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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 devided: **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 redeposition of black terrestrial and swamp clays, as well as sediments from bogs and pools that were developed in isolated bays and/or laggons; **B** – Grain supported limestone deposited as fine-grained to coarse-grained carbonate sands in a predominantly high-energy shallows, bars and sandy beaches; **C** – Micritic 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 wide 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.

Ključne riječi: Karbonatni facijesi, Periplimni vapnenci, Ciklusi oplićavanja naviše, Okoliši plimnih prudova, Donja kreda, Vapnenački agregati, Tehnička svojstva vapnenaca

Donjokredni vapnenci kamenoloma Lakovići pripadaju bazalnom dijelu aptskih vapnenaca kojima, nakon opće gornjoaptske emerzije, počinje druga transgresivno-regresivna megasekvencija u Istri. Unutar 50-ak metara debljine vapnenaca koji se eksploatiraju u kamenolomu Lakovići izdvojene su na osnovu petrografsko-sedimentoloških karakteristika četiri facijesne jedinice. To su: **A** – Mikritom bogati vapnenci taloženi kao ciklusi oplićavanja naviše koji počinju brečama s glinovitim matriksom ili završavaju tamnosivim glinama; **B** – Zrnasti vapnenci taloženi kao sitnozrnati do krupnozrnati vapnenački pijesci u plićacima s pretežito visokom energijom vode i na pješčanim plažama; **C** – Mikritom bogati vapnenci taloženi u zaštićenim potplimnim plićacima s niskom energijom vode i **D** – Zrnasti vapnenci taloženi kao sitnozrnati vapnenački pijesci u plićacima i plažama s pretežito visokom energijom vode. Rezultati petroloških, sedimentoloških i tehničko-tehnoloških istraživanja pokazuju da vapnenci svake pojedine facijesne jedinice imaju različita tehnička svojstva, posebice ona vezana uz poroznost, prostornu masu i upijanje vode, tj. da je velika varijabilnost tehničke kvalitete kamena u kamenolomu izravna posljedica njihovih facijesnih karakteristika. Izdvojenim facijesnim jedinicama određena je i selektivnost stijenske mase u kamenolomu u odnosu na, kako petrološka svojstva, tako i tehničko-tehnološku kvalitetu kamena.

Introduction

The petrological features of carbonate rocks are a direct consequence of their deposition environment and diagenic processes. Individual changes in the deposition environment, markedly changes in depth and energy of the shallow-water settings due to sea level changes, as well as variation of diagenetic processes expressed as changes from purely marine zones, to mixes ones 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 detailied 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 unite 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 flysh deposits (Polšak, 1965a, 1965b; Tišljar, 1978; Velić & Tišljar, 1988; Tišljar & Velić, 1991; Velić et al., 1995a).

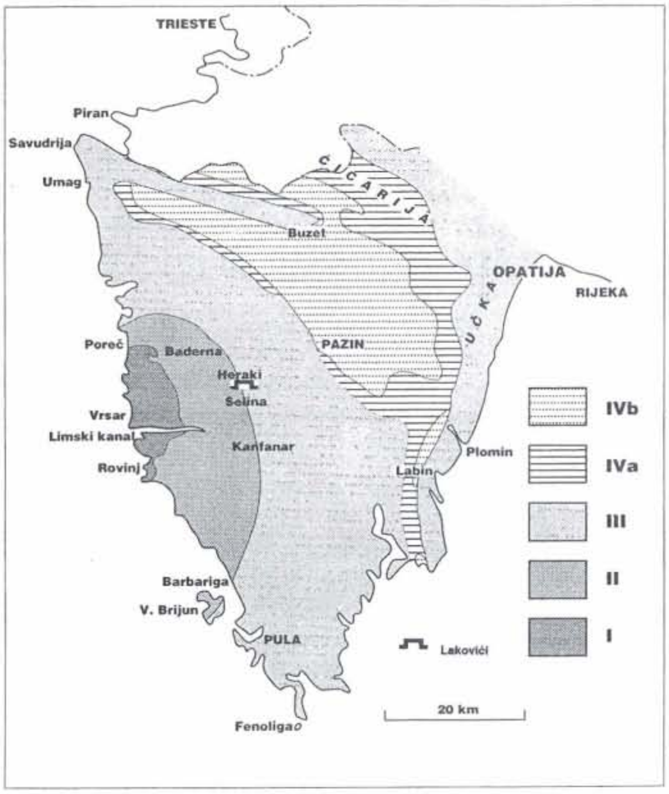

Fig. 1. Geological sketch-map with surface distribution of outlined megasequences in Istria (after: Velić et al., 1995a; very simplified, tectonic elements omitted):
I = 1st megasequence Bathonian – Lower Kimmeridgian;
II = 2nd megasequence Upper Tithonian – Upper Aptian;
III =3rd megasequence Upper Albian – Lower Campanian;
IV = 4th megasequence Palaeocene – Eocene: **a** = Foraminifera limestone, **b** = Transitional beds and flysh

Basic geological structure of the Istrian peninsula is the western istrian anticline (Polšak & Šikić, 1973; Marinčić & Matičec, 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, lagoonal 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 & Tišljar, 1987; Velić et a al., 1995b).

Carbonate deposits of Istria are, in a sence 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 Lakovići quarry (located between the villages Heraki and Selina, Fig. 1) near St. Lovreč in central Istria are composed of Lower Cretaceous – Aptian and Albian – limestones. The stone quarried at Lakovići belongs to the oldest Albian carbonate rocks witch 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 Lakovići 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 Transgressie-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 shallowing-upward parasequences, beginning by the oscillatin 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 shallowing-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 shallowing-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 shallowing-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-Berremian peritidal carbonates part of dinosaur skeletons 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 interreaction 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 *Salpingoporella dinarica* RADOIČIĆ, occur only in central part of Istria (in the vicinity of Dvigrad and Kanfanar) in thicknes of about 3–4 m. The other areas of Istria, area of Lakovići 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 reductive conditions and deposition of black sediments enriched in plant remains and pyrite formed by sulphate bacteria (Tišljar et al., 1995).

