p. 251)

the studied sequences contain several fossils typical of shallow-marine environment: *Lithocodium, Bacinella, Thaumatoporella* living under well-illuminated, oligotrophic conditions (LEINFELDER et al. 1996; SCHMID 1996; SHIRAISHI & KANO 2004, among others). The oolithic horizons point to the environments of shoals or tidal bars. Microbial bindstones with fenestral structures or sedimentary breccias are representative of an inter-tidal environment. At the initial stages of the Aj-Petri reef history, the temporary siliciclastics influx took place from the adjacent continent. Most of the sediments from the lower and middle parts of the studied KB and KR sequences are massive limestones deposited in the central reef which grade up the sequence into the back-reef facies. In the KC sequence, detrital sediments are more frequent, reflecting a higher-energy environment. The bedded limestones overlying or laterally replacing the massive varieties represent the transitional environment from back-reef to lagoonal and intertidal facies.

Considering the occurrence frequency of various microfacies, several limestone complexes were distinguished (Fig. 5), that can be attributed to particular depositional systems prevailing in particular sequences. Such complexes represent main development trends of the Aj-Petri reef. In most of these complexes, the lower-rank sequences can be distinguished. However, at the present stage of studies, these sequences are difficult to define due to applied field study methods reflecting the large size of exposure, hard access and similarities in macroscopic view of studied rocks.

The occurrence of several alternating horizons such as oncolithic, detrital, wackestones, microbial biolithites with common fenestral structures as well as stromatoporoid-microbial patch-reefs and biostromes reflect the shallowing trend of the see level. In the shallow, subtidal environments even insignificant bathymetric changes may result in substantial modification of depositional conditions (DUPRAZ & STRASSER 1999), as exemplified by complex structure of the Aj-Petri reefs. Due to the diversified paleomorphology of the reef, sediments representing various environments occur at the same elevation levels of the reef complex. Moreover, sedimentary breaks, borings and sedimentary breccias, indicate numerous periods of ceased deposition and periodical dominance of erosion (Fig. 6c). The oncolithic horizons and other grainstone-rudstone sediments were usually the first in a row of consecutive, short-term sedimentary sequences. Gradation from detrital sediments to wackestones may reflect the deepening of depositional environment. Rising sea-level provided the accommodation space, which, under the oligotrophic conditions, have facilitated the intensive growth of stromatoporoids, making them a principal component of the Aj-Petri reef. The upper parts of the studied sequences are dominated by *Bacinella* oncoids, intraclasts, oolithic grainstones-rudstones and intertidal fenestral bindstones-mudstones, which are all evidence of sea level lowering.

In the development of the Aj-Petrii reef complex an important role was played by numerous although small stromatoporoid-microbial patch-reefs. Their common occurrence points out to the presence of conditions favouring such bioconstructions during the most time of the reef growth. The first phase of patch-reef development started due to colonization of hard components, e.g., bioclasts providing a solid foundation for buildups. The rising sea level brought accommodation space and oligotrophic conditions facilitating the development of shallow, subtidal bioconstructions. Succession in the growth of stromatoporoid patch-reefs (similarly to coral patch-reefs; cf. OLIVIER et al. 2005; HELM & SCHÜLKE 2006) illustrates the characteristic inhabitation stages, mostly by microencrusters. Their growth and succession were strongly controlled by gradual development of the reef and limitation of reef cavites, resulting in reduction of light access and affected later water circulation and oxygenation.

Dominance of tightly packed stromatoporoids promoted the intensive growth of microencrusters in the interskeletal spaces and contributed to binding and stabilization of skeletons. Thus, skeletons remained undestructed and undisplaced. If the interskeletal

Fig. 9. Examples of stromatoporoid – microbial patch-reefs from the massive Aj-Petri limestones. **a** – Stromatoporoid – microbial framestone. Successive development stages of the patch-reef are visible together with *Lithocodium* (*L*) growing upon the surfaces of skeletons. Interskeletal spaces are filled with thrombolite (T) with geopetal material in cavities (arrows); sample KB 12a. **b** – Stromatoporoid framestone. Tightly packed, branching stromatoporoids; interskeletal spaces are filled mostly by detritus and *Bacinella* (*B*); sample KB 51j.

