INFLUENCE OF SEDIMENTARY ENVIRONMENT ON THE TECHNICAL PROPERTIES OF THE LOWER CRETACEOUS LIMESTONES FROM THE LAKOVIĆI QUARRY IN ISTRIA (CROATIA)

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The Lower Cretaceous limestones from the Lakovići quarry belong to the basal part of the Aptian limestones. These limestones are the beginning of the second transgressive-regressive megasequence in Istria which followed a general Upper Aptian emersion event. Within the approximately 50 m thick limestone sequence that is quarried, four facies units were defined according to their petrographic and sedimentological features. The following facies units were defined: A – Micritic limestones, which were deposited as shallowing-upward cycles and which begin with breccias containing clay matrix or terminate with dark-gray clays sporadically accompanied by deposition and red depositional of black terrestrial and swamp clays, as well as sediments from bogs and pools that were developed in isolated bays and/or lagoons; B – Grain supported limestone deposited as fine-grained to coarse-grained carbonate sands in a predominantly high-energy shallows, bars and sandy beaches; C – Micrite limestones deposited in restricted low-energy shallow subtidal environments; D – Grain supported limestones deposited as fine-grained carbonate sands in high-energy shallows and bars. The results of petrological, sedimentological and technological investigations show that the limestones from each individual facies unit have different technical properties, notably porosity, bulk density and water absorption, i.e. the whole range of technical quality of the limestones quarried is a direct consequence of their facies characteristics. The outlined facies units enable separation of rock mass in the quarry not only by their petrological characteristics but also according to the technical quality of the rock.

Introduction

The petrological features of carbonate rocks are a direct consequence of their deposition environment and diagenetic processes. Individual changes in the deposition environment, marked changes in depth and energy of the shallow-water settings due to sea level changes, as well as variations of diagenetic processes expressed as changes from purely marine zones, to mix zones and from meteoric/freatic to vadose diagenetic zones, produce a petrological, structural and textural variability in the vertical profile, resulting also in a similar variability in the physical/mechanical as well as technical properties of the rock mass. These assumptions were the basis for the systematic petrological and sedimentological investigations of Lower Cretaceous shallow-water limestones from the Lakovići quarry in central Istria, which are exploited as crushed stone of variable technical quality. The source of the technical quality variation in the 60 m thick carbonate rock succession was studied through analysis of the facies characteristics of the rocks. Approximately 40 m of this succession is quarried.

Detailed study of the changes in deposition conditions along the vertical succession – geological column – of a 60 m thick part of the Lower Cretaceous deposits, allowed a very accurate definition of petrological composition patterns, textural and structural, as well as facies characteristics of the rock mass in the quarry.

Following detailed field studies, sampling, labeling of sample positions and the changes in rock types in the quarry, as well as detailed microscopic-petrological and sedimentological analysis in the laboratory, it was possible to outline four facies units and interpret the corresponding deposition conditions and environments. Samples for analysis of technical properties of the rocks were taken along the vertical succession – geological column – at the same sampling points as the samples for sedimentological analysis, i.e. at precisely defined positions inside the outline facies units.

The results of investigations of physical and mechanical properties of rock samples were statistically evaluated for each individual facies unit separately, also correlation of petrological and facies characteristics was performed together with the assessment of their influence on the technical quality of stone.

Stratigraphic and sedimentological setting of Istria

Istrian peninsula (Fig. 1) represents the NW part of the spacious Adriatic Carbonate Platform: It is composed of more than 2,000 m thick sequence of carbonate deposits. Mostly limestones, rarely dolomites and carbonate breccia, of the Dogger to the Eocene age, and is covered by the Eocene flysch deposits (Polšak, 1965a, 1965b; Tišlar, 1978; Velić & Tišlar, 1988; Tišlar & Velić, 1991; Velić et al., 1995a).
Basic geological structure of the Istrian peninsula is the western Istrian anticline (Polšak & Šikić, 1973; Marinčić & Matiće, 1991), as shown on Fig. 1.

Jurassic and Lower Cretaceous deposits of Istria, ranging from the Bathonian to the Upper Albian, are characterised by predominantly shallow-marine, in general peritidal, tidal flat, tidal bar, lagoon to low-energy limestones and late-diagenetic dolomites, rarely supratidal early-diagenetic dolomites, and — during emersion phases — breccia, clay and bauxite deposits (Tišljar, 1978; Tišljar et al., 1983; Velić et al., 1987; Velić et al., 1995b).

