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ORIGINAL PAPER

Quaternary over-elevated torrential channels. Characteristics and depositional significance: the Maresme model (Catalonia, NE Spain)

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Abstract Channel-levee deposits that occur in some large sand-dominated fluvial systems are commonly elevated above the surrounding floodplain. However, the over-elevation processes of small and isolated fluvial channels are poorly documented. The Maresme zone located NE of Barcelona (Spain) offers many examples of small over-elevated channels. This area is characterised by weathered granodiorites forming a thick coarse-grained sand-dominated regolith, which was initially covered by dense forests. In the XVIII and XIX centuries human activity led to the destruction of the vegetal cover, resulting in subsequent erosion and in the intense remobilisation of sediments during storms. Thus, large amounts of sand were transported during historical times. The intermittent discharges were confined to short (few km) and straight channels with high and uncommon gradients from 3.2 to 3.4%. These discharges flowed at high velocities towards the Mediterranean Sea, the regional base-level. High infiltration rates contributed to the accretion of sandy sediments along the channels coevally with levee development. This sandy lithosome, which is usually elevated above the surrounding floodplain, displays a characteristic convex-up cross section.

Keywords Channel-levee · Infiltration · *Biorhexistasy* · *Maresme* · *Ramblas* · *Rieras* · Barcelona

Introduction

Some large rivers in wide floodplains (Mississippi, Po) and in deltas (Rhine, Meuse) form deposits that display a convex-up cross section. Recurrent episodes of spill-over result in the flooding of the surrounding plains. Thus, the channel bed together with the levees rises above the level of the floodplain, generating a large-scale convex-up cross section (Allen 1965; Schumm 1977; Miall 1985, 1996; Einsele 2000; Gupta 2007; Said 2012). The sandy lithosomes of these river beds in a deltaic sedimentary environment are laterally associated with low-lying settings (interchannels, marshes, peat bogs, evaporitic ponds, etc.) where subsidence and compaction produce an inversion of the topography (Syvitski et al. 2005, 2009; Hoogendoorn et al. 2008). A main channel with prominent levees formed by recurrent mass-flows or debris-flows is characteristic of alluvial fan settings. Similar patterns of the main channel produced by lava flows are common in volcanic environments (Cas and Wright 1987). Channels whose stream beds are elevated above their surrounding plains are frequent in deep-sea fan sedimentary environments (Hesse and Rakofsky 1992; Imran et al. 1998; Gardner et al. 2003; Keevil et al. 2006; Leeder 2011). Several authors have attributed the discharge in the channels and the spill-over of the levees to their vertical coeval accretion and development (Kneller 2003; Pirmez and Imran 2003; Peakall et al. 2007). These elevated channels that are made up of deep-marine, or continental mass flow or lava flow facies are not applicable to the explanation of the genesis of the channels in the Maresme since they are constituted by sand-dominated fluvial deposits. A short stream with a bed elevated above its floodplain is very rare in non-marine sedimentary environments (Daniels 2008).

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The term “over-elevated channel” is used in this study. By contrast, the term “superelevation” is often employed in fluvial hydrodynamics to distinguish the free surface level of the inner and the outer banks in a meander (Dey 2014). In alluvial channels the term “superelevation” is used to determine the height of the levees above their surrounding floodplains (Mohrig et al. 2000). Moreover, in deep-water systems “superelevation” is the capacity of turbidity currents to run over obstacles several times higher than their flow thicknesses (Lane-Serff et al. 1995; Lamb et al. 2008). Over-elevated channels with prominent levees, which are very common in the Maresme area (NE Barcelona), have been interpreted as sedimentary macrostructures caused by an alluvium followed by an erosive phase (Ribera 1945). This suggests that over-elevation of these streams is a generalised natural phenomenon in the study area. In an alluvial setting, over-elevation is an accumulation of sediments (preferably sand) generated only in a singular fluvial environment. In the Maresme, the over-elevated channels (Riba 1997) have variously been termed *rambla, riera, rial, arroyo, torrent*...etc. as a function of their discharge and topographical and geometrical characteristics. The term *“arroyo”* is used in diverse places (Spain, USA, Mexico, Chile, Colombia, Argentina etc.) to indicate ephemeral streams that are incised in the surrounding materials. The denomination *“torrent”* refers to short and episodic stream that join other streams or reach the coast. By contrast, the term *“riera”* (Catalonia) is a short (few kilometres in length), straight, sandy stream (with a steep gradient and episodic discharges) that always reaches the coast (Fig. 1). The terms *“rambla”* and *“riera”*, are interchangeable, the only difference being that the *“rambla”* is longer and broader. Given that *“riera”* is the local name used in the Maresme, this term is used in our study (Figs. 2, 3). Very few studies have focused on the topographic anomalies in the Maresme area. These include some works on the granodioritic basement (Enrique 1979; Solé et al. 1998), on their geomorphology (Ribera 1945) on their sedimentary characteristics (Gutiérrez-Camarós 1992; Riba 1980, 1997; Riba and Colombo 2009). Other works include those by historians (Olivé 1993), geographers and biologists (Bech 1977; Bech et al. 1983; Martín-Vide 1985; Riera and Amat 1994; Llasat 1999; Forn 2002; Llebot 2005). Thus, in view of the lack of works on this type of over-elevated channel in international geological journals to date, our study attempts to redress the balance.

The present work focuses on the main sedimentary and geometric characteristics of the non-marine Quaternary deposits in the Maresme. We therefore, propose the denomination “Maresme model” for over-elevated torrential channels generated in a morphological context characterised by a source area with a granodioritic substratum under the influence of a Mediterranean-type climate.

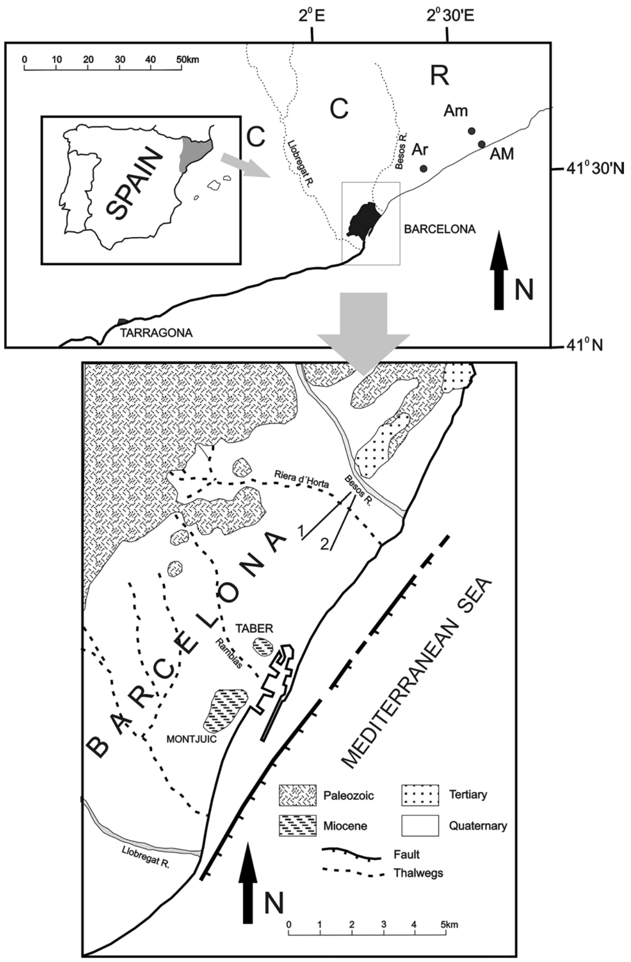


Fig. 1 Location of the study area. *CCR* Catalan Coastal Ranges. The villages located in the Maresme are: *Ar* Argentona, *Am* Arenys de Munt, *AM* Arenys de Mar. Detailed area of the city of Barcelona between the *Llobregat* and *Besós* rivers. *1 La Verneda* old road; *2* National II old road—*Pere IV* street. The *Montjuic* and *Taber* topographic elevations (hills) are prominent. Note the location of the *Riera d'Horta*. The *Ramblas* promenade is the remnant of a former *riera*

