Pliocene Alluvial Sediments in the Drava Depression of the Virovitica–Slatina Area, Northern Croatia

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Abstract

Clastic sediments in the vicinity of Virovitica (Northern Croatia) consist of gravels, sands, silt clays and marls. Gravels with discontinuous sheet-like geometry are typical for an alluvial fan system. The most abundant sediment, quartz rich sand, originates from a sandy braided river system. Silt, clays, and marls were deposited in the flood plain. They contain fossil macroflora indicative of moderate climate conditions, including maidenhair leaves (*Ginkgo*), the presence of which suggests that these sediments were deposited before the Pleistocene glaciation.

1. INTRODUCTION

Clastic sediments in the vicinity of Virovitica, previously described as Late Pliocene–Early Pleistocene in age (GALOVIĆ et al., 1981; MARKOVIĆ, 1986), unconformably overlie the Pliocene "Rhomboidea beds", and are unconformably overlain by Pleistocene loess, lacustrine–marsh silts and clays.

These sediments are well exposed in gravel/sand quarries (Cabuna, Rezovac, Bistrica) south of the Drava river (Fig. 1), and their thickness varies reaching a maximum of 50 m. They are tectonically deformed and, in most cases, dip towards the North or Northeast.

The basal part of the clastic complex, known as the "Belvedere beds", is alluvial to lacustrine in origin. BABIĆ et al. (1978) suggested the Late Pliocene age, while PRELOGOVIĆ & VELIĆ (1992) presumed a Lower Pleistocene age for these sediments. Quartz gravels predominate, interbedded with thin beds of arkose sandstones, clays and marls. According to GALOVIĆ et al. (1981) high-grade metamorphic rocks were the source of the clastic material. The real thickness of the gravels can not be measured, because the basal part of these sediments is not exposed at the surface.

The upper portion of the clastic complex consists of arkose sandstones with very thin clay intercalations. At surface outcrops sands directly overlie the basal "Belvedere beds", but in deep hydrological bore-holes, clay with peat intercalations occurs at the base of these sediments. An Early Pleistocene age was proposed by BABIĆ et al. (1978). A lack of index fossils in these sediments precludes a precise biostratigraphic analysis.

2. LITHOLOGY

The investigated sediments are in most cases horizontal or subhorizontal, tectonically undisturbed, except in the Cabuna quarry, where they thin towards the Northeast. Gravel is predominant in the 5–20 m thick lower portion of the clastic complex, while sand dominates in the upper 10–40 m of the investigated sections.

Gravel consists almost completely of quartzite clasts (95%), with scarce clasts of sandstones, metamorphic rocks and dolomites. Clasts are subrounded to rounded, varying from granule to cobble size. Small pebbles (4–32 mm in diameter) predominate. The largest cobbles are 256 mm wide. Clasts are supported with a fine–coarse-grained sand matrix. Some units exhibit open-framework packing. Clast sorting varies from moderate to good.

Sand is extremely rich in quartzite grains, associated with a stable muscovite and labile, predominantly feldspar component, together with lithoclasts of carbonate and metamorphic rocks. They vary from fine- to coarse-grained types, but medium-grained type is dominant. Grains are subrounded to rounded, with generally good sorting. Bedding is clearly visible. Trough-cross to tabular-cross stratified sets are up to 0.4 m thick. Most of the sandy portions exhibit synsedimentary deformations. The cross-stratification measurements suggest eastern and northeastern directions of the palaeostreams.

Fine-grained sediments are silts, clays and marls composed of clay minerals and silt-grade quartz. X-ray analysis has shown that these sediments contain calcite, dolomite, quartz, muscovite–illite, chlorite and smectite (Table 1). Carbonate minerals (calcite and/or dolomite) could be of detrital or authigenic origin. Smectites (predominantly montmorillonites) are possible products of volcanic ash. Illite is probably of the same origin

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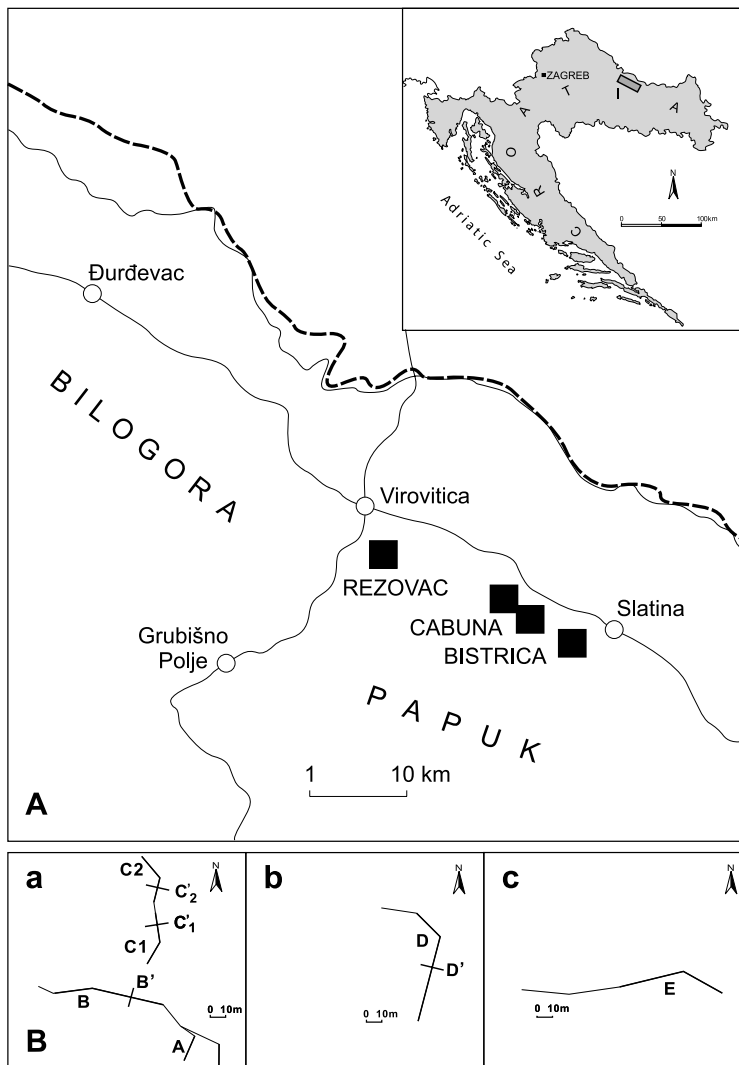
Fig. 1 (A) Location map. (B) Position of lateral profiles and logs: a) Cabuna quarry, b) Rezovac quarry, c) Bistrica quarry.

(KELLER, 1970), although it can also be the result of diagenetic processes if the temperature is below 50°C, and potassium ion concentration between 0.2 and 0.3% (BAILEY, 1987), which is not very likely in this case. Quartz and chlorite are also probably of detrital origin. Fine-grained sediments alternate with thin intervals (0.2–2 m) of horizontally and cross-stratified sands.

3. METHODS

The architectural-element and bounding surface analysis methods developed by MIALL (1985, 1988a, b) follow-ing earlier work by BROOKFIELD (1977) and ALLEN (1983) were used in examination of lateral and vertical facies changes and environmental interpretation. For this purpose, laterally extensive outcrops in the gravel/sand quarries located between Virovitica and Slatina (Figs. 1 & 2) were selected for study. Their sedimentological analysis consists of sketching primary sedimentological features, measuring grain size, and palaeocurrent directions and making photomosaics of the entire length of each exposure. In order to utilize photomosaics properly, maximum resolution and minimum geometric distortion of the features is achieved. Characteristic details were noted by close-up photographs. A

sample phase	12	13	14	15	17	CII9	SK
Calcite	-	+	+	-	-	+g	+g
Dolomite	+	+g	+g	+	+g	-	-
Quartz	+g	+g	+g	+	+	+	+g
Muscovite-illite	+g	+	+	+	+	+	+
Chlorite	+g	+	+g	+g	+g	+	+
Smectite	+	+g	+	+g	+g	-	-

Table 1 X-ray analysis of fine-grained sediments. Legend: g) main mineral in sample; +) accessory mineral in sample; -) no mineral in sample.

Fig. 2 Detailed sedimentological analysis of profile B was done using mountaineering equipment.

study of lithological and sedimentary features enabled a six-fold bounding surface hierarchy to be established (Table 2) and eight architectural elements (Table 3) and 13 lithofacies (Fig. 5) were distinguished.

4. LATERAL PROFILE ANALYSIS

The contact between lower (gravelly) and upper (sandy) portions of the investigated profiles is sharp, partly marked by an erosion surface with well developed palaeorelief, up to 1 m high (Figs. 7a, b, 17a, b). Along the B-profile in Cabuna quarry palaeosols were detected at the base of sands.

4.1. Gravel complex

In vertical sections the lower part is generally well sorted, with clearly visible gravel bodies in the form of sheets (element GS) (Figs. 3 and 4). The thickness of gravel sheets varies between 10–40 cm, and their lateral extent is from 10 to >20 m. Clasts in gravel sheets vary from granules, through pebble, to cobble size. Sheets with smaller clasts are more extensive than those with coarser grains. In cobble-sized sheets imbrications of the b-axis are visible, but poorly developed.

Well developed flat bedding (Facies Gh) up to the massive, non-stratified portions (Facies Gm) can be distinguished. Sheet base varies from erosionally irregular, to planar, or amalgamated. Upper sheet surfaces can be smooth, or also amalgamated. Sheets are in most cases composed of a combination of flat-bedded pebble-sized gravels, granule gravels and laminated coarse grained granule sands (Facies Gh, Sh).

At some places elements of sheets surround planar cross-stratified sets of sand gravels with pebble-sized clasts, 30–50 cm thick (Facies Gp) (Fig. 6a, b). Inclination of foresets is towards the south and southwest. This facies is very scarce in comparison with Gh and Gm facies.

