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An Upper Jurassic–Lower Cretaceous carbonate platform from the Vâlcan Mountains (Southern Carpathians, Romania): paleoenvironmental interpretation

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Abstract: The results of a biostratigraphic and sedimentological study of the Upper Jurassic–Lower Cretaceous limestones cropping out in the southern sector of the Vâlcan Mountains in Romania are presented, including the definition of microfacies types, fossil assemblages and environmental interpretation. Six microfacies types (MFT 1–MFT 6) have been identified, each of them pointing to a specific depositional environment. The deposits are characteristic of a shallow carbonate platform. They contain normal marine or restricted marine facies deposited in low or high energy environments from the inner, middle and outer platform. The age attribution of these deposits (Late Jurassic to Berriasian–Valanginian–?Hauterivian, and Barremian) is based on foraminiferal and calcareous algae associations. The micropaleontological assemblage is exceptionally rich in the Vâlcan Mountains and brings new arguments for dating the Upper Jurassic–Lower Cretaceous limestones in this area.

Key words: Upper Jurassic–Lower Cretaceous, Vâlcan Mountains, paleoenvironment, carbonate platform, carbonate sedimentology, microfacies.

Introduction

The Vâlcan Mountains are located in the Southern Carpathians between the Jiu Valley (to the east), the Petroşani Basin (to the north), the Motru Valley (to the west) and the Getic Depression (to the south). The Upper Jurassic–Lower Cretaceous limestones crop out on the southern border of the Vâlcan Mountains and they were studied in stratigraphic sections along the Cheii, Pocuia, Sudoieşului, Valea lui Mareş, Cireşului, Albului, Pârgavului, Bistriţa, and Sârbului Valleys. More than 800 samples have been collected and analysed.

In spite of the large number of previous regional geology studies on this area, there are only a few data regarding the biostratigraphy and lithology of the local sedimentary deposits. This is due to the scarcity of biostratigraphic markers within these deposits and to their recrystallization caused by late Senonian tectonics (Pop & Bucur 2001). This study represents a synthesis of the data obtained from a vast area in the Vâlcan Mountains. It aims to describe the facies and microfacies, to reconstruct the paleoenvironments and their evolution in time, and to bring some new biostratigraphical data.

Geological setting

The structure of the western part of the Southern Carpathians is represented by three groups of tectonic units. The lowermost unit is the Danubian Nappes, also called Danubian Euxinides (Balintoni 1997), the Danubian Domain or Danubian Autochthonous. This unit is overlain by the Severin Nappe, representing the suture between the Danubian Nappes and the Getic Nappe, which is the uppermost unit. Except for some thin strips belonging to the Getic Nappe, the Vâlcan Mountains are dominated by the crystalline and volcanic rocks of the Lower Danubian Nappes (Berza et al. 1983), and by their Mesozoic cover (Fig. 1). The Mesozoic deposits belong to the sedimentary cover of the Lainici Nappe (Berza in Balintoni et al. 1989).

The succession of the Mesozoic deposits in the area starts with Liassic deposits in Gresten-type Facies, followed by carbonate deposits of variable thickness (1–20 m), Middle Jurassic in age. The Upper Jurassic is represented by three formations: the Valea Pragurilor Formation (Oxfordian) — a calcarenitic sequence, often consisting of dolosparites; the Valea Cheii Formation (Upper Oxfordian–Lower Kimmeridgian) — a siliciclastic formation with regressive character (1–20 m thick); and the Topeşti Formation (Kimmeridgian–Tithonian) — consisting of shallow-water carbonate deposits dominated by blackish, fine to coarse stratified calcarenites and calcilutites. On the top of the Upper Jurassic deposits, a 40 m thick Neocomian limestone succession crops out. The Izvarna Formation (Barremian–Aptian) is the last carbonate formation developed in this region and it consists of Urgonian limestones, followed transgressively, and sometimes unconformably, by Upper Cretaceous clayey marls, marly-limestones and clays (Pop 1973; Pop & Bucur 2001) (Fig. 2).

New biostratigraphic data

In a previously published study (Michetiuc et al. 2008) we performed a micropaleontological study concerning only the

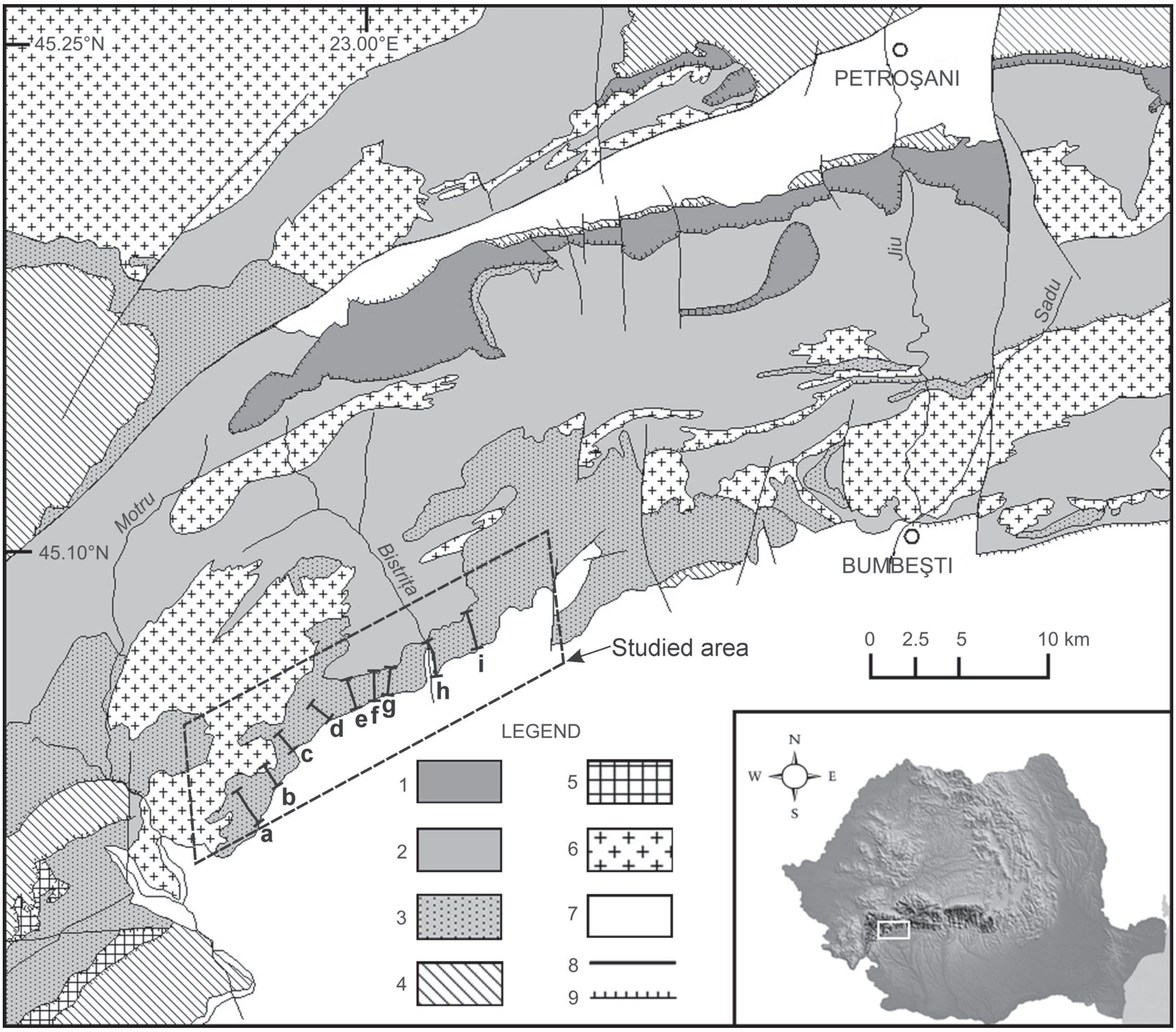

Fig. 1. Location of the studied area (simplified map after Berza et al. 1994). **1** — Upper Danubian Nappes, **2** — Lower Danubian Nappes, **3** — Jurassic–Cretaceous cover, **4** — Getic Nappe, **5** — Severin Nappe, **6** — Pre-Alpine granitoids, **7** — Cenozoic basins, **8** — Fault, **9** — Overthrust. **a–h** — studied sections: a — Cheii, b — Pocuia, c — Sudoieşului, d — Valea lui Mareş, e — Pârgavului, f — Albului, g — Cireşului, h — Bistriţa, i — Sârbului.

Lower Cretaceous deposits from several sections (Cheii, Sudoieşului, Cireşului, Albului, Pârgavului) in the Vâlcan Mountains. We combined here the micropaleontological data published earlier with new ones, in order to provide a synthetic image of the stratigraphic succession (Fig. 3). The studied deposits can be assigned to the Upper Jurassic–Lower Cretaceous (Oxfordian–Barremian) with some uncertainties regarding the Hauterivian deposits which were not documented paleontologically due to a lack of reliable biostratigraphic markers. Here we focus on our new findings which are discussed in order to stress their biostratigraphical significance.

