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Laterally variable development of a basin-wide transgressive unit of the North Dalmatian foreland basin (Eocene, Dinarides, Croatia)

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ABSTRACT

The Palaeogene Promina Beds (PB), exposed in the Dinaric coastal range, is about a 2km thick heterogeneous succession representing a late sedimentary fill of the North Dalmatian foreland basin. The paper focuses on the middle part of the PB represented by a prominent transgressive unit. The study of this unit is based on field mapping, logging and facies analysis, as well as the investigation of stratigraphic surfaces and facies successions. The unit extends for more than 63km, along the entire basin. Deposition began transgressively over both alluvial deposits of the Lower PB and karstified basin basement. Along its extent the studied unit may be represented either by stacked (high-frequency), marine transgressive-regressive cycles, by lacustrine deposits, mainly limestones, or by a single, marine limestone unit. An ideal transgressive-regressive cycle includes a transgressive segment of limestones, and a regressive segment of storm-wave dominated shelf to gravelly beachface (coarsening-upward) deposits. Gravelly beaches are represented by several types. One of them included the steeply inclined, lower beachface which is situated below the intertidal zone. The cycles are separated by lower-rank discontinuity surfaces (flooding surfaces), while their two segments are separated by a lower-rank transgressive-regressive turnaround surface. Lacustrine deposits originated due to a rise in groundwater induced by a sea-level rise basinwards. The deposition of a single limestone unit resulted from a transgressive onlap over uplifted, Eocene and Cretaceous carbonates of the basin basement. The end of the transgression is marked by condensation processes indicated by glauconite, skeletal debris, planktonic foraminifera and hardgrounds, and a major transgressive-regressive turnaround. The subsequent evolution is almost uniform along the entire extent of the studied unit, and includes shelf to delta and shelf to beach cycles of the highstand. The studied allostratigraphic unit is here given a formal name: the Novigrad Alloformation.

Keywords: Transgressive-regressive cycles, Transgressive limestones, Gravelly beach, Beachface sequence, Condensation, Novigrad Alloformation, Promina Beds, Dinarides

1. INTRODUCTION

An understanding of key stratigraphic surfaces and facies pattern in sedimentary units is fundamental for any attempt to improve the understanding of a basins history (WILGUS et al., 1988; POSAMENTIER & ALLEN, 1999; CATUNEANU, 2006). This is especially true for stratigraphic units of broad extent within a sedimentary basin. The identification of such units is important for stratigraphic correlation, which is a basic prerequisite in the analysis of a sedimentary basin (MIALL, 2000). A widely-distributed transgressive unit of this type has been investigated in the sedimentary fill of the Palaeogene North Dalmatian foreland basin, which is located within the Dinaric coastal range. Although the importance of this unit has been recognised previously, only partial descriptions have been provided (BABIĆ & ZUPANIČ, 2007; BABIĆ et al., 2010; ZUPANIČ & BABIĆ, 2011). Based on field mapping and logging, this paper describes the extent of the unit, and details of complex, laterally varying vertical successions encountered along its basin-wide extent. Based on facies analysis, we interpret facies successions that represent carbonate platform settings, shelf to beachface environments, as well as lacustrine settings. Specific features characterising both the onset and end of the unit, and relevant sequence-stratigraphic aspects, are discussed in particular. A description of high-frequency depositional cycles is also given. Part of the paper deals with coarse-grained beach sequences, which are difficult to observe in present-day environments, but can be compared to examples described from the stratigraphic record (e.g. CLIFTON, 1981; WRIGHT & WALKER, 1981; DUPRÉ, 1984; LEITHOLD & BOURGEOIS, 1984; MASSARI & PAREA, 1988; HART & PLINT, 1989). The studied unit is proposed as Novigrad Alloformation.

2. GEOLOGICAL SETTING, OUTLINE OF THE STRATIGRAPHY AND PREVIOUS WORK

The transgressive unit which is the subject of this paper, forms part of the approximately 3km thick sedimentary fill of the Palaeogene North Dalmatian foreland basin. The basin is situated within an imbricate and folded belt stretching along the Outer Dinarides (Fig. 1). Towards the NE, the belt is bound by larger Dinaric thrust units. On its SW, Adriatic side, it is bound by the foreland, which is a common foreland to both the Dinarides and the Apennines (Fig. 1a). The imbricate-folded belt consists of Cretaceous to Eocene platform carbonates, Eocene-Oligocene foreland basin deposits (mainly clastics), minor Neogene sediments, and Quaternary deposits (reviews in MAJCEN & KOROLIJA, 1973; MAMUŽIĆ, 1975; IVANOVIĆ et al., 1976, 1978). During the major part of the Mesozoic, the area represented a segment of the carbonate platforms that formed a major part of the future Outer Dinarides (VLAHOVIĆ et al., 2005; KORBAR, 2009). The propagation of tectonic deformation of the Dinaric orogen towards the SW, caused the migration of foreland basins, and led to basin formation in the area of the present-day imbricate-folded belt during the Middle Eocene (e.g. IVANOVIĆ et al., 1976; MAMUŽIĆ, 1975; for alternative dating see MIKES et al. (2008) and Appendix). This is an example of a well-known relationship by which the deformation and foreland basin migrate and develop together (BEAUMONT, 1981; MIALL, 2000; ALLEN & ALLEN, 2005). The early basin evolution started with a forebulge stage reflected in the subaerial exposure of Cretaceous carbonates, and continued to develop through ramp limestone, hemipelagic and turbiditic stages of SINCLAIR's (1997) "underfilled trinity" (BABIĆ & ZUPANIČ, 2008) until the Middle Eocene. Subsequent evolution of the basin may be designated as a molasse stage corresponding to conditions

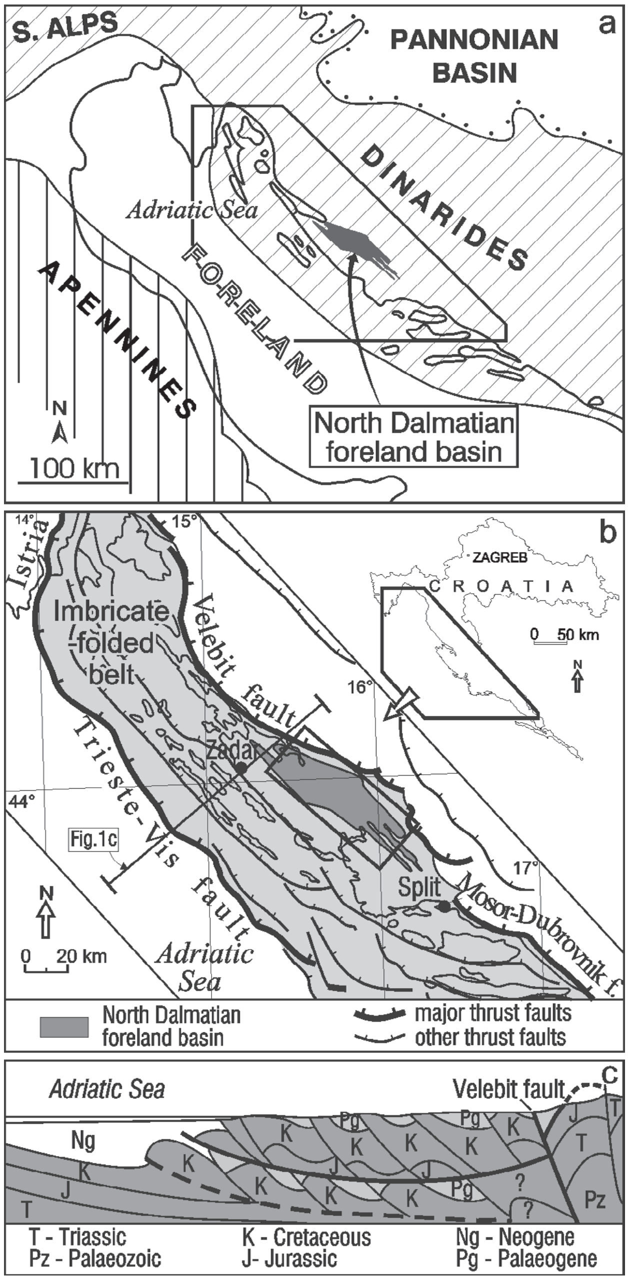


Figure 1: a – Location of the North Dalmatian foreland basin in the Dinarides, and the position of neighbouring, larger tectonic units. Framed area is shown in 1b. **b** and **c** – Position of the North Dalmatian foreland basin within the imbricate and folded belt, which is bound by important thrust faults. **b** – Simplified after PRELOGOVIĆ et al. (2003). Framed basin area is shown in Fig. 5. **c** – Simplified after KORBAR (2009). The cross-section covers a small, NW part of the present-day basin.

when shortening slowed down and subsidence rate became outpaced by sedimentation rate, which results in shallow-marine and continental depositional settings (e.g. SINCLAIR, 1997; MIALL, 2000). During this stage, the major part of the sediments deposited in present day N Dalmatia, has commonly been designated as the Promina Beds (PB) (SCHUBERT, 1904, 1908; MAMUŽIĆ, 1971; IVANOVIĆ et al., 1973, 1977), and dated as Late Lutetian to Early Oligocene (MAMUŽIĆ, 1975; IVANOVIĆ et al., 1978; SAKAČ et al., 1993). MARINČIĆ (1981) envisaged the deposition of the PB and flysch as laterally-equivalent facies, in proxi-

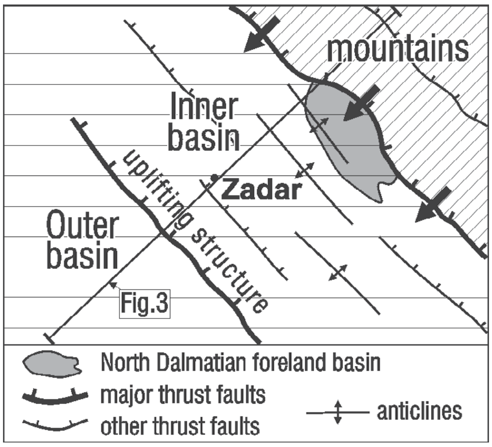


Figure 2: Hypothetical position of the present-day coverage of the North Dalmatian foreland basin sediments in the late Middle to Late Eocene. It was located in an inner basin, close to larger thrusts of the Dinarides, the source area for the detritus delivered to the basin (arrows). Inner and outer basins are separated by an uplifting structure (envisaged by ŠIKIĆ, 1969), which becomes less influential towards the NW, where there was a better connection between the two. Smaller scale, NW–SE trending, synsedimentary folds and thrust faults occurred within the inner basin (also documented here). Not to scale.

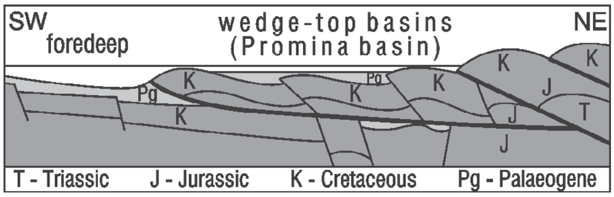


Figure 3: Late Eocene Promina basin envisaged as piggy-back (wedge-top) basin(s) riding on a huge, complex nappe moving towards the Adriatic foredeep. Simplified after KORBAR (2009).

mal and distal parts of the basin, respectively. It has also been proposed that the PB originated in a basin that was bounded by a precursor of the Velebit fault to the NE, and an outer, uplifting structure to the SW (Fig. 2; ŠIKIĆ, 1969). The basin was presumably open towards the NW, and besides the sediment supply from the orogen to the NE, there was NW palaeotransport along the SE-NW oriented tectonic structures (BABIĆ et al., 1995). ŠIKIĆ (1969) envisaged a NE-directed migration of the Promina basin, based on an overall, NE directed younging and onlap of the sedimentary succession, which were described by QUITZOW (1941). Hence, the basin may have been formed and carried piggy-back on a nappe, in front of a major thrust fault (or zone), while its outer flank may have been an anticline or an initial thrust fault located somewhere along the future outer side of the Zadar archipelago (BABIĆ et al., 1995). A comparable tectonic situation has been envisaged by KORBAR (2009), who depicted the Late Eocene Promina basin situated on top of a huge, complex nappe (Fig. 3).

While the entire PB are of late Middle Eocene to Late Eocene and possibly Oligocene age (MAMUŽIĆ, 1971, 1975; IVANOVIĆ et al., 1973, 1976, 1977, 1978), the transgressive unit described here is located within the Late Eocene interval of these authors.

Subdivisions of the PB, largely based on facies successions and sequence stratigraphy, have been proposed for specific parts of the basin and parts of the overall sedimentary succession (BABIĆ et al., 1995, 2010; MRINJEK et al., 2005; BABIĆ & ZUPANIČ, 2007; MRINJEK, 2008; MRINJEK & PENCINGER, 2008; ZUPANIČ & BABIĆ, 2011).

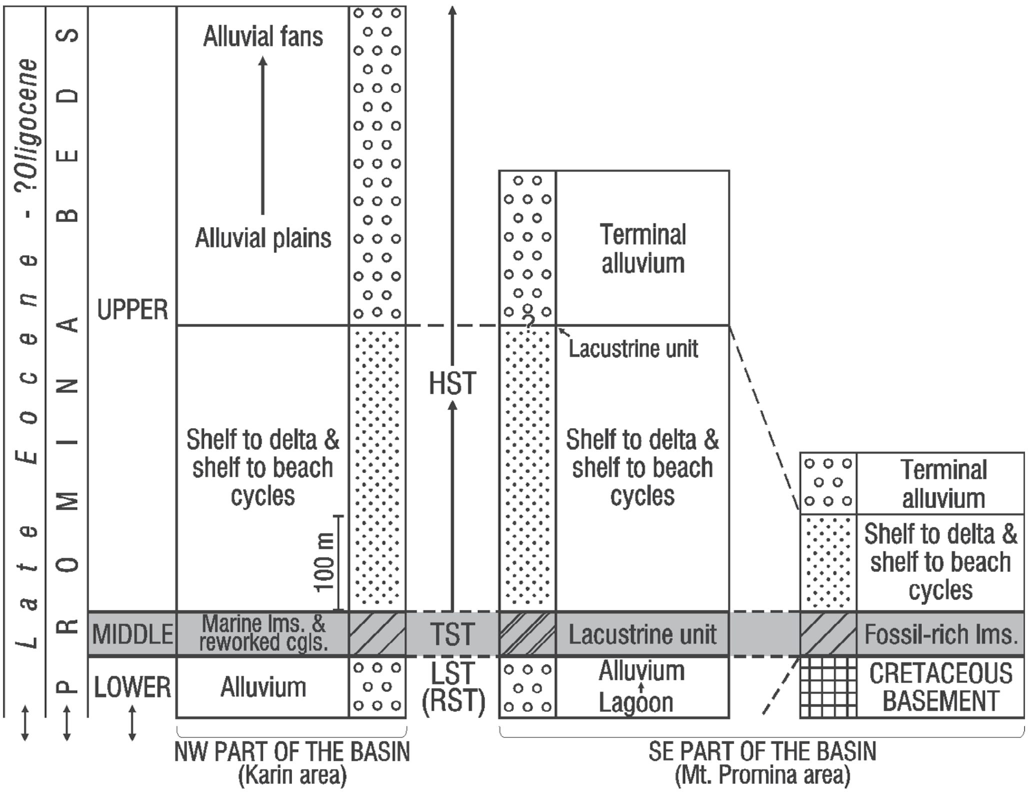


Figure 4: Stratigraphic position of the studied transgressive unit (TST, equivalent to Middle Promina Beds) in the NW and SE parts of the basin. Compiled from BABIĆ & ZUPANIČ (2007), BABIĆ et al. (2010) and ZUPANIČ & BABIĆ (2011). The meaning of the lacustrine unit marked by "?" is problematic. Thickness of TST is exaggerated.

However, only some of the previous descriptions include brief accounts of a transgressive unit represented by marine limestones and conglomerates, as well as minor lacustrine deposits, which have been proposed to represent a transgressive systems tract (BABIĆ & ZUPANIČ, 2007; BABIĆ et al., 2010; ZUPANIČ & BABIĆ, 2011) (Fig. 4). Further study of these sediments has revealed that they form more complex and laterally variable sedimentary successions than previously reported, and the relevant results are presented here.

3. METHODS

We integrate the tracing and mapping of the studied transgressive unit and its bounding surfaces, field study of facies and relevant bounding surfaces, logging and the analysis of more than 200 thin-sections. The thin-sections were mainly used for identification of pedogenic features, distribution of benthic and planktonic foraminifera, occurrence of glauconite and lacustrine carbonates, as well as for confirmation and the refinement of relevant field observations. Our investigations also included parts of the underlying and overlying sediments. Most of the studied sections include covered intervals and/or intervals where sedimentary features are poorly discernable and where only basic lithology is recognizable. This required investigation of an increased number of sections, as well as the collection of scattered data along the trace of the unit, together with the tracing of stratigraphic surfaces. Mapping was performed at a 1:25000 scale and it covered the transgressive unit itself and parts of the underlying and overlying units.

