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Sharply-Topped Alluvial Gravel Sheets in the Palaeogene Promina Basin (Dinarides, Croatia)

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Key words: Alluvial architecture, Gravel sheets, Fluvial belts, Promina Basin, Dinarides, Croatia.

Abstract

The upper part of the Promina Beds at their western extent is represented by two alluvial units: the Kunovac Beds and the Upper Alluvial Unit. The Kunovac Beds contain a high proportion of fine-grained sediments, and generally lacks debris flow deposits. The principal architectural components of the Kunovac Beds are (1) complex (multilateral, multi-storey) gravel-dominated sheets, which originated by the advance of mobile-channel belts, and were terminated by sudden abandonment, (2) smaller heterogeneous gravelly-sandy sheets, which originated in fluvial belts from a combination of sheet flows and channelized flows, (3) small isolated ribbons reflecting the filling of small channels, and (4) floodplain mudstones and sandstones.

The basic style by which the Kunovac Beds, as well as the most part of the Promina alluvium were built up are the repeated advances and abandonments of the alluvial belts, and related stacking of coarse-grained sheets and floodplain deposits. The most important factors responsible for the dominance of this sheet-like geometry are high sediment supply and high aggradation and subsidence rates.

Deposition of the Kunovac Beds occurred on alluvial plains, situated between the basin-margin proximal alluvium (including fans) and marginal-marine zone of the Promina Basin. The alluvial Promina Beds represent a transverse type of basin-fill pattern, whereas the deepest portion of the basin experienced longitudinal palaeotransport.

1. INTRODUCTION

Alluvial sediments of the Palaeogene Promina Basin in Northern Dalmatia have been deposited within alluvial fan and braidplain environments (BABIĆ & ZUPANIČ, 1988, 1990; KURTANJEK, 1992), situated between the rising Dinarides, and the shoreline. A specific feature of these sediments is the occurrence of gravelly sheet-like bodies with sharp upper bounding surfaces (KURTANJEK, 1992). A study of these sedimentary bodies, which represent natural depositional units and entities, and their relationship with other sedimentary bodies, will be presented here in order to explain the relevant generative processes. Allowance has been made for two different opinions concerning the origin of these gravelly sediments. KURTANJEK (1992) has suggested that the gravel bodies reflect deposition during the advancing stages of overall alluvial fan progradation, which were induced either by basin margin tectonics or by switching of the fan lobes. However, MRINJEK (1993b) proposed a comparison of the gravel unitsas well as alternating sands and muds, to the products of the Donjek- and Scott-type rivers (sensu MIALL, 1978). The origin of the sharp upper bounding surfaces of the conglomerate bodies is discussed as these have been considered to reflect the deactivation of streams (KURTANJEK, 1992). Coarsening-upward trends appearing within the studied sediments (KURTANJEK, 1992; MRINJEK, 1993b) are also discussed, as vertical trends in braided alluvium may reflect different sedimentary processes, and be related to both internal and external controls (HEWARD, 1978; MCLEAN & JERZYKIEWICZ, 1978; MIALL, 1985). It will also be shown that alluvial environments of the studied sediments occupied a specific position within the overall trend of the Promina Beds, and a specific place within the Promina Basin.

2. GEOLOGICAL SETTING

The coastal Dinarides are characterised by thick platform carbonates ranging in age from Late Triassic to Middle Eocene. In the Middle Eocene a foreland basin was formed on top of the carbonates, in front of the rising Dinarides. According to MARINČIĆ (1981) this basin has been asymmetrically filled in response to Dinaric thrusting from the NE. The most complete succession of the basin fill occurs in Northern Dalmatia, in the area between Obrovac and Benkovac, where it includes sediments deposited within various settings such as turbiditic basin, slope, shelf, coast/deltas, alluvial plains, and fans (BABIĆ & ZUPANIČ, 1983, 1988; POSTMA et al., 1988), and is Middle Eocene to Lower Oligocene in age (Figs. 1 to 4). In this area the lower and southwesterly part of Palaeogene clastics has been assigned to the "Flysch" unit, and the upper and landward portion corresponds to the Promina Beds (Fig. 2).

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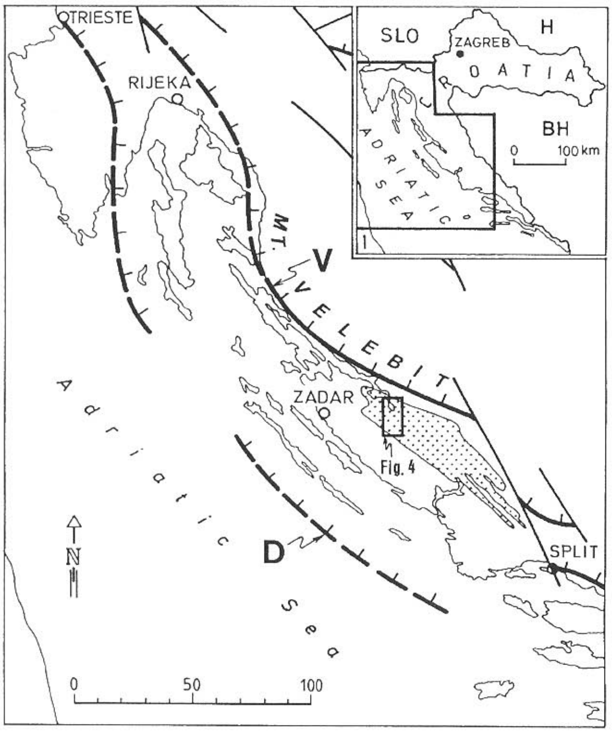

Fig. 1 Location map of the study area. The Promina Basin is situated within the inner portion of a 60-70 km wide imbricate/folded belt bounded by the Dugi Otok Fault Zone (D) to the SW, and by the Velebit Thrust (V) to the NE. Tectonic structure according to ALJINOVIĆ et al. (1987).

The Promina Beds are an approximately 1900 m thick succession of marine to alluvial deposits (Figs. 3 and 4). According to ŠIKIĆ (1969) The Promina Basin was formed between the rising Mt. Velebit and an outer (SW) uplifted zone, and basin axis migrated successively northeastward. The Promina Beds conformably overly the "Flysch" unit to the SW, and onlap the previously deformed, uplifted, and denudated NE part of the basin (Fig. 2; QUITZOW, 1941; ŠIKIĆ, 1969; IVANOVIĆ et al., 1969, 1976; SAKAČ, 1961; SAKAČ et al., 1993). The sediments described here represent the lower part of the alluvial Promina Beds (Figs. 3 and 4; BABIĆ & ZUPANIČ, 1988, 1990; POSTMA et al., 1988; KURTANJEK, 1992; BABIĆ et al., under review), and are named the Kunovac Beds.

The tectonic structure of the area mainly reflects NE-SW oriented compressional deformation, which produced folded, imbricate, and thrusted structures with tectonic transport toward the SW (Figs. 1 and 2). The most important deformations occurred during the Middle Eocene and continued during deposition of the Palaeogene clastics (IVANOVIĆ et al., 1969, 1976). Thrusting was most active during the Late Oligocene-Middle Miocene, and Late Pliocene times, and is currently ongoing (ALJINOVIĆ et al., 1984; PRELOGOVIĆ, 1989). While older compressional structuring was oriented NE-SW, later movements were mainly governed by a N-S oriented stress regime (PRELOGOVIĆ, 1989).

3. STUDY AREA

In the Benkovac-Obrovac area the upper part of the Promina Beds, which is alluvial in character (BABIĆ & ZUPANIČ, 1983, 1988), consists of two parts: the Kunovac Beds and the Upper Alluvial Unit (Figs. 3 and 4). The Kunovac Beds comprise the subject of the present study. The study area is a 14 km zone of sediments located between underlying, cyclically arranged shelf to coastal-deltaic deposits (POSTMA et al., 1988; BABIĆ & ZUPANIČ, 1990) and the Upper Alluvial Unit (Fig.

