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THE FACIES AND SEDIMENTARY EVOLUTION OF THE UPPER JURASSIC-LOWER CRETACEOUS DEPOSITS FROM THE PIATRA CRAIULUI MASSIF

PhD Thesis Summary

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Keywords

Microfacies, biostratigraphy, sequence stratigraphy, subaerial exposure, isotope chemostratigraphy, small scale sequences, medium scale sequences, shallowing upward, carbonate megasequence, Upper Jurassic-Lower Cretaceous

INTRODUCTION

Mesozoic tropical carbonate platforms are well known for their extensive paleogeographic distribution. The southern part of the Tethys Ocean was marked by large scale development of such paltforms (Ferreri et al., 2004). They form distinct sedimentary units which are defined by clear bedding and high rates of sediment accumulation. The main goal of this study is to highlight the cyclic carbonate sedimentation in an upper Tithonian–lower Valanginian carbonate succession, by integrating various analysis techniques. The carbonate deposits from these region were studied on a large scale by various authors. Jekelius (1938), Oncescu (1943), Popescu (1966), Bucur (1978), Patrulius et al. (1980), Pleş et al. (2013), Mircescu et al. (2014), Mircescu et al. (2016)]. The applied methodology allowed us to 1) identify small scale sequences; 2) group such sequences into middle scale sequences; 3) perform a detailed biostratigraphic analysis of the entire succession; 4) apply chemostratigraphic and microfacies analysis techniques on marker beds in order to highlight subaerial exposure processes; 5) reconstruct the evolution of the entire carbonate platform in a sequence stratigraphic context.

1. Piatra Craiului Massif. Location and geological framework

Piatra Craiului Massif forms a 25 km long NE-SW oriented calcareous ridge (Fig. 1). Here, the sedimentary succession from this massif represents part of the easternmost sector of the Getic Carbonate Platform. These sedimentary formations are included in the Getic Nappe (Săndulescu, 1984) which is part of the Median Dacides (Fig. 2). The geological evolution of this tectonic unit is marked by the late Jurassic closure of the East Vardar Ocean (Mațenco et al., 2010) and the tectonic movements associated with the Cretaceous continental colision (Schmid et al., 2008). The carbonate succession from the Piatra Craiului Massif forms an integrating part of the ,,Braşov Series" (Patrulius, 1969). They form large scale outcrops arround Braşov (Postăvaru and Piatra Mare Massifs, Măgura Codlei), in the Piatra Craiului Massif, Dâmbovicioara Area, and the Bucegi Mountains. The early Tithonian–early Valanginian sediment accumulation was strongly influenced by a paleobathimetric deepening which corresponds to a NW-SE alignment. This alignment starts from the Piatra Craiului Massif and stretches towards the Bucegi Mountains through the Postăvaru-Piatra Mare Massif (Patrulius, 1969; Bucur et al., 2010).

The Piatra Craiului Massif comprises the western flank of a homonymous syncline unit which represents an integrating part of the Dâmbovicioara Couloir (Patrulius, 1969) (Fig. 2). Bajocian–Bathonian detrital and carbonate deposits form the first term of the sedimentary succession. They cover directly the basement belonging to the Cumpăna and Leaota metamorphic Groups. The next term of the sedimentary cover includes upper Callovian–Oxfordian carbonates and siliceous rocks (Jekelius, 1916; Oncescu, 1943; Patrulius, 1969; Bucur, 1980; Beccaro and Lazăr, 2007). Kimmeridgian–lower Valanginian shallow water carbonates represent the bulk of the entire Mesozoic succession. They were studied in detail by several authors (Popescu, 1966; Bucur, 1978; Panaiotu, 2000; Bucur et al., 2009; Pleş et al., 2013; Mircescu et al., 2014; Mircescu et al., 2016). They are defined by a gradual transition from reef slope deposits to inner platform peritidal carbonates.

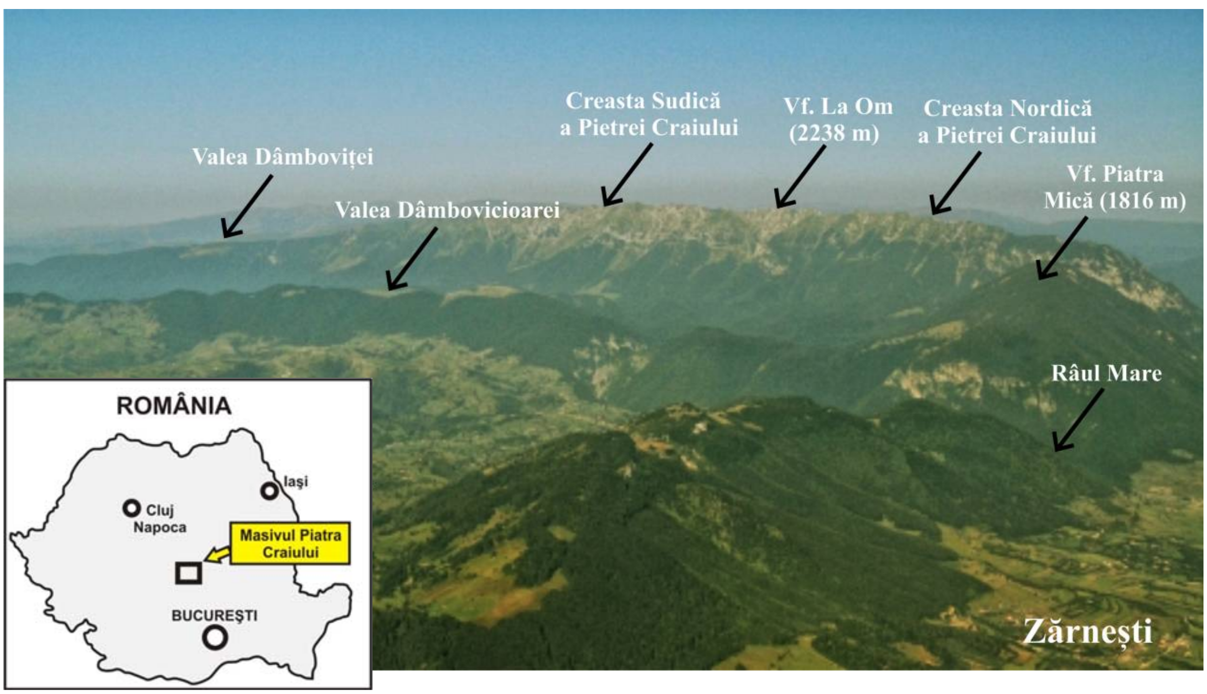

Fig. 1 Location of the Piatra Craiului Massif and the most important geomorphological elements (from http://www.nikonisti.ro/articole/zbor-peste-transilvania-dragos-asaftei/801)

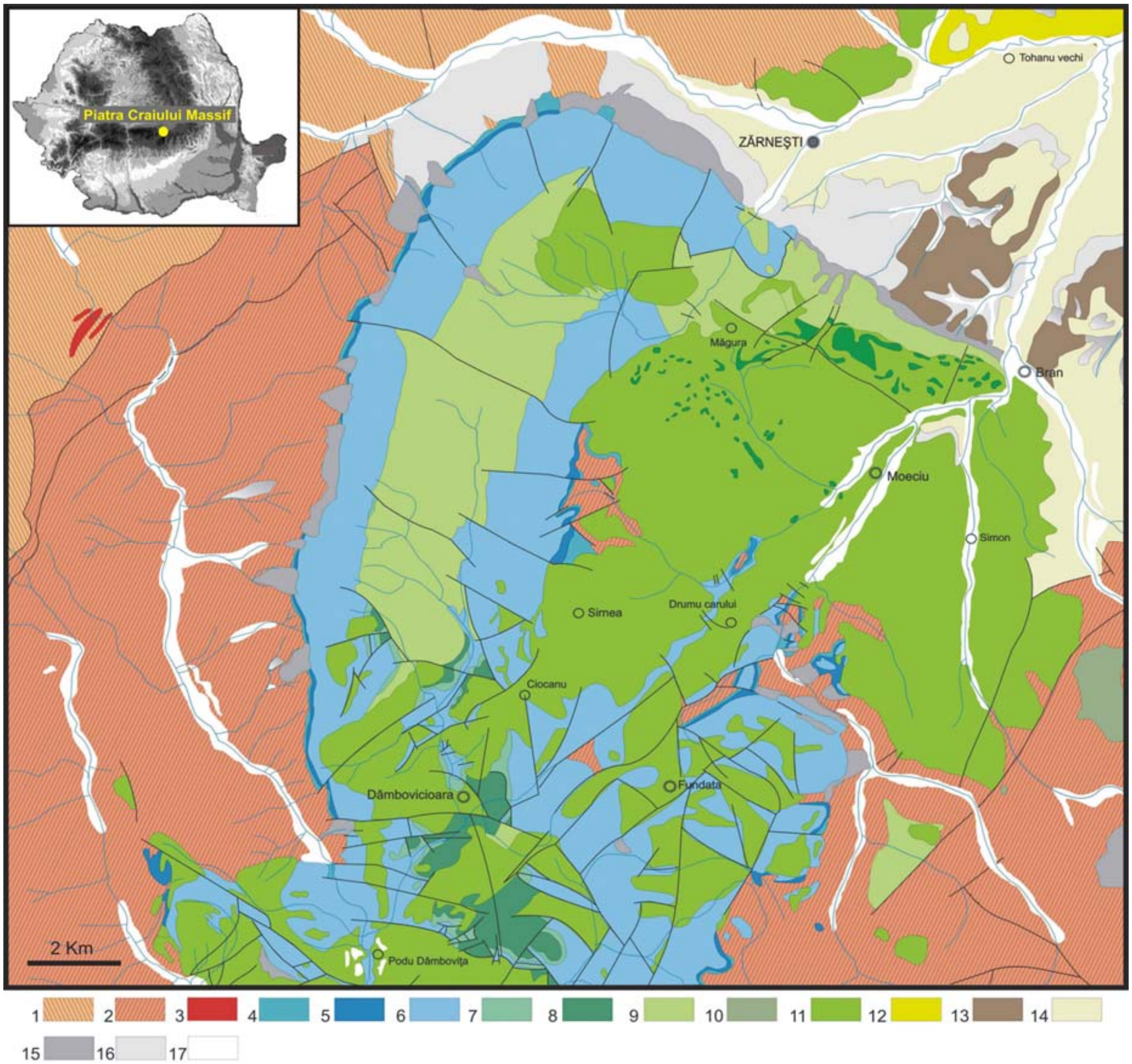

Fig. 2 (1- Cumpăna metamorphic series; 2- Leaota metamorphic series; 3- Magmatic rocks; 4- Bajocian-Callovian; 5- Callovian-Oxfordian; 6- Kimmeridgian-?Valanginian inferior; 7- Hauterivian; 8- Barremian; 9- Aptian; 10- Albian; 11- Vraconian-Cenomanian; 12- Turonian-Maastrichtian; 13- Paleogen; 14,15,16,17- Cuaternary deposits; after Dimitrescu et al., 1971; Dimitrescu et al., 1974; Patrulius et al., 1971; Săndulescu et al., 1972, with slight changes)

2. Materials and methods

Fieldwork activities were deployed between 2016-2017. A total number of 1163 samples were collected and 1163 thin sections were prepared. An additional number of 1000 previouslz collected samples were reinterpreted. Sampling was performed at meter to centimeter resolution. Bed thickness measurements were made in the field. Standard microfacies classification follows Dunham (1963) and Embry and Klovan (1971). Ten sections were studied: Poiana Zănoaga-Vf. Piatra Mică, Poiana Zănoaga-Gura Râului, Turnu-Curmătura, Padina Închisă-Drumul lui Lehmann, Padina Popii, Ciorânga Mare-Vf. Ascuțit-Padinile Frumoase, Padina lui Călineț, Vlădușca, Zaplaz-Lanțuri şi Padina Lăncii (Fig. 3). Isotope chemostratigraphy was performed on 37 carbonate powders. Marine limestones were sampled from their matrix, by carefully avoiding fractured areas. For the supposed subaerially exposed limestones, samples were taken either from the iron-oxide pigmented matrix or from black pebble type intraclasts. Isotope analysis was performed at the Iso-Analytical Limited Laboratory from Cheshire, Great Britain.