The Late Jurassic age attribution is based on foraminifera: *Alveosepta jaccardi* (Schrodt) (Fig. 4.1), *Parurgonina caelinensis* Cuvillier, Foury & Pignatti Morano (Fig. 4.2), *Kurnubia palastiniensis* Henson (Fig. 4.3), *Protopeneroplis striata* Weyschenk (Fig. 4.4), *Neokilianina* sp., *Verneuilina* sp., and on several dasycladalean algae: *Megaporella boulangeri* Deloffre & Beun (Fig. 4.5), *Clypeina sulcata* (Alth) (Fig. 4.6), and *Salpingoporella annulata* Carozzi.

Among the foraminifera, the most significant species is *Alveosepta jaccardi* (Schrodt). It was first described by Schrodt (1894, as *Cyclammina jaccardi*) from Upper Oxfordian–Middle Kimmeridgian deposits in Switzerland. It was subsequently reported from Upper Oxfordian–Lower Kimmeridgian formations in France and in Romania (Pelissié & Peybernès 1982; Cociuba 1997; Pop & Bucur 2001). Septfontaine (1981) proposed an *A. jaccardi* Biozone, ranging from Middle Oxfordian to Early Kimmeridgian. The species was also described from Kimmmeridgian rocks in Turkey and Mexico (Altiner 1991; Omaña & Arreola 2008).

Parurgonina caelinensis Cuvillier, Foury & Pignattti Morano was first described from Kimmeridgian–Portlandian forma-

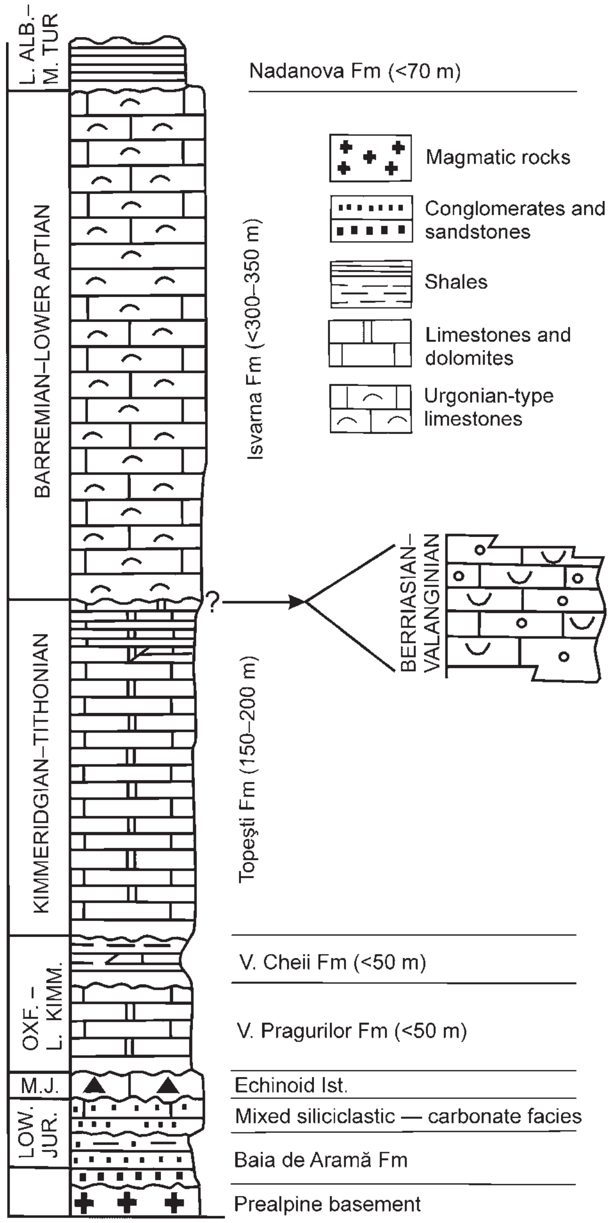

Fig. 2. Stratigraphic succession of the Jurassic-Cretaceous deposits from the Vâlcan Mountains (after Pop & Bucur 2001).

tions by Cuvillier et al. (1968). The species was placed either in the Lower Kimmeridgian (Pelissié et al. 1984; Tasli 1993), the Kimmeridgian-Lower Tithonian (Pop & Bucur 2001; Bucur & Săsăran 2005; Velić 2007), or the Oxfordian-Middle Tithonian (Bassoullet 1997a).

Kurnubia palastiniensis Henson is another typical foraminifer from Upper Jurassic deposits. It was found in Lower Oxfordian (Pelissié & Peybernès 1982), Oxfordian-Kimmeridgian (Peybernès 1976; Clark & Boudagher-Fadel 2002), Kimmeridgian (Hottinger 1967; Altiner 1991; Omaña & Arreola 2008), Kimmeridgian-Lower Tithonian (Pop & Bucur 2001; Schlagintweit et al. 2005) or in Oxfordian-Middle Tithonian (Bassoullet 1997a; Bucur & Săsăran 2005; Velić 2007) formations. To summarize, the distribution interval for this species is Oxfordian-Middle Tithonian.

The same time interval is indicated by the calcareous algae assemblage. *Megaporella boulangeri* Deloffre & Beun was described from the Kimmeridgian of Morocco (Deloffre & Beun 1986). Recently, Bouaouda et al. (2009) revised the distribution of this alga in the Moroccan Atlantic basin; they assigned it to the Callovian-Oxfordian interval. In the Tethyan area, the species was identified by Pop & Bucur (2001) in Kimmeridgian-Tithonian deposits from the Southern Carpathians, Romania. *Clypeina sulcata* (Alth) is typical for the Kimmeridgian-Berriasian interval (Granier & Deloffre 1993; Bassoulet 1997b; Bucur 1999).

In the Berriasian-Valangian-?Hauterivian deposits, a micropaleontological association consisting of foraminifera: *Haplophragmoides joukowskyi* (Charollais, Broennimann & Zaninetti), *Andersenolina cherchiae* (Arnaud-Vanneau, Boisseau & Darsac) (Fig. 4.7), *Montsalevia salevensis* (Charollais, Broennimann & Zaninetti) (Fig. 4.8), *Bramkampella arabica* Redmond, *Vercorsella camposaurii* (Sartoni & Crescenti) (Fig. 4.9), *Mohlerina basiliensis* (Mohler), *Mayncina* sp., and calcareous algae: *Clypeina parasolkani* Farinacci & Radoičić, *Clypeina* sp., *Salpingoporella circassa* (Farinacci & Radoičić), *Salpingoporella annulata* Carozzi, and *Macroporella praturloni* Dragastan has been identified.

Andersenolina cherchiae (Arnaud-Vanneau, Boisseau & Darsac) has been frequently reported from Berriasian-Valanginian deposits (Arnaud-Vanneau 1980; Neagu 1994; Bucur et al. 1995; Mancinelli & Coccia 1999; Pop & Bucur 2001). Velić (2007) considered *H. joukowskyi*, *M. salevensis* and *V. camposaurii* to be index fossils for the Valanginian of the Adriatic carbonate platform.

The Barremian-Aptian foraminiferal association consists of the following species: *Paracoskinolina*? *jourdanensis* (Foury & Moullade) (Fig. 4.10), *Montseciella arabica* (Henson) (Fig. 4.11), *Orbitolinopsis* sp.?, *Paracoskinolina* sp.?, *Paracoskinolina* cf. *maynci* (Chevalier) (Fig. 4.12), cf. *Palaeodictyoconus actinostoma* Arnaud-Vanneau & Schroeder (Fig. 4.13), ?*Palorbitolina* sp. (Fig. 4.14), *Vercorsella scarsellai* (De Castro) (Fig. 4.15), *Everticyclammina hedbergi* (Maync), *Pseudolituonella gavonensis* (Foury), *Debarina hahounerensis* (Fourcade, Roul & Vila), *Neotrocholina friburgensis* Guillaume & Reichel, *Sabaudia minuta* (Hofker), *Pseudocyclammina lituus* Yokoyama, *Nautiloculina broennimanni* Arnaud-Vanneau & Peybernès, *Everticyclamina* sp., *Vercorsella* sp., *Nautiloculina* sp., *Charentia* sp. and *Commaliama* sp. The association of calcareous algae includes: *Salpingoporella muehlbergii* (Lorenz), *Salpingoporella melite* Radoičić, *Salpingoporella* cf. *cemi* Radoičić, *Salpingoporella* sp., *Clypeina solkani* Conrad & Radoičić, *Clypeina* cf. *solkani* (Conrad & Radoičić), *Suppiluliumaella tuberifera* (Sokać & Nikler), *Milanovicella* sp., *Clypeina* sp., *Pseudoactinoporella fragilis* Conrad, *Similiclypeina conradi* Bucur, *Salpingoporella* cf. *genevensis* (Conrad), *Salpingoporella heraldica* Sokać, *Salpingoporella urladanasi* Conrad & Peybernès, and *Falsolikanella danilovae* (Radoičić).

