



Crescentiella-microbial-cement microframeworks in the Upper Jurassic reefs of the Crimean Peninsula

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Abstract

In the Upper Jurassic reef successions of the Crimean Peninsula (Sudak and Jalta areas), the microencruster *Crescentiella morronensis* (Crescenti), microbialites, and multiple generations of cements, form microframeworks. They were observed in two stages of the carbonate platform evolution, in the Middle–Upper Oxfordian, and in the Upper Kimmeridgian–Tithonian. Generally, in both stages, the features of the microframeworks are similar and consist of densely packed *Crescentiella* associated with microbialites and branched colonies of the sclerosponge *Neuropora lusitanica* Termier. The difference between the occurrences of the two stages is the variable amount of nubecularid foraminifera and enigmatic tube-shaped structures forming the central cavities of *Crescentiella*. The *Crescentiella*-microbial-cement microframeworks formed under phreatic conditions in the upper slope and seaward marginal depositional settings where intensive syndepositional cementation took place. They formed in the initial stages of long cycles of restoration and blooming of the reefs. The late Jurassic examples resemble the Permian algae-microbial-cement reefs as well as the Triassic *Tubiphytes* and cement crust-dominated reefs. Concurrently, all these examples formed a transitional facies zone between typical slope facies to shallow subtidal platform margin facies characterized by high taxonomic diversity of calcified sponges, corals, and microencrusters forming the principal part of the reefs.

Keywords Microencrusters · *Crescentiella* · Microbialites · Cement crusts · Reefs · Late Jurassic · Crimea

Introduction

In the Tethyan realm and its margins, the Late Jurassic was a time of intensive growth of reefs. The North Tethys/Atlantic reefs that developed on extensive ramp-type platforms can be assigned to three broad compositional types: (1) coral-dominated, (2) siliceous sponge-dominated, and (3) microbialite-dominated (e.g., Leinfelder et al. 2002). In contrast hereto, the isolated reefs growing at the margins of intra-Tethyan platforms were dominated mostly by mixed, corals-calcified sponges (including stromatoporoids and chaetetids) facies (e.g., Turnšek et al. 1981; Leinfelder et al. 2002, 2005; Vlahović et al. 2005; Ivanova et al. 2008; Rusciadelli et al. 2011; Della Porta et al. 2013; Hoffmann et al. 2017). Their

characteristic lateral assemblages allow the zonation of these reef complexes, corresponding to fore-reef, reef crest, and flat to back-reef environments.

Unlike other Upper Jurassic reefs from both western and southern Europe, which have deserved a number of detailed studies, the reefs from the Crimea-Caucasus region have received less attention, as yet. Most of the studies were mainly descriptive, whereas detailed data were rarely published. For the Southern Crimea, Nikishin et al. (2015a, b) presented a ternary plot showing the Late Jurassic reef-building communities of Crimean reefs based upon data from, among others, the Ai-Petri Massif (Krajewski 2008, 2010). The main reef-builders were microbial mats/microencrusters, corals and sponges, which correspond to assemblages known from the Caucasus Mts. (e.g., Bendukidze 1982; Guo et al. 2011). In the Crimea Mts, the most spectacular Oxfordian coral reefs are reported from the Sudak area (e.g., Muratov 1973; Geister et al. 2007; Nikishin et al. 2015b) although detailed studies on their facies and microfacies have so far not been published. A few papers with details concerning Upper Jurassic reefs were published from

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the Demerdzhi Plateau (Piskunov et al. 2012; Rud'ko et al. 2014, 2017), the Mt. Pakhkal-Kaya (Baraboshkin and Piskunov 2010) as well as the Jalta and the Ai-Petri massifs (Krajewski and Olszewska 2006; Krajewski 2008, 2010; Bucur et al. 2014; Schlagintweit and Krajewski 2015). These publications describe several Upper Kimmeridgian–Berriasian Štramberk-type shallow-water facies and microfacies documenting the development of Crimean carbonate platform.

In recent papers dealing with both the Tethyan northern shelf and the intra-Tethyan platforms, still-growing attention is paid to the presence and the role of a wide spectrum of so-called “microencrusters” (e.g., *Crescentiella*, bacinellid fabrics, *Thaumatoporella*, *Radiomura*, *Lithocodium*, *Iberopora*, etc., e.g., Schmid 1996; Leinfelder et al. 1996; Ivanova et al. 2008; Pleş et al. 2013, 2017; Kaya and Altiner 2015; Hoffmann et al. 2017) in the formation of reef frameworks. Apart from microbial crusts, these microencrusters were important components of coral and sponge reefs as secondary reef-builders. Sometimes they form microbial-microencruster boundstones with a significant content of early cements. Late Jurassic to earliest Cretaceous microbial-microencruster-cement-boundstones (microframeworks) assigned to outer margin-upper slope depositional settings have been reported from various intra-Tethyan (mostly southern Tethyan) platform carbonates: Austria (Schlagintweit and Gawlick 2008, Plassen Limestone), Bulgaria, Czech Republic and Poland (Ivanova et al. 2008; Hoffmann et al. 2017, Štramberk-type Limestone), Romania (Pleş et al. 2013, 2017), Italy (Rusciadelli et al. 2011, e.g., Table 1, *Ellipsactinia* Limestone), Turkey (Kaya and Altiner 2015) and Japan (Shiraishi and Kano 2004; Ohga et al. 2013, Torinosu Limestone). For a paleogeographic sketch displaying these occurrences in the western part of the Tethys see Fig. 11 in Kaya and Altiner (2015). In terms of microfacies and micro-/macrobiota assemblages, they differ from time-equivalent ramp deposits of the European northern Tethyan margin (see Leinfelder et al. 1994, 2002).

A common and widespread taxon of microencruster inhabiting the Upper Jurassic–Lower Cretaceous platforms is *Crescentiella* (former *Tubiphytes*) *morroneis* (Crescenti 1969) (Senowbari-Daryan et al. 2008, for details). It represents an enigmatic microorganism of controversial systematic position (e.g., Flügel 1981; Schmid 1995; Senowbari-Daryan et al. 2008; Kaya and Altiner 2015; Pleş et al. 2017) interpreted as encrustation or symbiosis between nubecularid foraminifera or enigmatic, spar-filled, tube-shaped structures and cyanobacteria where foraminifera, tubes and/or other biogenic components provide a substrate for the growth of microbialites.

A significant share of *Crescentiella* in the formation of reefs, besides the typical reef-builders, was noticed by, e.g., Schlagintweit and Gawlick (2008) who proposed a new type of Upper Jurassic reefs (or part of the reefs) dominated by

microencrusters-cement microframeworks, based upon data from the Northern Calcareous Alps of Austria. Less common is the pure dominance of *Crescentiella*, which is the case described and discussed in the present paper. It must be emphasized that a significant contribution of *Crescentiella* in microframework building was described also from the Tethyan northern shelf (Germany, southern Poland), where Oxfordian microbial-*Crescentiella* boundstone facies (*Tubiphytes* reefs) occurs (e.g., Pomoni-Papaioannou et al. 1989; Leinfelder et al. 1994; Matyszkiewicz 1997; Krajewski et al. 2016). For example, in southern Poland, such facies was found on the slopes of grabens active in Late Jurassic times, where the marine cements common in microbial-*Crescentiella* boundstones were accompanied by similarly abundant, stromatolite-like cavities (Matyszkiewicz 1997; Olchoway 2011; Matyszkiewicz et al. 2012; Krajewski et al. 2016).

In the Upper Jurassic reef successions of the Crimean Peninsula, reef facies were observed where *Crescentiella*, microbial crusts and cements were prevailing components thereby forming microframeworks. Such structures have so far not been described in detail from the Crimea-Caucasus region. Hence, the following paper aims to characterize such microframework based on data from two typical occurrences of Late Jurassic reefs in the Crimea. Furthermore, the position and the role of these Upper Jurassic microframeworks in the reef formation will be discussed.