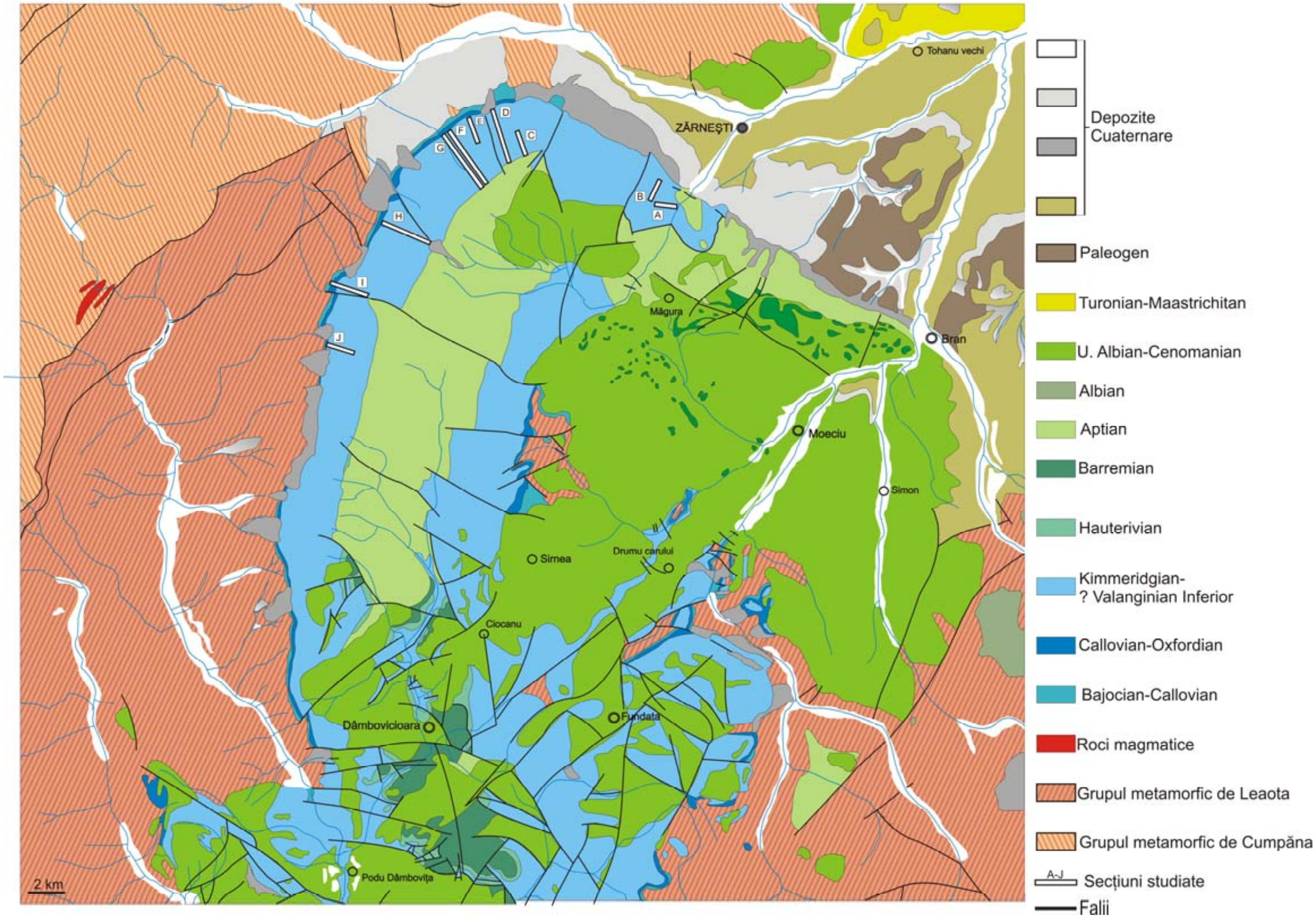

Fig. 2 Location of the studied sections (A-Poiana Zănoaga-Gura Râului; B-Poiana Zănoaga-Piatra Mică; C-Curmătura-Turnu; D-Padina Închisă-Drumul lui Lehmann; E-Padina Popii; F-Ciorânga Mare-Vf. Ascuțit-Padinile Frumoase; G-Padina lui Călineț; H-Vlădușca; I-Zaplaz-Lanțuri; J-Padina Lăncii) (from Dimitrescu et al, 1971; Dimitrescu et al, 1974; Patrulius et al, 1971; Săndulescu et al, 1972, with slight changes).

3. Microfacies and microfossils identified in the Kimmeridgian-Tithonian- ? Lower Valanginian deposits

Twenty-eight lithofacies types were grouped together in eight facies associations (Table 1) by applying sedimentological and compositional analysis techniques (Table 1). They form the main component of the studied sections

Reef slope deposits and bioconstructions

This facies association is represented by alternating coral-microbial microencruster boundstones and bio-intraclastic rudstones. Corals are encrusted by different associations of encrusting organisms (*Lithocodium*/*Bacinella* type structures), worm tubes and calcareous sponges (*Calcistella jachenhausenensis* Reitner) (Fig. 3-4).

Outer platform bioclastic deposits

These facies types mark the transition from the underlying reefal deposits to the peritidal carbonates which form the bulk of the entire carbonate succession (Fig. 5). They represent outer platform high energy deposits (bioclastic shoals). This supposition is strengthened by the subangular character of the clasts. The presence of micritic rims arround various bioclasts indicates that micritisation occured mainly in low energy environments. These bioclasts were subsequently reworked in such high energy settings. The faunal assemblage is diverse. It includes both reefal fragments (corals, calcified sponges) and inner platform bioclasts (bivalves, gastropods and dasycladalean algae)

Outer platform subaerially exposed carbonates

This carbonate unit has a total thickness o approximately 4 meters. It contains high energy, subtidal limestones (peloidal bioclastic grainstone, bioclastic grainstone, intraclastic bioclastic grainstone) (Fig. 6) with black pebble type intraclasts and fragments of iron-oxide matrix (Fig. 6). Blackened bioclasts (cyanobacteria nodules, coral fragments or calcified sponges) are frequently associated with such intraclasts (Fig. 6). Other reworked elements include fragments of iron-oxide rich matrix. Voids are filled with vadous silty-argillaceous or ferruginous material. Their margins are bordered mostly by dog-tooth cements (Fig. 6).

Low energy subtidal deposits

It comprises the following facies types: wackestone-floatstone with gastropods, bindstone with bacinellid structures, wackestone with dasycladalean algae (*Clypeina sulcata*) (Fig. 7). Faunal diversity is relatively high. Other bioclasts are represented by cyanobacteria nodules and mollusks (Fig. 7). Bioturbation is common.

Peritidal limestones

Facies associations seven and eight (F7-F8) characterize these limestones which were deposited in peritidal settings (Fig. 8). Their accumulation is strongly influenced by tidal activity.

Intertidal limestones

Facies association F7A comprises the following facies types: fenestral wackestone-packstone with cyanobacteria nodules, oncoidic wackestone-packstone, peloidal wackestone, fenestral wackestone, wackestone with laminoid fenestral structures.

Bioclasts are represented by cyanobacteria, miliolid type foraminifera and bivalves. Peloids may form distinct laminitic structures wich contain abundant meniscus cement. Fenestral pores are frequent. Their dimension ranges from 10 microns to 3 mm. They can form systems of laminoid fenestral structures which are filled with granular or microgranular sparite. Geopetal sediment is commonly asociated with these structures. Dessication cracks are disposed perpendiculary on the general orientation of the laminae .

Facies association F7B includes the following facies types: peloidal bioclastic grainstone, peloidal intraclastic grainstone, intraclastic packstone-grainstone, peloidal intraclastic bioclastic packstone-grainstone, intraclastic grainstone, peloidal fenestral grainstone, pel-oncoidal grainstone. These limestones contain abundant intraclasts and peloids. The faunal assemblage of the grainstone type facies includes mainly *Rivularia* type cyanobacteria. Small, subrounded peloids are commonly associated with micritic intraclasts. They may form moderate sorted laminitic structures with subangular to subrounded elements. Rounded to subrounded intraclasts are derived from cyanobacteria nodules. In other cases they are well sorted, with dimensions ranging from twenty to thirty microns. Micro-firmground surfaces are very well developed. Bioclasts include cyanobacteria nodules and rare bivalves, gastropods or foraminifera. Oncoids have a micritic composition. Their nucleus has a disorganised structure while the laminae contain fine grains wich form slightly discontinuous features. Cyanobacteria nodules or dasycladalean algae can form the nucleus of numerous ooids. Some aggregated ooids may present micritic rims and signs of algal-microbial perforations. Meniscus cement is present between all type of grains Sharp transitions from grainstone to wackestone facies types are common.

Supratidal deposits

This facies association is composed of homogeneous non-fossiliferous mudstone, different types of caliches, brecciated mudstone, mudstone-wackestone with structures resembling rhizoliths, mudstone-wackestone with rare fenestral structures or wackestone with vadoids (Fig. 9). Fenestral structures may be present. Brecciated structures are common and the microfauna is very scarce. It includes thin shell bivalves, ostracods and rare cyanobacteria. In some cases, microlaminitic structures are developed. They are composed of very fine, alternating layers of dark micrite and lighter microsparite. Small scale fenestral pores are generated by the lateral growth of cyanobacteria and microbes. They can agglutinate muddy carbonate particles which are subsequently washed away, in tidal flat areas. The brecciated structures contain vadous silt. Fenestral pores can be filled with geopetal sediment.

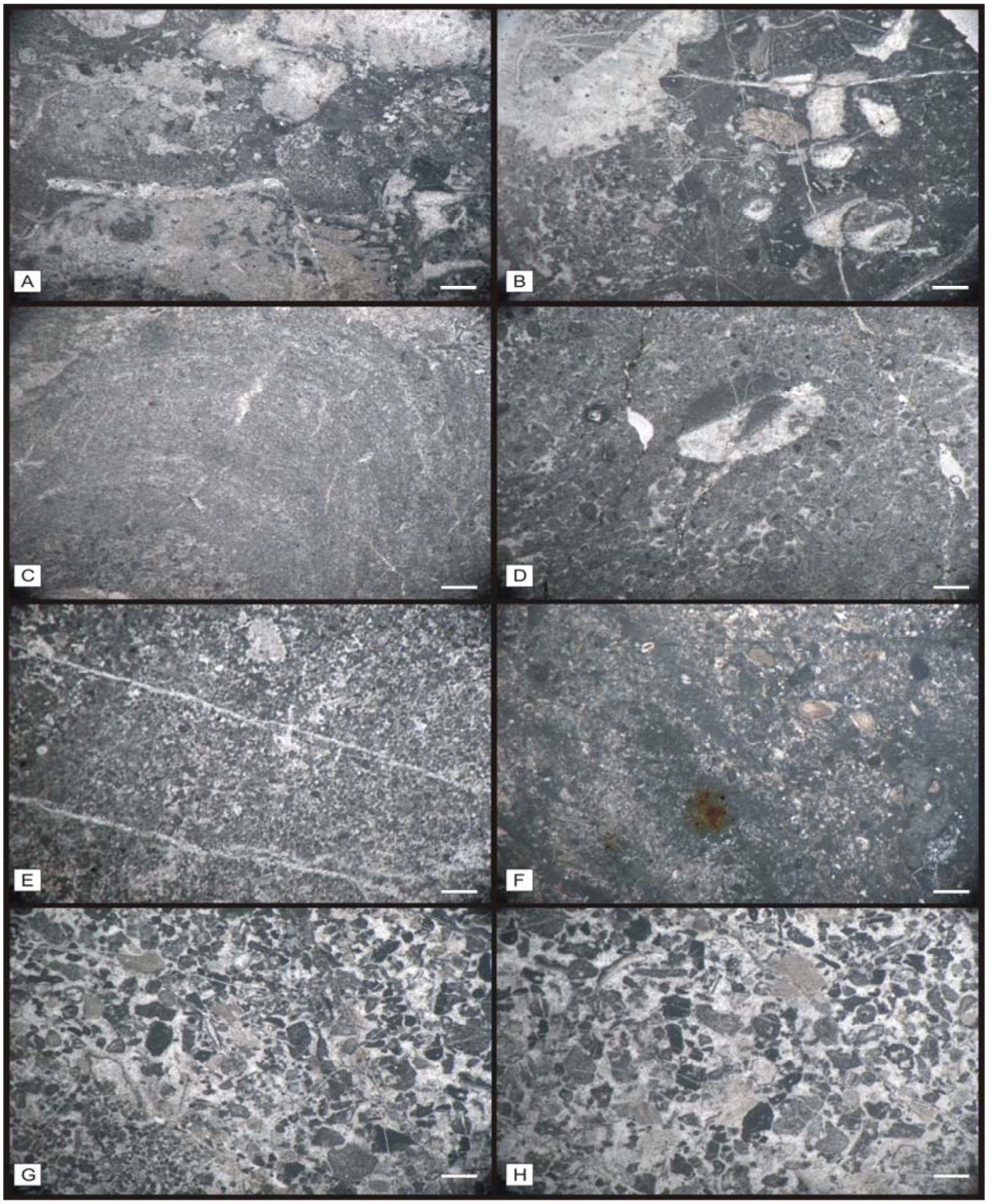

Fig. 3 Reef slope deposits (A-B-Coral-microbial boundstone with *Crescentiella morronensis*; C-Coral-microbial boundstone; D-Bioturbations; E-F-Silicified packstone; G-H-Bioclastic rudstone) (Scara: 1 mm)