Materials and methods

The analysis of detailed topographical cartography of the Maresme allows us to differentiate several types of *ramblas* and *rieras* that display sand-dominated lithosomes with a convex-up morphology. The Maresme comprises a hierarchical system of over-elevated streams that vary in size and significance. The area, which is well documented (Riba 1980) and is made up of granodiorites (Enrique 1979; Solé et al. 1983) of the Catalan Coastal Ranges (CCR), supplies large amounts of coarse-grained sand as a consequence of intense meteorisation in wet and hot climatic conditions in the Holocene during which different soils were developed (Bech 1977; Bech et al. 1983).

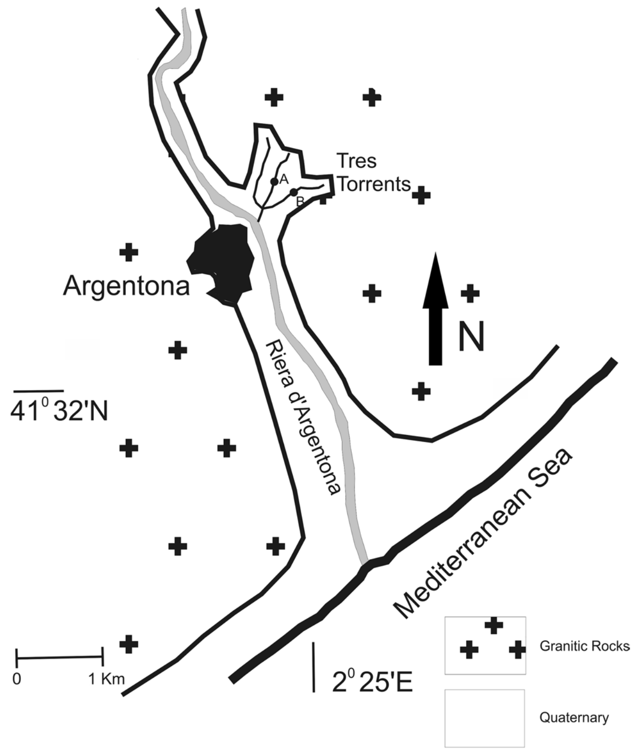


Fig. 2 Location of the *Riera d'Argentona*. Tres *Torrents* (Fig. 8) is indicated. *a, b* Corresponds to the situation of the GPR cross section in Fig. 9

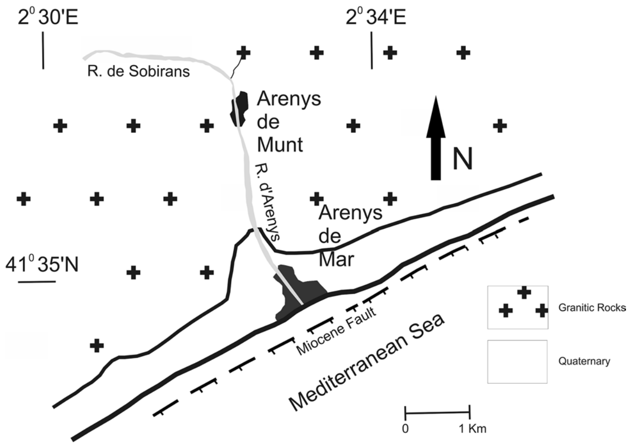


Fig. 3 Location of the villages of *Arenys de Munt and Arenys de Mar*. Location of the *Riera* d'Arenys and *Riera de Sobirans*

Ground Penetrating Radar (GPR) techniques (Jol 1995, 2008) were used to ascertain whether the subsuperficial levels were due to primary sedimentary episodes or to anthropogenic activity. The Georadar (supplied by the Mala Company, Sweden) is equipped with two types of antenna and provides signal data to study the internal structure of the over-elevated channels. These data were processed, filtered and amplified in the laboratory to obtain the best possible resolution, which enabled us to analyse and visualise the different sedimentary levels in the subsurface. In this work, two antennae one of 100 Mhz (Mega Hertz) and the other of 200 Mhz were used to confirm the validity of the signals. The best signals were obtained by means of the 100 Mhz antenna. Thus, two GPR configurations were used:

1. Reflection profiling mode (RPM). This is the most widely used in all the GPR surveys. It consists of two moving antennae that are separated by a fixed distance along the terrain surface. These antennae send pulses (shots) to the terrain and capture the reflection signal. All the shots were stacked and are displayed in the GPR profile.
2. Common mid point (CMP) or Common depth point (CDP) system. This involves moving only one antenna and provides velocities of the different reflectors located in the subsurface. In this work, the measures reached 0.08 metres/nanoseconds (m/ns).

Channel morphology

An over-elevated *Rambla* (or *Riera*) is a straight sandy stream that is short (hundreds of metres to few kilometres) and narrow (<20 m), with a low sinuosity index (<1.5), and a steep gradient (3.2 to 3.4% in the *Riera d'Argentona*, attaining 6 to 7.6% in the *Riera d'Arenys* locally). The *riera* drains a source area that supplies large amounts of sand (Fig. 4). Such sediments are mainly transported by means of high speed discharges (flash floods), generating upper flow regime bed forms (Paola and Voller 2005; Knigton 2013; Benito and Díez-Herrero 2015). When the flow peak decreases, the stream bed displays sandy braided river bed characteristics in a single channel. The cross over-elevation corresponds to the difference in elevation between the base of the river bed and the surrounding plain (Fig. 5). Schematically, the lithosome cross section is a clastic sedimentary unit that is constituted by a channel (in the upper part) consisting of a *riera* bed bounded on both sides by natural banks. The crests of the lateral banks (levees) limit the maximum level of discharge and confine the flow during the heaviest discharges. The present depth corresponds to the topographic differences between the bottom of the *riera* bed and the tangent surface to the crest of the lateral banks (avulsion surface), which is some metres higher than the surrounding plain. The cross over-elevation is the difference between the avulsion surface and the present depth (Oe = Ash-h). The over-elevated *riera* bed and the lateral banks results from successive sedimentary deposits (1, 2, 3, 4, 5) consisting of small (centimetric–decimetric)