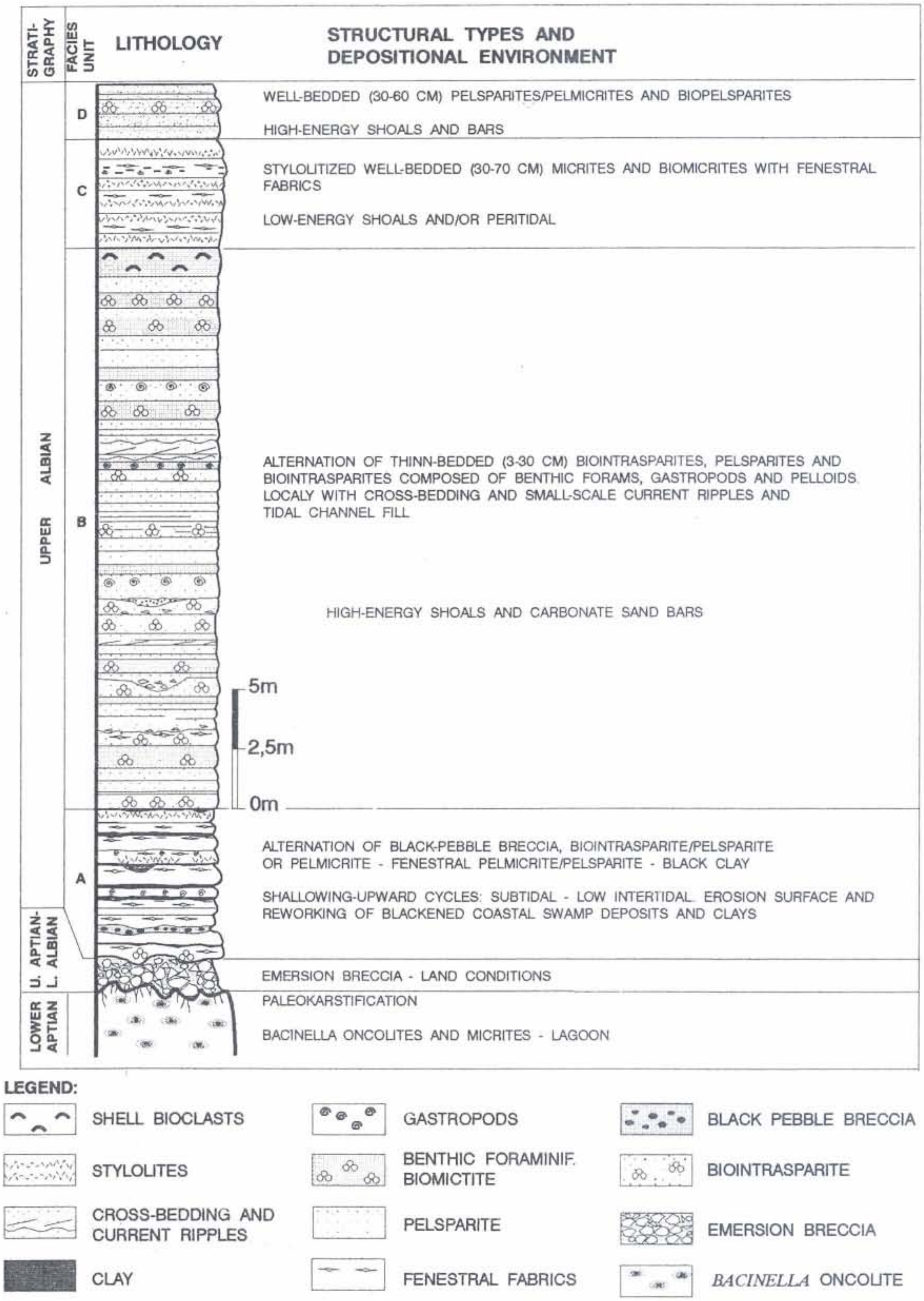

Fig. 2. Shematic column of the Lower Aptian to Upper Albian carbonate deposits of the Lakovici area with four facies units (= A, B, C, D) and interpretation of their depositional environments

– 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 Baderna 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), mainlly low-amplitued plicative forms (Tišljar et al., 1995).

– **Upper Albian - Lower Campanian Transgresive-Regressive Megasequence (3rd Megasequence)** is very thick

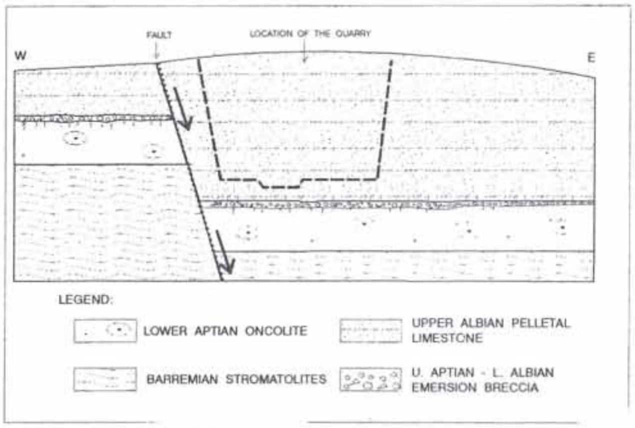

Fig. 3. Shematical drawing of the general stratigraphyc and tectonical setting of the Lakovići quarry (not in scale)

(>1 000 m), being composed of variable facies succession. After extensive emersion during the Late Aptian and Early Albian, i.e. by the beginning of the Late Albian, at first gradual (marked by 3–5 short-lasting emersions containing smectite clay of probable volcanic origin), and later complete ingression occurred: the shallow-water platform carbonate system was reestablished in the Istrian part of the Adriatic Carbonate Platform.

Several sedimentary units can be separated, each characterised by relatively similar sedimentary conditions and environments. The main units are (Velić et al., 1995a):

- the peritidal and foreshore sedimentary system during the Albian;
- differentiation of sedimentary systems during the Vraconian and Cenomanian;
- the drowned platform system during the youngest Cenomanian and Turonian;
- the shallow-watter sedimentary system during late Turonian, Coniacian and Santon-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 pelloidal packstones/grainstones alternating with foram-pelloid packstones and wackestones, while LLH-stromatolites and storm-tide coarse-grained deposits (limestone breccia) are not so frequent.

The transition from Lower to Upper Cretaceous (Vraconian – Lower Cenomanian) is marked by the establishment of different sedimentary environments in northern and southern Istria. In northern Istria (the Umag–Savudria–Buzet area) stable peritidal conditions like those in the Albian continued into the eariliest Cenomanian (Vlahović et al., 1994). The younger part of the Early Cenomanian and the older part of the Middle Cenomanian are characterised by the facies differentiation with the establishment of peritidal – shallow-water sand bar – gently inclined inner carbonate ramp lateral facies (Tišljar et al., 1995).

General geological and sedimentological features of limestone from the Lakovići quarry

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 microfosils, prevailing benthic foraminiferas and green-algae *(Miliolidae, Nummoloculin heimi* BONET, *Sabaudia minuta* (HOFER), *Cuneolina pavonia* D'ORGIGNNY, *Nezzazzatinella picardi* (HENSON), *Salpingoporella* sp., *Cylindroporella* sp., *Charophytes,* primitive *Orbitolinidae),* ostracods and gastropods.

In the base of these beds lies the Lower Aptian massive limestone, a famous Istrian natural stone known as – ***Istrian Yelow*** – (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 – emersion 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 escavation front of the quarry, and in the quarry itself they are situated approximately 10 m below the lowest excavation level, as presented on the geotectonic outline presented on Fig 3. This implies that the quarry is located within a large tectonic block, which is, in relation to the beds situated laterally, displaced approximately 20 m downwards along the fault zone (Fig. 3).

Within the larger tectonic block a number of smaller faults occur, which are accompanied by smaller or larger dislocations of beds inside the quarry limestones. Dark clay intercalations, dark conglomerate and dark-gray limestone interbeds within the lowest 4 to 6 m above the main level of the quarry and within the recently excavated deepest quarry level (facies A on Figs. 2 and 4), indicate a transgressive cyclic deposition during an oscillating transgression, i. e. the gradual and cyclic flooding of the Lower Cretaceous exposed surface during the Albian. The black clays and dark-gray to black limestone beds are deposited during the fall in the relative sea level fall when swamp and pool or bog environments were development on the coastal area (Tišljar, 1986; Tišljar 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.

The well-bedded limestones from the central part of the quarried rock mass (facies B on Figs. 2 and 4) were deposited in shallow water environments with carbonate sand bars, which developed when the cyclic oscillation of the sea level was established or more precisely, in stable conditions of a shallow-water deposition environment with high carbonate production in marine high-energy shallow-water.

The presented short summary of deposition characteristics of the limestones quarried at Lakovići are the major factors that govern their petrological, physical and mechanical properties, hence the quality of the stone. Therefore the deposition characteristics of the limestones will be elaborated in detail in the following chapter.

Facies units, conditions and deposition environments of limestone from the Lakovići quarry

In the Lakovići 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 emerssion breccia oncoid limestones of Lower Aptian age (= *Istrian Yellow*) to about 6.4 m above the manin 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-breccia or conglomerate (Fig. 5).

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

The first member is usually biointrasparite (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.

