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Sedimentology of high-stage flood deposits of the Tagus River, Central Spain

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Abstract

This paper details the sedimentology of high-stage flood deposits, with the definition of sedimentary environments and their characteristic sequences, along two bedrock reaches of the Tagus River (Central Spain). High-stage flood deposits accumulated in bedrock canyons include slackwater flood deposits (SWD) and other types of deposits located at flow separation zones and associated with slow-moving flow (<1 m s^{-1}). These flood deposits are common indirect indicators of flood stages used in palaeoflood studies for estimating the discharges associated with Quaternary floods. Depositional environments of flood deposits include (1) channel widening, (2) canyon expansion, (3) bedrock obstacles, and (4) backflooded areas along tributary streams. These flood deposits can be found associated with other non-fluvial environments, namely aeolian reworked and slope washflow facies. Channel widening, due to flood stage variations, comprises internal and external zones of the channel margins, and their characteristic sequences contain similar facies to those of alluvial floodplains. Canyon expansion environments favour vertical accretion of slackwater units and the development of flood deposit benches, which contain four sequences related to bench elevation and distance from the channel's main thread of flow. At the lee side of bedrock obstacles, characteristic sedimentary sequences are dominated by reverse flow structures (e.g. climbing ripples migrating upstream) due to eddies with a high sand concentration. Flood deposits located within tributary mouths contain typical sequences of reworked floodplain deposits. Backflooding of tributaries during flood stages produces deposition from suspension of sand, silt and clay within three sequences characterised by non-structure or parallel lamination and intense bioturbation. A better understanding of the flood deposit sequences may contribute to the characterisation of flood magnitudes and flood hydraulics and can also be applied to some ancient depositional environments.
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Keywords: Palaeoflood hydrology; Palaeoflood sedimentology; Slackwater flood deposits; Spain

1. Introduction

Palaeoflood hydrology combines a multidisciplinary approach (stratigraphy, sedimentology, geomorphology and hydraulics) in the study of past or ancient floods, to decipher, quantitatively, past flood discharges, extending the record of extreme floods from centuries to thousand of years (Baker et al., 1988). This information can be used in risk assessment and in the assessment of climatic change on floods (Jarrett, 1989).

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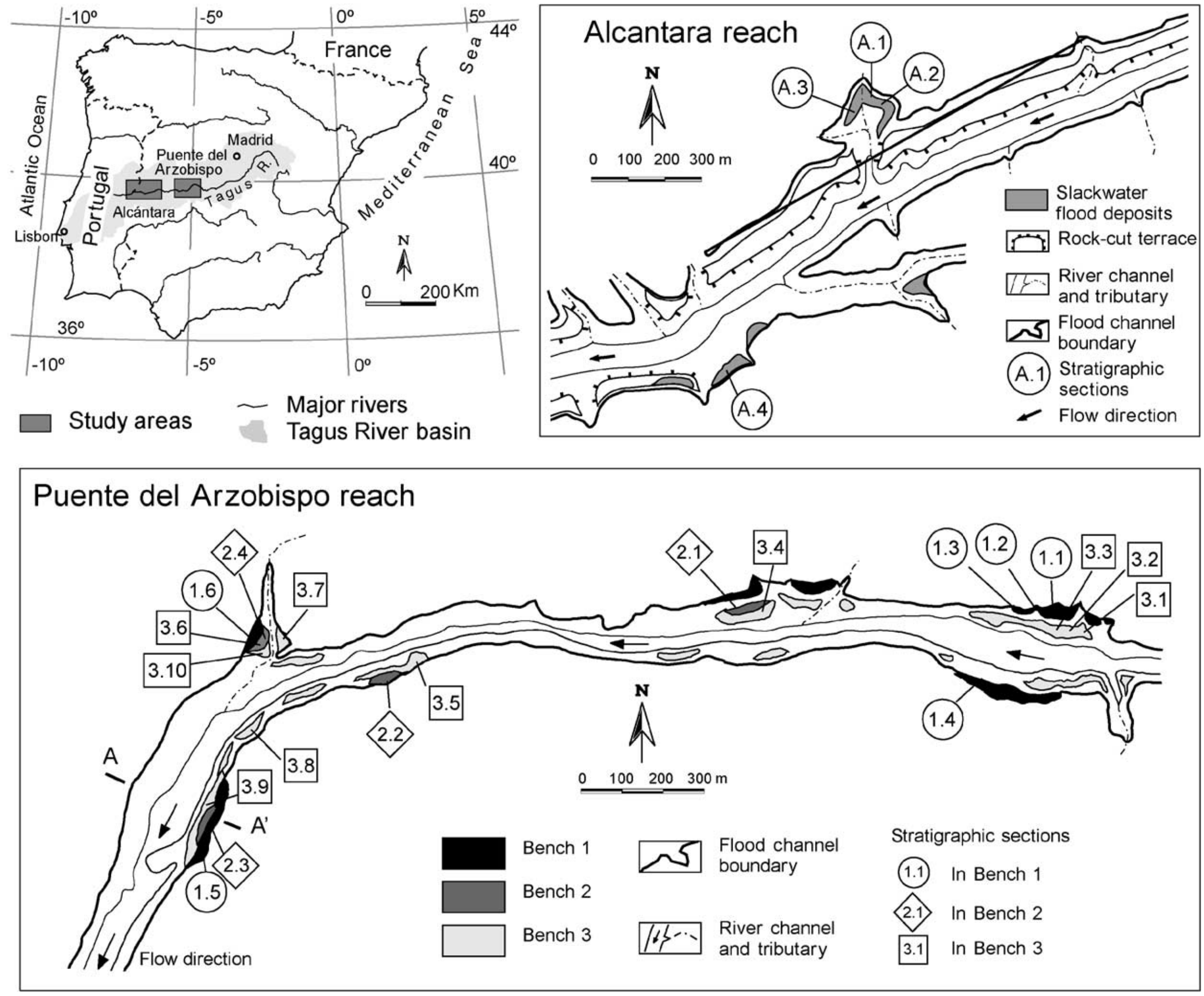
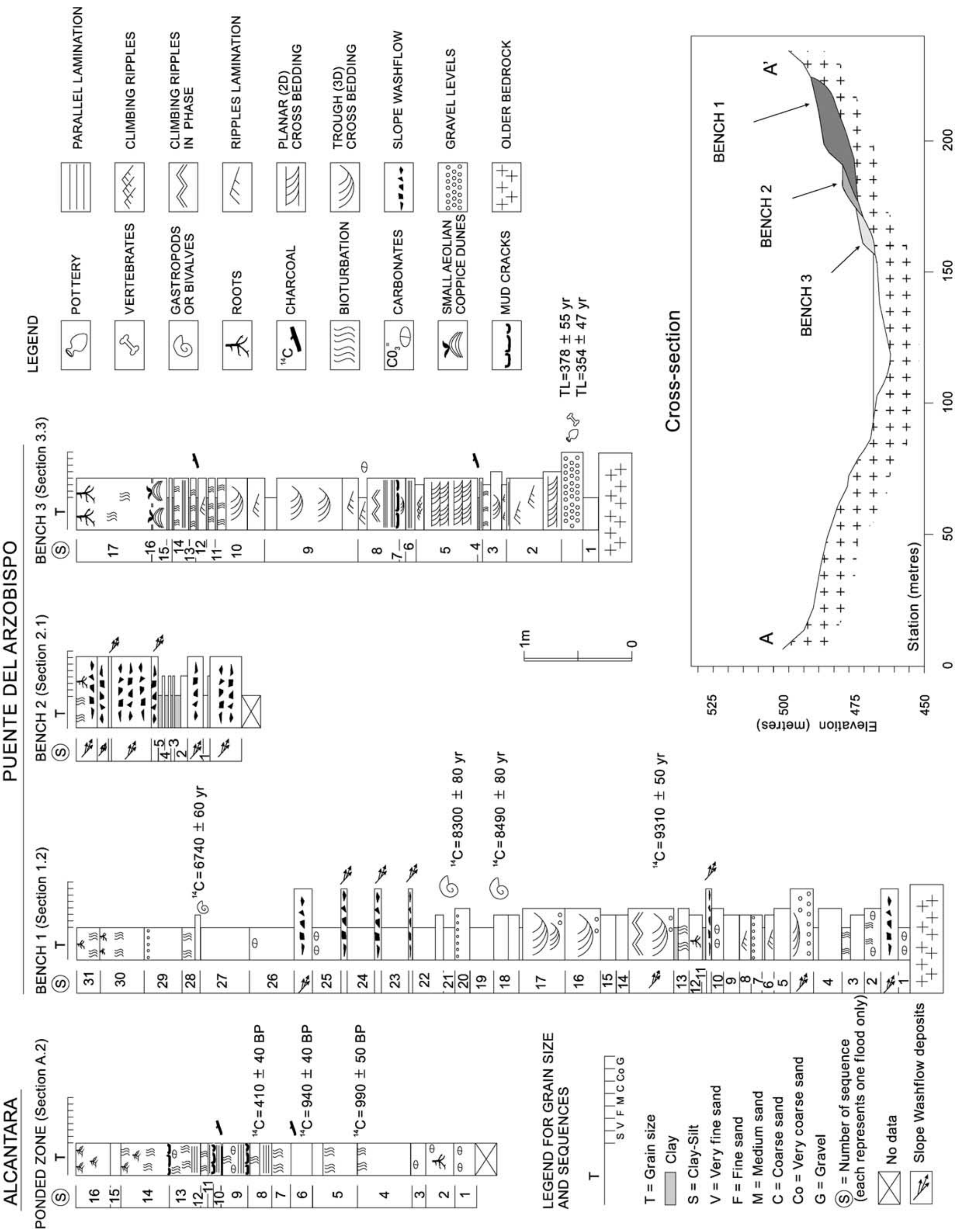


Fig. 1. Location of the Tagus basin and study reaches. Below: High-stage flood deposits along the El Puente del Arzobispo gorge and the stratigraphic sections within Bench 1 (circles), Bench 2 (diamonds) and Bench 3 (squares). Above: High-stage flood deposits along the Alcántara gorge and the stratigraphic sections where flood sequences were described.

Palaeoflood studies are based on geologic evidence of flood stages and channel geometry, which lead to the estimation of flood discharges. Common indirect evidence of flood palaeostages includes sediments (palaeostage indicators, PSIs), erosional landforms (stripped soils, flood scarps, highflow channels), and high-water marks (e.g. drift wood, tree impact scarps, silt lines). These palaeoflood indicators can be correlated to define the palaeoflood water surface profiles along the river channel. Hydraulic computations using either one-dimensional or two-dimensional hydraulic models can provide a good estimation of the discharges associated with palaeostage indicators (O'Connor and Webb, 1988; Denlinger et al., 2002), which together with numerical age dating, will allow the reconstruction of flood magnitude and frequency

Fig. 2. Representative stratigraphic sections of high-stage flood deposits in the Puente del Arzobispo and Alcántara study reaches. The cross-section shows the geomorphological relationships of the slackwater benches in the El Puente del Arzobispo study area. Location of the cross-section (A–A′) and stratigraphic sections is shown in Fig. 1.


