Microfacies characteristics of the Lower Jurassic lithiotid limestone from northern Adriatic Carbonate Platform (central Slovenia)

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Abstract

The lithiotid limestone is characteristic for many Late Sinemurian – Pliensbachian tropical and subtropical carbonate platforms of the Neotethys and the Piemont-Liguria Oceans. On the northern edge of the ancient Adriatic Carbonate Platform (present NW External Dinarides) the lithiotid limestone forms a few hundred kilometres long belt. Sedimentological characteristics of the lithiotid limestone have been recorded in samples taken from three sections located in central Slovenia. Peloids, ooids, aggregate (lump) grains, benthic foraminifera, and micritised bivalve shells (cortoids) are the dominant grains. The microfacies association suggests restricted to open marine interior of a carbonate platform bordered by marginal sand shoals, or an inner ramp setting. Subtidal conditions were occasionally interrupted by emersions.

Introduction

The Early Jurassic sea-level rise (\textit{Hallam}, 2001), a gradual recovery of biota after the alleged biocalcification crisis in the latest Triassic (\textit{Hautmann} et al., 2008; \textit{Greene} et al., 2012), and, in many cases, extensional tectonics (\textit{Ruz\-\textendash}Ortiz et al., 2004; \textit{Smuc}, 2005; \textit{Verwer} et al., 2009) brought a gradual change from flat, uniformly shallow and skeletal-poor carbonate platforms of the earliest Jurassic (\textit{Dozet}, 1993; \textit{Buckovi\textendash}\v{c}i\v{c} et al., 2001; \textit{Azeredo} et al., 2003; \textit{Eren} et al., 2002; \textit{Barattolo} & \textit{Romano}, 2005; \textit{Pomoni\textendash}Papaioannou & \textit{Kostopoulos}, 2008; \textit{Wilmsen} & \textit{Neuweiler}, 2008; \textit{Bosence} et al., 2009; \textit{Ogorelec}, 2009) into the middle Early Jurassic platforms characterised by the abundance of biota and a variety of facies types (\textit{Galli}, 1993; \textit{Fugagnoli} & \textit{Loriga Broglio}, 1998; \textit{Masetti} et al., 1998; \textit{Bломeier} & \textit{Reijmer}, 1999; \textit{Scheibner} & \textit{Reijmer}, 1999; \textit{Cionni} & \textit{Picotti}, 2001; \textit{Fraser} et al., 2004; \textit{Wilmsen} & \textit{Neuweiler}, 2008). Among the more extensively researched carbonate platforms of the Early Jurassic is also the Adriatic Carbonate Platform (AdCP), a large carbonate platform with an approximate length of 600 km (\textit{Dragi\textendash}\v{c}evi\c & \textit{Velc\i}, 2002; \textit{Ti\v{s}ljar} et al., 2002; \textit{Vla\v{c}o}vi\c et al., 2002, 2005; \textit{Cadjenovi\c} et al., 2008), positioned in the western part of the Neotethys Ocean (\textit{Thierry}, 2000; \textit{Bosence} et al., 2009) (Fig. 1).

One of the most distinct facies types on the AdCP is the Late Sinemurian – Pliensbachian (according to \textit{Sabatino} et al., 2013 also earliest Toarcian) lithiotid limestone (\textit{Bus\v{s}er}, 1965;
At the northern part of the AdCP, structurally belonging to the north-western External Dinarides (Placer, 1999), the lithiotid limestone extends in over 100 km long belt from Trnovski gozd in the west towards Kočevje and further to the east-southeast (Buser & Debeljak, 1996). The lithiotid limestone was quarried south of Ljubljana and became known as the “Podpeč limestone” (Ramovš, 2000; Štukovnik et al., 2011; Kramar et al., 2015). Dozet named it the Lithiotid Limestone Member of the Podbukovje Formation (Dozet & Strohmenger, 2000) or the Lithiotid Limestone Member of the Predole beds (Dozet, 2009). On the basis of a detailed description of the lithiotid limestone from Trnovski gozd Črne and Gorican (2008) advocated a ramp model for the northern part of the AdCP, gradually passing into the deep-water Slovenian Basin to the north, while previous studies suggested a rimmed carbonate platform model (Buser & Debeljak, 1996).