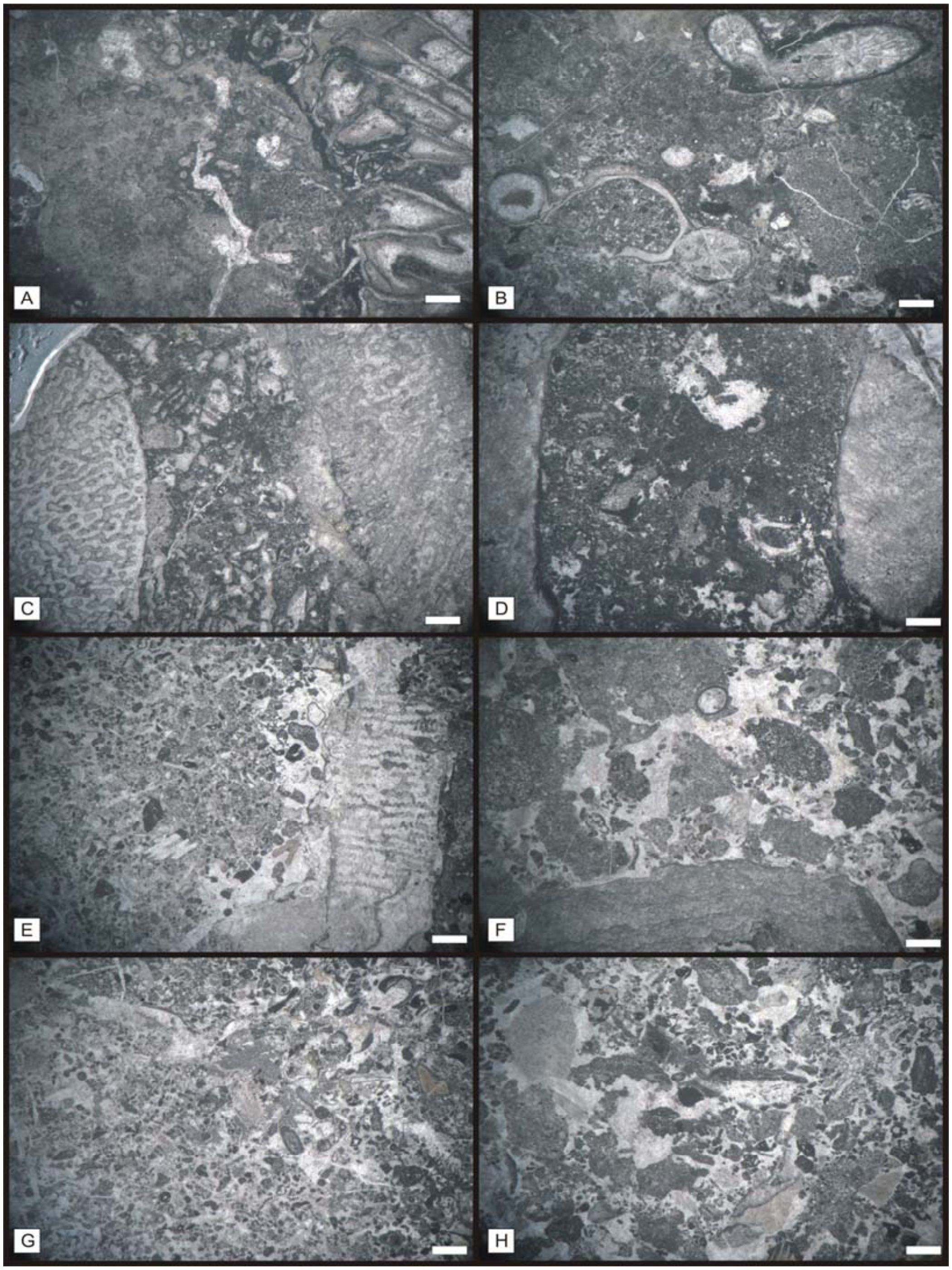

Fig. 4 Bioconstructions [A-Coral-microbial boundstone with *Crescentiella morronensis*; B-Internal sediment with various bioclasts; C-D-Boundstone with peloidal wackestone type internal sediment; E-H-Bioclastic rudstone (Scara: 1 mm)]

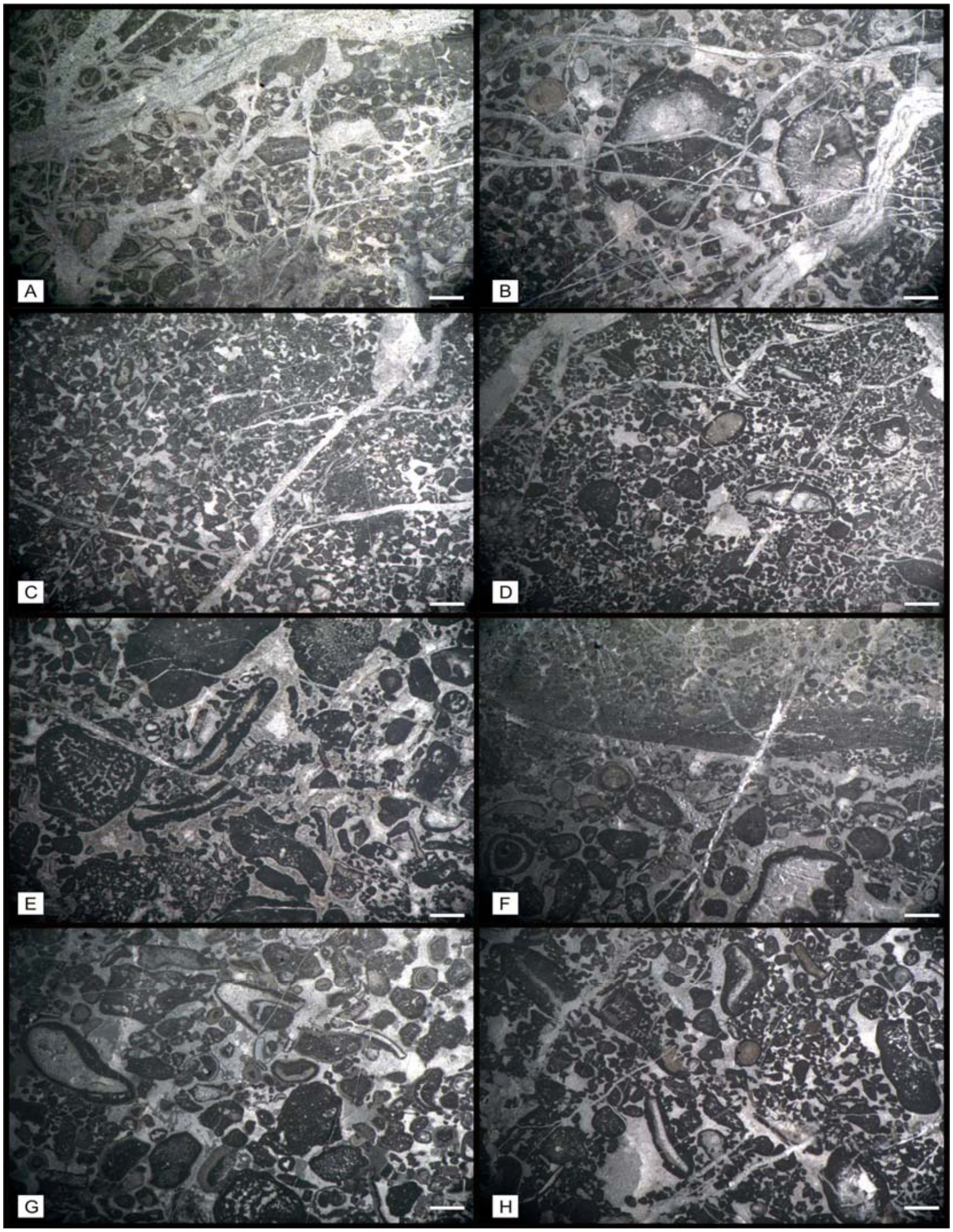

Fig. 5 Outer platform bioclastic limestones (A-B-Ooidic bioclastic grainstone with dasycladalean algae and cyanobacteria nodules. The ooids are frequently broken and regenerated. Their nucleus contains cyanobacteria nodules; C-Peloidal grainstone with cyanobacteria nodules; D-Bioclastic peloidal grainstone with gastropods, echinoderm plates and cyanobacteria nodules; E-F-Coarse bioclastic grainstone with gastropods, bivalves, cyanobacteria nodules and foraminifera. Micritic rims are developed around various bioclasts; G-H-Coarse bioclastic grainstone with coral fragments, crustaceans, echinoderms and gastropods. Scale: 1 mm)

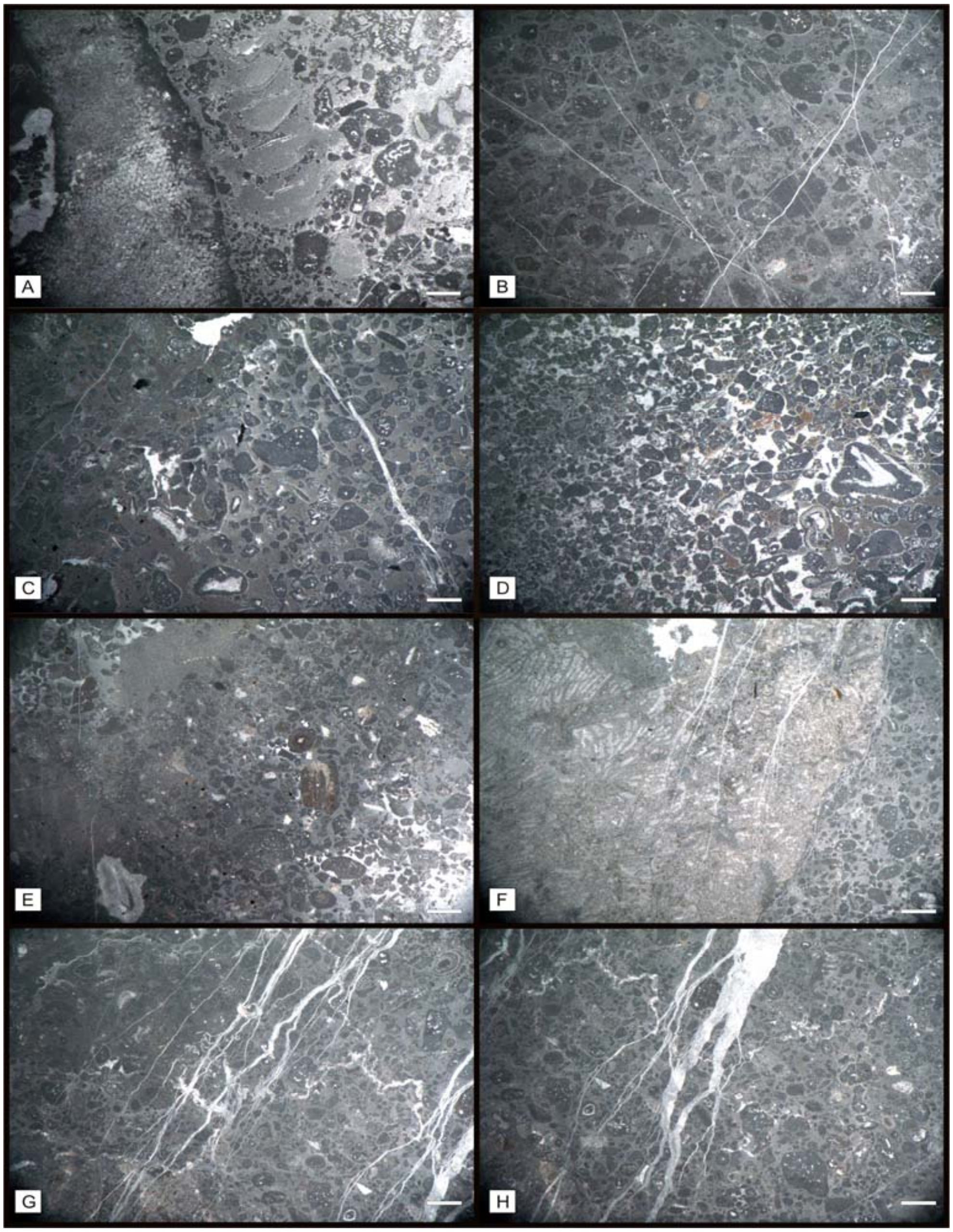

Fig. 6 Outer platform bioclastic carbonates with subaerially exposed intraclasts (A-Intraclastic bioclastic grianstone with micritised coral fragments, gastropods and cyanobacteria nodules; B-subaerially exposed peloidal intraclastic grainstone; C-Peloidal bioclastic grainstone with cyanobacteria nodules; D-Peloidal bioclastic grainstone. Bioclasts are represented by coral fragments, crustaceans and cyanobacteria nodules. Iron oxides and dog-tooth cement fill the voids between various bioclasts and peloids. Rare bioclasts include some cyanobacteria nodules. Blackened bioclasts and reworked black pebbles are common; F-Blackened coral fragment; G-H: Altered peloidail intraclastic grainstone with cyanobacteria nodules. Scale: 1 mm)