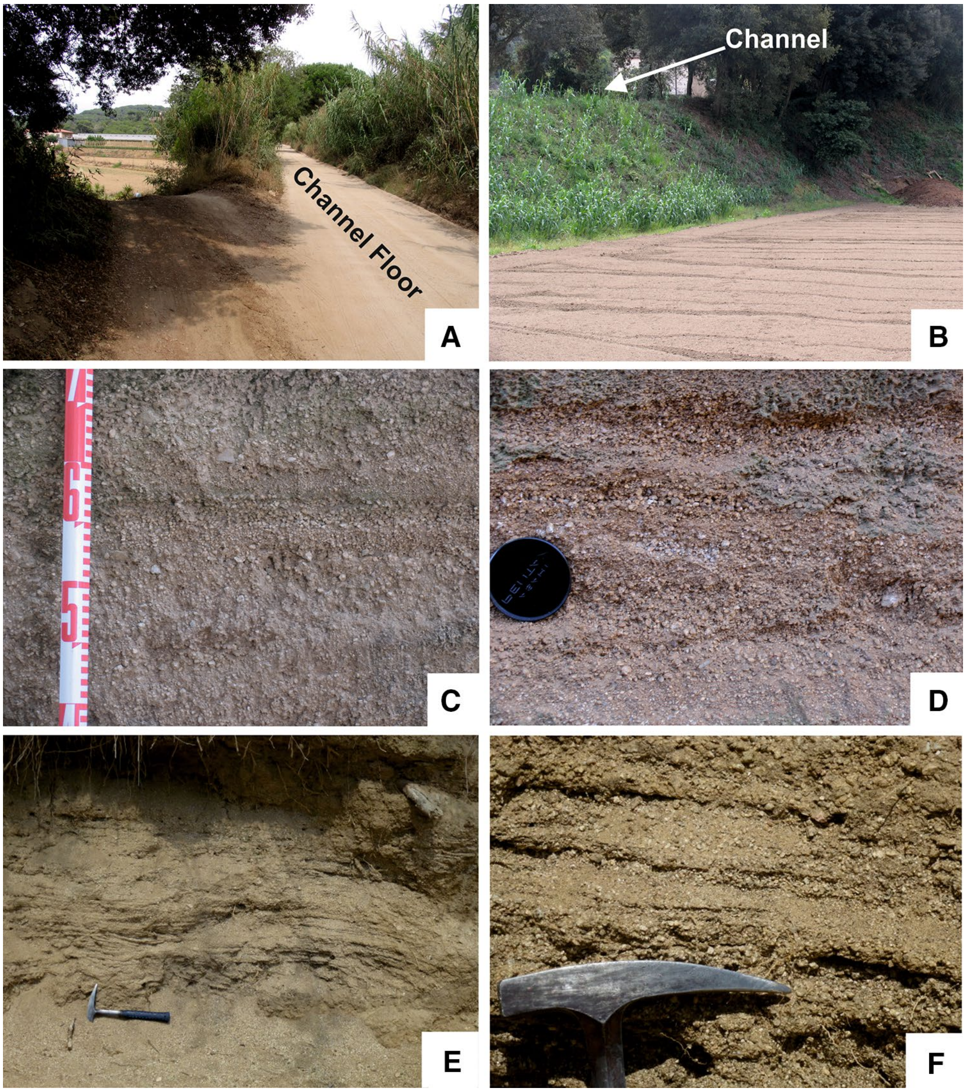


Fig. 4 **a** *Riera* bed (channel floor), which is 4 m wide, attains an over-elevation of more than 2 m above its alluvial plain. *Torrent de Can Martí* channel at *Tres Torrents* (Figs. 2, 8). **b** Over-elevation of the channel reaches values of about 4 m above its alluvial plain. *Riera de Sobirans* (Fig. 10). **c** Close-up of coarse-grained sandy plane beds. *Riera d'Argentona* tributary channel. Scale in centimetres. **d** Close-up of coarse-grained cross-stratification. *Torrent de la Reimina* channel at *Tres Torrents*. Cap lens (6 cm in diameter) for scale. **e** The levee convex-up cross section is noteworthy. *Riera de Sobirans*. Hammer for scale. **f** Close-up of levee cross-stratification. *Riera de Sobirans*. Hammer for scale

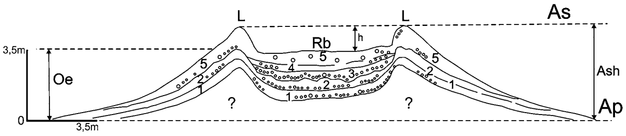


Fig. 5 Conceptual cross section of the upper levels of a sandy convex-up lithosome. *L* levees, *Rb Riera* bed, *h* channel depth, *As* avulsion surface, *Ash* avulsion surface height, *Oe* cross over-elevation, *Ap* alluvial plain. The accretion storeys (*1*, *2*, *3*, *4* and *5*) are magnified by discontinuities that correspond to isochronous lines

sequences of vertical accretions and distributed along the lithosomes. Some storeys do not reach the avulsion surface, but contribute to the over-elevation and to the instability of the system (Fig. 6). The channel width is usually about 4 m and is elevated between 3 and 5 m above the surrounding plain.

Hydrodynamics

The hydrological regime of a *rambla* is characteristic of a Mediterranean-type climate (Llasat and Puigcerver 1997) with a medium annual rainfall of 500–700 mm and a very irregular annual distribution: drought in summer (July–August) and heavy discharges in autumn (September–December). Given that the area includes a number of small towns and villages crossed by several *rieras*, the hydrograms of the superficial runoff have been well known for centuries and detailed descriptions for each village are available (Gutiérrez-Camarós 1992). A typical discharge observed from a given *riera* (or village) is made up of different phases. Thus, in the initial phase, a discharge less than 25 cm deep, reached the village rapidly. After 15–20 min, the second phase of the discharge involving a mass of water that moved faster but with less bed-load debris reached the village accompanied

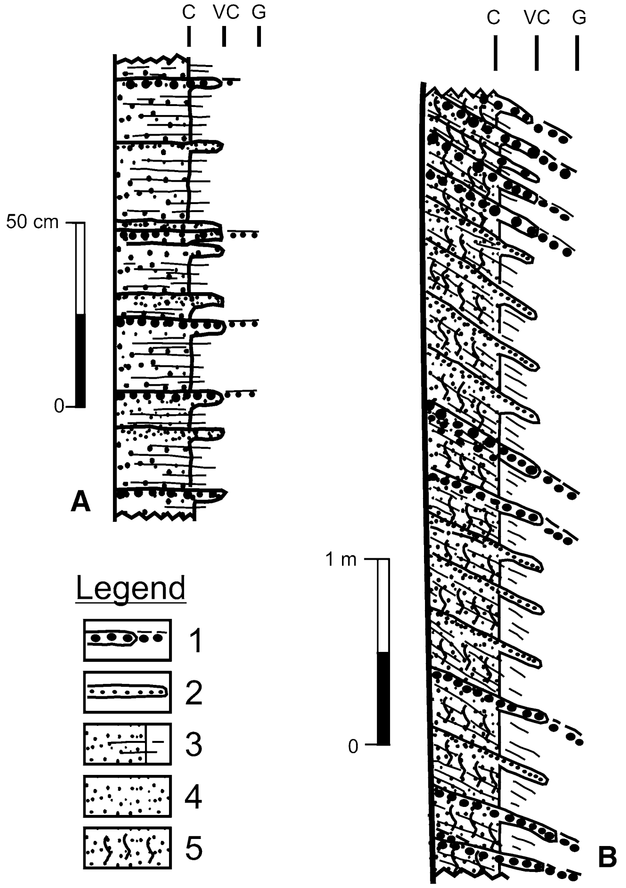


Fig. 6 Synthetic depositional sequences of the sand-dominated deposits. Grain-size legend: *G* granule, *VC* very coarse, *C* coarse. **a** Channel bed, **b** levee. Note that the upwards dip of the small sequences of the levee is progressive. The poorly defined granule-size levels are enhanced. *1* Granule lineations, few cm thick; *2* very coarse-grained sand lineations, few cm thick; *3* coarse-grained sand lineations, few mm thick; *4* sand accumulations; *5* vertical bioturbation. Compared with the close-ups **c**–**f** in Fig. 4

by strong noise. The volume of the discharge, which increased as a result of the water supply until the peak was reached, was maintained for a few hours. Thereafter, the discharge gradually decreased about 1 h after the cessation of the rain. Thus, the conceptual hydrograms of the superficial runoff in the Maresme yield two curves (Fig. 7):

A. A smooth curve produced over time as a result of the normal cyclonic rainfall of low intensity and short duration at any time of the year.
B. A curve with marked variations corresponding to rapid discharges (flash floods) of short duration and great intensity separated by prolonged periods of drought.