Location and geological setting

The study area is located along the southwestern shoreline of the Crimean Peninsula, in the Sudak and the Jalta areas (Fig. 1). The core of the Crimea Mts. is formed by sedimentary rocks ranging from Triassic to Lower Cretaceous in age (e.g., Muratov 1973; Mileev et al. 2006; Krajewski and Olszewska 2007; Nikishin et al. 2015a, b; Arkadiev et al. 2018). Both the age and the evolution of particular tectonic units however still remain controversial (Mileev et al. 2006; Yudin et al. 2015; Oszczytko et al. 2017). According to Nikishin et al. (2015b), these sedimentary rocks represent three major mega-sequences: (a) Triassic–Early Jurassic; (b) Aalenian–Bathonian; and (c) Callovian–Berriasian. The latter mega-sequence includes three tectonic units: (1) the Southern Crimean Shelf Basin, (2) the Sudak Deepwater Trough, and (3) the Alchak-Kaya Shelf Basin at the northern margin of the Shatsky Ridge. These authors divide the Southern Crimean Shelf Basin into a Callovian–Oxfordian syn-rift sequence (Sudak Series) and a Kimmeridgian–Berriasian post-rift succession (Yaila Series) (Nikishin et al. 2015b).

The field studies were run in the two regions of Upper Jurassic reefs occurrences: in the vicinity of Sudak town where Upper Jurassic deposits belong to the Sudak Series

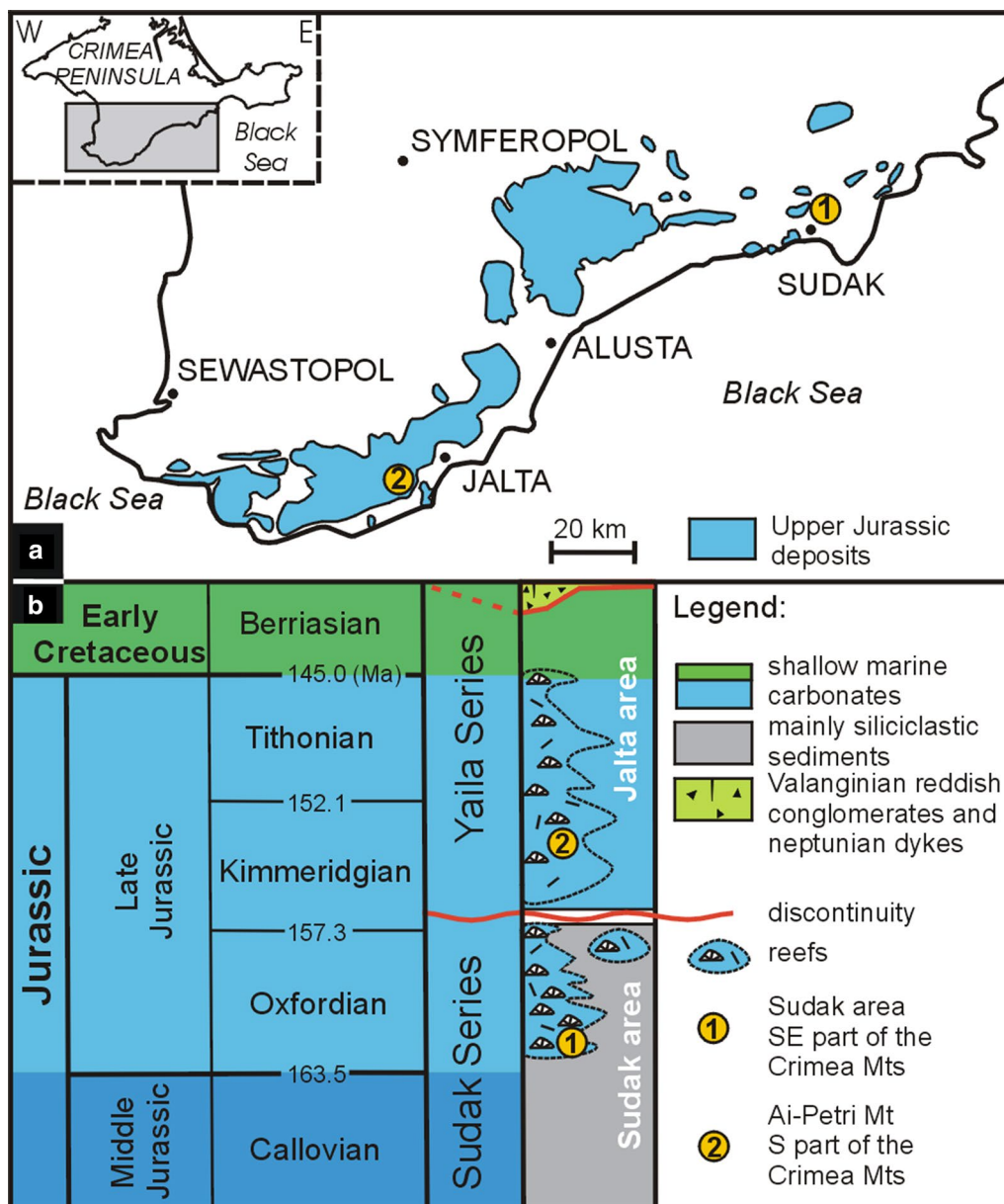


Fig. 1 a Location map of the study areas. b General Jurassic lithostratigraphy of the Crimean Mountains with position of the studied reefs (SudaK and Jalta area). Modified from Mileev et al. (2006) and Krajewski (2010)

and in the vicinity of Jalta town where the Ai-Petri Massif is built of sedimentary rocks of the Yaila Series (Fig. 1). According to Nikishin et al. (2015b), the reefs observed in the SudaK region represent a fragment of the Upper Oxfordian reef belt extending along the northern margin of the Shatsky Ridge carbonate platform. These reefs are regarded as close analogues to the Late Jurassic reefs found in the Shatsky Ridge (Afanasenkov et al. 2005; Guo et al. 2011). The Ai-Petri Massif is a spectacular example of the Late Kimmeridgian–Tithonian reef complex (Krajewski and Olszewska 2006, 2007) resembling the Štramberg-type

reefs well known from the Pontides, Moesia, Southern Carpathian, Polish and Czech Outer Carpathian, Southern Crimea and the Northern Caucasus Mts (e.g., Matyszkiewicz and Słomka 2004; Bucur and Sășăran 2005; Ivanova et al. 2008; Guo et al. 2011; Piskunov et al. 2012; Pleş et al. 2013; Kaya and Altiner 2015; Kołodziej 2015; Strzeboński et al. 2017; Hoffmann et al. 2017; Vincent et al. 2018). The main part of the Late Jurassic successions from the Crimean Mts. was deposited onto the marginal part of the epicontinental basin, which rimmed the northern margin of the Tethys Ocean (Golonka 2004; Nikishin et al. 2015a).

Materials and methods

The rock samples were collected in the years 2005–2012. The outcropping massifs have generally very steep to vertical walls, which hamper facies mapping (Fig. 2). Sometimes the structures of the reefs are poorly visible due to their massive character as a result of strong cementation. In both the Sudak and the Jalta areas, samples of microframeworks

with *Crescentiella* originated from both the lower and rarely the central parts of the reef complexes. In the upper part of the reef successions, *Crescentiella* is less common, patchily distributed and does not form any microframeworks. In the Sudak area, observations were made in the following localities: the Koba-Kaya Mts., (N44°49'22"; E34°55'00"; Fig. 2a), the Sokol Mts. (N44°50'05"; E34°55'29"), and in a quarry located close to Dachnoye village (N44°53'04"; E34°57'13"). In the Jalta area, studies were carried out in the steep part of