The second member is absent in some shallowing-upward cycles but where present consits 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 emerssion occurs accompanied by formation of reducing coastal pools and bogs or swamps in which black clays, mires or marls (third member) were deposited. This acompanied 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 redoposition 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-breccia consists 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-pebbles 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 (Tišljar, 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 Lakovići quarry are interpreted as a consequence of oscillatory sea level fluctations caused by synsedimentary tectonics and uneven sedimentation rate by tidal flat progradation and migration of shore line. This is due to the minor tectonicaly tilting of the carbonate platform i. e., low amplitude plicative forms with small amplitudes (mm to cm range) and relatively high (few hundred m to several km) fold wavelengths (Tišljar, et al., 1995; Matičec, et al., 1996). In a smaller extent the relative sea level changes could have been induced by allocyclic 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 bedding 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).

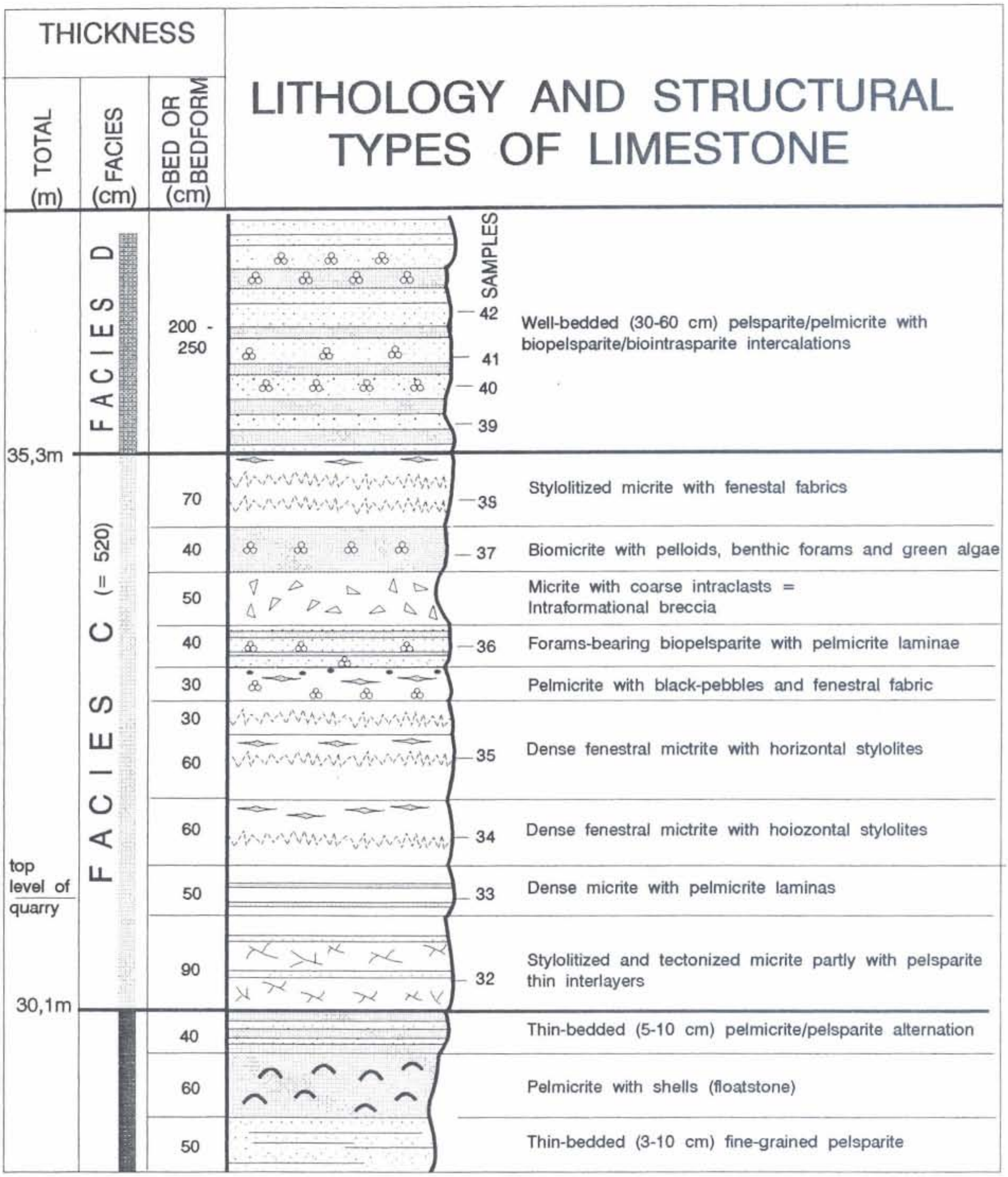

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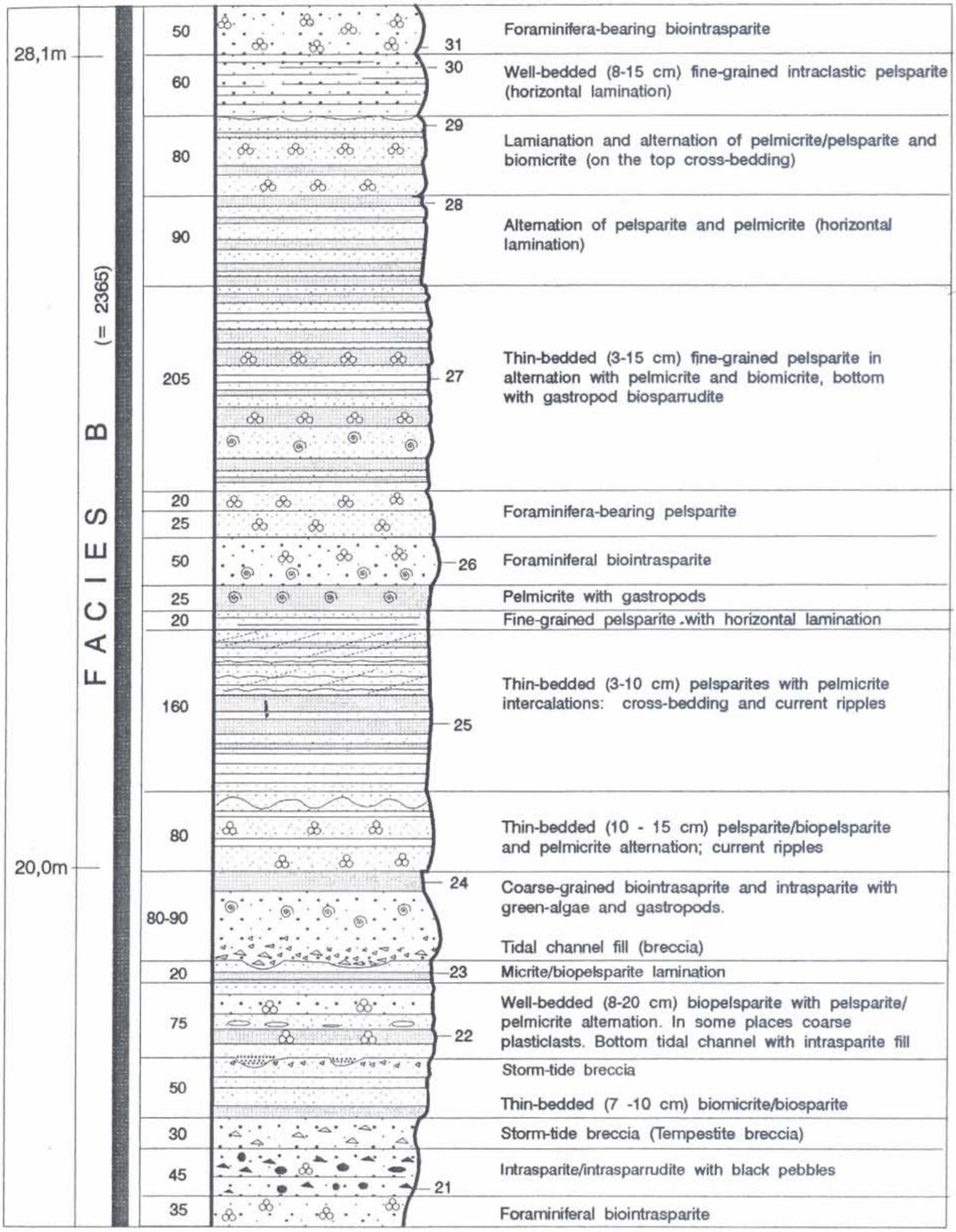
Fig. 4. Geological column of the Lakovići quarry with main litological and structural characteristics and four facies units