As a whole, this association is characteristic of the Barremian interval in the Mesogean area. Among the species in this association, the most important biostratigraphically are the orbitolinids such as *Paracoskinolina*? *jourdanensis* (Foury & Moullade). It represents clear paleontological evidence for the

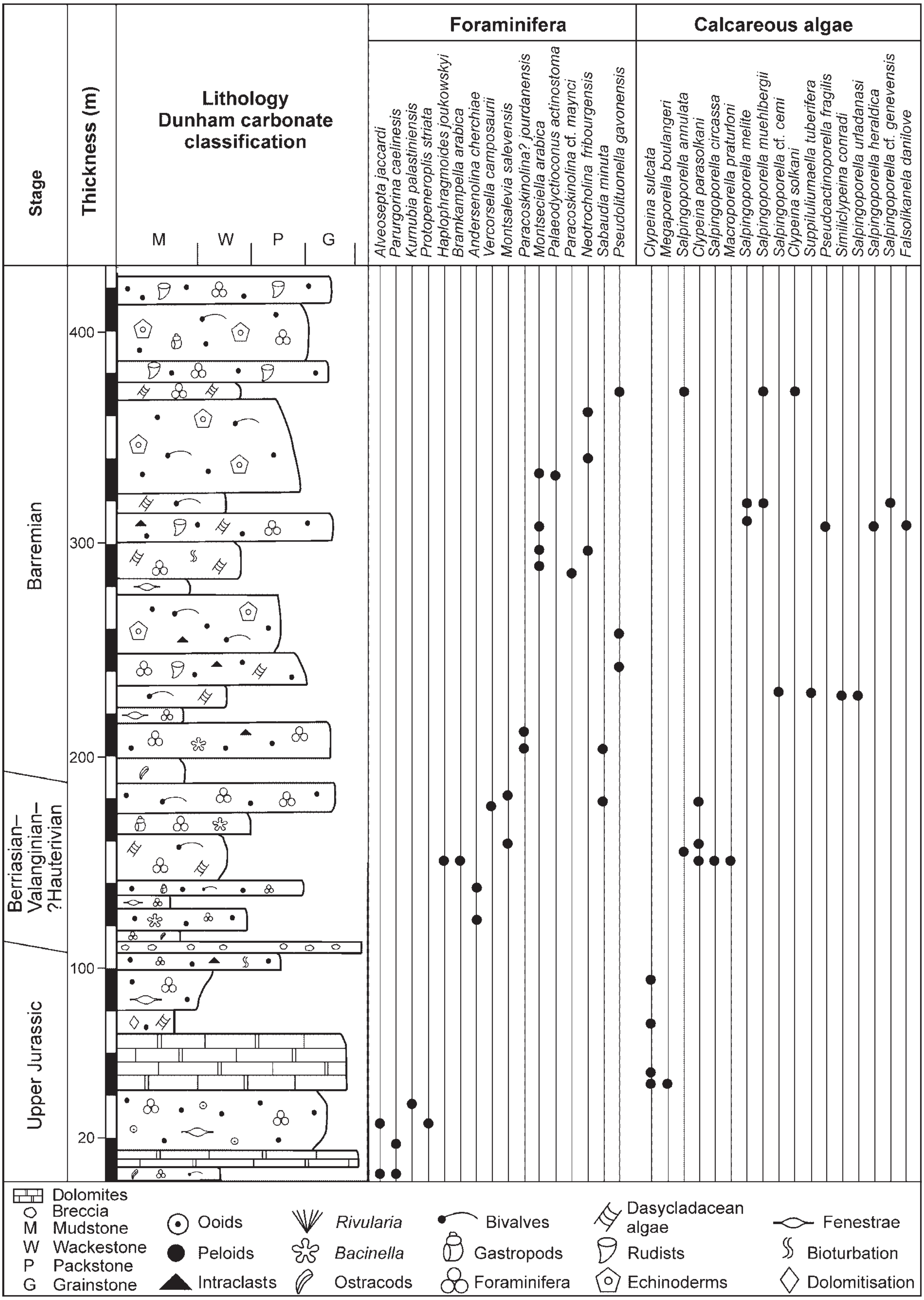

Fig. 3. General succession of the carbonate deposits from the Vâlcan Mountains, with vertical distribution of the identified marker microfossils (composite section).

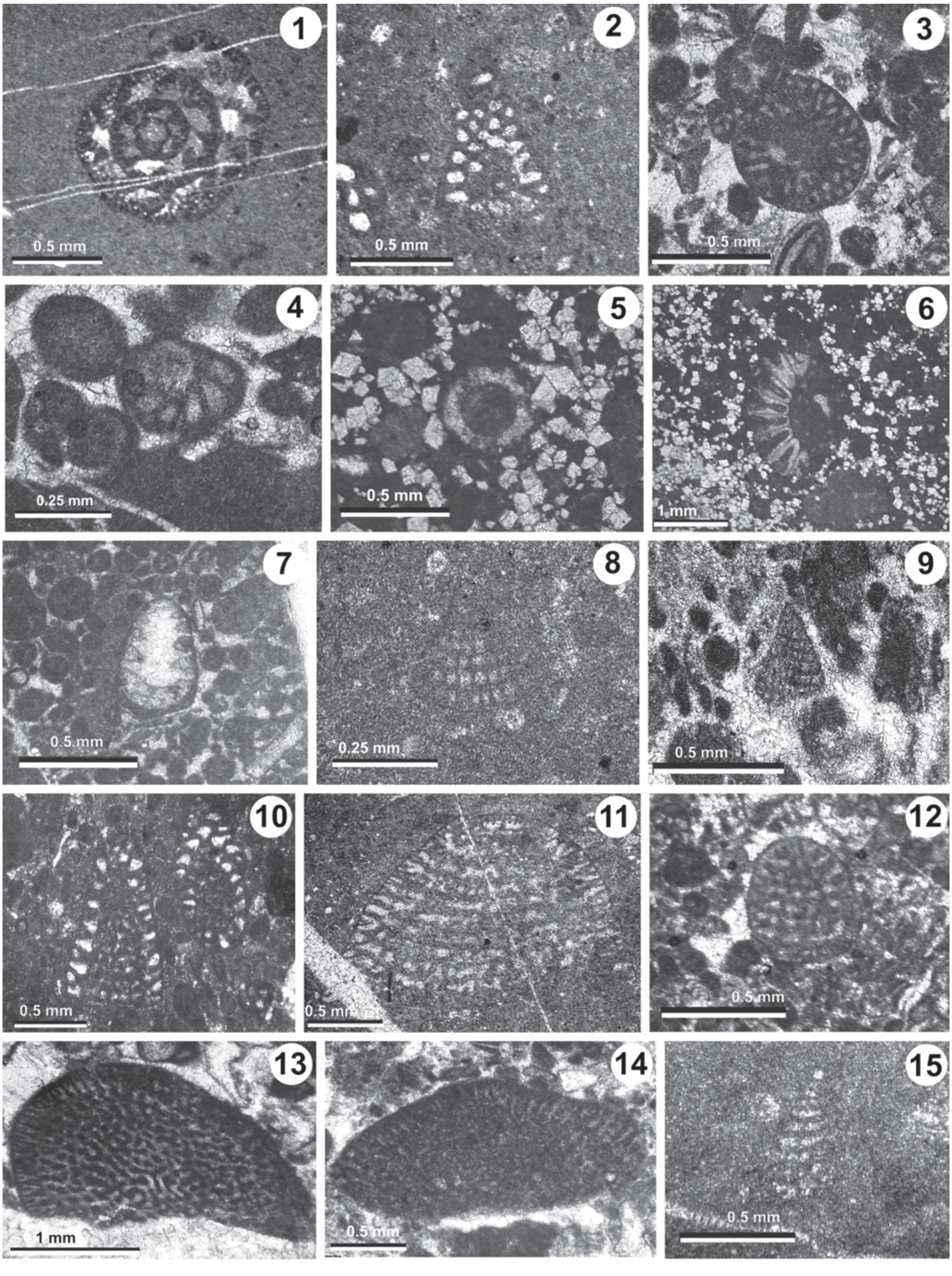

Fig. 4. 1–6 — Microfossils from the Upper Jurassic association. **1** — *Alveosepta jaccardi* (Schrodt) (Sample 9345A); **2** — *Parurgonina caelinensis* Cuvillier, Foury & Pignatti Morano (Sample 9499); **3** — *Kurnubia palastiniensis* Henson (Sample 11); **4** — *Protopeneroplis striata* Weyschenk (Sample 7); **5** — *Megaporella boulangeri* Deloffre & Beun (Sample 9502); **6** — *Clypeina sulcata* (Alth) (Sample 9502). 7–9 — Microfossils from the Berriasian–Valangian–?Hauterivian association. **7** — *Andersenolina cherchiae* (Arnaud-Vanneau, Boisseau & Darsac) (Sample 208); **8** — *Montsalevia salevensis* (Charollais, Broennimann & Zaninetti) (Sample 45); **9** — *Vercorsella camposaurii* (Sartoni & Crescenti) (Sample 253). 10–15 — Microfossils from the Barremian association. **10** — *Paracoskinolina*? *jourdanensis* (Foury & Moullade) (Sample 9517); **11** — *Montseciella arabica* (Henson) (Sample 9577); **12** — *Paracoskinolina* cf. *maynci* (Chevalier) (Sample 9600); **13** — cf. *Palaeodyctioconus actinostoma* Arnaud-Vanneau & Schroeder (Sample 262); **14** — *Palorbitolina* sp. (Sample 263); **15** — *Vercorsella scarsellai* (De Castro) (Sample 9571).

presence of Lower Barremian in the studied limestone succession (Michetiuc et al. 2008). The orbitolinids *Paracoskinolina* cf. *maynci* (Chevalier) and cf. *Palaeodictyoconus actinostoma* Arnaud-Vanneau & Schroeder, encountered in the upper part of the succession from Sârbului Valley, have also been identified in the interval between the upper part of Lower Barremian and the Lower Aptian (Masse 1976; Arnaud-Vanneau 1980; Bucur 1997). Clavel et al. (2010) revised the biostratigraphic distribution of the orbitolinids by correlation with ammonite zonations placing the first occurrence of *Paracoskinolina maynci* (Chevalier) in the Upper Hauterivian and that of the *Palaeodictyoconus actinostoma* Arnaud-Vanneau & Schroeder in the lowermost Barremian. The calcareous algae assemblage characterizes the Barremian–Aptian time interval (Granier & Deloffre 1993; Bucur 1999).