4. DESCRIPTION AND INTERPRETATION OF SEDIMENTARY SUCCESSIONS

The studied transgressive unit extends across the entire North Dalmatian foreland basin (Figs. 5, 6). The unit shows lateral differences, and there are also differences in the character of the underlying deposits and related bounding surface. This variability has been used to delineate seven types of sedimentary successions (T1S to T7S), going from the NW to the SE. The following descriptions also involve neighbouring parts of the underlying and overlying units. The correlation of the studied successions is discussed later.

4.1. Type 1 Succession (T1S) – Novigrad (Figs. 6, 7)

4.1.1. Description

The exposures along the coast, close to Novigrad (Figs. 6, 7) start with Middle Eocene Foraminiferal Limestones, the top of which is marked by karstification and local bauxite deposits. They are overlain by an approximately 90m thick unit of lime packstones, wackestones and rudstones which contain bivalves, gastropods, corallinaceans, smaller and larger benthic foraminifera (including *Fabiania, Nummulites, Discocyclina*, and *Chapmanina*), corals, bryozoans, echinoids and worms. These limestones have already been separated and mapped by SCHUBERT (1908, 1909), who designated them as the Upper Nummulite Limestone ("UNL" in Fig. 7), or Lithothamnium Limestone, while SAKAČ (1961) mapped the area in the same way. They are followed by roughly a 50m wide, covered interval which might hide a fault and an unknown part of the succession.

The remaining part of the succession is organised cyclically, with ideal cycles consisting of limestone units and coarsening-upward (CU) units (Figs. 7, 8).

Limestone units may start with a *basal layer,* which overlies an older CU unit. It is represented either by a conglomerate (< 10cm thick) containing benthic foraminifera, or by a lime packstone including granules and/or pebbles. Both of these are followed by nodular lime wackestones, packstones and subordinate mudstones (Fig. 9a). Almost invariably, they contain smaller and larger benthic foraminifera, and may also include corallinaceans, bivalves, gastropods, echinoids,

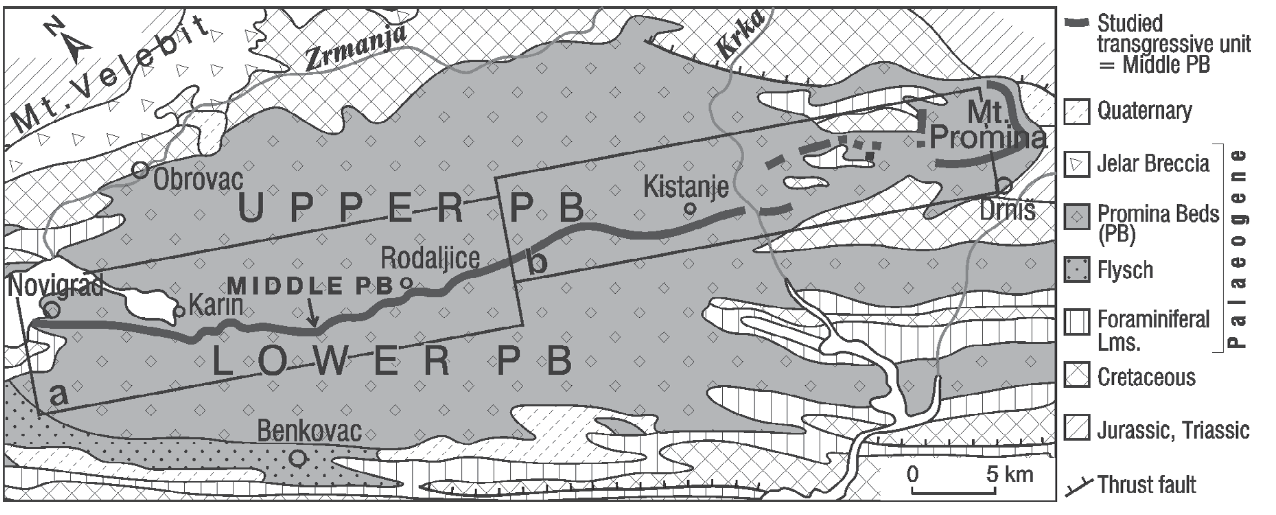


Figure 5: Geological map of the major part of the North Dalmatian foreland basin (in grey) and its surroundings (partly simplified after SAVEZNI GEOLOŠKI ZAVOD, 1970). Location of the studied transgressive unit, equivalent to the Middle Promina beds is indicated by thick, dark line. Framed areas (a & b) are shown in Fig. 6. The transgressive unit from Novigrad to the Krka River is strike-parallel and separates the fields of the Lower PB to the SW from those of the Upper PB to the NE. SE of Krka River and close to NE basin margin, the studied unit is involved in fold and fault structures which resulted in a complex distribution of the unit not entirely represented on the map.

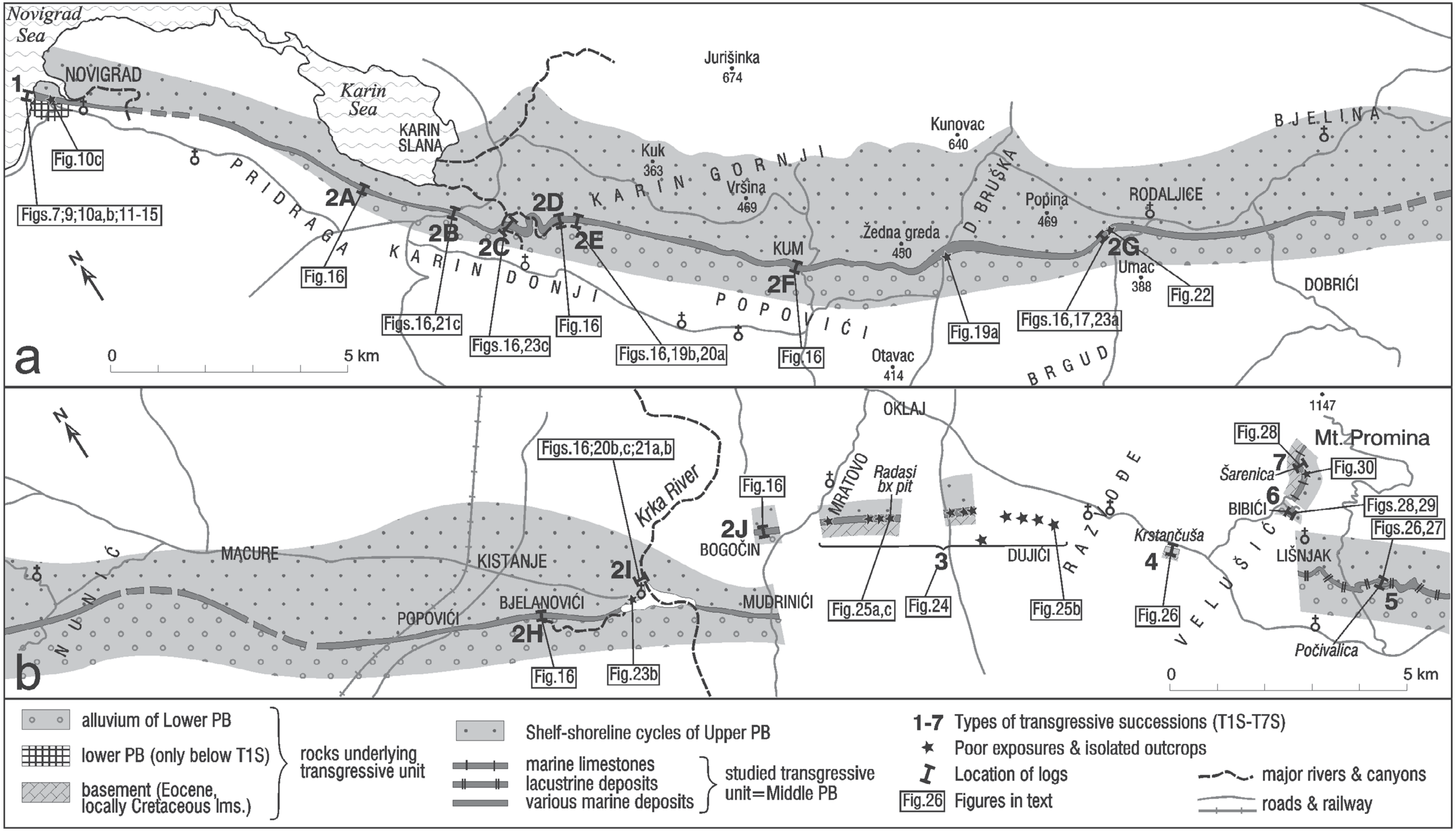
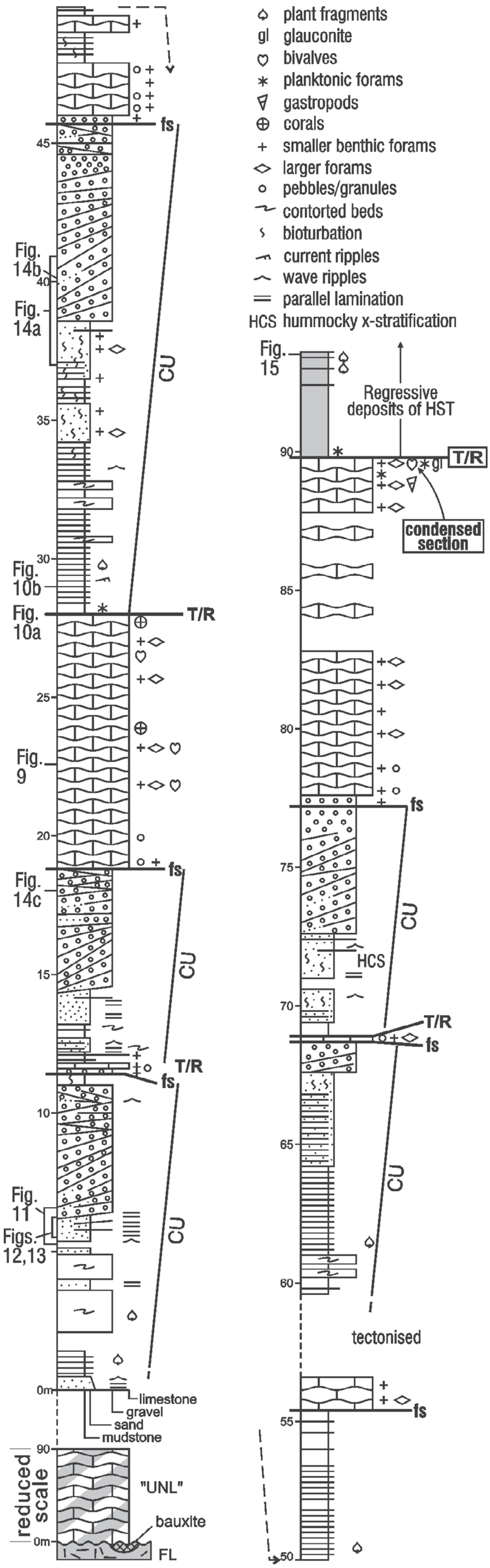


Figure 6: Geological map of the studied transgressive unit and parts of its bounding units, with the location of sections, isolated outcrops and photographs. **a** and **b** are enlarged segments of the map in Fig. 5. Smaller shifts along faults involving the transgressive unit are not included. They have been observed close to 2B, in the Bruška area, W of Nunić, S of 2I and close to Lišnjak. SE of Krka River the studied unit also occurs in other places, aside from locations shown on the map, as a result of the complex tectonic structure of the area.



bryozoans, and corals, as well as scattered pebbles and granules. The foraminifera include miliolids, and smaller rotaliids, *Discocyclina, Asterigerina, Nummulites, Assilina, Orbitolites, Fabiania* and *Heterostegina* (Fig. 9b).

The uppermost ~0.4m portion of the uppermost limestone unit (Fig. 7: above 89m) differs from all the other limestones. It is dominantly represented by mudstones and wackestones containing planktonic foraminifera and glauconite, along with larger foraminifera (*Discocyclina, Operculina, Spiroclypeus, Heterostegina),* smaller benthic foraminifera, echinoids and bryozoans. These limestones are also characterised by intense bioturbation, with common bored skeletons and abundant skeletal fragments.

Coarsening-upward units start with a thin mudstone or directly, with alternating laminae of mudstones, calcisiltites and calcarenites locally showing ripples (Figs. 10a, 10b). The mudstones may contain smaller benthic foraminifera, and only the lowermost mudstone of one CU unit also contains a few planktonic foraminifera (Fig. 7: 28m). This alternation is followed by thicker, up to 20cm thick, calcarenite beds and only minor mudstones. These calcarenites are erosionally-based, may display flat laminae and rarely, wave ripples at the top (Fig. 10c), and contain plant debris. Vertical *Ophiomorpha,* 25cm long shafts, are rare features. Intercalations of contorted units which do not display preferred orientation may be present in this part. Upwards, mudstones disappear, while the calcarenite beds become thicker and may be amalgamated. They are mostly parallel laminated and may include intervals with thicker laminae. Wave ripples are rarely observed. Some CU units include calcarenites which are bioturbated, display relics of horizontal laminae, wave ripples and possible hummocky cross-stratification, and contain miliolids and rare nummulites.

The subsequent, middle part of CU units consists of alternating calcarenites and small to large pebble conglomerates. The calcarenites are amalgamated, parallel laminated, while the conglomerates are erosionally based, thin, commonly one-pebble thick and discontinuous, and may laterally be replaced by scattered, individual pebbles.

The middle part of the lowermost CU unit is thicker, more extensively developed and shows more details compared to most of the CU units (Figs. 11 to 13). Its lower part includes thin, partly discontinuous conglomerate beds based by irregularly undulating low-relief erosional surfaces (Fig. 12). They may be replaced laterally by scattered, individual pebbles draping shallow scours. These conglomerate beds are quasi-horizontal (parallel to bounding calcarenites). Upwards, conglomerate beds become thicker on average (up to 25cm thick), and more and more steeply inclined seawards, finally merging with the overlying, conglomerate clinoform

Figure 7: Log of T1S (Novigrad). FL, Foraminiferal Limestones (Middle Eocene). "UNL", Upper Nummulite Limestone of SCHUBERT (1908, 1909). Thick, framed T/R is the major transgressive-regressive turnaround surface which separates the studied transgressive unit (TST) and overlying regressive deposits of the HST succession. Smaller T/R and fs are lower-rank transgressive/regressive turnaround surfaces and flooding surfaces, respectively. For further explanations see text. Location in Fig. 6.