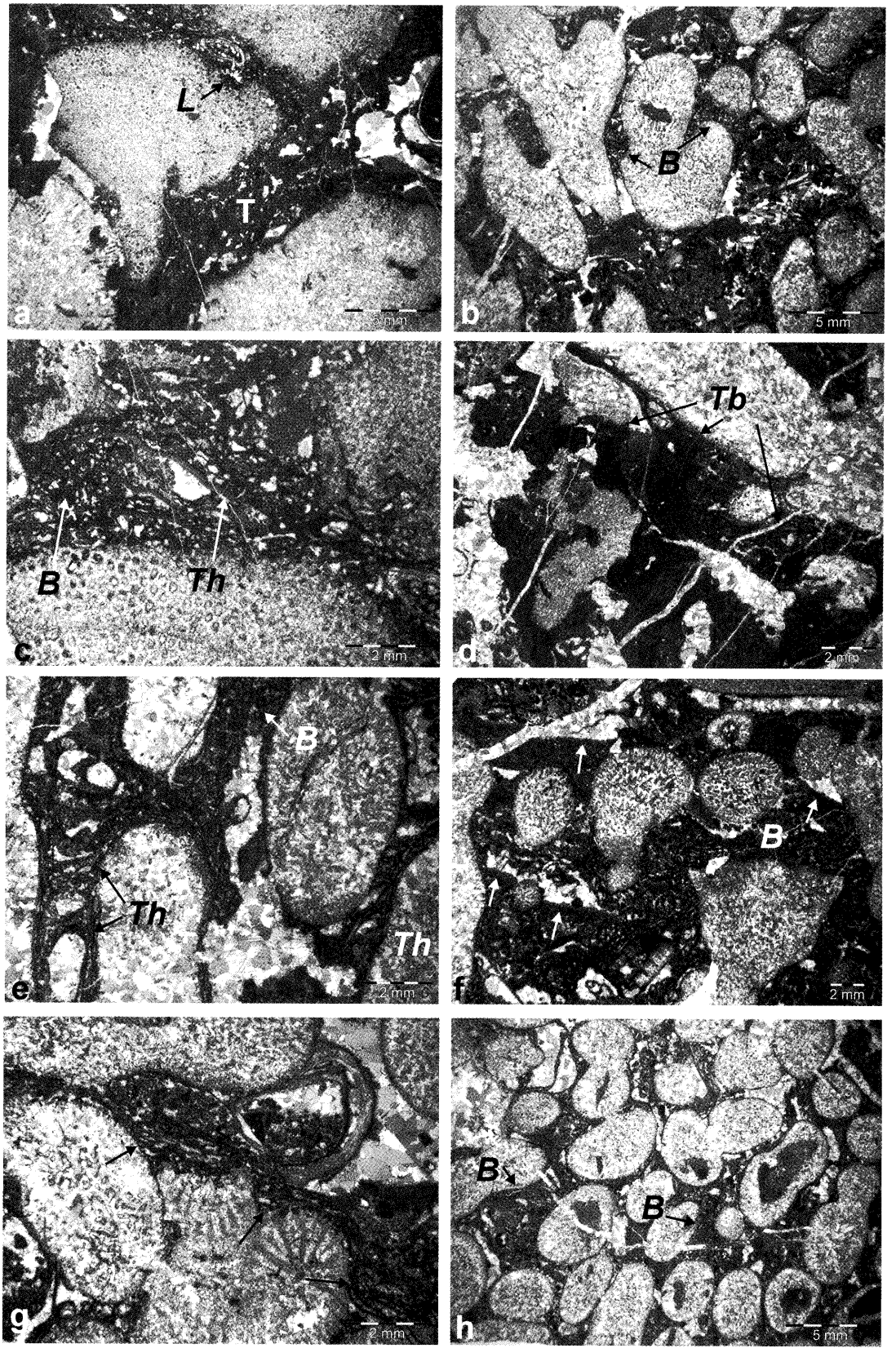

Fig. 10 (Legend see p. 253)

spaces exceeded several millimeters, these were usually filled with detrital sediment working as framework stabilizers. If the stromatoporoid skeletons were not densely packed, these were typically destroyed and displaced. Taking into account the high regeneration abilities of stromatoporoids, such redeposited skeletons might have participated in the expansion of organisms and ensured the growth of new stromatoporoid patch-reefs.

Two scenarios of stromatoporoid patch-reef development can be distinguished, both demonstrating a high tolerance of organisms for changing environmental conditions (cf. LEINFELDER et al. 2005). The first scenario involves the growth of metazoans and pioneer settlers such as *Lithocodium* inhabitating the upper surfaces and *Thaumatoporella* living in interskeletal spaces, under oligotrophic conditions and at low deposition rates. This was followed by a filling the interskeletal spaces by *Bacinella, Tubiphytes* and thrombolites under more mesotrophic conditions. At the final stage, most parts of the patch-reefs were entirely covered with microbialite.

