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Shoreline Cross-bedded Biocalcarenites (Middle Miocene) in the Podvrško-Šnjegavić Area, Mt. Psunj, and their Petroleum Significance (Požega Subdepression - Eastern Croatia)

Josipa **VELIĆ**, Josip **TIŠLJAR**, Ivan **DRAGIČEVIĆ** and Ivan **BLAŠKOVIĆ**

Key words: Cross-bedded biocalcarenites, Shoreline deposits, Subaqueous dune, Petroleum and gas reservoir sandstone, Synsedimentary tectonics, Badenian, Požega subdepression, Pannonian basin, Eastern Croatia.

Abstract

The extensively distributed bioclastic sedimentary bodies in the Podvrško-Šnjegavić Area, Mt. Psunj (Požega Subdepression, Eastern Croatia) are mostly composed of fragments of bryozoans, echinoids, lamellibranchs and corallinaceans. Apart from this, a relatively compositionally uniform, but granulometrically variable bioclastic detritus occurs, which also contains a smaller proportion (5-30%) of siliciclastic grains of medium to coarse sand, as well as sporadic pebbles up to 60 mm in diameter. These sediments are characterised by remarkably large-scale cross-bedding with erosional surfaces clearly delimiting the sets. They are interpreted as shallow-marine shoreface subaqueous dunes, sand bars and barriers formed on the nearshore - mainly shoreface area during the Late Badenian in a high-energy depositional cycle with strong synsedimentary tectonics.

With regard to the petroleum-geological reservoir characteristics, the described Middle Miocene cross-bedded biocalcarenites are compared with numerous large oil and gas pools globally, and in other localities in Croatia on the margins of inselberg massifs between the Drava and Sava rivers and south of the Sava river.

1. INTRODUCTION

Due to their lithological and sedimentological characteristics, the geometry and genesis of sedimentary bodies of biocalcarenite with large-scale cross-bedding attract special attention in studies of the Neogene sediments on the hill-sides of the Slavonian Mts. They are characterised by a variety of cross-bedding sets in respect to the thickness and angle of inclined beds, type of cross-bedding within certain sets and dimensions of the sets, as well as to their lateral and vertical relations with or without prominent erosion and redeposition. In spite of the fact that such Neogene sediments are widely distributed along the Croatian SW margins of the Pannonian basin, not much data has been published. This is especially true for the interpretation of the depositional systems in which these biocalcarenitic sediments were formed. Apart from a short review of the contemporary understanding of such sediments, this paper deals with the structure and interpretation of the cross-bedded biocalcarenites in the Podvrško-Šnjegavić area on the SE slope of Mt. Psunj (Fig. 1) and with their significance (potential) as petroleum and gas reservoir rocks.

In the last 25 years, the Požega subdepression and its marginal parts have been explored on several occasions. Gravimetric and geoelectrical measurements as explained in the work of KOVAČEVIĆ & MUJAGIĆ (1975) led to a number of conclusions - the depression has a markedly blocky structure; the maximal thickness of Neogene and Quaternary sediments is at least 2500 m; there is a predominance of fine-grained clastics and faults were determined along the northern and western margin of the valley.

In a later paper (MILJUŠ & VUGRINEC, 1997) faults at roughly the same positions are shown in maps and cross-sections. A prognosis for the thickness of the transgressive Miocene sediments was given for the first time. For example, 5 kilometres in the direction of the valley from the basement outcrops on its western margin (the location of the Podvrško-Šnjegavić cross-bedded biocalcarenite sedimentary bodies), the transgressive Miocene sediments reach a thickness of 1000 m.

Results of a more comprehensive study of the Požega subdepression were published by NAJDENOVSKI & UDJBINAC (1980). Their set of subsurface maps depict the strike of faults and their throws at various marker horizon levels, the position of a number of anticlines and synclines, as well as the thickness of specific sediment intervals. The Požega subdepression was determined by NAJDENOVSKI (1988) to be a typical intramontane basin, *tectonogenetic microtectonocon - centre* with certain sedimentary phases marked by inverse movements - the western part subsided faster during deposition of the Miocene sediments, and the eastern part subsided more in the Pliocene.

In the Okučani-Pakrac-Novska area on the western slopes of Mt. Psunj, seven lithofacies were determined within a continuous zone of Badenian sediments (BLA-

University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Pierottijeva 6, HR-10000 Zagreb, Croatia.