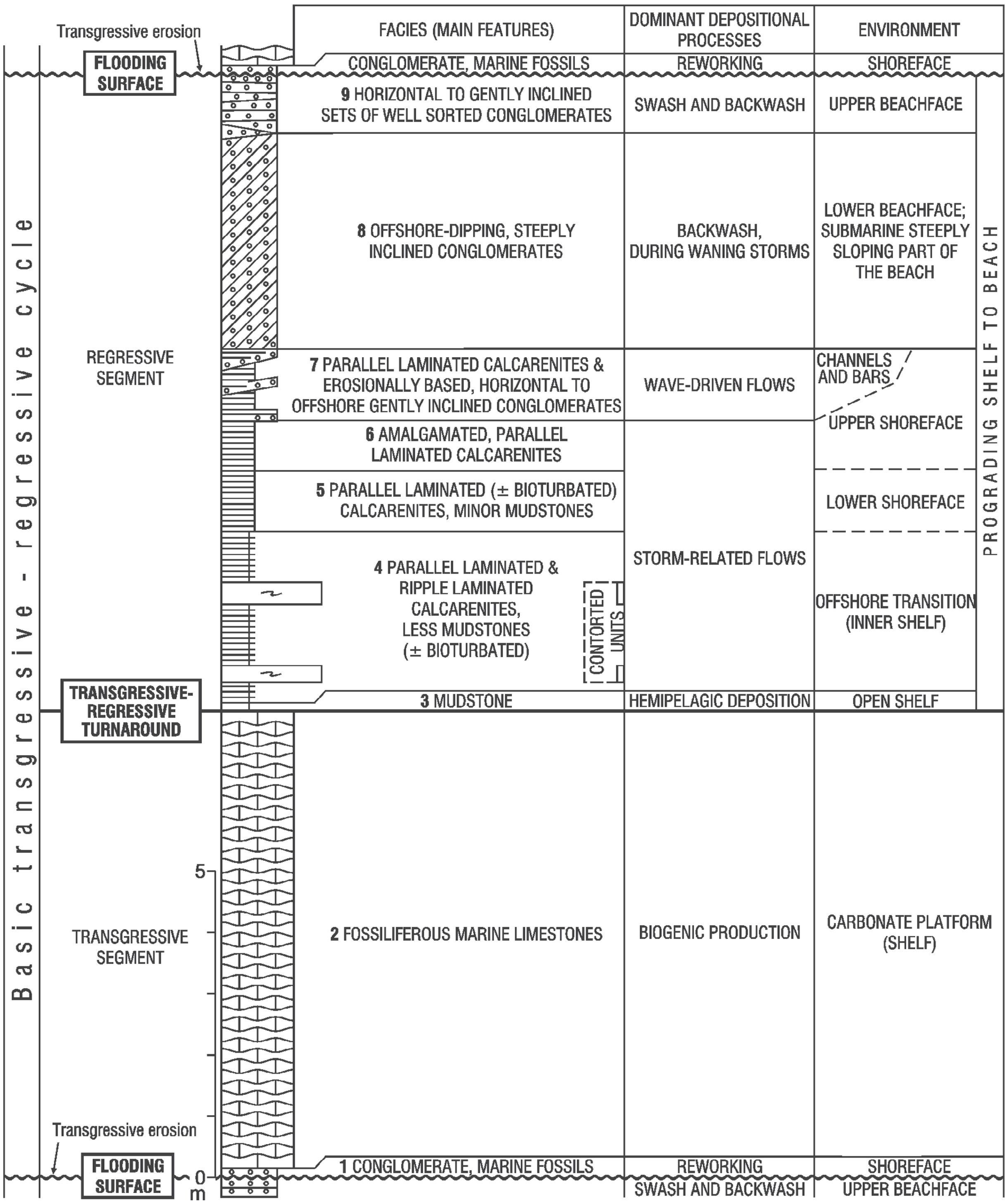


Figure 8: Summary diagram presenting the model (complete) facies succession of the basic transgressive-regressive cycle, based on Type 1 Succession of the studied transgressive unit. 1 to 9 represents divisions of the model succession. For details see text and Fig. 7.

body. The conglomerates disappear within calcarenites offshore (Fig. 11), while the calcarenites wedge out landwards due to the erosion of their upper parts (Fig. 13a). Conglomerates also form lenses, filling erosional depressions which are apparently oriented obliquely to the palaeo-shoreline, and also fill up to 15cm deep and up to one metre wide channels, oriented approximately E–W, i.e. approximately normal to the palaeo-shoreline (Fig. 13b). Convex up, dune-like bodies (Fig. 11) also occur, as well as an example of cross-bedding directed offshore. Very thin conglomerate beds and lenses may be poorly to well sorted. Other conglomerates are commonly well sorted and mostly show bimodality, with modes in pebble and sand sizes, the latter representing the matrix. Very rare clasts attain cobble size, up to 11cm in diameter. Inclined conglomerate beds cut underlying calcarenites obliquely seawards up to 0.5m deep (Fig. 13a). Pebble imbrication (probable a-axis) dominantly dips onshore (Fig. 12b) and rarely offshore. Calcarenites are mostly amalga-

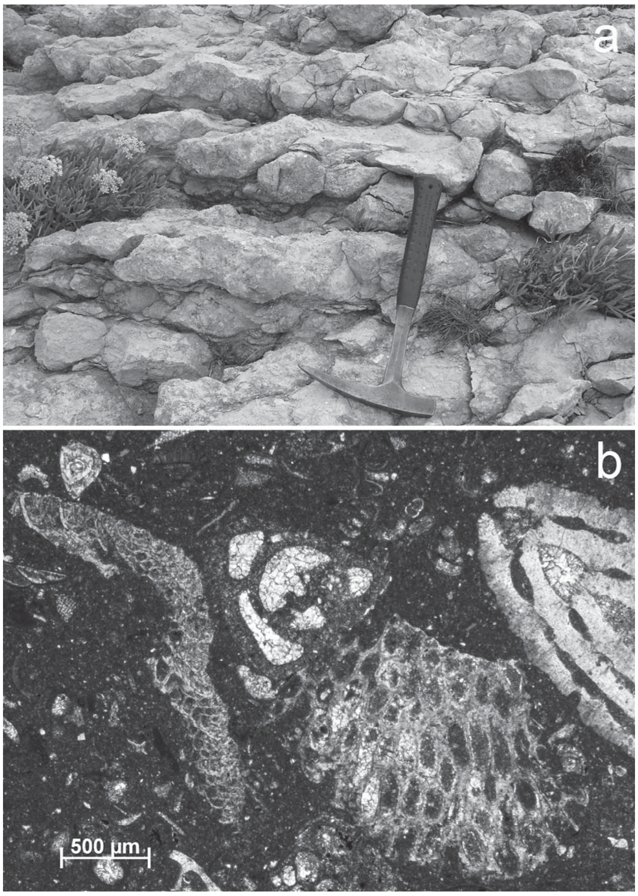


Figure 9: T1S. Example of fossiliferous limestone from the transgressive segments of a transgressive-regressive (T-R) cycle. 22.5–23m in Fig. 7. **a** – Typical appearance of nodular, bioturbated limestones. Hammer = 32cm. **b** – Thin-section of a lime wackestone to packstone: largest constituents (from left to right) are *Fabiania*, agglutinating foraminifer, bryozoan and Nummulites.

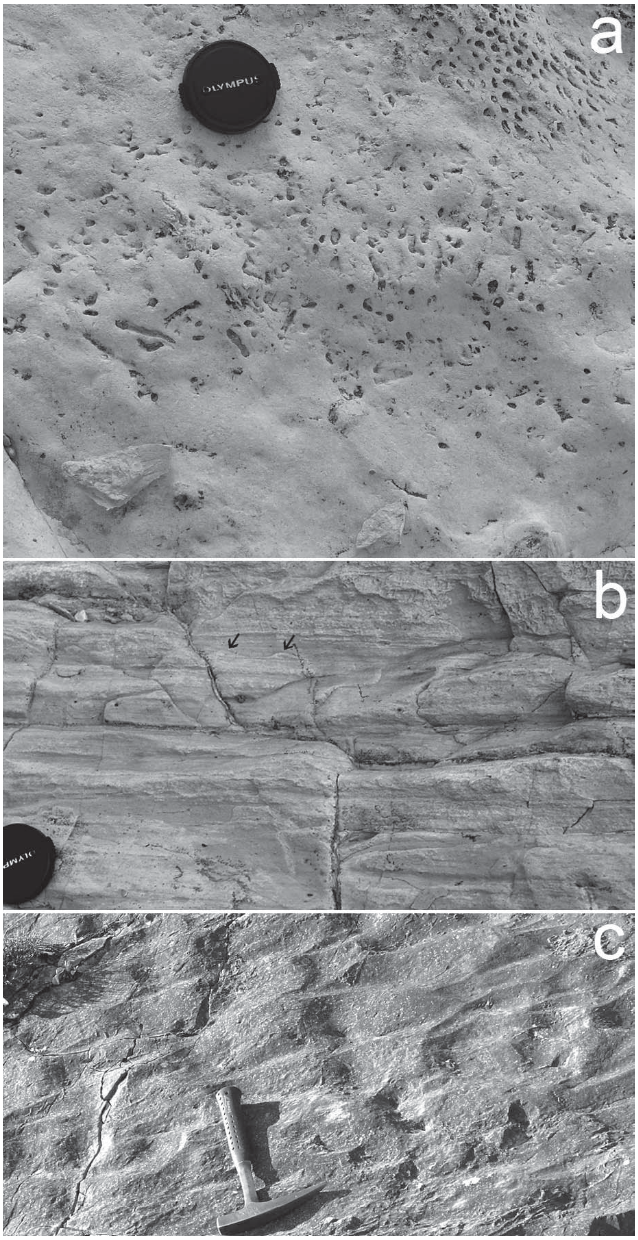


Figure 10: T1S. Examples of the lower part of the regressive (CU) segment of T-R cycles. **a** – Basal part of the regressive mudstone (light) overlies coral bushes of the top of a transgressive limestone unit. The outcrop surface is almost parallel to bedding. This contact surface separates lower, transgressive and upper, regressive segments of a basic depositional cycle, a part of the studied transgressive unit. 28m in Fig. 7. Lens cap = 4.4cm. **b** – Alternating mudstones and thin calcisiltites and calcarenites occurring closely above a. Arrows point to two current ripples. Lens cap = 4.4cm. 29m in Fig. 7. **c** – "Interference" ripples in calcarenites of a CU unit. Road cut, close to Section 1 (Fig. 6). Hammer = 32cm.

mated, parallel laminated, rarely showing converging/diverging laminae at very low angles, and sometimes gently wavy lamination. They onlap inclined conglomerate beds, and close to the contact, they may be inclined landwards (Fig. 13a).

The upper part of CU units is represented by pebble conglomerate bodies with well marked clinoforms which include two parts. Their lower part is up to 5m thick, develops from the segment described above by wedging out of calcarenites, while conglomerate bed attitudes assume steep inclinations (7° to 20°) (Fig. 14a) towards WNW, W and WSW . There are also examples where the transition is sharp without interfingering. An angular basal contact is also observed. Conglomerate beds are mostly 5 to 15cm thick, may be erosionally based and some of them pinch out down-slope, between bounding conglomerate beds. Beds are usually well segregated, and may be very well to moderately sorted (Fig. 14b). Rare examples of poor sorting occur close to the base of the segment, in the case of a sharp transition (angular contact) from the underlying segment of the CU unit. Most conglomerates are bimodal with modes in pebble and sand grades, the latter representing the matrix. The pebble imbrication almost invariably dips onshore, and a few observations revealed that a-axes are imbricate. Offshore dipping imbrication is exceptional and very restricted laterally. Only a single intercalation of parallel laminated calcarenite has been found in some conglomerate bodies. The transition to the upper part of the clinoforms seems (not clearly observed) to be achieved by a gradual reduction of bed inclination. In some cases, the transition is marked by thicker beds of poorly

Figure 11: T1S: a part of the lowermost CU unit. In the lower part there are amalgamated, parallel laminated calcarenites of the shoreface. Upwards, they become intercalated with thin, erosively based conglomerates which may be discontinuous, one-pebble thick and pinch out seawards (left). A dune-like conglomerate feature is seen in the middle right. In the uppermost left, there are conglomerates of the lower beachface. The wall surface is approximately normal to the inferred palaeo-shoreline, land to right. 5.4–7.5m in Fig. 7.

sorted conglomerates. The upper part of clinostratified bodies is mainly formed by sub-horizontal and gently inclined, dm-thick sets of thin conglomerate beds which may be bound by low angle, commonly flat, erosional surfaces (Fig. 14c). Beds are mostly well segregated, on average thinner, and the conglomerates are well to very well sorted and on average finer-grained compared to the steeply inclined part of the body. Rarely observed imbrication is offshore and onshore, and, an offshore dipping b-axis imbrication has been observed in only one case. A conglomerate bed is covered by symmetrical ripples, sinusoidal in outline, with wavelength of 23cm which are draped by calcarenite (Fig. 7: 10.25m). This part of the clinoforms may include landward directed, low-angle sets of conglomerates. There are also minor, thin intercalations of parallel laminated and/or low-angle laminated calcarenites which either pinch out landwards or form lenses due to the erosion of their upper parts.

Examples of partial cycles include the alternation of limestone units and lower parts of CU units (e.g. 46–56.6m in Fig. 7), and probable repetitions of lower-to-upper clinoform facies.

Type 1 Succession (T1S) is first overlain by mudstones containing rare, smaller benthic and planktonic foraminifera, very rare molluscs, and common plant remains. The mudstones quickly become intercalated with sharply based, thin, laminated calcarenites (Fig. 15).

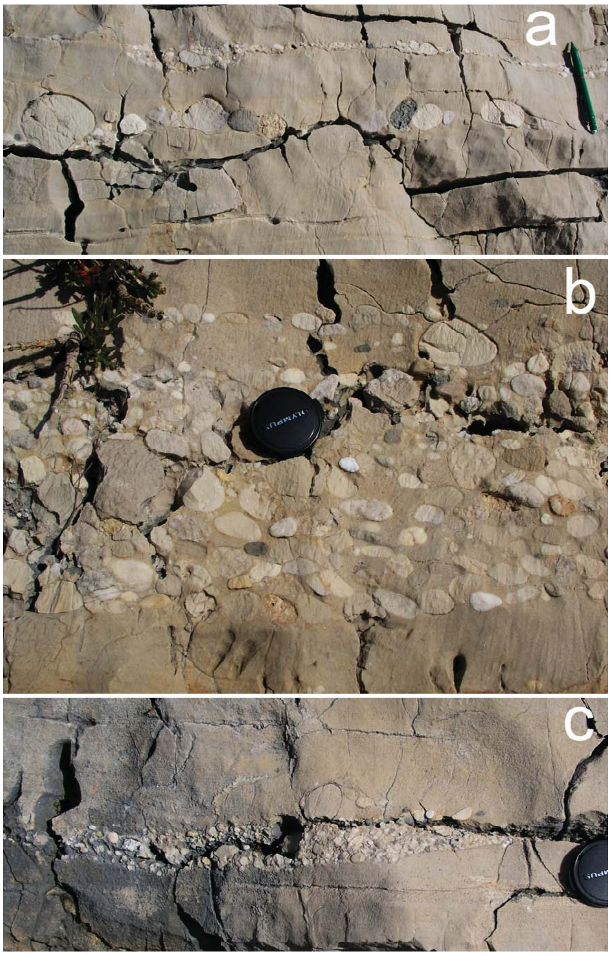


Figure 12: T1S. Details of inferred upper shoreface deposits of the lowermost CU unit. 5.5–6.2m in Fig. 7. **a** – Even, locally wavy and low-angle laminated calcarenites include erosively based conglomerate intercalations. The upper one includes a small, channel-like scour. The outcrop surface is approximately normal to the palaeo-shoreline, land to right. Pencil = 14cm. **b** – Erosively based, imbricate conglomerate and even laminated calcarenites of the upper shoreface. Imbrication in the conglomerate is dipping toward the right (landwards). Note the bimodal character of the conglomerate (modes in pebble and sand sizes). Above these deposits there is a thin conglomerate lens and isolated, smaller pebbles. Lens cap = 4.4cm. **c** – Small, gravel-filled depression (channel or gutter cast), scoured in evenly laminated shoreface calcarenites, and possibly oriented diagonally to the palaeo-shoreline. A few isolated pebbles above it may have been brought in at the very beginning of the post-storm recovery, from the beachface. Section is approximately normal to the palaeo-shoreline, land to right. Lens cap = 4.4cm.

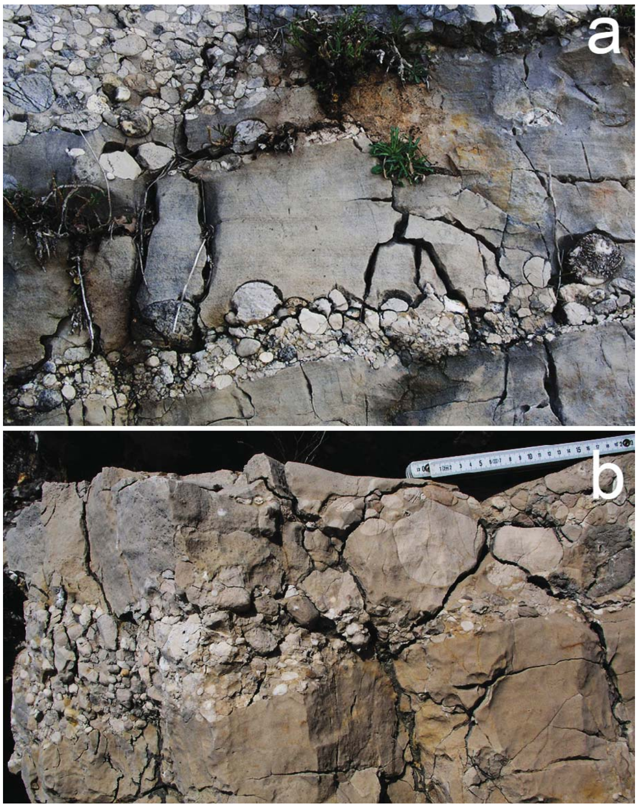


Figure 13: T1S. Calcarenites and conglomerates of the inferred upper shoreface. About 6.5m in Fig. 7. **a –** Calcarenites are mostly parallel laminated, and locally show converging/diverging laminae. Toward the right (landward) they onlap a lower, inversely graded conglomerate bed (largest clast is 7cm in diameter), which obliquely and irregularly cuts underlying calcarenites. Both the one-pebble thick conglomerate lens and conglomerates in the upper left cut underlying calcarenites in a similar way. **b –** Two gravel-filled channels scoured in upper shoreface calcarenites, (the right part of the lower one and the left part of the upper one are visible). Section approximately parallel to the palaeo-shoreline, the sea is in the direction of view. Scale in cm.