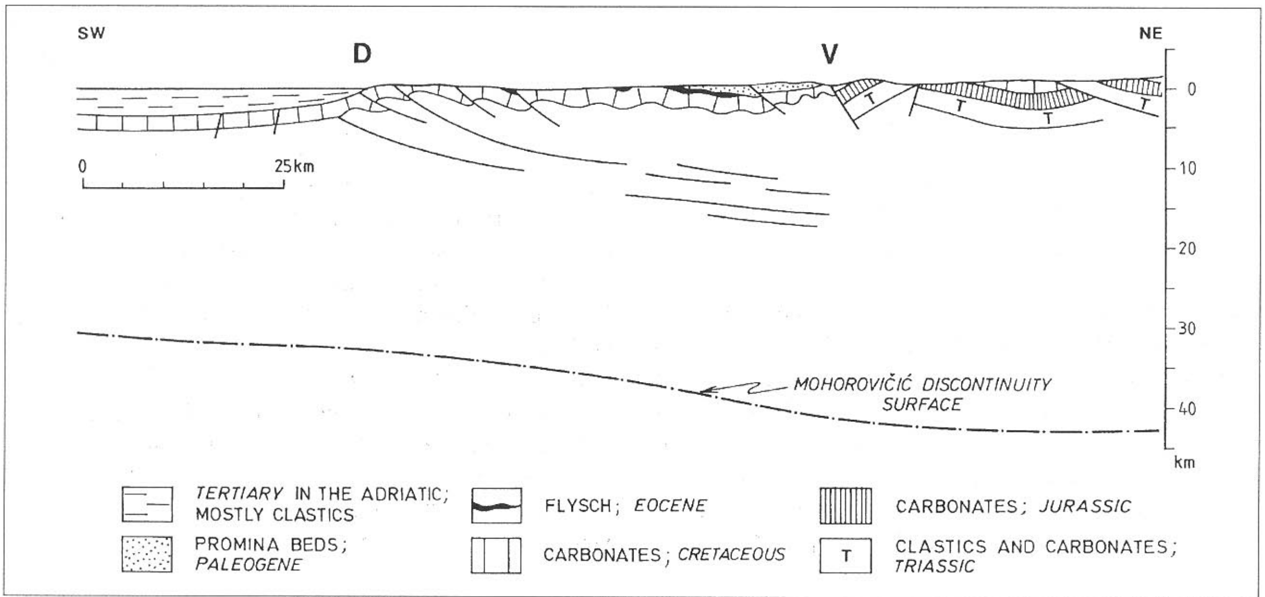

Fig. 2 Outline tectonic structure of northern Dalmatia (see also Fig. 1) showing the location of the Promina Basin (stippled) in the inner portion of the imbricate/folded belt bounded by Dugi Otok Fault Zone (D) and Velebit Thrust (V). The Dugi Otok Fault Zone separates underthrusted Adriatic plate (autochton) and overthrusted Dinaric units, and presumably continues into sole thrust planes. Compiled from IVANOVIĆ et al. (1969), MILJUSH (1973), MILJUŠ & PENSA (1978), ALJINOVIĆ et al. (1984, 1987), and PRELOGOVIĆ et al. (1995).

	Informal Units		Approx. thickness (m)	Facies/ Environments	Average palaeotransp. direction	Age
PROMINA BEDS	CONGLOMERATE UNIT	(b2) Upper Alluvial Unit	320	alluvial fans alluvial plains	SW	Late Eocene - Early Oligocene
		(b1) Kunovac beds	140	alluvial plains	SW	
		(a)	150	cyclic shelf and delta/coast	SW	Late Eocene
	INTERMEDIATE UNIT		100	alluvial and marginal marine deposits		
				various marine deposits, slumps		
	CALCARENITE UNIT		1200	shelf(?) sandstones/mudstones turbidites, megabeds	W, NW	late Middle - Late Eocene

Fig. 3 Stratigraphy and facies/environments of the Promina Beds in the Benkovac-Obrovac sector (see Fig. 4) with the position of the Kunovac Beds. Double line within the sediments of the Intermediate Unit refers to the sequence boundary. Compiled from BABIĆ & ZUPANIČ (1983, 1988, 1990), POSTMA et al. (1988), and unpublished data. Age data from IVANOVIĆ et al. (1969, 1976).

4). The boundary between the Kunovac Beds and the Upper Alluvial Unit is at the base of a distinct marker horizon consisting of sediment package up to 8 m thick of (1) locally occurring massive debris-flow deposits (up to 1.6 m thick) at the base (Fig. 5), and (2) bedded pebble to cobble (locally boulders up to 0.8 m) streamflow conglomerates, minor sandstones and mudstones. The marly-sandy matrix, presence of very large clasts and clasts of hybrid sandstones (carbonate and non-carbonate grains) scattered among carbonate clasts make this package outstanding in the field. Differences between the Kunovac Beds and the Upper Alluvial Unit are described below.

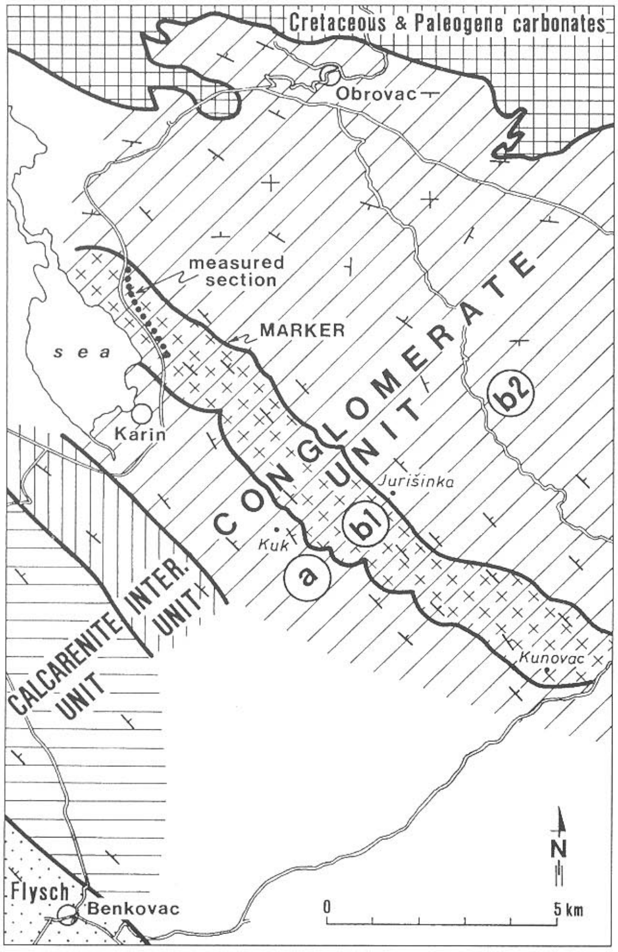

Fig. 4 Location map of the lower Promina alluvium (b1=Kunovac Beds) and measured section (shown in Fig. 5). For the stratigraphic scheme and relevant environments see Fig. 3. Deposits of the cyclic shelf/coast (a) are underlying the Kunovac Beds. The Upper Alluvial Unit (b2) begins with the marker unit described in text. The map of Promina units has been compiled from BABIĆ & ZUPANIČ (1983, 1988, 1990), POSTMA et al. (1988), KERHANI (1992), and unpublished data. Bedding attitudes and outer boundaries of the Promina Beds after IVANOVIĆ et al. (1976).

Data for this study has been collected along the strike of the Kunovac Beds within the area shown in Fig. 4. Most data has been derived from the measured section (in a road cut) and its surroundings, which encompass the best exposures of the Kunovac Beds (Figs. 4 and 5; details in KURTANJEK, 1992), and from the southern slopes of the Mt. Kunovac (Figs. 4 and 6).

Special attention has been paid to the tracing and study of bounding surfaces of coarse-grained bodies, their large-scale geometry, and lateral changes checked by vertical profiles of individual bodies. Field work included selective mapping at scales 1:10.000, 1:5.000 and 1:2.500.

4. THE KUNOVAC BEDS: DESCRIPTION OF SEDIMENTS

The Kunovac Beds consist of four types of sedimentary bodies, which may be regarded as representatives