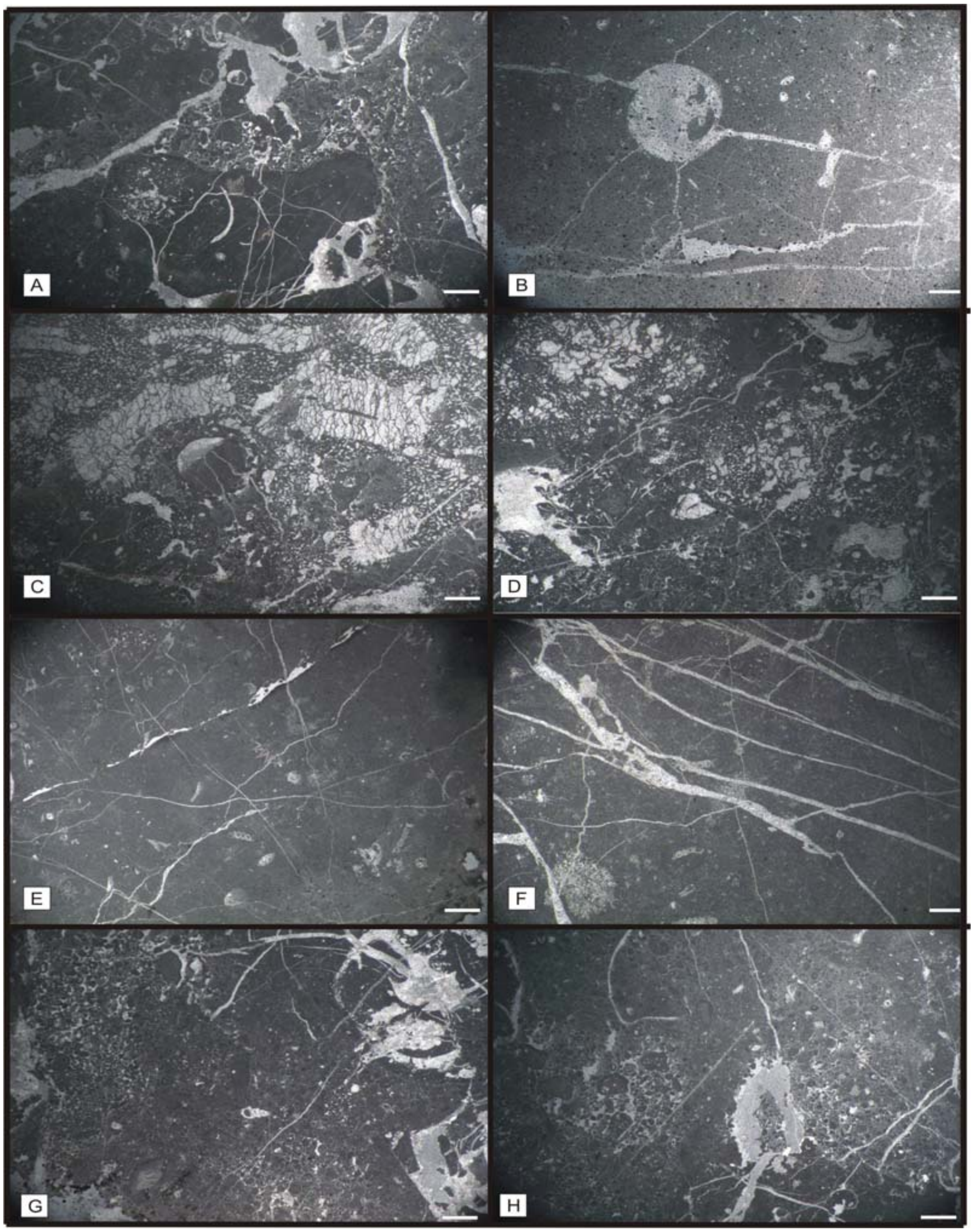

Fig. 7 Low energy subtidal deposits (A-Intraclastic wackestone with bivalve fragments and scarce peloids; B-Wackestone with thick shell gastropods; C-D-Wackestone with *Bacinella* and *Lithocodium* type structures; E-F-Wackestone with *Clypeina sulcata*; G-H-Wackestone with bivalves and gastropods. Scale: 1 mm)

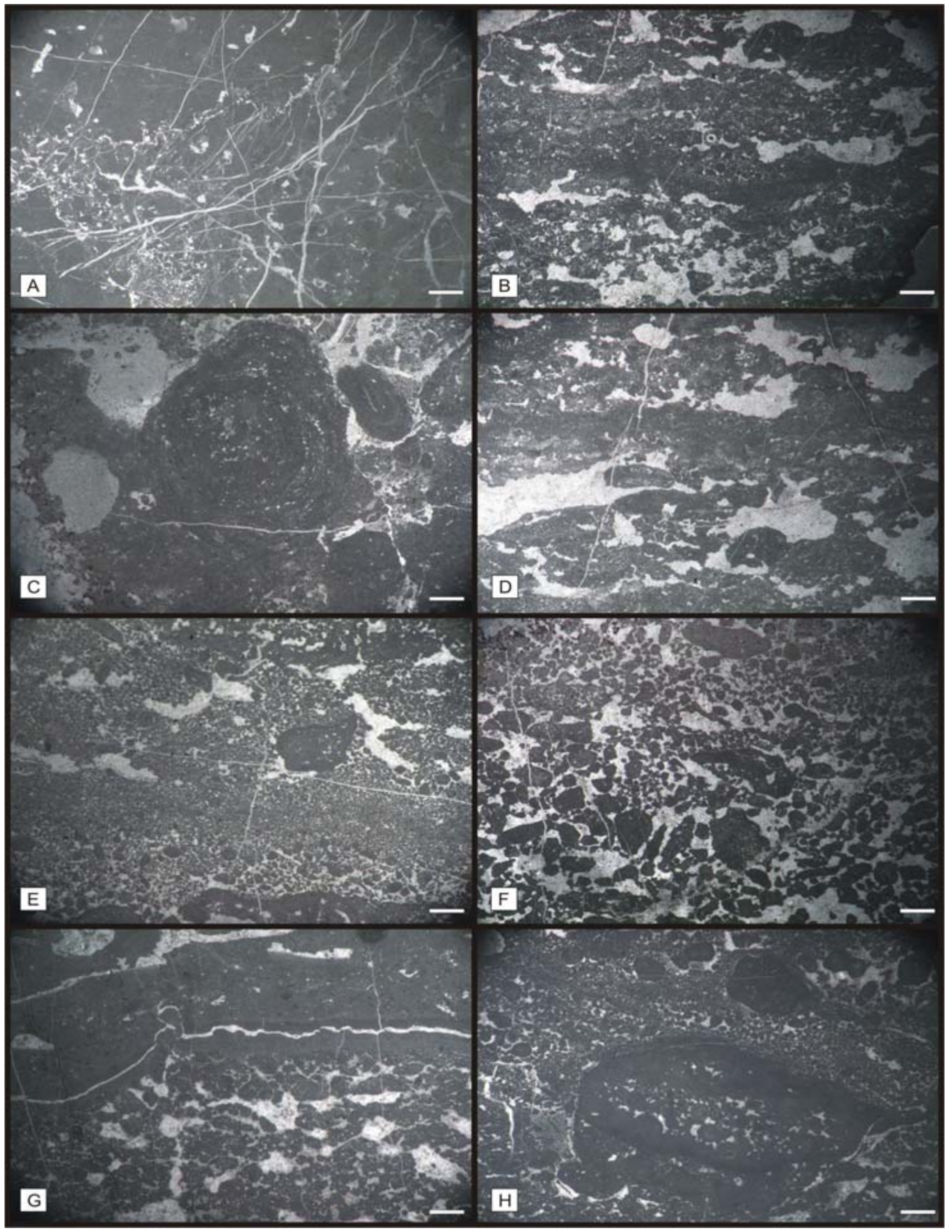

Fig. 8 Intertidal limestones (A-Fenestral wackestone; B-Fenestral laminoid wackestone with peloidal laminitic structures; C-Oncoidic wackestone-packstone; D-Fenestral laminoid wackestone with rare peloids and dessication cracks; E-Peloidal intraclastic grainstone. Meniscus cement is present between peloids, intraclasts and other grains; F-Transition from an ooidic grainstone to a laminoid fenestral wackestone; G-Transition from a peloidal grainstone to fenestral wackestone; H-Peloidal oncoidic grainstone with cyanobacteria nodules. Meniscus and gravitational cements are present between peloids and intraclasts. Scale: 1 mm)

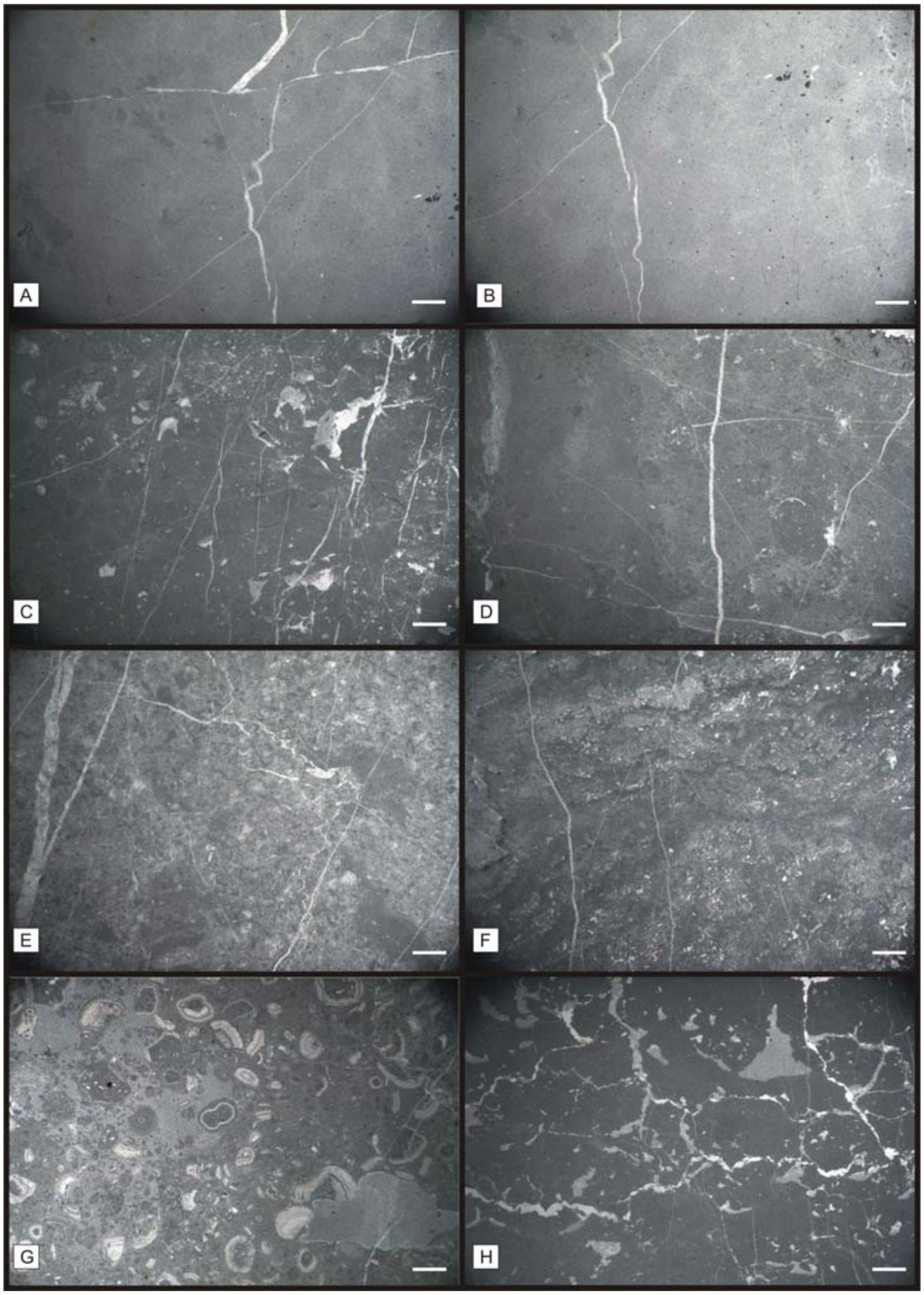

Fig. 9 Supratidal limestones (A-B-Homogeneous, non-fossiliferous mudstone; C-Fenestral wackestone. Geopetal sediment is filling the fenestral pores; D-Mudstone with rare thin shell bivalves and cyanobacteria nodules; E-F-Caliches; G-Vadoids; H-Brecciated mudstone)

4. Interpretation of microfacies analysis data

Litostratigraphic interval I (Fig. 10) is represented by alternating coral-microbial microencruster boundstones and bio-intraclastic rudstones. Corals are encrusted by different associations of encrusting organisms (*Lithocodium*/*Bacinella* type structures), worm tubes and calcareous sponges (*Calcistella jachenhausenensis* Reitner).