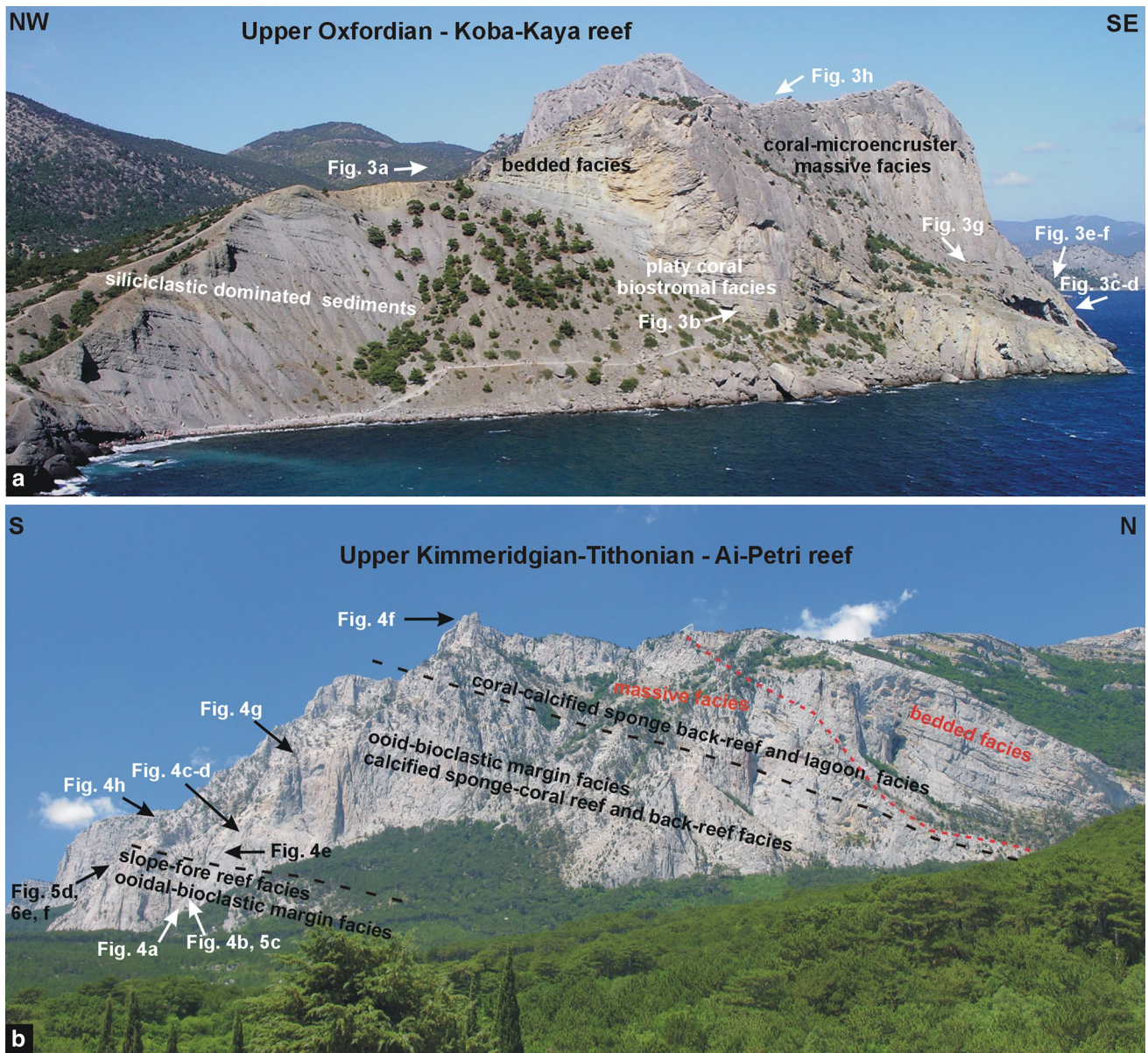


Fig. 2 Examples of the Upper Jurassic reefs of Crimea. *Arrows* indicate the approximate position of examples presented in Figs. 3, 4, 5, 6, 7. **a** Sudak area (Novyi Svet); Upper Oxfordian Koba-Kaya Mts (altitude: 165 m) reef, which is mainly composed of platy coral facies and coral-microencruster facies; laterally massive facies pass into bedded facies and siliciclastic-dominated sediments. Rock walls are

up to 140 m high. **b** Jalta area; Upper Kimmeridgian–Tithonian Ai-Petri Mts (altitude: 1234 m), which are mainly composed of calcified sponge-coral, ooidal-bioclasic and coral-calcified sponge facies; the general trend in reef succession has been marked. For detailed logs see Krajewski (2008, 2010). Rock walls are up to 600 m high

the Ai-Petri Massif (N44°26'33"; E34°02'58"; KB, KC sections in Krajewski 2008; Bucur et al. 2014; Fig. 2b).

The main research method was macroscopic observations, microfacies analysis and cathodoluminescence (CL) microscopy. CL observations were carried out using a cold-stage cathodoluminescence microscope CLmk3 A of CIT Ltd., coupled to the Nikon Eclipse 50 T. The accelerating voltage was 15–17 kV and the electron-beam intensity 450–500 μ A. Earlier field studies regarding full reef succession enabled the first author to collect 1047 representative samples for microfacies (e.g., Krajewski and Olszewska 2006; Krajewski 2008, 2010; Bucur et al. 2014). The thin sections marked with numbers indicated in Figs. 3, 4, 5, 6 and 7 are stored at the Faculty of Geology, Geophysics and Environment Protection, AGH University of Science and Technology in Kraków, Poland (M. Krajewski's Crimea Collection).

Results

Field occurrence of the *Crescentiella*-microbial-cement (Cmc) microframeworks

Sudak area (Upper Oxfordian reefs)

In the Sudak area, investigations were carried out in the Koba-Kaya Mts., the Sokol Mts. and in the quarry close to Dachnoye village (Figs. 2a, 3). The sediments encountered there represent the Upper Oxfordian massive and bedded facies (e.g., Muratov 1973; Nikishin et al. 2015b; Figs. 2a, 3a). The bedded, partly marly facies is formed by coral floatstones with platy microsole-nids whereas the massive facies is dominated by coral-microen-cruster boundstones (Fig. 3; Nikishin et al. 2015b). In the lower parts of the reefs and down the reef slope, both platy micro-solenids and *Actinaraea* occurred (Fig. 3b). Both nodular and massive colonies coexisted with branching and dendroid corals (Fig. 3e–g). In a significant number of the reefs, branching scleractinians occur. Among the corals forms such as *Calamophyl-liopsis*, *Stylosmilia*, *Thecosmilia*, and *Heliocoenia* were identified. In the reef slope, coral-bioclasic grainstones–rudstones accumulated (Fig. 3c, d). In the massive facies, growth cavities with geopetal infillings were seen, indicating that the Koba-Kaya and the Sokol reefs have not been tectonically tilted. In the uppermost part of the reefs, syndimentary breccias and microbial laminites have been observed (e.g., in the Koba-Kaya Mts.; Fig. 3h). Similar observations in the nearby Oxfordian reef (Sudak fortress mountain) were carried out by Geister et al. (2007). In a brief description, they distinguished a barrier reef system with lateral coral facies change from back-reef over the reef crest with dominating upright branching scleractinians to a steep reef slope with increasing presence of platy corals (Geister et al. 2007).

In the lower parts of the reef successions, bioclasic wackestones and coral floatstones are prevailing. Higher in the sequence, massive gray limestones appear classified as bioclasic grainstone-rudstones with *Crescentiella* as well as *Crescentiella*-microbial-cement (Cmc) boundstones (Fig. 5a, d). Both the lateral and vertical ranges of the Cmc boundstones are difficult to estimate due to the steepness of the terrain. In the best-accessible, lower part of the quarry near Dachnoye village (Fig. 5a), the Cmc lateral extension is up to several meters and the vertical one is about 1.5 m. Up the sequence, the facies with numerous *Crescentiella* grades into coral boundstones-floatstones (Fig. 5a, b). The contact between *Crescentiella*-microbial facies and coral facies is sharp.

Jalta area (Upper Kimmeridgian–Tithonian reef)

The Ai-Petri reef complex comprises strongly lithified, gray, massive Štramberg-type reef facies grading laterally into thick- and thin-bedded facies (Fig. 2b) with some intervals of mixed, siliciclastic–carbonate facies in both the lower and its central parts (Krajewski 2008, 2010). Based on biostratigraphic analyses the massive facies of the Ai-Petri reef is Upper Kimmeridgian–Tithonian in age whereas the bedded facies encountered in the uppermost part of the reef (Fig. 2b) is of Lower Berriasian age (Krajewski and Olszewska 2006, 2007). Generally, several main intervals are observed in which the slope and the fore-reef, marginal, back reef, and lagoonal facies are evident, all reflecting the reef evolution (Fig. 2b). Moreover, several smaller, repeating, low-rank sedimentary sequences can be observed (Krajewski 2008, 2010).