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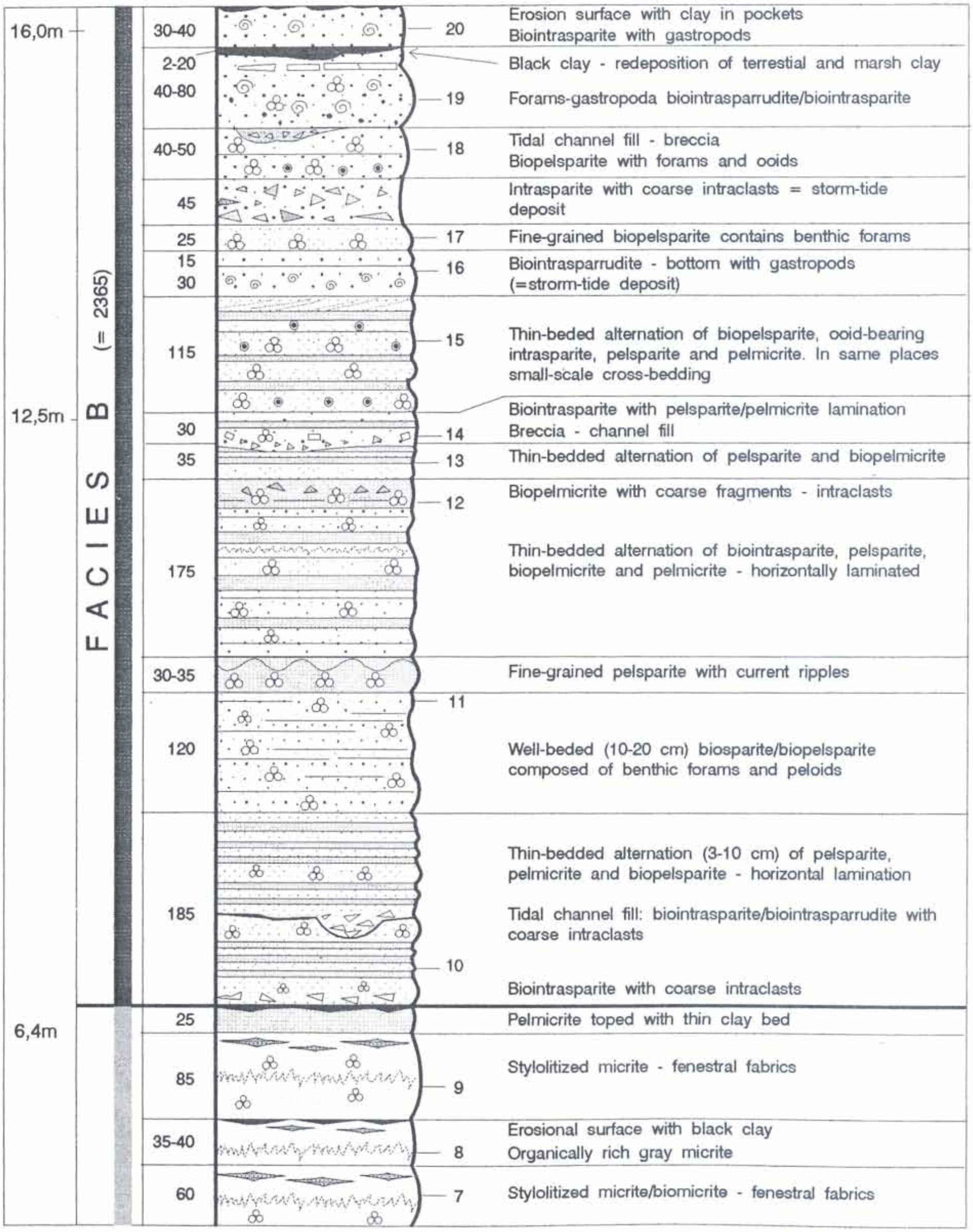

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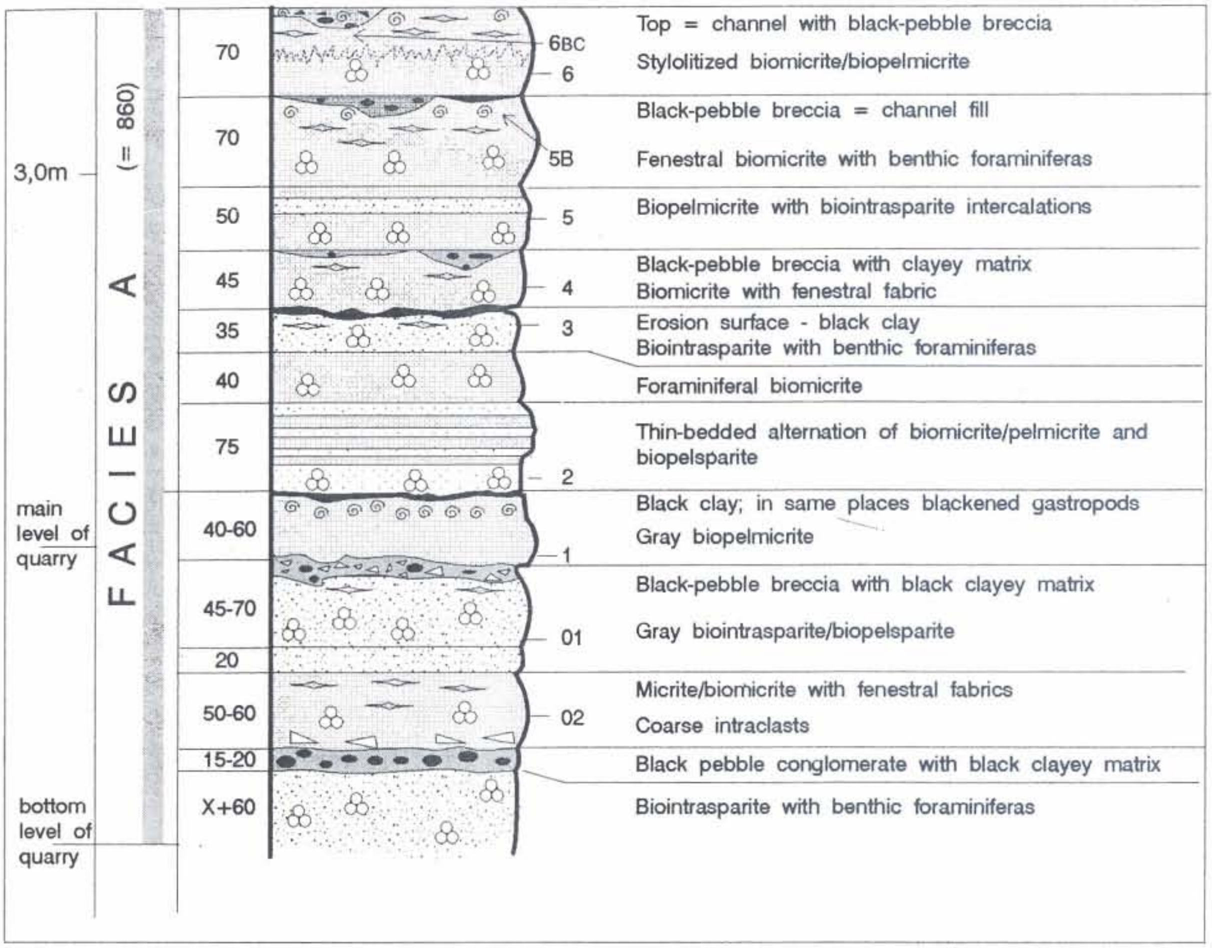