Litostratigraphic interval II includes coarse bio-intraclastic grainstones with gastropods, dasycladalean algae, calcified sponges, echinoderm fragments and benthic foraminifera (Fig. 10). Intraclasts are represented at some levels by various-sized black pebbles (mm to cm). Some have a brecciated structure consisting of blackened bioclasts encased in a muddy matrix which is pigmented with iron oxides. In some cases they consist of darkened bioclasts (cyanobacteria nodules, dasycladalean algae). This litostratigraphic interval contains a correlatable horizon which can be traced laterally in the studied sections. These facies types mark the transition from the underlying reefal deposits to the peritidal carbonates which form the bulk of the entire carbonate succession (Fig. 2; Fig. 5A-B). They represent outer platform high energy deposits (bioclastic shoals). This supposition is strengthened by the subangular character of the clasts. The presence of micritic rims arround various bioclasts (Fig. 5H) indicates that micritisation occured mainly in low energy environments. These bioclasts were subsequently reworked in such high energy settings. The faunal assemblage is diverse. It includes both reefal fragments (corals, calcified sponges) and inner platform bioclasts (bivalves, gastropods and dasycladalean algae) (Mircescu et al., 2016; Săsăran et al., 2017) (Fig. 5D-H).

Reworked black pebbles may indicate the proximity of a subaerially exposed horizon (Vera and Cisneros, 1993). Blackened bioclasts and black pebbles are commonly sourced from adjacent intertidal or supratidal depositional environments (Strasser, 1984). Subaerial exposure occurs when the eustatic sea-level drops and large quantities of carbonate material fill the available accomodation space, above the reef crest/slope (Hillgärtner, 2001; Săsăran et al., 2017). The presence of meniscus micrite could represent another argument which sustains the subaerial exposure of the rock fragments.

The presence of such bioclasts, encased in a muddy, micritic matrix indicate accumulation in low energy subtidal lagoonal settings (Tucker and Wright, 1990). The muddy, micritic facies are interbedded with high energy outer platform deposits. This feature suggests deposition under low energy subtidal conditions, between the topographically elevated outer platform bioclastic shoals.

Litostratigraphic interval III comprises the middle and upper parts of the carbonate deposits from the Piatra Craiului Massif (Fig. 10). Peloidal wackestone-packstone facies alternate with homogeneous mudstones with cyanobacteria. However, some levels of of bioclastic packstone/grainstone with dasycladalean algae and foraminifera were also identified in the uppermost part of this interval (Fig. 10). Fenestral structures are commonly associated with intertidal environments (Lucia, 1972; Tucker and Wright, 1990). The presence of very well sorted peloids and ooids indicates prolonged transport periods, in a littoral area, with strong wave activity. The muddy facies contain fenestral structures, laminoid fenestral structures and abundant cyanobacteria nodules (Fig. 8B, E). These features indicate that carbonate sediment was deposited in intertidal restricted ponds or beaches (e.g. Bucur and Săsăran, 2005; Săsăran, 2006). These ponds were isolated from the littoral areas were the coarser material was transported and deposited (Săsăran et al., 2013). Pedogenetic alteration is responsible for the development of such brecciated structures or dessication cracks (Platt and Wright, 1992; Armenteros and Daley, 1998; Freytet and Verrecchia, 2002). Algal microbial mats are formed by cyanobacteria, in restricted environments. The presence of scarce ostracods indicates deposition in supratidal flat areas which were periodically flooded by waves. Rare fenestral structures commonly indicate transitions from intertidal to supratidal depositional settings (Săsăran et al., 2017).

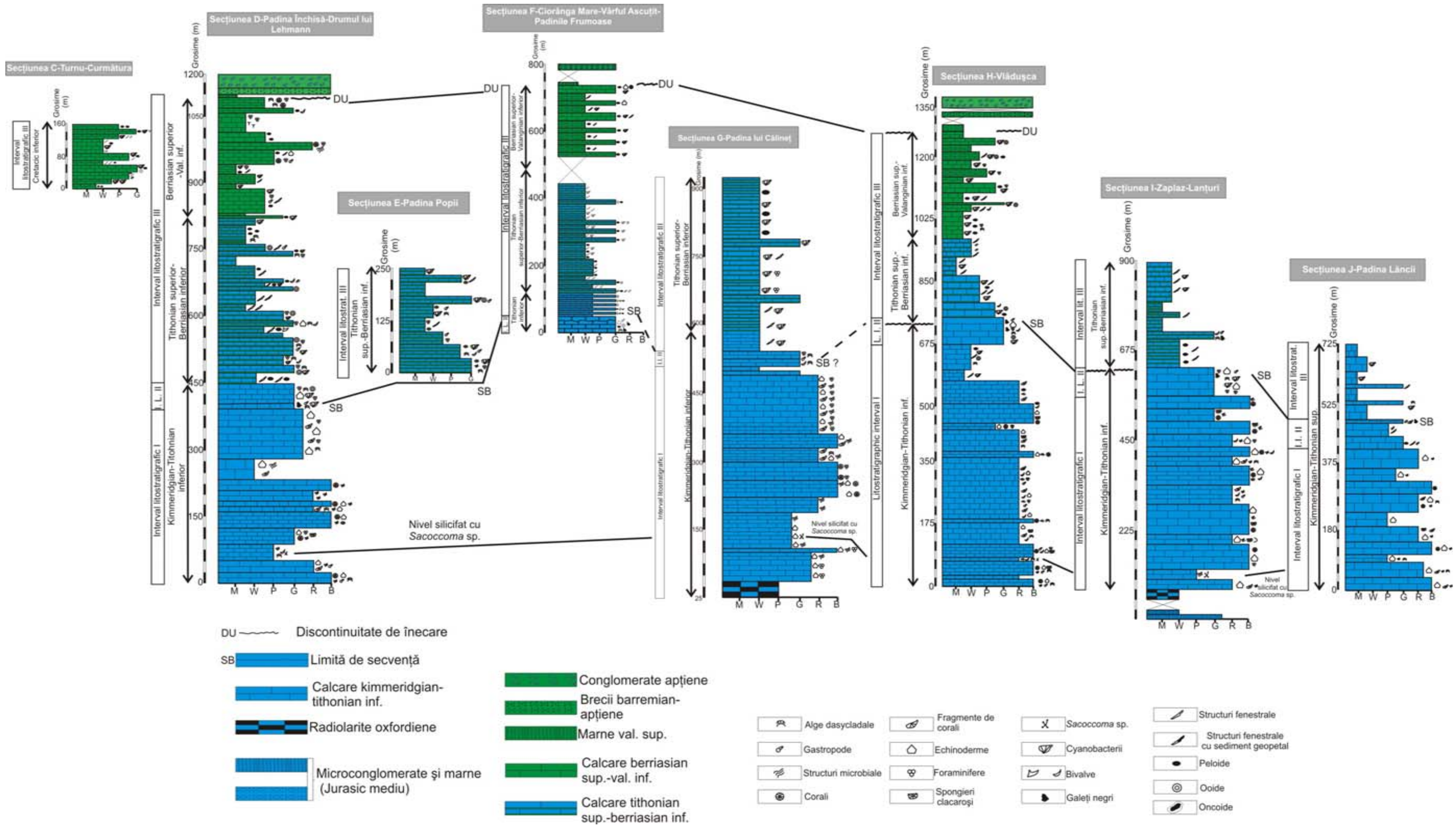

Fig. 10 Correlation of the studied section wich indicates the correlatable horizons and the texture of the most important carbonate levels

5. Biostratigraphy. Age of studied sections

5.1 Biostratigraphic interval A (Kimmeridgian–early Tithonian) (Fig. 11)

The first interval contains the following biota: *Salpingoporella pygmaea* (GÜMBEL, 1891) *Clypeina sulcata* (ALTH, 1882), *Campbeliella striata* (CAROZZI, 1954), *Steinmanniporella kapelensis* (SOKAČ & NIKLER, 1973), *Petrascula bursiformis* (ETALLON, 1859), *Neoteutloporella socialis* (PRATURLON, 1963), *Salpingoporella annulata* CAROZZI, 1953, *Nodosaria sp., Lenticulina* sp., *Bramkampella arabica* REDMOND, 1964, *Everticyclammina praekelleri* BANNER & HIGHTON, 1990, *Labyrinthina mirabilis* WEYNSCHENK, 1951, *Lituola baculiformis* SCHLAGINTWEIT & GAWLICK, 2007, *Redmondoides lugeoni* (SEPTFONTAINE, 1977), *Neokilianina rahonensis* (FOURY AND VINCENT), 1967, *Parurgonina caelinensis* CUVILLIER, FOURY & PIGNATTI MORANO, 1968, *Coscinoconus alpinus* (LEUPOLD), 1936, *Mohlerina basiliensis* (MOHLER, 1938), *Everticyclammina* sp. and *Coscinophragma* sp.. The microfossil association identified within this interval (0-410 m) is characteristic for the Kimmeridgian–Lower Tithonian interval. Even if some species of algae (e.g. *Salpingoporella pygmaea* or *Clypeina sulcata*) have a larger stratigraphic distribution, most of the identified taxa represent usefull bistratigraphical arguments.

Salpingoporella pygmaea is known from Bajocian–Aptian carbonate deposits (Granier & Deloffre, 1993; Bucur, 1999; Carras *et al*., 2006) with a high frequency in the

Upper Jurassic (Kimmeridgian–Tithonian) (Farinacci & Radoičić, 1991; Senowbari-Daryan *et al*., 1994).

Clypeina sulcata is characteristic for the Kimmeridgian–Berriasian interval. It was mostly described from Upper Jurassic, Kimmeridgian–Tithonian sediments (Bassoullet *et al.*, 1978).

Campbeliella striata was mentioned by several authors from Kimmeridgian–Lower Berriasian limestones (Carozzi, 1954; Farinacci & Radoičić, 1964). However, it was often identified in Kimmeridgian–Tithonian deposits (Jaffrezo, 1970; Bernier, 1971).

Petrascula bursiformis and *Neoteutloporella socialis* are two species of algae which are common for the Upper Jurassic. They were identified in many Kimmeridgian–Tithonian deposits of the Tethyan realm (Dragastan, 1975; Schlagintweit & Ebli, 1999; Bucur *et al.*, 2005; Meinhold *et al*., 2009; Schlagintweit, 2011).

Steinmanniporella kapelensis is a rare species known only from Tithonian deposits (Sokač & Nikler, 1973; Schlagintweit & Ebli, 1999; Bucur & Săsăran, 2012; Mircescu *et al*., 2014).

Regarding the foraminiferal assemblage, *Neokilianina rahonensis*, *Parurgonina caelinensis* and *Labyrinthina mirabilis* represent the most biostratigraphical important taxons for this interval. They were reported mainly from Kimmeridgian–Tithonian sediments (Cuvillier *et al*., 1968; Septfontaine, 1988; Tasli, 1993; Pop & Bucur, 2001; Velić, 2007; Pleş *et al*., 2015).

Considering this, the whole micropaleontological association identified in this biostratigraphic interval (Fig. 2) belongs to the Kimmeridgian–Lower Tithonian. Even if some species of foraminifera (*P. caelinensis*, *N. rahonensis* and *L. mirabilis*) appear in the geological record starting with the uppermost Oxfordian (Septfontaine, 1988; Bassoullet, 1997; Velić, 2007; Pleş *et al*., 2015), the presence of radiolarites dated as Oxfordian (Mészáros & Bucur, 1980; Beccaro & Lazăr, 2007) just below the limestones of interval A, as well as the main associated biota (*S. pygmaea*, *C. sulcata, P. bursiformis*, *R. lugeoni*, *E. praekelleri*, *C. alpinus*, *M. basiliensis*) which represent typical Kimmeridgian-Tithonian taxa (Bucur, 1999; Schlagintweit *et al*., 2005), are arguments for assigning this interval to Kimmeridgian–Lower Titonian. Most of the mentioned taxa are known from carbonates no older than Lower Kimmeridgian (Bassoullet, 1997). In addition, the presence of *Steinmanniporella kapelensis* and several sclerosponge species (*Calcistella jachenhausenensis*, *Neuropora lusitanica* and *Thalamopora lusitanica*) confirms the Tithonian age of the upper part of biostratigraphic interval A.