Microfacies analysis

We have identified six main microfacies types (MFT) within these successions. Microfacies types (sensu Flügel 2004) are defined according to criteria that allow attribution of specific environmental factors and specific depositional settings. The microfacies criteria used here include: depositional texture and fabric, grain composition and early diagenetic features. Each MFT and its occurrence is described and the environmental interpretation is discussed.

MFT 1: non-fossiliferous, fenestral, laminated mudstone/wackestone and subaerial exposure facies

This facies type is scarcely represented in the stratigraphic succession, but is more frequent in the lower part. The most typical diagnostic features are the presence of non-fossiliferous (or poorly fossiliferous), unstructured or finely-laminated, fine granular micrites, locally including cryptomicrobial (Fig. 5.1,2) or *Rivularia*-type structures. Scattered dolomite rhombs are locally present in the micritic matrix and grains. Sometimes the original structure is obliterated by mosaics of euhedral to subhedral dolomite crystals. Biodiversity is very low, microfossils being mainly represented by ostracods, rare foraminifera and gastropods (Fig. 5.3). Charophyte fragments (stems and gyrogonites) are also locally present in a homogeneous or fenestral matrix (Fig. 5.4). Some reworked bioclasts from the subtidal area may also occur.

Also included in this facies association are sediments that have undergone subaerial exposure. Exposure features include desiccation cracks, paleosols and paleokarst. They are more common in the lower parts of the profiles from the Sârbului and Bistrița Valleys.

Interpretation: Non-fossiliferous, finely laminated carbonate muds and cryptalgal fabrics are common constituents of supratidal or upper intertidal environments with low water energy. In these areas the fluctuating salinity and frequent subaerial exposures do not permit proliferation of infauna or browsing organisms that homogenize the primary sedimentary structures (Shinn 1983). The presence of charophyte remains is usually regarded as good indicator of freshwater environments (Tucker & Wright 1990), but salinity-tolerant forms were also reported from recent and ancient brackish environments (e.g. Burne et al. 1980; Feist & Grambast-Fessard 1984; Climent-Domènech & Martín-Closas 2009). In the studied area the charophyte remains appear along with a brackish fauna of ostracods, and some are impregnated with Fe-oxides. The preferential staining of bioclasts is probably similar to the preferential blackening of Pleistocene corals in Florida, attributed by Strasser (1984) to the percolation of staining fluids through their skeletons. The red pigmentation is probably related to subaerial alteration (Wright et al. 2000; MacNeill & Jones 2006).

Evidence of pedogenic influence such as desiccation-brecciation, mottling, glaebule development, black pebbles, root structures and microkarst (Esteban & Klappa 1983; James & Choquette 1984; Demicco & Hardie 1994), are all common features of this facies association.

The *in situ* brecciation of muds has led to the formation of polygonal fracture networks filled with sparite or with sediment containing peloids and pisoids (Fig. 5.5). Brecciation can be induced by desiccation (Fig. 5.6), displacive crystallization of calcite, root activity and/or dissolution (Flügel 2004). Carbonate nodules (or glaebules in soil terminology, see Esteban & Klappa 1983) are also frequent constituents of caliche profiles, but their origins are not fully understood (Wright & Tucker 1991). Circum-granular cracks, filled with spar cement, usually develop around glaebules (Fig. 5.7). They are formed by alternate shrinkage and expansion induced by seasonal drying/wetting cycles (Esteban & Klappa 1983). Mottling from red-brown, yellow to grey is also present (Fig. 5.8). This pedogenetic process may develop as a result of fluctuating Eh–pH conditions or through redistribution of iron oxide and iron hydroxide particles (Buurman 1980). The presence of black pebbles 'floating' in this type of matrix is probably related to the burning of organic matter because features like the gradation of blackening and the angular nature of the pebbles (Fig. 5.9), seen here, are arguments cited by Shinn & Lidz (1988) as characteristic of subaerial blackening by fire. Other interpretations include impregnation by dissolved, colloidal or finely particulate organic matter (Strasser 1984) or the blackening by finely disseminated pyrite (Wright 1986a).

No rhizocretions have been encountered but some alveolar-septal structures were found (Fig. 5.10). Similar structures have been reported from ancient and recent paleosols (Adams 1980; Klappa 1980; Wright 1986b; Wright et al. 1988). They have been interpreted by Wright (1986b) as resulting from fungal activity around roots. Root traces represented by rounded or irregular voids lined with dense micritic coatings (Fig. 5.11) are interpreted as being the products of void lining biofilms or calcitic cutans (MacNeil & Jones 2006).

Microkarstic products represented by collapse breccias, solution voids, and some speleotems (flowstone) (Fig. 5.12) are also present. Such structures probably represent the upper vadose zone (Esteban & Klappa 1983).

MFT 2: fenestral wackestone/packstone-grainstone

This MFT is interlayered at different levels within the whole stratigraphic succession and is characteristic for the intertidal