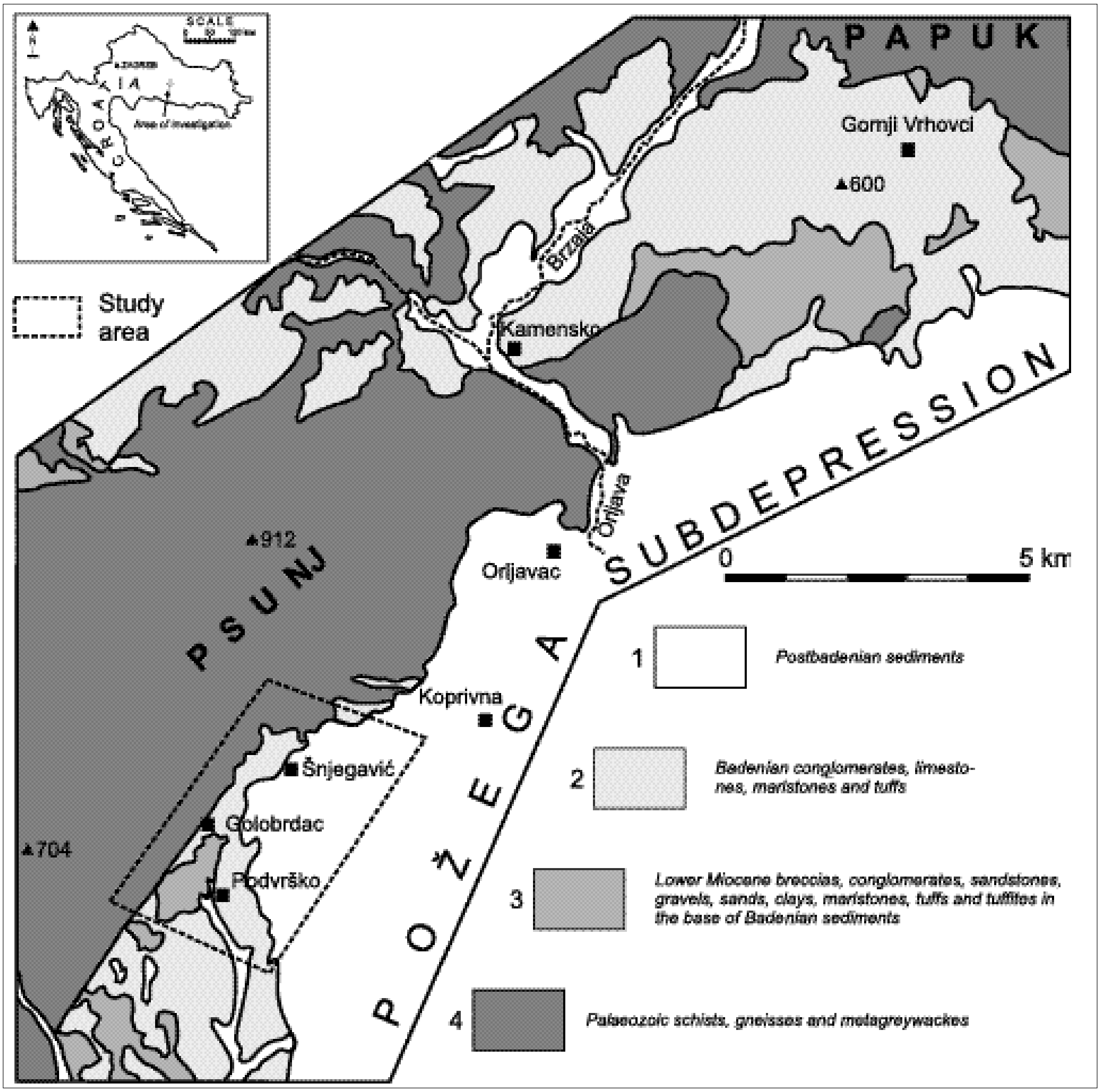

Fig. 1 Location map and geological setting (JAMIČIĆ, 1989; JAMIČIĆ & BRKIĆ, 1987).

ŠKOVIĆ et al., 1982). They range from coarse-grained near-shore and the biohermal and biocalcarenite fore-reef and back-reef sediments, through slope facies to turbidites. Large masses of horizontal and cross-bedded biocalcarenites with 5-40% of siliciclastic grains were described. They were interpreted in terms of bioclastic sands that originated from decomposition of biolithite reefs, and were transported and deposited during cyclic variations in water energy, predominantly waves and tide currents. Hydrodynamics controlled the intensity of reef destruction, as well as the transport, sorting and accumulation of detritus in shallow high-energy environments.

Based on outcrop analysis in the vicinity of the Podvrško village, the cross-bedded bioclastic Badenian sediments on the SE slopes of Mt. Psunj, close to the margin of Požega subdepression, were interpreted as submarine fan-delta deposits (BLAŠKOVIĆ et al., 1985). The authors had postulated the basic principles of formation of such a delta and assumed (later found to be correct) that kind of large cross-bedded sedimentary body and other similar ones surely exist at other places on the rim of the Požega subdepression. Similar conclusions were reached during the survey for the Basic geological map. JAMIČIĆ et al. (1987) explained that the Badenian sediments in the Gornji Vrhovci area are developed in a delta facies. The studied, nearly 100-m-thick section of conglomerates consists of several tens of cross-bedded sets that are 0.5 to 3 metres thick. The conglomerates are composed of well-rounded pebbles of different metamorphic and igneous rocks, as well as of lithothamnium, lamellibranch and echinoid fragments. The Badenian sediments in the broader surroundings of Podvrško were also found to be of deltaic origin (JAMIČIĆ et al., 1989). Within almost a hundred metres of the conglomerate sequence, a number of cross-bedded sets were discerned.

Lower Miocene freshwater clastics that were deposited before the Badenian cross-bedded biocalcarenites were studied by PAVELIĆ (1998) at Mt. Požeška gora, not far from the Podvrško locality. He interpreted these freshwater sediments, probably of Ottnangian age, to have been formed in two successive sedimentary-tectonic phases - an older alluvial and a younger lacustrine phase.

The uninterrupted Ottnangian-Badenian sequence of sediments along the southern margin of the Pannonian basin system was described by PAVELIĆ et al. (1998) in terms of a depositional sequence that can be divided into three parts. The lower part is composed of laminated lacustrine siltstones with sandstone interbeds and of horizontally bedded offshore-shoreface sandstones that contain bioclasts of shallow-marine organisms. The middle and upper part of the sequence is characterised by trough cross-bedded sandstones interlayered with thin-bedded horizontally laminated biocalcarenites (mostly composed of the fragments of corallinaceans, bryozoans, lamellibranchs and echinoids) and by trough cross-bedded conglomerates with erosional contacts between the sets. The authors interpreted these sediments as having been formed by migration of subaquatic 3D-dunes in the upper shoreface environment. The planar cross-bedded sandstones and conglomerates with inclination of sets in the 20-30° range and dipping towards the sea compose the middle part of the succession. They are interpreted in terms of the small-scale foresets of the Gilbert-type marine fan-deltas. The top part of the succession is composed of massive marls with biocalcarenite interbeds. These marls are interpreted as the offshore sediments, and biocalcarenites as turbidites - T_{a-b} intervals of the Bouma sequences. In light of the above knowledge on the Badenian biocalcarenites our aim was to give more details on their genesis, synsedimentary tectonic influence and petroleum geology significance, bearing in mind the distribution of such deposits and their global importance as reservoir rocks.

2. LITHOLOGIC COMPOSITION, STRUCTURE AND GEOMETRY OF THE SEDIMENTARY BODIES

In the Podvrško-Šnjegavić area (Fig. 1) the Miocene (mostly Badenian) sediments unconformably and transgressively overlie the crystalline rocks of Mt. Psunj. The sediments are mostly periclinally positioned and as a rule covered by younger deposits.

The cross-bedded biocalcarenite sedimentary bodies in the Podvrško-Šnjegavić area have a monotonous lithological composition: sandy biocalcarenites prevail over biocalcirudites. Apart from the more or less uniform, but granulometrically very variable bioclastic detritus, they contain a minor amount (5-30%) of siliciclastic particles which have dimensions of medium- to coarse-grained sand, and sporadically pebbles up to 60 mm in size. Fragments of reef and fore-reef organisms are most frequently found. There is a marked predominance of more or less rounded and abraded, poorly to well sorted bioclasts of bryozoans, echinoids, ostreids and of corallinacean algae (lithothamnions), and fragments of corals and benthic foraminifers are less abundant.