5.2 Biostratigraphic interval B (late Tithonian–early Berriasian) (Fig. 11)

In the second biostratigraphic interval (B), dasycladalean algae are less frequent while foraminifera are more abundant. Within this interval we have identified the following species: *Salpingoporella annulata* CAROZZI, 1953, *Clypeina parasolkani* FARINACCI & RADOIČIĆ, 1991, *Seliporella neocomiensis* RADOIČIĆ, 1963, *Pseudocyclammina lituus* (YOKOYAMA, 1890), *Rectocyclammina chouberti* HOTTINGER, 1967, *Anchispirocyclina lusitanica* (EGGER, 1902), *Pseudotextulariella courtionensis* BRÖNNIMANN, 1966.

Clypeina parasolkani was described by Farinacci and Radoičić (1991) from Upper Tithonian-Berriasian deposits from Turkey (Pontides). Its presence is common in simillar deposits from Sardinia (Dieni & Radoičić, 1999), Italy (Apennines) (Bruni *et al*., 2007), or Switzerland (Granier et al., 2014).

Selliporella neocomiensis is a typical species for the Berriasian shallow water carbonates (Peybernès, 1976; Luperto-Sinni & Masse, 1986; Granier & Deloffre, 1993; Bucur, 1999; Săsăran & Bucur, 2001).

Anchispirocyclina lusitanica was mentioned by different authors mostly from Upper Tithonian–Berriasian deposits (Fourcade, 1970; Jaffrezo, 1980; Dya, 1992; Schlagintweit *et al*., 2005).

Pseudotextulariella courtionensis is a Berriasian froaminifer commonly found in Lower Cretaceous limestones from Switzerland (Brönnimann *et al*., 1966), France (Darsac, 1983) or Spain (Pyrenees) (Schroeder *et al*., 2000).

Pseudocyclammina lituus has a Kimmeridgian–Lower Valanginian distribution with a high frequency in Tithonian–Berriasian deposits (Darga & Schlagintweit, 1991; Mosshamer & Schlagintweit, 1999).

It is difficult to trace the boundary between Tithonian and Berriasian inside the interval B. The micropaleontological assemblage of this stratigraphic interval (Fig. 2) indicates rather an Upper Jurassic-Lower Cretaceous transition.

The first occurrence of *Anchispirocyclina lusitanica* is recorded at the base of biostratigraphic interval B (Fig. 2). This foraminifer is associated with *Clypeina parasolkani* and *Pseudocyclammina lituus* within the same stratigraphic interval. The transition towards Berriasian is indicated by the first occurrence of *Seliporella neocomiensis* (Fig. 2) and *Pseudotextulariella courtionensis,* thus the upper part of biostratigraphic interval B can be attributed to the Lower Berriasian (Granier & Bucur, 2011)

5.3 Biostratigraphic interval C (late Berriasian–early Valanginian) (Fig. 11)

Simillar to interval B within the interval C the foraminifera are more abundant than the algae. The main microfossils are represented by: *Pseudocymopolia jurassica* (DRAGASTAN, 1968), *Salpingoporella praturloni* (DRAGASTAN, 1978), *Ammobaculites sp., Bulbobaculites sp., Pseudocyclammina lituus* (YOKOYAMA, 1890) , *Pseudocyclammina sp.*, *Everticyclammina kelleri* (HENSON, 1948), *Frentzenella involuta* (MANTSUROVA & GORBATCHIK), 1982, *Coscinoconus campanellus* (ARNAUD-VANNEAU, BOISSEAU & DARSAC), 1988, *Coscinoconus cherchiae* (ARNAUD-VANNEAU, BOISSEAU & DARSAC), 1988, *Nautiloculina bronnimanni* (ARNAUD-VANNEAU & PEYBERNÈS), 1978, *Montsalevia salevensis* (CHAROLLAIS, BRÖNNIMANN & ZANINETTI), 1966, *Scythiolina sp.* (Fig. 5J), *Paracoskinolina*? *jourdanensis*

FOURY & MOULLADE, 1966, *Pfenderina neocomiensis* (PFENDER, 1938), *Freixialina planispiralis* RAMALHO, 1969, *Protopeneroplis ultragranulata* (GORBATCHIK, 1971).

Dasycladalean algae (*Pseudocymopolia jurassica*, *Salpingoporella praturloni*) are rare. They were identified in a stratigraphic level which is located in the uppermost part of this interval. Foraminifera (*Protopeneroplis ultragranulata*, *Paracoskinolina*? *jourdanensis*, *Pfenderina neocomiensis*, *Coscinoconus cherchiae*, *Coscinoconus campanellus*, *Nautiloculina bronnimanni*, *Montsalevia salevensis, Freixialina planispiralis*) are abundant within the same level (Fig. 2).

Pseudocymopolia jurassica and *Salpingoporella praturloni* are generally known from Berriasian–Valanginian deposits (Dragastan, 1975; Jaffrezo, 1980; Bucur, 1985; Farinacci & Radoičić, 1991; Bucur & Săsăran, 2005).

Protopeneroplis ultragranulata has a large stratigraphic distribution (Middle Tithonian-Barremian) with an acme in the Berriasian-Valanginian (Altiner, 1991; Chiocchini *et al*., 1994; Bucur, 1997).

Paracoskinolina? *jourdanensis* was described for the first time from Lower Barremian deposits by Foury and Moulade (1966). However, it is frequent in Upper Berriasian–Valanginian deposits, in association with *Pfenderina neocomiensis* (Bucur *et al*., 1995).

Montsalevia salevensis is known from numerous Valanginian deposits throughout Europe (Charollais *et al.*, 1966; Velić & Sokač, 1983; Boisseau, 1987; Ciocchini *et al*., 1988; Bucur, 1988; Schroeder *et al*., 2000).

Coscinoconus cherchiae and *Coscinoconus campanellus* are commonly found in Upper Berriasian-Lower Valanginian carbonate rocks from Italy (Mancinelli & Coccia, 1999), Serbia (Bucur *et al*., 1995), Romania (Neagu, 1994) or Bulgaria (Ivanova, 2000).

Concluding, the above mentioned assemblage indicates a late Berriasian-early Valanginian age, but the exact position of the boundary between Berriasian and Valanginian is difficult to be precised.

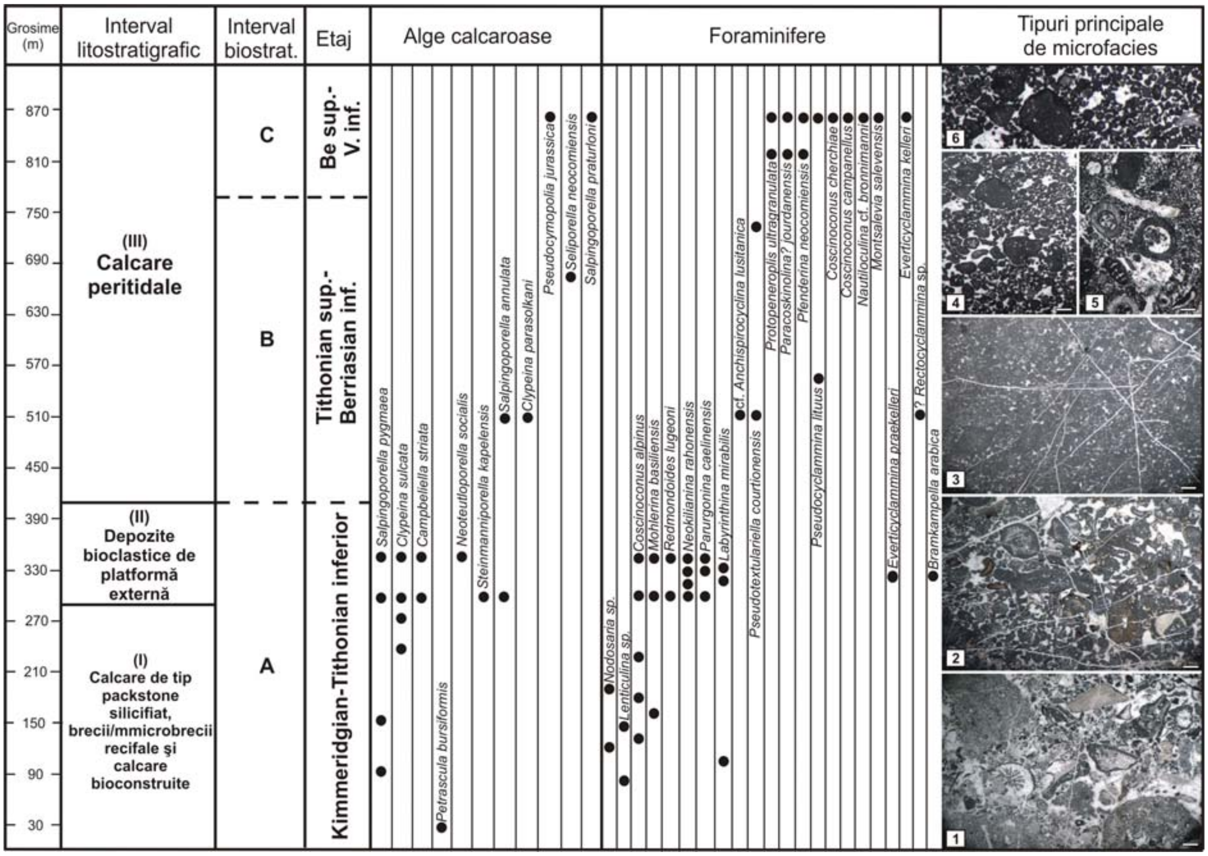

Fig. 11 Litostratigraphic and micropaleontological characteristics of the carbonate succession from the Piatra Craiului Massif [1-Bioclastic rudstone with coral fragments, echinoderm spines; 2-Coarse bioclastic intraclastic grainstone with cyanobacteria nodules, dasycladalean algae (*Neoteutloporella socialis*; *Campbeliella striata*) and gastropods. Black pebbles consist of blackened cyanobacteria nodules; 3-Peloidal fenestral packstone with cyanobacteria nodules; 4-Peloidal intraclastic grainstone with cyanobacteria nodules and angular/subangular micritic intraclasts; 5-Peloidal bioclastic intraclastic grainstone. 6-Peloidal grainstone with cyanobacteria nodules] (Scale bar: 1 mm).

6. Isotope chemostratigraphy

6.1 Isotope values of the studied intervals

Platform margin carbonates were sampled for isotope chemostratigraphic analysis in two main sections: Ciorânga Mare-Vârful Ascuțit-Padinile Frumoase and Zaplaz-Lanțuri (Fig. 12-13). The thickness of sampled intervals ranges between 8 and 10 meters (Fig. 12-13).

6.1.1 Ciorânga Mare-Vârful Ascuțit-Padinile Frumoase section

The samples located below the black pebble bearing level (1082-1094, Fig. 14D, bellow red rectangle) record values between 0.92 ‰ $\delta^{13}C$ şi 2.58 ‰ $\delta^{13}C$. The carbon isotope curve increases from 0.92 ‰ $\delta^{13}C$ to 2.58 ‰ $\delta^{13}C$. Then, it drops to 0.61 ‰ $\delta^{13}C$ and it increases again to 2.05 ‰ $\delta^{13}C$. Carbon isotope values are positive (samples 1095-1098) and record similar values both for the black pebbles and for the iron oxide pigmented matrix. For this reason, their values were plotted on the same line. The oxygen curve is parallel with the carbon curve (Fig. 14D), and their direction is strikingly similar. The oxygen values record a slight increase, bellow the black pebble bearing level , from -4 ‰ $\delta^{18}O$ to -1 ‰ $\delta^{18}O$ (samples 1082-1086). Its values drop again to -4 ‰ $\delta^{18}O$ and remain constant between -4 and -3 ‰ $\delta^{18}O$ (samples 1088-1093). For the black pebble bearing level, the values drop from -1.5 ‰ $\delta^{18}O$ to -2.8 ‰ $\delta^{18}O$.