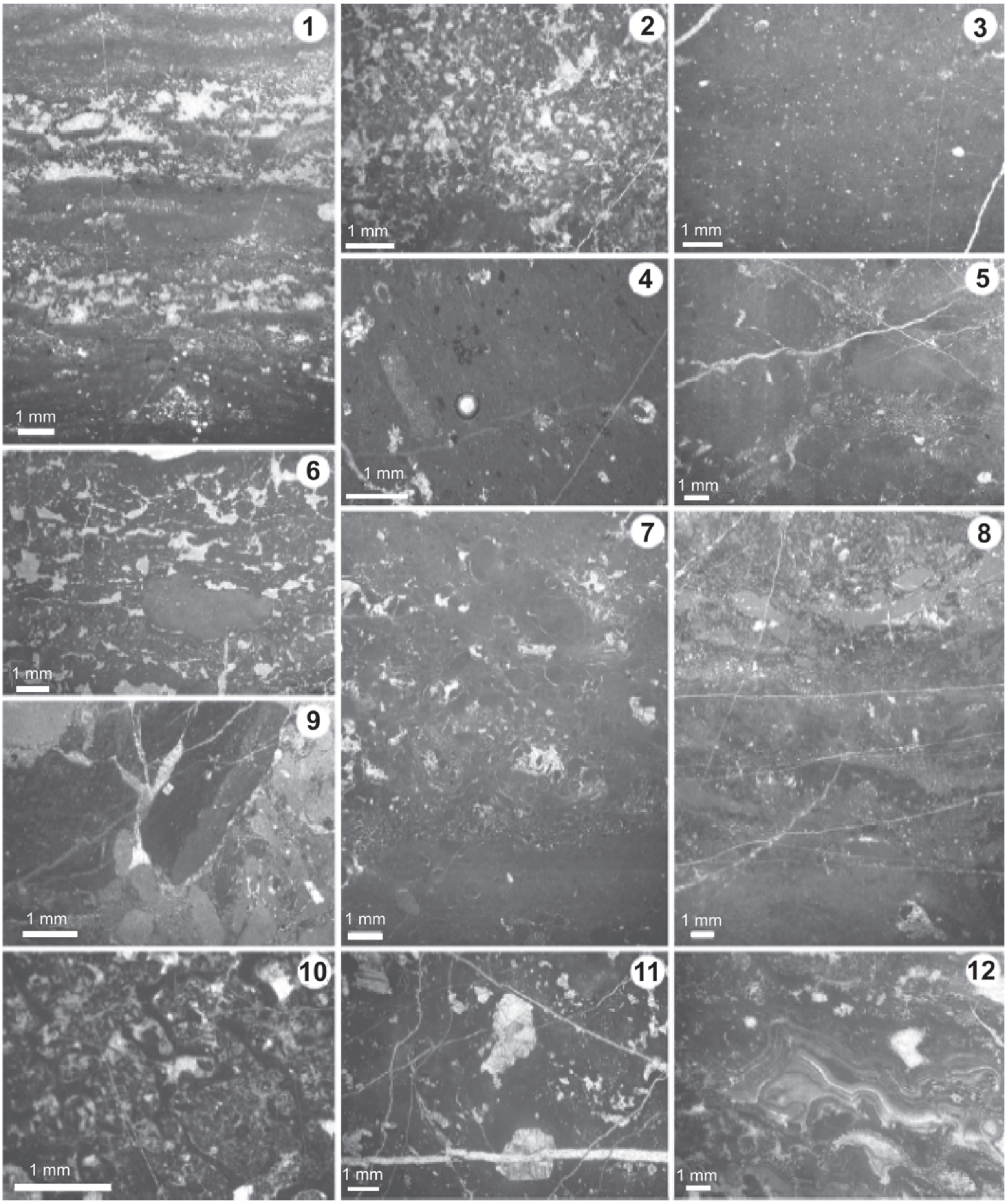

Fig. 5. Deposits from the supratidal zone (MFT 1). **1** — microbial mats displaying crinkled lamination (Sample 220, Barremian); **2** — cryptomicrobial structures (Sample 9408, Upper Jurassic); **3** — mudstone with ostracods (Sample 9345, Upper Jurassic); **4** — mudstone with charophyte stems and gyrogonites (Sample 96, Barremian); **5** — brecciated micrite; fissures are filled with peloids and pisoids (Sample 234, Upper Jurassic); **6** — desiccation structures (mud chips) (Sample 9356, Upper Jurassic); **7** — incipient stage of glaebule development; glaebules are surrounded by complete or incomplete circumgranular cracks (Sample 244, Upper Jurassic); **8** — paleosoil development with intensive brecciation and mottling (Sample 236, Upper Jurassic); **9** — subangular black pebble displaying gradation of blackening (Sample 242, Upper Jurassic); **10** — alveolar-septal structures (Sample 9344, Upper Jurassic); **11** — root traces lined with dense micritic coatings (Sample 249, Upper Jurassic); **12** — flowstone structures (Sample 202, Upper Jurassic).

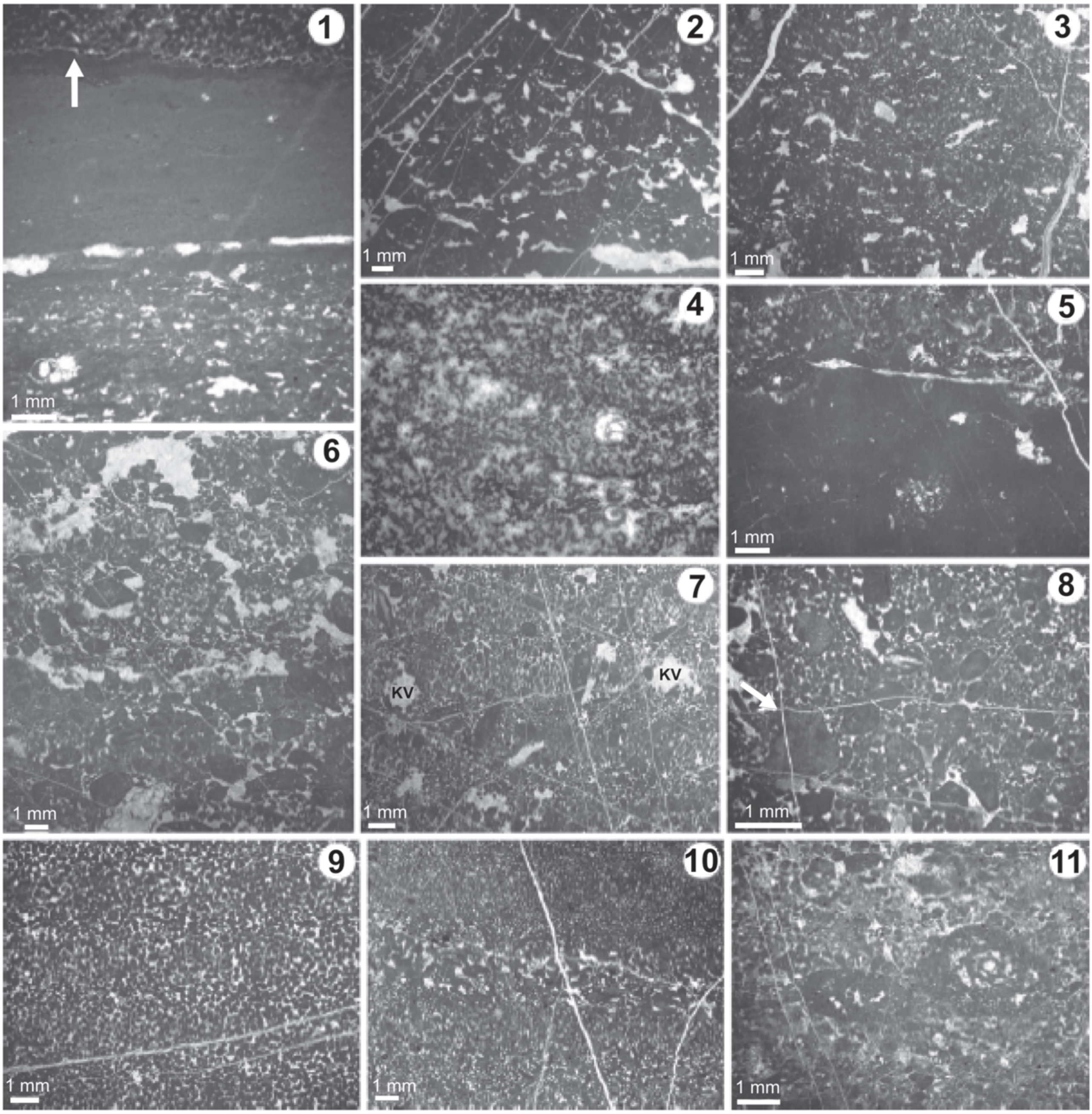

Fig. 6. 1–8 — Deposits from the intertidal zone (MFT 2). **1** — alternating deposition and erosion (arrow) processes, as a result of changes in current velocity: quiet water deposition (bottom of the picture) vs. higher energy deposition (top of the picture) (Sample 213, Neocomian); **2** — peloidal wackestone with irregular fenestrae (Sample 217, Neocomian); **3** — laminoid-fenestral peloidal wackestone (Sample 9391, Upper Jurassic); **4** — microbial mats with small gastropods (Sample 216, Neocomian); **5** — burrowed micrite containing *Favreina*-type coprolites grading into fenestral microbial mats (upper part) (Sample 9363, Upper Jurassic); **6** — intraclastic peloidal packstone-grainstone; note the early cementation by micritic cements and bimodal sorting (Sample 9513, Neocomian); **7** — peloidal intraclastic grainstone with keystone vugs (KV) (Sample 9465, Barremian); **8** — intraclastic peloidal packstone-grainstone with *Rivularia*-type microbial structure (arrow) (Sample 41, Neocomian). **9–11** — Deposits of the high-energy subtidal zone (MFT 3). **9** — very well-sorted peloidal bioclastic grainstone (Sample 7, Upper Jurassic); **10** — laminated peloidal grainstone (Sample 9396, Upper Jurassic); **11** — packstone-grainstone with large benthic foraminifera (*Pseudocyclammina lituus*) (Sample 9515, Barremian).

environment. One of the main features of these deposits is the presence of fenestral structures. The fenestrae are a few millimeters in size and their shapes are flat to spherical or irregular. They contain sparitic cement, geopetal infillings, or are filled with vadose silt, pointing to a meteoric water influence. A transition from muddy low-energy deposits to grainy high-energy deposits was encountered in some of the cases. The limit between them is usually marked by an erosional surface (Fig. 6.1). Two subtypes have been distinguished on the basis of structural and textural features: a) fenestral-laminated peloidal wackestone (formed in low-energy hydrodynamic conditions) and b) fenestral peloidal packstone-grainstone (formed when the hydrodynamic energy was intermittently high).

MFT 2a

The first subtype (Fig. 6.2,3) is commonly associated with microbial bindstones and wackestones. The biodiversity is still low; sometimes inside the fenestrae one can find charophyte oogones, probably reworked. Gyrogonites are easily transported, especially if they are desiccated (Wright 1990). Small gastropods are locally present in the microbial mats (Fig. 6.4). Sometimes intensely bioturbated micrites, containing many *Favreina*-type coprolites and rare ostracods, are grading into fenestral microbial mats (Fig. 6.5). The fenestrae associated with this subfacies are of laminoid-fenestral and irregular type.

MFT 2b

These deposits are moderately to well sorted, sometimes displaying bimodal sorting; the particles are represented by well-sorted and well-rounded peloids, micritic intraclasts and oncoids. Bioclasts are relatively rare, they are represented by foraminifera (miliolids, textulariids, *Sabaudia minuta* (Hofker), *Vercorsella* sp.) sometimes showing a micritic envelope, bivalves, gastropod molds, algae, or *Rivularia*-type structures (Fig. 6.6–8). The fenestral pores within these deposits are of spherical to irregular types, and keystone vugs are also locally present.