ALCANTARA
PONDED ZONE (Section A.2)
14C=410 ± 40 BP
14C=940 ± 40 BP
14C=990 ± 50 BP
PUENTE DEL ARZOBISPO
BENCH 1 (Section 1.2)
14C=6740 ± 60 yr
14C=8300 ± 80 yr
14C=8490 ± 80 yr
14C=9310 ± 50 yr
BENCH 2 (Section 2.1)
BENCH 3 (Section 3.3)
TL=378 ± 55 yr
TL=354 ± 47 yr
1m
0
LEGEND FOR GRAIN SIZE AND SEQUENCES
T = Grain size
Clay
S = Clay-Silt
V = Very fine sand
F = Fine sand
M = Medium sand
C = Coarse sand
Co = Very coarse sand
G = Gravel
S = Number of sequence (each represents one flood only)
No data
Slope Washflow deposits
LEGEND
POTTERY
VERTEBRATES
GASTROPODS OR BIVALVES
ROOTS
CHARCOAL
BIOTURBATION
CARBONATES
SMALL AEOLIAN COPPICE DUNES
MUD CRACKS
PARALLEL LAMINATION
CLIMBING RIPPLES
CLIMBING RIPPLES IN PHASE
RIPPLES LAMINATION
PLANAR (2D) CROSS BEDDING
TROUGH (3D) CROSS BEDDING
SLOPE WASHFLOW
GRAVEL LEVELS
OLDER BEDROCK
Cross-section
A
A'
BENCH 1
BENCH 2
BENCH 3
Elevation (metres)
Station (metres)

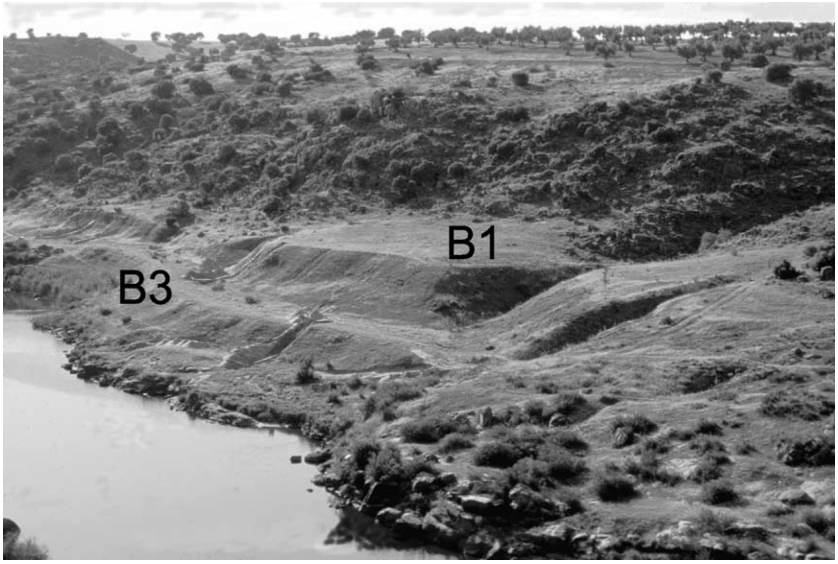


Fig. 3. Downstream view of the El Puente del Arzobispo gorge and flood deposits forming Bench 1 (B1) and Bench 3 (B3) within canyon expansion and channel widening zones, respectively.

over an extended period of time (centuries to millennia).

Bedrock canyons are the most suitable geomorphologic settings for reconstructing palaeoflood discharges because of their stable geometry and the sharp changes of flow energy conditions between the main channel flow and the margins of the canyon, where flow velocities are significantly reduced depending on the geometry of the channel. During flood stages, eddies, backflooding and water stagnation occur at marginal areas of the channel, producing low speeds and/or flow stagnation (slack water) which favours deposition from suspension of clay, silt and sand. These fine-grained deposits can be preserved in stratigraphic sequences, providing detailed and complete records of flood events that extend back several thousand of years (Patton et al., 1979; Baker et al., 1983; O'Connor, 1993) and distinguished two categories of suspended load deposits: the suspended load per se, and the washload. Slackwater flood deposits (SWD) are deposited in areas of flow stagnation or quiescence representing the washload component of the suspended load, whereas accumulation of other fractions of the suspended load can be found in areas of marked velocity reduction associated with recirculation zones or eddies (Eddy deposits; O'Connor, 1993). Eddy deposits are commonly found in tributary mouths, downstream of obstacles or bedrock projections into the flow, and in canyon expansions, whereas SWD (s.e.) are found in wide, backflooded basins, within rock-shelters and in tributary valleys where the flow is essentially stagnant (Baker, 1973; O'Connor, 1993).

Flood sedimentology in bedrock canyons is far from being fully understood, principally because the main goal of flood stratigraphy to date has been to identify breaks or contacts between flood units. In fact, although most palaeoflood studies include stratigraphic descriptions of slackwater deposits, little systematic work has detailed the sedimentological interpretation of facies and environments. The most detailed description of the stratigraphy and sedimentology of flood deposits were provided by McKee (1938) for the Colorado River flood deposits in the Grand Canyon, and by Kochel and Baker (1988) in the Pecos River slackwater sediments.

The aims of this paper are: (1) to contribute to the sedimentological characterisation of high-stage flood deposits (eddy and slackwater flood deposits), including the improvement of criteria for identifying flood contacts; (2) to relate the sedimentary sequences with the hydraulic and sediment load conditions through

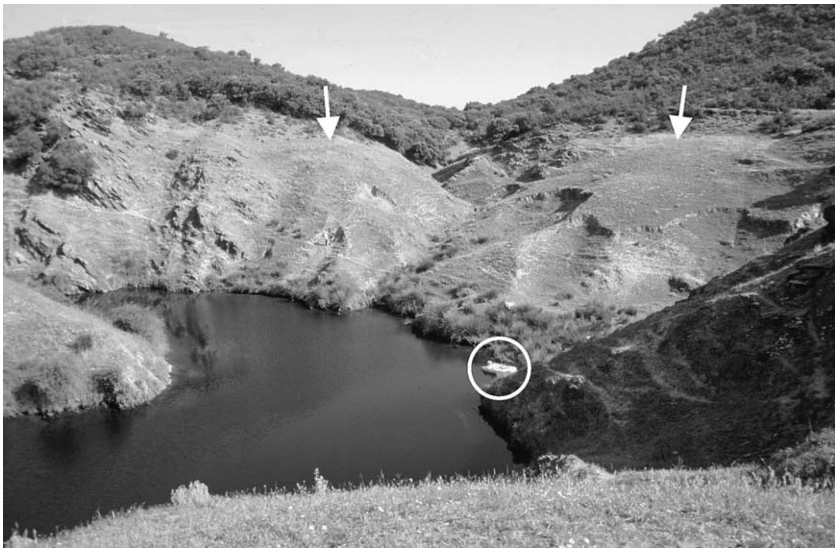


Fig. 4. The Alcantara study reach. Uptributary view of the ponded zone where a stack of slackwater flood deposits has accumulated. The Tagus river is 200 m away and the thickness of the flood deposits is about 21 m. Arrows show the uppermost part of flood deposits which correspond to minimum peak discharges of 11,000 m^3 s^{-1}. A boat, 4 m in length, is circled for scale.

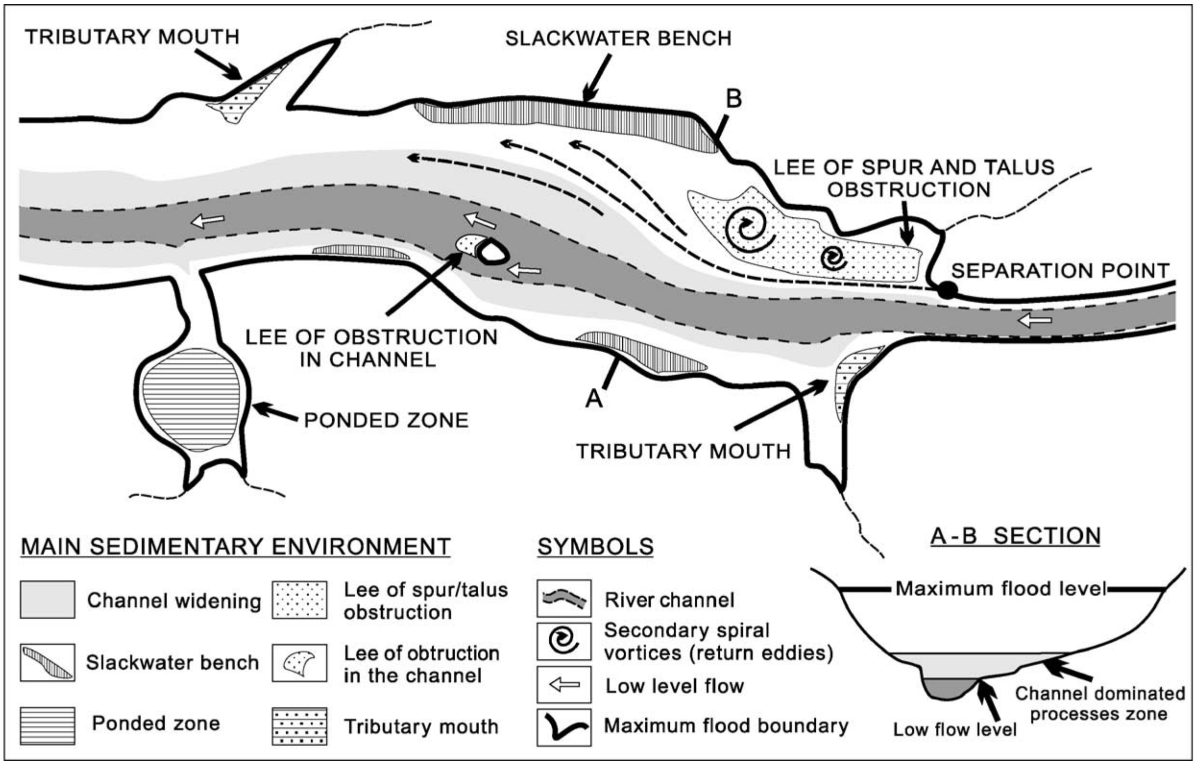


Fig. 5. Schematic diagram illustrating the location of sedimentary environments of high-stage flood deposition in the Tagus River.

the flood hydrograph; and (3) to understand the sedimentary environments in which different types of flood deposits are accumulated, their characteristic sequences and facies. The sedimentary environments discussed have been recognised and described along the Tagus River (Central Spain).

2. Study areas

The Tagus River drains the central part of the Spanish Plateau (Meseta), with an E–W elongated basin with headwaters in the Iberian Range and its mouth draining into the Atlantic Ocean at Lisbon

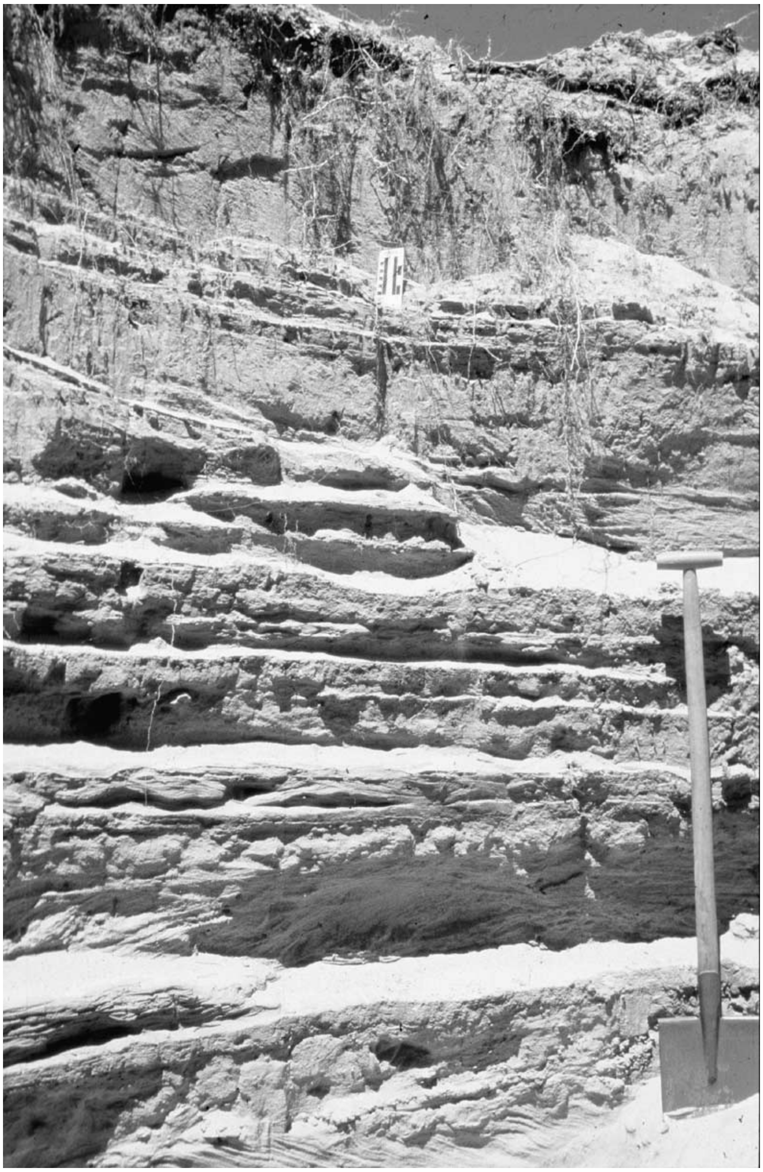


Fig. 6. A view of the flood deposits stratigraphy exposed in a trench dug within Bench 3. Note the multiple flood units with contacts frequently represented by hard surfaces and by fine drapes of silt and clay.