The aim of this paper is to extend the current knowledge on the lithiotid limestone at the northern edge of the AdCP by giving a detailed description of the lithiotid limestone from Trnovski gozd, described in Črne and Gorican (2008). Finally, the question of the platform geometry is discussed.
Geological setting

The northern part of the AdCP structurally belongs to the External Dinarides, which represent a deformed margin of the Adriatic tectonic microplate. The deformations in the External Dinarides are due to post-Cretaceous collision with the European plate, accompanied by folding and thrusting in SW direction during Late Cretaceous to Paleogene (PLACER, 1999; VRABEC & FODOR, 2006; PLACER, 2008; KASTELIC et al., 2008). The thrust units, from the uppermost to the lowermost, comprise: the Trnovo Nappe, the Hrušica Nappe, the Snežnik thrust block, and the Komen thrust block (Fig. 3). Thrust blocks consist of Late Paleozoic to Middle Triassic clastics and carbonates, followed by carbonates deposited on the AdCP. Towards north, the External Dinarides border the Tolmin thrust unit of the Southern Alps along the South–alpine reverse fault and the Marija Reka fault. The Tolmin thrust unit mostly comprises deep water sediments of the Slovenian Basin, originally extending along the northern margin of the AdCP (PLACER, 1999). Thrusts are further cut and displaced by dextral strike-slip faults active since the Pliocene (VRABEC & FODOR, 2006; KASTELIC et al., 2008; KASTELIC & CARAPA, 2012).

The Mt. Krim area structurally belongs to the Hrušica Nappe of the External Dinarides (PLACER, 1999). The geological structure of this territory was established by Lipold (1858), Kramer (1905), Vettens (1933), BUSER et al. (1967), BUSER (1968), and MILER and PAVŠIC (2008). The Mt. Krim area mostly consists of Upper Triassic to Middle Jurassic shallow water carbonates (BUSER et al., 1967; BUSER, 1968, 1989; OGORELEC & ROTE, 1993), which today form the southern hilly rim and the southern basement of the younger, post-Pliocene tectonic Ljubljana Moor Basin (JAMŠEK RUPNIK et al., 2015). Mesozoic carbonates are dissected by N-S and WNW-ESE to NW-SE running faults (BUSER et al., 1967; BUSER, 1968) (Fig. 4).

The Lower Jurassic succession in the Mt. Krim area conformably overlies the Norian-Rhaetian Main Dolomite (Fig. 5), which is characterised by medium to thick-bedded crystalline dolomite, laminated fenestral dolomite and intraclastic breccia, marking cyclically interchanging shallow subtidal, intertidal and supratidal conditions (OGORELEC & ROTE, 1993; MILER et al., 2007; MILER & PAVŠIC, 2008). The lowermost Jurassic
The facies analysis of the “Podpeč limestone” is based on three detailed sections, namely the Zalopate (45°56′09″ N, 14°27′21″ E), the Podpeč quarry (45°58′22″ N, 14°23′16″ E) and the Grad (45°55′46″ N, 14°30′14″ E) sections (Fig. 4). Bed thickness classification follows Tucker (2001). Altogether, 63 thin sections were investigated and described according to terminology of Dunham (1962), and Embry and Kløvand (1971). The proportion of grain types was estimated with the use of comparison charts of Bacelle and Boselli (1965). Sand-size, roughly spherical homogenous lime-mud particles are termed peloids sensu Friedman (2003). Microfacies (MF) types were compared to Standard Microfacies Types in Flügel (2004).