The lower part of reef complex in question comprises mainly bioclasic wackestones, platy corals floatstones with microsolenids and microbial boundstones, several tens of meters in thickness (Fig. 4a, b). Up the sequence, the fossil assemblage reveals a high diversity with dasycladalean and udoteacean algae (Fig. 4g), foraminifers, calcified demosponges (stromatoporoids and chaetetids, e.g., *Chaetetopsis spengleri*, *Pseudoseptifer*, *Actinostromaria*, *Milleporidium*, *Sarmentofascis? digitatus*, *Cladocoropsis*, *Stromatopora*, *Milleporella*; Fig. 4c, d), corals (e.g., *Stylina*, *Thecosmilia*, *Heliocoenia*, *Latomeandra*, *Stylosmilia*; Fig. 4e, f) and a wide spectrum of microencrusters including *Crescentiella morronensis*, *Pseudolithocodium carpathicum*, *Koskinobullina socialis*, *Thaumatoporella parvovesiculifera*, *Lithocodium aggregatum*. In the middle part of this sequence, bioclasic–oidal marginal facies sometimes prevails over the reef facies (Fig. 4h). The boundstones and floatstones are built mainly by calcareous sponges and corals skeletons. Densely packed skeletons reveal growth with microencrusters and microbialites representing secondary reef-builders. Both the sponge and the sponge-coral facies are observed especially in

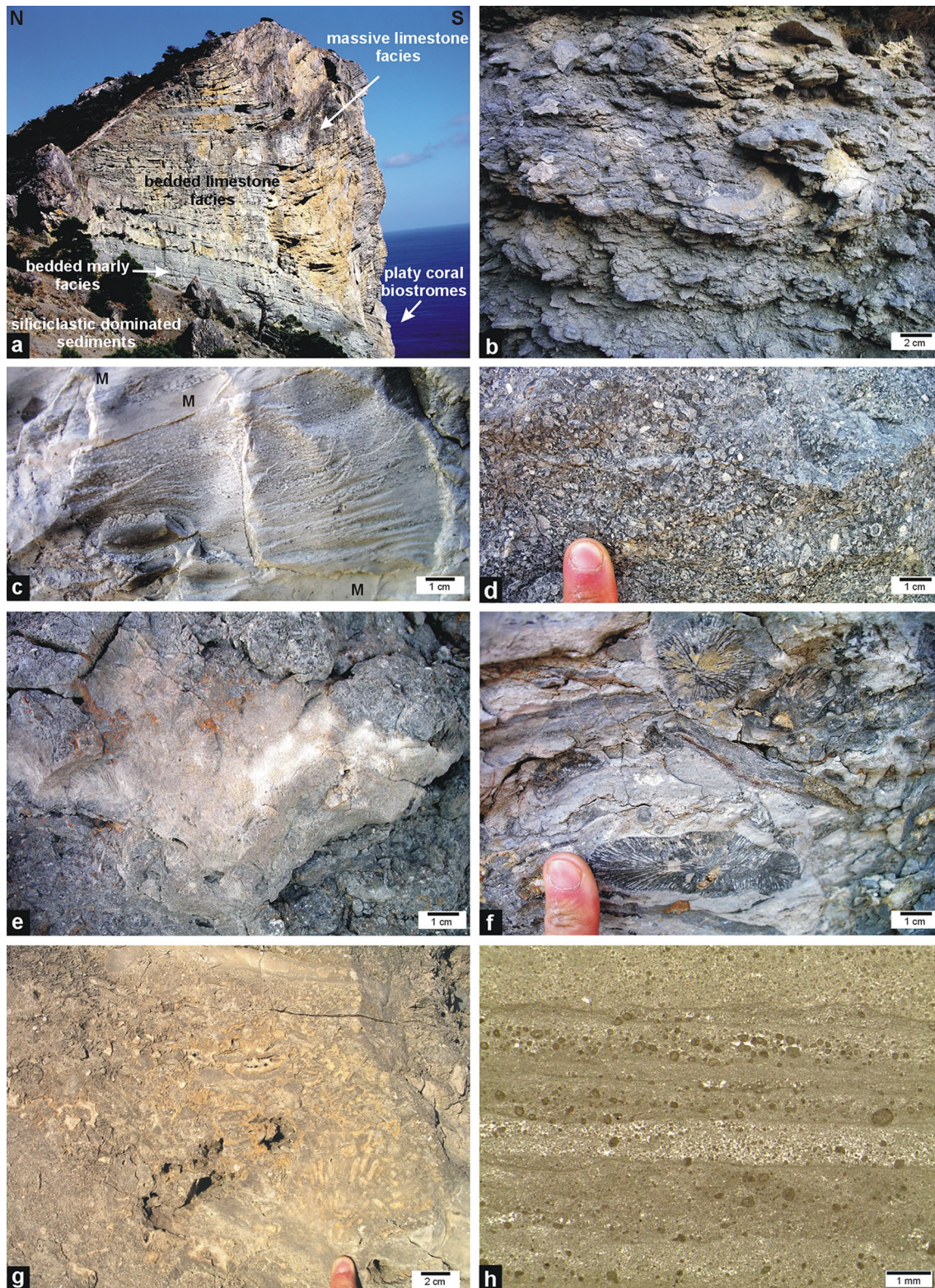


Fig. 3 Examples of Oxfordian reef facies from Sudak area. **a** Koba-Kaya reef; western slope, in the lower part bedded marly facies with platy coral; in the upper part transition zone from massive coral-microencruster facies to bedded bioclastic facies. The rock wall is up to 50 m high. **b** Platy coral bioherm observed in the lower part

of the reefs. **c** Reef slope facies with reef detritus and microbialites (M). **d** Reef slope with coral and bioclast detritus. **e–g** Coral-microencruster massive reef facies. **h** Microbial laminites from the highest part of the Koba-Kaya reef; sample Kob 2. Location of the examples is presented in Fig. 2a