Siliciclastic grains and pebbles, mostly of the size of coarse and medium-grained sand (0.2-1.5 mm) and partly gravel-sized (2-60 mm), are mainly composed of the monocrystalline and polycrystalline quartz grains, and fragments of crystalline rocks, feldspars and micas. Together with quartz grains, the quartzite fragments and mica-schists prevail over the granitoid, gneiss and phyllite fragments. Feldspars are represented by the exceptionally fresh grains of microcline and sodium plagioclases, and micas by the coarse leaves of muscovite and a small fraction of comparatively fresh biotite. The siliciclastic grains are generally poorly rounded, although semi-rounded and rounded grains and pebbles occasionally appear.

Within certain more lithified sets of cross-bedding, matrix is practically absent and the biocalcarenites are characterised by the grain-support of the bioclasts and siliciclastic grains. The intergranular, intraskeletal and interskeletal pores are filled with a relatively large quantity (in comparison with the total rock volume) of macrocrystalline drusy mosaic calcite cement, and all the echinoid bioclasts are covered by the variously thick layer of syntaxial calcite cement. In these kinds of biocalcarenites, where the detritus is very much washed out, the more prominent or total lithification of the sets of cross-bedding is caused by the three factors: the absence of the micrite and clayey matrix, high level of sorting and comparatively high proportion of the syntaxial and drusy mosaic calcite cement. Lithified sets of cross-bedding stand out between the majority of the sets, or parts of sets in most of the sets of cross-bedding, that are poorly lithified or unlithified (Figs. 2, 4 and 5). So, there was some primary reason for the development of the cyclically changing character of the clast fabric, i.e. composition of the coarse-grained foresets and fine-grained bottomsets (Fig. 4).

Apart from the poorly sorted bioclasts and variable ratio of siliciclastic grains, the upper parts of the sets of large-scale trough cross-bedding of the biocalcarenites contain a large proportion of fine bioclastic detritus (silt-sized) with a very small amount of finely dispersed clayey matrix. This composition hindered lithification, especially cementation, of this type of biocalcarenite making them very poorly lithified and subjected to erosion (Figs. 2, 3 and 4). It is common when grain avalanche is the main transport mechanism on foresets that grain size increases downward.

Fig. 2 Sets of cross-beds of variable lithification due to variations in grain size and in sorting of the same biocalcarenite beds. In the middle part of the photo there is a low-angle cross-bedded unit (X) with rapid erosion of the large-scale cross-bedded biocalcarenites. Podvrško, Mt. Psunj.

Among the most prominent characteristics of these sediments, and the most important one from the sedimentological point of view, is the well-observable cross-bedding (Figs. 2, 3, 4 and 5) with erosional surfaces that clearly delimit certain sets of the large-scale trough cross-bedding (Figs. 3, 4 and 5). The sets of cross-bedding are between 60 cm and 3 m thick and have a width in the range of 1.5-15 m (Figs. 3, 4 and 5). The sets are thinning upwards.

The succession of foresets within one set of cross-bedding is characterised by a regular repetition of granulometric composition and of the ratio of fossil and siliciclastic material. The foresets of the cross-bedding have the greatest thickness in cross-sections oriented parallel to direction of transport, where thickness in the 5-30 cm range can be measured and the angle of dip maximally reaches 25-35° in sections perpendicular to transport. Following the reduction of thickness, the angle of foresets is reduced until it finally becomes parallel to the position of the bottomsets, if bottomsets are developed (Fig. 4). The coarse-grained foresets (biocalcarenite - biocalcirudite) indicate tangential or sigmoidal foresets deposited by grain avalanche, and fine-grained bottomsets (Fig. 4) turbulence deposition of fine grains from cloud instead of grain avalanche. Poor cementation of fine-grained bottomset sediment (Fig. 4) is due to the granulometric composition of bottomsets (rich in carbonate silt and pelite).

The upper margins of the sets of large-scale cross-bedding are usually sharply cut and have the character of an eroded surface (Figs. 2, 3 and 4). A number of colateral sets are cut by the same erosional surface and

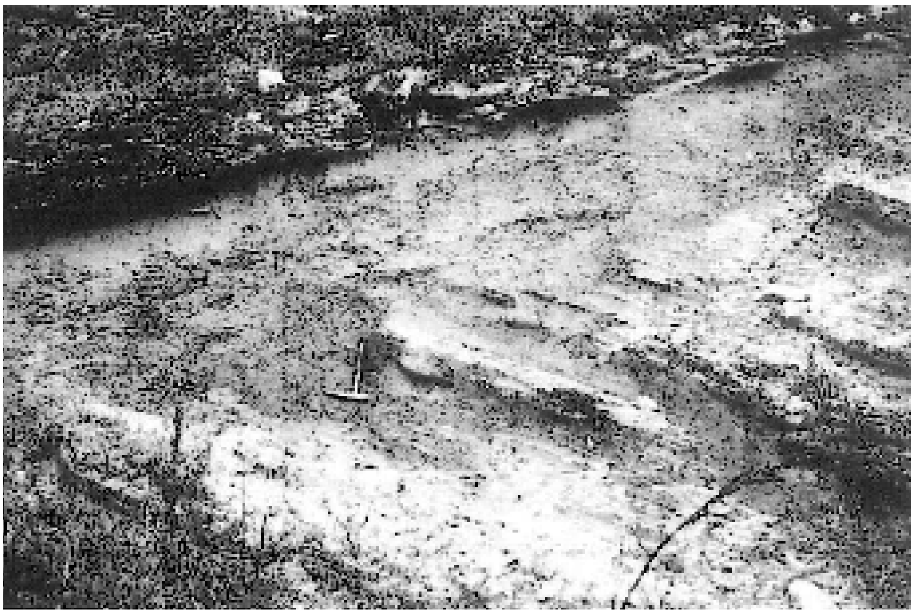

Fig. 3 Detail from Fig. 2: erosional surface at the top of a large-scale cross-bedding biocalcarenite and a low-angle cross-bedded unit (X).

Fig. 4 Typical weathering morphology of the cross-bedded biocalcarenites with lithified coarse-grained foresets and unlithified fine-grained bottomsets - Podvrško, Mt. Psunj.

covered by a 10-70 cm thick layer of low-angle (mostly 3-10°) cross-bedded biocalcarenite (X on the Figs. 2 and 3). They are mostly composed of well-sorted bioclasts with 10-15% siliciclastic grains. In the upper part they contain no matrix and are strongly cemented by large quantities of syntaxial rim calcite cement and drusy mosaic calcite cement. This layer has the shape and sedimentological characteristics which used to indicate a high-energy and relatively shallow water environment: at about the level of breaking waves ("outer planar facies" - ELLIOT, 1986) or may be in the swash zone. Thin layers with low-angle cross-bedding often occur between large-scale cross-bedded foresets in the upper part of biocalcarenite bodies (Fig. 2).