**Description of sections**

The Zalopate section (Fig. 6) is 42.5 m thick and consists mostly of grey to black limestone of variable textures. Bed thickness ranges from 6 cm to 320 cm, but thicker beds predominate in the lower part of the section, whereas thin to medium thick beds are more common in the upper half of the section. The texture of the limestone varies from mudstone to floatstone with grainstone (Hettangian-Sinemurian) succession consists of medium to thick-bedded finely crystalline dolomite, finely laminated dolomite, bedded micritic, rarely peloidal and oolitic limestone. Emersion surfaces are indicated by red-stained irregular upper bedding planes. This succession also deposited in peritidal and shallow subtidal setting (Miler & Pavšič, 2008; Ogokelec, 2009). Discontinuous, up to several tens of meters thick bodies of mud-supported breccia are locally present (Busser, 1965), as well as up to a meter wide dikes, filled with large angular blocks of dolomite in dolomitised matrix (visible along road cut south of Pijava Gorica). Upwards, oolitic and bioclastic limestone predominates, gradually passing into dark grey to black limestone with lithiotid bivalves, bioclastic packstone, floatstone, ooid packstone and grainstone (Busser & Debelač, 1996; Miler & Pavšič, 2008). On the basis of lithiotid bivalves and foraminifera, a Late Sinemurian–Pliensbachian age has been determined for the lithiotid limestone (Busser & Debelač, 1996; Gale, 2014). Discontinuous, but much rarer bodies of black limestone breccia can be laterally found (Busser, 1965), for example west of Jezero. The Lower Jurassic succession ends with the Toarcian thin-bedded, often nodular micritic limestone (A. Košir, pers. com.). The Middle Jurassic succession consists of strongly dolomitised thick succession of oolitic limestone (Busser, 1965, 1968; Miler & Pavšič, 2008).
Figure 7. The lithiotid-rich “Podpeč limestone” from the type locality in the Podpeč quarry. Two overlapping sections were measured. Early Pliensbachian. Number in brackets refer to mikrofacies type.
support, or often within the same bed, either through grading, or through irregular mixing (at least in part due to bioturbation) and lateral pinching out. Normal grading is the most common sedimentary structure. Some accumulations of fossils (mostly fragmented bivalve shells) can be found at the bottom of beds. Bivalve shells are more commonly dispersed in oolite. Several bedding planes show irregular morphology, reddish colouration, and thin intercalations of red or yellow claystone. Lithiotid bivalves are rare, and only up to 5 cm long, undetermined specimens were found, in one case accumulated above a score structure, cutting through mudstone with birdseyes-type porosity and red clayey surface. Cross-lamination is rarely found in oolitic limestone. The section is placed in the Orbitopsella primaeva partial-range zone of Late Sinemurian to early Early Pliensbachian age (VELIĆ, 2007; not into the early Late Sinemurian Lituosepta recoraensis zone as stated in GALE, 2014).

In the Podpeč quarry two sections were logged and correlated: Podpeč 1 (33 m thick) and Podpeč 2 (12 m thick) (Fig. 7). Limestone predominates, but up to several centimetres thick intercalations of red claystone are common. The measured section starts with 3 m thick packstone/grainstone with superficial ooids and recrystallised bivalve shells concentrated near the upper bedding plane in a 20 cm thick layer. Grainstone is followed by almost 7 m thick packstone/grainstone with lithiotid bivalves oriented perpendicular to the bedding plane, with commissures oriented upwards (i.e., preserved in toto). A 20 cm thick limestone bed with claystone intercalations follows. Throughout the rest of the section thick to very thick limestone beds predominate. Grey oolitic limestone is the most common lithological type. Dispersed bivalve shells may be present. Gradual transition from oolite into micritic limestone or vice versa is common. Oncoids are frequent in the upper part of the section. Mudstone and wackestone are also present. The latter may contain dispersed, randomly oriented terebratulid brachiopods or megalodontid bivalves. Limestone beds are often separated by red claystone layers, which may be several centimetres thick. Red claystone partings are common near the top of individual beds, and may be present also inside limestone beds. Irregular subvertical pockets filled with yellowish claystone were also found near the top of the measured section (8.5 m above the base of Podpeč 2 section in Fig. 7). Some limestone beds and claystone interlayers contain accumulated shells of lithiotid bivalves oriented parallel to the bedding plane, but often with both valves preserved together. Up to 15 cm large fragments of shells are commonly found eroded from the latter. According to BUSER and DEBELJAK (1996), Lithioperna scutata is present in the lower part of the Podpeč quarry succession, whereas Cochlearites loppianus appears higher. The section belongs to the Early Pliensbachian Orbitopsella praecursor taxon range zone (GALE, 2014).

The Grad section measures 8 m in thickness (Fig. 8). Medium to thick beds predominate, which are internally often heterogenous. Mudstone, wackestone, bioclastic and ooid packstone, floatstone and rudstone with brachiopods and bivalves were determined in the field. Few beds have wavy lower boundaries and chaotic shell accumulations at the bottom, gradually passing into ooid packstone and wackestone. Lithiotid bivalves are present, but shells are randomly distributed and fragmented. The section belongs to the Early Pliensbachian Orbitopsella praecursor taxon range zone (GALE, 2014).
Microfacies description

Eleven microfacies (MF) types were recognised, although subtle variations in some of them could lead to several subtypes. Comparison of described MF types with standard microfacies types (SMF) is given in Table 1.

**MF 1 – Mudstone**

A very common facies type is grey or black micritic limestone in thin to very thick beds. Micritic matrix is devoid of grains. Fenestrae (5% of the thin section surface) show geopetal fabric formed by crystal silt in the lower and blocky spar in the upper part (Fig. 9.1).