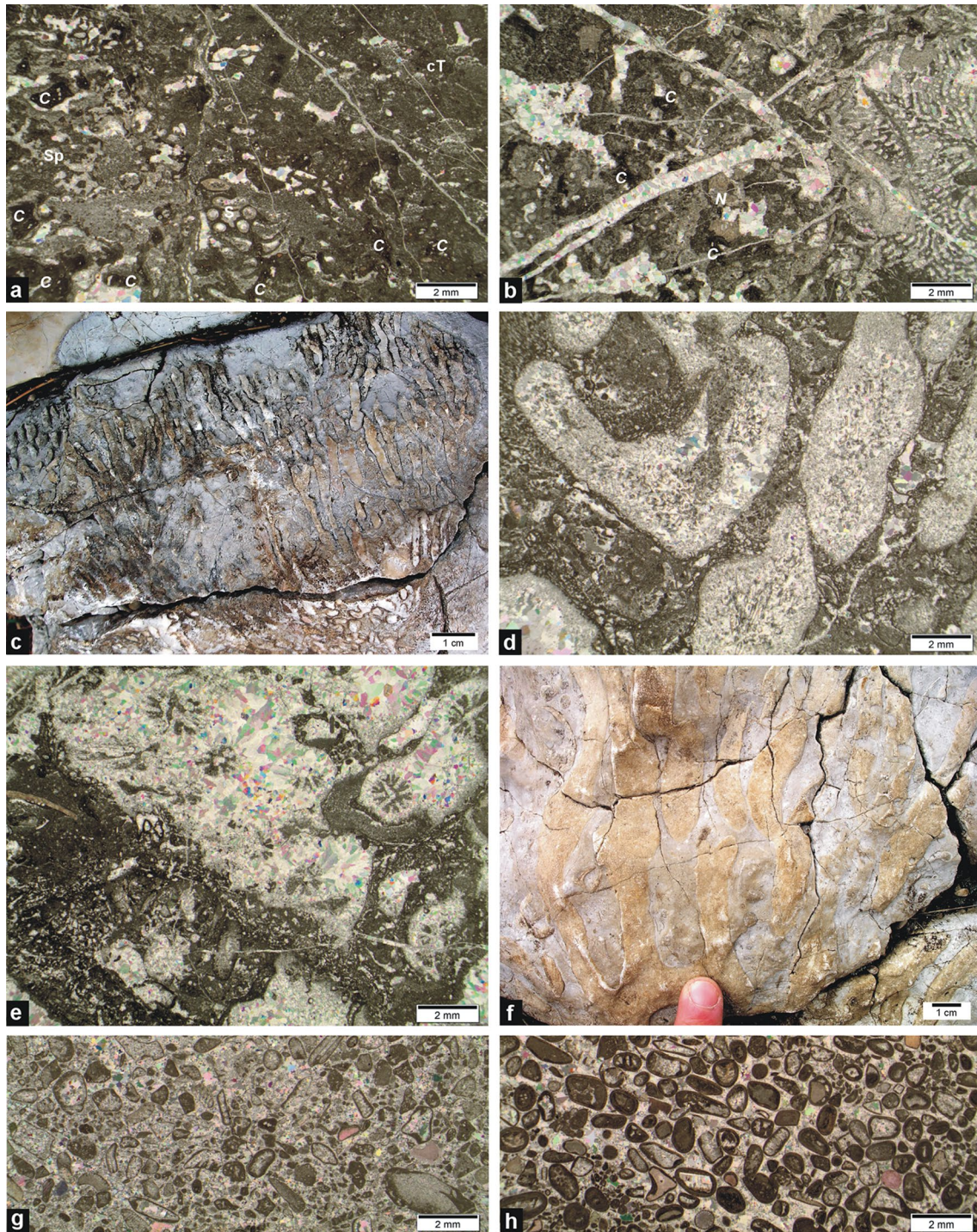


Fig. 4 Examples of the Upper Kimmeridgian–Tithonian reef facies from Jalta area. **a** Microbial boundstone; *Sp* sponge, *S* serpulids, *C* *Crescentiella*, *cT* clotted thrombolite; lower part of the Ai-Petri reef; sample KB 7g. **b** *Microsolena*-thrombolite boundstone; *C* *Crescentiella*; *N* *Neuropora*; lower part of the Ai-Petri reef; sample KB 36d. **c** Weathered rock surface showing calcareous sponge skeletons of *Sarmentofascis? digitatus* Schlagintweit & Krajewski mostly longi-

tudinal-oblique sections. **d** Sponge-microencruster boundstone; sample KB 51a. **e** Coral-microencruster boundstone; fragment of *Helio-coenia* cf. *variabilis* colony; sample KB 41c. **f** Coral floatstone; upper most part of the Ai-Petri reef. **g** Bioclastic grainstone with fragments of calcareous green algae; sample KB 6c. **h** Ooid-cortoid grainstone; sample KC 19c. Location of the examples is presented in Fig. 2b

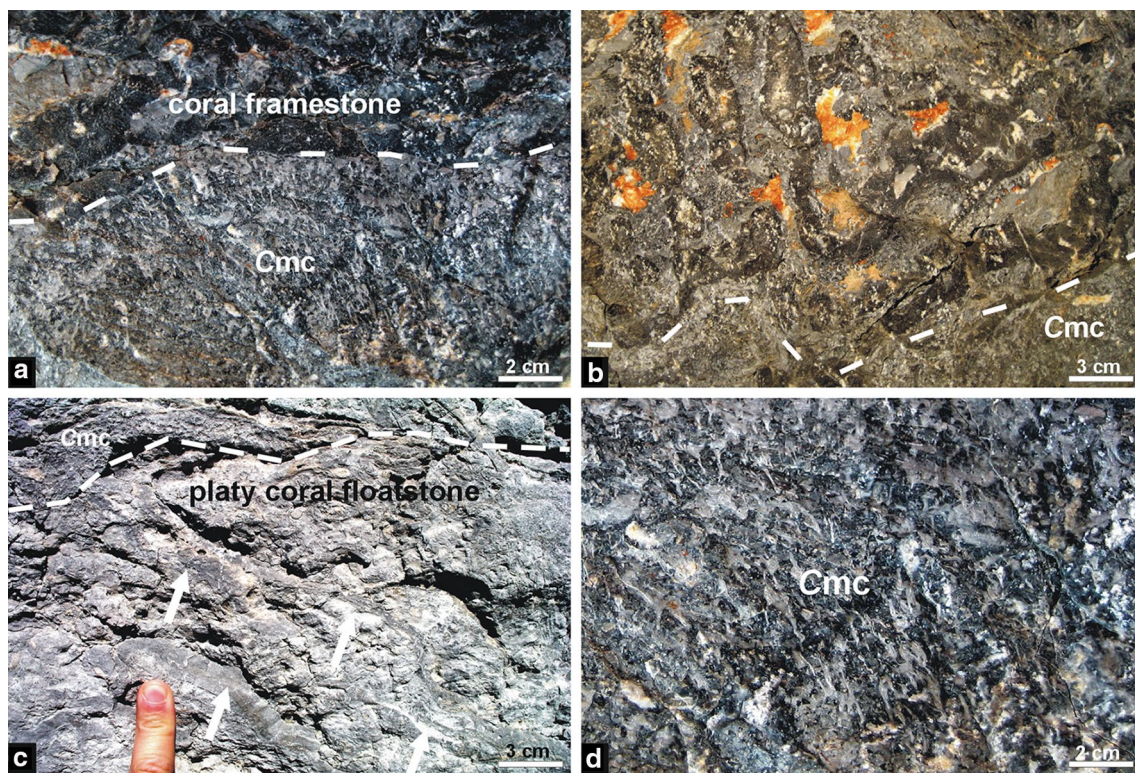


Fig. 5 Field views of the *Crescentiella*-microbial-cement microframeworks in the Upper Jurassic reefs of Crimea. **a, b** Upper part of the *Crescentiella*-microbial-cement microframework (Cmc) succession; in the lower part Cmc microframework; in the upper part coral framestone; the boundary is sharp and undulated; Dachnoye quarry. **c** Lower part of the *Crescentiella*-microbial-cement microframework

(Cmc) succession; in the lower part platy coral (arrows) biostrome; in the upper part Cmc microframework; Ai-Petri Mts. **d** *Crescentiella*-microbial-cement microframework (Cmc); densely packed aggregates of branching individuals of *Crescentiella*; numerous voids (white or yellow parts) are filled with early and late cements; Dachnoye quarry

the lower and the middle parts of the reef sequence whereas the coral-sponge facies is more common in its uppermost part.

The sedimentary sequence with the Cmc microframework was observed in the lower portions of the Ai-Petri reef succession (Figs. 2b, 5c) and, less commonly, in its middle portion (Krajewski 2010). In the upper reef succession, *Crescentiella* occurs dispersed in the peri-reefal bioclastic wackestones–floatstones or growing on skeletons of sponges and corals. The lower reef succession is dominated by bioclastic wackestones and coral floatstones followed upward by microbial, *Crescentiella*-microbial and calcified sponge-coral facies. The Cmc microframeworks of meter-scale lateral, and decimeter-scale vertical extensions were noticed although it is difficult to estimate their true lateral extent due to the steepness of the terrain.

Microfacies of the *Crescentiella*-microbial-cement (Cmc) microframework

Generally, in both the Upper Oxfordian and the Upper Kimmeridgian–Tithonian reefs from the Crimea area, the

macroscopic features of the Cmc microframeworks are similar (Figs. 5, 6, 7, Table. 1): both are dark-grey (Sudak area) or light-grey (Jalta area), hard, lithified limestones (Fig. 5a–d). The sediment consists of densely packed *Crescentiella*, mostly in growth position (Figs. 5a, d, 6e, f). Common are caverns filled with various generations of cements, some of them representing stromatactis-like caverns with geopetal infillings (Fig. 6e). The microframeworks are dominated by *Crescentiella* accompanied by microbialites and specimens of the branching sclerosponge *Neuropora lusitanica* Termier (Fig. 6a, b). Some specimens of *Crescentiella morronensis* are up to 1.3 cm in height. Within the *Crescentiella* laminae, foraminifers and fine bioclasts are observed. *Crescentiella* is formed by encrustation or symbiosis between nubecularid foraminifers (Figs. 6e, f, 7a) or enigmatic, spar-filled, tube-shaped structures (Fig. 6a–d) and the microbial envelopes (Senowbari-Daryan et al. 2008; Schlagintweit and Gawlick 2009; Pleş et al. 2017). The basic difference between the Upper Oxfordian and the Upper Kimmeridgian–Tithonian specimens is the variable amount of nubecularid foraminifera and tube-shaped structures forming the central cavities