Interpretation: As many authors mentioned (e.g. Tucker & Wright 1990; Flügel 2004) the assignment of ancient limestones to the intertidal environment is a difficult task. This is due to the lack of reliable diagnostic features, and to the similarities with the adjacent supratidal environments. Fenestral structures in ancient and recent carbonate deposits are usually regarded as good indicators of upper intertidal to supratidal settings (Shinn 1983; Tucker & Wright 1990). Shinn & Robbin (1983) showed that open fenestrae are destroyed by mechanical compaction so that the preservation of fenestrae of all types in mudstones signifies that the host sediments were cemented before even shallow burial. Such an early cementation is a characteristic feature of peritidal deposits (Grover & Read 1978; Shinn 1983; James & Choquette 1984; Tucker & Wright 1990). Fenestrae have polygenic origins and may be caused by wetting and drying of carbonate mud, by degassing of decaying organic material, by drying out of the surface of cyanobacterial mats (in case of laminoid and irregular fenestrae), or by air and gas bubbles trapped during deposition of the host sediment or generated by post-depositional decay of organic matter (in the case of spherical fenestrae) (Demicco & Hardie 1994). Keystone vugs present in the grain-supported facies are probably the result of air-bubble trapping during storm deposition in the swash zone on beaches or in the sheetwash zone on tidal flats (Shinn 1986; Demicco & Hardie 1994; Flügel 2004). Irregular fenestrae associated with cyanobacterial mats can be the result of irregular growth of these mats (Săsăran 2006).

Other characteristic features of the intertidal regime are erosion alternating with deposition, as well as rapid changes in current and wave velocity (Ginsburg 1975).

Fenestral limestones containing abundant fenestrae, associated with distinctive early diagenetic features (crystal silt, leached fossils, micritization of bioclasts originating from normal marine environments), erosional surfaces, cryptalgal sediments, and a restricted fauna (ostracods and gastropods) suggesting periodic emergence and desiccation, point to an intertidal environment of formation in the case of these deposits.

MFT 3: peloidal bioclastic packstone/grainstone

These limestone types are interlayered at several levels within the stratigraphic succession. The granular facies mainly consists of moderate- to well-sorted peloids with subangular to rounded morphologies (Figs. 6.9,10), besides rare superficial ooids, micritic intraclasts and oncoids. Micritized bioclasts are common. Skeletal grains appear in various quantities and are represented by gastropods, fragments of bivalves and echinoderms, benthic foraminifera (Fig. 6.11), and dasycladalean algae. The foraminifera include: *Kurnubia palastiniensis* Henson, *Protopeneroplis striata* Weyschenk, *Andersenolina cherchiae* (Arnaud-Vanneau & Boisseau), *Mohlerina basiliensis* (Mohler), *Paracoskinolina*? *jourdanensis* (Foury & Moullade), *Pseudocyclammina lituus* Yokoyama, *Sabaudia minuta* (Hofker), *Vercorsella* sp. The dasycladalean algae are represented by *Clypeina parasolkani* Farinacci & Radoičić, *Pseudoactinoporella fragilis* Conrad, *Salpingoporella* sp. Also microbial nodules (of *Rivularia*-type) occur.

Interpretation: The non-skeletal components, such as peloids, intraclasts, ooids, cortoids and oncoids, and mostly sparitic, or at least partly sparitic groundmass indicate an agitated subtidal environment. The diverse skeletal components, such as larger and smaller benthic foraminifera and calcareous algae point to normal-marine, well-oxygenated conditions. These deposits were formed in shallow subtidal environments above the fair-weather wave base.

MFT 4: packstone-grainstone with rudists and wackestone/packstone with green algae and foraminifera

These deposits, characteristic of the middle and upper part of the section, consist of wackestone/packstone, and packstone-grainstone with highly diversified paleontological assemblages: molluscs, benthic foraminifera, and green algae. At certain intervals, rudists took part to the colonization of the substrate building-up a typical Urgonian-type facies (Masse 1979, 1995; Gili et al. 1995) (Fig. 7.1,2). The rudists characterizing this facies have a patchy distribution, thick shells, large sizes, and they show no signs of perforation, micritization or encrustation. The sediment associated with this facies is usually represented by poorly washed packstone-grainstone with small and very diverse foraminifera (especially miliolids, cuneolinids and textulariids) and peloids (Fig. 7.3).

Another microfacies, associated with the rudistid one, is represented by wackestone-packstone with green algae and large benthic foraminifera (Fig. 7.4,5). The main characteristic

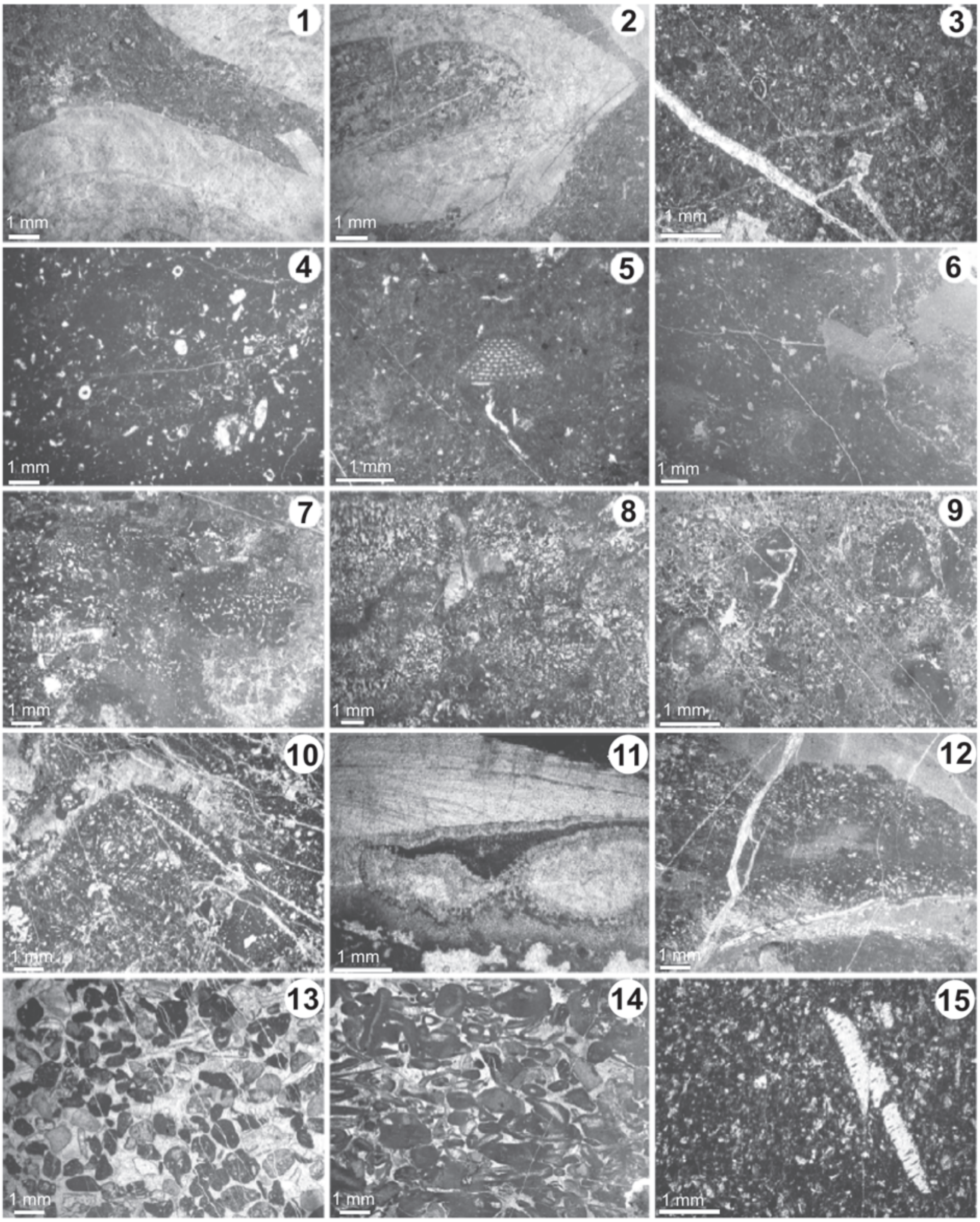

Fig. 7. 1–6 — Deposits from the shallow subtidal environments (MFT 4): **1–2** — poorly washed packstone-grainstone with large rudists and small foraminifera (Samples 53 and 9488, Barremian); **3** — packstone-grainstone with abundant small foraminifera (Sample 9467, Barremian); **4** — bioturbated wackestone with abundant dasycladalean algae fragments (Sample 207, Neocomian); **5** — wackestone with orbitolinids (*Montseciella arabica*) (Sample 95, Barremian); **6** — normal-marine deposits affected by subaerial exposure, leading to dissolution and vadose silt infiltration (Sample 9486, Barremian). 7–12 — Deposits from the restricted subtidal environments (MFT 5). **7** — inhomogeneous wackestone-packstone with *Lithocodium* (Sample 9498A, Barremian); **8** — *Bacinella* bindstone containing rudist fragments (Sample 98, Barremian); **9** — packstone with *Bacinella* oncoids (Sample 9460, Barremian); **10** — bored and micritized rudist fragment, encrusted by *Bacinella* and *Lithocodium* (Sample 79, Barremian); **11** — rudist fragment consumed by microbes; note the microstalactitic microbial cement formed beneath it (probably also of microbial origin as suggested by their micropeloidal structure) (Sample 218, Barremian); **12** — pervasive dissolution of rudist fragment and matrix and subsequent deposition of vadose silt (Sample 9472, Barremian). 13–15 — Deposits from the offshore zone (MFT 6). **13–14** — well sorted bioclastic grainstone with echinoderm plates and other recrystallized or micritized bioclastic fragments (Samples 101 and 9492, Barremian); **15** — packstone with angular bioclastic fragments; the large bioclastic fragment is a brachiopod shell (Sample 9538, Barremian).