The upper part of the gravel complex is 1–2 m thick, in the Cabuna and Rezovac quarries it is characterized by horizontal- and cross-stratified, 10–30 cm thick gravel sets with pebble or granule-sized clasts (Facies Gh and Gp). Set bases are usually erosional and they

Order	Description	Interpretation
First	Boundaries between sets. Generally slightly erosive and flat. Surfaces can be traced few cm to few meters.	Represent deposition of the same small- to medium-scale units (ripples, dunes, horizontal lamination).
Second	Boundaries between sets or cosets assemblages. Slightly erosive, flat or concave. Surfaces can be traced few dm to few meters.	Represent slight changes of flows during continued sedimentation.
Third	Present within sets and/or cosets assemblages. Dip 5-25 down, oblique or transverse to flow. Slightly erosive, flat or concave. Can be traced >1 m along flow. Facies assemblages above and below the surfaces similar.	Represent reactivation surfaces within macroforms indicating flow changes and changes of bedform orientation.
Fourth	Bounding surfaces of macroforms such as LS, DLA, DU, LB and CS. Either erosional (irregular or concave-up) or accretionary flat to undulatory or convex-up) surfaces extending 5 m to >20 m laterally.	Separate elements with similar palaeocurrent patterns, grain size, facies assemblages, as well as channel complexes from floodplain elements.
Fifth	Erosional flat, irregular or concave-up with up to 1 m relief extending >50 m transverse to flow direction. Overlain by coarser deposits than underlying ones.	Lower bounding surfaces of CH, HF and GS elements. Erosionally truncated channell-fill and floodplain elements.
Sixth	Erosional flat to irregular surface extending several km laterally. Incised into GS elements.	Encompass stacked CH elements. Indication of allocyclic, mainly tectonic processes.

Table 2 Bounding surface hierarchy in the Pliocene alluvial sediments.

Architectural elements	Lithofacies assemblages	Description
GS Gravel sheets	Gh (minor Gm, Gp, Sh)	Sheet-like bodies, 0.1 to 0.4 m thick extending 10 m to >20 m. Composed of Gh, rarely of Gm, Gp and Sh. Basal surfaces erosionally irregular to flat or indistinct (amalgamated). Upper surfaces flat or indistinct.
Sand channel-fill		
CH Sand channels	Sp, St, Sh, Sl (minor Ge, Se, Si, Sr)	Sheet-like bodies, 0.1 to >8 m thick extending >50 m. Basal surfaces erosionally irregular or concave. Upper surfaces erosionally planar to concave. Composed of Sp, St, Sh, Sl and minor Ge, Se, Si and Sr. Embrace smaler-scale architectural elements such as DU, LS, LB DLA and rarely HF and SF.
DLA Down-stream and lateral accretion macroforms	Sp, Sl (minor Sh and Sr)	Sheet-like or wedge-like bodies up to 3 m thick extending >15 m in downstream direction or down-dip direction. Composed of Sp, Sl and rarely of Sh and Sr. Reactivation surfaces within bodies. Erosively irregular to planar bases and upper surfaces.
DU Sand dune complexes	St, Sp, (minor Sl, Ge, Se)	Sheet-like bodies 0.4 m to 3 m thick and extending >20 m laterally. Composed of amalgamated dunes (St, Sp, and rarely Sl, Ge and Se). Multistorey bodies with erosively irregular or concave bases. Upper surfaces irregulary eroded, where not eroded planar or even gradational with overlying elements.
LS Laminated sand sheets	Sh, Sl, (minor Sp, St, Ge, and Se)	Sheet-like bodies 0.5 m to 2 m thick and extending >30 m laterally. Planar stratified sands with common parting lineation, laterally transition to low-angle planar cross-stratified sands (Sh, Sl, minor St, Sp, Ge and Se). Erosively irregular, planar to concave lower surfaces. Upper surfaces erosively planar to concave, where not eroded planar to slightly convex.

Table 3 Summary of architectural elements in the Pliocene alluvial sediments.

extend laterally for up to 5 m. Cross-stratified sets are wedge-shaped, often with reactivated surfaces. In most cases they are separated from each other by stratified gravel sets. Gravel sets are often interbedded with 5–15 cm thick horizontally stratified granular sands, of >3m lateral extent (Facies Sh) (Figs. 4, 8 and 9). Some stratified sands are normally graded or massive, or show low angle planar cross stratification, but, in most cases,
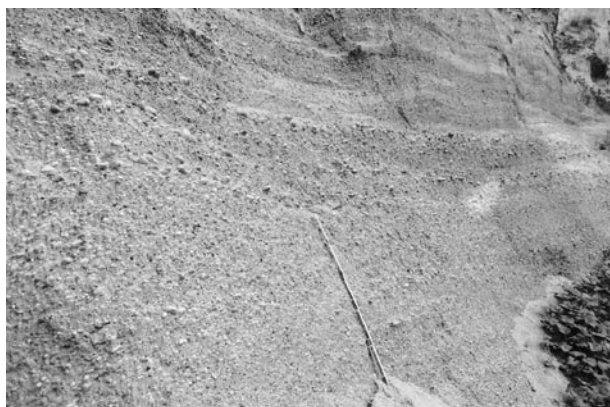

Fig. 3 Well developed flat bedding gravels (Facies Gh). Stick is 1 m long. Profile B, Cabuna quarry.

Fig. 4 Gravel sheets (GS) composed of facies Gh. The top of the gravel complex is composed of facies Gh, Sl and Sh. Stick is 1 m long. Profile B, Cabuna quarry.

Architectural elements	Lithofacies assemblages	Description
LB Linguoid bedforms	Sp (minor St, Sl, and Sh)	Sheet-like bodies, 0.5 to 2 m thick extending >10 m. Composed of amalgamated sets or group of sets. Basal surfaces erosionally irregular to concave. Upper surfaces graditional or erosionally flat to irregular.
SF Scour fills	Ge, Se (minor Gt)	Lens-like bodies, 0.1 to >0.7 m thick extending to 5 m. Sheet-like bodies, 0.1 to >0.5 m thick extending >10 m. Composed of sands with granules and mud clasts. Basal surfaces erosionally irregular or concave. Upper surfaces graditional to erosionally flat or slightly convex.
HF Hollow fills	Si, Sl (minor Sp)	Lens-like bodies, to 3.5 m deep and to 12.5 m wide. Composed of granule sands to sands. Basal surfaces erosionally concave (trough like). Upper surfaces gradational to planar.
Floodplain complexes		
OF Overbank fines	Fm, Fl (minor Sh, Sr)	Sheet-like bodies 0.1 m to 1.5 m thick and extending >60 m laterally. Basal surfaces planar or transitional. Erosional or irregular upper surfaces. Composed of silts and muds with common leaf prints, rare rooth traces and mudcracks. Very rare horizontal and riple cross-laminated sands.
CS Crevasse splays	Sh, Sl, (minor Sp, St, and Sr)	Sheet- or wedge-like bodies 0.2 m to 2 m thick and extending >20 m laterally. Erosively planar to concave lower surfaces and planar to transitional upper surfaces. Composed of planar stratified sands with common parting lineation, trough and planar cross-stratified sands and ripple cross-stratified sands in the top part.

Table 3 (Continued).

they are horizontally stratified (Facies Sh). Their bases are flat to irregular, scarcely concave or indistinct, continuously deposited over the gravels.

The median part of the gravel complex at the A-profile in Cabuna (Fig. 6a, b) is characterized by a well developed erosional basal surface (5th order bounding surface, Table 3) with erosional relief of >3 m, incised into a 4 m thick sandy interval. The erosion becomes invisible at the right-side of the profile, due to the complete erosion of the sandy interval (amalgamated gravels). Near the erosion surface, gravels are massive or indistinctly stratified, and they contain <0.4 m diameter angular intraclasts of marls and clays (Facies Ge). The sandy interval is built up of planar to low angle cross-stratified sand units, which show synsedimentary deformation.

4.2. Sand complex

The sandy part of the profiles generally show a fining upward feature. In the Cabuna quarries the upper parts of the profiles are represented by ca. 10 m thick packages of fine-grained sediments (Profile B) (Fig. 7a, b). Description of sedimentary structures and architectural elements in the Cabuna and Bistrica sand-quarries is difficult because of synsedimentary deformation (Figs. 7a, b, 10a, b, 11a, b, 17a, b). Two types of sedimentation can be distinguished: channel and floodplain sedimentation (Table 4).

4.2.1. Channel elements

Sand profiles C1 and C2 (Figs. 10a, b, 11a, b) and sandy portions of profiles B in the Cabuna quarry (Fig. 7a, b), profile D in Rezovac quarry (Figs. 13 and 14) and profile E in the Bistrica quarry (FigS. 17a, b) are characterized by vertically superimposed sedimentary units in the form of sheets.

Sandy sediments consist of 1–8 m thick sandy channel sequences, over 50 m in lateral extent. A complete sequence, with a distinct fining upward trend in the upper portions, can only be observed in profiles B and D. Sandy gravels gradually pass into very coarse-grained sands, then fine-grained, cross- to horizontally stratified sands overlain by fine grained floodplain sediments (Figs. 7a, b, 13 and 14). In other cases sequences are incomplete – the uppermost parts are missing due to erosion. The base of the channel fill (5th order bounding surface, Table 3) is irregularly erosional, ca. 1 m incised into the base sediment, and it is built up by mas-
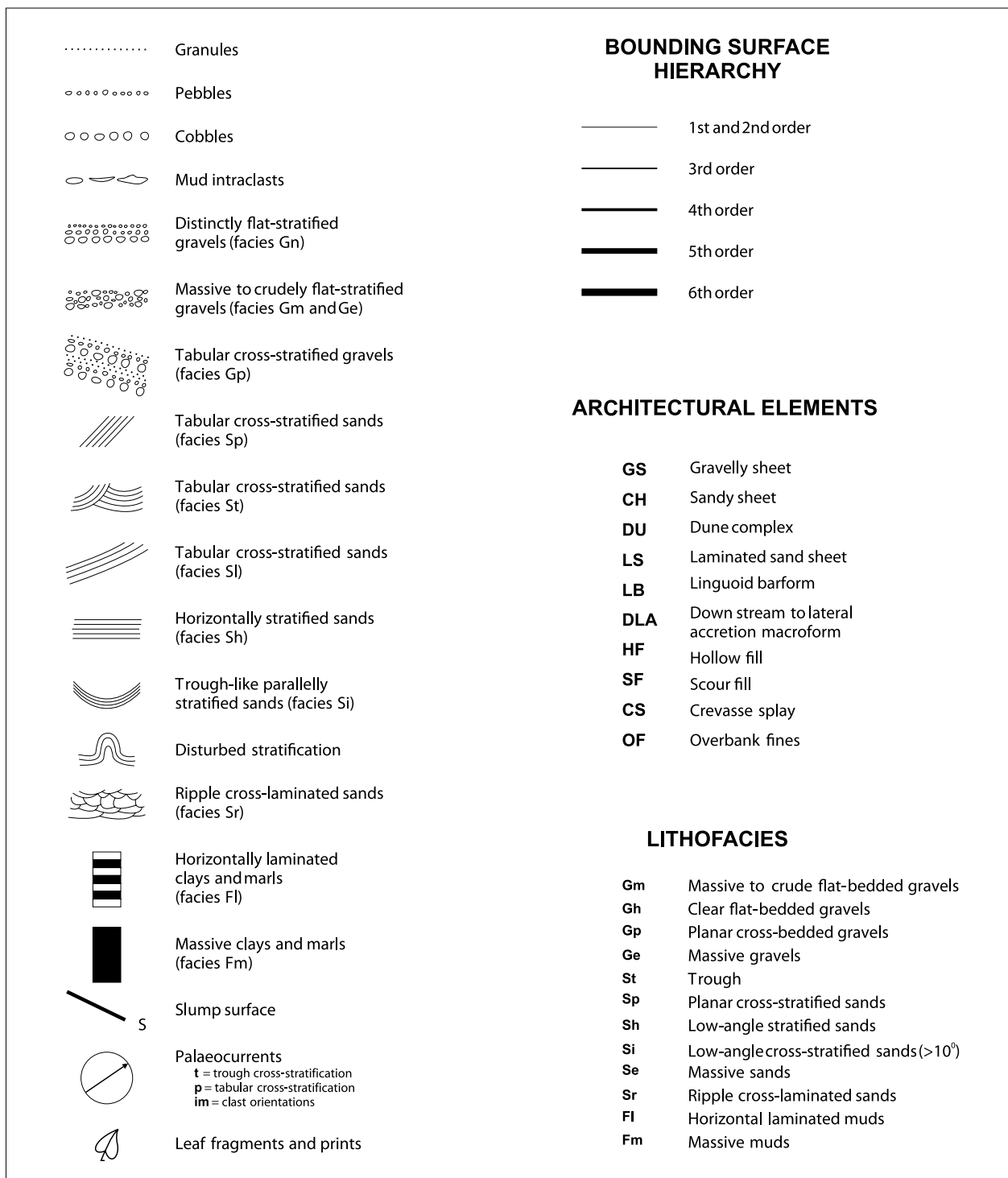
Granules