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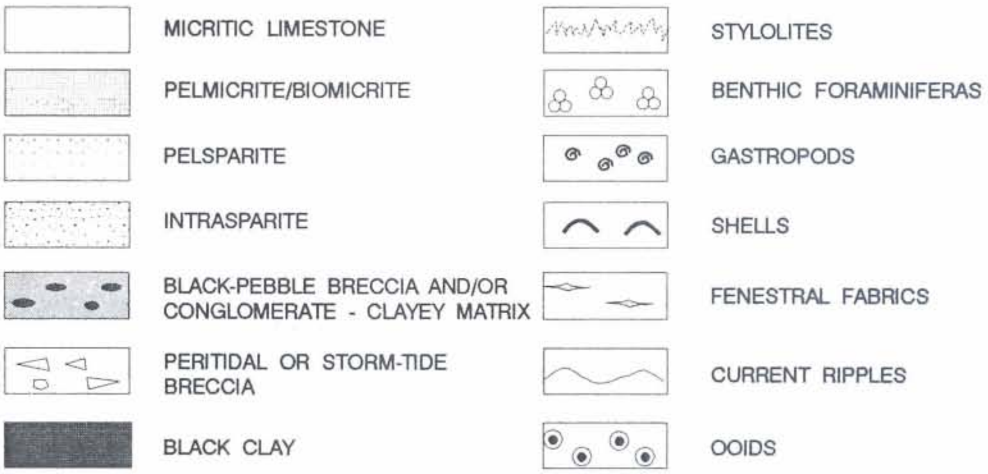

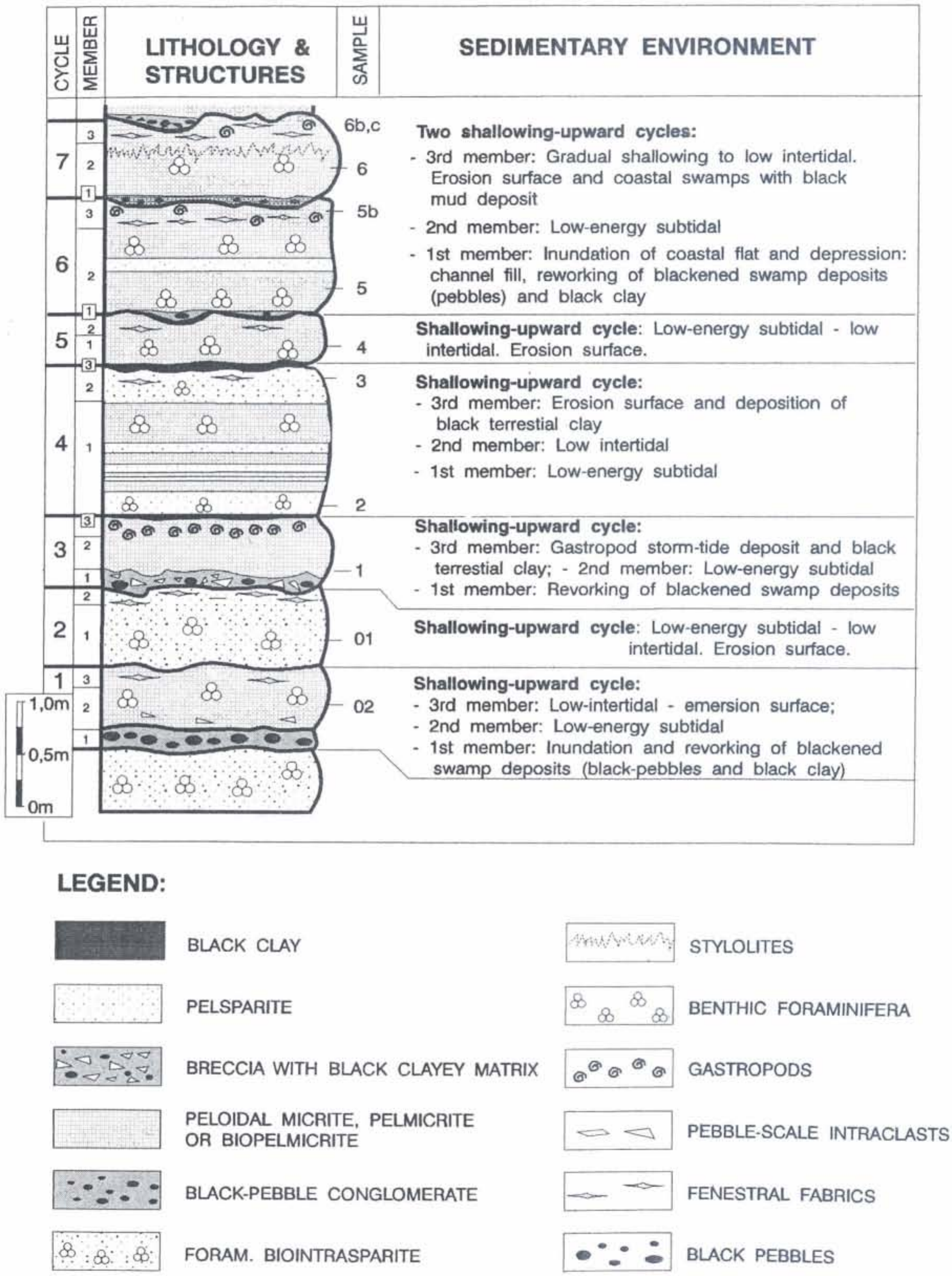

Fig. 5. Geological column of the facies unit A in the Lakovići quarry characterised by shallowing-upward cycles with black-pebble breccia and/or beds of black clays

During high-energy phase, for example during storm waves, the coastal bogs, bays and swamps or tidal channels are flooded and filled with gastropods, coarse and fine limestone debris, black pebbles, i. e. sediments from which the breccia developed, black pebble breccia and/or conglomerates, and also coarser or finer carbonate skeletal and nonskeletal carbonate detritus (= biointrasparite, biotrasparrudite, biopelsparite, and pelsparite 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-bedded and horizontally laminated, light-brown, fairly malleable and porous fine- to coarse-grained limestones of a biosparite, pelsparite, biopelsparite to 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 facies unit B is that they are either well bedded (10–30 cm) or display frequent alteration of thin layers (3–10 cm) of pelsparites, foraminifera-bearing biopelsparites/biointrasparites, with pelmicrite and micrite laminas. Commonly small-current ripples are present, as well as cross-bedding, tidal channels with fining-upward cycles, peritidal breccia and/or intrasparrudite storm-tide deposits.

The facies unit B limestones consist of well sorted fine- to coarse-grained carbonate detritus (sand-size, pebble-size) which contains aboundant spherical peloids, pellets intraclasts and benthic foraminifera shells and less frequently gastropod shells (Plate I. Figs 4, 5 and 6; Plate II. Fig. 1). 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 quantites 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 interskeletal primary porosity.

The limestone of this facies unit contains a relatively high portion 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 leachering of some aragonite and/or high Mg-calcite constituents from grainstones, and pelmicrite/biopelmicrite intercalations too, this porosity became even higher making the total primary and secondary (wuggy) porosity of facies unit B higher then those of the facies units A and C (Plate II, Fig. 2 and Fig. 6a). This is the main reason why these limestones have high water absorption and low abrasion resistance (Table 1).