Carbonate deposits of Istria are, in a sense of sequence after Sargg (1988), divided in four megasequences (Velić et al., 1995a), each terminated by important, long-lasting emersion (Fig. 1), i.e. type 1 sequence boundary.

The wider surroundings of the Laković quarry (located between the villages Heraki and Selina, Fig. 1) near St. Lovreć in central Istria are composed of Lower Cretaceous — Aptian and Albian — limestones. The stone quarried at Laković belongs to the oldest Albian carbonate rocks which contain clay lenses and intercalations, as well as clay matrix black-pebble breccia and conglomerates. These are sediments which according to Velić et al. (1995a) are a part of the third megasequence consisting of Jurassic-Cretaceous and Paleogene platform sediments in the Istrian part of the Adriatic carbonate platform (Fig. 1).

Since the wider area surrounding the Laković quarry belongs to the terminating sedimentary rocks of the second megasequence and the initial sedimentary rocks of the third megasequence, and that the deposition conditions and environments are a direct consequence of events that took place at the end of the second and the beginning of the third megasequence, the sedimentological features of the two megasequences will be shortly summarized.

— Upper Tithonian — Upper Aptian Transgressive-Regressive Megasequence (2nd Megasequence) is very complex, especially with regard to its facies heterogeneity and great thickness (465—495 m). It is mostly composed of peritidal shallow-upward parasequences, beginning by the oscillation transgression by the end of the Late Tithonian, and ending by regional Late Aptian emersion (Velić et al., 1989). It is divided into six units:

— Upper Tithonian stilolitized limestones characterised by shallow-upward parasequences generally showing a decrease in the thickness of subtidal members, and an increase in the thickness of intertidal, supratidal and storm-tide deposit members with vadose features (Tišljar et al., 1995).

— Late-diagenetically dolomitized uppermost part of the Upper Tithonian limestones and Berriasian shallow-upward parasequences consisting of late-diagenetically dolomitized subtidal-intertidal limestone and supratidal early-diagenetic dolomites capped by fenestral dolomite stromatolites with desiccation cracks and erosion surfaces (Füchtbauer & Tišljar, 1975; Tišljar et al., 1983).

— Upper Berriasian, Valangianian, Hauterivian and Barremian limestones with shallow-upward parasequences mainly composed of subtidal pelletal and/or gastropod/green-algae wackestone — intertidal LLH stromatolites and/or emersion breccias (Tišljar, 1978). On the seaside of the western Istria in transition Hauterivian-Barremian peritidal carbonates of dinosau sanitizeos have been found (Dalla Vecchia & Tarlao, 1995), as well as their footprints at the island of Veli Brijun in the Upper Barremian limestones (Velić & Tišljar, 1987).

— Lower Aptian massive limestones (= natural stone known as Istrian Yellow) are composed of mudstone (higher sedimentation rate) and Bacinella-oncolite (lower sedimentation rate) cycles with hard-ground characteristics (Tišljar, 1978). This unit was deposited as a consequence of relatively important and rapid relative sea-level rise, controlled by intercession of eustatic change and synsedimentary tectonics. Major part of the carbonate platform, including dominant part of Istria, was drowned, as represented by establishment of protected deeper subtidal environments sporadically connected with the open sea, while in some parts of Istria contemporaneous tectonic uplift resulted with formation of wide emerged areas (Velić et al., 1989).

— Upper Aptian shell floatstone and algal wackestones, with frequent Subingaporoida dinairea RADOČIĆ, occur only in central part of Istria (in the vicinity of Dvigrad and Kanižar) in thickness of about 3—4 m. The other areas of Istria, area of Laković quarry too, were emerged during the Late Aptian and Early Albian. Transitional zones between the shallow-water environments and emerged parts of the platform were characterised by extensive coast marshes with reducing conditions and deposition of black sediments enriched in plant remains and pyrite formed by sulphate bacteria (Tišljar et al., 1995).
Emersion with paleokarstified effects (locally with bauxite pockets), emersional breccia and/or clay bed contain smectite clay of probable volcanic origin, is 1–2 m thick. It represents the stratigraphic gap from the Late Barremian (in north-central part – area of Raderna on the fig. 1) or Early Aptian (major part of Istria) to the beginning of the Late Albian. This emersion was triggered by sea-level fall, but was controlled by synsedimentary tectonics (Velić et al., 1989), mainly low-amplitude plicative forms (Tišlar et al., 1995).