Pebbles

Cobbles

Mud intraclasts

Distinctly flat-stratified
gravels (facies Gn)

Massive to crudely flat-stratified
gravels (facies Gm and Ge)

Tabular cross-stratified gravels
(facies Gp)

Tabular cross-stratified sands
(facies Sp)

Tabular cross-stratified sands
(facies St)

Tabular cross-stratified sands
(facies Sl)

Horizontally stratified sands
(facies Sh)

Trough-like parallelly
stratified sands (facies Si)

Disturbed stratification

Ripple cross-laminated sands
(facies Sr)

Horizontally laminated
clays and marls
(facies Fl)

Massive clays and marls
(facies Fm)

Slump surface

Palaeocurrents
t = trough cross-stratification
p = tabular cross-stratification
im = clast orientations

Leaf fragments and prints

BOUNDING SURFACE HIERARCHY

1st and 2nd order

3rd order

4th order

5th order

6th order

ARCHITECTURAL ELEMENTS

GS	Gravelly sheet
CH	Sandy sheet
DU	Dune complex
LS	Laminated sand sheet
LB	Linguoid barform
DLA	Down stream to lateral accretion macroform
HF	Hollow fill
SF	Scour fill
CS	Crevasse splay
OF	Overbank fines

LITHOFACIES

Gm	Massive to crude flat-bedded gravels
Gh	Clear flat-bedded gravels
Gp	Planar cross-bedded gravels
Ge	Massive gravels
St	Trough
Sp	Planar cross-stratified sands
Sh	Low-angle stratified sands
Si	Low-angle cross-stratified sands ($>10^0$)
Se	Massive sands
Sr	Ripple cross-laminated sands
Fl	Horizontal laminated muds
Fm	Massive muds

Fig. 5 Legend for profiles and logs and lithofacies description.

sive to indistinctly cross-stratified coarse-grained sands and intraclasts (channel lag) of fine grained overbank sediments (Facies Ge and Se) (Figs. 11a, b, and 15).

Besides the described basal facies, several other sandy facies were observed. Planar cross-stratified sets (Facies Sp) are rather frequent at all localities. These sets extend up to 5 m in lateral view. The thickness of sets varies from 10–40 cm (Figs. 16 and 19), usually increasing in a downstream direction, and their basal surface changes from non-erosive to erosive. Contact of the foresets and lower boundary surface is angular or asymptotic. Looking downstream, modification of foresets can be observed, from angular (with gradient 20–25°) to asymptotic (gradient 10–15°), or even sigmoid. Reactivated surfaces (3rd order bounding surface, Table 3) can often be observed in sections parallel to the inclination of foresets. Reactivated surfaces are usually less inclined than foresets (gradient 10–20°), and can extend through one or several sets. These surfaces are usually overlain with coarse grained sand, with scattered gran-
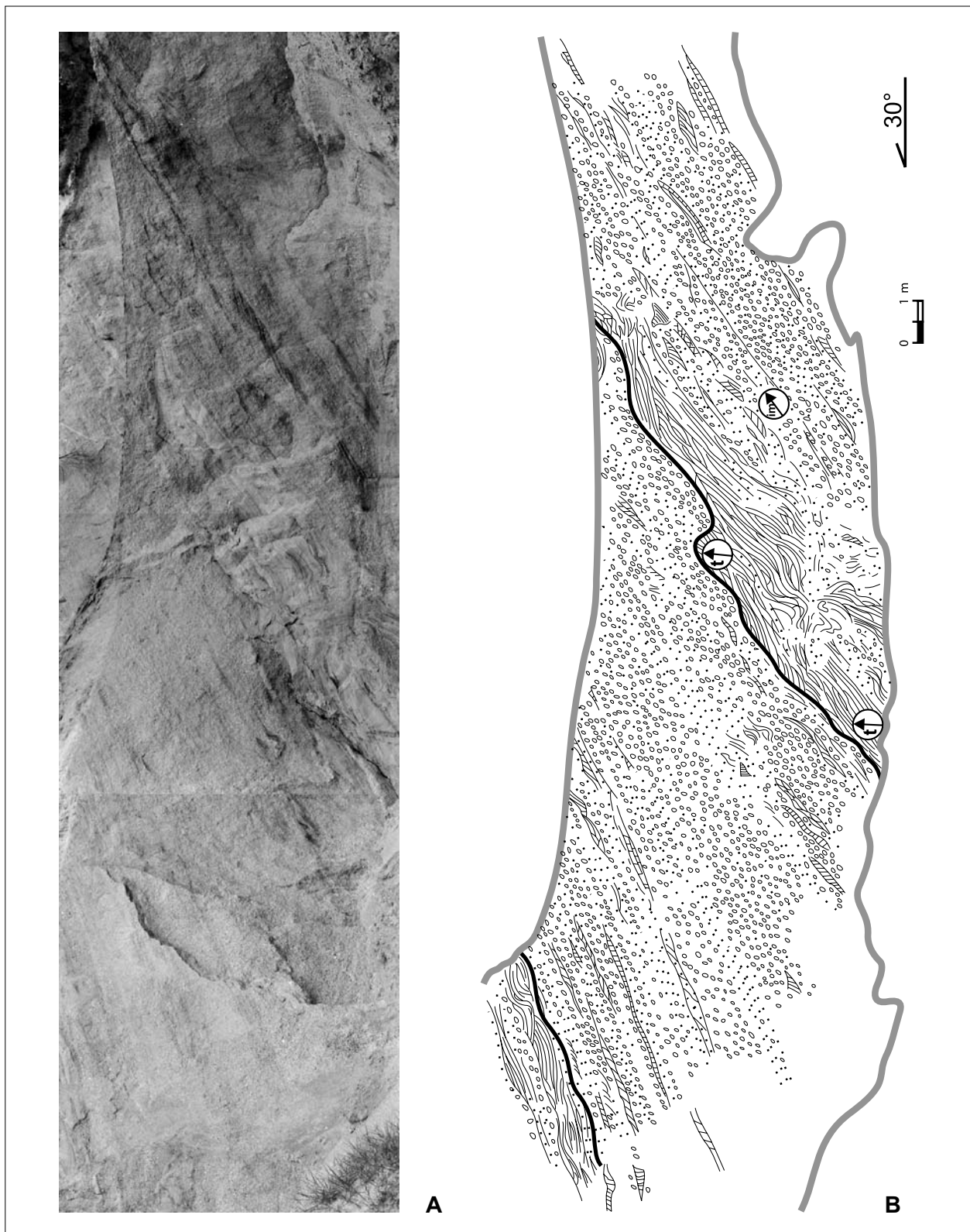
Fig. 6 (A) Photomosaics of Profile A. Cabuna quarry. (B) Detailed sketch of Profile A. Legend is shown in Fig. 5. Lithofacies and element description and interpretation are shown in Fig. 5 and Tables 2 and 3.

ules. In most cases, the inclination of foresets below and above the reactivated surface is similar.

Trough cross-stratified sand units (facies St) are less frequent in the studied profiles. They occur as isolated sets or cosets (Fig. 18). Trough sets are 10–30 cm thick, with 40–80 cm wide troughs. Their foresets are asymptotic in the base, which is either irregular, or partly concave, due to erosion. They consist of medium to coarse grained sand. Inclination of foresets is from 10–20°, and the position of the trough axis is towards the north

PLANT GROUP	SPECIES
GINKGOES	*Ginkgo adianthoides* (UNGER) HEER
FLOWERING PLANTS	
A. HAMAMELIDIDAE	
Hamamelidales	*Liquidambar europaea* A.BRONGNIART
Fagales	*Fagus haidingeri* KOVATS
	"*Quercus*" ex.gr. *mediterranea* UNGER
	"*Q.*" cf. *lonchitis* UNGER
	"*Q.*" kamischinensis GÖPPERT
	Betula alba LINNÉ
	Alnus julianaeformis (STERNBERG) KVACEK & HOLLY
	Carpinus betulus LINNÉ
Urticales	*Ulmus laevis* PALLAS
Myricales	*Myrica lignitum* (UNGER) SAPORTA
	Myrica sp.
B. ROSIDAE	
Fabales (=Leguminosae)	Leguminosae gen. et sp. indet.
Sapindales	*Acer platanoides* LINNÉ

Table 4 Flora found in facies Fm and Fl. Profile B. Cabuna quarry.

or northeast. At the base of a trough, sands are in most cases coarse grained, with a high percentage of granules and even small pebbles. Within the trough cross-stratified sets it is hard to distinguish bounding surfaces from reactivation surfaces. Sets usually overlie erosional surfaces (5th order bounding surface), and partly alternate with planar cross-stratified and horizontally stratified sand sets.