(Fig. 1). It is the longest river of the Iberian Peninsula (1200 km) with the third largest catchment area (81,947 km^2), and an average flow discharge of 500 m^3 s^{-1}, close to the river mouth in Lisbon. Hydrologically, the Tagus River is characterised by extreme seasonal and annual variability including severe floods with peak discharges more than 30 times the average discharge.

The analysis of palaeofloods presented in this paper was focused within the middle and lower reaches of the Tagus River, particularly at El Puente del Arzobispo and Alcántara (near the Portuguese

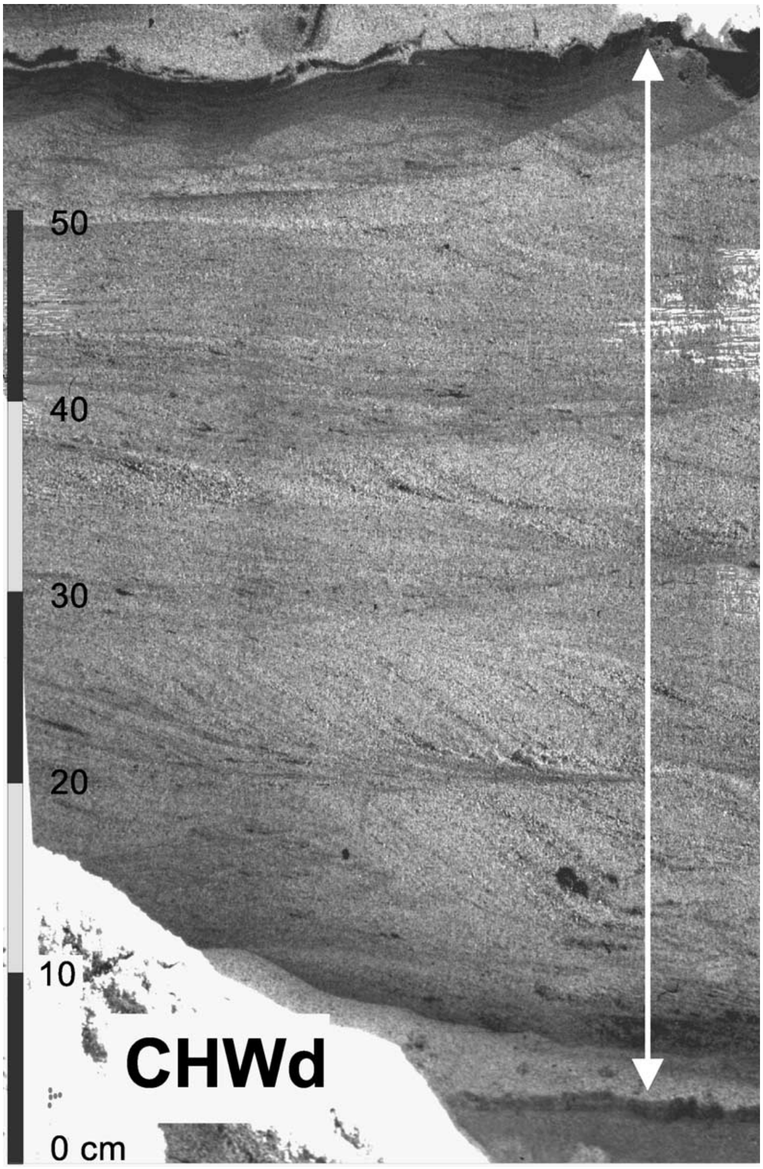


Fig. 7. Detail of a flood sequence (CHWd) corresponding to the channel widening sedimentary environment. Note the clay layers at the bottom and the top of the sequence showing the contacts between flood events.

Table 1
Facies sequences in flood environments

Channel widening (Fig. 9)

CHWa (from bottom to top)
- Unstratified to crudely stratified clast supported gravels, commonly resting on erosional surfaces. Occasionally, these gravels contain vertebrate bones and pieces of pottery.
- Parallel lamination produced by aggradation on a plane bed in coarse-grained sand. Avalanching develop locally infilling previous small hollows or topographic depressions.
- Medium-grained sand characterised by small trough cross bedding (3D) according to the classification recommended by the SEPM (Ashley et al., 1990). Occasionally, some current ripples are also present.
- Fine- to very fine-grained sand characterised by current ripples or thin parallel lamination.
- Significant variations in flow velocity, or grain size transport sediment, result in a new level of coarse-grained sands with small trough cross bedding.
- Massive very fine-grained sand produced by vertical accretion highly bioturbated
- Very fine to silt-grained sand characterised by convoluted bedding.
- Massive silt–clay, with desiccation cracks.

CHWb
- Fine- to very fine-grained sand with parallel lamination produced by aggradation on a plane bed. Mud clasts may also occur. Occasionally, some current ripples are also present.
- Medium- to fine-grained sand characterised by convoluted bedding.
- Fine- to very fine-grained sand characterised by current ripples or thin parallel lamination.
- Silt-grained sand or massive silt with desiccation cracks.

CHWc
- Medium- to fine-grained sand with parallel lamination or current ripples.
- Coarse to medium-grained sand characterised by small trough cross bedding (3D). Occasionally, some current ripples are also present.
- Massive and highly bioturbated very fine-grained sand to silt produced by vertical accretion. Occasionally, some current ripples are present.

CHWd
- Very coarse-grained sand characterised by small planar cross bedding (2D), following SEPM classification (Ashley et al., 1990). Laminae may be locally separated by mud drapes.
- Medium-grained sand with climbing ripples in drift, grading upward into climbing ripples in phase.
- Alternating very fine sands and silt–clay units, both massive and with desiccation cracks.

Canyon expansion (Fig. 11)

Slackwater bench

CSBa
- Massive and highly bioturbated medium to fine-grained sand produced by vertical accretion. Occasionally, some asymmetrical to near symmetrical ripples are also present.

Table 1 (*continued*)

Canyon expansion (Fig. 11)

Slackwater bench

CSBa
- Fine to very fine-grained highly bioturbated sands.
- Occasionally, a pebble or bivalve shell pavement occurs at the top of the sequence.

CSBb
- Vertical accretion of plane beds in fine to very fine-grained sand.
- Massive silt, locally bioturbated.

CSBc
- Fine-grained sand characterised by parallel lamination.
- Fine- to medium-grained sand characterised by current ripples.
- Parallel lamination produced by aggradation on a plane bed in medium-grained sand.

CSBd
- Medium-grained sand characterised by small trough cross bedding (3D) overlaying a scoured base.
- Massive fine-grained sand.

Bedrock obstacles (Fig. 12)

Lee of bedrock spur and talus obstruction

BSOa
- Medium-grained sand with small return current trough cross bedding (3D). Occasionally, return current planar cross bedding (2D) is also present.
- Medium-grained sand with return current climbing ripples in drift, occasionally in phase. Sometimes climbing ripples in phase resembles wave ripples in morphology.
- Medium- to fine-grained sand characterised by convoluted bedding bioturbated at the top.
- Silt-grained sand, with small return current ripples or parallel lamination, or massive silt–clays, both highly bioturbated.

BSOb
- Silt–clay and very fine-grained with linsen bedding structure.
- Coarse- to medium-grained sand characterised by current ripples.
- Massive silt to very fine sand.
- Medium-grained sand with return current climbing ripples in drift.
- Medium- to fine-grained sand characterised by current ripples.
- Medium-grained sands, structureless and highly bioturbated.

BSOc
- Silt and very fine-grained sand with linsen bedding structure.
- Parallel lamination produced by aggradation on a plane bed in coarse- to medium-grained sand.
- Massive silt to very fine sand.
- Coarse- to medium-grained sand characterised by current ripples.
- Massive silt to very fine sand.
- Coarse- to medium-grained sand characterised by reverse trough cross-bedding (3D).
- Massive silt- to very fine-grained highly bioturbated sand.

Lee of obstruction in channel

BLO
- Medium- to fine-grained sand characterised by current ripples.
- Return trough cross-bedding (3D) in fine-grained sediments.

(continued on next page)

Table 1 (*continued*)

Bedrock obstacles (Fig. 12)
Lee of obstruction in channel
BLO
Massive clay.
Backflooded tributaries and tributary mouth (Fig. 16)
Tributary mouth
TMB
Medium- to fine-grained sand with parallel lamination produced by aggradation on a plane bed commonly resting on an erosional surface. Mud clasts also occur at basal sediments.
Silt deposits with parallel lamination.
Ponded zone
PZa
Alternating non-structure silts and clays.
PZb
Silt size deposition from suspension.
Clay size sediments. Subaerial exposure results in mud cracks. Occasionally intense bioturbation due to vegetation and burrows made by annelids and arthropods can be observed.
PZc
Very fine-grained sand with parallel lamination or occasionally current ripples.
Silt size massive sediments.
Clay sediments. Occasionally, mud cracks and intense bioturbation can be observed.

border) where the river is confined within bedrock canyons (Fig. 1).

2.1. El Puente del Arzobispo

The Tagus River downstream of El Puente del Arzobispo town (ca. 35,000 km^2 drainage area) cuts through granitic rocks of Palaeozoic age following Late Hercynian structures and develops into a 125-m-deep gorge (Fig. 1). The remnants of eroded Pleistocene soils, only 6 m above the present thalweg, indicate that incision of the gorge during the Holocene was minor. Late Pleistocene and Holocene deposits along the gorge are related to flood dynamics and local slope processes. Sudden changes in water stage due to flooding are frequent during the winter, producing a set of erosional and depositional features that allow reconstruction of flood dynamics.

Three benches, each with multiple flood units, were recognised in the study area (Fig. 1). The higher bench (Figs. 2 and 3) is located 17 m above the present channel bottom. This bench is >8 m in thickness and it is composed of silt and fine-medium sand units with very diffuse contacts, brown to yellow in colour, massive structure, and extremely consolidated. A total of 5 trenches were cut in this bench along the study reach (sites 1.1 to 1.5 in Fig. 1) in which up to 31 flood units related to individual flood events were distinguished at some profiles. A pollen extract from the lowest unit of this bench at profile 1.1 provided a radiocarbon (AMS) age of 14,090$\pm$100 ^{14}C year BP (Lab. code: AA-22452), whereas a river mollusc extracted from one of the upper flood units of profile 1.2 (Figs. 1 and 2) was dated to 6740$\pm$60 ^{14}C year BP (Beta-098317).

Inset within Bench 1, the intermediate deposit (Bench 2 in Fig. 1) appears 12 m above the channel bottom. The development of this bench along the study reach is very poor with thicknesses ranging from 1 to 2 m, and comprising between four and six slackwater sedimentation units (Fig. 2), dark brown in colour, composed of medium to fine sand and silty sand. Intercalations of slope washflow deposits are also frequent. No datable material has been found in these flood units.

The lower flood bench (Bench 3 in Fig. 2) is either inset within Bench 1 and Bench 2 or attached directly to the channel margins at sites protected by bedrock. This bench is the most ubiquitous one along the study reach. The top surface of Bench 3 along the study reach is about 10 m in elevation, and its thickness ranges from 2 to 5 m, containing between seven to nineteen sedimentation units of 15 to 75 cm in thickness (Fig. 2). The sedimentation units fine upwards from coarse sand to silt with decreasing energy conditions, and contain a rich sequence of sedimentary structures. At the upstream part of the study reach, this bench overlies an archaeological site with abundant remains of pottery and bones dated by a thermally stimulated luminescence technique as 378$\pm$55 and 354$\pm$47 year BP. The archaeological site predates the flood sedimentary sequence. Flood deposits were also found at tributary mouths, developing three inset benches which overlay the tributary bed (lower bench) and granite bedrock (upper bench).