6.1.2 Zaplaz-Lanțuri section

In this section, the isotope curve trends are different. The samples located bellow the black pebble bearing level have positive values (+ 2 ‰ $\delta^{13}C$) (Samples 624-625, Fig. 15D, G). Above this level, the carbon isotope values drop until + 0.5 ‰ $\delta^{13}C$ (Sample 634b f). Isotope values are negative within the black pebble interval. Such values characterise both the black pebbles and the iron oxide pigmented matrix. Carbon and oxygen isotope data shows simillar values for the matrix and black pebbles. For this reason, the values were plotted together on the same line. Isotope values record a slight decrease from -0.9 ‰ to -1.1 ‰ $\delta^{13}C$ (Samples 626-628) and stay constant at -1.4 ‰ $\delta^{13}C$ (Samples 630, 631-632). Furthermore, they drop until -1.9 ‰ $\delta^{13}C$ before they increase again to -0.5 ‰ $\delta^{13}C$ (Samples 634 a). The oxygen isotope values record extreme negative values of -4 ‰ $\delta^{18}O$ for the samples located bellow and above the black pebble bearing level (Samples 625 and 634 b). Between these points they range between -1.5 ‰ şi -2.00 ‰ $\delta^{18}O$. In this section, the carbon and oxygen isotope curves do not have a parallel direction. They are defined by a mirror type arrangement.

6.2 Interpretation

Carbon stable isotopes represent the best method for highlighting subaerial exposure surfaces in carbonate environments (Banner and Hanson, 1990; Oehlert and Swart, 2014). Oxygen isotopes are used on a lesser extent since diagenesis has a stronger impact on their values (Allan and Mathews, 1982). Fragments of subaerially exposed carbonates are present in the outer platform deposits of the Ciorânga Mare-Vârful Ascuțit-Padinile Frumoase section. The presence of black pebbles and blackened bioclasts in a predominat marine, packstone-grainstone matrix (Fig. 14F-G) represent additional arguments in this sense. Carbon isotope values record positive values both for the black pebble intraclasts and for the matrix. Upper Jurassic carbon isotope curves were produced mainly from pelagic deposits of the Tethyan and Boreal domains (Weissert and Channel, 1989; Weissert and Mohr, 1996; Katz et al., 2005; Michalik et al., 2009; Žák et al., 2011; Coimbra and Oloriz, 2012). The carbon isotope curves from the Ciorânga Mare-Vârful Ascuțit-Padinile Frumoase section are simillar with other carbon isotope values obtained by various authors from Tithonian pelagic carbonates of the Tethyan domain (Weissert and Channel, 1989-Italy; Price et al., 2016-Hungary; Weissert and Mohr, 1996-Switzerland). Isotope chemostratigraphy studies were performed on a lesser extent on Tithonian shallow water carbonates. Thus, a quality check and a comparison with other pelagic data is necessary, in order to create a suitable chemostratigraphic model. Amodio et al. (2008) indicate that the Middle Jurassic–Lower Cretaceous pelagic isotope curves are simillar with their analogue shallow water correspondent. The isotope, microfacies and diagenetic characteristics of the Zaplaz-Lanțuri samples confirm the existence of subaerial exposure processes. The negative values of the black pebble carbon isotope samples (Zaplaz-Lanțuri section) suggest enrichment in organic matter. Longmann (1980) indicates that such processes may occur under subaerial exposure conditions. As a consequence, carbon isotope values will become more negative. In addition, the matrix hosting these intraclasts has the same negative values. Black pebbles are frequently associated with subaerial exposure and meteroric diagenesis (Freytet and Plaziat, 1982; Strasser and Davaud, 1983; Strasser, 1984). Their development is associated with terrestrial plant decay and impregnation of pre-existing carbonate material with organic matter. Meteoric diagenesis will trigger carbonate material alteration and such negative shifts of carbon isotope values (Gradstein, 2012). These values characterise subaerially exposed surfaces (samples 634 a-b) (Allan and Mathews, 1983; Lohmann, 1988; Algeo et al., 1992) where dissolution processes are very active under the action of meteoric water. Dissolution alternates with short-lived carbonate reprecipitation and the carbon isotope composition shifts progressively towards more negative values (Salomons and Mook, 1986). Meteoric diagenesis is indicated by the presence of vadous silt (Longman, 1980) and meniscus micrite (Fig. 15B, yellow circles). This type of cement is formed durring meteoric diagenesis and subaerial exposure (Longman, 1980; Hillgärtner et al., 2001). In this diagenetic context, it can be associated with abundant micritic rims and meniscus sparite (Fig. 15B, yellow circles) (Hillgärtner et al., 2001). The existing microfossil asociations indicate a lower Tithonian age for these intervals. These are equivalent, outer platform carbonate levels which contain fragments of reworked subaerially exposed limestones or in situu subaerially exposed carbonates. The two sections show simillar microfacies characteristics. However, their geochemical imprint is totally different. A possible scenario could suggest that the carbonate levels from the Ciorânga Mare-Vârful Ascuțit-Padinile Frumoase were forming a more distal depositional area. Black pebbles and blackened bioclasts were sourced from an adjacent subaerially exposed surface. By contrast, in the Zaplaz-Lanțuri section, the subaerial exposure is evident and in-situu

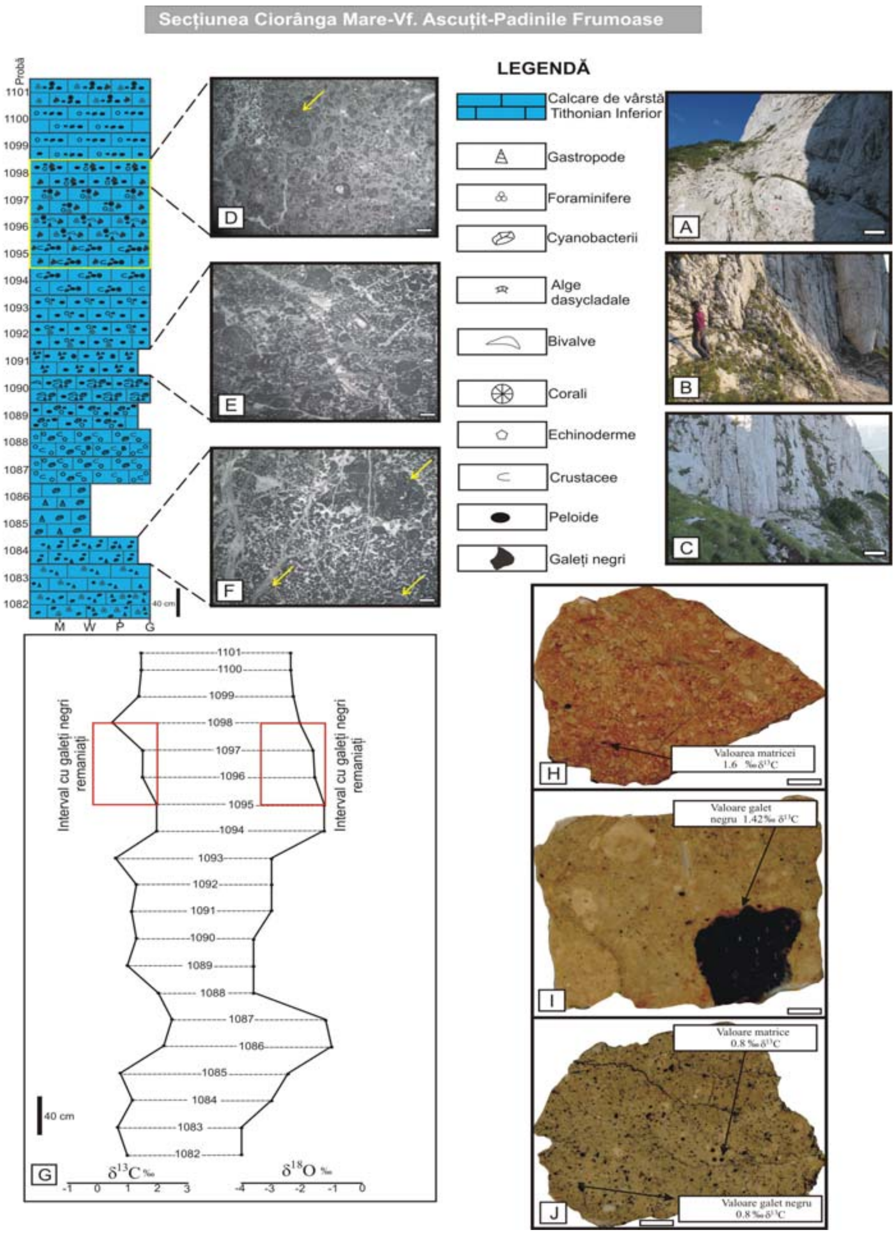

Fig. 12 Microfacies and isotope values from the outer platform deposits of the Ciorânga Mare-Vârful Ascuțit-Padinile Frumoase section [(A-B- Altered intraclastic peloidal grainstone; C-Peloidal intraclastic grainstone; D-Isotope values of the sampled interval; E-G-Polished slabs indicating isotope values for both matrix and black pebble type intraclasts) (Scale: A-C-1 mm; E-G-1 cm).

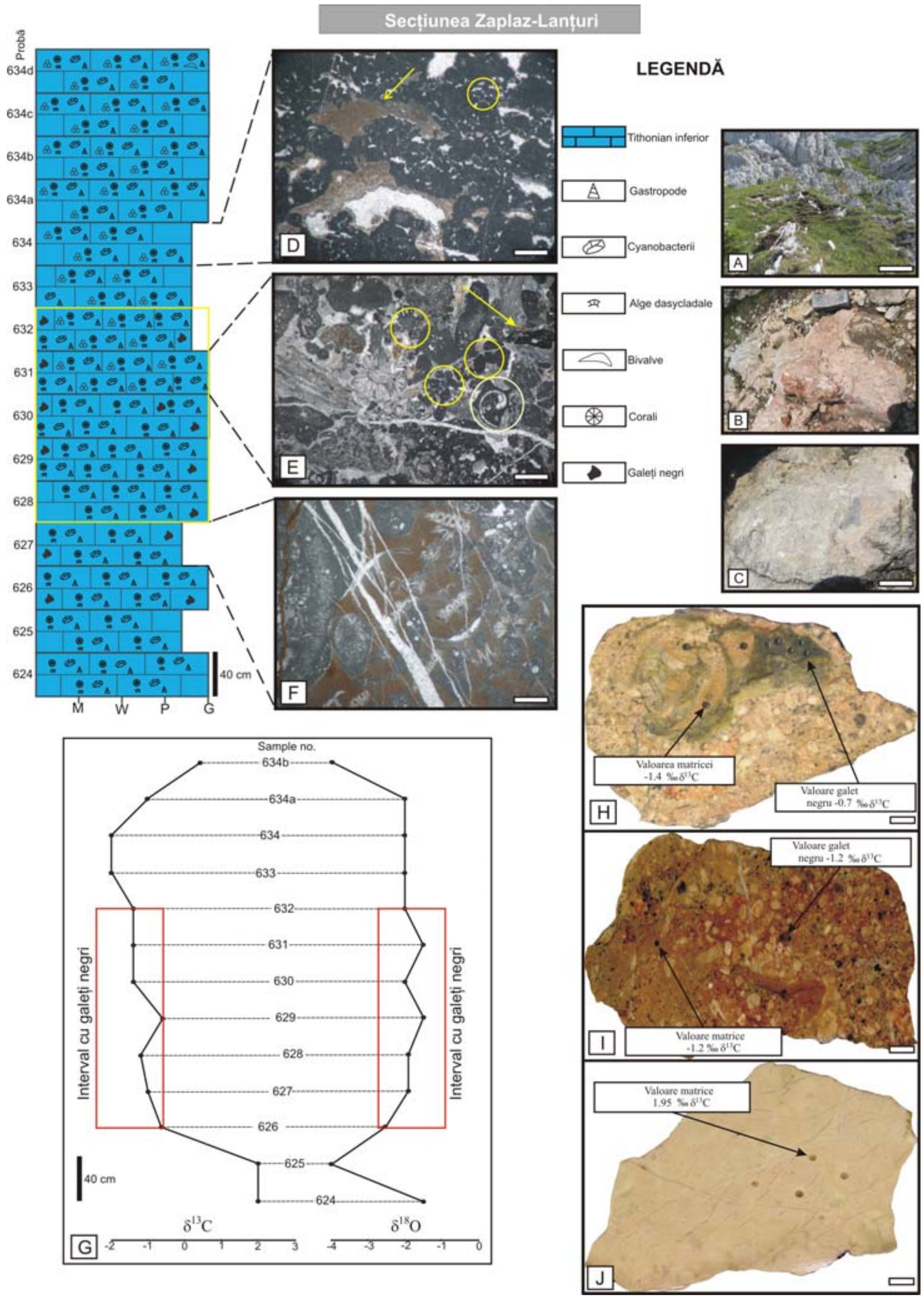

Fig. 13 Microfacies and isotope values from the outer platform deposits of the Zaplaz-Lanțuri section [A-Peloidal intraclastic packstone. It contains fenestral pores filled with vadous silt. In addition, meniscus micrite and sparite form bridges between well sorted peloids (yellow circle); B-Bioclastic grainstone with corals and cyanobacteria nodules. Meniscus micrite is present between various peloids and intraclasts (yellow circles). Micritic rims are developed on gastropod fragments (white circle). The yellow arrow indicates the presence of black pebble type intraclasts; C-Altered bioclastic grainstone with dasycladalean algae and cyanobacteria nodules. The original sparite is replaced by abundant iron oxides; D-Isotope values for the studied interval; E-G-Polished slabs indicating isotope values for both matrix and black pebble type intraclasts] (Scale: A-C-1 mm; E-G-1 cm)