Horizontally stratified sands (facies Sh) are present in relatively thin intervals (0.1–2 m; Fig. 19). They overlie the irregular erosional surface, or alternate with planar cross-stratified sands. In the former they contain coarse-grained sand with scattered granules, and are 0.5–2 m thick. Horizontally stratified sands extend laterally up to 10 m. In some cases, downstream, they become low-angle planar cross-stratified sets (Facies Sl).

At profiles E and B a concave depression (5th order bounding surface) can be observed (Figs. 7a, b, 17a, b and 20). It is symmetrically infilled with facies Si and Sl, and therefore resembles the infill of small channels. It is impossible to reconstruct the 3D geometry, but it is obvious that the axis dips in an upstream direction. Therefore it is presumed that the depression is trough-like rather than an elongate cylinder in shape. Its dimensions are 3.6x12.5 m.

4.2.2. Flood plain elements

The upper part of profile B and the uppermost portion of profile D are composed of silt clays and marls, alternating with medium- to fine grained sands and silts (Figs. 7a, b, 12–14).

Fine grained beds are 0.1–1.2 m thick, massive or horizontally stratified. Locally, these sediments contain numerous remnants of fossil macroflora (Table 4; Figs. 21–23). Sand and silt intervals take the form of sheets or lenses, with irregular erosive to concave bases (Figs. 7a, b, 12 and 14). They are 0.2–2 m thick, extending laterally from 5 to >20 m. They consist of low angle cross-stratified to horizontal stratified units, 0.05–0.3 m thick. Thin ripple sets can be observed in the upper portions of these bodies.

5. INTERPRETATION

5.1. Gravel complex

The vertical and lateral characteristics of gravel sheets (element GS) indicate that these sediments were deposited from catastrophic unconfined sheet flows that expand as they move down the steep slope of an alluvial fan, probably when leaving the channel at the top of the fan. Such sediments can be clearly distinguished from other gravitational flows due to their different hydraulic features (high Froude number, abrupt decrease of flow intensity, rapid deposition of material). Flow conditions were in most cases supercritical, due to the steep slope. Alternation of transportation and depositional phases of the coarse- and fine-grained gravel was caused by changes in hydraulic conditions during the expansion of flow and the decrease in slope inclination, as well as the autocyclic variations of depth and velocity of the supercritical flow. A large number of gravel sheets could have been deposited from a single catastrophic flow (BLAIR, 1987).

Facies Gp represents deposition from antidunes (Fig. 6a, b), which were moving together with the largest gravel clasts in the period of maximum velocity and
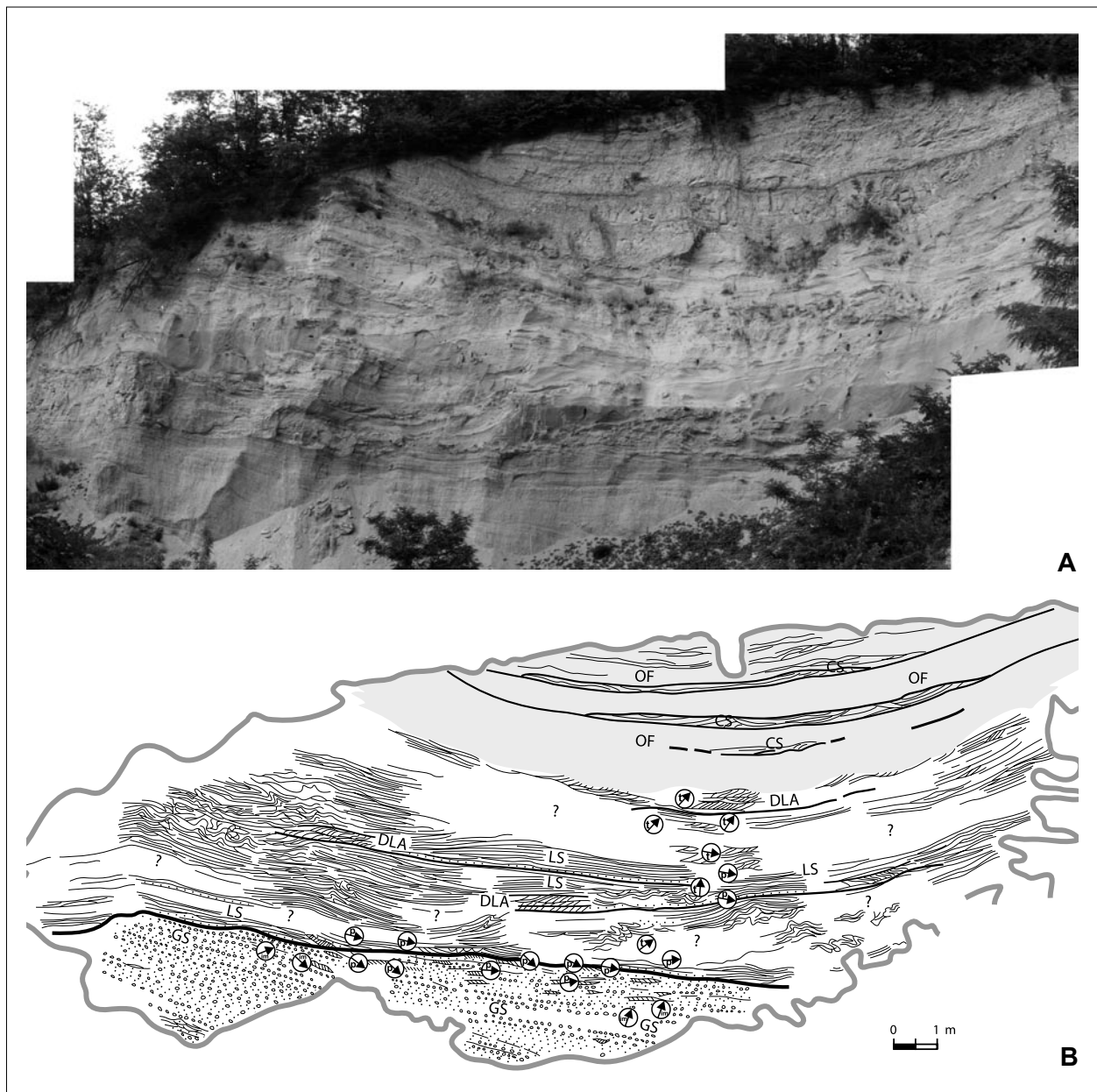
Fig. 7 (A) Photomosaics of Profile B. Cabuna quarry. (B) Detailed sketch of Profile B. Legend is shown in Fig. 5. Lithofacies and elements description and interpretation are shown in Fig. 5 and Tables 2 and 3.

height of the flow (BLAIR, 1987). Smaller, pebble and granule sized clasts, as well as sands, could have been suspended-load.

Massive gravel overlying the erosional surface in Profile A (Fig. 6a, b) was probably deposited from gravity flows (currents) in the incised fan channel (BLAIR & McPHERSON, 1994).

According to the lithology, facies associations and depositional processes, it can be concluded that the gravelly part of the section probably represents deposits of alluvial fans, with dominant gravel sheet facies. BLAIR & McPHERSON (1994) concluded that the majority of recent alluvial fans were deposited from cohesive debrite-flows (Type I alluvial fan), or from rapid streams in the form of sheets (Type II alluvial fan), which depend on the lithological conditions, as
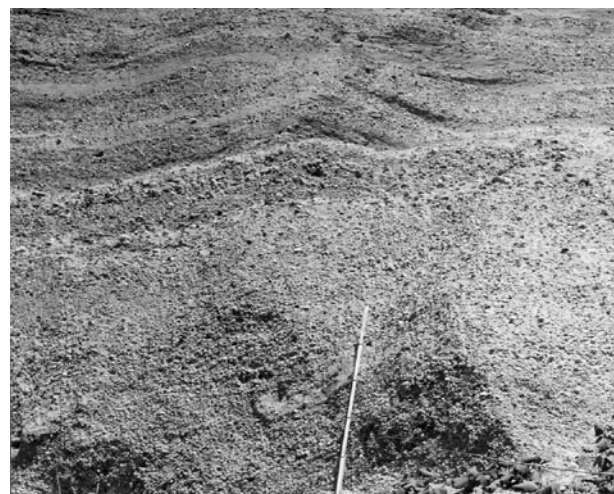
Fig. 8 Alternation of facies Gh, Gp and Sh on the top of the gravel complex. Stick is 1 m long. Profile B, Cabuna quarry.

Fig. 9 Facies Gh and Gm with lens-like facies Sh and Sl on the top of the gravel complex. Scale is 10 cm long. Profile D, Rezovac quarry.

well as on weathering processes in the fan drainage area.

Investigated gravels originate from a hinterland composed of quartz conglomerates and sands and/or rapidly uplifted and eroded granites and gneisses. North and north–east palaeotransport directions indicate a possible source area – the crystalline massifs of the Psunj and Bilogora Mts. Hard rocks of different lithologies must have been poorly chemically, but strongly mechanically weathered. This can be concluded from the dominant sheet elements and their lithological composition, with the absence of clays.

Facies types in the upper part of the gravel complex could represent deposits from a very shallow braided river system, with low longitudinal bars deposited during the decrease of the catastrophic flow, or between the two catastrophic flows, during the phase of erosion processes and modification of fan morphology. Such secondary processes are particularly common in Type II alluvial fans, due to the erosive capacity of their surfaces (BLAIR & McPHERSON, 1994).

5.2. Sandy complex

5.2.1. Channel elements

The main feature of the sandy portions of the analyzed profiles is the presence of sandy channels (element CH), which were in most cases deposited by torrents or floods. Rapidly deposited channel complexes consist of dunes (element DU), lateral or downstream elements (element DLA), linguoid bedforms (LB) and laminated sand sheets (LS).

Down-stream and lateral accretion macroforms (DLA), with radial distribution of migration directions, and overlain by DU and/or LS elements, can be compared with cross-channel bars (CANT & WALKER, 1978) or with mid-channel or side bars (MIALL, 1988b). The thickness of DLA elements varies from 0.5–3 m, depending on the channel depth and growth direction (parallel, oblique or perpendicular to the main direction of the palaeostreams). Though it is impossible to determine their exact length and width in the profiles, it is obvious that they were longer than 15 m. In

most cases these units decrease in thickness and grain size upwards, due to the decline of the stream and long term deposition by moderate to slow streams (MIALL, 1991).