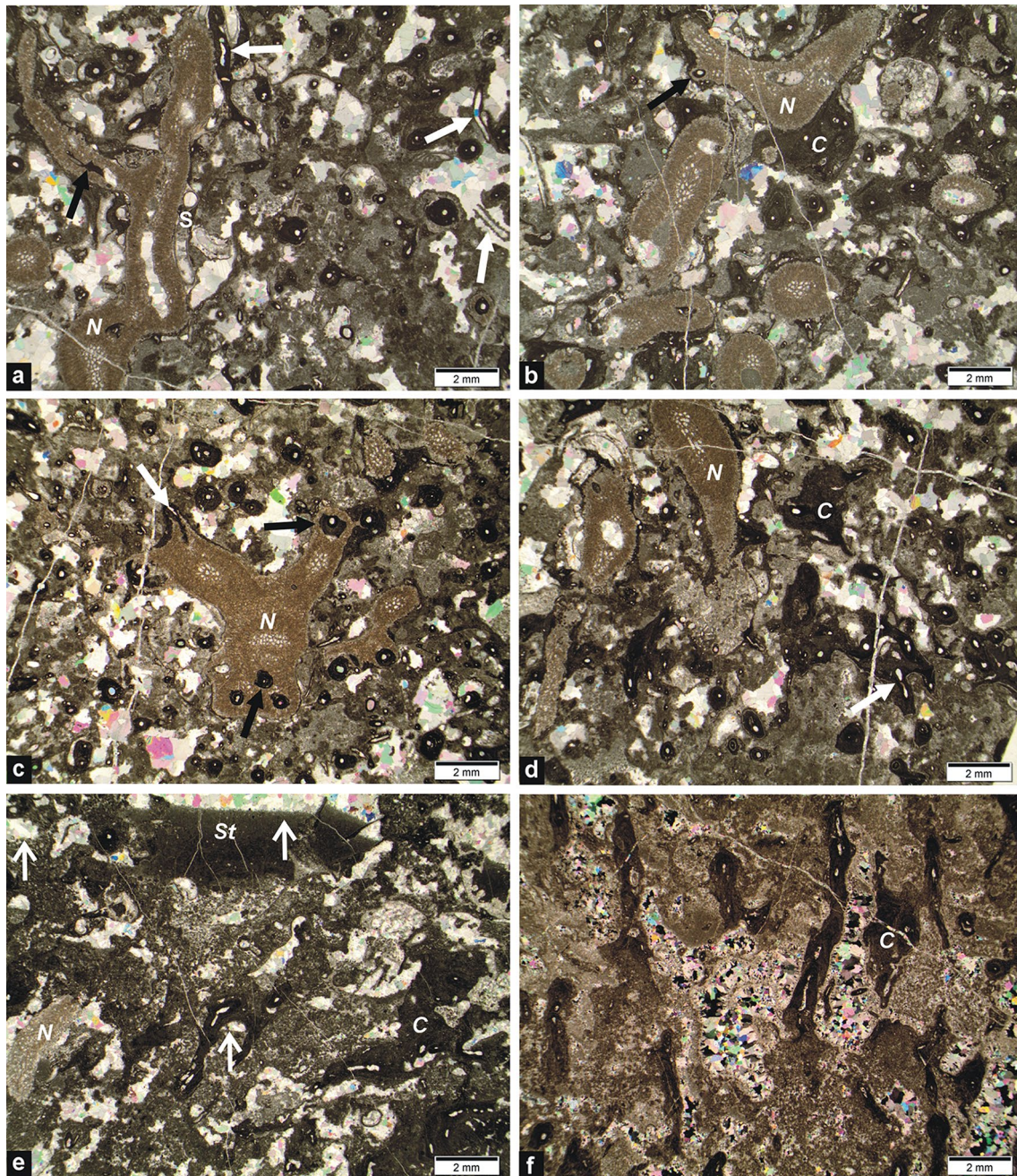


Fig. 6 *Crescentiella*-microbial-cement microframeworks. **a–d** *Crescentiella*-microbial boundstone; numerous longitudinal and transverse sections of *Crescentiella* and branches of *Neuropora* with serpulid encrustations; some specimens of *Crescentiella* (C) overgrow *Neuropora* (N) or filled borings (black arrows); *Crescentiella* is formed mostly by enigmatic tube-shaped structures (white arrows) and microbial envelopes; Sudak area, samples D2b, D2c, D2d. **e** *Crescentiella*-microbial boundstone; in the left lower part *Neuropora* (N);

in the upper part stromatactis-like cavity (St), growth cavities and borings with geopetal infillings (white arrows); *Crescentiella* (C) is formed mostly by nubecularid foraminifers and microbial envelopes; Jalta area; sample KC7c. **f** *Crescentiella*-microbial boundstone; microframework created by *Crescentiella* (C); voids filled with multiple cement generations (for details see Fig. 7; Ai-Petri reef; sample KC7b)

of *Crescentiella*. In the Upper Oxfordian samples, higher amounts of tube-shaped, enigmatic structures are observed whereas in the Upper Kimmeridgian–Tithonian specimens, nubecularid foraminifers prevail.

In both areas, *Crescentiella* is commonly accompanied by the branching sclerosponge *Neuropora*, more common in the Oxfordian reefs from the Sudak area (Fig. 6a–d). Usually, specimens of *Neuropora* grow vertically as delicate,

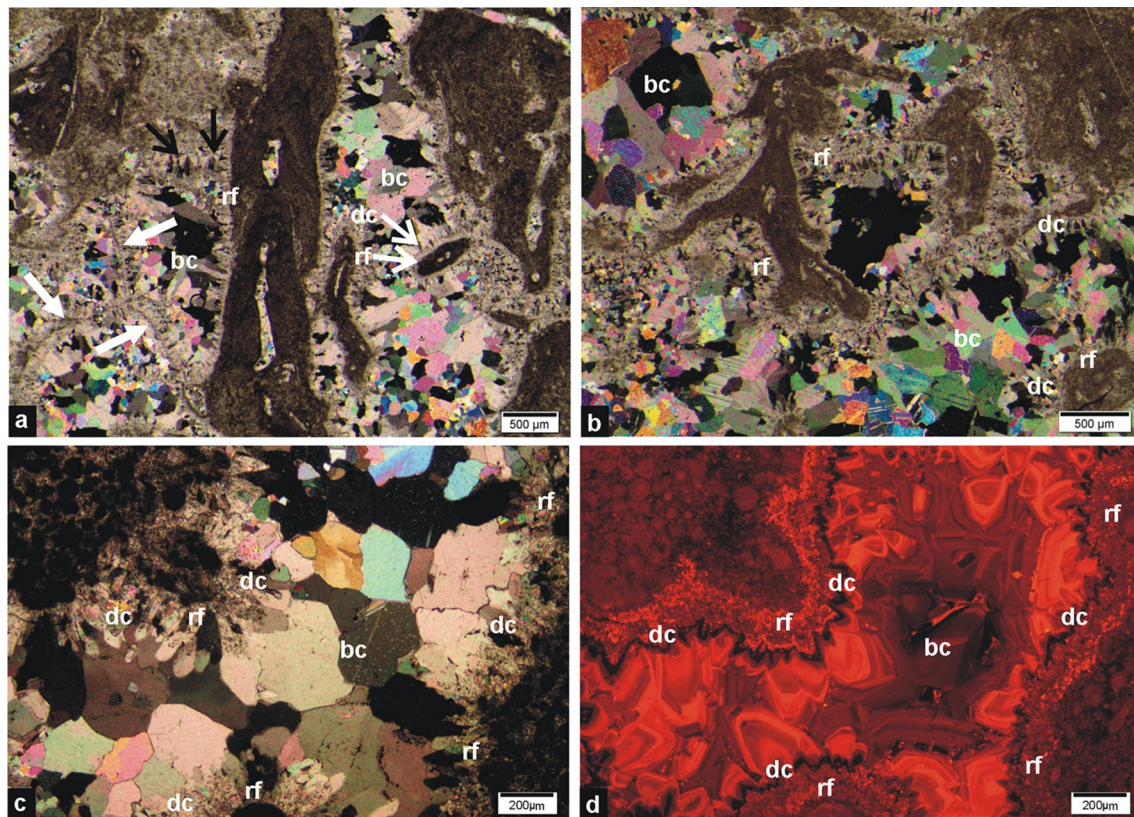


Fig. 7 *Crescentiella*-microbial-cement microframeworks. **a, b** *Crescentiella*-microbial-cement microframeworks; multiple cement generations are visible; the first generation of cement is represented by a fine rim of radiaxial-fibrous cement (rf) surrounding *Crescentiella* and voids followed by dog tooth spar (dc) and a final generation of blocky cement (bc). Sometimes the morphology of the cements resembles splay or botroid fabrics (black arrows); in voids, thin micritic films are visible; on micritic films fibrous cement is devel-

oped (white arrows); sample KC7b. **c, d** crossed nicols (c) and CL image (d) of the void filled with different generation of cements in the microframework and chronological order of cementation is highlighted by cathodoluminescence; radiaxial-fibrous cement (rf) is covered with non-luminescent, marine, phreatic dog tooth cement (dc), which shows red luminescence only in the outer zones of crystals; the center of the void is filled with blocky cement (bc); sample KC7e

ramified colonies with branches ranging from 2 to 5 mm in diameter and showing dendroidal forms (Fig. 6a). In many cases, *Crescentiella* was growing on *Neuropora* specimens thereby connecting the branches (Fig. 6a, b). Similar to bryozoans and serpulids, *Neuropora* prefers cryptic habitats and is regarded as frame encruster (Fürsich and Werner 1991).