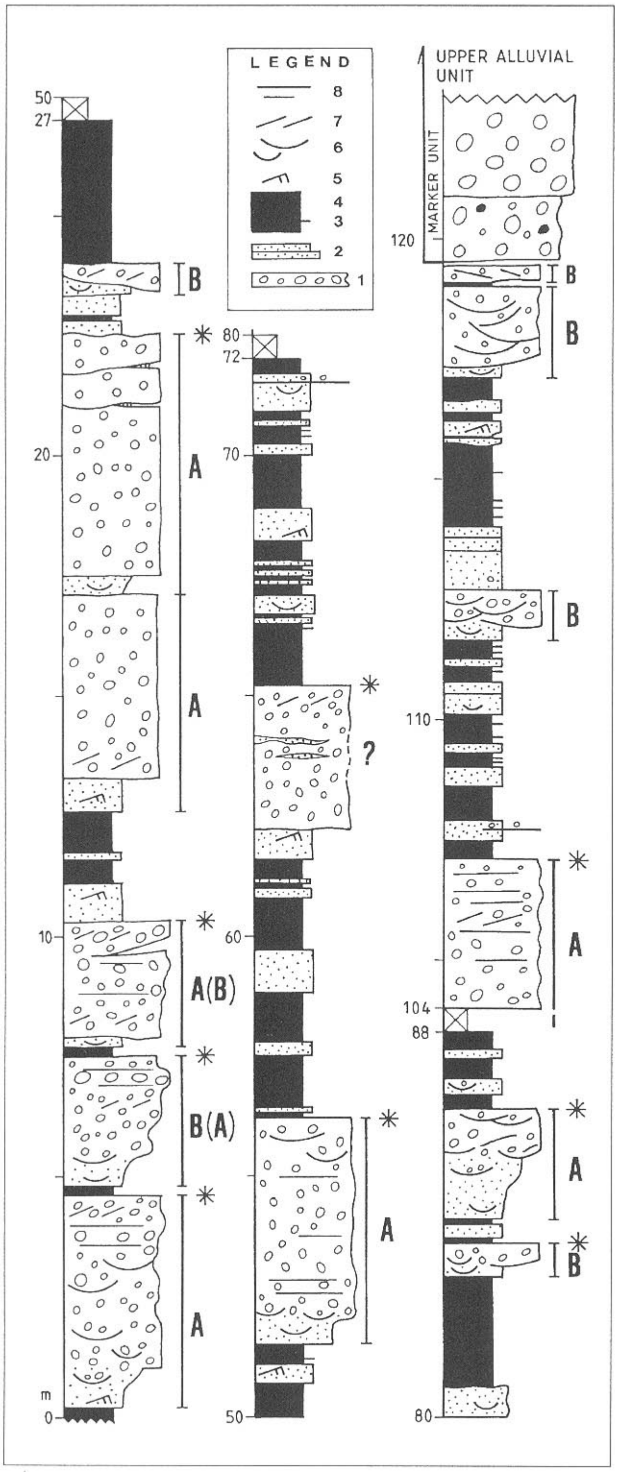

Fig. 5 Measured log of the Kunovac Beds. Location in Fig. 4. Below the measured section there are some 20 m of alluvial sediments underlain by cyclically arranged shelf and delta/coast deposits. The Upper Alluvial Unit starts with the marker horizon described in text. Legend: 1) Conglomerates; 2) Sandstones; 3) Sandstones, 4 to 10 cm thick; 4) Mudstones including siltstones, and less than 4 cm thick sandstone intercalations; 5) Cross-lamination; 6) Trough cross-bedding; 7) Planar cross-bedding; 8) Horizontal strata; Asterisks - sharp upper bounding surfaces of sheet bodies. A and B denote two types of sheet-like bodies discussed in text, while A(B) and B(A) denote gravel sheets showing features characterising both types. After KURTANJEK (1992) and an unpublished report (BABIĆ, ZUPANIČ & CRNJAKOVIĆ, 1990: The role of transitional coarse-grained systems in the evolution of the Palaeogene sedimentary basin of the Outer Dinarides; Croatian Natural History Museum, Report No. 269964), modified.

of two facies associations: coarse-grained facies association (CFA) represented by 3 types of sedimentary bodies, and fine-grained facies association (FFA). The term facies association is used here for natural sediment groupings into integral bodies consisting of genetically related component deposits. The facies associations in Kunovac Beds are represented by sedimentary bodies, which are clearly differentiated in the field, and separated from associated, but genetically less related sediments and facies associations by specific boundary surfaces. Further details are described below.

Carbonate detritus is highly predominant in all size grades of Kunovac sediments (KURTANJEK, 1992), and the detritus was mostly derived from exposed Cretaceous and Palaeogene sediments (BABIĆ et al., under review). Non-carbonate constituents are mostly terrigenous quartz and chert grains.

4.1. COARSE-GRAINED FACIES ASSOCIATION (CFA)

The coarse-grained bodies described here are *sheets* and *ribbons* following the criteria of FRIEND et al. (1979), who proposed a distinguishing value of the width/height ratio of 15. In the Kunovac Beds, these bodies are well defined, coarse-grained units, separated by floodplain sediments (Figs. 6 and 10). This is in contrast to the character of "sheet-like" and "channel-fill" units described by RAMOS & SOPENA (1983; they have also distinguished other facies types), which represent architectural components/elements of a larger coarse-grained complex from the Buntsandstein of the central Spain. E. g. conglomerate sheets in the Buntsandstein are 0.5 to 1.5 m thick and tens of metres wide, and are tightly associated with other gravel facies and some sands. Similar sheets, which are also amalgamated with other coarse-grained facies have been recognised by MRINJEK (1993b) in the Promina alluvium. These sheets are not easily delineated within the Promina and represent architectural components of the large-scale, well defined sheet-like bodies (Fig. 10). Similarly, channel fills such as described from the Buntsandstein (RAMOS & SOPENA, 1983) could also be identified in the Kunovac Beds, where they are welded with other coarse-grained facies and thus represent an architectural component of the larger sheet-like bodies. In contrast, ribbons defined by FRIEND et al. (1979) and described here, are isolated bodies enveloped by floodplain sediments (Figs. 6 and 10).

4.1.1. Sharply topped gravel sheets (A-type bodies)

The units of this type show sheet-like geometry, and are up to 6 m thick (Figs. 6, 7 and 10). Some of them can be traced laterally for more than 4 km and seem to be more than 7 km long along depositional strike. Their width/height ratio is greater than 500. Other A-type bodies are more than several hundred metres wide along depositional strike, have a width/height ratio of 50-500, and pinch out within mudstones and sandstones of the fine-grained facies association (FFA). The map

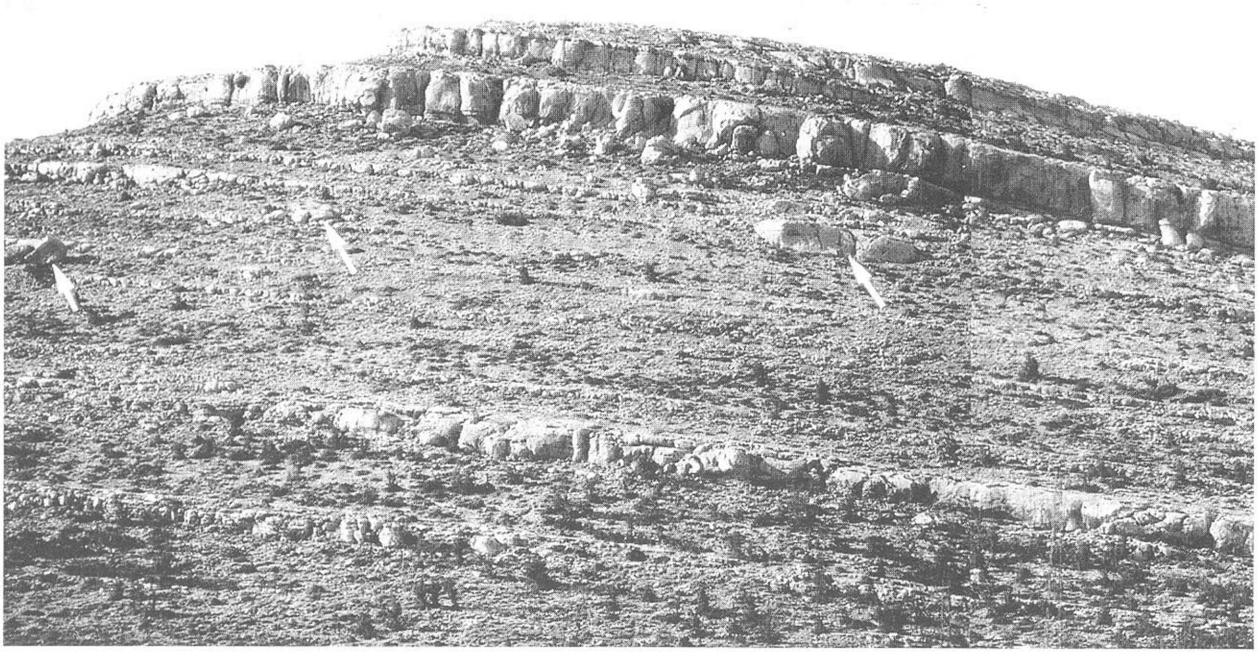

Fig. 6 Southern and south-southeastern slopes of the Mt. Kunovac showing approximately lower 2/3 of the thickness of the Kunovac Beds. The maximal width of the view is ca. 300 m. The beds are gently inclined toward the NE. The slopes are oblique to the average palaeotransport direction in the Kunovac Beds, which is toward SSW (scarce measurements). Sharp and even upper bounding surfaces of sheet-like bodies are well displayed. The largest scarp showing an extensive A-type gravel sheet is 6 m high. The largest sheet in lower part of the photo pinches out toward the right. Arrows point to the bases of three ribbons (C-type bodies); the left one is behind the fallen block. The sheet (probable B-type body) just above the middle ribbon is thinning to the left.

of an upper part of the Kunovac Beds made by MRINJEK (1993a; the map also includes some 350 m thick portion of the upper alluvial unit) shows 2 to 4 km wide conglomerate and sandstone/mudstone units, although the log measured across these units (MRINJEK, 1993b) reveals a larger number of thinner coarse-grained units of an unknown lateral extent.