Step-backwater calculations of water surface profiles of discharges, associated with the elevation of the flood deposits identified were performed using the US Army Corps of Engineers River Analysis System computer program HEC-RAS (Hydrologic Engineering Center, 1995). The computation procedure is based on the solution of the one-dimensional energy equation, derived from the Bernoulli equation, for steady gradually varied flow. This procedure accounts for energy expended by the flow between discrete cross-sections. These energy losses are the estimated flow-friction losses associated with channel roughness (Manning's n), and the form losses from channel expansion and contractions. Parameters used in the hydraulic modelling include slope, channel cross-section area and discharge. The palaeohydrological reconstruction is based on the calculation of a step-backwater profile producing the best correlation with the geological evidence of flow stage, namely the flood sediments (O'Connor and Webb, 1988). The step-backwater calculations, in conjunction with the elevation of the described benches, indicates minimum peak discharges for Bench 1 of between 1200 $m^3\ s^{-1}$ (base of bench) and 4200 $m^3\ s^{-1}$ (highest end-point of the flood bench), for Bench 2 between 1000 and 2000 $m^3\ s^{-1}$ and for Bench 3 between 400 and 1200 $m^3\ s^{-1}$ (Benito et al., in press).

2.2. Alcántara

The Alcántara reach (Fig. 1) is located near the Portuguese border, ca. 170 km downstream from El Puente del Arzobispo, with a catchment area of 51,958 km^2. In this reach, the Tagus River flows through a 500-m-wide constricted segment that is incised ca. 150 m into schist and slates of Palaeozoic age. The Tagus River bedrock channel is incised 15 m to a rock-cut terrace which alternates along both sides of the river within the gorge (Fig. 1). The highest flood deposits are found forming narrow benches parallel to the river valley with thicknesses varying from 1 to >5 m. Stratigraphic descriptions show at least four flood units (profile A 4; Fig. 1) composed of medium to fine sands and silts with a dominantly massive structure. A radiocarbon date of charcoal found in a slope unit in the middle part of the stratigraphical profile provided an age of 1200±40 ^{14}C year BP (Beta-119759). The most prominent accumulations of flood deposits are located at tributary mouths and at upstream tributary backflooded areas (Fig. 4). During flooding, this very-low energy backflooded environment favours deposition of very fine and fine sand, silt and even clay textures. The most complete profile (A 2 in Fig. 1 and ponded zone in Fig. 2) revealed at least sixteen flood units. Two pieces of charcoal dated in the lower part of the profile provided a date of 990±50 ^{14}C year BP (Beta-119758) and 940±40 ^{14}C year BP (Beta-119757), respectively, whereas in the middle part of the profile a charcoal sample was dated as 410±40 ^{14}C year BP (Beta-119756). The step-backwater calculations provided minimum peak discharges over 13,700 $m^3\ s^{-1}$ for the highest deposits and between 3400 and 11,000 $m^3\ s^{-1}$ for the ponded area (Benito et al., in press).

3. Sedimentology of flood deposits

Flood deposits can accumulate in four specific sedimentary environments (*s.l.*) during high flow stages (Fig. 5). These environments are: (1) channel widening, (2) canyon expansion, (3) bedrock obstacles, and (4) backflooded areas along tributary streams. The first three are related to their specific position in the canyon during the flood and with the specific flow conditions induced. The fourth is related also to the presence of tributary channels and their morphology (Fig. 5).

The channel widening environment comprises the bank nearest to the low flow channel (Fig. 5), which is inundated during the first stages of high flow. In these channel marginal areas, abrupt changes in the geometry of the channel boundary results in flow separation, where secondary flows and eddies may favour deposition including fine-grained deposits (see Allen, 1984, p. 18). The canyon expansion environment is located on the sides of the bedrock canyon which are flooded only during extreme floods (Fig. 5), accumulating flood sediments at higher benches. Note that in the canyon expansion environment, flow velocity is very weak or zero producing sedimentation from suspension of silt and fine sand (slackwater flood deposits within structureless sequences), whereas in the channel widening environment, flow structures indicate, in most of the sequences, some water motion. The bedrock obstacle environment comprises the trailing margin of the obstacle where separated flow downstream generates slow-moving backflow and sedimentation (Fig. 5). Tributary streams can be backflooded during flood stages of the main river, where slow-moving or stagnated water favours sedimentation (Fig. 5).

In these sedimentary environments, more than 25 trenches were cut (Fig. 1), and detailed stratigraphic descriptions of the flood deposits were carried out (Fig. 6). In the stratigraphy, a special emphasis was made on the identification of breaks or contacts between flood units, indicating individual flood events (Fig. 7). Field data on the vertical succession of grain size, sorting, sedimentary structure, geometry and flow direction of each individual flood unit were used to build up the tables (Table 1) of all the sedimentary sequences found at different depositional environments.

3.1. Channel widening environment

During flood events, the channel wet cross-section is dramatically enlarged as the flow extends into these marginal areas covering the nearest bank or lower bench. The location of the channel widening environment depends on the flood magnitude, therefore, for increasing flood magnitudes, these sedimentary facies are deposited at increasingly higher elevations within the bedrock canyon. In this depositional environment, two different sedimentation zones at the channel's nearest or internal zone and at the outer or channel external zone (Fig. 5) have been differentiated. The internal zone, nearest to the channel belt, shows

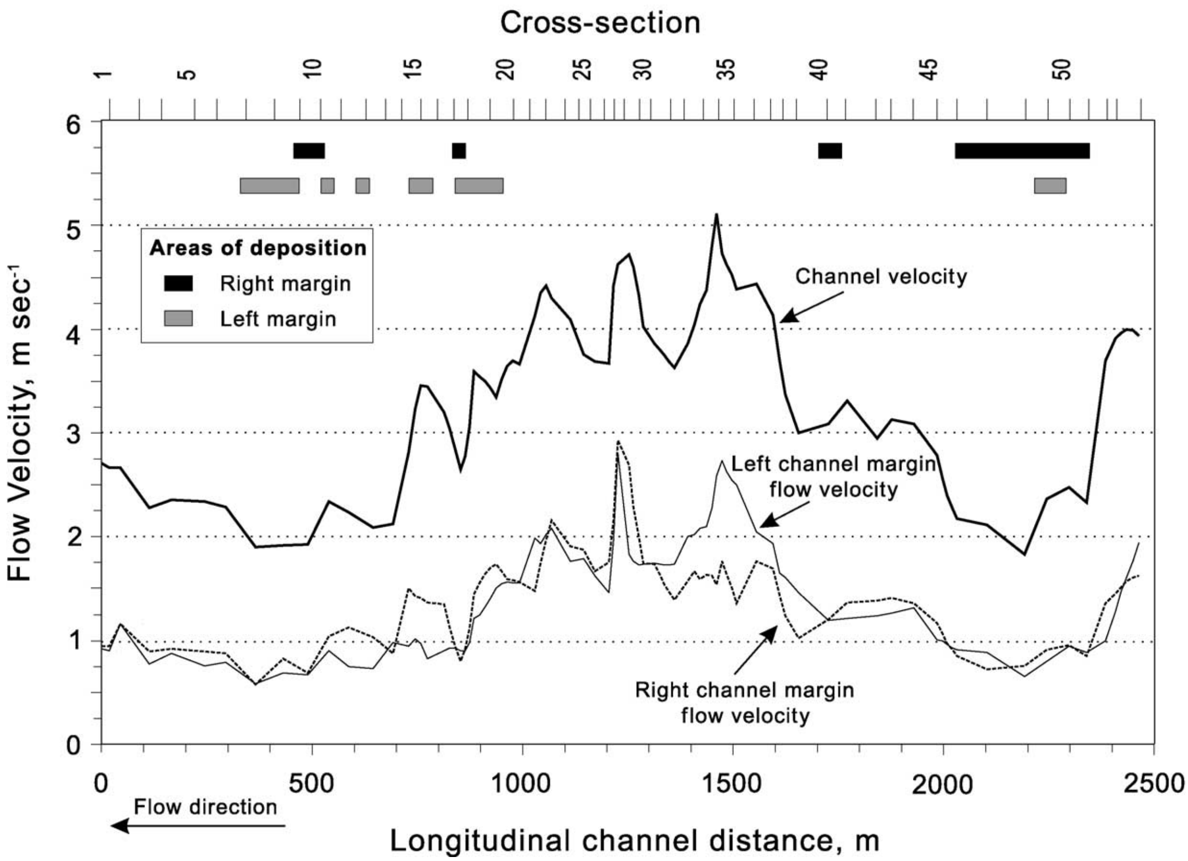


Fig. 8. Calculated mean flow velocities from step-backwater flow modelling along the El Puente del Arzobispo study reach, for a discharge of 1800 $m^3\ s^{-1}$. The longitudinal channel distance was measured along the channel thalweg of the study reach shown in Fig. 1, starting at the downstream end. Flow velocity was estimated for the main channel and the right and left marginal areas. The areas of deposition (indicated by horizontal bars on the graph) within channel widening environments are highly correlated to flow velocities below 1 $m\ s^{-1}$ on the marginal areas.

relative high-energy conditions during high magnitude floods, whereas the external zone local flow is characterised by lower energy associated with slow-moving water.

A first approximation of the flow velocities associated with some of these sedimentary environments was obtained using a one-dimensional model (HEC-RAS, Hydrologic Engineering Center, 1995). The one-dimensional nature of the modelling implies some limitations, for example, flow is considered to be strictly in the downstream direction, providing only partial characterization of the actual flow conditions at marginal areas. Therefore, hydraulic conditions associated with depositional environments located in areas of flow separation (eddy zones) and in the lee of resistant protrusions cannot be directly estimated from the step-backwater calculations. Only channel widening environments can be accounted for by the analysis of local fluid dynamics. Fig. 8 illustrates the good agreement between the spatial variations in flow conditions (velocity) and the distribution of channel widening depositional areas, for a discharge of 1800 $m^3 s^{-1}$, large enough to cover all the widening areas. Reaches with flood deposition on channel widening areas are associated with local flow velocities at channel margins lower than 1 $m s^{-1}$.

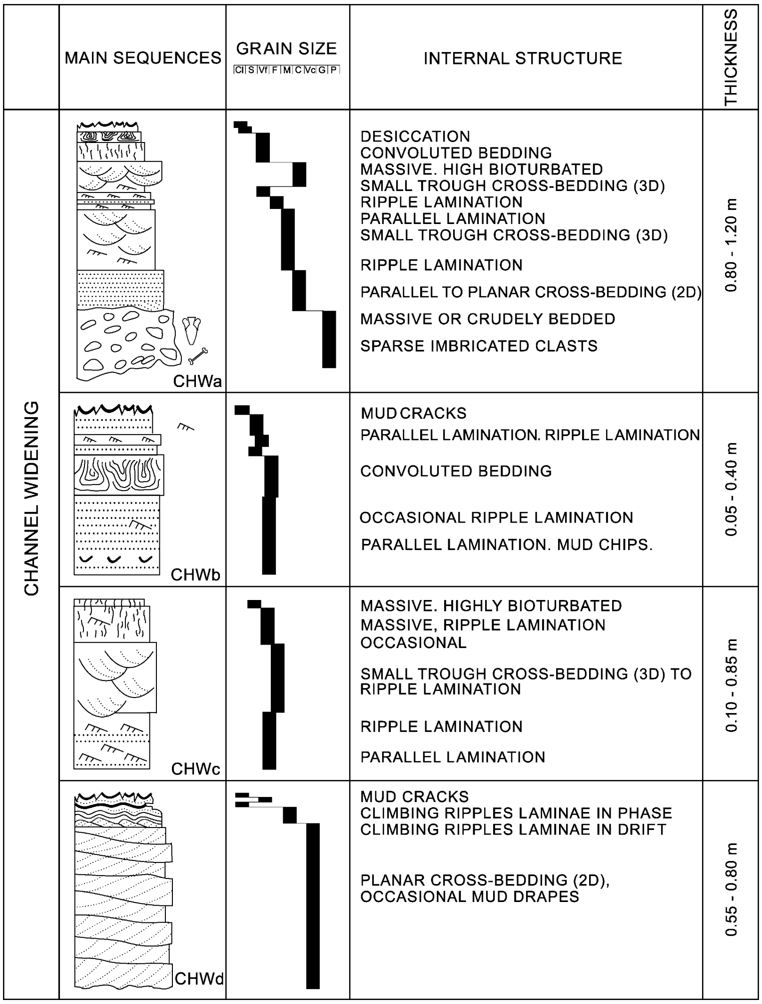


Fig. 9. Characteristics of vertical facies sequences in channel widening sedimentary environments.