The second scenario indicates an environment with an increased supply of detrital material. The interskeletal spaces were dominated by detrital sediments whereas microencrusters were rare. Detrital sediments were gradually baffled in the interskeletal spaces, thus contributing to stabilization of framework. In fact, both scenarios are commonly observed to operate within the same buildup, which may indicate growth of buildups during unstable, commonly changing depositional conditions. Development of microencrusters took place where supply of detrital material to the patch-reef was limited.

As with coral reefs, an important factor was stromatoporoids skeletons morphology (cf. HELM & SCHÜLKE 2006). Subtle differences in morphology of skeletons were observed for two scenarios; In the first one, the more massive forms of larger diameters prevail (Fig. 9a) whereas, in the second scenario, more elongated forms predominate (Fig. 9b).This may suggest that skeleton morphology of the same taxa was modified as a response to environmental changes.

8. Remarks on the genesis of the Aj-Petri reef complex

In conclusion, it is worth having in mind that massive reef limestones are relatively rare in the Crimean Mountains. Their development, origin and paleogeographic position are still poorly known. Bedded facies are dominant, comprising sediments laid down in environments from shallow to relatively deep-water. The origin of the Aj-Petri reef complex is difficult to explain due to the allochthonous structure of the Crimean Mts. However, the presence of such a large reef complex, a geological rarity in the Crimean Mts., inevitably raises the genetic discussion. Considering both the complicated structure and still controversial geological history of the Crimean Mts., various concepts can be discussed. Facies diversity of carbonate platforms usually results from various factors including the syndepositional tectonics and/or the basement structure (MATYSZKIEWICZ et al. 2006a, b). At the present stage of studies, the paleogeographic position of the Aj-Petri reef complex in the Late Jurassic and the Early Cretaceous cannot be determined beyond doubt. Some suggestions can be provided by the results of studies on the East Black Sea Basin between the Crimean Peninsula and the Caucasus Mountains, in the area of the northern Shatsky Swell (AFANASENKOV et al. 2005). Based on seismic data, comparative studies with the adjacent areas where drilling was completed and data from the Caucasus, two types of Upper Jurassic structures were

Fig. 10. Examples of stromatoporoid – microbial patch-reefs from the Aj-Petri massive limestones. **a** – Stromatoporoid – microbial framestone; numerous stromatoporoid skeletons with *Lithocodium* (*L*) growing on the surfaces. Interskeletal spaces filled mostly with thrombolite (T) with geopetal material in cavities; sample KB21a. **b** – Framestone-bafflestone. Numerous tightly packed stromatoporoid are visible, interskeletal spaces are filled with *Bacinella* (*B*) or peloidal packstone; sample KB51c. **c** – Framestone; interskeletal spaces filled with *Thaumatoporella*, free spaces between *Thaumatoporella* (*Th*) are filled with *Bacinella* (*B*) – arrows; sample KB21c. **d** – Framestone; *Tubiphytes* (*Tb*) seen in interskeletal spaces; sample KB38j. **e** – Framestone; numerous specimens of *Thaumatoporella* (*Th*) bind skeletons and *Bacinella* (*B*) tightly fills the interskeletal spaces; sample KB37a. **f** – Framestone; numerous growth caverns filled geopetally (arrows); interskeletal spaces filled with bioclastic packstone or *Bacinella* (*B*); sample KB51d. **g** – Stromatoporoid-coral biostrome; displaced skeleton fragments binded by microencrusters (arrows); sample KB51x. **h** – framestone-bafflestone; larger interskeletal spaces filled mostly with detritus, common *Bacinella* (*B*) grows onto the skeleton surfaces or fills narrow interskeletal spaces; transversal section; sample KB51g.

distinguished: the Yuzhnyi Adler shelf carbonate platform and the system of isolated carbonate buildups developing towards the Crimean Peninsula separated by a depression filled with younger deposits (AFANASENKOV et al. 2005). Growth of these buildups is related to a Callovian rifting phase, known from both the South Crimea and the Caucasus regions. This rifting, divided the Jurassic sea bottom into several tectonic blocks composed of pre-Callovian rocks. On such elevations, the isolated reef complexes have started to grow. Their sizes are similar to that of the Aj-Petri reef. It cannot be precluded that the Aj-Petri reef belongs to this system or that it represents a similar system built at the NW extension of that block. The appearance of siliciclastic sediments in the lower part of the Aj-Petri complex points out that, initially, the reef sediments might have been deposited at the margin of a land, which, similarly to the Shatsky Swell, may have been an isolated tectonic block composed of pre-Callovian rocks. At the initial stage of development, the block was a source area for siliciclastic deposition. With the rising sea-level, the land was submerged and the elevation provided surface for the intensive growth of a reef complex. At the end of the Early Cretaceous, the movement of crustal plates resulted in the displacement of the Aj-Petri massif and formation of the recent Crimean Mts.

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