**MF 2 – Lithiotid floatstone to rudstone**

Lithiotid bivalves are commonly accumulated in several horizons in Grad and Podpeč sections, whereas only up to several centimetres large specimens were recorded in the Zalopate section. Shells comprise up to 50% of the thin section surface. They are partly neomorphically altered into blocky spar, and retain fibrous outer layer. They are embedded into peloidal wackestone or packstone with some fenestrae (Fig. 9.2-9.3). Small fragments of shells are common and rare benthic foraminifera are present.

**MF 3 – Peloidal wackestone-packstone with Thaumatoporella**

This MF type was found in thin to medium-thick beds of the Zalopate section. The distinct feature of this microfacies is the abundance of the problematic algae *Thaumatoporella* and a low abundance of benthic foraminifera. The matrix is peloidal-bioclastic wackestone with some fenestrae, and with up to 45% of grains. Peloids represent 80–90% of grains. Subordinate are benthic foraminifera (*Meandrovoluta asiagoensis*, *Textularia* sp. and *Siphovalvulina* spp. predominate), mollusc fragments and *Thaumatoporella* thalli. Micritic matrix in places appears clotted (Fig. 9.5).

**MF 4 – Peloidal wackestone to packstone**

This MF type is similar to MF 3 by the high abundance of peloids, but contains more diverse biota. It was found in medium to very thick beds and is rather common in all sections. Accumulations of lithiotid shells are sometimes present in the lower part of the same beds.

**Table 1. Comparison of the determined microfacies (MF) types with Standard Microfacies Types from Flügel (2004).**

| Described microfacies Type | Standard Microfacies Type (Flügel, 2004) | Occurrence on flat-top platform | Occurrence on ramp |
|----------------------------|------------------------------------------|---------------------------------|-------------------|
| 1: Mudstone                | SMF 23                                   | FZ 8 (tidal flat)               | Inner ramp        |
| 2: Lithiotid floatstone to rudstone | SMF 12-Lithiotid               | FZ 8 (restricted platform and tidal flat), FZ 7 (open platform) | Inner ramp        |
| 3: peloidal wackestone-packstone with *Thaumatoporella* | ?SMF 18                          | FZ 8 (restricted platform; as bar sand channels, sand shoals heaped up by tidal currents in shallow lagoon and bays), FZ 7 (shelf lagoon with open circulation) | Inner ramp |
| 4: Peloidal wackestone to packstone | SMF 16- Non-laminated to SMF 10      | FZ 7 (open shelf lagoon), FZ 8 (restricted platform) | Inner ramp |
| 5: Bivalve floatstone to rudstone | SMF 12-Bs                          | FZ 8 (restricted platform), FZ 7 (open platform) | Open inner ramp   |
| 6: Oncoidal-peloidal floatstone | SMF 22                               | FZ 8 (low-energy part of shallow lagoon and tidal zone) | Middle and outer ramp |
| 7: Coated bioclastic floatstone with peloidal-bioclastic wackestone-packstone matrix | SMF 10                           | FZ 7 (open shelf lagoon) | Inner ramp |
| 8: Peloidal grainstone     | SMF 16-Non-laminated                 | FZ 8 (shallow platform interior) | Inner ramp         |
| 9: Cortoid floatstone to rudstone with peloidal-bioclastic grainstone matrix | (no single analogue; mostly SMF 14) | Shallow platform interior with moderate to high water energy | Inner ramp (shoal) |
| 10: Bimodal poorly to medium sorted ooidal-peloidal grainstone | SMF 17                           | FZ 7 (shallow open shallow platform) | (very rare) |
| 11: Well sorted ooidal grainstone | SMF 15                           | FZ 8 (restricted lagoon), FZ 7 (oolitic shoals, tidal bars, beaches) | Inner ramp |

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Grains represent 40–50 % of the thin section surface, and are well to very well sorted (Fig. 9.6). Peloid size is 0.1–0.15 or 0.2–0.35 mm.

Subangular to well-rounded peloids predominate (60–80 % of clasts; Fig. 9.7). Mollusc fragments (in some thin sections with micritic outlines) and micritic intraclasts represent 5 % of grains each. The rest of the clasts are represented by small benthic foraminifera (*Meandrovolutula* sp., *Lagenina*), pellets (*Parafavreina* sp.), *microproblematica Thaumatoporella* sp., green algae, echinoderms, and ostracods. Aggregate grains (mature lumps) are very rare. Subangular, sub-elongated mudstone intraclasts (mudchips) are rarely present.