of this microfacies is the diversification of organisms in mud-supported, sometimes bioturbated matrix. Dasycladalean algae are very frequent (*Clypeina solkani* Conrad & Radoičić, *Salpingoporella melite* Radoičić, *Salpingoporella muehlbergii* (Lorenz), *Similiclypeina conradi* Bucur), along with benthic foraminifera (*Montseciella arabica* (Henson), *Neotrocholina friburgensis* Guillaume & Reichel, *Vercorsella scarsellai* (De Castro)) and other skeletal grains similar to those of the high-energy environment (MFT 3).

Interpretation: The Lower Cretaceous rudists are usually regarded as characteristic inhabitants of very shallow waters and are especially linked to the inner, more or less protected parts of the Urgonian platforms (Masse 1976, 1979, 1992; Masse & Philip 1981; Skelton & Gili 1991). Their association with a grainy-muddy substrate containing abundant small foraminifera also suggests inner platform (lagoonal) conditions with moderate to low-energy conditions.

The intensely bioturbated bioclastic wackestone microfacies types containing normal marine fauna dominated by dasycladalean algae besides foraminifera with complex tests, rudist fragments, and gastropods have been interpreted as being formed in the lower subtidal environment with low hydrodynamic energy. The presence of dasycladalean algae points to warm, relatively shallow waters (Bucur & Săsăran 2005).

Some of the beds containing microfacies types 3 and 4 show traces of subaerial exposure, such as dissolution and recrystallization of bioclasts, or voids filled with vadose-silt (Fig. 7.6).

MFT 5: wackestone/packstone with rudist fragments and microencrusters, and packstone-grainstone with microbialite

This MFT is associated with the subtidal marine facies presented above and it is represented by peloidal wackestone/packstone with abundant microencrusters and bioclastic packstone-grainstone with microbialite. The diversity of flora and fauna is low, bioclasts being mainly represented by problematic microencrusters of *Bacinella*- (very abundant) or *Lithocodium*-type and *Rivularia*-type organisms (Fig. 7.7). *Bacinella* is present either in the matrix of these deposits, or inside and around the bioclastic fragments forming oncoids (Fig. 7.8,9). The bioclastic fragments are mainly represented by bored and micritized rudist fragments (Fig. 7.10) but never by whole rudist shells. The sediment is inhomogeneous, suggesting intensive burrowing.

Some of these deposits may contain a normal-marine fauna with foraminifera, green algae, echinoids or rudists, associated with peloids and intraclasts. This association witnesses an original normal-marine environment later grading into a restrictive one, a change leading to the colonization of the substrate by calcimicrobial structures (Fig. 7.11) and finally even to the subaerial exposure of the sediment, with related dissolution, reprecipitation and micritization processes affecting the bioclasts (Fig. 7.12).

Interpretation: This association is characterized by the presence of *Bacinella* and *Lithocodium* along with fragmented rudist shells. The systematic position of *Bacinella* and *Lithocodium* was intensely disputed; the first one being usually interpreted as a cyanobacterium (Schäffer & Senowbari-Daryan 1983; Maurin et al. 1985; Camoin & Maurin 1988) while the second one was regarded as a Codiacean alga, lituolid foraminifer, or cyanobacterium (for a comparison of different taxonomic interpretations see Schlagintweit et al. 2010). Recently, Schlagintweit et al. (2010) re-interpreted these organisms as being ulvophycean green algae.

Regardless of their taxonomic position, most authors regard the two microproblematic organisms as being characteristic of very shallow, well-oxygenated and relatively oligotrophic environments (Leinfelder et al. 1993; Dupraz & Strasser 1999, 2002; Pittet et al. 2002; Reolid et al. 2009). The large oncoids with lobate outlines, dominated by microencrusters (*Bacinella* and *Lithocodium*), correspond to oncoids of types 3 and 4 described by Védrine et al. (2007) or to the organism-bearing oncoids of Dahanayake (1977). The above-mentioned authors ascribed these types of oncoids to the low-energy open-lagoonal environments, where the microbial meshwork had time to grow. In contrast, the smaller, spherical oncoids, with micritic, homogeneous cortex (type 1 oncoids of Védrine et al. 2007) are often associated with packstone-grainstone and represent higher energy conditions.

Encrustation, borings, breakage, burrowing and micritization are common, indicating low accumulation rates (Enos 1983). Oncoid growth also requires low sedimentary rates (Peryt 1981; Flügel 2004; Védrine et al. 2007). The presence of abundant oncoids in the Oxfordian of the Swiss Jura was correlated (Védrine et al. 2007) with the beginning of a long-term sea-level rise. Furthermore, the authors correlated the different types of oncoids with small-scale sea-level fluctuations. Consequently, this facies was probably formed in a subtidal lagoonal environment characterized by reduced accumulation rates and was mainly controlled by water depth.

MFT 6: bioclastic packstone/grainstone

This facies dominates the upper part of the succession. The most typical carbonate particles included are bioclasts, represented by echinoid plates (sometimes comprising more than 50 % of the total) of arenitic sizes and recrystallized fragments of molluscs (Fig. 7.13). Most bioclasts either exhibit constructive micritic envelopes, or are marginally or completely micritized (Fig. 7.14). Besides, well-rounded to subangular peloids, micritic intraclasts, microbial nodules, bryozoans, brachiopods, foraminifera (*Montseciella arabica* (Henson), *Palorbitolina* sp., *Palaeodyctioconus actinostoma* Arnaud-Vanneau & Schroeder), and dasycladalean algae are present. The echinoid fragments are well-rounded and locally show syntaxial overgrowth cement. Some bioclasts are affected by processes of micritization, dissolution and recrystallization under the effect of meteoric waters.

Interpretation: These deposits showing evidence of intense reworking and containing a predominantly open marine fauna imply a formation in a marine environment with high hydrodynamic energy; they represent bioclastic shoals on the platform margin or on highs in the platform interior (corresponding to FZ 6 sensu Wilson 1975 and Flügel 2004). This microfacies is sometimes associated with wackestones and packstones containing angular bioclastic fragments and representing the perishoal offshore environment (Fig. 7.15).

Paleoenvironmental reconstruction and evolution

The detailed microfacies study allows the differentiation of several facies belts. In a transect from the shoreline to the platform margin the following facies zones occur: (1) inner platform, (2) middle platform and (3) outer platform (Fig. 8). For a better understanding of the depositional facies belts, comparisons with modern settings have been used.

1. Inner platform. In most of the studied sections the peritidal deposits dominate their lower parts, although some thin intercalations exist in the whole section. The supratidal facies belt was dominated by fine, non-fossiliferous muds (MFT 1) representing the result of sedimentation on the vast, protected supratidal marshes that were subject to periodic flooding by sea water during spring tides and storm events. The charophyte remains in some of these supratidal deposits suggests the presence of freshwater ponds.

No well-developed caliche profile or karstic features have been encountered in these deposits, but some evidence of subaerial exposure and pedogenesis do exist. In contrast, the supratidal deposits from the lower part of Sârbului section show greater thickness, no marine influence and more pronounced pedogenic features. Such deposits were defined by MacNeil & Jones (2006) as "disconnected palustrine deposits". Their local presence suggests lateral facies variability, probably caused by the inherited paleotopography or by differential subsidence. A modern example of such deposits are the Florida Everglades showing that the climate and topography were important controls of the marginal marine settings (e.g. Platt & Wright 1992).

The supratidal environments are good indicators of climatic conditions: even without having any clay-mineralogical data, but by virtue of sedimentological and early diagenetic data (lack of evaporites, paleosoil characteristics, meteoric water input) humid to sub-humid climatic conditions can be assumed, similar to those of the modern Andros Island (Ginsburg & Hardie 1975).

As already mentioned, recognition of the intertidal facies belt and its subenvironments in ancient carbonates is a difficult task. Based on the energy of the environment we distinguished a low-energy and a high-energy sub-environment. The first one contains cryptalgal fabrics associated with laminar-fenestral or irregular fenestral fabrics (MFT 2a). They contain a restricted fauna and were deposited on intertidal flats with shallow ponds. In recent intertidal environments, situated especially in more humid climates, ponds are a very common feature (Pratt et al. 1992). The presence of abundant crustacean coprolites and burrows and their association with microbialites are also indicative for intertidal environments. In recent environments, burrows by fiddler crabs are abundant in the lower intertidal flats and subtidal ponds (Shinn 1983, 1986).