As deduced from the general direction of dip of the layers with low-angle cross-bedding, the dip of the foresets of some troughs that were transected roughly parallel to direction of transport, the generalised direction of palaeotransport was to the SE. This was seawards from the Mt. Psunj crystalline massif that was land in Miocene times.

Such a general direction of progradation of the cross-bedded sediments is paralleled by the reduction of the dip angle of inclined layers, and by reduction of the thickness of inclined layers within the sets. It is also noted that certain cross bedded layers that cover erosional surfaces of a number of sets, thin in the same direction, and that there is a general change in the granulometric composition of the biocalcarenites. In the proximal parts of sets, the foresets are composed of the more coarse-grained, strongly cemented and clast-supported biocalcarenite that is rich in fossil fragments.

Fig. 5 Parts of two sets of the large-scale cross-bedded biocalcarenites with erosional surface and low-angle cross-bedded biocalcarenite unit (in the centre of figure).

The distal, mildly inclined layers are composed of the more fine-grained, matrix-rich and matrix-supported, poorly cemented sandy biocalcarenite. With increasing distance from the source area, there is a general increase in the ratio of the fine-grained detritus and matrix in respect to the coarser fossil detritus. Finally, the seaward ends of the sedimentary bodies are composed of the clayey-carbonate (marly) detritus, already mixed with the basin sediments.

Generally, in the direction of dip of the foresets - i.e. in direction of transport, with increasing distance from the source area sea-wards, the following characteristic changes are observed: a gradual thinning of the sets and of the foresets, general reduction of the dip angle of the foresets within the sets, the cross-bedding becoming markedly less observable together with lower visibility of the contacts between the sets.

2.1. CRYSTALLINE BASEMENT AND SEDIMENTS BENEATH THE CROSS-BEDDED BIOCALCARENITE SEDIMENTARY BODIES

The Neogene sedimentary complex of the Požega subdepression that transgressively (unconformably) overlies the crystalline basement (in petroleum-geological papers treated as the basement rocks) is illustrated in the schematic outline of sedimentation during the Badenian age (Fig. 6). Comparison of this schematic outline with the geological setting given in Fig. 1, facilitates an explanation for the character of the biocalcarenite basement. In the study area, the basement of the cross-bedded biocalcarenite bodies is mostly composed of clayey-silty-marly sediments that have the characteristics of fine clastic material deposited in a low-energy environment. There are no coarser fragments of crystalline rocks, which is interpreted as a quiet transgression in the Karpathian and Early Badenian. In spite of the fact that corrallinacean-bryozoan biolithite build-ups were not preserved *in situ* within both discussed study areas, the existence of numerous and widely distributed build-ups of this kind and of the fore-reef shoals (ecologically suitable for development of the thick-shelled lamellibranchs, echinoids and corals), is deduced from large quantities of their bioclasts.

The fine-grained silty-clayey clastics, rich in pelagic foraminifera, that are laterally equivalent to the bioclastic sedimentary bodies and are biostratigraphically determined as the Lower Badenian, were deposited in the deeper, undisturbed and clean, definitely marine environment. The following species are the most common: *Globigerinoides trilobus* (REUSS), *Globigerina concinna* REUSS, *Praeorbulina glomerosa* BLOW, *Orbulina suturalis* BRÖNNIMANN and *Orbulina bilobata* d'ORBIGNY.

Such relatively thin sediments (100-150 m in the Golobrdac area - Fig. 1) not only underlie the facies described above, but are also present in a more extensive area on the south-eastern slopes of Mt. Psunj where they have a variable thickness and comprise the basal member of other Badenian lithofacies. The contact between the silty-clayey basal part and the coarse sandy bioclastic facies is transitional, but over very short time-span (considering its thickness) and comprises a general upward-coarsening sequence.

2.2. LATERAL EQUIVALENTS OF THE CROSS-BEDDED BIOCALCARENITE SEDIMENTARY BODIES

Laterally to the cross-bedded biocalcarenite sedimentary bodies, the silty-clayey basal part of Badenian rocks is regionally overlain by several lithofacies characterised by the significant increase of a sandy component. This can either be bioclastic limestone detritus originating from the reefal material that was accumulated in the thicker biocalcarenite layers, or the succession of sand-clay-marl carbonate sequences that have some turbidite characteristics and are dominated by siliciclastic material.

As a rule, the cross-bedded biocalcarenite bodies in the studied areas pass laterally into the biocalcarenites with less marked bedding, or into massive biocalcarenites. This contact is transitional and poorly identifiable in the field due to the lack of outcrops. As a result of the periodicity of sedimentation, in the more distal part of depositional area, the prograding cross-bedded sedimentary bodies that are the most distant from the clastic source area, are characterised by a transitional contact between the underlying cross-bedded foreshore-shoreface biocalcarenite bars, barriers, or deltaic lithofacies and the turbidites. This is, for instance, the case between the Badenian sediments and Sarmatian and Lower Pannonian deposits on the western slopes of Mt. Psunj in the Okučani-Pakrac-Novska area (BLAŠKOVIĆ et al., 1982). Another example is within the massive marls with biocalcarenite interbeds - T_{a-b} intervals of Bouma-sequences on the southern slope of Mt. Papuk (PAVELIĆ et al., 1998).

2.3. SEDIMENTARY COVER OF THE CROSS-BEDDED BIOCALCARENITE BODIES

In spite of the fact that the locations with the best exposures of the cross-bedded biocalcarenite sedimentary bodies do not enable the analysis of the entire vertical lithofacies succession (there are no outcrops of overlying sediments), a number of conclusions can be drawn from the data acquired in the more general area. Sets of cross-bedding are gradually reduced in thickness, the dip angle of the foresets is reduced and the grains become smaller. All this, together with the less pronounced textural characteristics and domination of organic carbonate material over the siliciclastic in the apical parts, points to the weaker transport of material from the source area by increase in relative source distance and thus to the diminishing strength of the principal driving force of the periodic sedimentary transport.

The Badenian limestone bryozoan reefs containing various proportions of the corallinaceans, fore-reef lamellibranchs and echinoids take over the role of the main sedimentary source.

Continuous sedimentation resulted in the cross-bedded biocalcarenite sedimentary bodies being covered by the mostly massive biocalcarenites without clearly observable stratification.