Into microspar recrystallised matrix is bioturbated and contains some fenestrae. Vugs, filled with blocky spar, represent 2.5–5 % of the thin section surface.

**MF 5 – Bivalve floatstone to rudstone**

Present in medium thick beds, without apparent orientation of shells or with convex side turned downwards.

This MF is characterised by accumulation of up to several millimetres large bivalves and rare gastropods embedded in micritic matrix (Fig. 9.8). Both valves are present, mostly unbroken, without micritic outlines, and positioned oblique or parallel to bedding. The original shell material is replaced by blocky spar. Microcrystalline spar is present at the bottom of some valves, succeeded by blocky spar, suggesting dissolution of shells. Ostracods are very rare.

**MF 6 – Oncoidal-peloidal floatstone**

This type of microfacies was recorded in thick beds, overlying oolite with intraclasts and passing into ooid-intraclastic packstone to rudstone. It may also form a homogenous texture within individual beds.

This MF is characterised by 20–40 % of 4–12 mm large oncocids with micritic inner structure. Some peloids, small spar crystals, encrusting foraminifera, and *microproblematica Thaumatoporella* are found within the oncocids. A possible partly bored sponge was found in the center of one of the oncocids. Two subtypes may be distinguished on the basis of the matrix surrounding the oncocids.

In the first subtype, oncocids are embedded in packstone matrix (Fig. 10.1). Patches of peloidal grainstone with intergranular drusy mosaic spar are present along the packstone. Grains comprise 50 % of the area. They are poorly sorted, with an average size 0.15 mm. Peloids predominate (80 % of grains) over intraclasts (10 %), foraminifera (4 %), bivalve fragments (3 %), and *microproblematica Thaumatoporella* and *Tubiphytes* (2 %). Gastropods, echinoderms and green algae are very rare. Large litiolid foraminifera are rarely present. Echinoderm plates are overgrown by sintaxial calcite.

In the second subtype, oncocids are embedded in wackestone with patches of packstone (Fig. 10.2). Washed-out patches are rarer (2.5 % of surface), filled with drusy mosaic cement. Peloids are the dominant grain type. Superficial ooids, foraminifera, intraclasts, echinoderms, and serpulid fragments are subordinate.

**MF 7 – Coated bioclastic floatstone with peloidal-bioclastic wackestone-packstone matrix**

Present in medium to very thick beds, in places with erosional lower bedding planes.

Grains measuring 2–5 mm represent up to 25 % of the thin section area (Fig. 10.3–10.4). They consist of bivalve fragments, rarely gastropods, brachiopod shells, and aggregate grains. Fossils are neomorphically altered into mosaic or granular spar. Some are rounded due to abrasion/bioerosion, strongly bored at the surface or have micritic coatings. The supporting matrix is represented by peloidal-bioclastic wackestone-packstone with 30–50 % of grains (Fig. 10.5). These are dominated by peloids (80 % of grains). Common are mollusc shell fragments (10–15 % of grains), which are angular, without micritic outlines. Foraminifera (up to 5 % of grains diverse small and large benthic forms) and echinoderms (2.5 % of grains) are always present, whereas amount of superficial ooids varies (0–5 %). Gastropods (Fig. 10.6), ostracods, dasyclad green algae, and brachiopods are rare to very rare. Almost 2 mm wide stromatactis-like cavities are rarely present, filled with blocky spar.

Remark: This MF could alternatively be assigned to SMF 11 (Coated bioclastic grainstone), occurring in winnowed platform edge sands, rarely in inner- and middle-ramp settings. In Table 1, it is attributed to SMF 10 (Bioclastic packstone and grainstone with worn skeletal grains).
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**MF 8 – Peloidal grainstone**

Present in medium thick beds with cross-lamination, and massive beds.

This MF is distinguished from MF 7 in the smaller amount of clasts larger than 2 mm, and a lack of micritic matrix.

Up to 4 mm large clasts (up to 5% of the surface) comprise mudstone and wackestone intraclasts, fragmented bivalve shells with microborings on the outer surface, gastropods, and large benthic foraminifera. Clasts are parallel to the bedding and are floating in peloidal grainstone.

Around 50% of the peloidal grainstone consists of grains. These are well to very well sorted (Fig. 10.7–10.8). Rounded, 0.1–0.2 mm or 0.2–0.35 mm large peloids (in this case “pseudo-ooids”) predominate (70% of clasts). Subordinate are cortoids of small mollusc fragments (10% of grains), replaced by spar, sub-rounded to angular in shape, and sub-elongated or isometric in form. Superficial ooids (10% of grains) have nuclei of mollusc fragments, echinoderms or peloids. Echinoderms, foraminifera and lumps comprise each 5% of grains. Gastropods and calcimicrobes are very rare.