The characteristic sequence of this internal zone of channel expansion (CHWa; Table 1 and Fig. 9) is interpreted herein as a low-sinuosity bedrock channel fill subjected to variations in flow discharge and water depth during a flood, with a progressive decrease in flow velocity and in transport capacity of the flow. The CHWa facies association is complex due to the deposition of a high sediment-laden flow whose velocity progressively decreased towards the top of the sedimentary sequence. During the waning stage of the flood, at higher suspended-load fallout rates, deposition occurred from direct suspension. At this stage, very fine, to silty sand, was deposited (uppermost two members of the sequence). This kind of sediment is highly susceptible to the development of water-escape structures (Lowe, 1975, 1982) that result in convolute bedding. Desiccation cracks within the uppermost 1 cm of the sequence indicate subaerial exposure after the flood.

The sedimentary sequences that characterise the external zone (CHWb to CHWd; Fig. 9) show some similarities with floodplain facies developed within alluvial reaches, although they differ in having a larger grain size. These sequences are generated by larger floods reaching topographically higher positions than those associated with the internal channel belt. The sequence (CHWb; Table 1 and Fig. 9) is interpreted as vertical accretion produced by migration of plane beds, resting on reworked floodplain deposits which are occasionally incorporated in the lower units of the sequence as rip-up mud clasts (Fig. 10). Alternating current conditions result in ripple migration to plane beds migration if velocities increase or water depth laminae or grain size decrease. Fluid escape structures generated by density inversion produced convoluted bedding. At the waning flood stage, clay settling from suspension took place and finally subaerial exposure produced mud cracks.

The sequence CHWc (Table 1 and Fig. 9) is interpreted as vertical accretion produced by migration of plane beds or ripple migration depending on flow velocity. Small 3D dunes could be developed as a response to an increase in grain size without an increase in stream power, as predicted by the dimensionless velocity-size or depth-size graphs (Southard and Boguchwall, 1990). Vertical aggradation of fine to very fine sand produced by ripple migration occurs when the current decelerates, combined with an increase in

Fig. 10. Upper most part of a flood sequence (CHWd) showing the climbing ripple sequence and the vertical variation from climbing-in-drift to climbing-in-phase. The sequence is finished by a thin clay layer settled from suspension followed by subaerial exposure resulting in the formation of mud cracks. Note that some mud crack chips were ripped-up during the following flood event without their destruction. This is indicative of the low energy conditions associated with these flood sedimentary environments.

fallout from suspension (according to Jopling and Walker, 1968). Finally, subaerial exposure occurs.

The sequence, CHWd (Table 1 and Fig. 9), is interpreted as vertical accretion produced by small 2D dune migration. Occasionally, a rapid decrease in, or even termination of, flow velocity has generated mud drapes. Sand excess produced aggradation by the migration of climbing ripples, first in drift and, later, in phase (Fig. 10). The climbing ripple sequence, showing a vertical variation from climbing-in-drift to climbing-in-phase, is normal under waning flow conditions with a decrease in flow velocity and high rates of vertical sediment build-up from suspension (Ashley et al., 1982). The end of the sequence is represented by clay settling from suspension followed by subaerial exposure resulting in the formation of mud cracks (Fig. 10).

3.2. Canyon expansion environment

Canyon expansions are defined here as sites where the canyon sides widen so that the canyon width exceeds the particular reach average (Fig. 5). In canyon expansion environments, change in flow geometry is more abrupt and local flow conditions in these marginal areas will be close to standstill motion. Canyon expansion exists irrespective of the flow conditions while channel widening is a consequence of water level elevation during a flood. From the sedimentary point of view, both environments frequently coincide in the same geographical area but the sedimentary processes and sequences are different.

At canyon expansions, an expanding jet of flow emerges from the reach immediately upstream, generating flow separation with a sharp decrease in flow

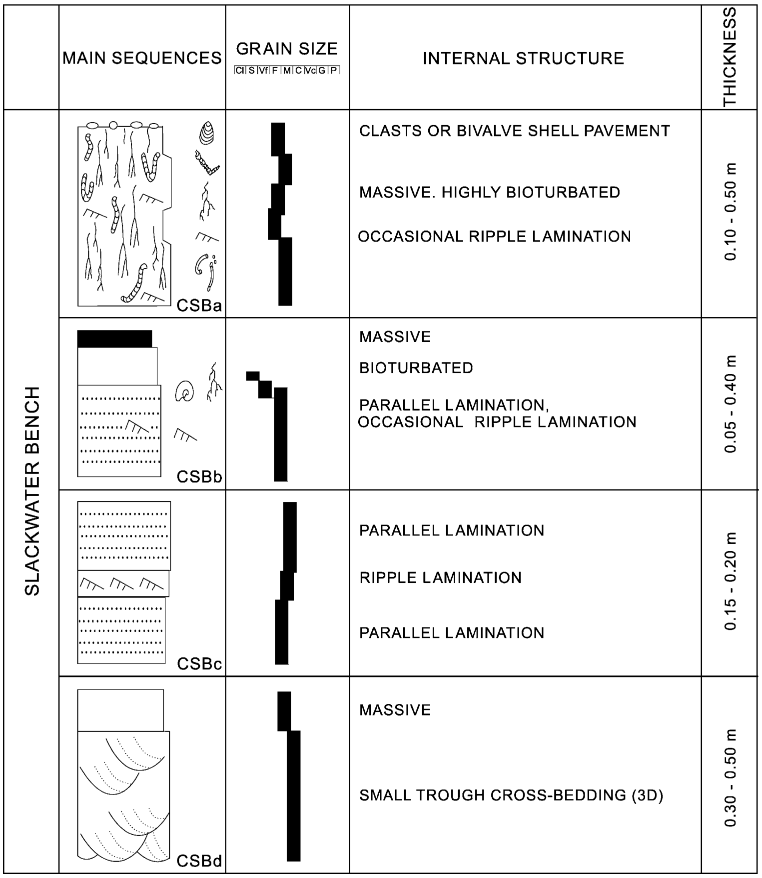


Fig. 11. Characteristics of vertical facies sequences in canyon expansion sedimentary environments.

velocity where accumulation of sequences of slackwater deposits can occur (Kochel, 1980; Baker and Kochel, 1988). These flood deposits are composed predominantly of sand and silt and exhibit a bench morphology (Benito et al., 1998). These benches are formed by vertical accretion of slackwater sedimentation units deposited by successive floods. These units show different combinations of sedimentary structures and sediment sizes suggesting different stream features according to local hydraulic conditions. Three main examples of such sedimentary sequences, forming Canyon Slackwater Benches (CSB), were found (Fig. 11).

Sequence CSBa (Table 1 and Fig. 11) is composed predominantly of massive medium sand. It is interpreted as the deposits of a sediment-laden stream flow whose velocity suddenly decreased at the flow separation area. This local deceleration in stream power resulted in the deposition from suspension of fine-grained sediments. The sudden fall in flow velocity produced a structureless, or weakly structured, sand fallout. Intense bioturbation due to vegetation and burrows made by annelids and arthropods partially destroyed such structures. Current ripples have often been modified by wind wave action and made symmetrical. Exceptionally, the flow may have swept the upper part of the sequence, washing away fine-grained sediments and leaving a pebble or bivalve shell lag (pavement) at the top.

Sequence CSBb (Table 1 and Fig. 11) is composed of fine to very fine-grained sand with parallel lamination and massive silt–clays. Parallel lamination in

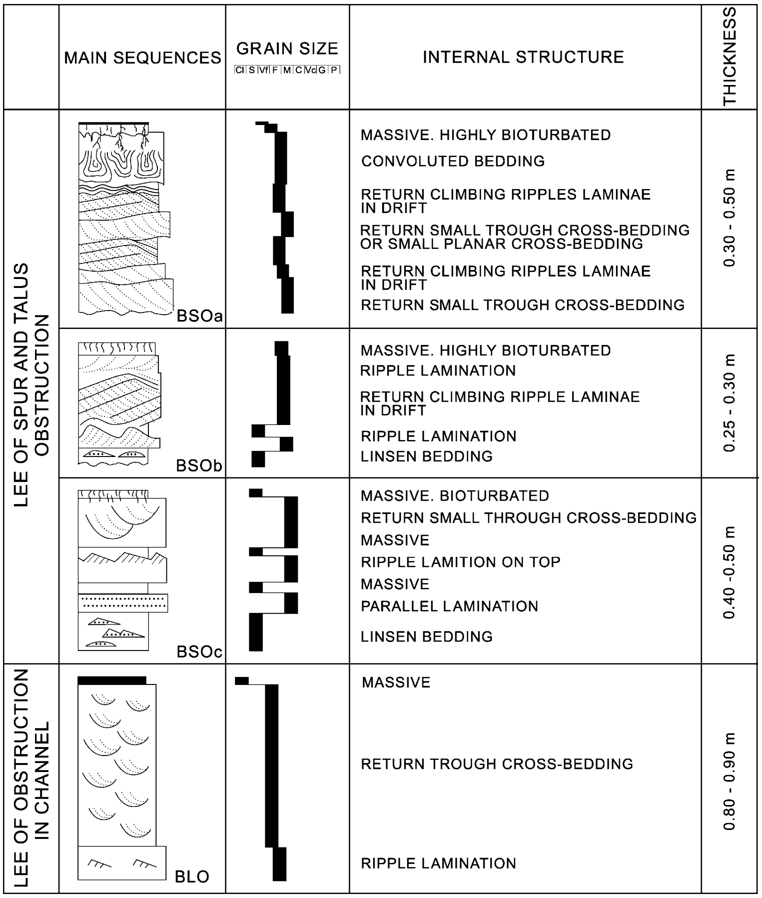


Fig. 12. Characteristics of vertical facies sequences in bedrock obstacle sedimentary environments.

this sequence is interpreted as aggradation produced by fallout onto a planar substrate without traction (Southard, 1993). Progressively finer-grained sediments were deposited until clay settles through a quasi-static suspension.

The sequence CSBc (Table 1 and Fig. 11) shows a distinctive coarsening-upward character. During flooding, a progressive increase in local energy conditions is followed by a sudden rise in flow velocity, probably due to a flood surge and a quasi-instantaneous waning stage. Parallel lamination in medium-grained sand at top of the sequence is interpreted as having been generated by sediment fall-out into a quiet column of water, and therefore, an origin without traction is proposed. These flood conditions can occur in sediment-laden river plumes during large floods (Southard, 1993). In the study reaches this sedimentary facies is associated with floods of the largest magnitude.

The sequence CSBd (Table 1 and Fig. 11) is characterised by an initial erosive phase that produced a scoured base. This sequence is interpreted as a result of vertical aggradation by 3D dune migration following a sudden decrease in stream power that resulted in structureless, fine grained, sediment deposition.

3.3. Bedrock obstacles

Bedrock obstacles create flow separation areas on their leeward side that give rise to the accumulation of distinctive sedimentary sequences. Bedrock-protected sites located both within the channel and at channel margins are characterised by slow-moving water where the flow becomes separated from the main eddy shear lines. Return currents can also be generated. Two different situations can be distinguished (Fig. 5).