Bounding surfaces of A-type bodies with FFA sediments represent the largest and most conspicuous surfaces in the Kunovac Beds. The lower bounding surfaces are even (Figs. 6, 7 and 10) and non-erosional, or locally irregular due to loading and erosional scouring mostly less than 0.4 m deep. On slopes they occur at the bottom of (or somewhat below) long rocky escarpments representing vertical sections of A-type sheets (Fig. 6). Upper bounding surfaces are sharp and even, and form conspicuous narrow morphologic terraces (Figs. 5 and 6). The upper surfaces may show well preserved palaeosols represented by a mixture of gravel, sand and fine-grained matrix with rhizocretions.

Some A-type bodies begin abruptly with conglomerates overlying FFA sediments, while the others contain a 0.2-1.2 m thick sandy to sandy-gravelly basal package (Figs. 5, 8 and 10; KURTANJEK, 1992). This package shows shallow scour-and-fill lenses, trough cross-bedding and cross-lamination (Figs. 5 and 8), and may only rarely contain root traces.

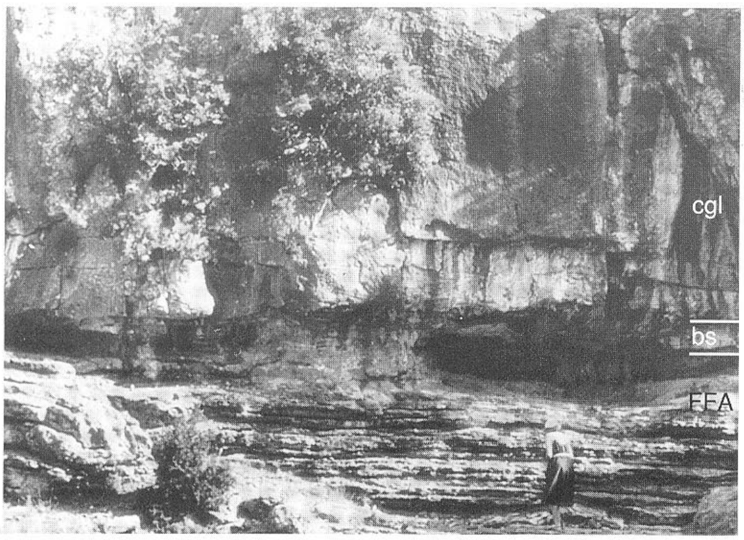

Fig. 7 Floodplain sandstones and mudstones in the lower part (FFA, foreground) are overlain by an A-type sheet massive conglomerate (cgl) with the basal sandy package (bs). The sediments shown correspond to a lower part of the Kunovac Beds. Person for scale.

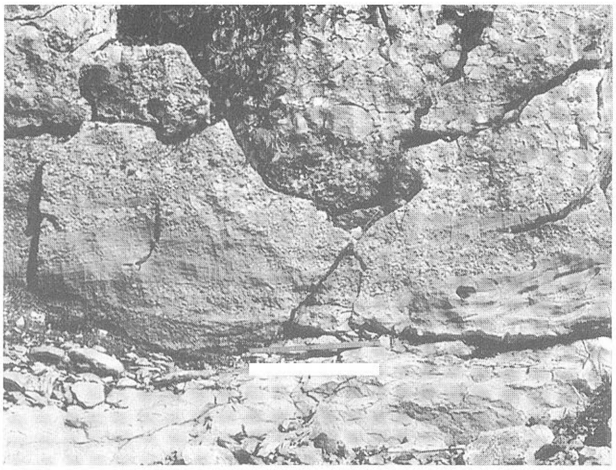

Fig. 8 The light lower part of the photo shows carbonate floodplain mudstones and sandstones. The overlying basal part of an A-type sheet consists of a thin and rather coarse variety of the basal cross-bedded sandstones transitionally overlain by conglomerates, which coarsen upwards. Bar = 0.4 m.

The conglomerates are internally similar to many conglomerates described previously from the Promina alluvium (BABIĆ & ZUPANIČ, 1988; KURTANJEK, 1992; MRINJEK, 1993b). They are clast-supported, and consist mainly of pebbles (locally granules or cobbles) with sandy matrix (locally sparry calcite). In sections perpendicular to the depositional strike, the conglomerates display gently to steeply (rare) inclined beds in up to 0.8 m thick, laterally restricted sets, and crude horizontal, thin discontinuous bedding, as well as up to 0.5 m (max. 1 m) deep erosional scours. Minor sandstone lenses are sometimes present. Sections parallel to the transport direction show crude horizontal stratification enveloping occasional cross-stratified units less than 0.7 m thick, and less than a few metres long. The top portion of some gravel bodies locally contains thin lenses of finer-grained gravel or sand. Generally, A-type gravel bodies show a multi-lateral and multi-storey (terms according to FRIEND et al., 1978, 1986) internal structure, in which small-scale gravelly components are tightly welded together.

4.1.2. Heterogeneous gravelly-sandy sheets (B-type bodies)

These bodies are mostly 0.6-1.8 m thick sheets, which can be traced for more than 50 metres along depositional strike and probably extend laterally for more than several hundred metres. Their thickness may vary laterally, and some bodies interfinger with FFA sediments. The basal bounding surface is irregular with erosional scours, or flat depositional. The upper bounding surface is flat, locally with root traces, or irregular but non-erosional. The sheets may be rather heterogeneous laterally (Fig. 10). They may include thin, extensive conglomerate and sandstone beds, small, lenticular erosionally-bounded conglomerate and subordinate sandstone bodies, small, ribbon-type multi-storey gravelly channel fills and occasional mudstone lenses. Individual scouring rarely exceeds 0.5 m. The B-type bodies show either an irregular vertical trend (dominant), fining-upward (FU), coarsening-upward plus fining-upward (CUFU), or coarsening-upward (CU) trend. In addition, a vertical trend may be replaced laterally by another trend within one and the same body. The basal surface of some small conglomeratic component units contains 1 m long and 7 cm wide fossil stems, as well as large palm leaves. B-type bodies, as well as associated FFA, may be disrupted by upright tree trunks, now represented by gravel to sand infill.

4.1.3. Ribbons (C-type bodies)

They are isolated conglomerate-sandstone bodies (Figs. 6 and 10), up to 5 m thick and 2-11 m wide in sections perpendicular to the palaeotransport direction and are surrounded by FFA sediments. Their width/height ratio varies from 0.5 to 4 and rarely to 10 or more. They are multi-storey bodies bounded by lower erosional, and upper, sharp depositional surfaces. Individual scours are mostly less than 0.5 m deep (max. 1.5 m). Gravelly or sandy wings run away from the main body and some of them are represented by extensive thin beds.

4.2. FINE-GRAINED FACIES ASSOCIATION (FFA)

FFA is represented by units up to 6.5 m thick consisting of fine-grained sediments alternating with sandstones.

Fine-grained sediments are predominantly laminated carbonate siltstones and mudstones, which can be altered by pedogenic processes, and are described in detail in KURTANJEK (1992) and BABIĆ et al. (under review). Palaeosol material is represented by mud-silt, and by mud-silt-sand mixtures, occasionally with gravel, which contain rhizocretions, various tubules, and other soil features. There are also primary massive carbonate mudstones and marls, occasionally containing small gastropods. Clays (less than several cm thick) are rarely present as well as associated coal seams (Fig. 9).

Sandstones (Fig. 9) are mostly fine-grained, current-ripple laminated, occur as laminae and thin beds, and have commonly been disturbed by pedogenesis. Cross-bedded and horizontally laminated sandstones occur locally. Occasionally, erosion-based, fine- to medium-grained, cross-bedded sandstones, locally containing gravel strings can be observed. A few sandstone beds were attached to the ribbon bodies. Some sandstone beds have been traced for more than hundred metres laterally. There are also sandstone sheets less than 0.5 m thick consisting of several beds, which may locally show an FU trend and contain some gravel at the base, which is erosional. A type of sheet-like bodies transitional between sandstone sheets mentioned above and coarser-grained B-type sheets also exists. Sandstones may contain plant leaves (including those of palms) and stems. Several palm trunks in living position, up to 1.6 m long, now consisting of sandstone and conglomerate, have been observed within FFA.