In the hydrograms, the growth time of the concentration curve was short. The almost vertical elevation curve and the peak runoff usually coincide with the head of the discharge. This corresponds to the frontal part of the discharge surge loaded with debris. An *in situ* observation of the behaviour of the *Riera de Sobirans* (Forn 2002) shows that the head of the discharge (1998/05/13) attained a height of 3 m above the channel bed. The diverse peaks in the hydrogram (1, 2 and 3, in Fig. 7) correspond to the contribution of the *riera* tributaries (*rials*). The total download time of the discharge is usually short (few hours).

The flow regime in the Maresme *torrents* and *rieras* is intermittent with frequent flash floods. The *rieras* may also undergo episodes of superficial discharge due to cyclonic rains which are sometimes caused by storms (Llasat and Puigcerver 1994, 1997; Llasat 1999; Llebot 2005). The heaviest precipitation recorded at Argentona and in the surrounding area (Tomás-Quevedo 1963), which attained 180 l/m^2 (litres per square metre) in 24 h (1962/09/25), generated a large flash flood. The velocities of the water during this discharge in the left margin of the *Riera d'Argentona* (*Tres Torrents*) calculated by applying the Rational Equation (Martín-Vide 1985; Témez 1991; Gutiérrez-Camarós 1992), attaining values of about of 2.7–3.8 metres per second (m/s). Similarly, in the *Riera d'Arenys*, the documented discharges covered distances of about 3 Km in 15–20 min (Forn 2002), involving velocities of about of 2.5–3.3 m/s.

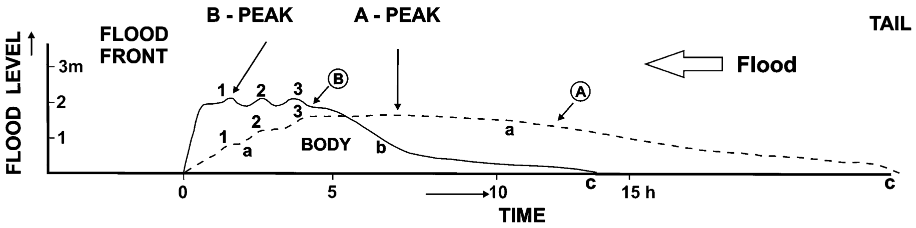


Fig. 7 Schematic distribution of the superficial runoff based on the data obtained from the current discharges. **a** Mean precipitation hydrogram; **b** intense precipitation hydrogram; *1, 2, 3* confluent flow; *a* concentration curve; *b* growing curve; *c* disappearing peak. Mean time of flooding (about 15 h)

Results

The Maresme displays several torrential river beds that are markedly elevated above their surrounding plains. These river beds are usually dry and are used as dirt roads by farmers. Since some of these river beds have been modified by anthropogenic activity, i.e. metallic water pipes have recently been installed in trenches along the course of the *Riera* de *Sobirans*, they were excluded from the study. Other river beds, which were well preserved, form part of this study, i.e. the tributaries along the left margin of the *Riera d'Argentona, Tres Torrents* near the village of Argentona (Fig. 8).

At the *Riera de Sobirans* the sieve analysis of the arkosic sandy materials reveal a predominance of coarse and very coarse sand classes and gravel (7 mm > M > 0.5 mm), whereas granules (>20 mm) are scarce. The lutitic fraction (silt + clay), which is very scarce (<1%), is made up of fine material removed directly from the regolith (Table 1). The grain morphoscopy (studied by means of a Meiji Emz-5TR binocular) shows that the grains are usually angular and subangular with brilliant facets. A large number of altered grains are dark in colour.

Table 1 Sand characteristics

Grain size (mm)	%	Fraction
>2	14.68	Granules
1/16	84.36	Sands
<1/16	0.96	Lutites (silts + clays)

Riera de Sobirans

Several tests were performed (mainly in *Tres Torrents* and *Riera d'Argentona*) to evaluate the percolation of water flow across the sandy sediments in the channel bed. Some of these were carried out by adding 200 ml (milliliters) of water to a cylinder infiltrometer until the superficial effective absorption of the sand in the channel bed was achieved. The tests were performed in a given locality after a prolonged period of drought (Table 2). The fine particles (<1/16 mm) that act as a matrix do not prevent infiltration of water resulting from diverse flood events. This infiltration has a sieve-like effect and contributes to the reduction of the poral space. The rate of infiltration depends mainly on capillary tension, temperature and gradient. The physical state of the sand, i.e. dry or water saturated must be considered in relation to cohesiveness. Dry sand is more easily eroded than saturated sand because it is much less cohesive. Effective infiltration begins when a dry bed absorbs the water. The dry sand becomes saturated as a result of infiltration which eliminates the air trapped in the bubbles that are randomly distributed inside the sediment. If these bubbles are superficial, the air escapes rapidly, but if the air in the bubbles is retained, the sand adopts a very fragile sedimentary structure (spongy). Under the river bed is a permanent phreatic aquifer with a variable water table level that depends on the rainfall. The thickness of the superficial layer of dry sand, therefore, depends on the season, the weather and the runoff.

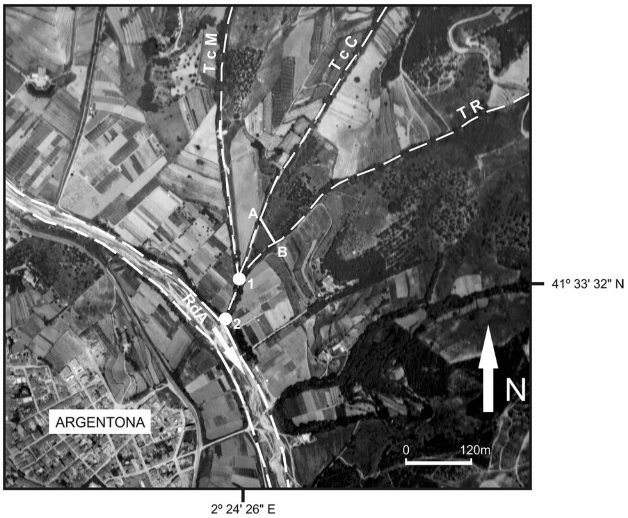


Fig. 8 *Tres Torrents* area displayed in an aerial photo (1977, October). The dirt roads (*white colour*) constitute the channel of each torrent, indicated by *dashed lines*. The levees are enhanced by the vegetation made up of shrubs and trees. Their straight morphology is noteworthy. *A*, *B* The cross section displayed in Fig. 9. *TcM* Torrent de Can Martí, *TcC* Torrent de Can Cabanyes, *TR* Torrent de la Reimina, *ARGENTONA* Argentona village, *RdA* Riera d'Argentona (the RdA banks are enhanced by the *dashed lines*)

Several samples with values of sediment transport ranging between 650 and 770 gr/l (grams per liter) were obtained in the *Riera de Sobirans* during a flood episode (2010/07/29) after heavy rain (about 50 mm in few hours). The relatively small river drainage basin (i.e. ranging 0.3–1.4 km^2 in the *Tres Torrents* area) is usually crossed by a single channel that can be divided into two longitudinal segments. The upstream segment, which is incised in the granodiorite outcrops, is about two third of the length of the channel, whereas the downstream segment is between one third and one half of the channel's length. The latter segment constitutes the main sedimentary transfer system and is located in a gently

Table 2 Infiltration intervals measured with a stopwatch

Seconds	mm
10	87.6
22	67.4
48	18.0
85	10.3

Riera d'Argentona

inclined plain (0.7–4%), draining to the Mediterranean Sea. The channelised and over-elevated sandy lithosomes are characteristic of alluvial plains, crosswise plains or wide valleys of the transfer zone between the CCR and the Mediterranean Sea (Riba 1997). The *ramblas*, which form convex-up channelised sandy deposits, are occasionally termed "sand prone channelized deposits" or "sand prone over-elevated creeks" (Allen 1965; Posamentier and Allen 1993; Einsele 2000).