7. Vertical facies stacking patterns, small scale sequences and medium scale sequences

Two distinct depositional units were identified by analysing the vertical stacking patterns of the most important facies types. The first one contains alternating low and high energy outer platform limestones. The second one is defined by inner platform peritidal carbonates (Fig. 14). They contain vertically stacked small scale sequences which are in turn grouped in middle scale sequences. The basal part of the Ciorânga Mare-Vârful Ascuțit-Padinile Frumoase section contains lower Tithonian outer platform carbonates which pass vertically into lower Tithonian–Berriasian–lower Valanginian peritidal limestones. Upper Tithonian–lower Valanginian peritidal limestones form the sedimentary succession of the Vlădușca section. Small scale sequences show hierarchical stacking patterns in both studied sections. Each small scale sequence is composed of elementary sequences. An elementary sequence comprises either an individual carbonate bed or a series of carbonate beds from the same depositional setting (Strasser et al., 1999; Strasser and Vedrine, 2009). In this study we use the scheme proposed by Strasser et al. (1999). These authors described in detail the concept of deepening-shallowing sequences. Such small sequences are bordered by flooding surfaces. They contain an initial transgressive component (blue triangles, Fig. 14), which is disposed directly on the basal flooding surface. Shallowing upward deposits overlay this initial transgressive unit (red triangles, Fig. 14) (deepening-shallowing sequences defined by transgressive surfaces). They are covered by another succesive flooding surface.

These structures represent the equivalent correspondent of a parasequence, sensu Van Wagoner et al. (1988). The application of this terminology represents the most suitable way to describe peritidal carbonates (Strasser, 1994). To be more precise, sequence stratigraphic concepts have to be integrated in the description of small scale sequences in order to explain their depositional history in a more dynamic context. The lack of a detailed geochronological study on the carbonate platform creates difficulties in asigning fifth to sixth order cycles or thirth to fourth order parasequences (sensu Van Wagoner et al., 1988; Husinec and Read, 2004; Anderson, 2004a, b). The existing microfossil assemblages did not allow a clear delineation of each stratigraphic stage. Thus, it is extremely difficult to establish a temporal connotation for these genetic units.

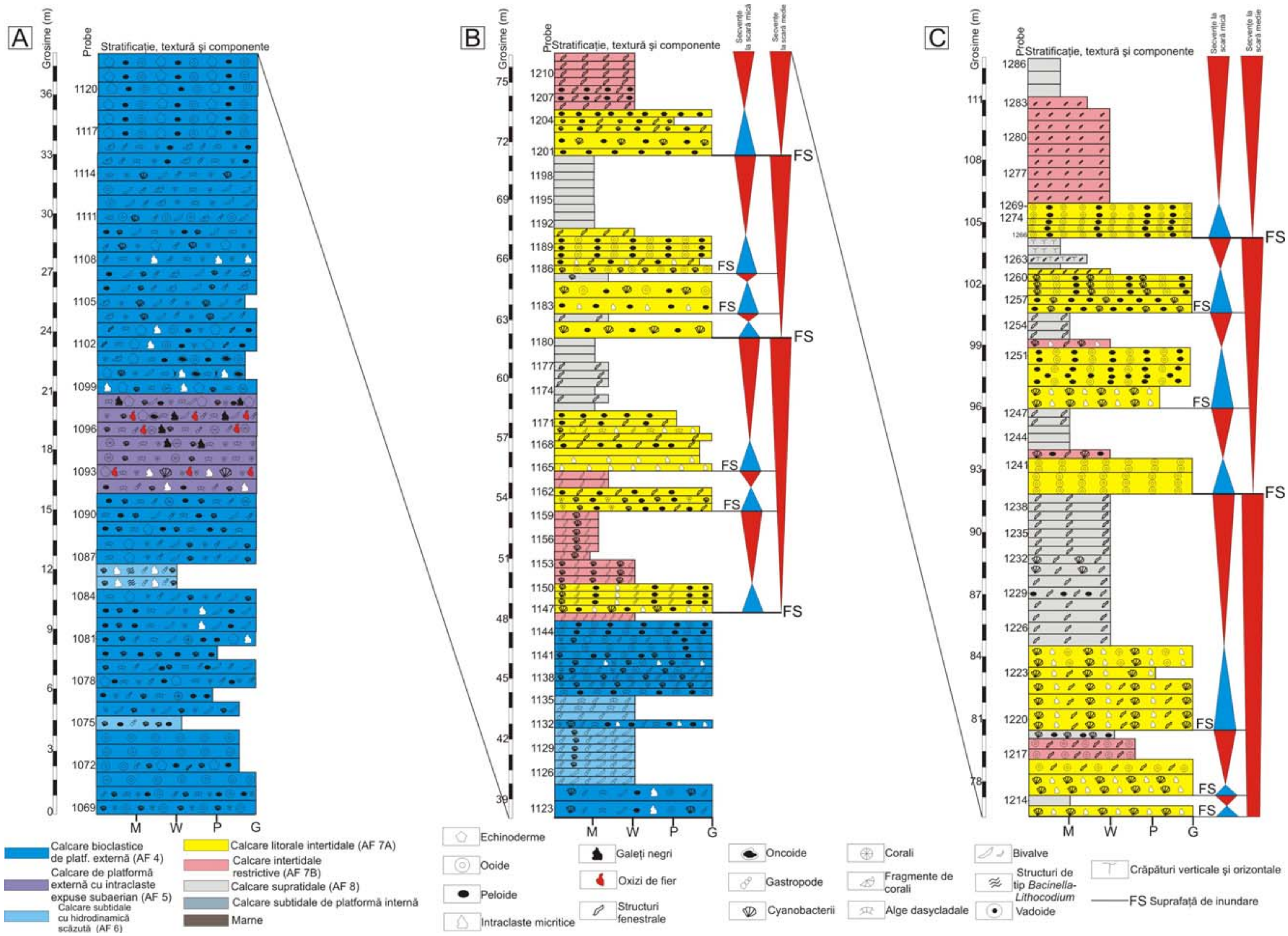

Fig. 14 Vertical facies distribution of the main facies types in the Cioranga Mare-Vf. Ascutit-Padinile Frumoase section

8. Sequence stratigraphic implications

Thick packages of slope and reef carbonates were deposited durring Kimmeridgian–Early Tithonian. Further details regarding the microfacies and depositional features of these limestones can be found in Pleş et al. (2013), Mircescu et al. (2014; 2016) and references therein. Lower Tithonian outer platform carbonates cover these Upper Jurassic basal units. The subaerially exposed horyzon can be associated with a laterally continuous sequence boundary. This hypothesis is strengthened by the existing microfacies, diagenetic and chemostratigraphic data. The sequence boundary is located in the middle part of the outer platform carbonates (Fig. 2). It is covered directly by thick packages of transgressive bioclastic and ooidic carbonates. Subaerial exposure and meteroric diagenesis are usually associated with such sequence boundaries wich are covered directly by transgressive units (Strasser, 1999; Hillgärtner et al., 2001). The initial flooding is followed by the development of aggradational deposits. Compact carbonate banks start to develop. Their thickness is constant (0.75 m, Fig. 14A) and vertical facies transitions are common, from pure oolitic to pure bioclastic units or a combination of these two cathegories. Such topographically elevated regions shelter low energy areas, where finer sediment will acumulate. Simillar depositional models were described by Enos (1977) or Purdy (1974). The entire peritidal succession has a prograding character. The small scale sequences represent incomplete carbonate cycles with missing subtidal units (Fig. 14).

Low amplitude marine level changes are indicated by the presence of very rare caliches and shallow water conditions (Husinec and Read, 2007). Autocyclic processes were responsible for the formation of the small scale sequences. They involve shoreline progradation and lateral transitions of intertidal and supratidal facies belts (Ginsburg, 1971; Matti and McKee, 1976; Pratt and James, 1986). Such processes are typical for shallow water carbonate platforms (Strasser, 1994). The thining tendencies of successive superimposed small scale sequences indicate a decrease in the available accomodation space and progradation of the entire succession. Littoral intertidal deposits are missing from the uppermost part of the succession. They are replaced by restricted intertidal or supratidal limestones. As the entire succession is prograding, conditions become restricted and the available accommodation space is reduced (Goldhammer and Lehmann, 1991). The formation of deepening-shallowing sequences follows two major stages. There is an initial stage when carbonate production is high. Accommodation space is created imediately above de flooding surfaces and littoral intertidal sediments are deposited. The presence of abundant peloids and ooids indicate open marine conditions. Maximum carbonate production in carbonate peritidal systems is commonly associated with initial sea-level rise and creation of accommodation space (Strasser, 1994). The second stage involves a sea-level drop which will create shallower conditions. Thining upward tendencies suggest a reduction of the available accommodation space and transitions towards shallow environments. Environmental conditions become more restricted and the intertidal ponds and swamps are isolated from open marine areas (Strasser and Vedrine, 2009). Carbonate sediment is produced mainly by *Rivularia* type cyanobacteria (Săsăran et al., 2013). As the accommodation space is reduced, restricted intertidal deposits will prograde and migrate laterally over the basal littoral intertidal deposits. Middle scale sequence facies distribution can be explained by such deepening-shallowing tendencies. This evolutional model shares simillar characteristics with other models proposed by various authors (Strasser, 1991; Strasser and Hillgärtner, 1998). Slight deepening and recurrent open marine conditions characterise the high energy subtidal deposits from the upper part of the studied sections. Normal marine conditions are indicated by the presence of abundant echinoderm plates. These lithological units mark the transition towards the upper Valanginian marlstones. A sharp contact separates the subtidal deposits from the overlying lithological units. This surface is equivalent with the same discontinuity identified by Patrulius (1969) in the Dâmbovicioara area. Grădinaru et al. (2016) described this limit as a drowning unconformity. The entire peritidal succession from the Piatra Craiului Massif contains deepening-shallowing small scale sequences which are grouped in middle scale sequences. The former have a general shallowing upward tendency. These deposits are bordered by two major diagnostic surfaces. The first one is a sequence boundary which coincides with the lower Tithonian black pebble horizon. The second one is a drowning unconformity which marks the contact with the upper Valanginian marlstones.

9. Conclusions

The entire Kimmeridgian–lower Valanginian carbonate succession from Piatra Craiului (eastern part of the Getic Carbonate Platform) has a total thickness of 1200 m. It is defined by a gradual transition from reefal, to outer platform and peritidal depositional settings. The outer platform carbonates were deposited in high energy conditions, overlaying directly the basal reefal deposits. They contain a large scale diagnostic surface which is represented by a laterally continuous sequence boundary. Isotope and microfacies data confirm the suberial exposure scenario.

1) Shallow water peritidal carbonates were accumulating in the Piatra Craiului sedimentary area and deep water pelagic carbonates were deposited in the Bucegi zone. The Postăvaru-Piatra Mare area represented an intermediary slope sector where allodapic depostion was common. These carbonate rocks contain a mixture of shallow water and calpionellid rich pelagic material.

2) The peritidal succession contains superimposed small to middle scale sequences. Deepening-shallowing tendencies characterise the small scale sequences. A general shallowing upward trend defines the middle scale sequences. Autocyclic processes were responsible for the formation of such structures. They involved mainly shoreline progradation and lateral migration of facies belts.

3) These incomplete peritidal cycles are marked by progressive transitions from intertidal to supratidal depositional settings. As the carbonate succession was prograding environmental conditions became more restricted. Carbonate material was produced by *Rivularia* type cyanobacteria.

4) Inner platform subtidal carbonates form the uppermost part of the studied sections. Their base marks a gradual deepening of the depositional environment in a slight transgressive context.

5) In terms of biostratigraphy, the age of the studied succession is lower Tithonian–lower Valanginian. The exisiting microfossil assemblages did not allow a

clear delineation of the most important stages. Thus, it is extremely difficult to determine the influence of allocyclic processes in the formation of small scale sequences.

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