3.3.1. Lee of bedrock spur and talus obstruction

Bedrock spurs in channel marginal areas generate a local flow energy dissipation that results in ineffective flow areas and local recirculation zones (Leeder and Bridge, 1975; Baker, 1984; Schmidt, 1990; Rubin et al., 1990, among others). The separation point occurs at the upstream end of the recirculation zone, probably on the spur, while the reattachment point varies greatly due to fluctuations in the point of eddy reattachment along the river bank and from the creation and destruction of eddies as river stage changes (Schmidt, 1990; Rubin et al., 1990). There are three main examples of sedimentary sequences within this

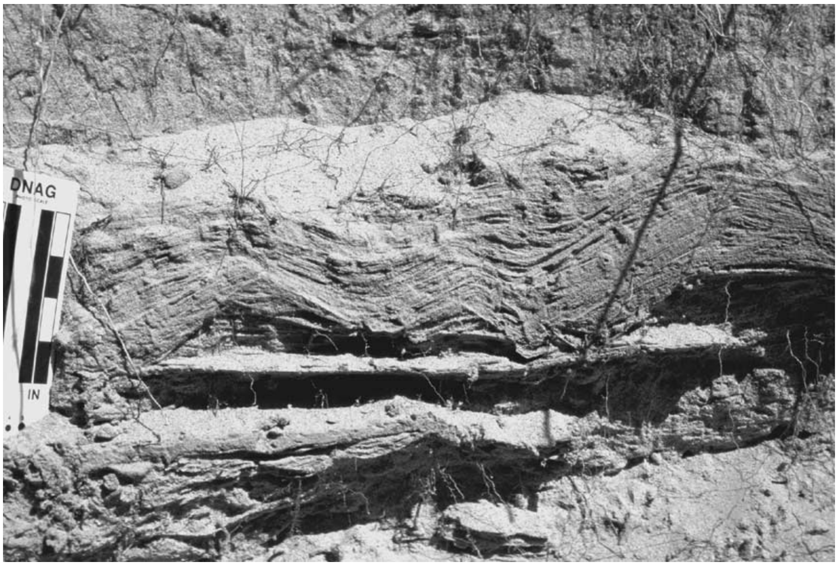


Fig. 13. Detail of the upper part of sequence BSOa showing return climbing ripples in phase as "wave-like" ripples in morphology. Although these ripples resemble oscillation ripples, waves are not involved in their formation. Lamina-to-lamina zig-zags at the ripple crest are interpreted as a result of fluctuations in the location of the reverse flow.

context (Table 1 and Fig. 12), labelled Bedrock Spur Obstructions (BSO).

Sequence BSOa (Table 1 and Fig. 12) is characterised by return current structures, interpreted as having been generated in a flow recirculation zone with a high sediment concentration. 3D dunes, locally 2D, as well as drift climbing ripples, migrated upstream as a consequence of the return current. Local fluctuations in velocity and sediment concentration in a reversing flow situation caused variation in vertical structure development. Reversing climbing ripple structures, similar to those described here, have previously been reported in Colorado River sediments (Rubin et al., 1990). The "wave-like" climbing ripples (Fig. 13) have been explained as the result of fluctuations in the position of the eddy reattachment point (Rubin et al., 1990). The higher suspended-sediment concentration and sudden sand deposition from suspension resulted in the development of water-escape structures during mass settling. Progressively finer-grained sediments were deposited until clay settles through a quasi-static suspension. After flooding, subaerial exposure and bioturbation occurred in the uppermost part of the sequence.

Sequence BSOb (Table 1 and Fig. 12) is also interpreted as having been generated inside a separation flow zone, but in areas of variable flow direction near the separation point (Fig. 5) or, more probably, near or at the reattachment point. These rotary flow areas were not fixed but rather fluctuated as a function of flow velocity (Schmidt and Graf, 1990; Schmidt, 1990; Rubin et al., 1990). Downstream flow is repre-

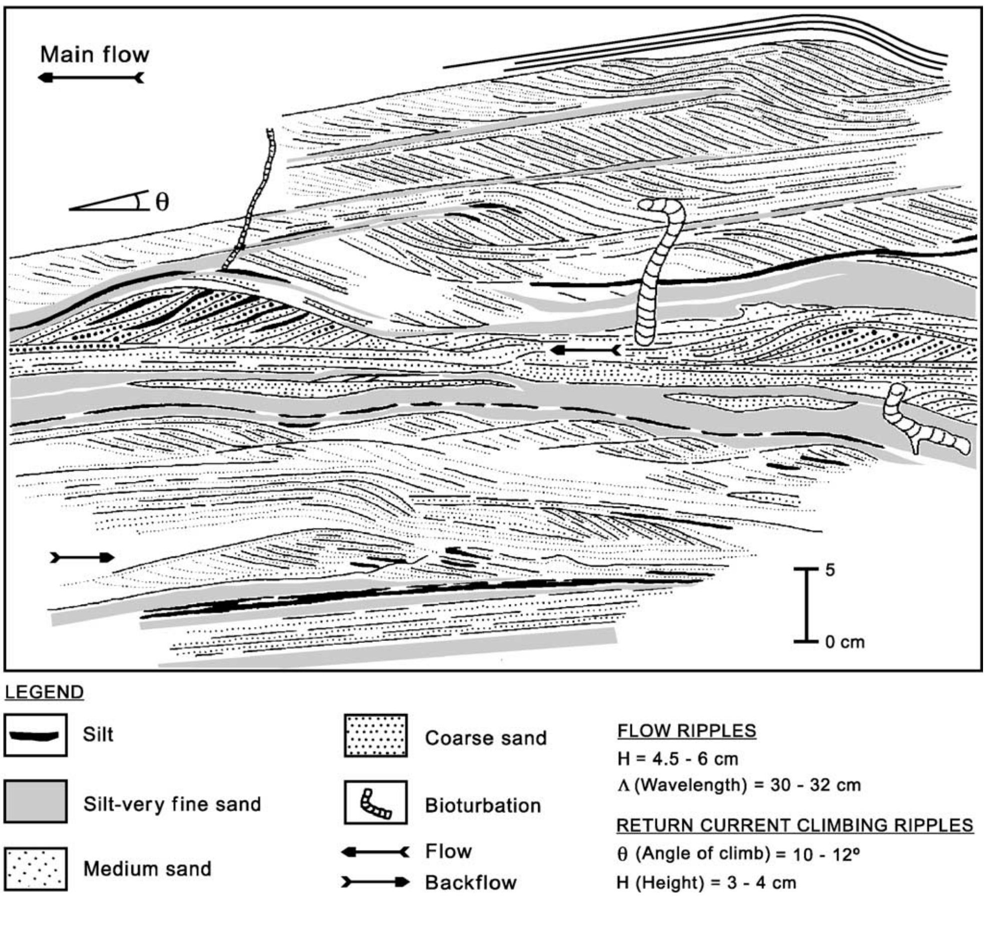


Fig. 14. Sketch drawn from a photo showing changes in the direction of current ripple migration produced by secondary return eddies.

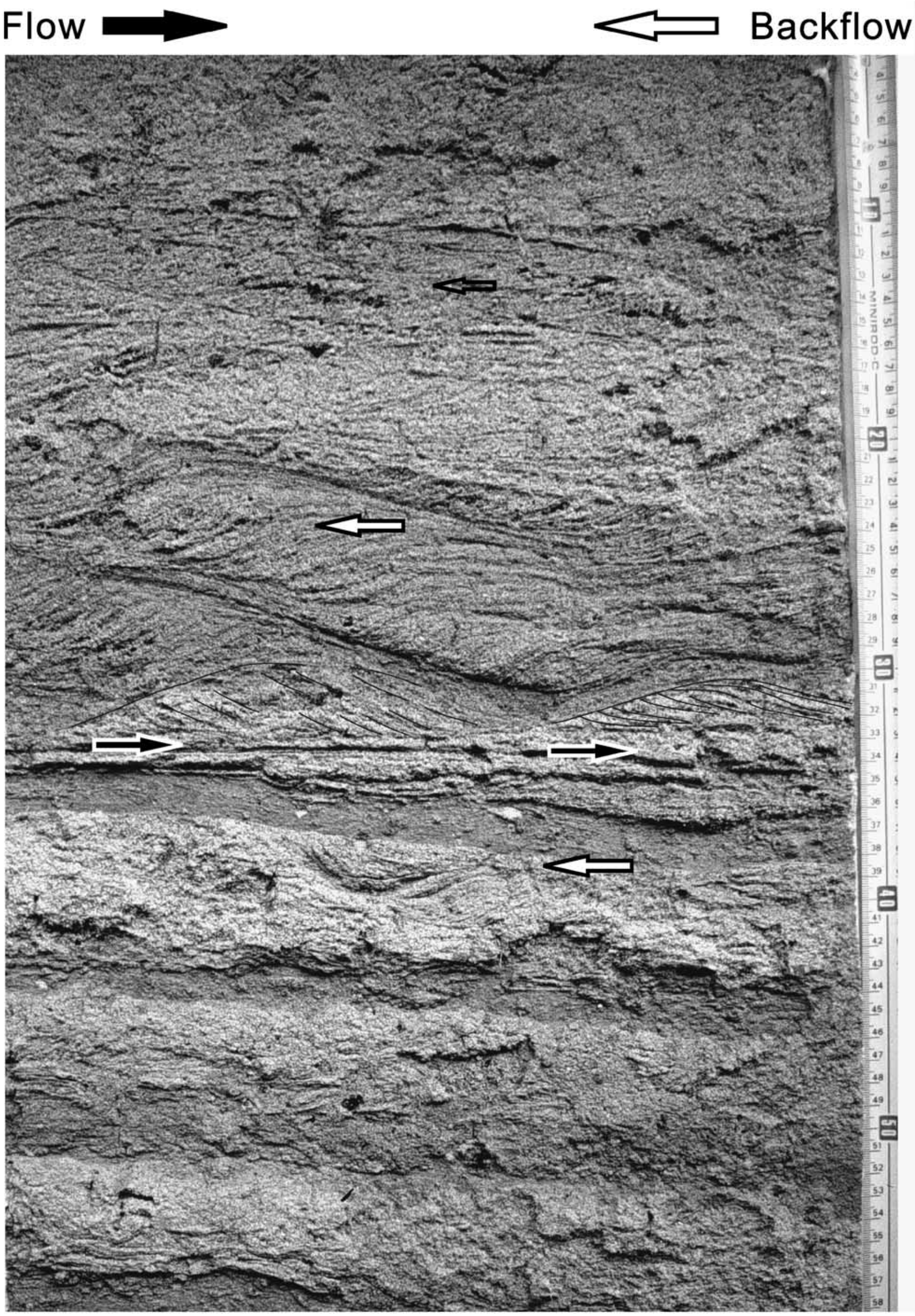


Fig. 15. Photograph of lacquer peel (60 cm high) of flood deposits from the external zone of the channel widening sedimentary environment at El Puente del Arzobispo. Note the opposite flow direction shown by the current ripples and produced by eddies in the recirculation zones.

sented in sequence BSOb by a succession of linsen-bedding and current ripple migration that appear to represent, initially, a starved current (low sediment concentration) that generated isolated ripple bodies preserved in mud, which became progressively loaded with sand and subsequently developed continuous ripple bodies. The change in migration direction of bedforms is marked by fine grain sediment deposition or silt drapes. Upstream flow is represented by climbing ripple migration generated by a return eddy inside the recirculation zone with a high sand concentration (Figs. 14 and 15). When flow velocity increases, downstream to upstream bedform migration takes place. At the waning flood stage, the production of a new downstream ripple migration, and/or structureless sand deposition during sudden fallout episodes, could occur. Later intense bioturbation has partially destroyed the uppermost structures.