**Upper Albian - Lower Campanian Transgressive-Regressive Megasequence (3<sup>rd</sup> Megasequence)** is very thick.
The studied deposits in the Lakovići quarry, which is located between the villages Heraki and Selina (Fig. 1), belong to the first unit of the third megasequence, i.e. peritidal and foreshore sedimentary system during the Albian. These are well bedded limestones with clay intercalations and black-pebble conglomerates and/or breccia of Late Albian age. The limestones contain large amount of microfossils, prevailing benthic foraminifers and green-algae (Midiolidae, Nummoloculin heimi BONET, Sabaudia minuta (HOFER), Cuneolina pavana D’ORGIGNY, Nezzazzatella picardii (HENSON), Salpingoporella sp., Cylindroporella sp., Charophytes, primitive Orbitolidae), ostracods and gastropods.

In the base of these beds lies the Lower Aptian massive limestone, a famous Istrian natural stone known as - Istrian Yellow – (Fig. 2). The ten meters thick bed of Istrian Yellow is overlaid by emersion breccia, clays and marls which were deposited due to the cessation of marine deposition conditions during an extensive terrestrial phase – erosion which persisted through Late Aptian and Early Albian (Figs. 2 and 3).

Due to faulting Lower Aptian – Istrian Yellow - limestone and Upper Aptian emersion breccia and clays occur laterally in relation to the western and eastern faults which were marked by 3-5 short-lasting earthquakes and environments. The main units are (Večić et al., 1995a):

- the peritidal and foreshore sedimentary system during the Albian;
- differentiation of sedimentary systems during the Vracsonian and Cenomanian;
- the drowned platform system during the youngest Cenomanian and Turonian;
- the shallow-watter sedimentary system during late Turonian, Coniacian and Santonian-Campanian.

The beginning of this megasequence is characterised by oscillating transgression in the Middle Albian, covering a formerly completely emerged area of Istria. During the Late Albian the entire Istrian part of the Adriatic carbonate platform was characterised by more or less stable peritidal - foreshore environments. Upper Albian peritidal and foreshore carbonates are characterised by thin-bedded, mostly well sorted fine-grained intraclastic to peloidal packstones/grainstones alternating with foraminiferal packstones and wackestones, while L.H.stromatolites and storm-tide coarse-grained deposits (limestone breccia) are not so frequent.

The well-bedded limestones from the central part of the quarried rock mass (facies B on Figs. 2 and 4) were deposited during the fall in the relative sea level fall when swamp and pool or bog environments were development on the coastal area (Tišlar et al., 1986; Tišlar et al., 1995). These pools or bogs develop within bays and inlets where sporadic storm waves flooded and deposited sea sand and numerous mollusk shells. The black-pebbles and black-pebble conglomerates were deposited by start of sea level rise, and light-gray and light-brown limestone beds (facies A on Figs. 2 and 4) were deposited during the periods of relative sea level rise, i.e. by inundation of the large coastal area.
Facies units, conditions and deposition environments of limestone from the Lakoviči quarry

In the Lakoviči quarry and in its the immediate footwall surroundings approximately 60 m thick succession of Upper Albian limestone were exposed during excavation and field autcrops. Within this limestone sequence according to its sedimentological and petrological features it is possible to distinguish four facies units with similar petrological and sedimentological characteristics. In the geological column (Figs. 2 and 4) these facies units are denoted as units A, B, C, and D.

Facies unit A:

Micritic limestone deposited as shallowing-upward cycles which begin with breccia containing clay matrix or terminate with dark-gray clays

The facies unit A comprises the carbonate deposits from the footwall emersion breccia oncoid limestones of Lower Aptian age (= Istrian Yellow) to about 6.4 m above the main quarry level (Figs. 2 and 4). Facies unit A consists shallowing-upward cycles as a consequence of repeated relative sea level oscillations in the peritidal shallow-water carbonate platform environment (Fig. 5). The cycles vary in thickness from 35 to 70 cm. Two types of cycles are distinguished, shallowing-upward cycles without black-pebble breccia/conglomerate and shallowing-upward cycles with black pebble-brecia or conglomerate (Fig. 5).