3. DEPOSITIONAL MODEL OF THE CROSS-BEDDED BIOCALCARENITE SEDIMENTARY BODIES

The exceptionally large and sporadically well exposed outcrops of the cross-bedded biocalcarenite sedimentary bodies (Figs. 2-5), compared with other data sources that will be discussed, enable a generalised interpretation of the depositional system to be made. The principal elements of this depositional system are defined by the lithological and sedimentological characteristics of these bodies, by their geographic setting in respect to the masses of Mt. Psunj and Mt. Papuk, as well as by the Miocene geological evolution of the area. The composition of the siliciclastic component, especially of the rock fragments, unaltered feldspars and biotite, combined with other data define the sedimentary source areas and the low grade of sedimentary maturity, i.e. that these sediments pertain to the first depositional cycle (of weathering, transport and deposition during the Badenian age). The source material for the sediments in Podvrško area was derived from the crystalline rocks of Mt. Psunj (Fig. 1). A large proportion of the organic limestone detritus (mostly of reefal bryozoans but also of corallinaceans and of fore-reef echinoid origin) points to the existence of significant biohermal build-ups and shallow-marine limestone sediments on the margins of the relatively shallow nearshore zone of the Badenian marine area (Fig. 6). It is impossible to asses how much of the detritus was derived from the Lower Miocene sediments, although JAMIČIĆ et al. (1989) mention the Lower Miocene clastics close to the peak of Mt. Psunj which may also be the potential source of detritus.

The majority of Badenian biohermal and organic shallow-marine limestone rocks were formed during the phase of transgression (Fig. 6) - worldwide uplift of the sea level (Late Karpatian to the Mid Badenian relative sea-level rise - HAQ et al., 1987). The maximal redeposition of organic detritus and progradation of bioclastics in high-energy conditions containing various proportions of siliciclastic material derived from the crystalline rocks happened during the relative sea-level fall (Late Badenian). Apart from the eustatic changes, contemporaneous tectonic pulses cannot be ignored. Synsedimentary tectonics are characterised by the intermittent reactivation of the marginal faults - uplift of the crystalline massifs and relative subsidence of the nearshore and central parts of the sedimentary area (Fig. 6). Tectonic movements on the marginal faults are referred to by KOVAČEVIĆ & MUJAGIĆ (1975), NAJDENOVSKI & UDJBINAC (1980), JAMIČIĆ (1983, 1989), NAJDENOVSKI (1988) and PRELOGOVIĆ et al. (1995, 1998).

The dynamics of depositional model are analysed in several phases. The **preliminary phase** serves to explain deposition of the underlying silty-marly sediments in the environment characterised by the similar bathymetric conditions. In conditions of relative tectonic quiescence, without significant uplift of the Mt. Psunj crystalline rock masses, but with minor relative rises of the sea-level, there is a reduction in the transport of terrigenous material in the shallow and wide nearshore zone of the sedimentary area. The mechanical and chemical weathering of the crystalline rocks takes place but without significant transport towards the area of deposition. There is also a lack of pronounced development of limestone reefs on the rims of the nearshore zone. Hydrodynamic factors influence deposition of the silty-marly material in a wider and deeper basin area without rock fragments or coarser particles in spite of the relatively close source area.

The **preparatory depositional phase** reflects the influence of certain regional changes that happened. These are: the rejuvenation of tectonic movements on the marginal faults (KOVAČEVIĆ & MUJAGIĆ, 1975; JAMIČIĆ, 1983, 1989; NAJDENOVSKI & UDJBINAC, 1980; NAJDENOVSKI, 1988; PRELOGOVIĆ et al., 1995, 1998), uplift of the land massifs and a general trend of the relative rise of sea-level in the basinal part, and relative sea-level fall at the nearshore (Fig. 6), and also changes in climatic conditions. The tectonic reactivation - uplift of the crystalline masses and a general relative rise of the sea level resulted in the faster mechanical weathering of the crystalline rocks and in the stronger influx of terrigenous material in a wide and morphologically variable coastal zone. The growth and development of bioherms on the reliefed rims of the shallow nearshore zone was favoured by the climatic conditions and a general trend of sea-level rise. In this way the back-reef platform became a shallow concave sedimentary area. The sea-level rise was compensated by the rate of deposition conditioned by the increased influx of detritus and tectonic uplift. In some places this balance resulted in preservation of the same bathymetric conditions. In the high energy nearshore marine environment, where relative sea-level fall occurred, there was strong destruction of reefs and the organic debris becomes further reworked and mixed with the siliciclastic material brought from the land by torrents and fluvial streams. The intrabasinal transport in the basinal part (Fig. 6) is reduced in this phase - only a small mass of the siliciclastic-bioclastic material that accumulates is distributed in the wider basinal area where it conformably overlies the previously deposited silty-marly sediments.

The **first phase of deposition of the cross-bedded biocalcarenite sedimentary bodies** reflects a relatively short-lasting process triggered by the reactivated tec-