Laterally broad (0.5–2 m wide; >30 m long) LS elements are common within the channel complex. Thin, but prominent scour fills (SF), parting lineation and numerous granules within the Sh facies indicate rapid deposition during the upper flow regime, and turbulent conditions, with a velocity probably in excess of 1 m s^{-1} (HARMS et al., 1975; ALLEN, 1983, 1984). Analysis of the geometry of the sedimentary body and the facies has shown the presence of long and narrow macroforms, possibly "plane-bedded simple bars" (PBSB) or compound bars described by ALLEN (1983) or "plane-bedded macroforms" (PBM) as described by MIALL (1988). It can be concluded that they were the result of seasonal changes in permanent, long-lasting flows.

LB elements are relatively scarce on DLA and LS elements (Profiles C1, C2 and D). They were deposited during decreases in the flow intensity.

Each of the elements described above, can be partly interpreted as a segment of a complex, large and long-lasting macroform, probably a sand flat sensu CANT & WALKER (1978). Under such conditions, the upper parts of DLA elements, which would be exposed during reductions in the flow rate, could represent a core, from which complex sand flats were deposited, through vertical aggradation and down-stream accretion.

Dune elements (DU) migrated down the deeper parts of a channel and/or covered sand bodies or sand flats (DLA, LS, LB), during periods of decreased flow rate or during the low-intensity flows. In most cases palaeocurrent directions are similar. Locally, dunes could have migrated obliquely or transversely to the main palaeocurrent direction (e.g. on the flanks of sand flats).

The origin of depressions (HF element) can be attributed to processes producing deep incisions where channels converged. Such processes were investigated both in the field and under laboratory conditions (MOSLEY, 1974; BEST, 1988). These studies have shown that deep erosion is typical for channel junctions, which
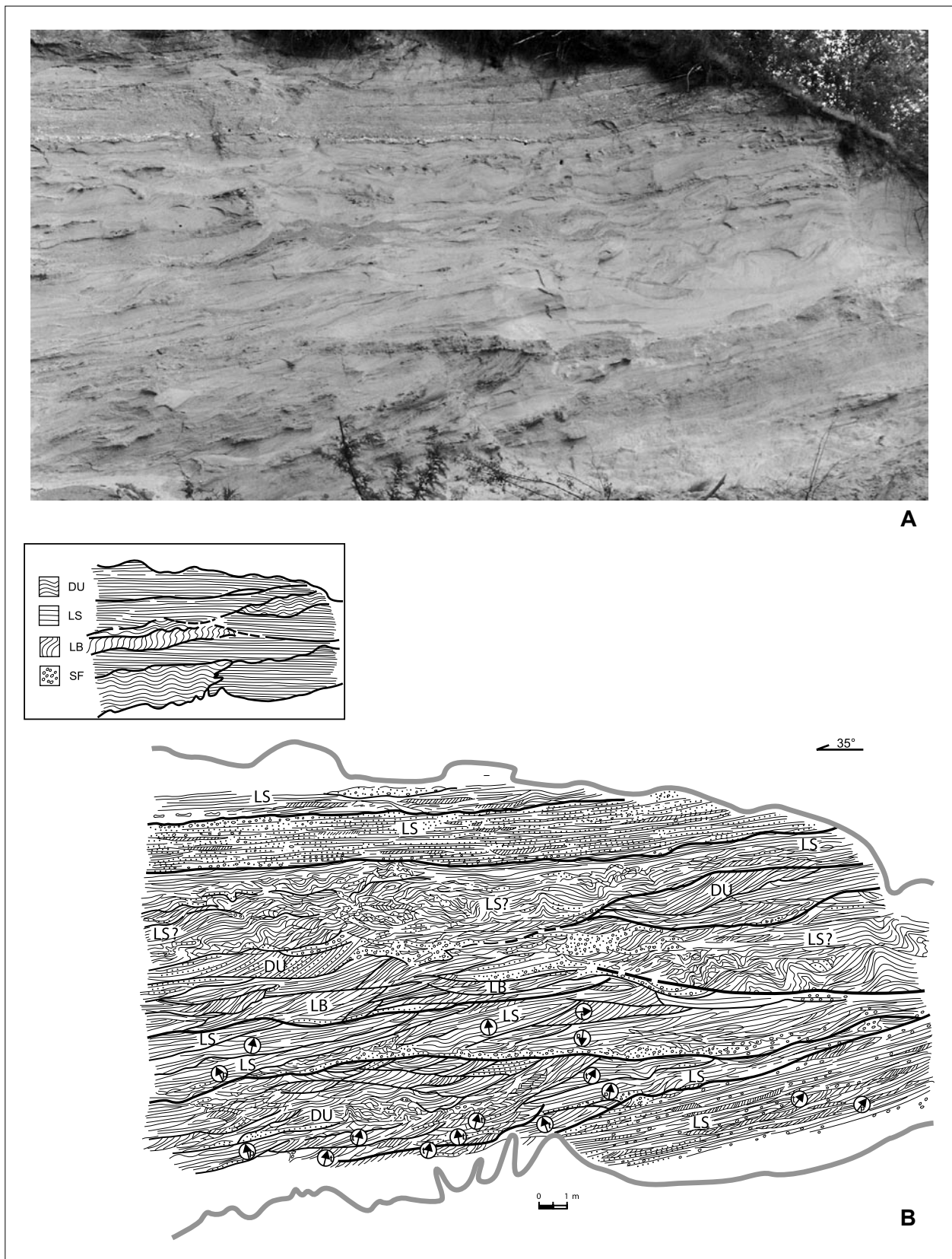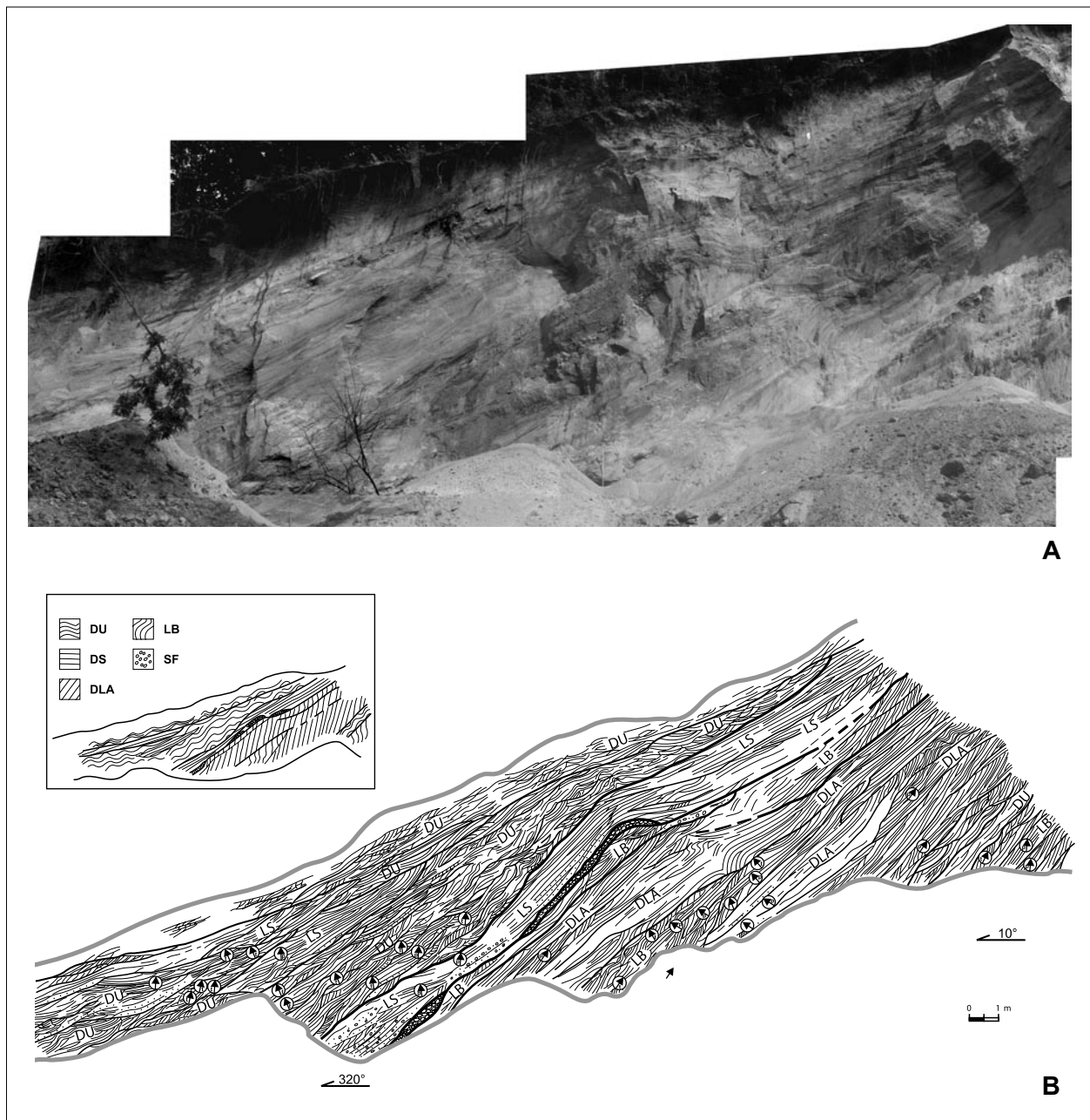
Fig. 10 (A) Photomosaics of Profile C1. Cabuna quarry. (B) Detailed sketch of Profile C1. Legend is shown in Fig. 5. Lithofacies and elements description and interpretation are shown in Fig. 5 and Tables 2 and 3.

are common in braided river systems (BEST, 1988).

Comparing different localities, current directions are variable, despite the low meandering rate of the river system. Therefore, significant dispersion of palaeocurrent directions can be observed. Lateral migration of the main channels was a continuous process, resulting in destruction or modification of sand flats. Avulsions, as well as aggradations and channel interruptions were

Fig. 11 (A) Photomosaics of Profile C2. Cabuna quarry. (B) Detailed sketch of Profile C2. Legend is shown in Fig. 5. Lithofacies and elements description and interpretation are shown in Fig. 5 and Tables 2 and 3.

common. Main channels were shallow (1–8 m, usually 1–3 m deep), very wide (>50 m), low grade sinusoidal (not highly meandering), with a general direction towards the north–east and east.