Shallowing-upward cycles without black pebble-brecia or conglomerate are composed of two or three members (Fig. 5):

The first member is usually biointrasparite or grainstone, biointramicrite, pelmicrite to biopelmicrite or micrite (wackestone, packstone, mudstone = Plate I, Fig. 2), therefore limestone sediment deposited in the peritidal mainly low-energy shallow-subtidal to low intertidal zone environment was gradually established in the platform.

The second member is absent in some shallowing-upward cycles but where present consists of fenestral pelmicrite to biopelmicrite or micrite (Plate I, Figs. 1 and 3). It usually terminates with an erosion surface (Fig. 5). This member developed as a consequence of gradual relative sea level fall. This member developed when a tidal zone environment was gradually established, in which fenestral limestone with internal sediment is formed, tidal channels are developed and later when the relative sea level fall further emersion occurs accompanied by formation of reducing coastal pools and bogs or swamps in which black clays, mires or marls (third member) were deposited. This accompanied by black staining of earlier deposited limestone in the footwall.

The third member, which in cycles where the second member is absent is the second member, is a dark-gray smectite clay rich in organic matter and pyrite (indicating deposition or redosposition of organically black clays, mires or marls from near-shore swamps and pools or bogs in isolated coastal depressions and/or smaller lagoons). The new deposition cycle begins with a renewed relative sea level rise, accompanied by the flooding of emerged parts of the platform, destruction, erosion and redeposition of black sediments, and deposition of subtidal limestones of the new cycle.

The shallowing-upward cycles with black pebble-brecia consist of three members (Fig. 5):

The first member is black pebble-breccia or conglomerate which usually occurs as channel or depression filling on eroded or karstified bed surfaces of the concluding member of the previous cycle. It contains angular or/and rounded black-pebble fragments from 10 to 50 mm in diameter, which are intertidal or subtidal limestone clasts stained black by organic matter and pyrite in coastal swamps, bogs or pools (Tištjar et al., 1986), blackened gastropod shells (the gastropod shells are washed into the reducing bog environments from the subtidal by waves and storm tides). The black pebbles and the gastropod shells lie in a black clay or marl matrix rich in organic matter and pyrite.

The second member is biopelmicrite (wackestone) with peloids and benthic foraminifera in a micritic groundmass. This is a subtidal member of the cycle, i.e. carbonates were deposited in a low-energy shallow-subtidal environment formed by inundation by relative sea level rise.

The third member belongs to fenestral pelmicrite to biopelmicrite or micrite. It commonly ends with an erosion bedding surface. The sedimentological features are identical to those of the second member of the first shallowing-upward cycle type. The new deposition cycle begins with a renewed relative sea level rise, accompanied by the flooding of emerged parts of the platform, and deposition of subtidal limestones of the new cycle.

The shallowing-upward cycles of the Lakoviči quarry are interpreted as a consequence of oscillatory sea level fluctuations caused by synsedimentary tectonics and uneven sedimentation rate by tidal flat progradation and migration of shore line. This is due to the minor tectonically tilting of the carbonate platform i.e., low amplitude phycal forms with small amplitudes (mm to cm range) and relatively high (few hundred m to several km) fold wavelengths (Tištjar et al., 1995; Matić et al., 1996). In a smaller extent the relative sea level changes could have been induced by alloyclic processes – the shore line migration, tidal flat and tidal bar progradation. Due to major differences in cycle thickness, as well as their individual members, and the fact that the cycles are not a regional feature during the Albian in Istria, but only a local feature, the existence of these cycles is difficult to interpret as a consequence of the influence of orbital forces, i.e., astronomical control of sea level fluctuations due to periodical changes in the polar ice melting as a result of earth's pole migrations – the Milovanović cycles.

Therefore the deposition limestone cycles of facies A unit have strictly defined structural/textural and petrological characteristics. These are mechanical discontinuities at the top or beginning of the shallowing-upward cycles: well defined erosion bedded plane surfaces with thicker or thinner layers of black clay in the first cycle type, i.e., intercalations or pockets of black pebble-breccia and/or black pebble-conglomerates with clayey matrix which were accumulated in tidal channels or depressions in second cycles type (Fig. 5).