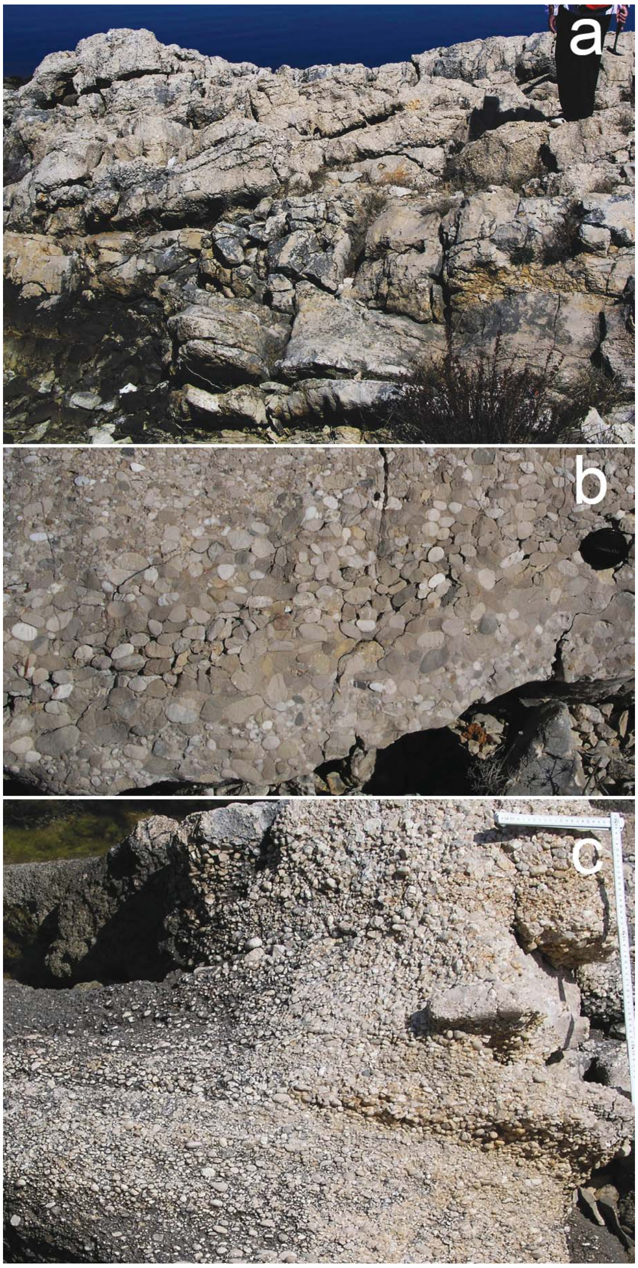


Figure 14: T1S. **a –** Even bedded and bioturbated shoreface calcarenites, in the foreground (lower part of the photo), locally containing thin conglomerate lenses, (not visible here) are overlain by steeply seaward inclined conglomerates of the lower beachface. Hammer = 32cm. 37–41m in Fig. 7. **b –** Dominantly well segregated, well sorted, pebble conglomerates of the lower beachface. Note the dominant bimodality (pebbles & sand), and partial openwork in the bed just above lens cap (= 4.4cm). 40m in Fig. 7. **c –** Two sets of thin bedded, well sorted conglomerates inclined at low angles in different directions, and inferred to indicate the upper beachface. Horizontal segment of the rule is 22cm long. Impression of different bedding attitudes is accentuated by the varied orientation of outcrop surfaces. Section is approximately normal to palaeo-shoreline, land to right. About 18m in Fig. 7.

Figure 15: T1S. Alternating calcarenites (dark) and mudstones (light), several metres above the major transgressive-regressive turnaround surface in Fig. 7. The thickest calcarenite is parallel laminated in the lower part and ripple laminated above, while other calcarenites are ripple laminated. Scale in cm.

4.1.2. Interpretation

Deposition of the "Upper Nummulite Limestone" unit directly above the karstified Middle Eocene Foraminiferal Limestones and bauxite, reflects a transgression of a shallow sea over an older limestone basement. The covered interval separating this unit and the remaining succession, as well as related, possible tectonic reduction, suggest that this unit might be older than the successions dealt with here, and will not be discussed further.

A complete (ideal) depositional cycle (Fig. 8) based on the succession at type section 1 starts with a foraminifera-bearing conglomerate or clast-bearing lime packstone of the *basal layer,* which reflects marine erosion, i.e. ravinement, and reworking of former shoreline gravels (discussed below). The basal layer therefore represents a marine transgressive lag. Reworking of gravel by storms continued during deposition of the *limestone unit* which follows and resulted in the presence of granules and pebbles embedded in limestones even more than a metre above their base, indicating a lateral occurrence of gravels which were being eroded. Diverse shallow-marine biota in limestones, including larger foraminifera, indicates well aerated, carbonate platform settings.

Coarsening-upwards units reflect progradation of coastal settings. Some CU units start with a thin mudstone reflecting hemipelagic deposition on an outer shelf. The majority of CU units start with heterogeneous deposits of alternating thin mudstones, calcisiltites and calcarenites, the features of which suggest deposition in an offshore transition zone. Contorted intercalations may have resulted from seismic shocks, considering the non-preferred orientation of deformations. The overlying, calcarenite-dominated part may reflect waning storm processes in the lower shoreface. *Ophiomorpha* burrows are consistent with rapid deposition. The above interpretation is in accordance with an overall shallowing-upward trend which is reflected in the upward disappearance of mudstones, deposition of medium and coarse-grained calcarenites, and common upper plane bed lamination, which recorded high-energy, storm related processes. These processes must have operated more intensely and more frequently than before, thus suggesting a comparatively shallower part of the shoreface (Fig. 8). Rare wave ripples could represent a fair-weather record which was otherwise mostly obliterated by strong, storm related flows. Bioturbated calcarenites with benthic foraminifera and relics of horizontal laminae, wave ripples and possible hummocky cross-stratification may also be ascribed to processes in the shoreface zone, where fair-weather intervals permitted colonization by benthic organisms, and storms did not completely remove or rework the resultant sediments.

The overlying, alternating conglomerates and calcarenites represent the progradation of an upper shoreface, partly based on their position between inferred shoreface deposits and lower beachface sediments (discussed below), and partly based on their own features (Fig. 8). Prominent erosional surfaces must have been generated by vigorous flows during the peaks of severe storms which removed much sediment from this zone. They also eroded sands from an outer part of the shoreface (amalgamation in the lower part of the CU), as well as the beachface gravels (discussed below). Gravel taken from the beachface was transferred and redeposited onto irregular, seaward inclined to quasi-horizontal, erosional surfaces. Alternatively, some thin gravel beds and lenses may have originated as a post-storm lag (CLIFTON, 1981), by winnowing of the finer fraction from already emplaced sediment by post-storm swell waves. The imbrication features suggest strong seaward flowing currents and related, rather dense gravel flows, additionally influenced by gravitational force (a-axis imbrication) and locally, by waves (bipolar imbrication). These processes were related to rip current activity responsible for both the strong erosion and gravel deposition. The gravel may have mostly been deposited in rip-channels directed perpendicularly and obliquely to the shoreface slope, and some of them in "gutters". Some thin gravel stripes might represent small, thin splays deposited at channel mouths. Some discontinuous, shallow erosional depressions might have also represented troughs of longshore flows induced by strong cell circulation. Narrow, sharp erosional scours might have originated by vortexes generated at the interference of seaward and oscillatory flows. The processes discussed above, therefore, mostly operated within a dissipative domain of the nearshore during peak storm conditions. Similar deposits and related processes including storm-related erosion and strong, seaward directed flows in the shoreface, have been described from sedimentary formations of different ages (DUPRÉ, 1984; LEITHOLD & BOURGEOIS, 1984; BOURGEOIS & LEITHOLD, 1984; MASSARI & PAREA, 1988; HART & PLINT, 1995). Namely, gravelly coasts which are basically reflective may become dissipative or include a dissipative domain during severe storms (MASSARI & PAREA, 1988, with references). Low-angle and convex upward lamination in calcarenites may reflect a growth of low sand bars located between scours. In general, the overall pattern and geometry of conglomerates and calcarenites are suggestive of lateral and vertical movements of the system of bars and channels, as a result of oblique wave incidence (MASSARI & PAREA, 1988). The climbing of inferred arenite bars over the beach slope represents a welding of bars to the beachface, i.e. the end of dissipative conditions and a return to a reflective situation and a recovery stage (*op. cit*.). It may also be mentioned that the interval of alternating conglomerates and calcarenites does not contain any record of fair-weather conditions, which emphasises the importance of storm-wave domination over the sedimentation.

In contrast to the lowermost CU unit discussed above, higher CU units show faster evolution of the alternation interval, where only one or a few thin conglomerate beds and lenses might indicate slightly less influential dissipative conditions compared to the first CU unit.

Shoreface settings subsequently developed into gravelly beachface settings represented by conglomerate bodies of the upper part of CU units. The term "beachface" is here used following BOURGEOIS & LEITHOLD (1984) and MASSARI & PAREA (1988) to refer to the whole sloping face of the beach, down to the landward boundary of the shoreface. The steeply inclined lower part of conglomerate bodies and gently inclined to sub-horizontal upper conglomerates,

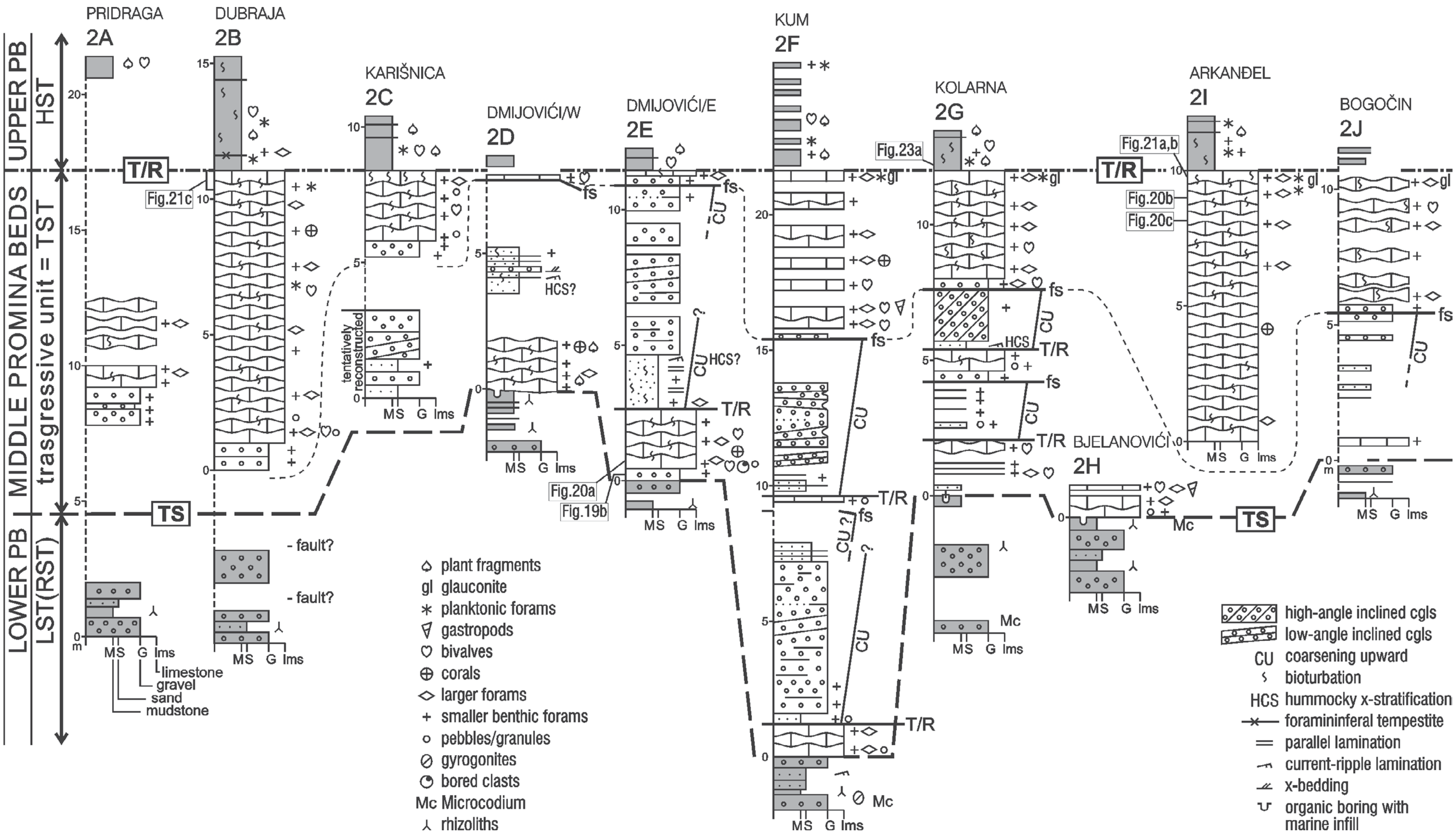


Figure 16: Logs of T2S, Pridraga–Bogočin. The studied transgressive unit is underlain by alluvial deposits, and overlain by regressive deposits (highstand). TS, transgressive surface. Thick, framed T/R is the major transgressive-regressive turnaround surface. Smaller T/R symbols and fs are lower-rank transgressive/regressive turnaround surface and flooding surface, respectively. Datum is the major transgressive-regressive turnaround surface. For details see text. Location in Fig. 6.

closely resemble lower and upper beachface gravel facies respectively, described by MASSARI & PAREA (1988) from the Apenninic Pleistocene, Italy. As discussed by these authors, erosional truncations may have formed during the peaks of storms, while their lower beachface gravels accumulated in the declining stages of high-energy events when the beachface profile tends to be restored. Highly dominant, onshore dipping a-axis imbrication, reflects a significant influence of gravitational force superimposed on backwash. Poorly sorted conglomerates locally observed at the base of clinoforms, may be explained by deposition from debris flows which originated by mixing of grain populations from several parts of the beachface, possibly related to the action of the most severe incoming waves. Poorly sorted conglomerates at the transition from the lower to upper beachface, might represent step-like features of coarse-grained, reflective beaches, which are produced by the interaction of breaking waves and backwash, which could have brought together particles from different zones, including the upper shoreface, lower beachface and berms (MASSARI & PAREA, 1988). The depth to the bottom of the beachface might be estimated using the thickness of the lower beachface conglomerates that can attain 5m in thickness. Flat and gently inclined erosional surfaces in the upper part of the clinoform bodies, are regarded as reflecting the action of steep waves in a foreshore during storms, while deposition of sub-horizontal to gently inclined, thin bedded sets of well-sorted conglomerates above the erosional surfaces, may result from low-steepness waves during the early recovery period (*cf.* MASSARI & PAREA, 1988). Wave ripples on top of a conglomerate bed could have been produced during the recovery stage or a minor storm. Onshore directed cross-beds were possibly deposited by swell, either as landward migrating bars or by swash washover in the back-beach area, but also in a beach-transverse channel, incised during a storm (*op. cit.*). Calcarenite intercalations represent erosional relics of sandy foreshore settings which were active during "fair-weather" conditions the record of which has otherwise been mostly destroyed. As no indications of tidal processes have been found, the tidal range may be considered very small.

The facies succession of an ideal (complete) cycle therefore includes a transgressive segment characterised by carbonate platform settings (limestone unit) and a regressive segment which resulted from deposition within shelf to beachface settings (CU units) (Fig. 8). The two segments are separated by a discontinuity surface reflecting the change from transgressive to regressive depositional trends. The cycles are bounded by discontinuities in sedimentation which may be considered as flooding surfaces of the sequence-stratigraphic classification which is supported by the relatively simple internal organisation of the cycles, as well as their stacking within a larger depositional unit. Hence, they represent the basic building units of a higher-rank unit, (sequence stratigraphy and related terminology are also discussed in section 5.).

The end of deposition of the uppermost limestone unit, which is equivalent to the depositional end of T1S, is specifically characterised by a decrease in biogenic production and sedimentation rates, i.e. condensation and deepening. It is indicated by the appearance of planktonic foraminifera, autochthonous glauconite, increased bioturbation intensity and organic boring, and inferred scavenger activity resulting in frequent skeletal fragments (review in FLÜGEL, 2004). Larger foraminifera in these limestones suggest that the area still remained within the shelf realm.

T1S is overlain by a coarsening-upward succession starting with outer shelf mudstones and alternating calcarenites and mudstones. They represent the lowermost part of shelf to delta and shelf to beach cycles of the highstand tract which extends across the entire basin (BABIĆ & ZUPANIČ, 2007; BABIĆ et al., 2010; ZUPANIČ & BABIĆ, 2011).

4.2. Type 2 Succession (T2S) – from Pridraga to Bogočin: 2A–2J (Figs. 6, 16)

4.2.1. Description

This type of facies succession characterises a 40km long stretch of the studied transgressive unit (Figs. 6, 16, 17). For the most part it is poorly exposed and only incomplete sections are found here and there.