Sedimentary accumulation commonly occurs in the lower reaches of the drainage basin and is consistent with the mobilisation and transportation of regoliths. Large volumes of loose sand have a relatively slow mobility depending on the environment, climate and anthropogenic activity.

The GPR profile (Fig. 9) carried out by RPM shows different reflectors along the section. The depth is about 8 metres (because of the technical characteristics of the device) and almost all the multiples of the reflectors were filtered. However, it was not possible to filter some aerial signals depicted by the dotted lines in the figure because these signals generated anomalous reflections as a function of the different slopes. The most significant signals provided by the reflectors display a subsurface structure clearly parallel to the present topography. The materials studied are coarse and very coarse-grained sandy sediments stacked at different levels in the channel course and in the levees. Two campaigns were conducted to study transects approximately orthogonal to the river beds to gain insight into their internal structure. In one campaign, data from the levels of the substratum were of no use given that the study area underwent a severe drought at the time of the survey. The same section was revisited after a period of heavy rain, and studies revealed subsuperficial structuration evidenced by diverse levels, probably because of their differential retention of the infiltrated water.

Despite the small number of morphological irregularities, it is necessary to ensure that the superficial levels show the same type of geometry. Thus, the lines of superficial reflectors clearly show parallel structures along both the channel bed and the levees, suggesting the existence of different sedimentary episodes.

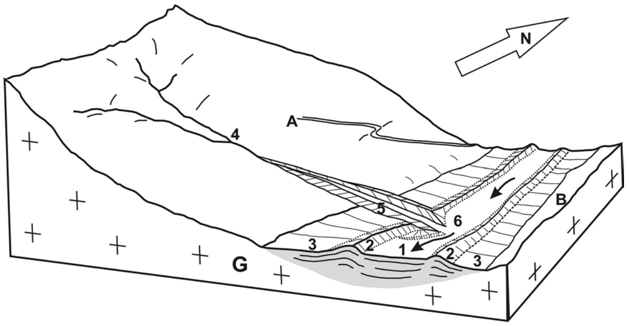
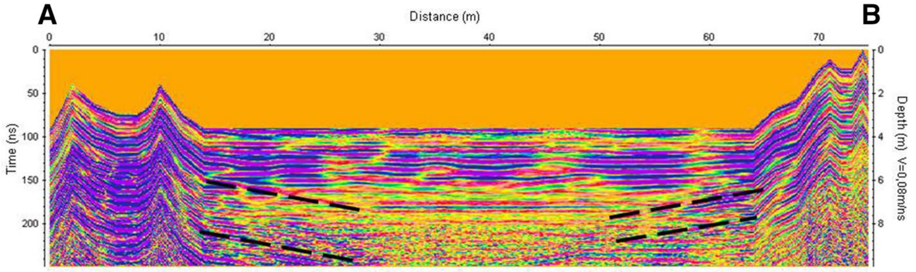


Fig. 10 Schematic distribution of the main forms in the *Riera de Sobirans. A Can Miró* farm; *B Can Vernís* farm; *G* granodioritic basement; *1 Riera* bed; *2 levees; 3* adjacent alluvial plain; *4* confluent thalweg; *5* confluent *levees; 6* over-elevated *riera* bed. The *riera* cross-section is an interpretation

Discussion

The generation of sediments could be explained by the *biorhexistasy* theory (Erhart 1955, 1956; Knox 1993, 2001). This theory accounts for the alternating periods of *biostasy* and *rhexistasy* in the Maresme. Thus, *biostasy* corresponds to the natural episode in which weathering and pedogenesis prevails, resulting in an *in situ* regolith (*sauló*). The regolith is usually protected from erosion and transportation by a well developed vegetal cover. *Rhexistasy* corresponds to the break in the natural stability episode defined in *biostasy* (Douglas et al. 1999). This can be natural or caused by Pleistocene climatic changes (Barriendos 1996–1997), volcanism, Quaternary variations (Llasat et al. 2005) or by anthropogenic factors (Riera and Amat 1994; Forn 2002; Gerhard 2004). Considerable changes such as agricultural development, forest fires, and uncontrolled exploitation of forests were wrought during the Neolithic period. From the XVIII Century onwards, commerce with America led to the proliferation of shipyards in the coastal villages of the Maresme. The deforestation of the surrounding areas resulted in the erosion of the sandy regolith materials *in situ* on the granodioritic substratum, and in their transportation towards the bottom of the valleys. This facilitated the generation of some over-elevated channels (Fig. 10). Thus, *rhexistasy* due to the climatic oscillations

Fig. 9 Cross section (between sites *a* and *b* marked in Figs. 2, 8) produced by means of ground penetrating radar (GPR) techniques. The subsurface structure is parallel to the present topography. The *dotted lines* represent some anomalous aerial signals



of the Little Ice Age (Barriendos 1996–1997; Forn 2002; Llebot 2005) also occurred. At the turn of the XX Century, the forest soils started to recover slowly, initiating a new phase of *biostasy*. The *biostasy-rhexistasy-biostasy* (*biorhexistasy*) cycle lasted almost 200 years and provides local evidence of the significant sedimentary variations in recent times (Wohl 2015), during the Anthropocene (Notebaert and Berger 2014; Lewis and Maslin 2015).