The upper parts of limestone beds besides having fenestral structure or erosion surfaces are commonly stained black – contaminated by black reductive swamp and bog or pool sediments (mud and mire), while the mainframe of the limestone beds consists of muddy or sand-sized sediments which were deposited during relative sea level rise in near-shore subtidal shoals, with mainly low water energy and only occasionally with high water energy. During low-energy phase were deposited carbonate mud – micrite, fine pellets, ostracods and benthic foraminifera tests (Plate I, Figs. 1, 2 and 3).
### Types of Limestone

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Lithology and Structural Characteristics</th>
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<tbody>
<tr>
<td>Well-bedded (30-60 cm)</td>
<td>Pelmicrite/pelites with bioeolian/pelites intrusions</td>
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<tr>
<td>Stylolitized micrite with fenestral fabrics</td>
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<tr>
<td>Laminated micrite with coarse intraclasts = Intraformational breccia</td>
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<tr>
<td>Forams-bearing pelite/pelites with pelites laminae</td>
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<tr>
<td>Pelmicrite with black-pebbles and fenestral fabric</td>
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<tr>
<td>Dense fenestral micrite with horizontal stylolites</td>
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<tr>
<td>Dense fenestral micrite with horizontal stylolites</td>
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<td>Dense micrite with pelites laminae</td>
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<tr>
<td>Stylolitized and tectonized micrite partly with pelites thin interlayers</td>
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<tr>
<td>Thin-bedded (5-10 cm) pelite/pelites alternation</td>
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<tr>
<td>Pelmicrite with shells (floatstone)</td>
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<td>Thin-bedded (3-10 cm) fine-grained pelite</td>
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**Fig. 4.** Geological column of the Lakovići quarry with main lithological and structural characteristics and four facies units.
Foraminifera-bearing biotraparite

Well-bedded (8-15 cm) fine-grained intraclastic peltsparite (horizontal lamination)

Lamination and alternation of pelmicrite/peltsparite and biomicrite (on the top cross-bedding)

Alternation of peltsparite and pelmicrite (horizontal lamination)

Thin-bedded (3-15 cm) fine-grained peltsparite in alternation with pelmicrite and biomicrite, bottom with gastropod biosparrulite

Foraminiferal biointrasparrite

Pelmicrite with gastropods

Fine-grained peltsparite with horizontal lamination

Thin-bedded (3-10 cm) peltsparites with pelmicrite intercalations: cross-bedding and current ripples

Thin-bedded (10 - 15 cm) peltsparite/biopelsparite and pelmicrite alternation; current ripples

Coarse-grained biointrasparrite and intrasparrite with green-algae and gastropods.

Tidal channel fill (breccia)

Micrite/biopelsparite lamination

Well-bedded (8-20 cm) biopelsparite with peltsparite/pelmicrite alternation. In some places coarse plasticists. Bottom tidal channel with intrasparrite fill

Storm-tide breccia

Thin-bedded (7-10 cm) biomicrite/biopelsparite

Storm-tide breccia (Tempesite breccia)

Intrasparite/intrasparrulite with black pebbles

Foraminiferal biointrasparrite

To be continued
Thin-bedded alternation of biopelsparite, pelmicrite and pelmicrite - horizontally laminated

Biointrasparite with coarse intraclasts

Biointrasparite with coarse intraclasts

Well-bedded (10-20 cm) biosparite/biopelsparite composed of benthic forams and peloids

Thin-bedded alternation (3-10 cm) of pelsparite, pelmicrite and biopelsparite - horizontal lamination

Tidal channel fill: biointrasparite/biointrasparite with coarse intraclasts

Tidal channel fill: biointrasparite/biointrasparite with coarse intraclasts

Erosional surface with black clay

Organoically rich gray micrite

Stylolitised micrite - fenestral fabrics

Stylolitised micrite - fenestral fabrics

To be continued
continue

LEGEND:

- MICRITIC LIMESTONE
- PELMICRIT/BIOMICRITE
- PELSPARITE
- INTRASPARITE
- BLACK-PEBBLE BRECCIA AND/OR CONGLOMERATE - CLAYEY MATRIX
- PERTIDAL OR STORM-TIDE BRECCIA
- BLACK CLAY
- STYLOLITES
- BENTHIC FORAMINIFERAS
- GASTROPODS
- SHELLS
- FENESTRAL FABRICS
- CURRENT RIPPLES
- OOLIDS
Tišlar, J., Dokić, Z. & Ženko, T.: Sedimentary environment and technical properties of limestones

Fig. 5. Geological column of the facies unit A in the Lakovići quarry characterised by shallowing-upward cycles with black-pebble breccia and/or beds of black clays.
During high-energy phase, for example during storm waves, the coastal bays, bays and swamps or tidal channels are flooded and filled with gastropods, coarse and fine lime-micro cleats, black pebbles, e. g. sediments from which the breccia developed, black pebble breccia and/or conglomerates, and also coarser or finer carbonate skeletal and non-skeletal carbonate detritus (= biointrasparite, biotransparitite, biopelmarite, and pelmarite types of limestone).