Figure 17: T2S at Kolarna village (Section 2G in Figs. 6 and 16). Below the transgressive surface (framed TS) there are conglomerate-dominated alluvial deposits. A subsequent transgressive unit (12m thick), ends at a major transgressive-regressive turnaround surface (framed T/R) which is first overlain by basal mudstones of the regressive succession.

The Type 2 Succession (T2S) is underlain by alluvial sediments represented by two main facies associations. The first one has been described as consisting of laterally extensive, sheet-like bodies of massive, horizontally bedded to gently inclined, and locally cross-bedded conglomerates, which include intercalations and lenses of laminated calcarenites, and are interpreted as representing deposits of braided channel belts (BABIĆ & ZUPANIČ, 2007; BABIĆ et al., 2010). The second facies association includes horizontally laminated, cross-bedded and current-ripple laminated calcarenites and mudstones, which commonly show pedogenic features and have been considered to reflect deposition on floodplains.

A Type 2 Succession resembles T1S in that it consists of limestone units and CU units, and in the character of the majority of its facies types.

Features of the *basal contact* vary with the type of underlying alluvial facies (Figs. 18, 19). In the case of floodplain mudstones, their uppermost several centimetres, which show rhizocretions, nodular fabric and/or mottling and fenestrae, also include organic burrows filled with marine fossils. Clasts of these mudstones may be found above the contact, in overlying marine, fossiliferous limestone. In the case of alluvial conglomerates, there is either a less than 8cm (possibly < 0.8m) thick basal conglomerate layer with marine fossils in muddy to calcarenitic matrix (e.g. 2E, 2G, 2H in Fig. 6), or directly, marine, fossiliferous limestones which may contain granules and/or pebbles. The clasts may display borings by probable lithophagids.

The basal *limestone* unit is present all along the extent of T2S, however, its thickness varies from several cm to 2m. The uppermost limestone unit extends along the entire stretch of T2S (Fig. 16) with a thickness varying from less than 2cm (2E in Fig. 6) to 10m. At some localities, there are intermediate, thin limestone units which are difficult to correlate and might belong to one or even two limestone horizons of unknown lateral extent. Limestones are poorly bedded, commonly nodular, bioturbated foraminiferal lime packstones and wackestones, and minor mudstones (Fig. 20). Among the foraminifera, the most common include miliolids, other smaller benthic forms, *Discocyclina* and *Nummulites.* There are also *Fabiania, Operculina, Asterigerina, Orbitolites, Heterostegina,* acervulinids, and less common *Sphaerogypsina, Pellatispira, Amphistegina* and *Chapmanina*. Other constituents include corallinaceans, bivalves, gastropods, echinoids, bryozoans and corals, as well as scattered pebbles and granules in the lower part. SCHUBERT (1904, 1909) and ŠIKIĆ (1969) reported on larger foraminifera, gastropods, bivalves and echinoids from several locations corresponding to the T2S. It should be noted that QUITZOW (1941) mentioned a "transgressive breccia" which he observed in the area between localities 2H and 2I in Fig. 6. According to this author, the breccia overlies conglomerates, consists of bivalves, gastropods and corals, and is overlain by mudstones. His conglomerates correspond to the top part of the alluvium, and the "breccia" probably belongs to the basal limestones of the studied transgressive unit.

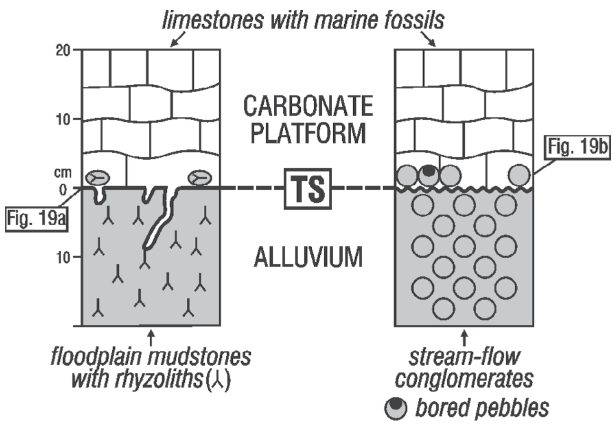


Figure 18: Along the stretch of T2S, the transgressive surface is represented by two types of contacts between the alluvial unit and overlying carbonate platform limestones of the transgressive unit. Left: floodplain mudstones with organic burrows and fractures filled with marine limestone are overlain by marine limestone including floodplain mudstone clasts at the base. Right: channel-belt, stream-flow conglomerates are first overlain by a basal conglomerate layer containing bored pebbles and foraminifera in the matrix (laterally: limestone rich in granules and/or pebbles), and subsequently, by marine limestones.

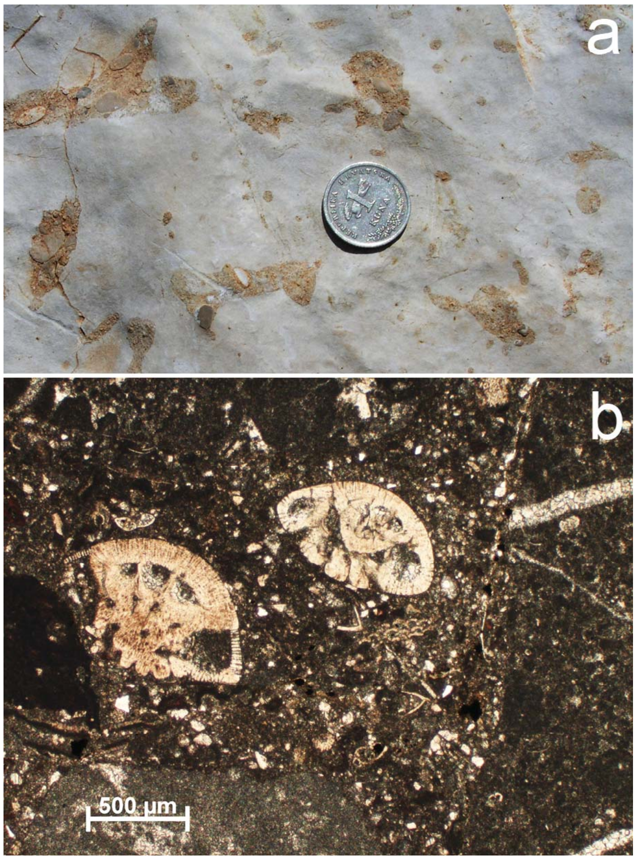


Figure 19: T2S. Two types of the contact encountered along the basal transgressive surface (TS) of T2S. **a** – The surface of the floodplain mudstone (light) is the top surface of the alluvial unit, and at the same time the major transgressive surface of the studied transgressive unit. The mudstone (seen in plan view) shows burrows infilled by marine, skeletal packstones including pebbles and granules. The surface is overlain by limestones of the transgressive unit (not shown in this figure). Coin = 1.9cm. Location in Fig. 6. **b** – Thin-section of basal conglomerate layer which contains foraminifera in the matrix. Section 2E in Figs. 6 and 16.

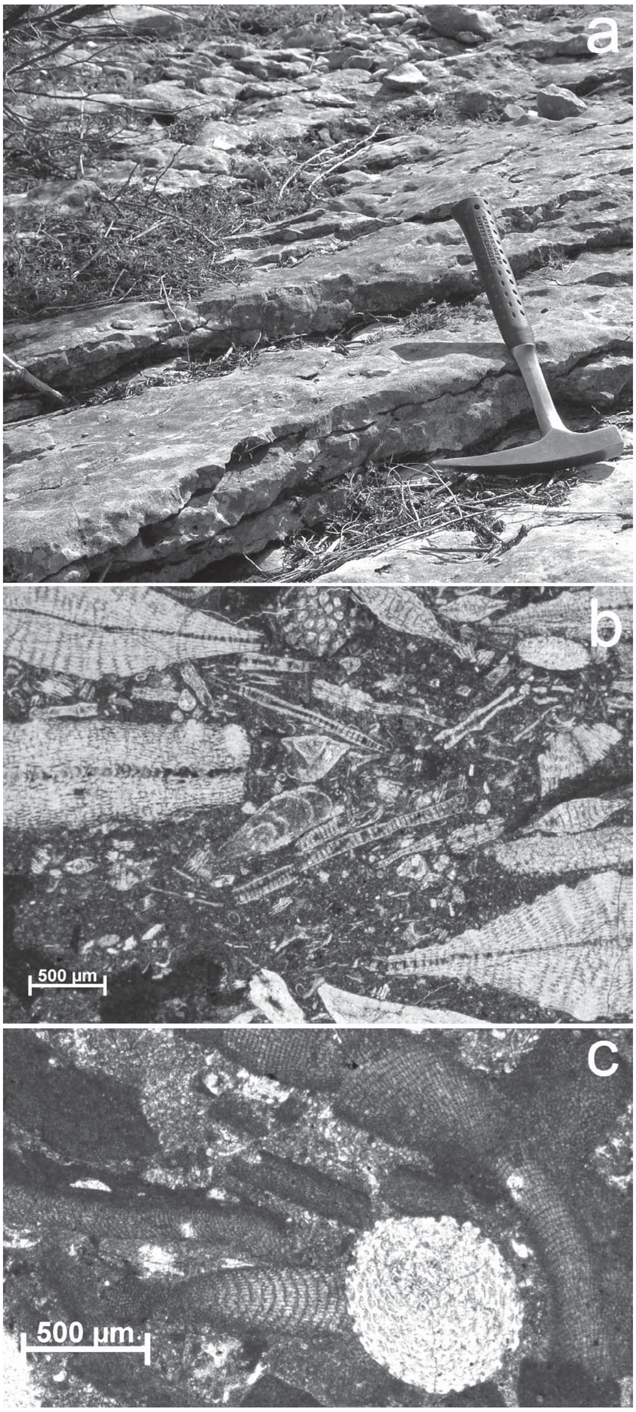


Figure 20: T2S. **a –** Thin, irregular bedding in basal fossiliferous limestone unit. Section 2E in Figs. 6 and 16. Hammer = 32cm. **b** and **c:** Thin-sections of fossiliferous limestones. Section 2I in Figs. 6 and 16. In **b:** *Discocyclina, Heterostegina, Operculina* and other fossils. In **c:** corallinaceans and *Sphaerogypsina.*

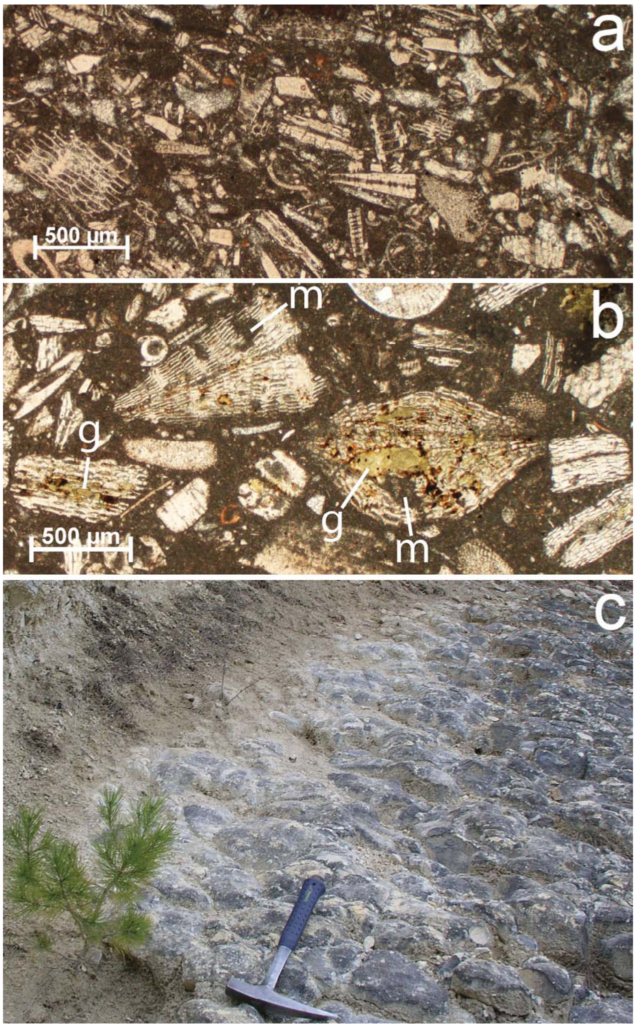


Figure 21: T2S. Condensation features. **a –** Thin-section showing fragmented skeletal remains (mainly foraminifera), inferred to have been produced by scavengers as a consequence of decreased sedimentation rates close to maximum transgression. **b –** Borings in foraminifera may contain mudstone (m) and/or glauconite (g). **a** and **b:** Section 2I in Figs. 6 and 16. **c –** Bioturbated hardground surface at the top of the transgressive unit (TST). Section 2B in Figs. 6 and 16.

As in T1S, the uppermost 0.5m thick portion of the latest limestone unit, equivalent to the top portion of the entire T2S, differs from other limestones by its content of planktonic foraminifera and glauconite, the dominance of *Discocyclina* among benthic foraminifera and the common occurrence of bored and fragmented skeletal remains (Figs. 21a, 21b). This part also includes one or two prominent, irregular bedding plains (Fig. 21c) which may display dense organic burrowing.

Coarsening-upward units are poorly exposed, and only parts of them may be recognised in several sections and isolated outcrops. Their lower part includes calcarenites with rarely recognisable parallel lamination, hummocky cross-stratification, wave ripples (?), current ripple lamination, as well as cross-beds. They may be rich in plant debris. Some calcarenites are bioturbated and contain benthic foraminifera; commonly miliolids and sometimes nummulites. This lower part of the CU units may also contain thin conglomerate intercalations which sometimes display cross-bedding and may also contain foraminifera. A unique, 40cm thick intercalation of a bivalve rudstone with sparse benthic foraminifera was observed close to Section 2G (Fig. 6).

The upper part of a CU unit (2G in Figs. 6, 16) includes a conglomerate clinoform body comparable to but slightly different from those in T1S. Its WSW part consists of beds inclined 15° to 18° towards the SW, which tangentially join their base where they interfinger with the underlying cal-

Figure 22: T2S. Landward (NE), steeply inclined conglomerates, possibly representing a fill of a channel incised in the beachface during a major storm. Gently inclined flooding surface above the conglomerate body is poorly visible. The same conglomerate body is laterally represented by seaward inclined conglomerates. For details see text. Close to Section 2G in Fig. 6 and 16. Hammer (in the middle of the photo) = 32cm.

carenites. The ENE part of the body includes tangentially based, NE inclined (12° to 20°) conglomerates, as well as those with SW and WNW directed dips (inclination up to 18°) (Fig. 22). The conglomerates are well defined, one- or a few clast-thick, well to moderately sorted and consist of pebbles and rarely granules. The uppermost part of the body consists of horizontal to sub-horizontal conglomerate beds which locally include erosionally based dm-thick sets of thin, well-sorted conglomerates. In a few other sections there are poorly exposed conglomerate intervals (e.g. 2E, 2F; Figs. 6, 16), which consist either of (a) horizontal to sub-horizontal and gently inclined, thin, well to poorly sorted, pebbly and locally granule conglomerates, locally comprising foraminifera in their matrix or (b) erosionally based, thin sets of gently inclined, thin, well sorted, pebble and minor granule conglomerate beds. Both of these conglomerate types locally include thin calcarenite intercalations.

At one location (SW of Donja Bruška village, Fig. 6), approximately in the middle of the transgressive unit there is a thin bed of lime wackestone/mudstone containing characean gyrogonites which overlie a poorly exposed conglomerate body.

The Type 2 Succession is first overlain by mudstones containing rare smaller benthic and planktonic foraminifera (Fig. 23a), rare molluscs, and common plant remains including leaves . A tree trunk or branch was also found in these mudstones (Fig. 23b). Shortly above, the mudstones are intercalated with thin calcarenites (Fig. 23c). The first intercalations in the mudstones may also be represented by thin foraminiferal packstones to wackestones (locality 2B in Figs. 6, 16).