Over-elevation primary processes

The over-elevation processes were controlled by intense infiltration during the discharges in torrential channels. We compare this infiltration with similar processes in an alluvial fan such as sand-dominated Hibbing Taconite (Parker et al. 1998), which displays an extensive distributary network but no individual channels over-elevated on the fan surface. In alluvial fan settings, sieve deposits (Hooke 1967; Milana 2010) accumulated rapidly with no channelized morphology over the fan surface. The generation of over-elevated channels could be compared with the processes undergone by terminal fans (TF) at the end of the alluvial system where the water flow petered out as a result of spreading, evaporation or infiltration (Kelly and Olsen 1993). The last process strongly suggests that large amounts of sand reached the TF area. However, this process is uncommon because the mud accumulated at the end of channels prevents the development of significant infiltration. Despite the controversy over the validity of the TF model (North and Warwick 2007), its gradient is rather gentle, which contrasts sharply with the steep gradient of the Maresme model. Parallels may be drawn between over-elevation processes of sandy alluvial streams controlled by high infiltration rates and the artificial regeneration of beaches. These infiltration processes may occur in environments in which the alternation of dry sand and water saturated sand materials are affected by sand-loaded superficial discharges. These processes may also take place in a sea foreshore with dry sand in fair-weather and wet sand during storms and during episodes of large waves and tides. Beaches normally “grow” in summer, and “thin” as a result of storms in the rest of the year. Experimental studies on “beach formation by waves” (Bagnold 1946) have shed light on artificial and natural regeneration of beaches. The regeneration of beaches in the Baltic Sea (characterised by brackish waters, Feistel et al. 2010) in Denmark was first applied in the late 1980s (Vesterby and Parks 1988). A method based on the control of the foreshore water saturation known as the “beach drainage system” (BDS) has been implemented with satisfactory results along the coast of Catalonia (Montori 2002). The BDS consists (Chappell et al. 1979; Weisman et al. 1995; Vesterby et al. 1999, 2000) in the utilisation of a forced fluctuation of the water table by means of a drainage (porous tubing) and pump system that facilitates the induced infiltration of water of the ascending wave in the non saturated area of the beach front. This induced infiltration leads to a marked reduction in the transport capacity of the return wave towards the sea, contributing to sand accretion in this part of the beach. A similar process occurs in the over-elevated alluvial river bed in summer when the sand dryness depends on atmospheric conditions. The over-elevated sandy bodies are caused by vertical accretion of the sediments controlled by the large infiltration that may have been significant in recent times. The dry river bed is invaded by sudden sand-loaded discharges, resulting in considerable infiltration that controls sediment retention. This process does not involve coeval erosion of superficial sand. In summer, heavy rainstorms give rise to intense discharges that facilitate sediment retentive infiltration, leading to a positive balance of accretion with respect to erosion. However, if the sand column is completely saturated, the balance is negative. Sand removal or non-sedimentation probably plays a major role in these processes because of the cohesiveness of wet sand. The geometrical characteristics of the telescopic-like internal structure of the channel and levees suggest that these structures were generated by rapid infiltration, resulting in recurrent vertical accretions (Brierley et al. 1997; Chen et al. 2011, 2015) in the channels and levees. This interpretation is corroborated by the vertical increase in the inclination of the storeys in the levees ranging from 20°–22° at the base to 28°–32° to the summit (Figs. 4, 6). These values are measured in the *Riera de Sobirans* (basal outcrop) and in the *Torrent de Can Cabanyes* (summit outcrop). The colonisation of the levees by oak trees (*Quercus Ilex*), seedbed trees (*Pistacea lentiscus*), strawberry trees (*Arbutus unedo*), pine trees (*Pinus pinea*), canes (*Arundo donax*) and other bushes suggests that the vegetation acts as a baffle to retain and fix the sediments during spill-over events. Moreover, vegetation is instrumental in the vertical growth of the levees (Friedman et al. 1996; Yager and Schmeeckle 2013).

Interaction of flow and sediments

Locally, the *riera* deposits undergo different episodes of accretion and ablation along time. When a sandy *riera* bed is dry, the porosity and permeability are usually very high. Large pores play a major role in capillarity and in effective infiltration. When water circulates along a dry sandy bed, the intense infiltration causes the sand to settle grain-to-grain and to adhere to the river bed, incorporating this sand as a new deposit (storey). The depositional lithosomes are constituted by successive accumulation of deposits of vertical and lateral accreted storeys (1, 2, 3...) interrupted by short episodes of erosion (Fig. 5). Thus, after each discharge, the surface of the river bed grows, generating an accumulation of sediments that contributes to over-elevation, thickness and instability of the lithosomes. Sediment diffusion on the overbank and over-elevation of the levees (Fig. 6) are controlled by the overflows (Pizutto 2006). Figure 11a, b shows a conceptual discharge containing clastic materials carried along the stream bed. Infiltration entails the accumulation of materials with a progressive increase in thickness corresponding to the body and tail of the flood. During discharge, sand accretion is coeval with ablation of varying intensity, giving rise to a balance that could be negative, positive or null. This balance is positive in the case of the *Maresme rieras* (Fig. 11c). The two contrasting processes (accretion and ablation) are separated by a time interval that is shorter than that of the flood.

Owing to the dryness of the *riera* bed, a considerable amount of water is infiltrated completely or partially and the bed load is accumulated along the *riera* bed as a result of a progressive decrease in current competence. The percolation of the infiltrated water favours suction to the water–sediment interface. This leads to a stable accumulation by accretion, resulting in the over-elevation of the *rieras*. The following factors play a significant role in this process: (1) the nature of the (quartz-dominated) coarse-grained sand; (2) the absence of gravel and lutites; (3) the very high infiltration causing the adhesion phenomenon of the sedimentary particles; (4) the differences between the adhesion processes of wet and dry sands; (5) the intermittent state of the superficial runoff (discharges) with long periods of drought; and (6) the existence of a subsurface aquifer whose water table undergoes significant changes along the year.

Conceptual depositional architecture

Two scenarios concerning the depositional evolution of two neighbouring over-elevated *rieras* whose courses are approximately parallel are proposed (Fig. 12): (1) whenever a crevasse in the *riera* 1 is produced by avulsion, sedimentation ceases and the diffluent water flows towards thalweg t_1 in the nearest interfluve to re-initiate another over-elevated *riera* construction process (Fig. 12a): (2) In the long term, other over-elevated *rieras* (3, ...etc.) may result (Fig. 12b), providing ample evidence of this type of sedimentary architecture (Fig. 12c). The variations of sedimentary supply could be attributed to climatic origin as discussed above, to the *biorhexistasy* cycle or to anthropogenic activity. However, we cannot rule out the possibility that the river bed over-elevation resulted from human activity such as the construction of lateral banks (levees) to forestall flooding of agricultural land. By contrast, the volume of sediments of the convex-up sandy lithosome of the *Riera de Sobirans* (more than 750.000 m^3), that of the *Ramblas* promenade (Fig. 1) in Barcelona (more than