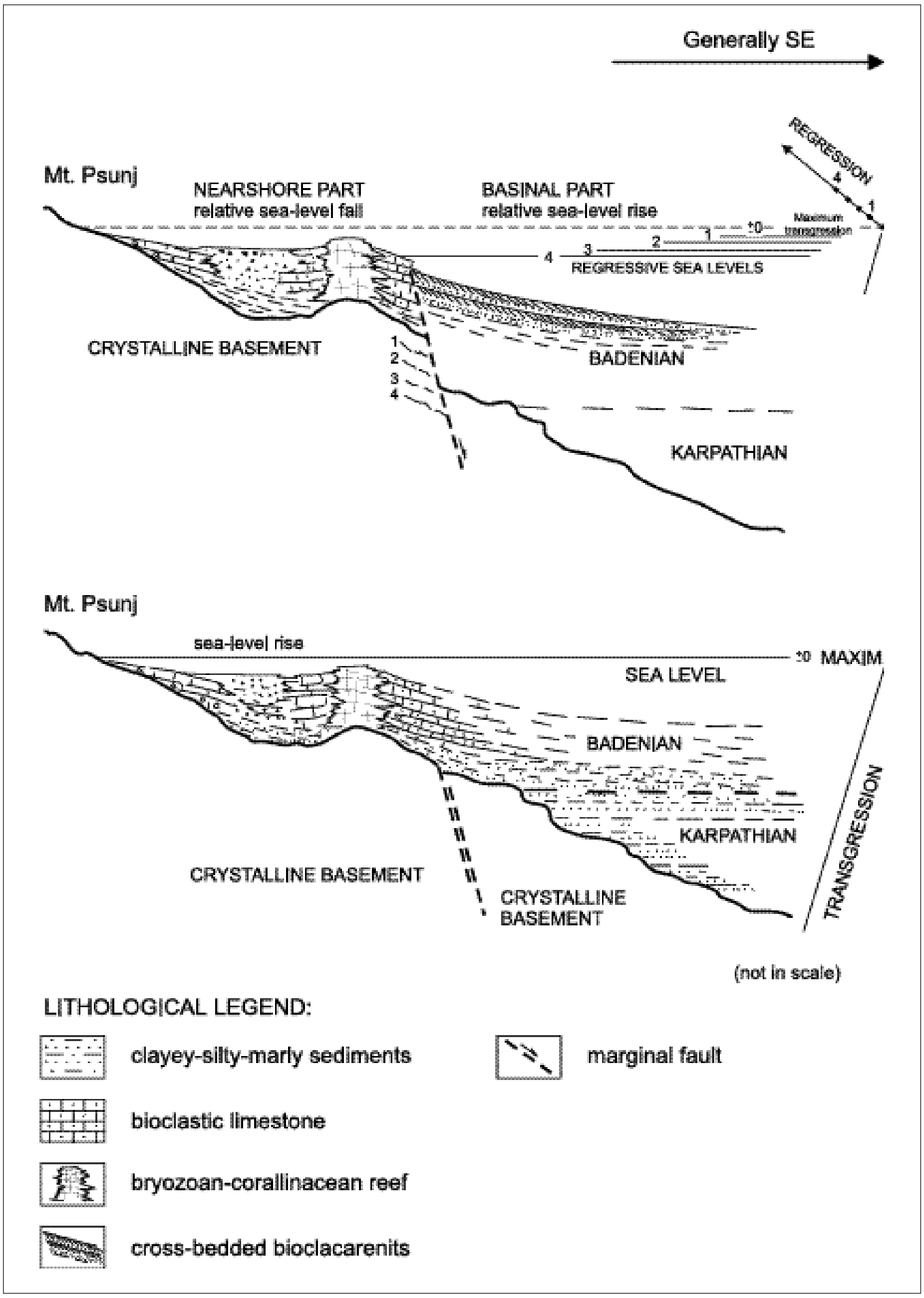

Fig. 6 Schematic outline of sedimentation during the Badenian age in transgressive and regressive conditions by different synsedimentary tectonics in a nearshore and basinal part.

tonic pulses due to the uplift of land massifs, and by the change in inclination of the dish-like back-reef platform. This caused the sudden transport and redeposition of large masses of bioclastic detritus and their mixing with the siliciclastic material on foreshore - shoreface environments. A sudden accumulation of the large masses of detritus occurs in the foresets of cross-bedded bodies - sand bars, barriers, 3D subaqueous dunes and ebb-deltas, partly with the characteristic sigmoidal shape of inclined layers. The fast progradation and grain avalanche or grain fall transport of bioclastic detritus is thereby presumed both for the bioclastic material from the pronounced reefs, fore-reefs and fore-reef shoals, and also for the siliciclastic detritus from the land. Ebb-deltas are formed between the large sand bars or barriers. Concurrently, apart from the bioclastic shore-barrier sand bars and subaqueous dunes, the turbidites were deposited on submarine slopes further offshore and in the basinal part (Fig. 6).

The gradual relative fall of sea-level in the nearshore part and a rapid progradation of the zone of shore-barrier bars with several biocalcarenite ebb-delta bodies between the biocalcarenite bars and barriers, gradually progrades seaward.

Large organic build ups (bryozoans and corallinacean reefs) were required to produce a large amount of bioclasts during relative sea-level highstand ("highstand shedding"). This is the period, when large quantities of bioclasts are produced and transported from the reef to the nearshore and offshore. The relative quiescence after the tectonic shock in the source area of the siliciclastic material, as well as in the reef and fore-reef zone and the back-reef platform, followed by the change in hydrodynamic conditions, results in termination of the fast grain avalanche or grain fall transport of the bioclastic and siliciclastic material. In conditions of low sedimentation rates in the shoreface and offshore-transition zone above the storm-weather wave base, and also on the spacious platform, the destruction of the top of cross-bedded sediments and foresets takes place. The high-energy conditions in the shoreface-zone result in formation of the subaqueous dunes. Well-sorted detritus is then redeposited without the fine-grained matrix, in the shape of variously thick low-angle cross-bedded units (Figs. 2 and 4), which used to indicate high-energy and relatively shallow water at the level of breaking waves (ELLIOT, 1986). In the foreshore-shoreface-offshore environments, the described mechanism of sedimentation, with numerous repetitions of the preparatory and main phases, enabled formation of a wide zone of the cross-bedded biocalcarenite sedimentary bodies of large dimensions.

Variously located bodies of the cross-bedded biocalcarenites along the margin of Mt. Psunj were deposited in different nearshore and offshore environments: there are prograding biocalcarenite shore-barrier bars, subaqueous dunes, ebb-deltas and the fluvial- or tidal-dominated deltas with trough cross-bedded channel fills or with the mouth sand bars. In the basinal - distal - part of the depositional area, the Badenian biocalcarenites occur as turbidite members, i.e. T_{a-c} intervals of the Bouma sequences. Namely, a part of the biodetritus was transported by gravitational flows along the distributary submarine channels and canyons in the deeper basinal part where it was deposited, together with other detritus as calcarenaceous sandstones or biocalcarenites of T_{a-c} intervals of the Bouma sequences within the turbidite fans (e.g. between the Badenian sediments and Sarmatian and Lower Pannonian ones on the western slopes of Mt. Psunj in the Okučani-Pakrac-Novska area (BLAŠKOVIĆ et al., 1982) and in the oil wells of the oil fields Obod, Ladislavci and Beničanci east from Mt. Psunj in the Drava depression (TIŠLJAR, 1993).

4. GEOMETRY OF THE BIOCALCARENITE SEDIMENTARY BODY AS A WHOLE

The biocalcarenite lithofacies has significant outcrop dimensions. In the Podvrško-Šnjegavić area on the SE slopes of Mt. Psunj (Fig. 1), the length of the cross-bedded biocalcarenite sedimentary body (measured parallel to the direction of transport that was determined by measuring the foreset dip directions) is in the 1500-2000-metre range. Due to dispersed dip directions of the foresets, the fan-shaped sedimentary body is interpreted with the lensoid transversal and clino-form - clinostratified longitudinal cross-sections. The vertical dimension of the cross-bedded biocalcarenites on outcrops with eroded surfaces is approximately 40 m.

Data on the subsurface geological structure of the Požega subdepression (NAJDENOVSKI & UDJBINAC, 1980; NAJDENOVSKI, 1988) were made use of in the reconstruction of the distribution of the biocalcarenite lithofacies in areas covered by the younger sediments. According to previous authors, there are significant faults along the eastern margin of Mt. Psunj and on the SE margin of Mt. Papuk - within the area of both studied locations. The throw of these faults at the Tertiary basement level (PT) is 1300 m or 1500-1900 in places, while the Miocene sediments in the Podvrško area are supposed to be approximately 1300 m thick. In the NW part of the Požega subdepression, close to the margin of Mt. Papuk, over 100 m of Miocene sediments in supposed. Towards the centre of subdepression, the thickness of Miocene sediments suddenly reaches 900 m.