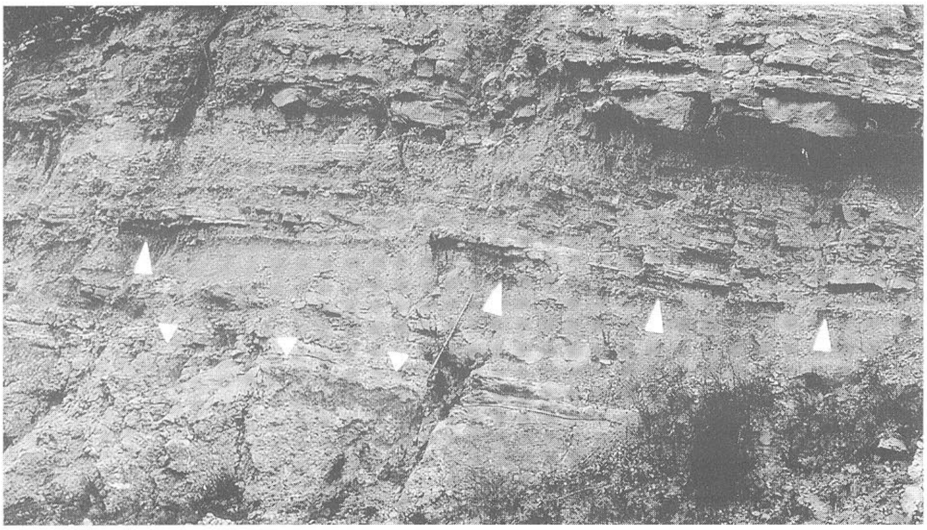

Fig. 9 The uppermost portion of the Kunovac Beds exposed at the locality of the measured section (Fig. 4). The lower part of the exposure shows the top portion of an A-type conglomeratic body ending with sharp even surface (lower arrows). It is overlain by floodplain sandstones and mudstones including a 0.1 m thick lacustrine limestone bed at the base, and a lamina thick coal horizon (upper arrows). Note a shallow scour below the prominent sandstone bed in the upper right. Stick in the lower center = 1 m.

Sediments of the FFA locally show convolute bedding, which involved soft sediment and was due to liquefaction.

4.3. PALAEOCURRENTS

Most palaeocurrent measurements were taken in the vicinity area of the measured section (Fig. 4). The orientation of a(t) b(i) imbrication of horizontally-bedded gravel indicates transport toward azimuths between 195° and 250° (symbols for fabric after WALKER, 1975). Several cross-stratified sets of gravel were directed toward the SW and W, while low-angle inclined gravel beds were variously oriented, and most commonly toward the ESE and WNW. The trough axes and erosional scours in the basal sandy-gravelly package of the A-type bodies were oriented NEE-SWW. The orientation of the erosional scours, and ribbons of gravel occurring within the B-type bodies was roughly ENE-WSW, and stems and leaves are oriented 235°-55° to 285°-105°. Trough axes in two cross-bedded sandstones occurring within FFA were oriented NE-SW.

In the Mt. Kunovac area sparse palaeocurrent measurements include the orientation of two ribbons, which were N-S, and NNE-SSW, and of several trough axes of the cross-beds, which were NE-SW.

In the area between the measured log and Mt. Kunovac, MRINJEK (1993a, b) measured the orientation of gravel imbrication reflecting an average palaeocurrent direction toward the SW.

5. SUMMARY DESCRIPTION OF THE UPPER ALLUVIAL UNIT

Parts of the Upper Alluvial Unit have been described in detail by BABIĆ & ZUPANIČ (1988), KURTANJEK (1992), and MRINJEK (1993b). In contrast to the Kunovac Beds this unit contains little mudstone, and occasional to locally abundant debris flow deposits (BABIĆ & ZUPANIČ, 1983, 1988; MRINJEK, 1993b). The unit mainly consists of 2 to 8 m thick extensive sheet-like gravel bodies. Internally, the bodies commonly show irregular vertical trends. KURTANJEK (1992) has observed gravel bodies with sharp and even upper bounding surfaces and with or without basal sands, comparable to A-type gravel sheets described here, and MRINJEK (1993b) has found occasional CUFU units. Gravelly-sandy and thin sandy FU units are also present (MRINJEK, 1993b), but we were not able to identify a great number of such units as shown by this author. The thin, dominantly sandy FU units are similar to some B-type sheets in the Kunovac Beds. Generally, the Upper Alluvial Unit, excluding basin-margin fans, also predominantly consists of sheet-like bodies.

Palaeotransport directions vary from WSW close to Obrovac (BABIĆ & ZUPANIČ, 1988), to SW east of the measured section (MRINJEK, 1993b), and to SSW, and even to the S in the area N and NE of Mt. Kunovac.

6. DISCUSSION

6.1. ENVIRONMENTAL EVOLUTION OF SHARPLY-TOPPED GRAVEL SHEETS (A-TYPE BODIES)

Initiation

As the basal surface of A-type bodies does not show significant erosion, the majority of bodies do not represent the fills of erosional depressions (Fig. 10). This is in contrast to commonly described fluvial sheet-like bodies, whose bases originated by successive lateral emplacement of channel scours (reviews in COLLINSON, 1986 and MIALL, 1988, 1992). The low intensity of erosional incision may have been related to high-rate aggradation and/or to high-rate subsidence (e.g. FRIEND et al., 1979; HAUGHTON, 1989), and may have nothing to do with cohesiveness of the floodplain muddy sediments, which otherwise influence the downcutting ability of fluvial streams.

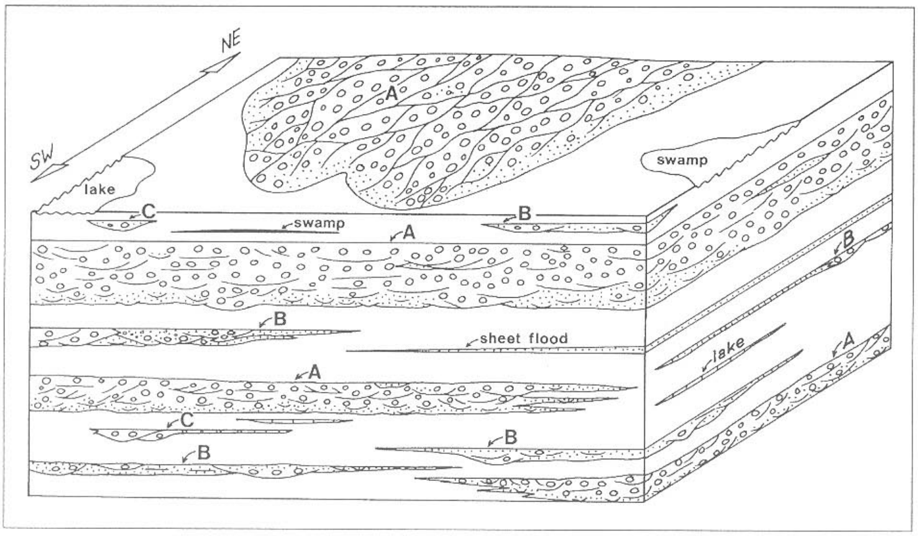

Fig. 10 Schematic model of the large-scale architecture of the Kunovac Beds and the main features of coarse-grained bodies described in the text. White = floodplain sediments, undifferentiated except selected details given for illustration: lenses of a swamp and a lake sediment, and a sheet-flood sandstone. The upper surface of the block shows an advancing A-type belt containing a sandy fringe. The upper A-type sheet shown in two sections represents a very extensive body (see text for the explanation, and Fig. 11). Not to scale.

Growth

The basal sandy-gravelly package reflects processes connected with shallow streams, which were mostly unconfined, as well as the erosion and deposition related to small, local, very shallow channels. Rarely occurring root traces witness the intermittent character of the streams.

The origin of the component gravel facies occurring within the A-type sheets have previously been described from several parts of the Promina alluvium including the Kunovac Beds (BABIĆ & ZUPANIČ, 1988; KURTANJEK, 1992; MRINJEK, 1993b). Horizontal to slightly inclined, crude, discontinuous stratified, imbricate gravel originated as sheets and low bars during high flow stage, while laterally restricted cross-beds resulted from lateral bar accretion during initial falling stage, and from up to 1 m deep channel scouring and filling (RUST, 1972, 1975, 1978; HEIN & WALKER, 1977; COLLINSON, 1986). Laterally restricted, low-angle sets likely represent limited lateral accretion units, which might have started as drapes of previously scoured depressions (RAMOS & SOPENA, 1983). Small-channel and scour-and-fill lenses, and discontinuous bedding resulted from erosion, winnowing, and reworking of gravel during decreasing and lower discharges. Sand lenses originated either as scour-fills, or represent erosional remnants, while the sand matrix infiltrated into the gravel frame during low discharges. All these processes are consistent with deposition by shallow, bed-load, braided streams, which operated at various discharge, and frequently switched and shifted laterally (op. cit.).