Grains are surrounded by circumgranular bladed spar. The remaining intergranular space is filled with mosaic spar. Sintaxial cement is present around echinoderm plates.

**MF 9 – Cortoid floatstone to rudstone with peloidal-bioclastic grainstone matrix**

This is a very common microfacies, building medium to very thick beds. The latter are often normally graded, with large bioclasts concentrated in the lower part. Indistinct grading may be present, with rudstone passing into floatstone. Larger bivalve shells are usually parallel to bedding, but variably concave- to convex-upwards. Geopetal structures may be present in gastropod shells. Lamination due to differences in grain size is in places present in the grainstone matrix.

Clasts larger than 2 mm (up to 11 mm in diameter) comprise 10–50% of the rock volume. They are mostly bivalve shells with micritised outer surfaces and replaced by mosaic spar (Fig. 11.1-11.2). Micritic coatings are also present. Packstone or mudstone matrix clings to some shells. Some large intraclasts with keystone vugs are locally present (Fig. 11.5). A minor part of larger clasts belongs to abraded and on the outside micritised gastropods. Their lumen is filled with packstone or with mudstone. Large benthic foraminifera, calcimicrobe Cayeuxia, dasyclad green algae geniculi, echinoderms, and packstone intraclasts represent a smaller amount of large grains.

The described large clasts float in peloidal-bioclastic grainstone (Fig.11.3–11.4). The mean size of peloids is around 0.2 mm, whereas bioclasts measure 0.5–1 mm. Grains are well rounded, sub-elongated to spherical in shape. Peloids or superficial ooids predominate (around 80% of smaller grains). The rest of the smaller grains are echinoderms (some with micritised outlines), mollusc fragments, benthic foraminifera, dasyclad green algae, brachiopod fragments, and aggregate grains.

Grains are surrounded by fibrous to bladed circumgranular cement. The remaining intergranular space is filled with mosaic spar. Larger vugs and umbrella-type vugs beneath some bivalve shells are filled with drusy mosaic spar. Echinoderms are enclosed in sintaxial cement.

Remark: There is no single SMF type to describe rudstone to floatstone with grainstone matrix. Instead, comparable lithology is interpreted as storm deposit (Pl. 127, fig. 2 in FLÜGEL, 2004; see also CARACUEL et al., 2005).

**MF 10 – Bimodal poorly to medium sorted ooid-peloidal grainstone**

This type of microfacies was recognised in thin beds, in very thick beds with inverse-to-normal grading, or in very thick beds with bivalve accumulations at the base. It was also encountered as lense-shaped accumulations.

Grains represent 60% of the volume and are bimodally distributed (Fig.11.6–11.7). Sorting is poor to moderately good. Grains are in point contacts. Larger grains (diameter 0.3 or 0.5–0.8 mm) are represented by ooids and aggregate grains. Interstices between larger grains are more or less densely filled with smaller ooids (diameter 0.05–0.07 mm) and peloids.
Microfacies characteristics of the Lower Jurassic lithiotid limestone from northern Adriatic Carbonate Platform
Peloids account for 40% of grains. They are very well rounded and have hazy outlines. They are often grouped into small patches. Aggregate grains (lumps and mature lumps) represent around 30% of grains. They consist of ooids, bounded by micritic meniscus cement. Spheroidal ooids represent approximately 20% of grains. They are largely micritised and partly recrystallised; it is thus difficult to distinguish whether they were concentric or radial. Their nuclei include neomorphically altered shell fragments, echinoderm plates, rarely small gastropods, but most are micritic/micritised. The cortex (often micritised) consists of 9–15 or more laminae, each 8–10 µm thick. The cortex/nucleus ratio is 41–56%. Superficial ooids, formed around large benthic foraminifera, and a few spiny ooids are also present (Fig. 12.1). A minor amount of grains belongs to intraclasts of peloidal packstone. Cortoids (up to 5% of clasts) are mostly small fragments. Some larger bivalve shell fragments have strongly micritised outer surfaces. Some have uneven micritic coatings. The shells themselves are replaced by spar. Isolated (i.e., not included into ooids) benthic foraminifera are rarely found. Gastropods are rare.

Intergranular space is filled with drusy mosaic spar.