Such a great thickness of Miocene sediments along the mentioned faults undoubtedly supports synsedimentary tectonic activity. As a rule, this enables the progradation and development of the sand bar and deltaic depositional systems, which means that a comparatively large longitudinal area of distribution of the described lithofacies within the Badenian area of sedimentation can be expected. In this specific case, this means that the biocalcarenite lithofacies at Podvrško and in the similar area of the Gornji Vrhovci-Sokolina creek can maximally reach 5 km in the E-SE direction. This is, naturally, a supposition that has to be confirmed by additional surface and subsurface investigations of this area.

5. PETROLEUM-GEOLOGY POTENTIAL OF THE MIDDLE MIOCENE SHORELINE CROSS-BEDDED BIOCALCARENITES

At a certain stage in the course of exploration for accumulations of fluids - water, oil or gas, emphasis is put on the definition of the reservoir rocks. The general knowledge on them resulted from explorations in the field of the geology of oil and gas pools, which has experienced a boom since the thirties. Since the late fifties, attention was drawn to the stratigraphic types of traps among which one of the major groups of rocks with adequate porosity and permeability, i.e. with good reservoir properties, is represented by sands or sandstones. It was noted (MacKENZIE, 1972) that the main factors of reservoir formation within the sandstone stratigraphic traps are either the lateral variation of lithologic composition and/or the breaks of their continuity. The lateral variations of porosity are mostly the direct consequence of depositional environment, and to a lesser extent they were caused by the post-depositional processes of selective dissolution of the fossil debris and less stable mineral grains and of cementation. The aforementioned was, for instance, confirmed by the works of CLEVELAND & MOLINA (1990). Within the Cretaceous-Oligocene pools of the Cańo Limoń́ field in Columbia, they documented large variations of both the architecture of the sandstone sedimentary bodies and of the reservoir quality within the shoreline and sand bar systems.

After LeBLANC (1972), the genesis of sandstones can be observed in the three most typical depositional environments. The second one described comprises transitional environments of clastic sedimentation arranged in order from periphery to the centre of a depositional basin, wherein deltaic models and coastal-interdeltaic models are discerned. Cross-bedded biocalcarenites on the slope of Mt. Psunj should accordingly be put into the coastal-interdeltaic models, for which LeBLANC (1972) emphasises their importance for hydrocarbon accumulation. Namely, similar conclusions were reached by several groups of geologists working for example in the Gulf Coast region, southwestern Louisiana, upper Texas coast, Georgia, New England, northern Dutch, etc. In a trend of described tendencies of exploration for stratigraphic traps, SERRA (1985) studied the possibilities of identification of depositional environments by the means of well-logs. He managed to differentiate between approximately ten principal environments, among which the most interesting in this case is the shallow (siliciclastic) sea environment characterised by detrital deposits in moderate water depth (10-200 m), or on a nearshore continent under tides, waves, wind, longshore currents, or storms as dominant sediment-moving forces. It is not always easy to distinguish between the shallow siliciclastic and the deltaic environments according to well log responses and characteristics (SERRA, 1985). Examples are shown of composite-log and dipmeter results taken in the Powder River Basin and in the Godavari Basin in India. This illustrates that the rocks studied in this paper are the globally important HC reservoirs, and are exclusively treated as such - i.e. classified in a separate group.

It also deserves to be mentioned that the hydrocarbon-bearing potential of shoreline cross-bedded carbonate rocks was recognised even earlier. LEVORSEN (1956) for instance, stated that the cross-bedding may often be seen, however, on the weathered surfaces of clastic carbonate rocks. The rocks formed in this way are likely to be porous and therefore be good reservoir rocks, and they probably form a larger proportion of the carbonate reservoir rocks than is generally realised. The most detailed classification was made by RITTENHOUSE (1972). It can serve as a guide and will therefore be briefly explained. Firstly, all of the stratigraphic traps are classified in the two major groups - the ones that are not connected with unconformities and the unconformity-related ones. The first group is of interest here. It is subdivided in two - facies traps (I) and diagenetic traps (II). The facies traps (I) are formed either of current-transported reservoir rocks (A) or of ones that were not current-transported (B). The genesis of reservoir rocks by current transport is possible in seven environments, out of which the fifth one is interesting in this case. This, nondeltaic coastal environment of deposition is likely to be the one in which the Badenian cross-bedded biocalcarenites in the Podvrško area were deposited.

After many years of exploration through subsurface mapping, well-log interpretation (primarily of the spontaneous potential curve) and the stratigraphic interpretation of the seismic data ŠIMON (1980) interpreted the depositional environment of the Sava group (a large lithostratigraphic unit that encompasses sediments of approximately Upper Pannonian and Pontian age) in the Pannonian basin of northern Croatia. He applied the model of the so-called "concurrent deposition" of channel sediments and a concept of the so-called "sub-sea (sub-lake) fan". The discovered outcrops of the Middle Miocene (Badenian) delta and barrier-bar sediments partially corroborate such results, and they justify modern attempts to direct the HC exploration in Croatia more firmly to the stratigraphic traps. Naturally, this is the case of the relatively more modest, smaller bodies (several hundreds of metres in thickness and a few kilometres in length) as compared to the ones described by ŠIMON (1980), which is likely to be a consequence of the fact that the genesis of the described cross-bedded sedimentary bodies is connected to the different depositional environment with a probably smaller sedimentary source area.

It is characteristic that PIKIJA et al. (1993), while exploring the Miocene sediments of the pools of Croatia's biggest gas fields - Molve and Kalinovac (located close to the Hungarian border), determined that the six facies units can be defined at depths below 3000 m. The facies C predominates. It is composed of the Badenian biolithites and reef and fore-reef biocalcarenites to biocalcrudites, mostly deposited in high-energy environments.

The results stated above were achieved by investigations at locations with representative outcrops. Several specimens for porosity measurements were taken at Podvrško on the same occasion. The results were more than encouraging, because it was found that the porosity measured parallel to the sedimentary structures is 18.3%, and that perpendicular to the structures was lower as expected - 15.14%.