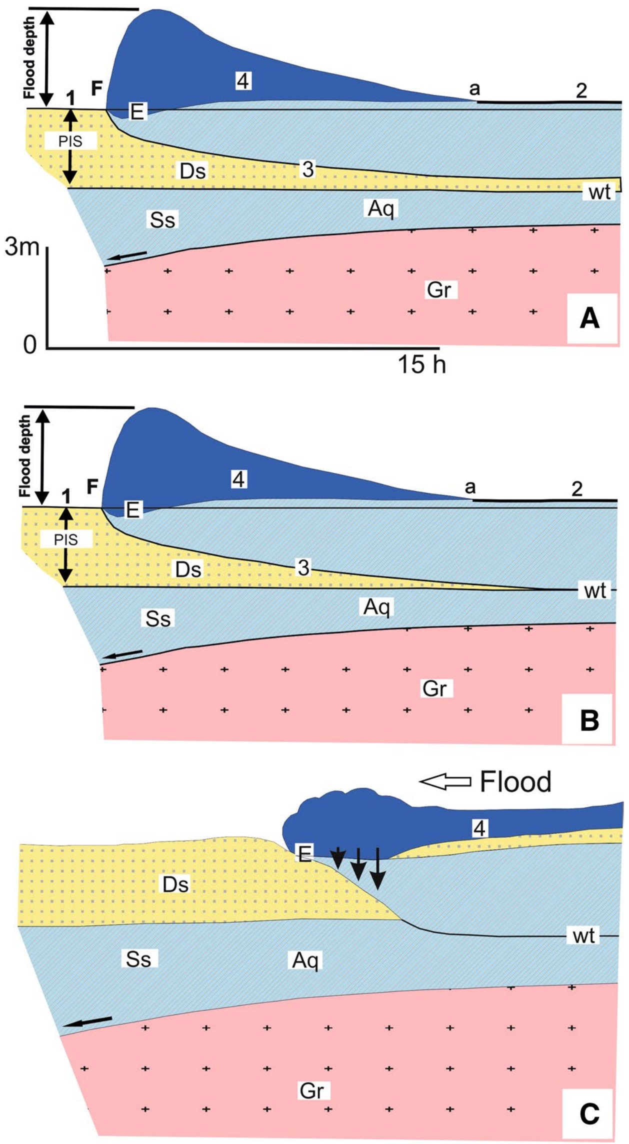


Fig. 11 Schematic conceptual discharge, parallel to the *Riera* thalweg, after a severe drought over the coarse-grained sand-dominated dry *Riera* bed which enhanced infiltration processes. Discharge towards the *left*. The Flood Level is the maximum water thickness reached by the discharge; *1* dry bed; *2* aggraded bed; *3* infiltration curve; *4* erosion (frontal part) to sedimentation (tail) curve; *a* disappearing peak; *E* erosion; *F* flood front; *PIS* potential infiltration space; *Ds* dry sand; *wt* water table; *Aq* aquifer; *Ss* saturated sand; *Gr* basement and altered granodiorites. The subsuperficial runoff of the groundwater (*arrow*) is indicated. The mean time of flooding is about 15 h. **a** First phase when the infiltration is completed. **b** Second phase when the infiltration is completed and reaches the groundwater table. **c** Discharge head (water front) detailed behaviour during a flood event. The length of the *arrows* indicates the intensity of the infiltration that reaches the groundwater table supplying large amounts of water to the phreatic aquifer. The first aggraded sand deposit accumulated over the initial erosional surface (generated by ablation) is noteworthy

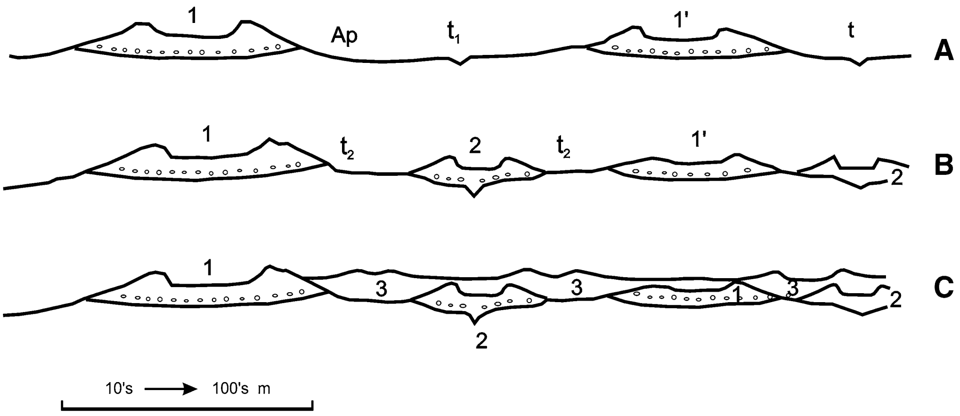


Fig. 12 Conceptual evolution of depositional history of two over-elevated adjacent *rieras* (*1* y *1'*); **a** after an overflow, the flow reaches thalweg t_1 placed in the alluvial plain (*Ap*), resulting in an avulsion; b the overflow of the adjacent *rieras* (*1, 1', 2*) reaches thalweg t_2; **c** overflows are repeated and the flow occupies position *3* etc. The final result corresponds to the accumulation of sandy convex-up lithosomes. Scale from tens to hundreds of metres

250.000 m^3), and the volume of the (Fig. 13) *Riera d'Horta* in Barcelona (more than 5.500.000 m^3) suggest that these sediments could not have been mobilised by anthropogenic action because of the absence of heavy machinery before the 1950s. In addition, given that the internal structure of over-elevated channel lithosomes displays a marked parallelism of the main reflectors, the over-elevation of the river bed must be attributed to natural phenomena. Anthropogenic activity must, therefore, be ruled out since this prominent parallelism of the main levels of artificial accumulations cannot be maintained. Moreover, anthropogenic activity could have been sporadic, strongly suggesting that the accumulation of transferred materials had very marked boundaries and irregular geometrical configurations. Thus, given that these characteristics did not materialise, the sedimentary episodes (storeys), enhanced by the different main reflectors would be accretional owing to natural processes. Other factors such as timing, discharge duration and accumulation of sediments have played a major part in the over-elevated *riera* deposits in recent times.

Examples in the maresme

Tres torrents

The area of *Tres Torrents* (three creeks) is located (Fig. 8) on the left margin of *Riera d'Argentona* (RdA) opposite the village of Argentona. The three creeks are active coevally. They are prominent and the course of each channel is highlighted by densely vegetated levees. The *Torrent de Can Martí* (TcM), the *Torrent de Can Cabanyes* (TcC) and the *Torrent de la Reimina* (TR) form a confluence of

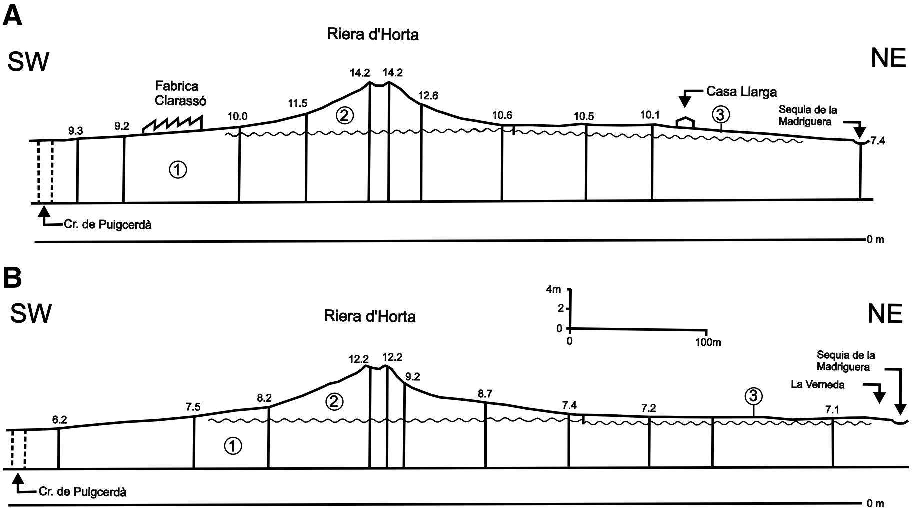


Fig. 13 *Riera d'Horta* cross sections: **a** the *Fabrica Clarassó-Casa llarga* and **b** the *La Verneda* (*Camí de la Verneda*) streets (Fig. 1). The *Riera* bed over-elevation attains values between 3.7 and 5 m above its alluvial plain. The *Puigcerdà* road (*Cr. de Puigcerdà*) is indicated. *1* The *Poble Nou* Fm (Quaternary) is composed of sands accumulated in a beach setting; *2* over-elevated channel deposits placed unconformably over the *Poble Nou* Fm; *3 Besos* River floodplain. The *La Verneda* quarter and a former small irrigation channel (Sequia de la Madriguera) are distinguished. 0 m is the present Mediterranean Sea level

the three streams (1 in Fig. 8) where a wide (about 8 m) channel joins the RdA (2 in Fig. 8). Surprisingly, the area of the confluence does not provide evidence of sand accumulation that could generate a sedimentary deposit, such as an inland delta or alluvial/fluvial fan. In the latter case, the deposit was due to a significant variation in the flow, which probably triggered the sedimentation. However, the continuity of the gradient of each channel across the confluence as far as the RdA, their straight courses and plain form and the increase in the section of the new channel (1 to 2, in Fig. 8), all seem to facilitate discharge and transport of sediments towards the RdA, which acts as a local base-level. The knick point would be located at the channel mouth where this reaches the RdA (2 in Fig. 8). Thus, the main sedimentary accumulation would occur downstream of this point in the course of the main *riera*. In the RdA, the major continuity of the discharge together with its increased intensity probably controlled the large remobilisation of sediments across the *Tres Torrents* towards the Mediterranean Sea. These processes probably prevented the development of a prominent sedimentary body in the area of the confluence (1 in Fig. 8).