Further important components are microbialites, which form clotted fine, peloidal fabrics between the *Crescentiella* colonies (Fig. 6a–f). Sometimes, faint layered structures can be observed. In the voids, thin micrite films onto which thin, fibrous cement crusts grow can be observed (Fig. 7a).

Among the biogenic components, bryozoans and serpulids occur, developed mostly on sponges (Fig. 7a) and encrusting foraminifers (e.g., Nubeculariidae) together with numerous, enigmatic, irregular, polymorphous, spar-filled, tube-like microfossils resembling some taxa of mutualistic

sponge-epibiont consortia (Schlagintweit and Gawlick 2009).

Numerous voids show the irregular shapes of inorganic origin (growth-framework porosity) or the oval shapes of possible organic provenance (biomoulds; Fig. 6a–f). In the caverns, faint relics of dissolved sclerosponges can be observed displaying poorly preserved internal structures (Fig. 6a, b). In the microframework, stromatolite-like cavities (sensu Matyszkiewicz 1997) are common (Figs. 5d, 6e). Cavities reach 3 cm in length and are up to 1.5 cm high. In their basal parts, the cavities contain internal sediments, followed by calcite cement. Internal sediment is represented by mudstone-thin bioclastic wackestone.

Although the Crimean Late Jurassic reefs are mostly organic reefs, it must be noticed that the Cmc microframeworks are also composed of various cements, which may constitute up to 30% of its components. The radiaxial fibrous cements represent the first generation of cements which developed as thin layers on the walls of voids (Fig. 7a–d), on

Table 1 Characteristics of the *Crescentiella*-microbial-cement microframeworks in the Upper Jurassic reefs of the Crimean Peninsula. Reef classification after Riding (2002)

Location	Sudak area	Jalta area
Age	Upper Oxfordian	Upper Kimmeridgian–Lower Berriasian
Type of bioconstruction	Mainly: Coral biostrome, coral-microencruster cluster, segment and frame reef Locally: Skeleton-cement and microbial reef	Mainly: Calcified sponge-coral-microencruster segment and frame reef, coral biostrome Locally: Skeleton-cement and microbial reef
<i>Crescentiella</i> -microbial-cement microframework	Present	Present
Position in the sequence	Lower part of the sequence; between platy mainly microsolenid biostromes and coral microencruster reefs	Mainly lower part of the sequence between microbial reefs, microsolenid biostromes and stromatoporoid-coral-microencruster reef and ooid facies
Main components	<i>Crescentiella</i> , <i>Neuropora</i> , microbialites cements, serpulids, foraminifers	<i>Crescentiella</i> , <i>Neuropora</i> , microbialites, cements, serpulids, foraminifers
<i>Crescentiella</i>	Central cavities: mainly enigmatic tube-shaped structures, rarely nubecularid foraminifers; microbial envelopes	Central cavities: mainly nubecularid foraminifers, rarely enigmatic tube-shaped structures; microbial envelopes
Cement content	Moderate	Moderate, locally high dominating
Cements	Radiaxial-fibrous, blocky	Isopachous, radiaxial-fibrous, dog tooth microcrystalline, blocky
Microfacies	<i>Crescentiella</i> -microbial-cement boundstone	<i>Crescentiella</i> -microbial-cement boundstone
Size	dm-scale thickness m-scale or more extent	dm-scale thickness m-scale or more extent
Structure	Densely packed <i>Crescentiella</i> with stromatactis-like cavities	Densely packed <i>Crescentiella</i> with stromatactis-like cavities
Facies interpretation	Forereefal to upper slope	Upper slope to marginal setting

Crescentiella specimens (Fig. 7a) as well as on thin, micrite films cutting through the voids (Fig. 7a). Important infillings of the voids are represented by massive, radiaxial fibrous and dog tooth cements (Fig. 7a). The central parts of the voids are filled with blocky cement type.

Micropaleontology of the *Crescentiella*-microbial-cement (Cmc) microframework

Microencrusters

Genus *Crescentiella* Senowbari-Daryan et al. 2008.

Crescentiella morronensis (Crescenti 1969) Figs. 5, 6, 7

Remarks: For a detailed description and interpretation see Senowbari-Daryan et al. (2008). We may note here that in the same year when Crescenti described *Tubiphytes morronensis* from the Late Jurassic of Italy, this microorganism was also described by Dragastan (1969) neutrally as “micro-oncolites” from the Late Jurassic of Romania, but without application of Linnean nomenclature. Subparallel growing, transversely sectioned specimens of *C. morronensis* might refer to a taxon described by Dragastan (2010), pl. 78A recently as *Sarsteinia getica* (interpreted as a sponge) from

the late Tithonian of the Getic Carbonate Platform of Romania. In the material from the Crimea, the elongated specimens attain a length of up to 8 mm and a thickness of up to 1.5 mm (mostly 0.8–1.0 mm). The internal sparite-filled cavity (or core) maybe either a cylindrical tube of unknown systematic position or a foraminifera (*Nodophtalmidium*, *Nubeculinella*) with superimposed amphora-like chambers (Figs. 6, 7a). Most of the Crimean forms belong to the gregarious *C. morronensis* forma *colligaris* morphotype with laterally connected laminated crusts as described by Senowbari-Daryan et al. (2008). In some cases, depending on the plane of sectioning, the differentiation of the two morphotypes (forma *morronensis* and forma *colligaris*) may be difficult if not impossible. This peculiar morphotype was described by (Dragastan 1969, Fig. 1, right side) as “micro-oncolithe, sous-type amalgame”. Individual specimens are observed filling borings affecting the skeletons of *Neuropora* (Fig. 6c). As *Crescentiella* has never been reported exhibiting an euendolithic potential, these borings were drilled by other organisms of unknown taxonomic origin. These specimens nicely show the inner microbial crust layer of the cortex to be denser and therefore darker (Fig. 6a, c).

Sclerosponges

Genus *Neuropora* Bronn, 1825. *Neuropora lusitanica* Terrier, 1985 (Fig. 6a–e)

Remarks: Termier in Termier et al. (1985) distinguished two morphotypes of *N. lusitanica* (Oxfordian of Portugal), encrusting and ramose (tree-like branching). The Crimean specimens belong to the ramose morphotype forming delicate, branched colonies with branches ranging from 2 to 5 mm in diameter. As already mentioned, many skeletons display macroborings that are often completely filled with *Crescentiella* specimens (Fig. 6c). It is worth mentioning that long time considered a bryozoan, the sclerosponge nature of *Neuropora* Roemer was evidenced by Kaźmierczak and Hillmer (1974).

Discussion

In the evolution of Jurassic platform of the Crimea Peninsula, the Cmc microframework was observed at two main stages of carbonate platform evolution, separated by erosional unconformity and stratigraphic gap (Nikishin et al. 2015b, cf. Baraboshkin and Piskunov 2010; Fig. 1, Table 1). Deposits of the first stage can be observed in the eastern part of Crimea Mts. (Sudak area) while the deposits of the second stage occur in the central and western parts (Jalta area). In the Middle–Late Oxfordian succession which represents the first stage of carbonate platform evolution, the Cmc microframeworks represent the initial evolution of the Sudak Series reefs. The Cmc microframework with stromatactis-like occur in the transitional phase, from relatively deep water bioclastic and platy coral facies (some tens of meters, e.g., Leinfelder et al. 1996; Insalaco et al. 1997; Lathuilière et al. 2005) to shallow subtidal coral-microencruster facies. The latter is dominated by massive and branching corals building the main parts of the reefs.