**Facies unit B:**

*Grain supported limestones deposited as fine-grained to coarse-grained limestone sands in high-energy shallows, bars and sandy beaches*

The limestones of the facies unit B are the bulk of the quarry rock mass (Figs. 2 and 4). This unit is made up of well-bedded to thin-bedded, cross-beded and horizontally laminated, light-brown, fairly malleable and porous fine- to coarse-grained limestones of biopelmarite, pelmarite, biopelmarite, biointrasparite (grainstone to rudstone and packstone) types (Plate I, Figs. 4, 5 and 6; Plate II, Fig. 1).

They include a succession 23.65 m thick, which starts above the layer where sample number 9 was taken and ends above the layer from which sample number 32 was taken (Fig. 4 and Table 1).

The major features of facies unit B is that they are either well bedded (10-30 cm) or display frequent alteration of thin layers (3-10 cm) of pelmarites, foraminifera-bearing pelmarites, with pelmicrite and micrite laminae. Commonly small-current ripples are present, as well as cross-beding, tidal channels with fining-upward cycles, peritidal breccia and/or intrasparite storm-tide deposits.

The facies unit B limestones consist of well sorted fine- to coarse-grained carbonate detritus (sand-size, pebble-size) which contains abundant spherical pebbles, pellets and small quantities of skeletal or pelletal detritus (Plate I, Figs. 4, 5 and 6). This carbonate detritus was mainly deposited in high-energy shallows, bars and sandy beaches (shoreface/foreshore) with tidal and erosion channels. The limestones contain very small quantities or even no carbonate mud – micrite – due to its washing-out by high-energy water. This loss of carbonate mud caused the carbonate sand to have a very high intergranular and intraskeletal primary porosity.

The limestone of this facies unit contains a relatively high proportion of calcite cement in the intergranular pores, but the cementation is not complete (Plate I, Fig. 4), which makes this limestone to have a very high primary porosity, due to later leaching of some aragonite and/or high Mg-calcite constituents from grainstones, and pelmicrite/biopelmicrite intercalations. This also caused even higher making the total primary and secondary (wuggy) porosity of facies unit B higher than those of the facies units A and C (Plate II, Fig. 2 and Fig. 6a).

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**Facies unit C:**

*Micritic limestones deposited in restricted low-energy shallow subtidal environments*

Facies unit C accounts for only a small portion of the total rock mass in the Lakovići quarry. It consists of several thick layers situated in the higher parts of the northern excavation front of the quarry and in the hanging wall above the northern quarry excavation front (Figs. 2 and 4). It is includes the layer from which sample 32 was taken and terminates with the layer where sample 38 is positioned (Fig. 4; Table 1) which make a thickness of the succession totaling 5.20 m.

The facies unit C consists of well-bedded (30-70 cm), stilolitic, compact micritic (mudstone to biomericite (wackestone) limestones, usually composed of carbonate mud – micrite and small quantities of skeletal or pelletal detritus (Plate II, Figs. 3 and 4). The uppermost parts of the beds commonly contain irregular fenestral features and desiccation cracks. These limestones were produced by lithification of fine-grained carbonate detritus, generally mud deposited in restricted low-energy shallow subtidal environments. They are characterized by low porosity (Fig. 6a), low absorption capacity (Fig. 6b and c), and relatively high compressive strength (Fig. 7).

**Facies unit D:**

*Grain supported limestones deposited as fine-grained carbonate sands in high-energy shallows and bars*

The facies unit D, which consists of well bedded (30-60 cm), grain supported limestones of biopelmarite, biointrasparite, pelmicrite and biomericite type (grainstone to packstone), overlie the C facies deposits, i.e. the layer where sample 38 was taken (Fig. 4; Table 1). The sedimentological and petrological features of this unit are very similar to the limestones of B facies unit.