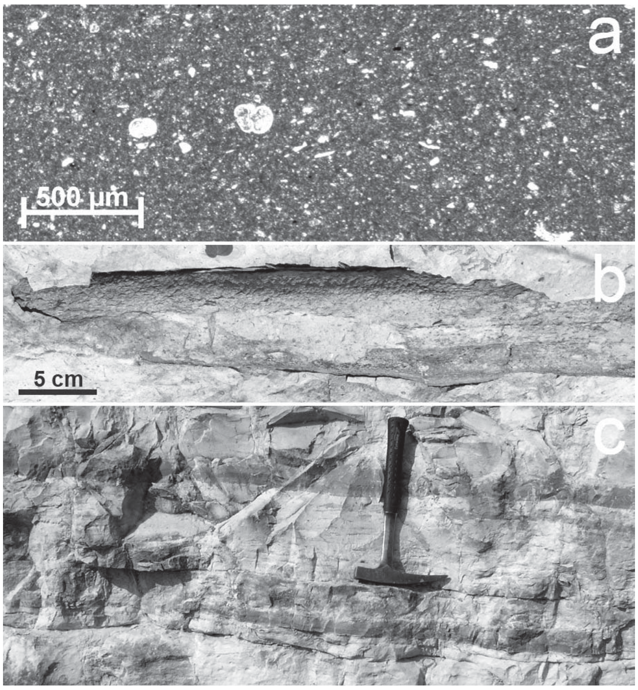


Figure 23: T2S. Lower part of the regressive succession overlying the studied transgressive unit. **a –** Mudstones with rare planktonic foraminifera occurring immediately above a major transgressive-regressive turnaround surface. Section 2G in Figs. 6 and 16. **b –** Imprint of a piece of tree trunk or branch in mudstones containing common plant material. Close to Section 2I in Figs. 6 and 16. **c –** Alternating mudstones (light) and calcarenites (grey), about 7m above the top of the studied transgressive unit. Calcarenites may change their thickness laterally over small distances and pinch out. Hammer = 32cm. Close to Section 2C in Figs. 6 and 16.

4.2.2. Interpretation

The deposition of T2S was initiated after a marine transgression of alluvial sediments. The transgression was accompanied by erosion (ravinement), and deposition of reworked clasts and marine fossils, as well as by the installation of carbonate platform settings.

Limestone units reflect similar conditions to those of T1S, based on almost identical features. Similarity between T1S and T2S also exists in the condensed sedimentation, deepening and more open conditions at the end of the youngest limestone unit, as indicated by the appearance of glauconite, planktonic foraminifera, abundant bored and fragmented skeletal remains, as well as prominent bedding planes representing hardgrounds which reflect seafloor cementation and sedimentary omission (review in FLÜGEL, 2004).

Coarsening-upward units were produced by prograding coastal systems. Their lower parts, dominated by calcarenites which locally display parallel lamination, current-ripple lamination, hummocky cross-stratification and possible wave ripples, and may contain benthic foraminifera, recorded the influence of waves and storms in the shoreface zone. Cross-bedded calcarenites as well as the intercalation of a cross-bedded conglomerate, might have resulted from the migration of bars across the shoreface which may reflect dissipative conditions during major storms (e.g. BOURGEOIS & LEITHOLD, 1984), in contrast to prevailing less energetic conditions. The unique bivalve rudstone bed within the inferred shoreface deposits may also have originated by storm processes or possibly, by tsunami waves.

Clinoform conglomerates represent prograding lower and upper beachface settings as discussed in section 4.1. Associated, onshore prograding conglomerates may have been deposited by the swell either as landward migrating bars, as swash washover in the backbeach area, or as the infill of a beach-transverse channel incised in the upper beachface during storms (or by a stream) (MASSARI & PAREA, 1988).

However, a steep gravelly beachface does not seem to have been common on the T2S coasts. Another gravelly type of coast generated (a) a succession of horizontal to sub-horizontal and gently inclined conglomerates, locally comprising foraminifera, which might represent small-scale cycles resulting from short transgressive and regressive episodes, possibly related to changing rates of sediment supply. A partly similar situation has been described by SIGGERUD et al. (2000). Still another type of coast was characterised by (b) erosionally based thin sets of sub-horizontal to gently inclined, well sorted conglomerates, directly neighbouring shoreface sands without an intermediate steep beachface. Such conglomerates typically originate in the foreshore zone (review in NEMEC & STEEL, 1984), and are otherwise identical to the upper beachface conglomerates described above from T1S. In comparison to the typical beachface characterising T1S (Figs. 7, 8) and probably occurring in Section 2G (Fig. 16), the majority of CU successions in T2S developed by coastal progradation where a steep beachface segment was absent.

Generally, there were two types of coasts which were generated during and along the stretch of T2S. While one of them was characterised by gravels forming a steep, lower beachface, and gentle, upper beachface, which are typical for T1S (Figs. 7, 8), the other, which was probably more common, was represented by foreshore gravels. The foreshore type of gravelly coasts in T2S might indicate lower storm-wave energy and/or a smaller fetch compared to the coasts with a steep beachface.

The characean-bearing limestone discovered above a conglomerate body probably represents a short-term coastal pond developed above the beachface gravel in the back-beach area, at the end of beach progradation.

The Type 2 Succession is overlain by open-shelf mudstones intercalated with tempestites which represent the basal part of the basin-wide highstand unit, generally consisting of shelf to delta and shelf to beach cycles as in T1S (BABIĆ & ZUPANIČ, 2007, BABIĆ et al., 2010; ZUPANIČ & BABIĆ, 2011).

4.3. Type 3 Succession (T3S) – Mratovo to Razvođe (Figs. 6, 24)

4.3.1. Description

This type of succession is represented by a synthetic log (Fig. 24) reconstructed mainly using rare, isolated, smaller outcrops found along the 5km long stretch (labelled “3” in Fig. 6). In fact, the lower to middle part of T3S is exposed in escarpments of abandoned bauxite pits. However, only the lowermost part of the succession, i.e. the basal contact and part of the lowermost limestone unit, were locally accessible for close observation while the rest was poorly exposed at the margins of the pits (e.g. Fig. 25a).

The Type 3 Succession is underlain by the basin basement, i.e. Middle Eocene Foraminiferal Limestones (locally, Upper Cretaceous limestones) and sporadic bauxite deposits (Fig. 24). The succession starts with limestones, either above an irregular, karstified surface, locally showing kamenica-type depressions (=solution pans; e.g. JENNINGS, 1985) and dense borings by lithophagid bivalves (Fig. 25b), or above the bauxite. In the later case, the uppermost bauxite layer may contain corals and bivalves (PAVLOVEC, 1959; SAKAČ, 1966), or there may be a few decimetres thick coaly shale lens above the bauxite.

The basal limestone unit is a prominent, fossil-rich unit, previously identified by SAKAČ (1970) in the SE part of its extent. It contains 10 to 20% non-carbonate component (PAVLOVEC, 1959), in contrast to the “cleaner” limestones of all the other limestone units. The abundance of fossils is shown by the common occurrence of skeletal rudstones (Fig. 25b), in addition to wackestones, packstones and mudstones. PAVLOVEC (1959) identified nummulites, miliolids, corals (35 species), bivalves (35 species including oysters), gastropods (32 species), echinoids, hydrozoans, scaphopods and cephalopods. *Discocyclina, Opeculina, Sphaerogypsina, Orbitolites, Chapmanina*, acervulinids and other foraminifera have also been discovered, as well as bryozoans and corallinaceans. In some bauxite pits, lime mudstones dominate the lower part of the succession and may contain common

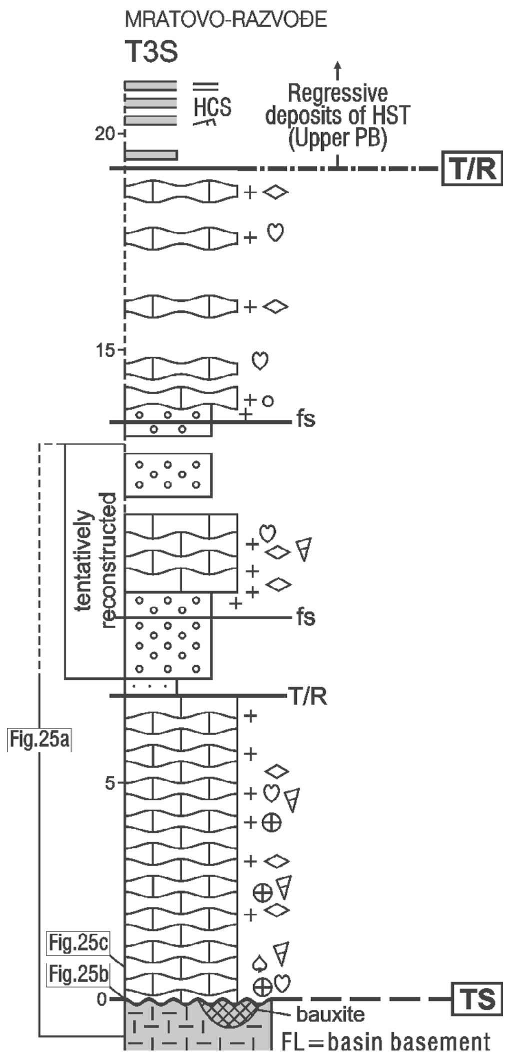


Figure 24: Log of T3S (Mratovo-Razvođe). Reconstructed using smaller, partial sections and isolated outcrops located along 5km long, discontinuous stretch of T3S (labelled “3” in Fig. 16). The basement is mostly represented by Middle Eocene Foraminiferal Limestones (FL) and locally, by Upper Cretaceous limestones. For other symbols see Fig. 16.

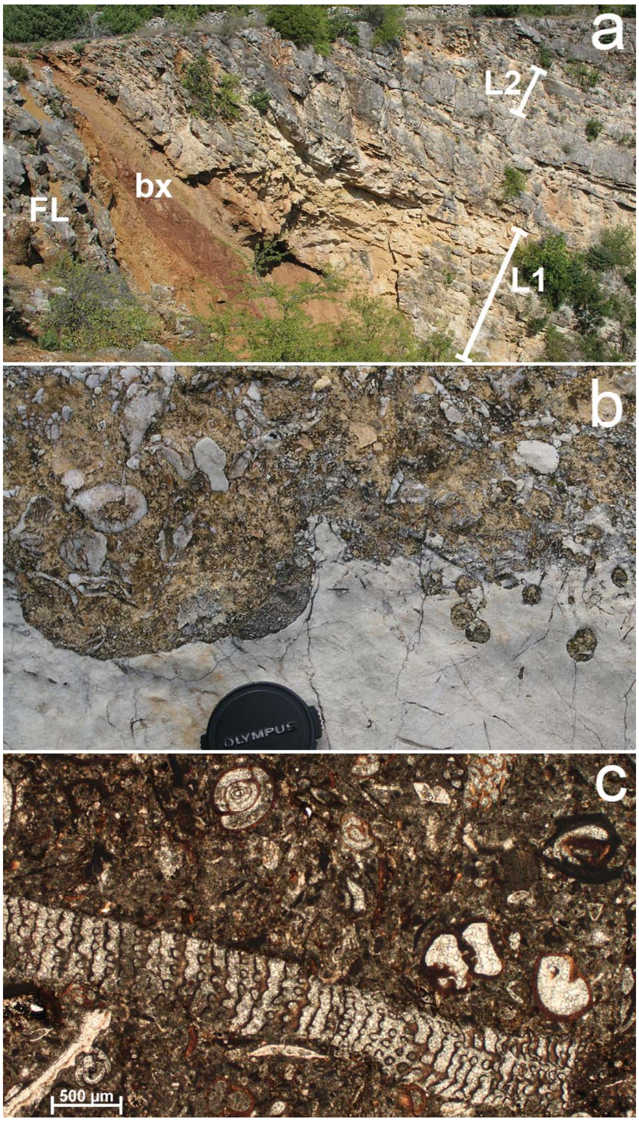


Figure 25: T3S of the Mratovo-Razvođe area, Figs. 6 and 24. **a** – Succession in Radasi bauxite pit, location in Fig. 6. Karstified Middle Eocene Foraminiferal Limestones (FL) of the basin basement is left, below bauxite (bx). The bauxite has been sheared and squeezed, and thins toward the topographic surface. It is overlain by a 3–5m thick fossiliferous limestone unit (L1, reduced in the upper left due to a thrust fault). The remaining succession is poorly known. It includes marine calcarenites and conglomerates, followed by a limestone unit (L2) and a younger unit of marine calcarenites and conglomerates. **b** – Transgressive surface separating light Cretaceous limestone, and brownish limestone, the basal part of the transgressive unit. Left, a kamenica type depression (solution pan). Right, lithophagid borings filled by transgressive, marine sediment. Transgressive limestone is a skeletal rudstone. Lens cap = 4.4cm. Bauxite pit E of Dujići village. **c** – Thin-section of limestone showing *Orbitolites,* miliolids and other foraminifera. Basal limestone unit in the Radasi bauxite pit. **b** and **c**. Location in Fig. 6.

carbonised plant remains. A bauxite pit shows two 40cm thick, erosionally based, normally graded, and inverse to normally graded layers of mixed gravel and skeletal debris, which alternate with mudstones and occur above basal limestones. They might belong to the middle part of the succession which is poorly known and might be laterally variable. An isolated outcrop of the middle part of the succession includes a limestone unit transgressively overlying probable shoreline conglomerates.

The uppermost limestone unit appears to be laterally persistent. As in T1S and T2S, it overlies conglomerates, starts with a foraminifera-bearing conglomeratic basal layer, and includes packstones, wackestones and mudstones with miliolids, larger foraminifera (e.g. *Discocyclina*), bivalves and gastropods. Close to its top, it contains abundant skeletal fragments and possible glauconite.

The Type 3 Succession is overlain either by mudstones or alternating mudstones and calcarenites comparable to those characterising T1S and T2S.

4.3.2. Interpretation

The transgression covered the karstified basement, as well as bauxite deposits as indicated by features observed along the contact. The creation of local marshes above the bauxite, (precursors of coaly deposits), was caused by rising groundwater which may have been related to marine flooding in areas located further seawards (sections 4.4. and 4.5.). The lowermost limestone unit reflects the installation of very shallow carbonate settings characterised by abundant and diverse biota (PAVLOVEC, 1959), in the close vicinity of land areas which is indicated by the increased clay content compared to other limestone units. This might result from locally restricted circulation in more isolated bays as suggested by frequent carbonised plant remains. Normally graded, and inverse to normally graded, fossiliferous conglomerates from the middle part of T3S, are event beds which could have originated by mixing of eroded shoreline gravel and shallow-marine skeletal material, and dumping into the quiet neighbouring environment. This could have been related to a strong storm or a tsunami. The middle part of the succession is poorly understood and is only tentatively reconstructed in Fig. 24.

The uppermost limestone unit evolved mainly in the same manner as those in T1S and T2S described above. This includes a carbonate platform setting and a decrease in sedimentation rates towards the top. The overlying shelf deposits are also similar to those from previously described successions.

4.4. Type 4 Succession (T4S) – Krstančuša (Figs. 6, 26)

Bauxite deposits overlying Middle Eocene Foraminiferal Limestones are in turn, overlain by a 0.1 to 2.3m thick lignite coal (NIKLER, 1982). Excavated rock debris around abandoned coal pits comprises fragments of coal, coaly shale, as well as laminated limestones with bivalves, which might represent lacustrine stromatolites overlying the coaly unit. Closely associated marine mudstones appear to overly the sediments of the pits.

Coaly sediments were deposited in marshes, which originated due to the rise of the water table related to a relative sea-level rise. Lacustrine limestones and marine mudstones which presumably represent subsequent sedimentation, might reflect a continuation of the groundwater and relative sea-level rise. Hence, the tentatively reconstructed succes-

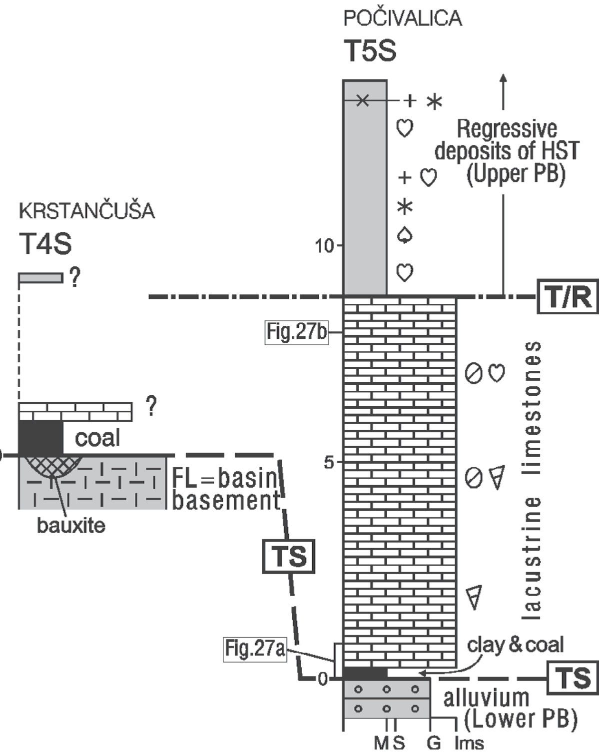


Figure 26: Logs of T4S (Krstančuša) and T5S (Počivalica). Note that limestones in the transgressive unit are lacustrine in character. T5S is mainly after ZUPANIČ & BABIĆ (2011). For details see text. FL, Middle Eocene Foraminiferal Limestones of the basin basement. For other symbols see Fig. 16. Location in Fig. 6.

sion and the character of correlatable successions suggest that the freshwater sediments represent a terrestrial variant of the marine transgressive unit (SHANLEY & McCABE, 1994), following the sequence-stratigraphic approach (Fig. 26-left; see also section 4.5. and discussion in section 5.), while the overlying mudstones belong to a regressive sedimentation.