Sequence BSOc (Table 1 and Fig. 12) is similar to the BSOb sequence but downstream structures are more prominent. Sequence BSOc is explained as having been generated inside an area of directionally variable flow that fluctuated as a function of flow velocity. Very-fine sand ripples preserved in mud, and linsen bedding facies, are interpreted as the result of a starved current. When flood sand load and velocities increased, or water depth decreased, plane bed migration occurred. The change in migration direction of bedforms is marked by fine sediment deposition from suspension. An increase in the energy flow conditions and subsequent eddy development produced high energy reverse upstream flow structures such as small 3D dunes. Massive silt, or structureless very fine sand deposition, seems to represent the final stage of the flood episode. Later intense bioturbation partially destroyed the structures.

3.3.2. Lee of obstruction within the channel

Bedrock obstacles within the channel generate ineffective flow areas and a reduction in flow velocity at the leeward side of bedrock obstacles. In these protected sites, the sequences that are deposited are

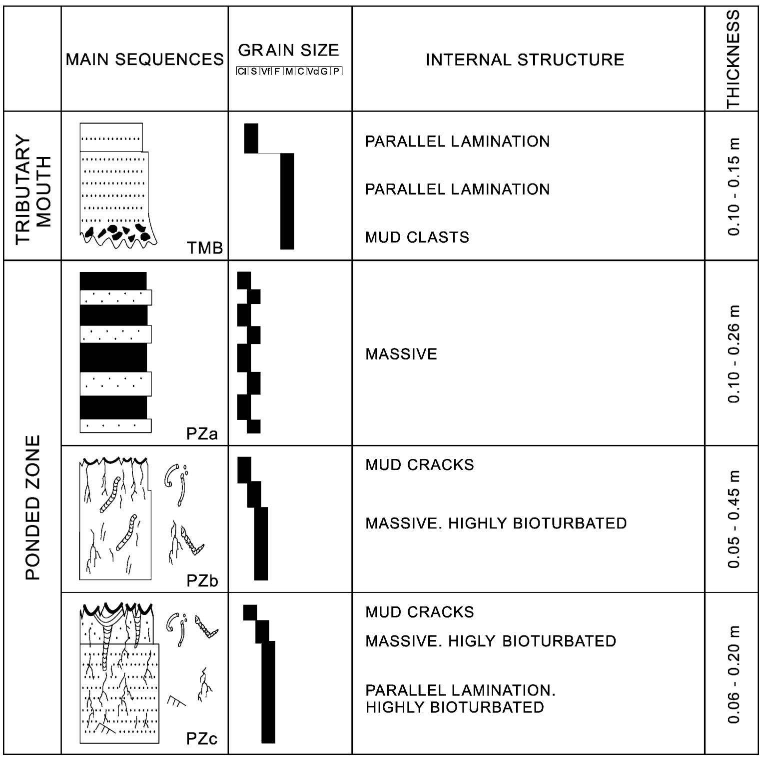


Fig. 16. Characteristics of vertical facies sequences in backflooded tributary sedimentary environments.

characterised by upstream structures. The main sequence, Bedrock Lee Obstruction (BLO in Table 1 and Fig. 12), is interpreted as the result of vertical accretion produced by ripple migration. The interval characterised by small 3D return-dune migration represents secondary backflow eddies within the channel. In extreme non-effective flow conditions clay settling from suspension took place.

3.4. Backflooded tributaries and tributary mouth environments

The main depositional areas are located at: (1) tributary mouths and (2) upstream backflooded areas where ponded flow conditions occurred during flood stages (Fig. 5). Although both subenvironments are related to the presence of tributaries, they contain very different sedimentary sequences that responded to different patterns of flow and to different energy conditions.

3.4.1. Tributary mouth

Tributary junctions are areas of flow separation, where streamlines diverge from the main thread of flow in the channel and become involved in recirculation zones, allowing for rapid deposition of suspended load (eddy bar of Baker, 1978; Baker and Kochel, 1988; O'Connor, 1993). The main sequence, Tributary Mouth Bar (TMB in Table 1 and Fig. 16), is interpreted as the result of an erosive event that reworked floodplain deposits and generated a scoured base with mud clasts. The prominent parallel lamination facies indicates migration of plane beds and reflects high energy during peak flow stage.

3.4.2. Ponded zone

As flood stage increases, water moves up the tributary valleys during most major floods generating backflooding up to the level of the flood in the main river. This backflooding produces stagnant water and deposition from suspension of slackwater deposits (Fig. 17). There are three kinds of sequences, PZa to PZc (Table 1 and Fig. 16), characterised by subtle differences in flow energy conditions.

The first ponded sequence (PZa in Table 1 and Fig. 16) is characterised by alternating silts and clays. Structureless deposits can be observed and silt–clay couplets have settled from suspension due to small variations in near to total slack water conditions.

The second example (sequence PZb in Table 1 and Fig. 16) exhibits different small scale variations from the general sequence outlined above, and can be interpreted as the result of flow stagnation or nearly stagnant conditions. Muddy sediments were deposited by settling with little or no participation by traction currents. The later modifications of the sequence can include subaerial exposure, producing mud cracks, or intense bioturbation.

The ponded sequence PZc (Table 1 and Fig. 16) includes the highest energy facies of this sedimentary environment. It is composed of very fine-grained sand with parallel lamination and, occasionally, current ripples. Energy variations inside this sequence are defined by the presence or absence of silt–clay sediments. This type of sequence is interpreted as a result of vertical accretion produced by fallout onto a planar substrate, with periodic small traction currents generating ripple lamination, draped by clay size sediments. Subaerial exposure resulted in mud cracks. Intense bioturbation, due to vegetation and burrows made by annelids and arthropods, also occurs.

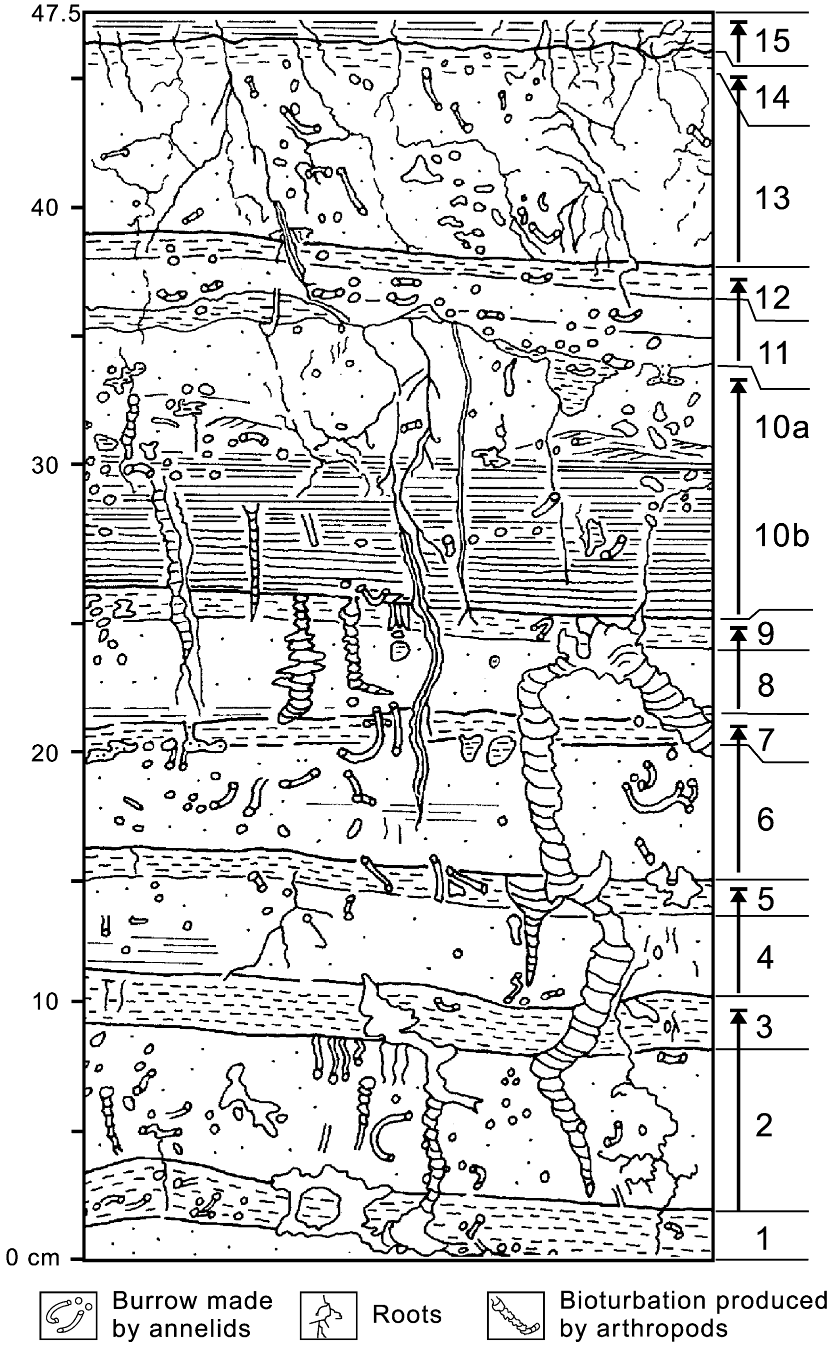
3.5. Associated deposits

Fluvial sedimentary sequences generated by large floods are not the only sedimentary deposits evident within the bedrock gorges studied. Non-fluvial deposits intercalated in the flood sequences may complicate flood interpretation and so are needed to be identified and interpreted. Two distinctive environments have

Fig. 17. Detailed field sketch of vertical sequences in a ponded zone of the Tagus River at the Alcántara site. (1) Clay–silt, medium dark grey colour. (2) Silt–very fine-grained sand, greyish pink colour. (3) Clay–silt, medium grey colour. (4) Silt–very fine-grained sand, moderate orange pink colour. (5) Clay–silt, medium-light grey colour. (6) Silt–very fine-grained sand, parallel lamination occasionally, moderate orange pink colour. (7) Clay–silt, dark grey colour. (8) Silt–very fine-grained sand moderate orange pink colour. (9) Clay–silt, light yellow colour. (10a) Silt–very fine-grained sand. Occasional ripple lamination. Light yellow colour. (10b) Silt–very fine-grained sand, parallel lamination. Greyish orange colour. (11) Silt–very fine sand, moderate orange pink colour. Erosive and sharp base. (12) Clay–silt, medium light grey colour. (13) Silt–very fine-grained sand, bioturbation produced mainly by annelids, pale yellowish brown colour. (14) Clay–silt, greyish purple colour. (15) Silt–very fine-grained sand, crudely parallel lamination.

been detected in the El Puente del Arzobispo and Alcántara study areas: (1) reworked slope deposits (slope washflow); and (2) reworked aeolian deposits.

The first of these sedimentary environments depends on the character of the local slopes and canyon lithology on which the mega-flood sequences have



been deposited. The latter environment is not specific but is related to later transformations occurring after flooding, for example aeolian reworking of the surfaces of the sedimentary sequences deposited during flood stages.