According to the geometry of the sediments, lack of palaeosols and palaeobotanical data, it can be concluded that the climate was humid, which enabled permanent streams, with periodic (seasonal?) flooding. The sandy parts of the profiles can be interpreted as rapidly deposited sediments in wide, low-meandering and complex channel environments. Presumed channel activities were similar to those in recent sandy braided rivers (SMITH, 1970; MIALL, 1977; CANT & WALKER, 1978).

5.2.2. Flood plain elements

The upper part of Profile B represents a relatively thick (10 m) sequence of flood plain (lacustrine?) deposits, laterally extending for more than 60 m. Sheet-like overbank fines (element OF) deposited after infilling of the channels by torrents are dominant, with several interstratified crevasse splays (element CS), deposited in shallow stagnant water on a flood plain after the penetration of levees. They are composed of rapidly deposited sands (Facies Sh and Sl), which are, in some places convoluted and overlain by facies Sr, deposited during the declining flow. Sheet geometry and fine grain size indicate that these sediments were deposited distally from the main channel, although precise distances can
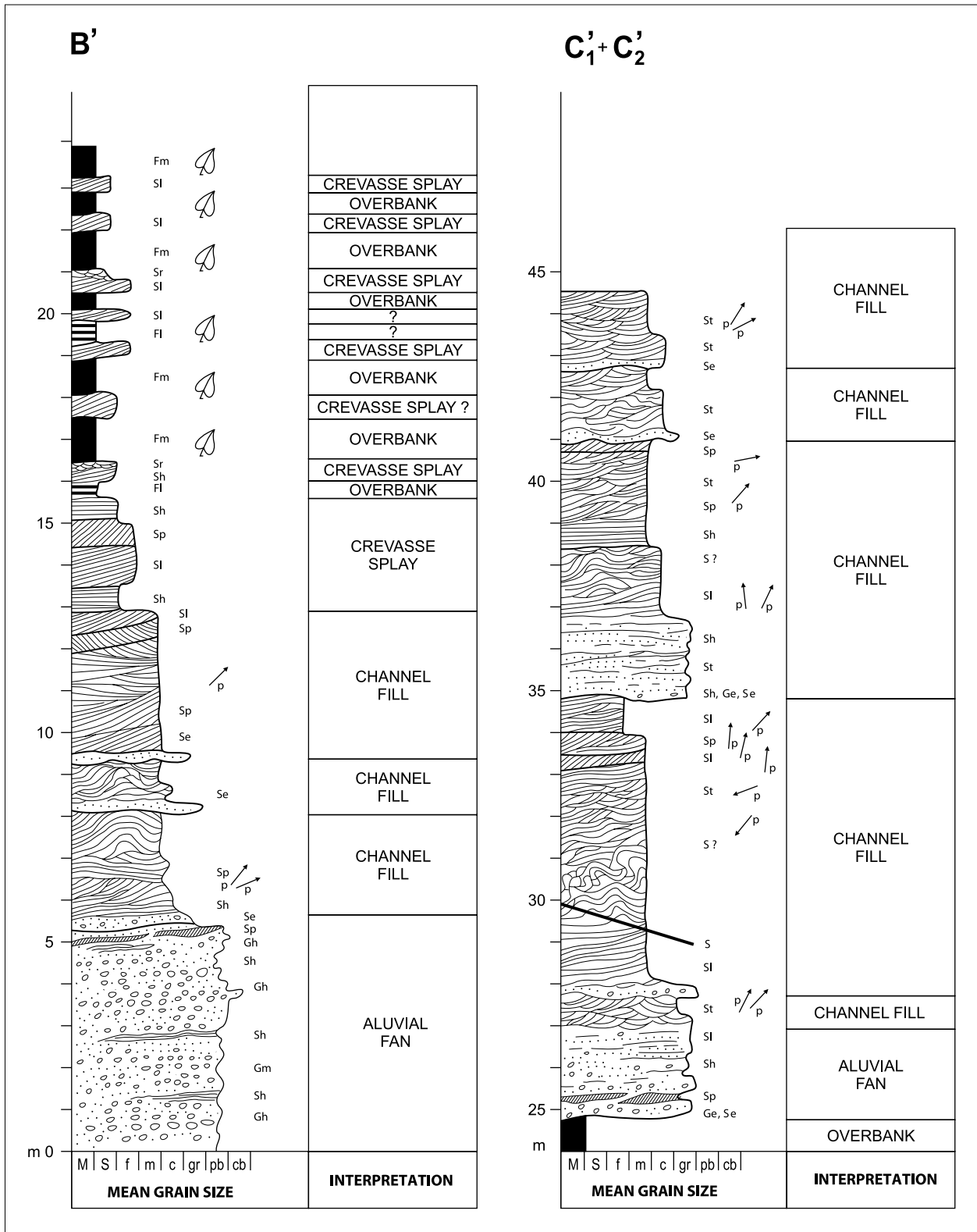
Fig. 12 Logs B and C. Legend is shown in Fig. 5. Cabuna quarry.

not be determined on the profile. Dominant CS elements and a lack of palaeosols indicate frequent flooding episodes.

Well preserved plant fossils were discovered in the fine-grained sediments. Flowering plants (angiosperms) are more common than gymnosperms (ginkgoes only)

(Table 4). Maple (*Acer*) and hornbeam (*Carpinus*) remnants predominate (Figs. 22 and 23). *Liquidambar*, *Myrica* and Mediterranean oaks are relics of the Miocene–Middle Pliocene warm period. Warming may have been related to changes in ocean circulation patterns, possibly combined with the greenhouse effect (CHAN-

Fig. 13 Numerous sets of planar cross-stratified sands in the upper part of log D. Part of log D is about 10 m long. Rezovac quarry. See legend on Fig. 5.

Fig. 14 Log D. Rezovac quarry. Legend is shown in Fig. 5. Lithofacies and element description and interpretation are shown in Fig. 5 and Tables 2 and 3.

DLER, 1997). The presence of betulaceans (beech, alder) indicates cooling of the climate, typical for the end of the Pliocene. Maples and hornbeams are known as the first colonizers of the unconsolidated soils. *Ginkgo adianthoides* (Fig. 21) similar to its recent congeneric, *G. biloba* LINNÉ, is an ecologically conservative genus. Throughout the late Cretaceous and Cenozoic, it was largely confined to disturbed streamside and levee environments (ROYER et al., 2003), and it can not be found at European and American localities after the Pliocene (see www.ucmp.berkeley.edu/seedplants/ginkgoales/gingkofr.html).

Thin, fine grained sediments (OF) in the uppermost part of profile D (Rezovac) were probably deposited on sand flats during a low water stand, when most of these sand macroforms acted as islands. OF elements were emergent and partly eroded during the periodic floods.

6. DEFORMATION STRUCTURES

Synsedimentary deformation of loose sands are well developed at the investigated localities. LS and DU elements (Table 4) in Profiles B, C1 and C2 (Figs. 7a, b, 10a, b, 14a, b) are partly or completely convoluted. Convolution can be described as a series of steep, high (0.5–1.5 m) antiforms divided by 1–3 m wide synforms. In most cases convolution was single phased, and it did not include previously deformed, cross-stratified sands. Large scale, multiphase deformation was observed exclusively within LS elements in profiles B and C1.
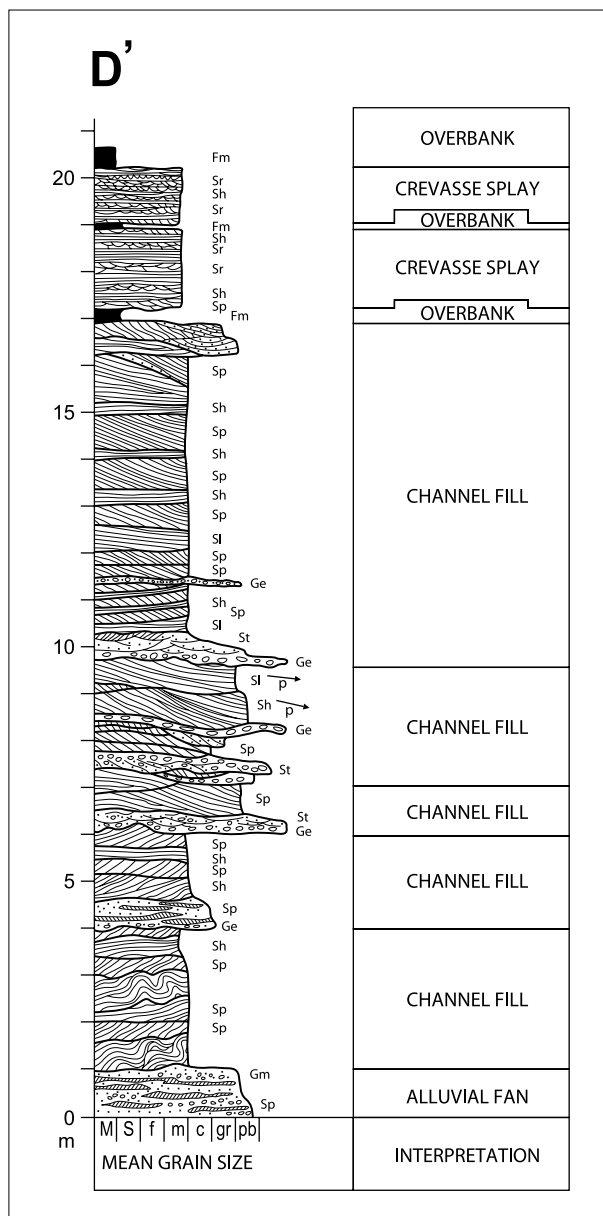
Such deformation includes several sets, and is abruptly interrupted in the base by a synsedimentary reverse fault (Fig. 24). Small blocks of massive sand indicate synsedimentary slumping. This deformation is also marked with antiforms, slightly overturned in the palaeocurrents direction.

Oversteepening and overturning can also be observed within isolated sets of HF, DLA and LB elements (Fig. 25). Deformations vary from foresets inclined more than the angle of rest to overturned foresets which resemble the overturned folds. Deformation increases in the upper part of the profiles.