In many of the marginal parts of the inselbergs in the Drava-Sava interfluve, as well as south of the Sava river (all in the southern part of the Pannonian basin that is in Croatia), sediments of the same time-span were determined. They have similar, but less pronounced sedimentological characteristics and different geological and geomorphological characteristics of the sedimentary source area. It is therefore possible to suppose the strike of sequences of differently sized delta and barrier-bar biocalcarenites, mostly based on the palaeogeographic and palaeotectonic reconstruction. The last remark is a justification of the above petroleum-geological text. Even more so considering the results like the ones in the paper from PIKIJA et al. (1993). Since these sediments have the significantly increased porosity and permeability that, together with other characteristics (lateral and vertical lithologic variability, isolation by the basal, lateral and overlying massive fine-grained sediments acting as the seal rocks, structural position and tectonic fabric), favours the formation of traps, it is concluded that the search for new fluid pools should also be targeted at them. The exploration should result in definition of the size, shape and palaeogeographic orientation of these sedimentary bodies and their relations to the neighbouring facies, as well as of their porosity and permeability distribution, firstly at the surface and then subsequently at depth, using geophysical and geochemical methods and finally the drilling.

6. DISCUSSION AND CONCLUSION

Sedimentological interpretations of cross-bedded sedimentary bodies often occur in the literature. This is especially true for the one example that would have more or less similarity with the subject of this paper in terms of their architecture, internal organisation and composition.

The Oligo-miocene cross-bedded calcarenites on the Northern island of New Zealand, are mostly composed of the bioclasts of bryozoans, echinoids and benthonic foraminifers with minor proportion of the corallinacean bioclasts. These where interpreted in terms of subaqueous dunes by ANASTAS et al. (1997). The prominent, mostly undirectional large-scale cross-stratification was interpreted as a consequence of the migration of subaqueous dunes on the sea-floor at depth of 40-60 m. The authors explain that such dunes were formed by strong tidal currents that flowed parallel to the sea coast and were combined with oceanic currents. Each of the defined cross-bedded sets was formed by a differently curved 3D-dune in conditions of very variable water current regime due to the changes in strength of the tidal and sea-currents, as well as of the variations in influx and transport of the bioclastic detritus.

The dimensions, architecture and internal organisation of the Miocene cross-bedded biocalcarenite sedimentary bodies treated in this paper have many more similarities in the literature in the examples of the siliciclastic cross-bedded sand bodies. Out of numerous papers, the following are singled out because the interpretations of depositional environments presented in them could, according to our views, be applied in the interpretation of the formation of the Badenian cross-bedded biocalcarenites on the hill-sides of the mountains within the Pannonian basin.

An important characteristic of the tide-dominated deltas, in contrast to the fluvial-dominated ones is that they do not have a pronounced delta-front because the majority of the sediment is accumulated in a very wide area, according to EINSELE (1992) by the deposition of large masses of the trough cross-bedded sands and sandstones with ripples. Such sands are deposited either in the shallow sea of the estuary mouths, or in the neighbouring deeper environment of a wide submarine delta platform. Differently from the ones in the fluvial-dominated deltas, the sands are here not positioned in the discrete and isolated mouth bars, but are rather repeatedly reworked and redistributed by tidal currents in the elongated bodies positioned perpendicular to the coastline. That is why they form the elongated sub-parallel sand ridges in places between the estuary distribution channels of the river mouths, and in the deeper - submarine part of the delta platform. Although the tidal-dominated estuarine deltas usually show a weak progradation, the delta complex as a whole gradually advances in a seaward direction.

The approximately ten metres thick trough cross-bedded sands that cover the pro-delta offshore mud, and are overlain by the planar cross-bedded sands with foresets of a small dip angle, were explained by GALLOWAY & HOBDAY (1983) as a consequence of the transport and constant progradation of sands in the foreshore/coastal barrier sand ridges within a wide-spread depositional system of a wave-dominated delta.

Large masses of the trough cross-bedded sands are interpreted by GALLOWAY & HOBDAY (1983) as the tidal sand ridges on the pro-delta platform of a tidal-dominated delta.

The analysed outcrops in the Podvrško-Šnjegavić area (Figs. 2-5) are located in the gorge of a creek and along the road that goes roughly perpendicular to the crystalline core of Mt. Psunj. Due to the poor exposure of terrain, especially because of the too small outcrops parallel to the crystalline core, and also because of the influence of the synsedimentary tectonics on depositional system, it remains to be clear which of the depositional models described above could be applied in an explanation of these cross-bedded biocalcarenite sedimentary bodies. Considering the relevant data on the composition, sedimentary structures and shape of sedimentary bodies, as well as the very important role played by the synsedimentary tectonics and variations in palaeogeomorphology, our interpretation given above has been little different from the simple application of the one of described depositional models.

The cross-bedded biocalcarenites in the Podvrško-Šnjegavić area on the SE slope of Mt. Psunj at the margin of Požega subdepression, shown in Figs. 2-5, are interpreted as parts of shoreline-shoreface large sand bar bodies, partly 3D subaqueous dunes, characterised by a steeply inclined foreset (20-35°) and rapid progradation, that were preserved from redeposition. Between large scale cross-bedded biocalcarenites thick low-angle cross-bedded units variously occur composed of well-sorted detritus without the fine-grained matrix with erosion base (Figs. 2 and 4). This indicates high-energy redeposition of sand bodies in relatively shallow water at about the level of breaking waves.

In the shoreface zone with the large masses of mostly bioclastic detritus ebb-deltas with seaward inclined foresets were formed between the bars or subaqueous dunes. Cross-bedded biocalcarenites with the landward inclined foresets were not found in the Podvrško-Šnjegavić area.

Due to the very complicated shoreline and variable morphology of the nearshore, shoreface and offshore area, together with the intermittent synsedimentary tectonic pulses and the consequent frequent changes in the rate of sedimentary influx and rate of sedimentation and in the rate of progradation, there were sudden changes in conditions and environments of sedimentation along the coastline, and especially in direction of the sea. Parallel to the predominant accumulation of biodetritus on the back-reef platform, reef and fore-reef shoals and in the shoreface area, submarine fans and/or turbidite fans are formed in the deeper offshore and basinal part. This was partly caused by tectonic uplift of the land area - the crystalline massif of Mt. Psunj and the shallowest parts of biohermal reefs and reef-fore-reef shoals that were closest to the coast, but also by the faulting and subsidence of the nearshore and offshore area. In this way, the rapid progradation of bioclasts and a comparatively steep inclination of foresets were preserved with similarities to Gilbert-deltas.

Regarding the petroleum-geological reservoir characteristics, the described sediments are correlated with numerous large oil and gas pools around the world and put in a separate group - reservoirs formed by current transport.

Sediments of the same geologic age and of similar sedimentological characteristics are also found in other places in Croatia - on the margins of inselberg massifs between the Drava and Sava rivers and south of Sava river. Because of the supposed size and contacts with neighbouring facies, it would be wise to direct the future search for the new oil and gas pools to these objects.

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