**MF 11 – Well-sorted ooid grainstone**

This type is present in medium thick beds with slight cross lamination, in thick and very thick beds (also following bivalve shell accumulation at the base), and as lens-like accumulations.

Grains represent 50% of the volume. Sorting is good to very good (Fig. 12.2–12.3, 12.5). Grains are in point contacts. Two MF 11 subtypes are distinguished on the basis of the prevalent ooids sizes: MF11a with 0.15–0.35 mm (mean size 0.30 mm) large ooids (Figs. 12.2–12.3, 12.5), and MF11b with 0.35–0.55 mm (mean size 0.40 mm) large ooids (Figs. 12.4, 12.6). In places, lamination is visible due to a slight change in grain size and packing (Fig. 12.3). The lamina boundaries may be slightly undulating and sharp (Fig. 12.5).

Ooids are spheroidal and present 95% of grains (Fig. 12.4). Nuclei are usually micritic, although small benthic foraminifera, mollusc fragments and echinoderm remains are present. As in MF 10, ooids are mostly strongly micritised, but there appears to be fewer (up to nine) laminae in cortices. The ratio cortex:nucleus amounts to up to 45% for the thickest ooids. Few superficial ooids, formed around shell fragments, foraminifera and echinoderms, are also present. Spiny ooids are very rare, as well as broken and half-moon ooids.

The remaining grains are neomorphically altered shell fragments (mostly free of micritic coating), echinoderms, gastropods, aggregate grains, and very rare green algae, ostracods, and brachiopod fragments. Foraminifera were found only as ooid nuclei.

Grains are rimmed by fibrous to bladed spar (Fig. 12.6), succeeded by drusy mosaic intergranular cement (Fig. 12.4). Sintaxial cement is present around echinoderm plates, and ooids are partly recrystallised. Keystone vugs, filled with drusy mosaic spar are common. Slightly irregular laminae of crystal silt are sometimes present within grainstone (Fig. 12.6).

**Discussion**

**Interpretation of the studied sections**

Reddish colouration of upper bedding planes, thin irregular intercalations of claystone and in one case subvertical pipes filled with yellowish claystone correspond to palaeosol and palaeokarst surfaces (Martínůš et al., 2012; see also Buser & Desbieljak, 1996), and suggest deposition in a very shallow sea, frequently interrupted by emersions. Spiny ooids are also indicative of vadose conditions (Flügel, 2004). On the basis of the thickest bed (7 m in Podpeč section), and the abundance of palaeosol horizons in the Podpeč section, the water depth might have been only a few meters.

Lithiotid bivalves preserved in living position in the lower part of the Podpeč section suggest a short transport of lithiotid shells found in slightly

Figure 11. Microfacies types of the Podpeč limestone.

1 – Bioclastic floatstone–rudstone with peloidal grainstone matrix. Note the neomorphic replacement of mollusc shells by drusy mosaic spar (arrowhead) and the sindepositional pore space beneath the shell, filled by spar (S). Thin section 523.

2 – Bioclastic rudstone with peloidal grainstone matrix. Thin section 429d.

3 – Details of the grainstone matrix. Note the highly micritised bioclasts (B), a large rounded micritic clast (completely recrystallised bioclast?) and a fragment of benthic foraminifera (arrowhead). Thin section 417.

4 – Details of the grainstone matrix. Note the crude lamination due to the difference in grain size and sorting (arrowhead points at the sub-horizontal boundary). Thin section 528.

5 – Large lithified intraclast (peloidal grainstone with large keystone vugs (K) – cemented beachrock) in bioclastic rudstone. Arrowhead points at the intensely cemented intraclast boundary. Thin section 420.

6 – Bimodal poorly to medium sorted ooid grainstone. Note large bivalves (B), keystone vugs (K) partly filled with internal sediment and some aggregate grains (arrowhead). Thin section 413.

7 – Bimodal poorly to medium sorted ooid grainstone. Note crude lamination (laminae running from top left to lower right) suggested by grain density. Thin section 429c, not oriented.
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younger claystone beds. It is also possible that accumulations of lithiotid shells in claystone result from subaerial exposure of the entire buildup, resulting in its demise, so these individuals may also be preserved in situ (hence the preservation of both valves).

Birdseyes vugs and cortoids further agree with deposition in a very shallow marine setting (FlüGel, 2004). A mixture of high- and low-energy environment and/or events is suggested by the co-presence of ooids and oncoids (turbulent water) and micritic limestone (stagnant water), and is reflected in the mixture of high and low energy microfacies types. Chaotic accumulations of mollusc shells suggest occasional influence of high-water-energy events, such as storms (Masetti, 2002; FlüGel, 2004).