Convolute deformations are partly of intrinsic origin, produced by synsedimentary processes (LEEDER, 1987). ALLEN (1984) interpreted these processes as

Fig. 15 Base of sand channel (5th bounding surface) overlain by facies Ge and Se. Hammer is 30 cm long. Profile C2. Cabuna quarry.
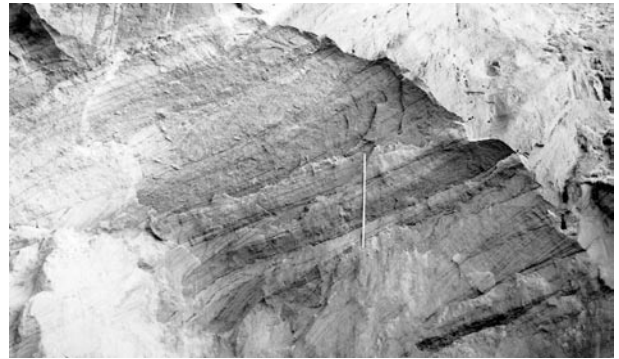

Fig. 16 Sets of planar cross-stratified sands (facies Sp) and horizontally stratified sands (facies Sh). Transition from planar cross-stratified sands to low-angle cross-stratified sands (facies Sl) and reactivation surfaces can be observed. Stick is 1 m long. Profile C2. Cabuna quarry.
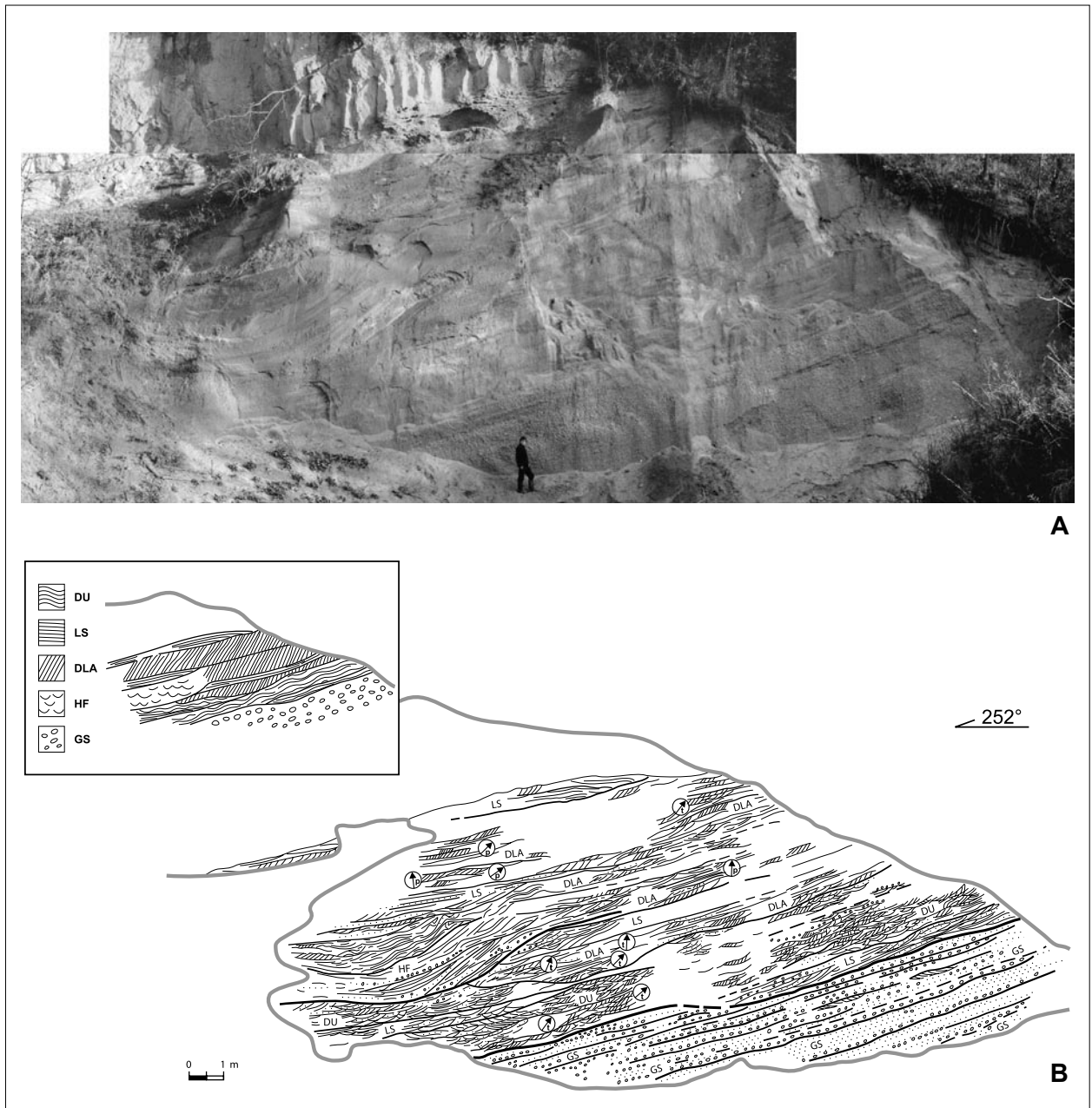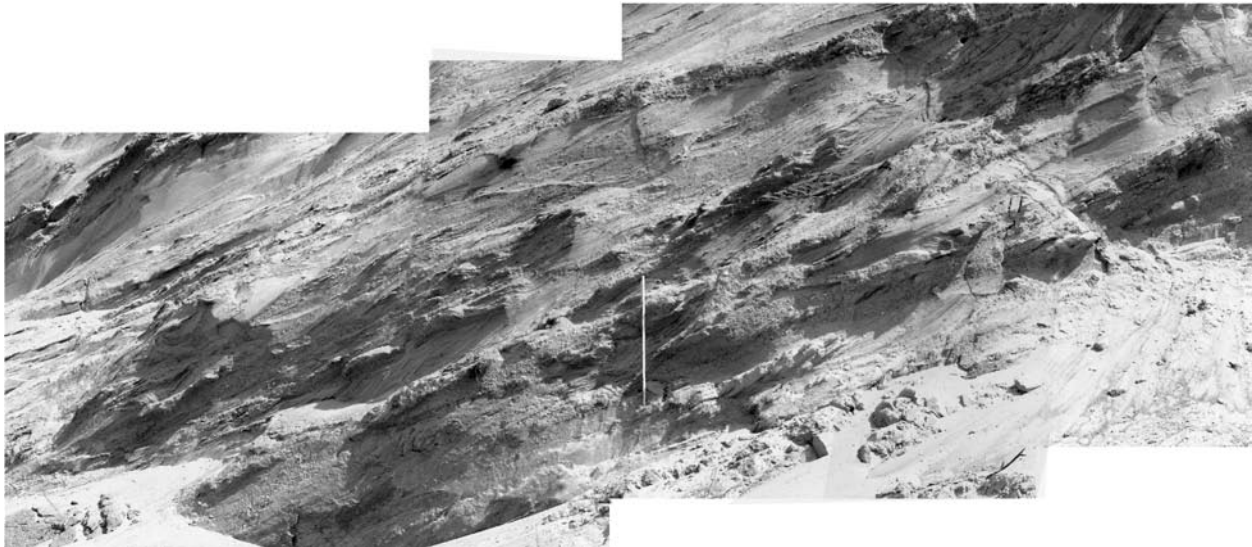

Fig. 17 (A) Photomosaic of Profile E. Bistrica quarry. (B) Detailed sketch of Profile E. Legend is shown in Fig. 5. Lithofacies and elements description and interpretation are shown in Fig. 5 and Tables 2 and 3.

Fig. 18 Sets of trough cross-stratified sands (facies St, element DU) overlain by sets of low-angle planar cross-stratified and horizontally stratified sands (facies Sl and Sh, element LS). Stick is 1 m long. Profile C1. Cabuna quarry.

Fig. 19 Sets of planar cross-stratified sands (facies Sp) and horizontally stratified sands (facies Sh). Transition from horizontally stratified sands (facies Sh) to low-angle cross-stratified sands (facies Sl). Stick is 1 m long. Profile C2. Cabuna quarry.

meta- and synsedimentary events, which took place during rapid deposition, or immediately after sedimentation. Liquefaction processes were triggered by the unstable density gradient.

Intensive, polyphase, laterally extensive deformations in Profiles B and C1 influencing whole set packages, suggest extrinsic origin. Seismic shocks were the probable cause of these events, as indicated by the following features: (1) size and extent of deformational structures; (2) deformed/undeformed sand body ratio; (3) synsedimentary faults; (4) proximity of the main transcurrent fault.

Rapid subsidence enabled the successful burial of sands and their saturation for liquefaction caused by seismic activity. An earthquake epicenter could not be precisely detected, but was probably situated within 20 km, considering the fact that a magnitude of at least 5 is necessary for the liquification of loose, saturated, fine- to medium-grained sands. In case of magnitude 7, the epicenter could have been within 40 km (IDRISS,

1985). The Southern marginal fault of the Drava depression is within these distances, and was the most probable location for the epicenter.

7. TECTONIC SETTING

The investigated area is situated along the southern margin of the Drava depression (according to the petroleum-geological division), within the southwestern part of the Pannonian basin system, which territorially belongs to the Republic of Croatia. This is an area of extremely strong tectonic processes, clearly divided into three periods, resulting in the formation of corresponding tectonic structures (PRELOGOVIĆ et al., 1995, 1998; LUČIĆ et al., 2001; SAFTIĆ et al., 2003):

(1) Initial structural changes during the Oligocene and Early Miocene. The onset of extensional tectonics, subsidence and sedimentation began as a result of the first syn-rift extensional tectonic phase;

Fig. 20 Concave depression (element HF) symmetrically infilled with facies Si and Sl. The right side of the depression shows synsedimentary deformation. Depression is 1.5 m deep. Profile E. Bistrica quarry.

Fig. 21 *Ginkgo adianthoides* (*UNGER*) *HEER*.

Fig. 22 *Carpinus betulus* LINNÉ.

(2) Major extensional processes during the Early and Middle Miocene;

(3) New reshaping processes (prevailing transpression) during the Pliocene, which is still present today. This model is dominated by wrench-faults.

According to the structural composition, three main zones can be distinguished, comparable with the western, southern and central marginal portions of the Pannonian basin system. They are outlined by the dominant regional faults: the Periadriatic–Drava fault, the Medvednica fault zone and the southern marginal fault of the Pannonian basin.