Barcelona

This city has occupied its present site on the coastal plain between the Mediterranean shore and the hills behind for more than twenty centuries (Riba and Colombo 2009). In the mid XIX century, the city underwent an expansion beyond the ancient ramparts but continued to occupy the coastal plain. The topography of the area was mainly preserved because of the absence of heavy machinery to modify it during the construction of new buildings, streets, squares, etc. A detailed observation of the present topography in the city allows us to detect the remnants of the natural irregularities that reflect the distribution of several ancient depositional bodies on the Barcelona plain. Thus, the examples in the city lend strong support to our hypothesis concerning the behaviour of over-elevated channels and the development of some sand-dominated lithosomes.

The Barcelona plain displays several over-elevated river beds (*Ramblas, Riera d'Horta*, etc.). These have been interpreted as hydrographical anomalies despite being the subject of much controversy among geographers and historians because of their distinctive morphology (Olivé 1993). Some of these channels generated sand-dominated lithosomes that have been interpreted as new anthropogenic lithostratigraphic units when modified by human activity (Colombo et al. 2013). The over-elevation has been confirmed by the map survey conducted by the Barcelona City Hall (1920–1930), i.e. the *Riera d'Horta* attains heights of <5 m above the floodplain. In addition, the sediment rate of some over-elevated channels has been evaluated:

(1) The rate of sedimentary accumulation can be calculated by studying the different heights of the artificial ford (Fig. 14) originally constructed in 1781 to enable the National II road to cross the *Riera d'Horta*. A bridge was built 89–96 years later (1870–1877) because of accretion episodes that affected this road. The rate of sedimentation ranged between 2.08 and 2.25 cm/year.

(2) The King Jaume I rampart was built in 1260 to protect the medieval town of Barcelona (Fig. 15). The foundation of this wall was discovered about 4 m below the current level of the *Ramblas* promenade. Because the circulation of free water was obstructed by the construction of the *Canaletes* rampart in 1447, a period of 187 years of sedimentary activity should be taken into account, i.e. the sedimentation rate is about of 2.14 cm/yr.

These two values (Riba and Colombo 2009) of sediment rate are consistent with sand rapid accumulation but it should be noted that the depositional episodes are very

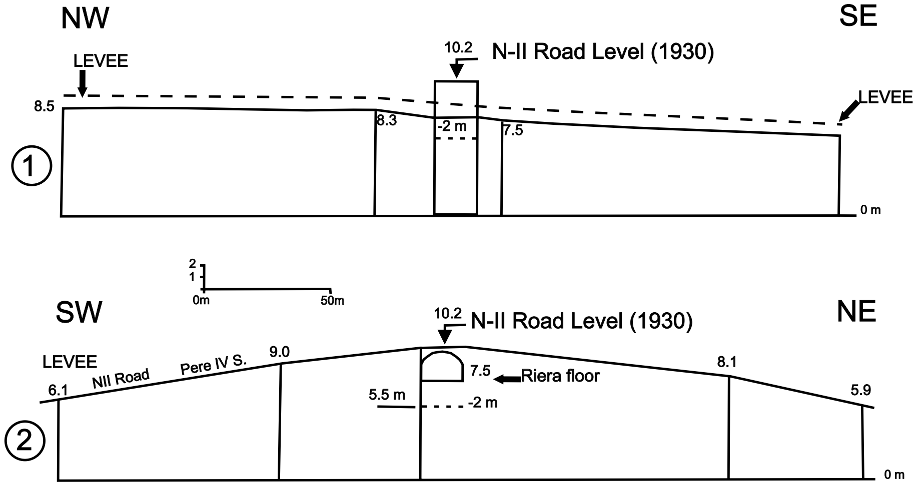


Fig. 14 Ford and bridge of the National II road across the *Riera d'Horta*. *1* Longitudinal section of the *Riera d'Horta*. The ford was discovered 2 m below the pavement of the old road. The *levee* level is displayed. *2 Riera d'Horta* cross section at the junction with National II road—*Pere IV* Street. The position of the buried bridge and that of the old *Riera d'Horta* floor are shown. The heights refer to the present sea-level position, which is 0 m

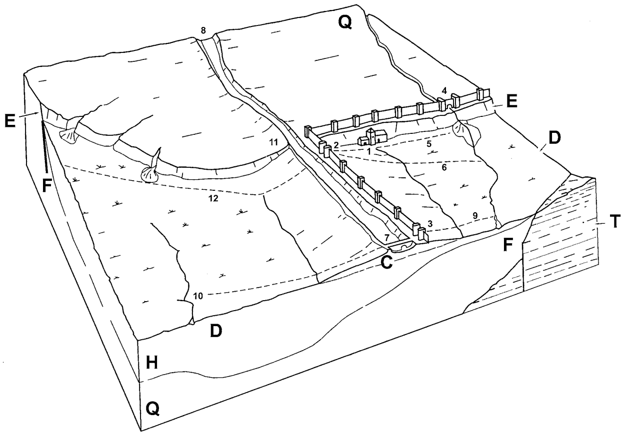


Fig. 15 Sandy lithosome of the *Ramblas* in Barcelona. Its convex-up cross geometry should be noted. The King Jaume I medieval ramparts are shown. *1 Santa Anna* church; *2 Santa Anna* gate; *3 Portaferrissa* gate; *4 Angel* gate; *5 Santa Anna* street; *6 Canuda* street; *7 Portaferrissa* bridge built in 1399; *8 Riera d'en Malla; 9 Portaferrissa* street; *10 Carme* street; *11 Catalunya* square, *12 Tallers* street; Q, Old Quaternary; *H* Holocene; *D* low plain; *E* Barcelona morphological step (*Graó barceloní*); *F* deduced fault; *C* Las *Ramblas* over-elevated bed; *T Taber* hill

irregular and punctuated by numerous non-sedimentation events.

Concluding remarks

Given the scant literature on the role of accretion in the over-elevation of a stream bed in continental settings, the following points should be borne in mind:

(1) The channels under study are short and straight with a high gradient. (2) The sediments consist of sand without gravels, very coarse sand with granules and a small amount of very fine sand. (3) There are no mud intercalations because of the absence of lutitic materials in the source and drainage areas. (4) Considerable porosity and permeability of sand contribute to a very high rate of infiltration. (5) The discharges are usually flash floods. (6) Intermittent discharges result in the formation of a superficial layer of dry sand. (7) The sedimentary accretion of the river bed is regulated by a phreatic aquifer with a variable water table, creating a potential space of infiltration. (8) Accretion is favoured by very high infiltration due to the adhesion of sedimentary particles to the surface of the river bed. (9) When the river bed is saturated owing to persistent rainfall, infiltration is ineffective with the result that sediment transport is facilitated. (10) The over-elevated river bed and the lateral banks are generated by the coeval accumulation of the deposits (storeys). (11) The internal structure of the over-elevated channels and levees is due to the rapid and high vertical accretions. (12) These processes lead to the anomalous inversion of the landforms that are locally characterised by a convex-up cross section. (13) The sedimentary activity of the over-elevated channels occurs in the space of few hours, and sporadically along the year. (14) The anomalous convex-up sandy lithosomes in the Maresme may be attributed to the accumulation of large amounts of sediment as a result of the considerable deforestation during the XVIII and XIX Centuries.

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