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), stilolithic, compact micritic (mudstone) to biomicritic (wackestone) limestones, usually composed of carbonate mud – micrite and small quantites of skeletal or pelletal detritus (Plate II, Figs. 3 and 4). The uppermost parts of the beds commonly contain iregular fenestral features and desiccation cracks. These limestones were produced by lithifaction 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 comprehensive 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 biopelsparite, biointrasparite, pelmicrite and biomicrite 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 depoisted 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 uncomplete cementation of intergranular pores within biopelsparites/pelsparites and sporadic elevated micrite deposition rates in biomicrite/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 (Figs. 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,b,c, 7a,b and 8a,b.

The limestones that characterize facies A unit, due to their sedimentological and petrological features – repeated emersion 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 micrite 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; /a,b and 8a,b).

The well bedded, laminated grainstone/packstone limestones defined and separated as facies unit B, due to essentially different petrological and sedimentalogi-

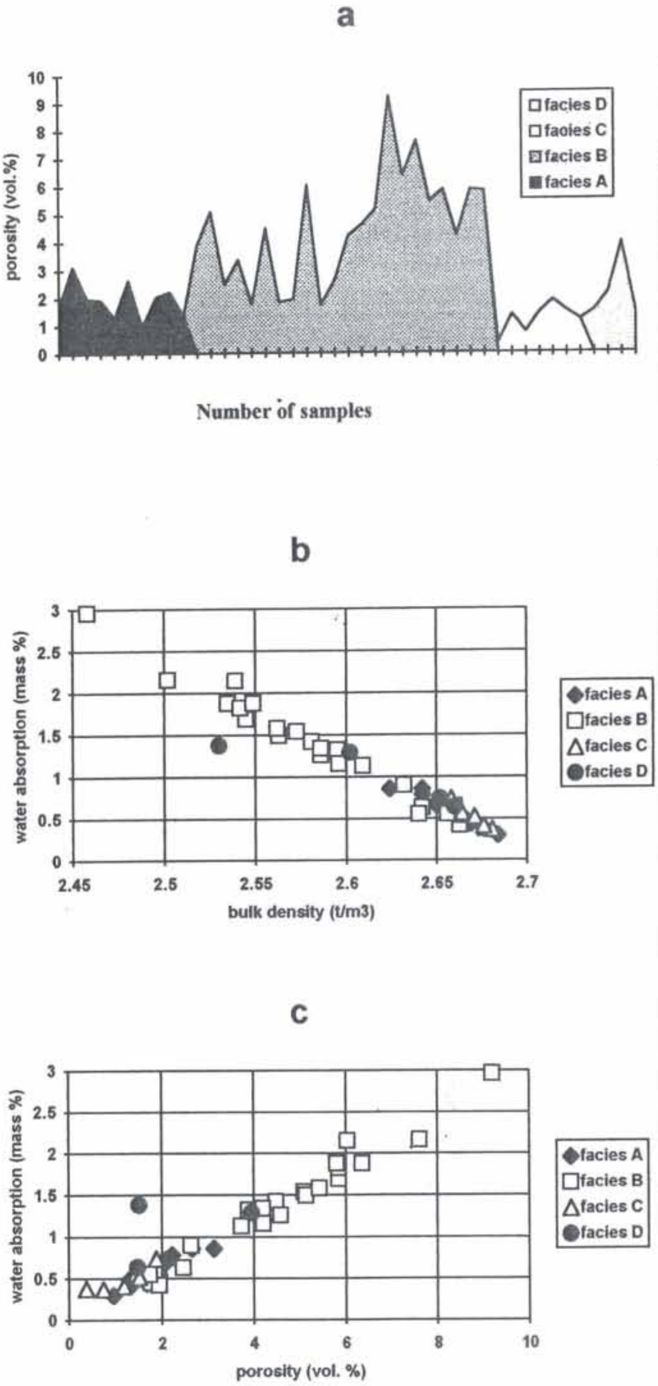

Fig. 6. Graphical display of porosity (**a**), the relationship between porosity and bulk density (**b**), and the relationship between water absorption and porosity (**c**) in limestones from the lithofacies units A, B, C and D.

Table 1: Analytical results of bulk density, porosity, water absorption, comprehensive strength and resistance by abrasion tests performed on limestones from the Lakovići quarry according to the defined facies

FACIES AND SAMPLE No	BULK DENSITY (t/m^3)	POROSITY (vol.%)	WATER ABSORPTION (mass %)	COMPREHEN-SIVE STRENGTH (NM/m^3)	RESISTANCE BY ABRASION BÖHME ($cm^3/50\ cm^2$)
A 1	2.669	1.69	0.44	180.70	17.42
A 2	2.624	3.13	0.86	140.82	15.13
A 3	2.650	2.00	0.66	175.67	14.94
A 4D	2.659	1.95	0.55	198.64	15.70
A 4G	2.666	1.30	0.49	176.17	15.88
A 5	2.642	2.65	0.86	168.71	17.37
A 6	2.684	0.96	0.30	167.83	14.93
A 7	2.650	2.03	0.67	–	14.90
A 8	2.642	2.22	0.79	157.14	15.33
A 9	2.668	1.37	0.44	174.02	19.29
B 10	2.595	3.89	1.32	154.28	16.58
B 11	2.573	5.09	1.54	148.80	18.21
B 12	2.642	2.47	0.63	–	–
B 13	2.609	3.73	1.13	–	–
B 14	2.660	1.77	0.45	–	–
B 15	2.581	4.48	1.42	–	15.31
B 16	2.640	1.85	0.55	169.47	16.01
B 17	2.663	1.95	0.42	184.18	14.29
B 18	2.539	6.03	2.15	185.74	21.10
B 19	2.656	1.74	0.55	145.40	16.36
B 20	2.632	2.63	0.90	–	24.42
B 21	2.596	4.21	1.16	192.07	15,81
B 22	2.586	4.58	1.26	172.74	17.58
B 23	2.563	5.14	1.49	141.68	14.87
B 24	2.458	9.20	2.96	157.24	28.39
B 25	2.535	6.35	1.88	194.40	18.49
B 26	2.502	7.61	2.16	158.94	24.49
B 27	2.562	5.43	1.58	155.09	16.43
B 28	2.545	5.85	1.69	160.41	17.54
B 29	2.586	4.19	1.34	178.27	18.15
B 30	2.542	5.85	1.82	162.64	23.41
B 31	2.549	5.80	1.88	150.90	18.35
C 32	2.677	0.37	0.38	168.67	14.27
C 33	2.664	1.37	0.54	154.72	15.33
C 34	2.681	0.74	0.37	161.34	13.91
C 35	2.664	1.44	0.57	139.30	14.45
C 36	2.658	1.88	0.74	152.60	15.40
C 37	2.671	1.51	0.52	171.41	14.06
C 38	2.676	1.18	0.41	181.98	11.49
D 39	2.530	1.51	1.38	148.55	20.74
D 40	2.662	2.14	0.74	172.47	16.86
D 41	2.602	3.95	1.29	209.80	16.03
D 42	2.660	1.48	0.64	163.37	13.58