The explored outcrops of the Pliocene clastic sediments are situated south of the Virovitica–Slatina line, on the northern slopes of the Bilogora and Papuk Mts. Their genesis was strongly influenced by tectonic processes, in relation to palaeogeographic conditions and climatic changes. This area is situated at the boundary between two large structures – the uplifted Bilogora and Papuk Mts. and subsided Drava depression. (Fig. 26). This boundary is identical to the NW striking dextral Periadriatic–Drava wrench fault. According to seismotectonic analysis (PRELOGOVIĆ et al., 1998), this fault actually represents a 5 km wide zone. After
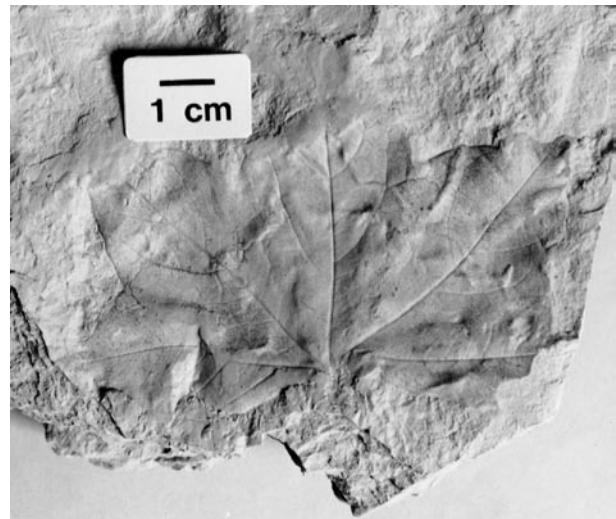

Fig. 23 *Acer platanoides* LINNÉ.

the first 7 kilometres of depth, which are characterized by a reverse movement of the hanging wall, this fault becomes almost vertical. Its position, width of the fault zone and dimensions of displacement were presented by SAFTIĆ et al. (2003).

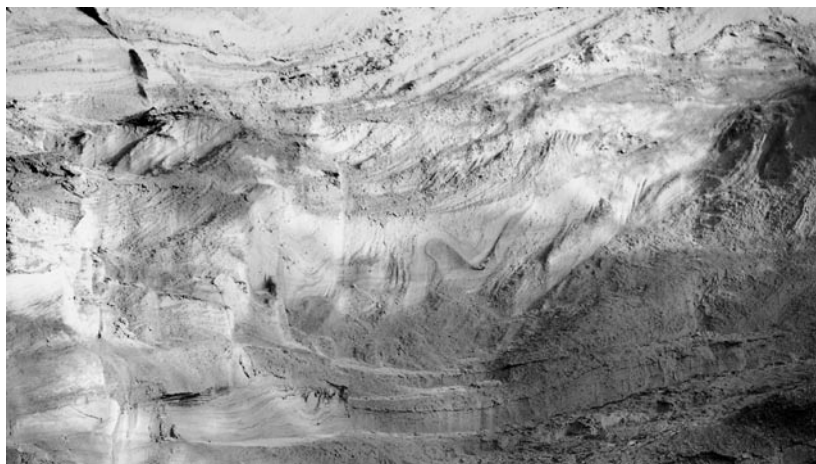One of the indicators of the presence of a fault is the sediment thickness, deposited due to its influence.

Fig. 24 Synsedimentary deformation expressed by overturned antiforms abruptly interrupted in their base by a synsedimentary reverse fault. Oversteepening and overturning can be also observed within isolated sets in the upper part of the photograph. The antiforms are about 1 m high. Profile C1. Cabuna quarry.
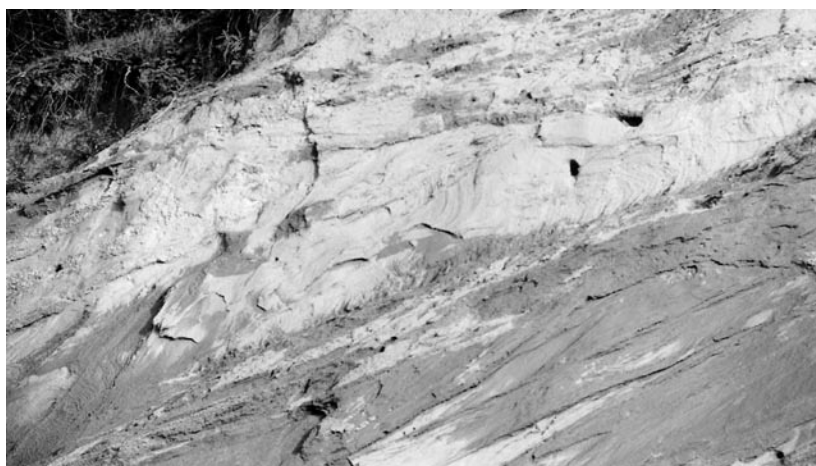

Fig. 25 Synsedimentry deformation expressed by oversteeping and overturning in the middle part of photograph. Oversteepened and overturned interval is 1 m thick. Profile C1. Cabuna quarry.

In the vicinity of Virovitica, the extreme depth (sometimes exceeding 6000 m) of the sediment filled Neogene–Holocene basin was observed (VELIĆ et al., 2002; SAFTIĆ et al., 2003). Extreme values were particularly measured for the sediments of the Pliocene, Pleistocene and Holocene, which are of great interest here. Northeast of Virovitica and Slatina, more than 1,500 m thickness was measured in these sediments. These data clearly emphasize the Pliocene–Holocene synsedimentary tectonic activity, which enabled the formation of such a prominent depositional centre.

The investigated clastic sediments belong to the 3rd megacycle, formed during Pliocene to Holocene basin inversion resulting in subsidence in the deepest zones, associated with uplift and – particularly important – erosion of the most elevated blocks (VELIĆ et al., 2002; SAFTIĆ et al., 2003). Rapidly uplifted blocks, the Slavonian Mts., Bilogora and Papuk Mts. represented the source area for the redeposited clastic material (well rounded pebbles of quartz, quartzite and other materials), combined with the influence of the moderately warm climate and intense precipitation (CHANDLER, 1997).

8. CONCLUSIONS

(1) The detailed analysis of lateral profiles exposed in sand/gravel quarries along the southern edge of the Drava depression, between Virovitica and Slatina, show the existence of a complex and variable alluvial system during the Late Pliocene.

(2) Gravels in the lower portion of Profiles A, B, D and E were deposited in alluvial fans. Gravel sheets deposited during catastrophic floods predominate. The composition and lithological features of the gravels indicate a tectonically uplifted and disturbed hinterland, composed of conglomerates and sands, with predominant mechanical weathering. Granites and gneisses are less probable as the source of the material, because well rounded quartz clasts suggest multiple phases of redeposition.

(3) North and northeastern directions of palaeostreams, derived from clast imbrications, are more or less perpendicular to the direction of the main Drava fault, indicating the Psunj and Bilogora areas as a possible source for clasts.

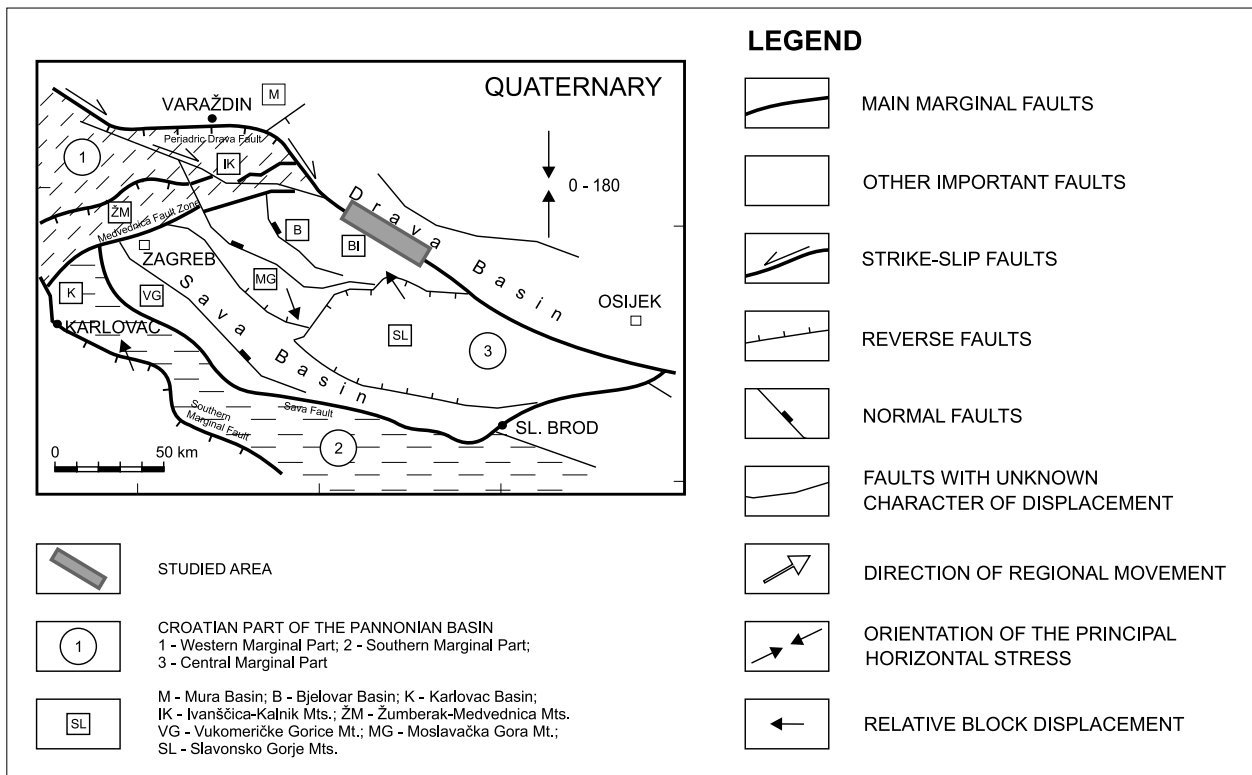(4) Preservation of alluvial fans in the investigated area suggests deposition in an extensive or transtensive

Fig. 26 Tectonic setting of the study area (from LUČIĆ et al., 2001).

land environment, surrounded by steep faults of vertical and/or horizontal character, which confirms the previously published data on tectonics in the wider area.

(5) Sandy facies of the braided river, which erosively overlie the alluvial fans, indicates the decline of tectonic activity. Climatic changes into a stable, moderately humid climate, could also be a reason for depositional changes thus forming fining upward fluvial cycles (Fig. 12).

(6) Deformation structures indicate the vicinity of earthquake epicenters, and extensional and transtensional faults.

(7) Source of the clastic material was probably relatively close, ca. 10 km south or southwest of the investigated area.

(8) Although the dominant flow direction of the main channel was subparallel to the palaeodirections on the fans, and very near the active faults, the water source could have been tens of kilometers or more from the source area of the clastic material in the alluvial fans.

Acknowledgement

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