The microfacies (MF) association agrees with the interpretation of the shallow-marine sedimentary environment (Table 1). Although MF types 1, 2, 3 and 5 were described only from the Podpeč section, and MF 6 only from the Zalopate section, this is attributed to the sampling bias, because only a small proportion of beds were sampled for microscopy.

**The northern part of the Adriatic Carbonate Platform**

On the basis of several schematic sections, Buser and Debeljak (1996) suggested a rimmed carbonate platform model. They positioned the Podpeč area close to the oolitic margin of the platform. A similar position was envisaged for the Spik section in Trnovski gozd. The ooid-rich margin of the platform is followed landward by a restricted lagoon in which mud-rich limestone with low energy index deposited (Buser and Debeljak, 1996). Dozet (1999) later described lithiotid limestone near Kočevice, where lithiotid-bearing dolomite is intercalated with thin layers of fine-grained intraformational breccia and coal-bearing horizons.

In contrast, Črne and Goričan (2008) suggested the ramp type model on the basis of similarities of the Kovk section with the Rumija in Montenegro. The lithiotid limestone in the Kovk section was divided into three units (Črne and Goričan, 2008). The lowermost of these comprises thick bedded peritidal limestone (subtidal wackestone, rarely packstone, inter- to supratidal fenestral mudstone or fenestral peloidal packstone, rarely peloidal grainstone with few ooids) with lithiotid bivalves. The second subunit consists of peloidal grainstone with ooids, and the third of peritidal wackestone and packstone with bivalves of the lithiotid facies. According to Črne and Goričan (2008), Kovk section belongs to the inner ramp setting.

The herein described association of microfacies types agrees with both interpretations (Table 1), and may correspond to the inner-ramp setting, or to the open and restricted lagoon interior of the rimmed platform model (FlüGel, 2004). However, the rimmed platform model is herein preferred due to the following reasons:

1. cortoids and aggregate grains are more common on a rimmed platform (FlüGel, 2004), although they are not excluded from ramps;
2. a rimmed platform would be more prone to small sea-level falls, and emersions are common in recorded sections, especially in the Podpeč sections;
3. the ramp model suggests that all known localities of the lithiotid limestone belong to the inner ramp setting (Fig. 13.1); this also suggests that an entire middle and outer ramp are currently missing due to latter thrusting or breaking of the AdCP margin;
4. the rimmed carbonate platform model on the contrary suggests a more widespread palaeogeographic distribution of localities (Fig. 13.2), and a less drastic post-Cretaceous crust shortening.

**Conclusions**

The microfacies association recorded in the Late Sinemurian – Pliensbachian lithiotid bivalves-bearing limestone at the northern margin of the Adriatic Carbonate Platform comprises: (1) mudstone, (2) lithiotid floatstone...
Figure 13. Discussed possible models for the northern part of the Adriatic Carbonate Platform. 1 - Rimmed platform. 2 - Carbonate ramp. Modified after FlüGel (2004).

to rudstone, (3) peloidal wackestone-packstone with Thaumatoporella, (4) peloidal wackestone to packstone, (5) bivalve floatstone to rudstone, (6) oncoidal-peloidal floatstone, (7) coated bioclastic floatstone with peloidal-bioclastic wackestone-packstone matrix, (8) peloidal grainstone, (9) cortical floatstone to rudstone with peloidal-bioclastic floatstone matrix, (10) bimodal poorly sorted ooid-peloidal grainstone, and (11) well sorted ooid grainstone.

The most common type of grains are ooids, aggregate grains and various skeletal particles (bivalve shells, large benthic foraminifera). Cortoids are common. Rare spiny ooids indicate occasional vadose conditions, and subaerial exposure surfaces point to occasional emersion. The most common type of cement, present in washed-out patches of micritic matrix or among grains in higher-energy facies types, is blocky or drusy mosaic spar. In several MF types, it is preceded by circumgranular fibrous to bladed spar.

The facies association corresponds to restricted and open marine interior (facies zones 8 and 7) of a platform bordered by marginal sand shoals, or to the inner ramp setting (FlüGel, 2004). This study does not give the final answer concerning the type of the platform due to the lack of seismic-scale profiles. However, the platform bordered by oolitic shoals and with a steep transition to the Slovenian Basin to the north may be a better model than the ramp model.

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