The granular subfacies (MFT 2b) contains light grey intraclasts and rounded peloids, suggesting reworking of an early lithified sediment from the tidal flats. Some of them may represent high-energy events affecting the flats, while those containing keystone vugs might represent poorly developed beach ridges generated seaward of the tidal flats in the zone of breaking waves. Bimodal sorting is also a characteristic of beach foreshores or beach storm layers (Taira & Scholle 1979).

In the studied sections, the peritidal deposits could not be individualized into cycles with clearly visible deepening-shallowing facies trends. This can be explained by lateral migration of tidal flat subenvironments (facies mosaic; Wilkinson & Drummond 2004; Wright & Burgess 2005).

2. Middle platform. The winnowed packstones and grainstones (MFT 3) rich in peloids, cortoids and intraclasts, containing different amounts of reworked benthic foraminifera and green algae, reflect deposition under high-energy conditions. Moderate turbulence is indicated by high packing density, good sorting and roundness of particles (Bauer et al. 2002). They represent subtidal sand bars moved by bottom currents. In some cases, especially in the lower parts of the sections, where they are associated with intertidal deposits, they might represent tidal channel infillings. Unfortunately, the presence of tidal channels can only be assumed because bipolar (herringbone) cross-stratification is not present, possibly having been destroyed by intense bioturbation.

The low-energy subtidal environments (MFT 4) dominate the middle–upper parts of the sections and were deposited in protected or semi-protected parts of the platform. The protection was ensured by the bioclastic shoals on the platform margin (see discussion below). The ecological requirements of fauna and flora (especially benthic foraminifera and green algae) suggest a shallow-marine environment. The same environment is inferred for the rudists assemblages, which were compared (Masse 1976; Masse et al. 2003) with the *Pinna–Pinctada* assemblages thriving in the shallow-waters of Shark Bay or the Arabian Gulf. Such shallow-water environments were very sensitive to bathymetric changes that could either open or isolate the carbonate platform.

These middle platform deposits show meter-scale cycles, each displaying a

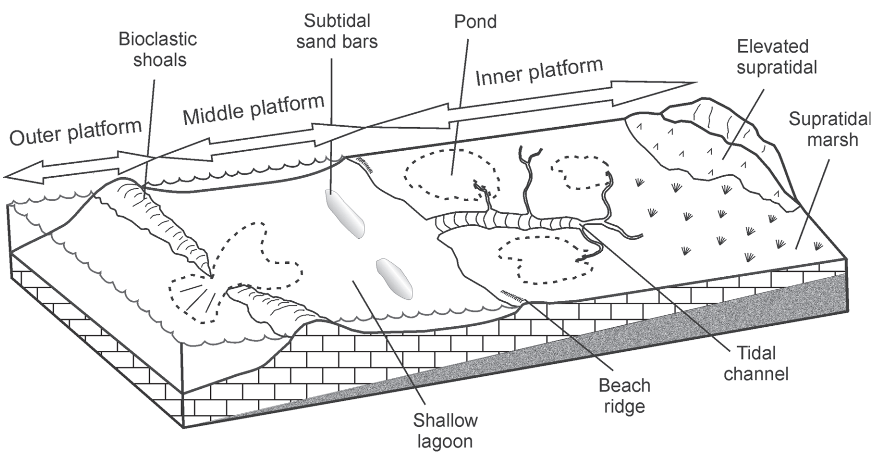

Fig. 8. Schematic reconstruction of the distribution of paleoenvironments of the Vâlcan carbonate platform.

shallowing-upward trend. At one end of the spectrum are the mud dominated algal, foraminiferal wackestone–packstones, representing the deeper, protected environments of the photic zone. They are followed by packstones–grainstones with small foraminifera, associated with rudists, representing shallower and more energetic environments. The lack of micritization, borings and encrustation on rudists shells suggests high depositional rates. In the middle part of the sections (Lower Barremian) the cycles are predominantly composed of rudist fragments and microencrusters (MFT 5). They also show a shallowing-up trend from deeper, low-energy environments, to shallower and more energetic environments. The presence of oncoids, intensive burrowing, perforations and micritization suggest lower sedimentary rates. The fragmentation of rudists is probably the result of intensive *in-situ* bioerosion (Gili 1992; Gili et al. 1995) or of periodic reworking by high-energy episodes.

Sometimes the cycles are capped by thin fenestral wackestones and mudstones of the intertidal zone. The superimposed meteoric diagenesis (grain dissolution, recrystallization, vadose silt) especially affected the MFT 5 and to some extent the MFT 4, suggesting frequent subaerial exposures.

Such shallowing-up sequences in peritidal settings can form through allocyclic or autocyclic processes (Strasser 1991). Autocyclic processes can be created by progradation or migration of sedimentary systems (e.g. Ginsburg 1971; Pratt & James 1986; Strasser 1991) without being related to a sea-level fall. Allocyclic control mechanisms are independent of the depositional processes and are commonly related to different orders of eustatic sea-level fluctuations (e.g. Vail et al. 1991; McLean & Mountjoy 1994; Strasser et al. 1999).

In our case, because of the bad outcrop conditions and the effects of late Senonian tectonics, a correlation of meter-scale cycles between sections is not possible, making it difficult to determine which of the two mechanisms (or a combination of both) was involved. Still, in some of these cycles vadose diagenesis directly overprints the subtidal facies, suggesting that allocyclic processes played an important role in the formation of these sequences (Strasser 1991; Strasser & Hillgärtner 1998; Burgess 2006).

3. Outer platform. The great thickness of the deposits, predominance of echinoderm fragments along with other stenohaline organisms, and the early diagenetic features suggest the existence of bioclastic shoals situated at the platform margin. These shoals were probably the main cause of platform restriction, separating the inner and middle platform from the open ocean (Fig. 8). The closest recent counterpart is represented by the bank-margin shoals of the Great Bahama Bank (Rankey & Reeder 2011). Even though this facies was encountered only in the Upper Barremian, the existence of a high-energy barrier at the platform margin before this period can be inferred from the prevailing restricted conditions. Likewise, in a section situated westward of the studied zone (Mehedinți Plateau), belonging to the same limestone formation, we encountered a Tithonian–Berriasian reef barrier represented by coral-microbial boundstones.

The shallowing-up trend of the meter-scale cycles is still maintained in the upper part of the sections, with the high-energy open marine shoals being covered by lagoonal environments. The great thickness of the high-energy, open marine deposits, and the abrupt backstepping of facies (migration of the platform rim toward platform interior) in the upper part of the sections, implies a rapid growth of the accommodation space. This may be related to a maximum flooding on the long-term sea-level evolution (Strasser & Hillgärtner 1998). The upward shallowing indicates that sedimentation kept pace with the created accommodation space.

Conclusions

The carbonate deposits from the Vâlcan Mountains have been analysed from a sedimentological and biostratigraphic point of view; lithofacies types, fossil assemblages, and their vertical distributions have been defined.

We have identified six microfacies types (MFT 1–MFT 6) within these deposits, based on biotic and abiotic components, sedimentary structures and textures, and early diagenetic features with an environmental significance. The deposits are characteristic of a shallow carbonate platform that can be further subdivided into an inner, middle, and outer platform.

The inner platform deposits are represented by tidal flat deposits and were best developed during the Late Jurassic. Deposition on the tidal flats occurred in a great variety of low- and high-energy sub-environments represented by supratidal marshes and disconnected palustrine deposits, intertidal flats, ponds, beaches and possibly channels. They reflect tropical humid to sub-humid climatic conditions.

These deposits were followed by predominantly middle platform deposits, developed during the Early Cretaceous. They were deposited in high-energy and low-energy environments formed in protected or semi-protected shallow subtidal conditions. Rudists and small benthic foraminifera were the main sediment producers during the Early Cretaceous.

The middle platform deposits interfinger, in the upper parts of the sections, with the outer platform deposits represented by high-energy bioclastic shoals and their associated open-marine deposits.

The vertical succession of microfacies reflects cyclic changes in water depth. They are more visible in successions from the middle and outer platform where they are arranged in shallowing-up cycles. These cycles are superimposed on an overall transgressive trend, testified by the predominance of the inner platform facies in the Upper Jurassic and the transition to middle and outer platform facies during the Early Cretaceous. This long term transgressive trend can be related to the second-order tectono-eustatic cycle (Vail et al. 1991), while the superimposed high frequency cycles can be the result of lower amplitude sea-level oscillations.

Following the micropaleontological study of some new sections, new biostratigraphic arguments have been added, completing and improving the few data available. Three associations of algae and foraminifera have been identified. The first association is characteristic of the Late Jurassic, the second points to Berriasian–Valanginian (possibly also Hauterivian) age, while the third one indicates the Barremian interval. The identified micropaleontological assemblages can also serve comparisons with other Tethyan regions containing Upper Jurassic–Lower Cretaceous deposits (e.g. Jaffrezo 1980; Soták & Mišík 1993; Bassoulet 1997a).

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