The limestones were deposited as fine-grained limestone sands in a shallows, bars and beaches (shoreface/foreshore environment) with mainly high water energy and shorter periods of low-water energy, which resulted in the absence of micrite and incomplete cementation of intergranular pores within biopelmarite/pelmarite and sporadic elevated micrite deposition rates in biomericite/pelmicrite interlayers. Similar to the properties of the facies B limestones, these limestones also are characterized by high porosity (Fig. 6a) and high water absorption capacity (Fig. 6b and 7a).

**The relationship between facies units and technical stone quality in the Lakovići quarry**

The results of test procedures including density, porosity, water absorption, comprehensive strength, and abrasion resistance after the method of Böhme performed on limestone samples from the Lakovići quarry are presented in Table 1, according to the described individual facies units. In Figs. 6, 7 and 8 graphical presentations of the relationships between porosity, bulk density, water absorption, comprehensive strength and abrasion resistance according to the recognized facies units. The pronounced differences in technical properties of facies units B and D as compared to the facies units A and C are obvious on Figs. 6a, 7a, b, b, and 8a, b. The limestones that characterize facies unit A, due to their sedimentological and petrological features – repeated erosion and flooding cycles of emerged and exposed parts of the carbonate platform, as well as influences of nearshore reducing environments in swamps, pools and bogs, resulting in the occurrence of thin layers of clays or black-pebble breccia with clayey matrix and specific physical/mechanical properties. This facies unit, just as facies unit C is characterized by prevailing micritic rich limestones deposited in low energy shallow-water environments with low porosity, low water absorption capacities and relatively well abrasion resistance (Figs. 6a, b, c, 7a, b and 8a, b).

The well bedded, laminated grainstone/packstone limestones defined and separated as facies unit B, due to essentially different petrological and sedimentologi-
Fig. 1. Graphical display of porosity (a), the relationship between porosity and bulk density (b), and the relationship between water absorption and porosity (c) in limestones from the lithofacies units A, B, C and D.

cal features, i.e., deposition of fine- to coarse-grained carbonate sands in a high-energy shallow-water environment (bars and beaches), have fundamentally different physical/mechanical properties than the limestones separated as facies units A and C. They have markedly higher porosity, water absorption capacities and abrasion resistance than the limestones of facies units A and C (Figs. 6a,b,c; 7a,b and 8a,b) and show a linear dependence of water absorption capacity value increase with the bulk density decrease (Fig. 6b) and porosity increase (Fig. 6c). A similar but slightly less obvious dependence of water absorption values and porosity and bulk density values are noticed in limestones from facies unit D (Figs. 5a,b,c, and 7a).

The higher limestone water absorption values of facies units B and D in comparison to facies units A and C is well illustrated on the diagram showing the relationship between comprehensive strength and water absorption (Fig. 7c). This diagram shows that the values of comprehensive strength do not change dramatically with water absorption increase. The diagram showing the relationship between density and water absorption (Fig. 7b) indicates that the limestones of facies units A and C despite the difference in density have similar water ab-

<table>
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<th>FACES SAMPLE No.</th>
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<th>POROSITY (vol %)</th>
<th>WATER ABSORPTION (vol %)</th>
<th>COMPREHENSIVE STRENGTH (N/mm²)</th>
<th>RESISTANCE BY ABRASION (BHIND. cm$^{2}$/50 cm$^3$)</th>
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Fig. 8. Graphical display of the relationship between resistance by abrasion Böhme (a) and water absorption capacity (b) in limestones from the lithofacies units A, B, C and D.

Discussion and conclusions

The limestone exploited as crushed stone–limestone aggregate – from the Lakovići quarry near Baderna in Istria belong to the youngest part of the Aptian carbonate sediments, with which, after an extensive Upper Aptian emersion event, begins the second transgressive-regressive megasequence in Istria. At the beginning the transgressive deposition system was characterized by oscillating transgression, which resulted in a large variability of deposition conditions and environments in the zone shore–near-shore swamps, pools and bogs–tidal flat–tidal sand bars–low-energy peritidal–high-energy shallow water environments (foreshore/shoreface).

Within the 50 m thick limestone succession which are exploited in the Lakovići quarry, the changes of deposition environments allowed the division of the succession into four facies units, with not only differing petrological/sedimentological features but also differing technical properties.