4.5. Type 5 Succession (T5S) – Počivalica (Figs. 6, 26)

4.5.1. Description

The Type 5 Succession is underlain by an alluvial unit consisting of two main facies associations similar to those below the T2S. The first one consists of laterally extensive sheet-like bodies of massive, horizontally bedded to gently inclined, and locally cross-bedded conglomerates, which include intercalations and lenses of laminated calcarenites, and represent deposits of braided streams (BABIĆ & ZUPANIČ, 2007; BABIĆ et al., 2010; ZUPANIČ & BABIĆ, 2011). The second facies association includes plane laminated, cross-bedded and current-ripple laminated calcarenites and mudstones which commonly show pedogenic alteration, and reflect deposition on floodplains (*op. cit.*).

The basal contact surface T5S is locally irregular and separates underlying alluvial conglomerates from a clay < 30cm thick, containing coal laminae, which is followed by limestones (Figs. 26, 27). Eastwards, outside the study area, this basal clay is overlain by a lignite horizon (up to several metres thick), which represents the main coal bed formerly mined in Mt. Promina (MARKOVIĆ, 2002). It is overlain by alternating clastics, limestones and coaly sediments, all of which are considered to represent the transgressive systems tract (ZUPANIČ & BABIĆ, 2011). During early coal mining, remains of a hog and a crocodile were found in these sediments (KERNER, 1901). W of Section 5 (Fig. 6), laminated limestones may directly overlie alluvial conglomerates. The limestones of T5S are commonly laminated and contain ostracods, gastropods and bivalves. Cyanobacterial filaments, characean gyrogonites (Fig. 27b) and incrustations of characean stems, as well as plant leaves have also been observed. Other limestones are mudstones, wackestones and rare packstones with ostracods and/or molluscs. The T5S limestones may be intensely bioturbated.

Limestones are overlain by mudstones which display rare, smaller benthic and planktonic foraminifera and bivalves. Plant remains, including leaves, are common. A few metres upwards, the mudstones become intercalated with laminae and thin beds of calcisiltites and calcarenites. They are sharply based and may be parallel or cross-laminated. The first intercalations in mudstones may laterally be represented by sharply based, bioturbated lime packstones dominated by benthic foraminifera.

4.5.2. Interpretation

The clay and lignite represent marsh deposits of forested areas (*cf*. TUCKER, 2001). Such environments were the habitats of hogs and crocodiles reported by KERNER (1901).

The features observed in the limestones reflect deposition in a lake, the bottom of which was largely covered by cyanobacterial mats, and partly vegetated by characeans and aquatic macrophytes. Ostracods, bivalves and grazing gastropods also inhabited the lakes. The overall conditions correspond to a shallow, hard-water lake (review in TUCKER

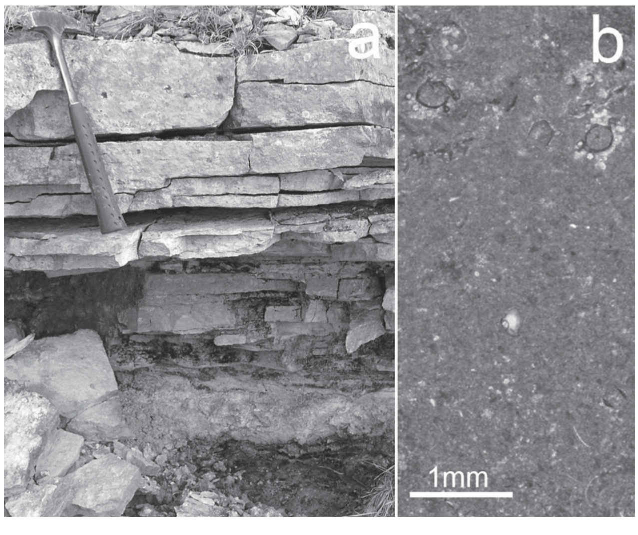


Figure 27: T5S, lower part of Section 5 (Fig. 26). Location in Fig. 6. **a** – The clay and coal in the lower part (dark) are overlain by thin bedded, laminated lacustrine limestones. Hammer = 32cm. **b** – Thin-section of the lacustrine limestone showing characean gyrogonites.

& WRIGHT, 1990). The onset of T5S was related to a rise in groundwater level which in turn was induced by a relative sea-level rise further basinwards (BABIĆ & ZUPANIČ, 2007; ZUPANIČ & BABIĆ, 2011).

The Type 5 Succession is overlain by mudstones, the features of which indicate a change in environmental conditions, from a carbonate lake to open marine setting. The mudstones and subsequent alternation of mudstones, calcisiltites and calcarenites, as well as foraminiferal tempestites, represent shelf deposits, i.e. the basal part of cyclic shelf to delta, and shelf to beach deposition of the highstand (BABIĆ & ZUPANIČ, 2007; BABIĆ et al., 2010).

4.6. Type 6 Succession (T6S) – Bibići (Figs. 6, 28)

T6S is underlain by alluvial sediments similar to those previously described from correlative sections located to the east (ZUPANIČ & BABIĆ, 2011). This alluvium ends with a thick conglomerate bed. The upper surface of this conglomerate exhibits bivalve borings filled with lime packstone (Fig. 29) containing miliolids, other smaller benthic foraminifera, echinoids, molluscs and rare limestone clasts. The conglomerate surface is overlain by 25cm (up to 50cm?) of lime packstones containing miliolids and other smaller benthic foraminifera, bivalves, gastropods, echinoids, bryozoans, as well as rare corallinaceans and planktonic foraminifera. After a gap in exposure, the succession continues with massive to crudely bedded mudstones with occasional gastropods and bivalves.

The transgression therefore started with the organic boring of a lithified alluvial substrate and an infilling of the voids, and continued by the installation of a shallow-marine carbonate environment which quickly deepened, as suggested by the occurrence of planktonic foraminifera close to the basal contact. The mudstones which follow indicate an offshore shelf setting at the beginning of the regression.

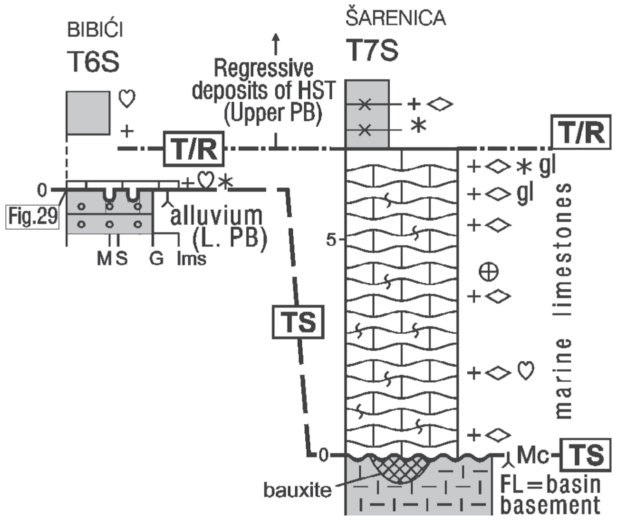


Figure 28: Logs of T6S (Bibići) and T7S (Šarenica). FL, Middle Eocene Foraminiferal Limestones of the basin basement. For other symbols see Fig. 16. For details see text. Location in Fig. 6.

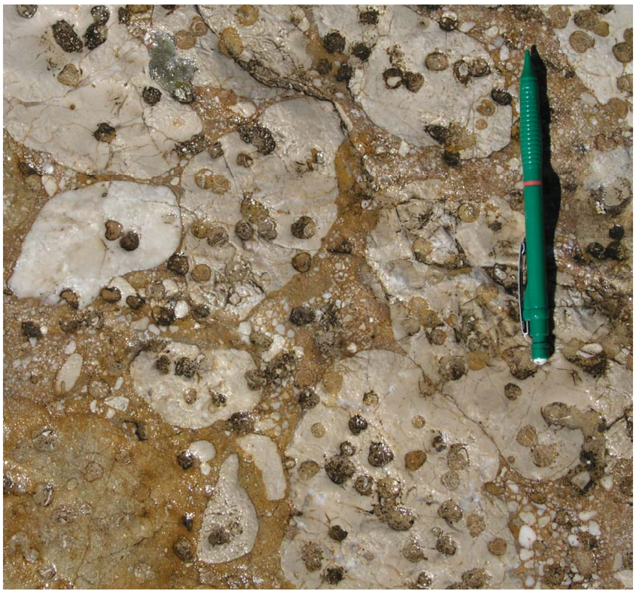


Figure 29: T6S (Bibići). Transgressive surface (seen in plan view) is represented by the upper surface of an alluvial conglomerate which displays lithophagid borings filled by lime packstones containing foraminifera, echinoids, molluscs and rare lithoclasts. The surface is laterally (out of the photo) overlain by marine limestones. See also log in Fig. 28. Location in Fig. 6.

4.7. Type 7 Succession (T7S) – Šarenica (Figs. 6, 28)

The Type 7 Succession is represented by a single, fossiliferous limestone unit which overlies Middle Eocene Foraminiferal Limestones of the basin basement and has already been identified and mapped by SAKAČ (1970). At the contact between the two units there are calcrete, *Microcodium* and limestone breccias, while the basal part of the fossiliferous limestones contains scattered bauxite particles. The limestones are nodular, bioturbated wackestones, packstones and mudstones (Fig. 30) containing smaller benthic foraminifera, *Nummulites, Discocyclina* (common), *Operculina,* corals, echinoids, bivalves, gastropods, bryozoans and corallinaceans. The upper part of the unit includes planktonic foraminifera and glauconite (ZUPANIČ & BABIĆ, 2011), as well as common skeletal debris. The limestones are overlain

Figure 30: T7S. Irregularly bedded (rippled?), bioturbated, marine limestones. Close to Section 7 (Šarenica) in Fig. 6. Hammer = 32cm.

by mudstones with occasional bivalves and planktonic foraminifera which are intercalated by thin, skeletal packstones rich in benthic foraminifera.

The limestones therefore start transgressively and unconformably above karstified carbonates of the basin basement. They reflect deposition on a carbonate platform which ended with condensed sedimentation in a relatively deeper platform setting. The deposition of T7S was followed by shelf muds with foraminiferal tempestites indicating a major change in depositional trend, representing the onset of the regressive trend (ZUPANIČ & BABIĆ, 2011).

5. DISCUSSION

5.1. Onset of transgression: variability of the major transgressive surface

The character of the studied unit, observed and compared across the basin, suggests that the sediments bounded by two major discontinuity surfaces are products of one and the same transgressive event. Instead, the onset of transgression was related to different situations encountered along the extent of the basal bounding surface that is summarised in Fig. 31 . The first case is represented by marine flooding over the alluvium, which includes transgressive erosion (ravinement), (T2S and T6S, Fig. 31). The resultant bounding surface is more specifically a transgressive surface of erosion, following sequence-stratigraphic terminology (review in CATUNEANU, 2006). Lacustrine flooding over the alluvium (T5S) forms part of the second case. This surface type may be generally termed the transgressive surface having in mind a basin-wide stratigraphic context (Fig. 31). However, it is also a maximum regressive surface (term after HELLAND-HANSEN & MARTINSEN, 1996), if the term is restricted here to imply the non-erosive character of the surface, i.e. the preservation of the underlying, uppermost regressive (alluvial) deposits. The third variation of the major bounding surface which has been encountered along its extent, is marked by flooding (marine and lacustrine) of Middle Eocene and Cretaceous basement rocks (T3S, T4S, T7S; Fig. 31). This relationship is related to a large stratigraphic hiatus which separates genetically unrelated strata, thus representing an important subaerial unconformity. Such features are usually taken to characterise sequence boundaries, and our examples may also be designated as a sequence boundary/transgressive surface (POSAMENTIER & ALLEN, 1993). This type of bounding surface resulted from a transgressive onlap over subaerially exposed parts of the basin basement (Figs. 31, 32). This contrasts with other boundary types located along the same bounding surface at short distances, and indicates tectonic uplift areas generated by previous intrabasinal folding and faulting. Such processes have previously been described from Mt. Promina and other parts of the basin where several periods of deformation occurred (ZUPANIČ & BABIĆ, 2011).

The differences along the basal discontinuity surface make it comparable to a 2nd or 3rd order sequence boundary of EMBRY (1995), which has been described as being represented by a conformable boundary in the undeformed part of the basin, and a subaerial unconformity at the deformed

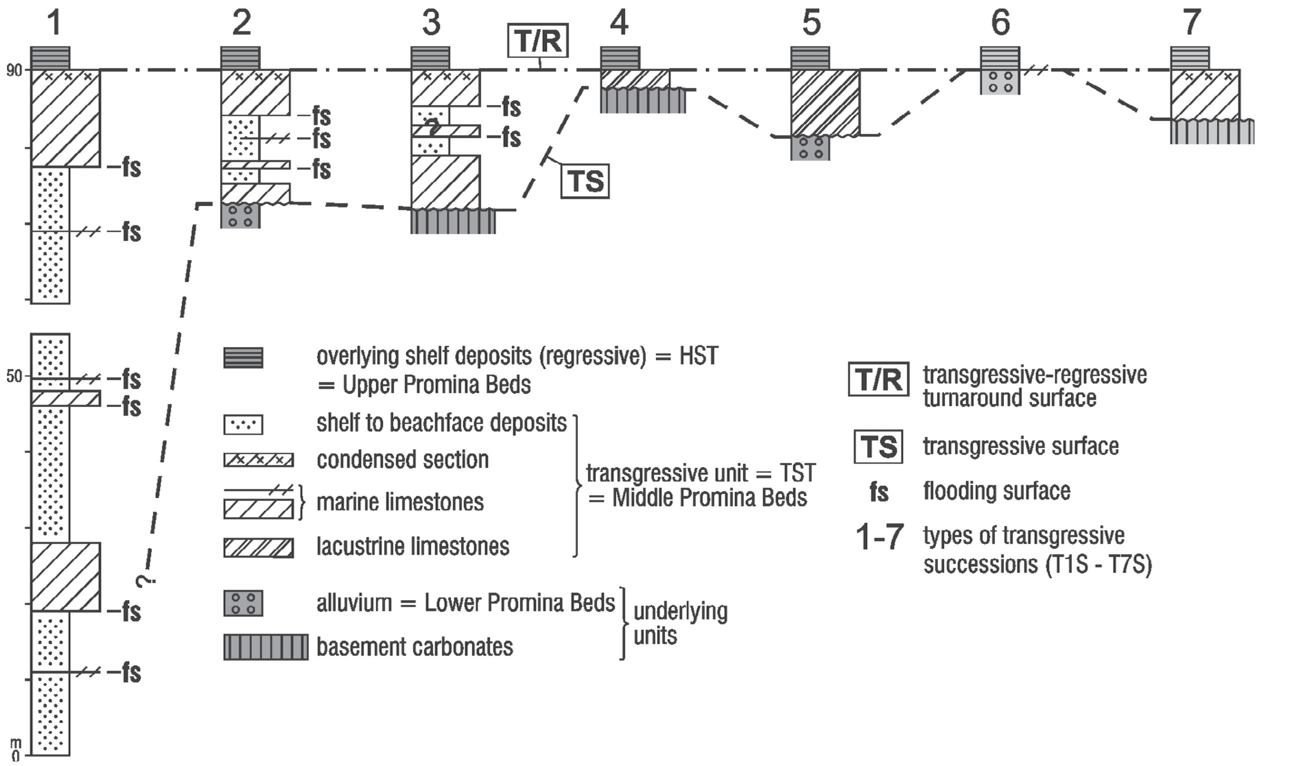


Figure 31: Comparison of all seven succession types (T1S to T7S) of the studied transgressive unit. Datum is the major transgressive-regressive turnaround surface. The correlation is allostratigraphic in character. Logs are simplified from those in Figs. 7, 16, 24, 26 and 28. Log 2 is a compilation of ten logs (2A to 2J in Fig. 16). Log 4 is a tentative reconstruction of T4S. For discussion see text.