Concerning the origin of the A-type sheets as the whole units (apart from sandy base) the sheet-like geometry, lateral extent, character of bounding surfaces, and complex internal organisation of component facies suggest the existence of laterally extensive fluvial belts. Multilateral and multi-storey internal organisation resulted from two processes, which *operated together*: (1) switching and shifting of internal, smaller-scale environments (e.g. channel and bar) within a belt, and (2) vertical accretion of the fluvial belt, leading to the tight vertical and lateral amalgamation of the component facies, and to the origin of the extensive sheet-like body. Thus, an A-type sheet does not represent amalgamated channel fills of a river, which was shifting across its floodplain, and consequently, an A-type sheet does not contain well-delineated internal erosional surfaces, which would resulted from the emplacement of new braided-channel tracts as in the case of amalgamated channels and tracts of the "classic" river types. The fluvial belts corresponding to A-type sheets might be compared to the "mobile-channel belts" of FRIEND (1983), although some crude stratified gravel was not necessarily deposited in strictly channel-related environments implied by FRIEND's notion of the "mobile channel belt". The largest fluvial belts were more than 4 km, and possibly more than 7 km wide, and the smallest ones were more than several hundred metres wide (Figs. 10 and 11).

The upward change from dominantly sand (basal part) to gravel deposition (main portion) within a fluvial belt reflects a gradual but rapid increase of stream competence within a wide front. The basal sandy unit may thus be inferred to represent the distal, sandy portion of an advancing belt or tongue (Fig. 10). Some basal sands might represent lateral equivalents of already active gravel belts, which operated laterally. The lack of sandy base might have resulted from the direct encroachment of gravel deposition over floodplain mud, without the sandy forerunner, or by local to complete removal of sand by more powerful currents, which supplied gravel. The same feature could have been produced if the sand fringe was overtaken by the gravel front. There are no data on the cementation history of these sands, but an initial cementation promoted by the waters rich in carbonate together with the presence of carbonate particles could increase the resistance to the erosion and thus influence the preservation potential of these basal sands.

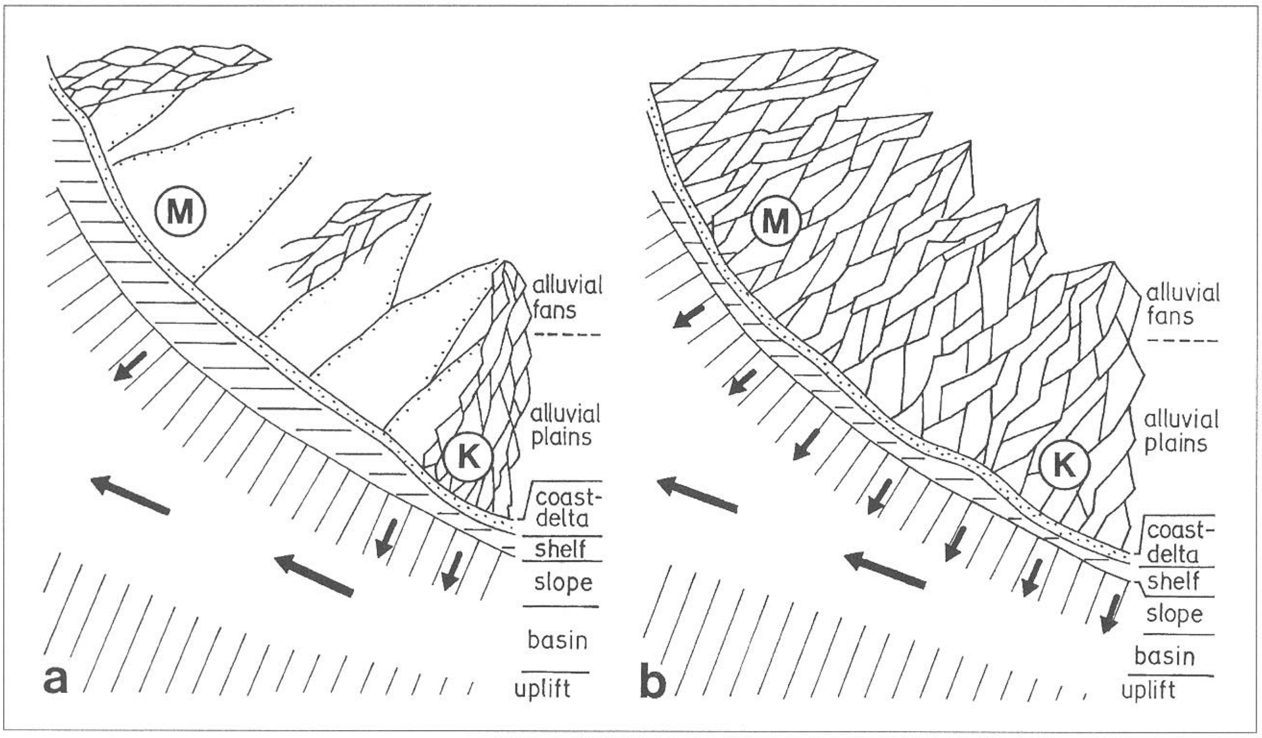

Fig. 11 Palaeogeographic reconstruction of the Kunovac Beds within the Promina Basin. The positions of the measured section (M) and southern slopes of the Mt. Kunovac (K) are indicated. (a) Predominant situation during deposition of the Kunovac Beds. Braided lines represent active fluvial belts (A-type). Lines with dots at one side delineate previously active A-type belts. (b) Situation during the activity of a very extensive A-type belt such as the largest one depicted in Fig. 10. Note the overall progradation of the alluvial and related systems. Arrows represent directions of gravity flows (BABIĆ & ZUPANIČ, 1983; VDOVIĆ, 1986). Uplifted area after ŠIKIĆ (1969).

Depositional palaeogeography

Based on the data and discussion presented above the growth of an A-type body (Figs. 10 and 11) may be regarded as representing the advancing depositional tongue or extensive festooned front of gravel, which might contain a sand fringe. The environmental pattern inferred for A-type belts is similar to the convex-upwards, lobate topography of some ancient and modern river systems described by FRIEND (1978).

Cessation

The remarkable upper bounding surface of A-type bodies must have been produced by swift deactivation of fluvial belts (KURTANJEK, 1992). The abandonment of a belt could be followed by colonisation by plants, which resulted in pedogenic modification of the uppermost portion of the gravel body, when this surface was a large-scale geomorphic feature, i.e. an extensive (deactivated) gravelly plain (Figs. 10 and 11).

Origin of coarsening upward trends: alternative interpretations?

Small-scale coarsening-upward (CU) sequences containing mudstones in their lower part and characterising some coarse-grained alluvial braided systems may be produced by the successive filling of abandoned channels (COSTELLO & WALKER, 1972). This idea has tentatively been applied to some packages in the Upper Alluvial Unit of the Promina Beds (BABIĆ & ZUPANIČ, 1988), but was not checked by lateral tracing. In the Kunovac Beds, the large lateral extent of both the fine-grained sediments (FFA) and the coarse-grained sheets precludes such an interpretation (Fig. 10).

Sandy to gravelly packages showing CU trend may result from the downstream migration of gravel bars in braided streams (BLUCK, 1979, 1986). The lateral extent of the sandy base in A-type bodies is too large to represent a drape of channel depressions, while sediments presented by BLUCK (1979, 1986) have filled channel depressions and are impersistent laterally. Finally, the complex (multi-storey, multi-lateral) structure of most Promina bodies cannot be compared to the growth structure of individual bars, which is related to flow depth. In addition, palaeocurrent measurements (although restricted in number) in the basal sands of A-type bodies correspond to the regional transport direction, whereas palaeocurrents measured in trough cross-bedded sands deposited in front of advancing bars are highly variable and commonly diagonal to transverse to the direction of bar progradation (BLUCK, 1979, 1986).

According to MRINJEK (1993b: Fig. 16A) a part of the Promina alluvium (mainly corresponding to the Kunovac Beds) is characterised by 2.3 to 9.6 m thick CU units formed by lower-rank FU cycles, which coarsen upwards. The sequences include mudstones, sandstones, and conglomerates. Thin FU units would represent flood cycles, while the CU units have been regarded as the channel fills of the Donjek-type rivers of MIALL (1978). However, the lower part of MRINJEK's (1993b) CU sequences consisting predominantly of mudstones and sandstones shows a large lateral extent and reflects the floodplain origin (KURTANJEK, 1992), that excludes the channel-fill origin. The gravelly portion of these CU sequences mostly belong to sheet-like bodies, whose origin was related to the fluvial belts. Besides, coarsening-upward channel fills are inconsistent with the Donjek model, in which an individual channel is filled by the erosionally-based FU sequence (MIALL, 1978). A comparison of the same sediments with the "facies assemblage G III", i.e. with "distal braided rivers and alluvial plains" of RUST (1978), also proposed by MRINJEK (1993), is not applicable either, as this model is also characterised by FU channel-fills.

Alternative interpretations discussed above are therefore not applicable to the Kunovac Beds.