The facies unit A consists of limestones deposited at the beginning of the Albian transgression, and are characterized by shallowing-upward cycles deposited by relative sea level change, during which deposition of carbonate materials occurs, sporadically accompanied
by deposition and redeposition of black terrestrial and swamp clays, as well as sediments from bogs and pools that were developed in isolated bays and/or lagoons. The carbonate deposition phases with deposition of limestone (mud with pellets, foraminifera and gastropods) occur during relative sea-level rise and fall, i.e. during the formation of shallow subtidal and intertidal environments. This is why facies unit A limestones are commonly micritic, pelmictic and bimictic type with low porosity, low water absorption values and relatively high resistance by abrasion (Figs. 6a, b, c and 7a, b and 8a, b).

The facies unit B define well bedded, laminated grainstone/packstone limestones deposited in a high-energy shallow-water foreshore-shoreface environments (bars and beaches) as coarse- to fine-grained carbonate sand with pebbles. These limestones are characterized by a significantly higher porosity and water-absorption capacity and low resistance by abrasion than facies A and C limestones (Figs. 6a, b, c; 7a, b and 8a, b). Compared to facies A and C limestones they show a strong positive dependence between water absorption and porosity (Fig. 6c). A similar, but less pronounced dependence between water absorption and porosity is exhibited by facies D limestones (Figs. 6a, b, c and 7a).

Facies unit C contains carbonate mud rich limestones (micritic and bimictic) deposited in a restricted low-energy shallow or lagoons, with petrological and technical features that resemble limestones of facies unit A (Figs. 6a, b, c and 7a). Facies unit D is made of a grain supported limestone succession containing pelsparite, biopelsparite, biointrasparrite and biomicrite (from grainstone to packstone). These limestones were deposited as fine-grained limestone sands in shallow-water environments and beaches with high-water-energy and shorter periods of low-energy water conditions. The main features of these limestones are the absence of micrite and incomplete cementation of intergranular pores within grain supported layers (biopelsparites/pelsparites) and sporadic micrite accumulation during periods of low-energy water conditions.

The facies unit B limestones and in a smaller extent facies unit D limestones although they do not differ greatly in density in comparison to facies A and C limestones, are characterized with significantly higher water absorption capacities and low resistance by abrasion. Their inferior technical properties compared to limestones of facies units A and C (Figs. 6b, d, e and 7a) are related with elevated water absorption which is a consequence of higher porosity caused by the specific deposition conditions and environments. To some extent diageneas has also influenced the limestone properties, i.e. mainly due to uncompleted cementation of intergranular pores between the sand-size carbonate detritus, as well as due to later dissolution of cement, probably of primary aragonite and high-Mg calcite composition, during diageneas in a mixed and/or meteoric zone. The migration of the zones was caused by relative sea-level changes.

The results of petrological, sedimentological and technological investigations of Lower Cretaceous limestones from the Lakovič quarry and the correlation of the results show a dependence of petrological and sedimentological features, i.e. the deposition conditions and environments with the technical quality of stone. With the aid of sedimentological/technological methods division of limestones was performed into individual facies units which display notably different technical/technological properties. The outlined facies units have not only different facies features but also different technical properties, which enables separation of rock mass of different technical quality in the quarry in advance by facies determination and division.

Therefore, by division of facies units and their selective exploitation it is possible to direct the rock mass excavation towards the desired technical quality of stone aggregates.

Acknowledgments

The authors thank Bojan Ogorelec and Branko Crnkoš for their constructive discussion and comments. This study was encouraged and sponsored by Vlaudik d. d. and performed as a part of the scientific project 195-005 supported by The Ministry of Science and Technology of the Republic of Croatia.

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REFERENCES


Plate II:
Fig. 1. Ooid intraclasts of the facies unit B composed of well sorted micritic intraclasts and ooids, and beach-rock type cement (micrite and fibrous calcite cement on the ooid surface and mosaic calcite cement into interparticle pores). Thin-section of the sample No 13.
Fig. 2. Biomicrite of the facies unit B is characterised by high moldic and vuggy porosity (white). Thin-section of the sample No 24.
Fig. 3. Biomicrite of the facies unit C is composed of micrite mass with ostracods and clotted micrite/pelmicrite laminae (middle part of foto). Thin-section of the sample No 34.
Fig. 4. Biomicrite of the facies unit C contain benthic foraminifera and small ostracod bioclasts in micrite matrix. Thin-section of the sample No 37.

Sedimentary environment and technical properties of limestones