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-

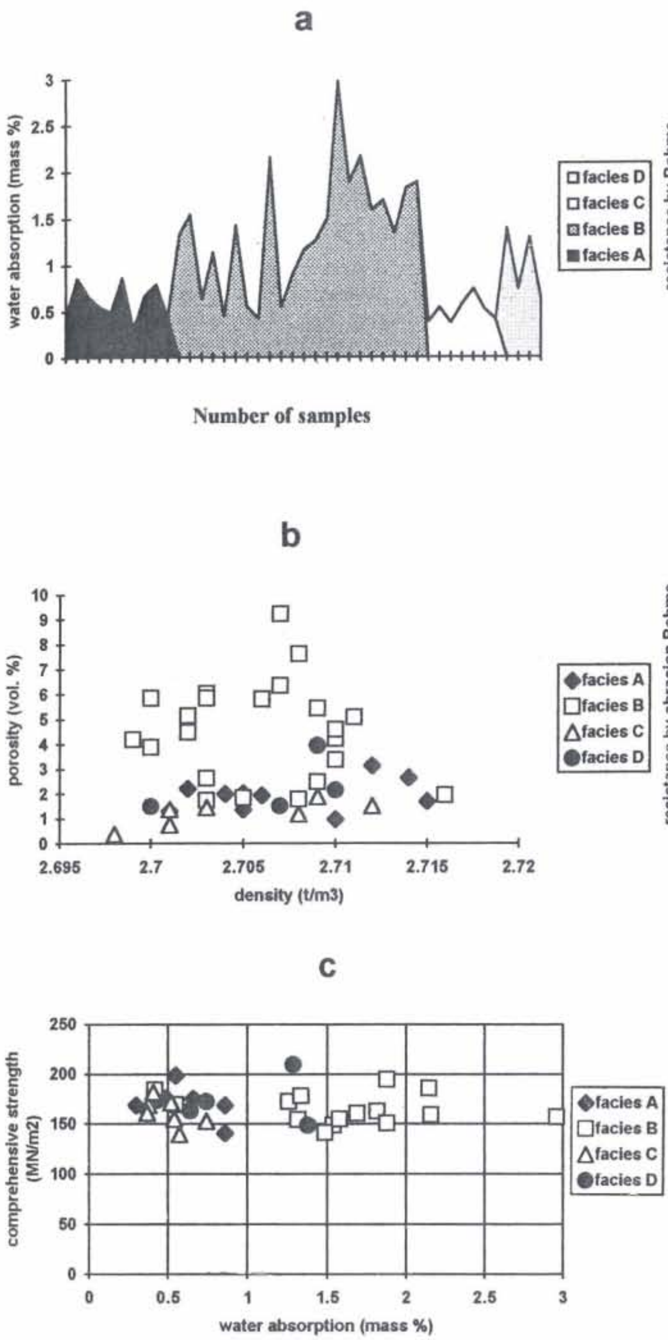

Fig. 7. Graphical display of water absorption (**a**), the relationship between water absorption and density (**b**), and the relationship between comprehensive strength and porosity, (**c**) in limestones from the lithofacies units A, B, C and D.

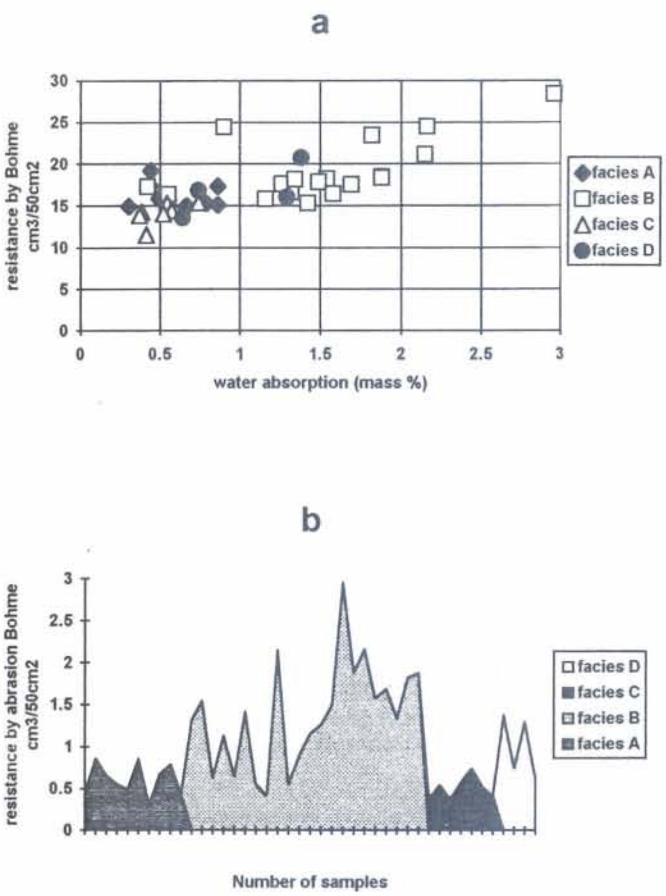

Fig. 8. Graphical display of the relationship between resistance by abrasion Böhme $cm^3/50\ cm^2$ and water apsorption (**a**), and resistance by abrasion Böhme (**b**) in limestones from the lithofacies units A, B, C and D.

sorption values. However, facies unit B limestones and in a smaller extent facies D limenstones although they do not differ greatly in density in comparison to facies A and C limestones, are characterized with significantly higher water absorption capacities (Fig. 6c), lower values of bulk density (Fig. 6b) and resistance by abrasion Böhme (Fig. 8a,b). Their inferior technical properties compared to limestones of facies units A and C (Fig. 6b, 7c and 8a,b) are related with elevated water absorption wich is a consequence of higher porosity caused by the specific deposition conditions and environments, and to some extent diagenesis – mainly to cementation processes of carbonate sand grains, as well as due to later dissolution of cement and/or probably primary aragonite components in a mixed or meteoric zone.

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

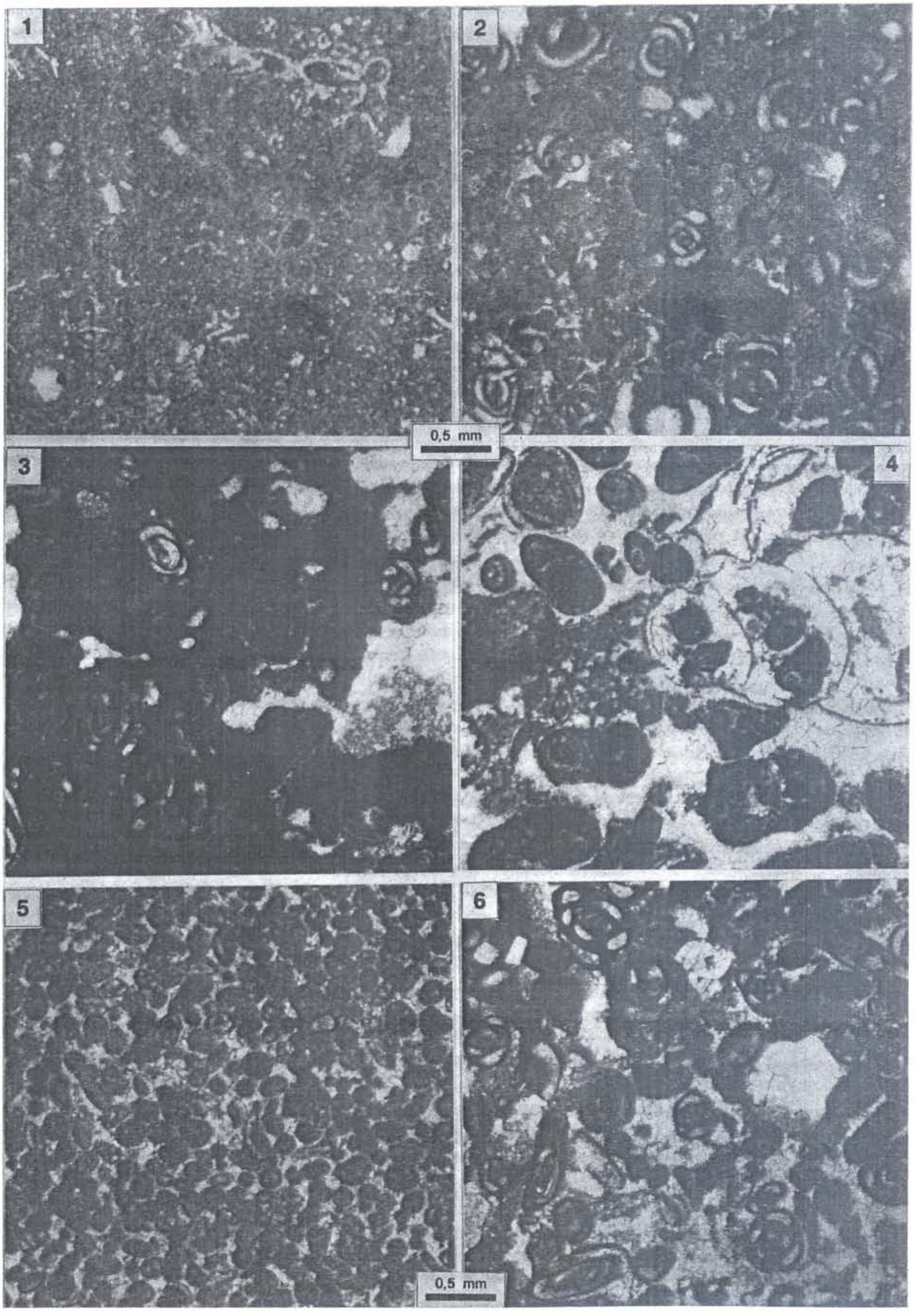
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Plate I:

Fig. 1. Thin-section of the tipical biopelmicrite of the facies unit A: The 2nd member of the shallowing-upward cycles is composed of micrite mass with green-algae skeletons and pelltes. Sample No 1.

Fig. 2. Foraminifera-bearing biopelmicrite of the facies unit A: The 1st member of the shallowing-upward cycles is composed of clotted micrite, benthic foraminiferas (Miliolids), micritic intraclasts and pelloids. Thin-section of the sample No 4.

Fig. 3. Foraminefera-bearing biomicrite with fenestral fabric: The 2nd member of the shallowing-upward cycles (facies unit A) is composed of micrite mass and benthic foraminiferas. Irregular fenestrae and/or solutional vugs are filled with vadose crystal silt (bottom) and mosaic calcite cement (white). Thin-section of the sample No 6.

Fig. 4. Biointrasparrudite (rudston) of the facies unit B composed of well rounded intraclasts, ooids and gastroped skeletons. Interparticle and intraskeletal pores are cemented with fibrous and drusy mosaic calcite cement. Thin-section of the sample No 16.

Fig. 5. Biopelsparite (grainstone) of the facies unit B composed of well sorted pellets/peloids, fibrous and drusy mosaic calcite cement into interparticle pores. Thin-section of the sample No 17.

Fig. 6. Foraminifera-bearing biointrasparite (grainstone) of the facies unit B. Benthic foaraminiferas and well-rounded intraclasts are cemented by drusy mosaic calcite cement (white) and partly with micrite cement (gray). Thin-section of the sample No 20.

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by deposition and redeposition of black terrestiral 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 micrite, pelmicrite and biomicrite type with low porosity, low water absorption values and relatively high resistance by abrasion (Figs. 6a,b,c; 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 significanlty 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 limestons (micrite and biomicrite) deposited in a restricted low-energy shallows or lagoons, with petrological and technical features that resemble limestones of facies unit A (Figs. 6a,b,c, and 7a).

The facies unit D is made of a grain supported limestone succession containing pelsparite, biopelsparite, biointrasparite 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 limestone are the absence of micrite and uncomplete 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 (Fig. 6b and 7c) are related with elevated water absorption which is a consequence of higher porosity caused by the specific deposition conditions and environments. To some extent diagenesis 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 diagenesis 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 Lakovići 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/petrological 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 aggreages.

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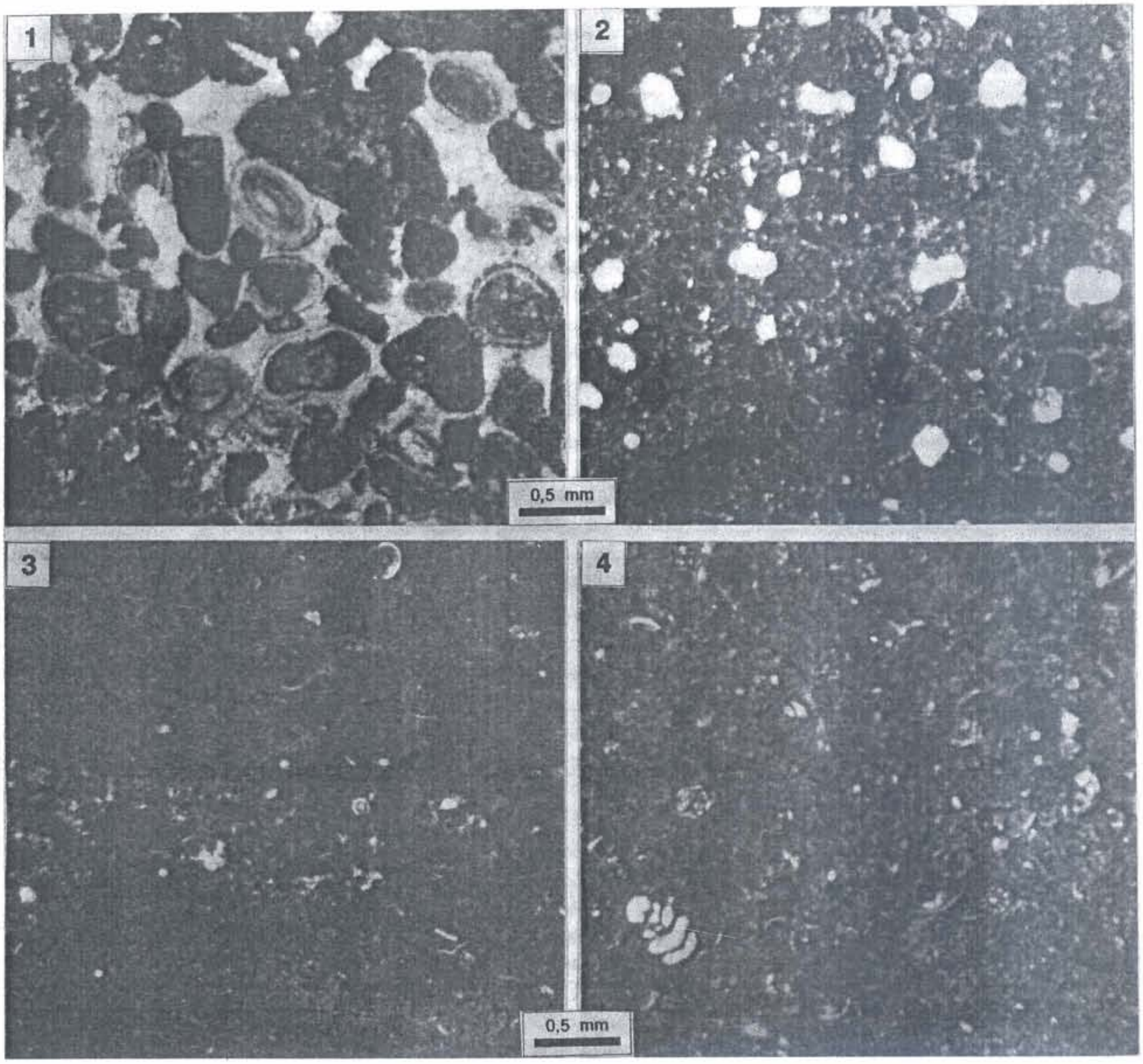

Plate II:

Fig. 1. Ooid intrasparite 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 ooide surface and mosaic calcite cement into interparticle pores). Thin-section of the sample No 15.

Fig. 2. Biopelmicrite 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 foraminiferas and small ostracod bioclasts in micrite matrix. Thin-section of the sample No 37.

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