3.5.1. Slope washflow

Large magnitude floods usually redistribute pre-flood regolith generating complex sedimentary sequences where sediment-gravity processes and fluvial action are intimately related. These slope-wash depos-

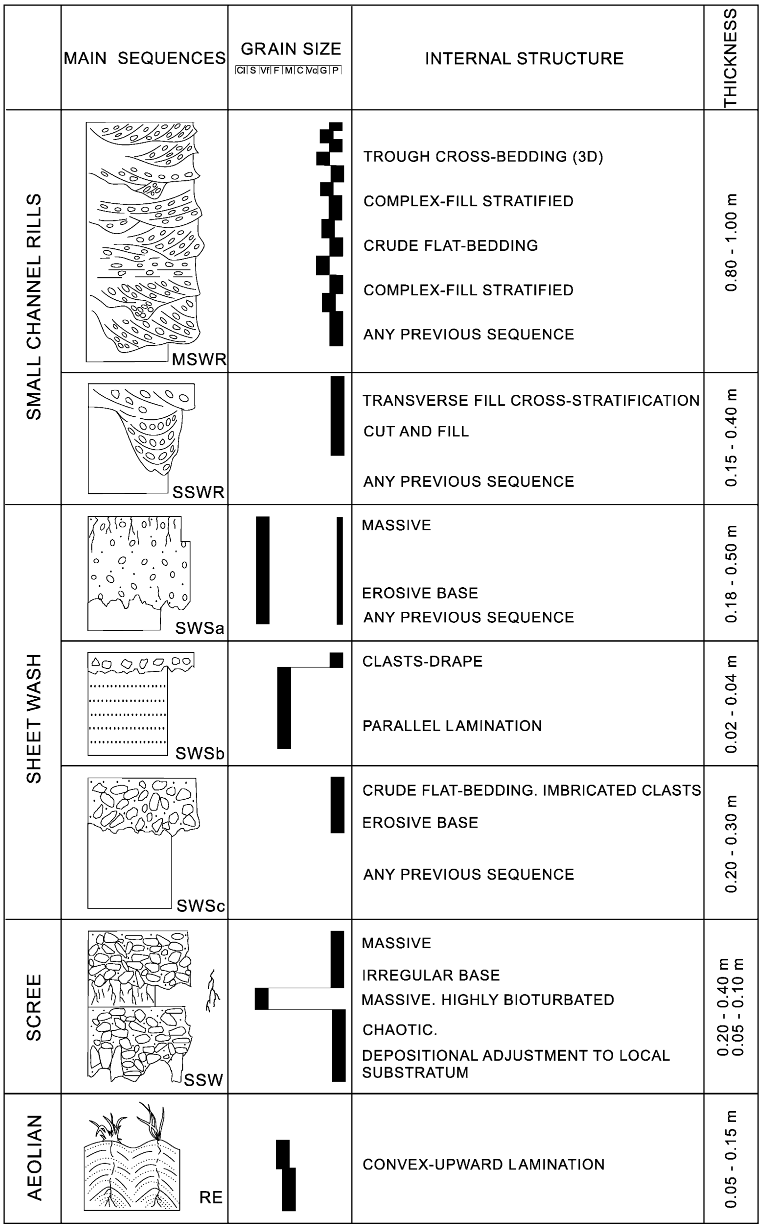


Fig. 18. Characteristics of vertical facies sequences of non-fluvial associated deposits in slope-wash sedimentary environments and in aeolian reworked sedimentary environments.

its have not been extensively studied from the sedimentological point of view, but the excellent work of Nemec and Kazancy (1999) provides clear diagnostic sedimentary criteria to recognize these kinds of deposits. In the study area, the most frequent sequences are related to small channel rills, sheet wash processes, and screes. These rill channels or gullies can be generated as a single event by one rill-and-fill episode or can represent multiple episodes. This episodic character can give rise to two basic types of sequences: single and multiple channel rill sequences.

The multiple slope washflow rill sequences (MSWR, Fig. 18) are characterised by scour bases and fine-pebble sand showing crude flat bedding, transverse fill cross-stratification, or more commonly, complex-fill stratification. Internal erosive surfaces are very common. Granules and sands with small trough cross bedding (3D dunes) are also present. This kind of sequence is interpreted herein as erosive water flow processes generating relatively deep and narrow scour bases, infilled by coarse-grained material, formed by high superficial run-off with multiple infill episodes indicating moderate but prolonged and repetitive episodes. Crude flat-bedding stratification indicates tractional deposition from poorly confined water flow, while complex-fill organisation suggests filling of local superficial depressions. Migration of small 3D dunes represents the final episodes of more confined floods when depressions are completely infilled. The second case corresponds to a single rill channel (SSWR in Fig. 18) characterised by a scour base and fine-pebble sand transverse fill cross-stratification. This sequence can be the result of rill-and-fill processes generated by high superficial run-off.

Sheet-wash slope deposits are characterised by abundant coarse size particles that are flushed by high–water surface events. These deposits, whose textures vary from matrix–rich to clast-supported, have been denoted and attributed to different depositional processes. The first sheet-wash slope sequence distinguished, sequence SWSa (Fig. 18), is characterised by a massive pebbly-mud texture. The sequence occasionally shows shallow scour that apparently represents peak run-off phases when the unconfined water flow had a higher transport competence and tended to erode the substratum. Flushed slope material was incorporated in the waterflow load and deposited at the same time as muddy suspension material by fast drop in transport competence. Intense bioturbation due to vegetation is frequent. Another sequence type (SWSb in Fig. 18), with different texture, is the one composed of fine-to medium-grained sand with vertical accretion produced by migration of plane beds from sheetflow processes, occasionally covered by a one coset gravel horizon with shallow scour that may represent peak run-off. The sheet-wash sequence SWSc (Fig. 18) is distinguished by a pebbly clast-supported texture with an erosive base and crude flat-bedding stratification with imbricated clasts. This sequence is interpreted as poorly confined water flow that eroded the substratum.

The scree deposits are chaotic angular gravel accumulated by avalanches related to slope ravines. Bed bases show depositional adjustment to the local substratum (sequence SSW in Fig. 18).

3.5.2. Reworked aeolian

Aeolian reworked is related to periods in between flood events. In general, these deposits, although infrequent, can appear within any subenvironment. Their main interest is that they provide criteria for distinguishing between different flood events within the sedimentary sequences.

The sequence that characterises this subenvironment is delineated by medium- to fine-grained, well-sorted, sand with convex upward lamination (RE in Fig. 18). This sequence is interpreted as a result of cone sand accretion generated by the presence of some fixed obstruction in the path of a sand-laden wind. Small plants can constitute the most frequent obstacles that cause wind deceleration and result in a baffle effect against the wind-transport of sand, acting as the nuclei to fix the sand, developing a very small coppice dune (Collinson, 1978).

4. Conclusions

Slackwater flood deposits have been used as a generic term for any sediment deposited from suspension in separated flow areas, associated with abrupt changes in the channel/canyon geometry. This study on the Tagus River points out the diversity of the sedimentary environments within these marginal areas, including slackwater flood deposits s.e. and other type of high-stage flood sediments. High-stage

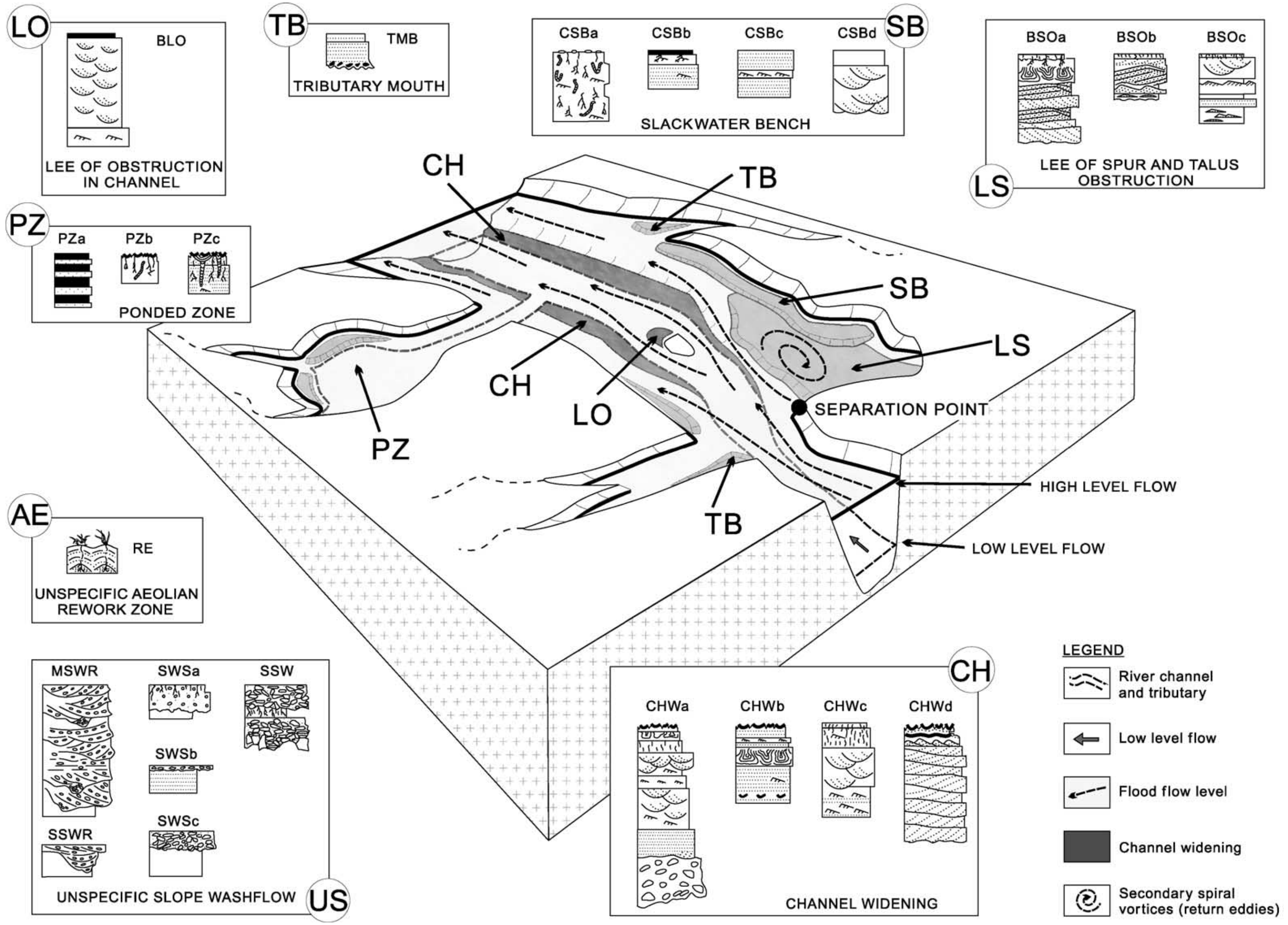


Fig. 19. Block diagram displaying the location of flood facies associations and sedimentary sequences in the Tagus River. Aeolian (AE) and slope washflow (US) sequences may be intercalated within any flood-related sequence.

deposit accumulation areas include channel widening zones, canyon expansion zones, bedrock obstacles, backflooded tributaries and tributary mouth areas. In these settings, a detailed description of flood deposits including analysis of textures, sedimentary structures, facies assemblages and interpretation of the sedimentary environment was accomplished. Sedimentological sequences were classified according to the sedimentary environment.

Fig. 19 synthesises the principal settings and main flood-sequences in the Tagus River. Seven different sedimentary contexts related to local hydraulic flow conditions have been illustrated. All of them occur at areas of flow separation, usually at marginal zones of the canyon. Channel widening during flood stages are characterised by sequence CHWa, at the internal channel belt, and sequences CHWb to CHWd at the external zone of the channel. These sequences show similarities to some fluvial channel fills located in floodplain areas and exposed to variations in flow discharge and water depth, but those of bedrock canyons differ in their larger grain size and topographically higher positions. At the canyon expansion sites, or zones where the canyon width exceeds the particular reach average, vertical accretion of slackwater units generates multiple benches with heights related to different flood magnitudes. The highest slackwater bench is characterised by the CSBb sequence, while in intermediate and lower benches the more frequent sequences are CSBa and CSBd, respectively. On the lee side of spur and talus obstruction sites local flow energy dissipation associated with recirculation zones leads to sedimentation with a characteristic sequence shown in BSOb. The sequence BLO is a consequence of secondary backflow eddies within the channel and non-effective flow conditions that predominate in the lee of channel obstructions. Tributary mouth areas are characterised by a marked velocity reduction from the main thread of flow in the channel to the low velocity flow areas at the separation zones (sequence TMB). Ponded zones generated by backflooding within tributaries, up to the stages of the flood within the main river, are represented by slackwater deposit sequence PZa as the most frequent type.

These high-stage flood sediments have not been described in ancient sediments probably because they are developed in confined channels and/or their atypical sedimentary sequences in fluvial environments including reversal planar and trough cross beds and “wave-like” ripples may have been misinterpreted in some ancient depositional environments. A better understanding of the processes of sedimentation during floods and the resulting sedimentary structures may contribute to a reinterpretation of some features and sequences encountered in these ancient sediments.

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