Rank of bounding surfaces

Prominent bounding surfaces of A-type bodies are the highest-rank bounding surfaces occurring in the Kunovac Beds. They correspond to the higher-order class of bounding surfaces of various authors. The "major" surfaces of BRIDGE & DIEMER (1983), 3rd-order surfaces of ALLEN (1983), and 5th-order surfaces of MIALL (1988, 1992), have all been described as erosional basal contacts of sandy bodies. Bounding surfaces of A-type bodies are similar to these classes in delineating complex bodies, whose origin is related to channel processes. However, surfaces described here bound predominantly gravel bodies. Their lower surfaces may be either depositional or erosional, while the upper surfaces are most conspicuous being sharp, even, and non-erosional. Following MIALL's (1992) classification the bounding surfaces of "channel belt sequences", that is the bodies, which are genetically comparable to the A-type sheets described here, are 6th-order surfaces. As some upper bounding surfaces of A-type bodies in the Promina alluvium are of considerable lateral extent, they might even represent a landward correlative of sequence boundaries (see below), and thus would correspond also to the 7th-order bounding surfaces of MIALL (1992).

Lower-order units (architectural elements of MIALL 1985, 1988), and related bounding surfaces in conglomerates are related to smaller-scale component facies forming A-type sheets and are not classified here.

6.2. DEPOSITIONAL ENVIRONMENTS OF OTHER COARSE-GRAINED BODIES

Heterogeneous gravelly-sandy bodies (B-type bodies)

Complex and variable internal geometry (Fig. 10) resulted from the activity of both sheet flows locally inducing scouring, and from shallow channelized flows. These processes alternated in space and time in a generally irregular manner. This, as well as the sheet-like geometry of the entire bodies, and interfingering with flood-plain sediments (FFA) indicate laterally and vertically variable stream activity including their frequent switching and shifting within a fluvial belt. This variability resulted in various vertical trends with predominance of irregular trends, and in laterally different vertical trends occurring within one and the same body. Various character of bounding surfaces suggests different styles of the beginning and cessation of the activity of streams, although sudden abandonment which resulted in sharp even top surfaces, as with A-type bodies, seems to have been common. The B-type fluvial belts are not strictly comparable to the channel belts of FRIEND (1983), as the B-type sheets reflect a combination of three classes of the fluvial architecture recognised by this author, which are differentiated on the basis of transport mode and resulting geometry: sheet flood, mobile-channel belt, and fixed channel. Thus, the relevant fluvial belts are of a combined type. In general, the B-type belts were likely less wide, and streams less energetic than those responsible for the origin of A-type sheets.

The existence of the transitional types of sedimentary bodies between B-type bodies and floodplain sandstone sheets suggests, that stronger floods produced B-type bodies instead of the thin sandy sheets produced by weaker floods.

Bounding surfaces of the B-type sheets might be compared to the 6th-order bounding surfaces of MIALL (1988, 1992), which delineate "channel belt sequences" (see the discussion on A-type bodies). If the B-bodies would be regarded as products of the processes which operated in floodplains (crevasse splaying, sheet floods), then the 5th-order bounding surface of MIALL would better fit these sediments. However, if they represent the continuations of A-type bodies, their bounding surfaces are of the same 6th-order.

Ribbons (C-type bodies)

Isolated ribbons reflect a stable position of shallow, narrow channels (Figs. 6 and 10), situated within the floodplain, for short periods ("fixed channel" of FRIEND, 1983). Short wings represent proximal levee and channel-margin deposits, and laterally extensive sheets attached to the ribbon main bodies may be regarded as distal levee deposits (see ALLEN et al., 1983). Bounding surfaces are those of 5th-order of MIALL (1988, 1992), as they define channel fills.

6.3. ORIGIN OF THE FINE-GRAINED FACIES ASSOCIATION

These sediments have originated from processes on alluvial floodplains, as indicated by alternating deposition and pedogenesis, and by close association with coarse sediments, which were laid down by streams (for details see KURTANJEK, 1992; BABIĆ et al., under review).

According to BABIĆ et al. (under review), laminated, dominantly carbonate mudstones originated by flood flows, and represent a carbonate analogue of widely present, well known siliciclastic floodplain mudstones. Massive carbonate mudstones and marls reflect deposition in ephemeral lakes and ponds. Promina floodplains were characterized by high-rate aggradation, and a high watertable, based on poorly represented features indicating exposure, immature soils, and rather common preservation of primary lamination (BABIĆ et al., under review).

Some alternating traction-flow sands probably represent levee and crevasse splay deposits, as suggested by physical connection with B- and C-type bodies. Other sandstones, particularly the extensive beds, and those showing high-regime flow (horizontal laminae) have likely been produced by sheet floods (KURTANJEK, 1992). Thin sandstone sheets, which may show either FU or some other vertical trend, or no trend at all, were probably deposited during one or several floods (ELLIOT, 1974; MCLEAN & JERZYKIEWICZ, 1978; BRIDGE, 1984).

6.4. THE PLACE OF THE SHARPLY-TOPPED GRAVEL SHEETS IN THE LARGE-SCALE ARCHITECTURE OF THE KUNOVAC BEDS AND OVERALL DEPOSITIONAL DYNAMICS

The data presented suggest the character of the large-scale architecture of the Kunovac Beds presented schematically in Fig. 10. Advances of the belts produced the A-type sheets, while heterogeneous sheets (B-type bodies) and ribbons (C-type bodies) could represent temporary "branches" of A-type belts situated laterally and/or distally. Some B-type bodies were possibly the lateral fringes of the A-type sheets. Generally, the stacking of the belt-generated sheets and intervening floodplain deposits is the basic style of the upbuilding of the Kunovac Beds.

The high-rate floodplain aggradation, which was connected with a wet climate (BABIĆ et al., under review), must have been connected with high-rate deposition of associated coarse-grained bodies. It may be considered that large areas were submerged during high water stages. This is consistent with the low intensity of erosional incision, belt-type river activity, and resulting dominant sheet-like geometry of the coarse-grained bodies. The high aggradation rate was also a very important factor responsible for the specific evolution of fluvial belts and relevant growth of individual sheets as well as for stacking of the belts/sheets and intervening floodplain deposits. It is thought that among a number of factors, which may influence the geometry of coarse-grained fluvial bodies and have been discussed by FRIEND et al. (1979, 1986), the high-rate aggradation and high-rate subsidence, which is otherwise indicated by conspicuous coastal onlap at the inner margin of the Promina Basin, were the most important.

As most of the coarse-grained bodies (i.e. A- and B-type bodies) show a sheet geometry and originated by activity within fluvial belts, a comparison of sediments of the Kunovac Beds with depositional products of partly Donjek- and partly Scott-type rivers of MIALL (1978) as proposed by MRINJEK (1993b) is not justified. In fact, the vertical profile approach of MIALL (1978), and the use of the facies "assemblages" of RUST (1978), which are also based on vertical profiles, as applied by MRINJEK (1993b) for Promina alluvium, have a limited diagnostic value concerning the understanding of the fluvial architecture, and related river processes and patterns (MIALL, 1985, 1988).

6.5. DEPOSITIONAL ENVIRONMENTS OF THE UPPER ALLUVIAL UNIT: A SUMMARY

The upper alluvial unit originated in stream-dominated alluvial environments, partly in basin-margin alluvial fans, and partly in alluvial plains/braidplains (BABIĆ & ZUPANIČ, 1988, 1990; KURTANJEK, 1992; MRINJEK, 1993b). A higher proportion of conglomerates, occurrence of debris flow deposits, and few mudstones compared to the composition of the underlying Kunovac Beds reflect a larger-scale progradational trend. Thus, the upper alluvial unit reveals the character of the proximal equivalents of the Kunovac Beds. This progradation is otherwise a segment of the general progradational tendency of the Promina Beds (MARINČIĆ, 1981; BABIĆ & ZUPANIČ, 1983).

The A-type bodies reflect the activity of fluvial belts including their rapid deactivation explained by KURTANJEK (1992) and here. Some FU sequences could be produced by individual channel filling or bar aggradation, although small FU sequences are produced by various processes and at various scales (GODIN, 1991; MIALL, 1992). However, the prevalent sheet geometry of the majority of relevant coarse-grained bodies must have been produced within the fluvial belts, whose activity gradually waned across a part of or across their entire extent. Occasional individual units showing a CUFU trend (MRINJEK, 1993b) also belong to extensive sheet-like bodies, and consequently, they also resulted from the processes operating within fluvial belts. In general (and excluding the alluvial fan deposits occurring close to the basin margin), there was a dominant role of the fluvial belts in the evolution of the upper alluvial unit and relevant alluvial architecture. As already discussed for the underlying Kunovac Beds, the dominant character of the alluvial architecture and relevant river type are better described by stacking of fluvial belts than by using the "classic" fluvial models based on vertical profiles as proposed by MRINJEK (1993b) also for this part of the Promina alluvium.