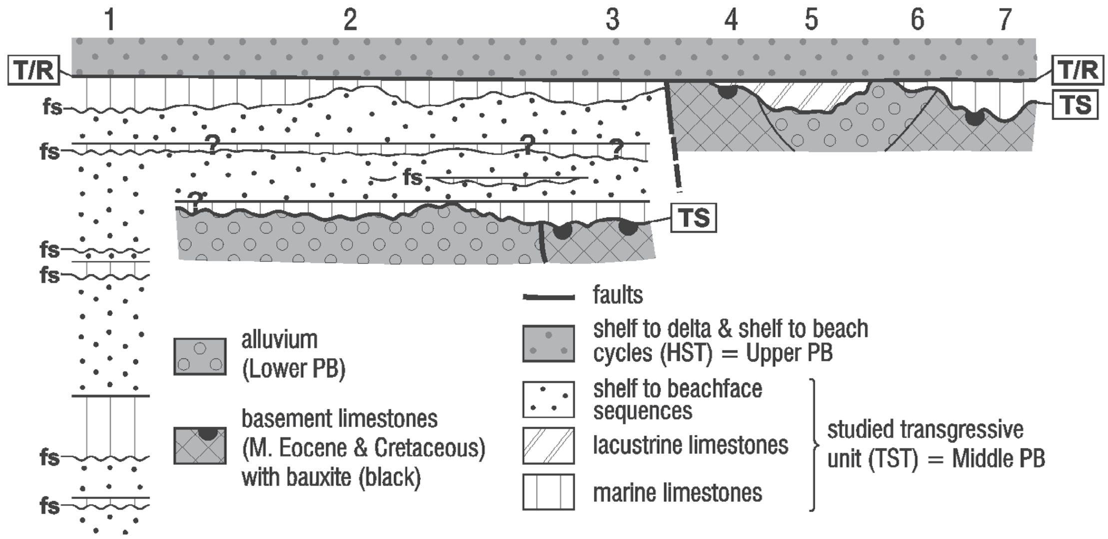


Figure 32: Tentative, highly simplified section including all succession types (1–7) of the studied transgressive unit. Datum is the major transgressive-regressive turnaround surface. Types 1 and 2 are strike parallel over the major part of the basin (Figs. 5, 6). Types 3 to 7 are situated in more complex tectonic structures and their original distribution is only partly known. Note lateral difference in the character of the rocks which were transgressed (below TS), which contrasts laterally uniform character of the overlying deposits (above T/R surface). The correlation shown for the middle part of the unit in succession types 2 and 3 is poorly documented. The character of two inferred faults is not implied. TS, T/R and fs are transgressive surface, transgressive/regressive turnaround and flooding surface, respectively. For discussion see text. Not to scale.

basin margin. At the same time, our transgressive unit may represent the transgressive segment of EMBRY's (1995, 2002) transgressive-regressive sequence of 2nd or 3rd order. This sequence-stratigraphic classification and terminology, as well as related views, may be used for Promina units as alternatives to that discussed above and should be considered in further studies in this foreland basin.

5.2. End of transgression: maximum flooding and major transgressive-regressive turnaround

The condensed horizon indicating a lowering of sedimentation rates and more open, deeper marine settings toward the end of transgression, reflects a relative sea-level rise which outpaced carbonate production. Namely, carbonate production generally decreases with increasing depth, other parameters being about equal (TUCKER & WRIGHT, 1990). The condensed horizon corresponds to the "condensed section" of the sequence stratigraphic approach, which originated when the shoreline was at its farthest landward position (e.g. LOUTIT et al., 1988; POSAMENTIER & ALLEN, 1999). The studied examples show that the condensation processes started close to the major turnaround from transgressive to regressive trends, and coincident maximum flooding. Shelf to delta and shelf to beach cycles which follow this surface have been proposed as corresponding to the highstand systems tract (BABIĆ & ZUPANIČ, 2007; ZUPANIČ & BABIĆ, 2011). The relevant turnaround surface is inferred to continue laterally into the surface separating lacustrine limestones and the overlying, cyclic, marine deposits of the same regressive succession mentioned above (Fig. 31). The upward transition from lacustrine to marine settings, might have been brought about by the ingress of marine waters into depressions hitherto occupied by lakes. In this case, maximum flooding could have been located slightly above the major transgressive-regressive turnaround surface, within overlying regressive mudstones. The possibility that dark mudstones revealed at the base of regressive deposits in E Mt. Promina, (out of the study area) reflect a restricted circulation at the very beginning of the regression, as speculated previously (ZUPANIČ & BABIĆ, 2011), awaits further investigation.

5.3. Importance of the studied transgressive unit and its bounding surfaces for basin stratigraphy

As described and discussed in previous sections and summarised in section 5.1., and Figs. 31 and 32, the lower bounding surface of the studied unit, acquired different characteristics along its extent, including the characteristics and ages of the underlying units. This variability, as well as common gaps in exposure, may complicate its identification at some locations and tracking, especially in the tectonically more complex areas SE of the Krka River. In contrast, the upper bounding surface of the transgressive unit, i.e. the major surface of the transgressive-regressive turnaround, can be more easily identified by its own features and its position within vertical successions. This is consistent with general experience that this type of key sequence-stratigraphic surface is easier to identify than other types (GALLOWAY, 1989; review in CATUNEANU, 2006). This is also the reason why this type of stratigraphic surface was proposed by GALLOWAY (1989) to be marked as a sequence boundary, i.e. the main bounding surface used for subdivision and correlation of sedimentary successions.

The studied transgressive unit and its bounding surfaces are the only stratigraphic elements described until now which extend across the entire North Dalmatian foreland basin (Figs. 5, 6). Hence, their features may be useful in further studies of basin stratigraphy and evolution.

Out of the study area and much lower within the basin succession (Lower Promina Beds), there are surfaces envisaged to represent sequence boundaries (BABIĆ & ZUPANIČ, 2007; MRINJEK, 2008; BABIĆ et al., 2010) which might be important for an extensive stratigraphic correlation in the lower part of the basin fill. However, their number and lateral extent remain to be studied and their importance evaluated.

5.4. Basic building units: high-frequency transgressive-regressive cycles

Within the major part of the basin, (from Novigrad to Razvođe; T1S, T2S, T3S; Figs. 6, 7, 16, 24) the studied transgressive unit consists of lower-rank (high-frequency) stratigraphic units, which ideally includes a transgressive, limestone segment, and a regressive, CU segment (section 4.1., Fig. 8). These units are called cycles here which is a more general term compared to parasequence. In fact, similarities of the cycles described here with the units commonly treated as parasequences do exist, as both of them are stacked, build the units of systems tracts, and are bounded by flooding surfaces. However, the use of the term parasequence is recommended for flooding-surface-bound, shoaling-upward successions, principally originating in shallow, near-shore environments, which commonly start with a transgressive lag and are separated by a thin limestone, phosphate or glauconitic deposit (POSAMENTIER & ALLEN, 1999; CATUNEANU, 2006). In contrast, the cycles described here may include relatively thick transgressive segments (limestones), the thickness of which may even surpass the thickness of the overlying regressive (= shoaling-upward) segment. Consequently, the term parasequence is not regarded as appropriate for the current examples.

Alternatively, the cycles described here are comparable to the 3rd or higher order transgressive-regressive (T-R) sequences of EMBRY (1995, 2002) which are only traceable along part of the basin. As previously mentioned above, this classification and related views on the stratigraphy should be considered in future work in the N Dalmatian foreland basin.

5.5. The studied transgressive unit as formal stratigraphic unit: definition of the Novigrad Alloformation

Correlation of the studied sedimentary successions is summarised in Fig. 31, which shows the characteristics of the studied transgressive unit as a whole. It is proposed that the unit be defined as a formal allostratigraphic unit of alloformation rank, in accordance with the requirements of NACSN (1983). The unit is shown to be mappable, and is described by its bounding discontinuities, extent, relative stratigraphic position, lithologic features, as well as its lateral and vertical variability. Along its extent, it may be represented by alternating transgressive limestones and a regressive clastics (T1S, T2S, T3S; Figs. 7 to 25), lacustrine deposits, mainly limestones (T4S, T5S; Fig. 26), and by a single marine limestone unit (T6S, T7S; Figs. 27 to 30). Genetic interpretations are not required, however they can help in choosing boundaries and matching sediments along the extent of the unit (NACSN, 1983), as was the case here. The thickest and best exposed section at Novigrad (T1S, Figs. 7 to 15) is proposed for the type section and the name of this town as the geographic part of the unit name, hence the Novigrad Alloformation. Its variability required definition of reference sections in order to demonstrate the totality of the stratigraphic unit (NACSN, 1983), as well as to compensate for the incompleteness of available sections. For this purpose, sections 2D, 3 (Radasi), 5 and 7 (Figs. 16, 24, 25a, 26, 28) are chosen, as they document the character and variability of the basal bounding discontinuity. Two of these sections (5, 7) also display the lithological variability of the unit as it is represented by lacustrine deposits and a single limestone unit, respectively, in contrast to other, lithologically heterogeneous sections including the type section. Section 2G (Figs. 16, 17) is also selected as a reference section as it includes the best exposure of the upper bounding surface of the unit.

Two stratigraphic units previously described from Mt. Promina represent parts of the newly proposed Novigrad Alloformation: "Middle lacustrine unit" and "Fossiliferous limestones" (ZUPANIČ & BABIĆ, 2011). The first one is represented by Section 5 (Fig. 26), and the second one is identical to the limestones of Section 7 (Fig. 28). Each of the previously described units has been given two formal names of both the lithostratigraphic and allostratigraphic categories (e.g. Počivalica Formation and Počivalica Alloformation), however, it was not mentioned which of the two is chosen. Hence, these formal names cannot be valid.

5.6. Possible driving mechanisms for generating the stratigraphy of the studied sediments

The basin-wide extent of both the transgression at the base of the studied transgressive unit and transgressive-regressive turnaround at the end of the unit, suggest allogenic control on related processes.

The transgression might have been mainly caused by backtilting of an inner part of the foreland basin (in front of Dinaric nappes) related to a tectonic pulse (ZUPANIČ & BABIĆ, 2011). This would have caused an increase in subsidence rates in the study area and a landward shift of detrital sedimentation related to thrust-load emplacement, as proposed in models by HELLER et al. (1988) and BURNS et al. (1997). According to the model by HELLER et al. (1988), the transgressive-regressive turnaround could have been induced during the "postorogenic phase of adjustment", when clastics eroded from the orogen deformed by the previous tectonic pulse, reached relevant part of the basin.

Alternatively, the transgression might have resulted from a eustatic rise, which accelerated relative sea-level rise in the proximal part of the foreland basin characterised by increased subsidence rates compared to its distal part, (POSAMENTIER & ALLEN, 1993) or by eustatic sea level rise alone. The onset of clastic deposition, i.e. the transgressive-regressive turnaround, might have been predominantly influenced by a decrease in eustatic sea-level rise which enables clastics to prograde. Precise dating of sedimentary successions, (currently unavailable) might be relevant in answering these questions.

The origin of basic, transgressive-regressive cycles is poorly understood due to difficulties in correlation along their lateral extent. Lateral differences, locally identified over rather short distances, suggest that important parts of successions have been generated under the influence of local conditions, such as the lateral variation in sediment supply and lateral shifting in local depocentres, as well as localised tectonic processes. These processes may have been combined with an overall, relative sea-level rise due to allogenic processes. As to T1S, which is considerably thicker compared to neighbouring T2S and T3S, the difference could have resulted from a higher rate of synsedimentary subsidence of this part of the basin. This could have been related to the position of this area in the NW part of the basin, where there was a better connection with the open sea (section 2; Fig. 2).

5.7. Aspects of time correlation

It is known that not only the transgressive surface but also the maximum flooding surface may be diachronous, both perpendicular and parallel to the shoreline (reviews in POSAMENTIER & ALLEN, 1999; CATUNEANU, 2006). A small scale illustration of the process is provided by the input of lithoclasts to the carbonate depositional area identified about 1m above the base of the limestone, i.e. above the basal transgressive surface (section 4.2.). This feature shows a coeval advance of flooding over the underlying alluvium, and related diachroneity along the relevant stratigraphic surface. The onset of T6S and T7S, consisting of a single marine limestone unit (Fig. 28), might represent later flooding of the area in the close vicinity of the larger tectonic structures, i.e. a later marine onlap onto the basement rocks of the inner basin margin, where the same surface becomes not only a transgressive surface but also assumes the character of a surface which would commonly be designated as the sequence boundary. It is possible that the marine transgression related to the deposition of these limestones is coeval or partly coeval with the condensation basinwards. The origin of the lakes, presumably related to rising groundwater levels, was in turn related to a relative sea-level rise elsewhere, (the situation reviewed by SHANLEY & McCABE, 1994), and lacustrine deposition may be regarded as being coeval with the lower part of the marine deposition basinwards (out of the study area). This does not exclude the possible connection of the lakes to fluvial systems which were located landwards (out of the study area).

The end of the transgression, identical to the transgressive-regressive turnaround, may or may not be quasi synchronous throughout the study area. Instead, it might have been slightly older landwards (primarily T6S and T7S) in comparison to the situation basinwards.

5.8. Stratigraphic and genetic interpretations and related field relationships

In the NW part of the basin (between Pridraga and Rodaljice, Fig. 6a), the studied unit extends across two stratigraphic units of MRINJEK & PENCINGER (2008). (1) SW of the Karin Sea, their map and log (their Figs. 4 and 5) include an approximately 75m thick unit of off-shore mudstones with thin calcarenites, proposed to represent a transgressive-regressive unit (their Karišnica Unit). Our observations in this area indicate that the lower part of their unit includes a rather thick alluvial unit, dominantly conglomerates, which are followed by the transgressive unit described here, while the upper part of their unit is represented by cycles consisting of shelf to conglomeratic shoreline deposits (BABIĆ & ZUPANIČ, 2007; BABIĆ et al., 2010; this work; Fig. 6a). (2) The second unit of MRINJEK & PENCINGER (2008) is > 450m of regressive deposits interpreted to consist of lower shoreface to mouth-bar sequences (their Žedna Greda Unit). Based on our data, a considerable part of the relevant area is occupied by alluvial deposits. They are overlain by the transgressive unit described here which stretches obliquely across the middle part of the supposed regressive unit (between Karin Donji and Rodaljice, Fig. 6a).

In the central part of the basin, (between Nunić and Mudrinići, Fig. 6b), MRINJEK (2008, his Figs. 6 and 7), envisaged a belt consisting of an approximately 140m thick, transgressive to regressive unit of shelf deposits (his Kistanje Unit), believed to be underlain and overlain by both deltaic and fluvial facies. Based on our observations, the succession in this area consists of an alluvial unit at the base, a transgressive unit, and shelf to shoreline cycles (BABIĆ & ZUPANIČ, 2007; BABIĆ et al., 2010; this work; Fig. 6b).

6. SUMMARY AND CONCLUSION

The sedimentary fill of the Palaeogene North Dalmatian foreland basin includes a prominent transgressive unit, which stretches for more than 63 km along the basin and represents the Middle Promina Beds. It is bounded by major, objectively delineated discontinuity surfaces: the lower, transgressive surface, and upper, transgressive-regressive turnaround surface. Hence, the studied unit is allostratigraphic in character and is formally named the Novigrad Alloformation. It overlies both the braided alluvium of the Lower Promina Beds and karstified Middle Eocene and Cretaceous carbonates of the basin basement. The unit exhibits a lateral variability and may be represented either by stacked, high-frequency, transgressive-regressive cycles, by lacustrine deposits, or a single marine limestone unit. An ideal transgressive-regressive cycle includes a transgressive segment of shallow-marine limestones, and a regressive segment of storm-wave dominated, shelf to gravelly beachface (CU) deposits. Gravelly beaches have been represented by several types. One of them included the steeply inclined, lower beachface which is situated below the intertidal zone. The cycles are separated by lower-rank discontinuity surfaces (flooding surfaces), while two segments are separated by a lower-rank transgressive-regressive turnaround surface. Lacustrine deposits originated due to a rise in groundwater which was induced by a sea-level rise occurring basinwards. The single limestone unit exhibits a transgressive onlap over tectonically uplifted, exposed basin basement.

Maximum transgression is indicated by a condensed horizon overlain by a major transgressive-regressive turnaround surface. The evolution following the transgressive unit is almost uniform along its extent, and includes shelf to delta and shelf to shoreline cycles of the Upper Promina Beds (highstand). The identification of the studied allostratigraphic unit may be useful in further studies of the basin stratigraphy and evolution.

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APPENDIX

The Palaeogene versus Neogene age controversy

The work on facies analysis related to this study must have included identification of the main fossil groups. Among them, larger foraminifera reported from the majority of limestone units, have been identified at a generic level. They may be used to briefly comment on considerable differences in the hitherto proposed age interpretations of N Dalmatian foreland basin sediments. Namely, in contrast to the Eocene age for the largest part of the North Dalmatian foreland basin sediments, and possible Oligocene age for their uppermost part, suggested by several authors (SCHUBERT, 1905; MAMUŽIĆ, 1975, IVANOVIĆ et al., 1976, 1978, with references), MIKES et al. (2008) proposed a Miocene age for the lower part of the basin fill (traditionally called flysch, Fig. 5) based on nannoplankton. The unit described here occurs within the middle part of the overall basin succession, and foraminiferal associations found in shallow-marine limestones of this unit (section 4) indicate an Eocene age, apart from the presented generic level of taxonomic determinations (BOUDAGHER-FADEL, 2008). It follows that the entire succession of this basin situated below the studied unit, and including sediments analysed by MIKES et al. (2008), is Eocene in age, as suggested by previous authors. Consequently, reconstructions of the tectonic evolution of North Dalmatia cannot be based on a Miocene age of these sediments as suggested by MIKES et al. (2008).

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