In the Late Kimmeridgian–Tithonian, which represents the second stage of carbonate platform evolution, represented in the Yaila Series (Fig. 1), the development of Cmc microframeworks was related to the consecutive stages of reef growth. The Upper Oxfordian–Early Kimmeridgian depositional break caused by tectonic movements was followed by the gradual restoration of reef communities. The bioclastic wackestones-floatstones and platy coral-microbial boundstones-floatstones located in the lower part of reef succession can be linked to the platform slope facies (Krajewski 2008, 2010). Up the sequence, the reefs structures evolved into meter-scale, low-relief microbial reefs with Cmc microframework, and stromatactis-like caverns. Higher up the reef succession is dominated by shallow subtidal massive sponge and coral boundstone or marginal oolitic facies (Krajewski 2008, 2010).

At both large-scale phases of reef development, the microbial and the Cmc boundstones contributed to the stabilization of loose substrate, which enabled the vigorous growth of calcified sponges and corals constituting the

main parts of the reefs, together with common microencrusters such as *Lithocodium*, *Thaumatoporella* etc. Hence, the described Cmc microframeworks from the Sudak and the Jalta areas represent the initial stages of long cycles of restoration and blooming of the reefs in the Middle–Late Oxfordian and in the Late Kimmeridgian–Tithonian. The main phase of reef growth was characterized by vigorous expansion of a wide spectrum of massive and branching skeletal metazoans and microencrusters building the Frame Reef sensu Riding (2002).

Although the Cmc microframeworks were mostly observed in the lower parts of the reef successions, their infrequent presence must be mentioned also in the middle parts of the reef successions of the Ai-Petri massif where they were accompanied by minor metazoans. In the Ai-Petri reef, the repeating, vertical facies changes represent lower-rank cycles (Krajewski 2008, 2010). The appearance of microbial and Cmc microframeworks together with the deficit of main reef builders can be explained by a crisis in metazoans growth caused by paleoenvironmental stress then followed by the flourishing sponge-coral-microencruster communities. Similar to recent reefs, the Late Jurassic reefs were very sensitive to environmental changes (sea level fluctuations, tectonic events, climate, nutrient content, temperature, etc.). In the Ai-Petri reef, periods were documented during which carbonate production was disturbed by the influx of siliciclastic material and nutrients (Krajewski 2008, 2010; KB and KC sections). Such episodes, triggered by tectonic activity in the surrounding areas, resulted in periodical breaks in the reef growth. However, after the crisis, the restoration of reefs took place, as indicated by deposition of detrital bioclastic wackestones-floatstones followed by microbial and Cmc boundstones and, finally, succeeded by sponge-coral-microencruster framestones showing high biodiversity. In both the high and low sedimentary cycles of the Crimean reefs, the Cmc microframework also appears at the initial phase of reef growth after the breaks in metazoans development, during the restoration of the reef fauna assemblages.

The Cmc microframestone formed under phreatic conditions, in the upper slope, fore-reef and seaward marginal depositional settings where intensive syndimentary cementation took place. Such environments are characterized by marginal topography and intensive fluid flow (e.g., Della Porta et al. 2003; Flügel 2004; Seeling et al. 2005; Marangon et al. 2011). Both *Crescentiella* and the microbialites were not only able to adapt to unstable environmental conditions but also stabilized the sediments, thus supporting the development of skeletal metazoans building the main parts of reef complexes. Significant contents of early cement crusts are typical of reefs showing low sedimentation rates and higher rates of water agitation, i.e., conditions preferred by low-growing microbialites and *Crescentiella*.

These cements formed prior to burial, when the voids were open for the early cementation formed marine phreatic conditions. The syndimentary origin of the fibrous cement is evidenced by microencrusters overgrowth (cf. Kendall and Tucker 1973; Koch and Schorr 1986; Flügel 2004; Schlagintweit and Gawlick 2008). The presence of thin micritic films in cavities intercalating various cement generations indicates that the early marine cementation took place when the voids were opened to marine water (e.g., Payne et al. 2006). In the massive reef sediments, the burial diagenesis is represented by blocky cement constituting the latest cement generation (e.g., Koch and Schorr 1986; Flügel 2004). In the Sudak reefs, large crystals of blocky cement partly replaced the earlier, fibrous cements as a result of burial/meteorite solution. In the Ai-Petri reef, the generations of cements are well preserved. The reefal limestones rich in microbialites and cements are typical of steep, high-energy upper slope depositional setting (e.g., Della Porta et al. 2003, 2013; Flügel 2004; Marangon et al. 2011). The lack of dasycladacean algae and typical shallow water microporoliths (e.g., *Lithocodium*, bacinellid fabrics, *Thaumatoporella* etc.) described from higher part of the Crimean reefs (Krajewski 2008; Baraboshkin and Piskunov 2010; Piskunov et al. 2012; Bucur et al. 2014) suggest that the Cmc microframework is rather deeper than several meters.

The examples of Cmc microframework encountered in the Crimea Mts., formed by small, low-growing *Crescentiella* and microbialites, and rich in early cement crusts resemble Permian algae-microbial-cement reefs (e.g., Edwards and Riding 1991; Flügel 1994; Saller et al. 1999; Wood 1999; Weidlich 2002; Schlagintweit and Gawlick 2008; Kosakowski and Krajewski 2014) as well as Triassic *Tubiphytes* and cement crust-dominated reefs (Senowbari-Daryan et al. 1993; Flügel 2002; Schlagintweit and Gawlick 2008; Marangon et al. 2011; Senowbari-Daryan 2013; Popa et al. 2014).

Conclusions

1. In the lower, rarely in the middle part of the Upper Jurassic reef successions of the Crimean Peninsula *Crescentiella morronensis*, microbialites and cements form cement-supported reefs. Although the Crimean Late Jurassic reefs are mostly organic reefs, it must be noticed that the *Crescentiella*-microbial-cement microframeworks are also composed of multiple generations of early and late cements, which may constitute up to 30% of its volume. Such structures have so far not been described in detail from the Crimea-Caucasus region.

2. In the evolution of Jurassic carbonate platforms of the Crimea Peninsula, the *Crescentiella*-microbial-cement microframeworks were observed in two main stages of carbonate platform evolution. Generally, in both the Middle–Upper Oxfordian and the Upper Kimmeridgian–Tithonian phases of Crimean reefs development, the features of the *Crescentiella*-microbial-cement microframeworks are similar. They consist of densely packed *Crescentiella* accompanied by microbialites and branched colonies of *Neuropora lusitanica*. The main difference between the Middle–Upper Oxfordian and the Upper Kimmeridgian–Tithonian specimens is the variable amount of nubecularid foraminifera and tube-shaped structures forming the central cavities of *Crescentiella*.
3. In the Middle–Late Oxfordian reef successions exemplified in the Sudak area, the metric-scale *Crescentiella*-microbial-cement microframeworks occur in the transitional realm from relatively deep water bioclastic and platy coral facies to shallow subtidal massive and branching corals facies. The Upper Oxfordian–Early Kimmeridgian depositional break was followed by the gradual restoration of reef communities. In the Late Kimmeridgian–Tithonian which represents the second stage of carbonate platform evolution, exemplified in the Jalta area, the development of *Crescentiella*-microbial-cement microframeworks was related to the consecutive stage of reef growth. The relatively deep water mainly microsolenid facies, up the sequence of the reefs structures evolved into meter-scale, low-relief cement-supported reefs with *Crescentiella*-microbial-cement microframework. Higher up, the reef succession is dominated by shallow subtidal Štramberk-type massive calcified sponge and coral boundstone and oolitic facies. Hence, the described *Crescentiella*-microbial-cement microframeworks from the Sudak and the Jalta areas can be observed in the initial stages of long cycles of restoration and blooming of the reefs in the Middle–Late Oxfordian and in the Late Kimmeridgian–Tithonian.
4. The *Crescentiella*-microbial-cement microframework in the Crimean reefs formed under phreatic conditions, in the upper slope and seaward marginal depositional settings where intensive syndimentary cementation took place. Both the *Crescentiella* and the microbialites were not only able to adapt to unstable environmental conditions but also stabilized the sediments, thus supporting the development of skeletal metazoans building the main parts of reef complexes. Significant contents of early cement crusts are typical of reefs showing low sedimentation rates and higher rates of water agitation, i.e., conditions preferred by low-growing microbialites and *Crescentiella*.

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