6.6. DEPOSITIONAL SETTING OF THE KUNOVAC BEDS

Many workers (e.g. QUITZOW, 1941; ŠIKIĆ, 1969; IVANOVIĆ et al., 1969, 1976; BABIĆ & ZUPANIČ, 1988, 1990) have inferred a supply of the detritus to the Promina Basin from the NE-situated Dinaric mountains. The combination of palaeocurrent data and clast composition (KURTANJEK, 1992; MRINJEK, 1993a, b; BABIĆ et al., under review) characterising the Kunovac Beds is in accordance with such a general pattern. Close to the rising Dinaric mountains there were alluvial fans, and towards the SW they were replaced by alluvial plains, and subsequently by coastal and deltaic environments, and the shelf (Fig. 11; BABIĆ & ZUPANIČ, 1988, 1990; POSTMA et al., 1988). The transverse alluvial systems correspond partly to the models 1 and 2 of typical alluvial basin-fill patterns summarised by MIALL (1981). The narrow shelf continued into the slope, and even further to the SW there was the deepest area of the basin (BABIĆ & ZUPANIČ, 1983). According to ŠIKIĆ (1969) the Promina Basin was bounded to the NE by the rising Mt. Velebit, and to the SW by an uplifting outer zone. ŠIKIĆ (1969) has also inferred a constant subsidence of the inner (NW) part of the basin (the side of Mt. Velebit), and related migration of the basin axis in the same direction during the deposition of the Promina Beds. Longitudinal palaeocurrent directions toward the WNW, revealed from Promina turbiditic sandstones (BABIĆ & ZUPANIČ, 1983; VDOVIĆ, 1986) are consistent with ŠIKIĆ's (1969) reconstruction of the gross basin morphology (Fig. 11). In addition, these directions reflect a lowering of the basin axis toward the WNW. However, there is still no evidence of the closure of the basin to the SE, and the existence of a bay-head delta related to a longitudinal trunk river as speculated by BABIĆ & ZUPANIČ (1983). Such a pattern possibly existed during the latest history of the Promina Basin. The outer flank of the basin defined by ŠIKIĆ (1969) might have represented a low anticlinal ramp or the frontal ramp of a thrust sheet. The existence of an Eocene thrust at a position similar to that of the present-day Dugi Otok Fault Zone (Figs. 1 and 2) has been proposed by TARI-KOVAČIĆ & MRINJEK (1994). If correct, the Promina Basin was carried piggyback (*sensu* ORI & FRIEND, 1984) on an early generated tectonic unit, which will later become the imbricate/folded belt situated between the Dugi Otok Fault Zone and Velebit Thrust (Figs. 1 and 2).

6.7. THE QUESTION OF INTERNAL AND EXTERNAL FACTORS

The carbonate composition of the detritus, transverse pattern of the alluvial transport, high sediment supply, high aggradation rate, and high rate of subsidence have all been related to external factors. However, both internal and external factors of various intensities may be responsible for the origin of upward coarsening and fining trends of different orders (HEWARD, 1978; MCLEAN & JERZYKIEWICZ, 1978; MIALL, 1985). The shifting of channels within channel belts may be regarded as representing a predominantly internally-induced mechanism, although such behaviour is generally dependent on a high sediment supply, and depositional slope, which are mostly related to the external factors. Shifting of the entire belts might have been provoked internally, taking into account the comment made above. The emplacement of a lobe/belt may have been additionally influenced by the location of somewhat lower topography between former, convex-upward buried belts. On the other hand, minor tectonic pulses might be responsible for small-scale local subsidence, which induced the sudden deactivation of a belt and the onset of the advancement of a new belt.

Within the Promina Basin, fluvial gravelly belts continued into the coarse-grained coasts/deltas and both systems advanced and retreated together (ZUPANIČ et al., 1988; BABIĆ & ZUPANIČ, 1990; POSTMA, 1990). This is also supported by an obvious similarity between the coarse-grained bodies produced in these two settings: the sharp and even upper bounding surface reflecting deactivation, and CU trend at the base, which indicate progradation (sandy base in the fluvial counterparts is not always present). It is thought that the rhythmicity displayed by the Promina Beds has been caused by rhythmic, rapid subsidence along a fault-bounded, inner basin margin, that provided space for the thick accumulation of carbonate detritus stemming from the erosion of rising mountains (ŠIKIĆ, 1969; IVANOVIĆ et al., 1969, 1976; BABIĆ & ZUPANIČ, 1988, 1990; POSTMA et al., 1988; ZUPANIČ et al., 1988; MRINJEK, 1993b). According to MRINJEK (1993b), the Promina alluvium contains two, ca. 70 and 100 m thick conglomerate-dominated mega-sequences, which would have been related to the coastal/deltaic units such as those underlying progradational units described by POSTMA et al. (1988) and BABIĆ & ZUPANIČ (1990) and mentioned above. MRINJEK (1993b) suggested that two thick, conglomerate-dominated mega-sequences could reflect two progradational trends corresponding to two tectonically quiet ("postorogenic") periods, while three alternating mega-sequences (with less conglomerates and more mudstones) would reflect retrogradation during subsidence ("syntectonic") intervals. However, the advancement of individual gravel belts/fronts discussed here produced gravel sheets less than 10 m thick, which may have continued into progradational coastal/deltaic units (Fig. 11; KURTANJEK, 1992) such as described by POSTMA et al. (1988) and BABIĆ & ZUPANIČ (1990). Examples of rather thin progradational, alluvial-deltaic units (5 to 25 m thick), which followed subsidence events (and are therefore "postorogenic"), have been described by STEEL et al. (1977) and GLOPPEN & STEEL (1981). Moreover, HELLER et al. (1988) suggested that in the foreland basin settings, distal alluvial areas, which may be compared to the alluvial plains of the Kunovac Beds, may be characterised by thin, prograding gravel sheets. In general, the thickness of alluvial conglomerate-dominated units is not necessarily related to the amount of progradation (STEEL & FROSTICK, 1993). Therefore, A-type gravel sheets described here may have been connected with their coastal-deltaic progradational counterparts, and the most extensive A-type sheets have probably been connected with extensive prograding coastal/deltaic systems such as those described by POSTMA et al. (1988) and BABIĆ & ZUPANIČ (1990) (Figs. 10 and 11b). In addition, these progradations, especially those related to extensive A-type sheets, may have been induced by external factors, and particularly by subsidence events.

In fact, there are still other uncertainties concerning tectonic factors. The rise of an anticline or a thrust ramp at the outer (SW) side of the Promina Basin, as well as the itinerary of the movements along the relevant thrust plane (if the thrust existed) may have been related to the activity along the sole thrusts (Fig. 2). This activity including possible blind thrusts and folds (see BURBANK & RAYNOLDS, 1988) could affect the subsidence and depositional dynamics of the inner portions of the basin. Thus, the tectonic factor could be important and complex.

7. CONCLUSION

(1) The principal architectural components of the alluvial Kunovac Beds are three types of coarse-grained sedimentary bodies, and alternating mudstones and sandstones. The sedimentary bodies are well-delineated by the highest-rank bounding surfaces occurring in the alluvium studied. The geometry of these bodies and the character of bounding surfaces are critical for understanding of the fluvial architecture, and related alluvial processes and systems (river type) in the Promina alluvium.

(2) Complex gravel-dominated sheets (A-type bodies) originated by tight vertical and lateral stacking of smaller-scale component facies within "continuously" growing fluvial belts. A belt of this kind evolved by the advance of a tongue-like apron, or an extensive front. The advancing tongue or front may have been fringed by sand, which became a thin sandy-gravelly basal unit of the resultant sheet-like body. The end of the belt activity was due to rapid abandonment, which was also responsible for the origin of a conspicuous, sharp, and planar upper bounding surface. The abandonment caused the transformation of the belt into a gravelly plain, which may have been colonised by plants, and was subsequently covered by floodplain deposits.

(3) Other coarse-grained bodies include smaller gravelly-sandy sheets (B-type bodies) originating in fluvial belts from a combination of sheet-like and channelized flows, and isolated ribbons (C-type bodies) indicating short-lived narrow channels.

The mudstone-sandstone alternation was produced in floodplains by flooding, and within shallow lakes/ponds, and swamps.

(4) The advances and abandonments of the alluvial belts, and stacking of the belts and intervening floodplain deposits was the basic style by which the alluvial Kunovac Beds were built up. This style persisted also during the deposition of the rest of Promina alluvium.

(5) High sediment supply, fast aggradation, and high sudsidence rate were the most important factors, which were responsible for the low intensity of channel incision and for the predominance of sheet-like geometry of coarse-grained bodies in Promina alluvium.

(6) The alluvial Kunovac Beds have been deposited within a zone of alluvial plains situated between proximal, i.e. basin-margin alluvium (including fans), and a marginal-marine zone. While the alluvium reflects a transverse pattern of the basin-fill, the deepest portion of the basin experienced a longitudinal transport.

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