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River response to Quaternary subsidence due to evaporite solution (Gállego River, Ebro Basin, Spain)

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Abstract

The stream terrace evolution of the Gállego river during the Quaternary was controlled by both climatic change and subsidence. Quaternary terrace deposits, overlying Tertiary clay and limestone, are between 2 and 5 m thick, whereas above evaporite formations the alluvial deposits may be as much as 110 m thick. Chronologically, the first period of alluvial thickening involved the stream terraces T2 (+105 m above the present thalweg), T3 (+95 m) and T4 (+85 m), which have been dated by paleomagnetic reversals as Matuyama (pre-780,000). The second subsidence period affected the deposits of the stream terrace T9 (+30), dated as Brunhes (post-780,000). In both thickening periods, the subsidence was due to solution of the underlying evaporite formations (halite and gypsum), presumably, during intervals of high water flow. In the proposed model, the valley subsidence was balanced by stream aggradation maintaining the river equilibrium profile. The subsidence recorded in the alluvial deposits shows a complex spatial and temporal evolutionary pattern and total subsidence was assumed to be equal to the alluvial thickening for each subsidence period, reaching up to 165 and 25 m, respectively. © 1998 Elsevier Science B.V.

Keywords: stream terraces; subsidence; evaporite solution; Quaternary; Ebro Basin, Spain

1. Introduction

Stream terraces and valley fills have been studied by geomorphologists and sedimentologists to reconstruct the evolution and changes in the behaviour of fluvial systems through time (Schumm, 1977, 1981, 1986; Bull, 1990). Conventionally, three types of stream terrace have been described in the literature: climatic, tectonic and complex response stream terraces (Schumm, 1977). These genetic factors may result in aggradational surfaces (fill terraces) and degradational surfaces cut in bedrock (strath or rock-cut terraces) or in older alluvium (fill-cut or fill-strath terraces) (see Howard et al., 1968 p. 1117; Bull, 1990). Fill terraces may represent aggradation in response to fluctuations in sediment loads due to climate change (Leopold et al., 1964; Bull and Knuepfer, 1987), strath terraces may indicate a sud-

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den movement along a fault or an increased rate of uplift (Bull, 1990; Merrits et al., 1994) and cut-and-fill terraces are commonly the result of sudden changes in climatic regime (Leopold et al., 1964, pp. 458–486).

The evolution and morpho-sedimentary features of some of the most important river systems of the Iberian Peninsula, such as the Ebro and Tagus rivers, have been controlled by the karstification of the evaporitic bedrock and the subsequent subsidence confined to the river valleys. The solution-induced subsidence has given place to significant thickenings and gravitational deformations in alluvial deposits. In the Jarama and Tagus rivers in the Madrid Basin, the alluvial thickening due to dissolution of the evaporitic bedrock (Pérez-González, 1971; Pinilla et al., 1995) seems to be combined with neotectonic activity and halokinetic processes. Nevertheless, evaporite solution subsidence has been claimed to be the main factor controlling the alluvial Quaternary evolution in the following rivers: (a) the Gállego (Benito, 1989; Benito and Pérez-González, 1990, 1994) and Ebro rivers (Leránoz, 1993) in the Ebro Basin and (b) the Alfambra (Gutiérrez et al., 1985; Moissenet, 1989) and Jalón–Jiloca rivers (Gutiérrez, 1994a,b, 1995, 1996) in the Teruel and Calatayud Grabens, respectively. Subsidence phenomena have also been recognized in sediments filling small tributary valleys in the Ebro Basin (Arauzo and Gutiérrez, 1994, 1995; Gutiérrez and Arauzo, 1997). In this paper subsidence is described in the lower course of the Gállego river, a major tributary of the Ebro river. This river has undergone a complex evolution throughout the Quaternary due to a synsedimentary subsidence phenomenon caused by the alluvial karstification of the soluble substratum. The Gállego alluvial sediments, up to 110 m thick beneath the river flood plain, fill a solution-induced trough approximately 30 km long by 8 km wide.

The fluvial response to synsedimentary karstic subsidence recorded in stream terraces gives rise to more complex geomorphological, sedimentological and structural features than in tectonically active areas. The alluvial deposits affected by subsidence caused by the karstification of the underlying bedrock are made up of sedimentary bodies deposited in subsiding areas. They show a complex spatial and temporal evolutionary patterns. In this paper, a model for the long-term river response to subsidence is proposed from the analysis of the geomorphology, sedimentology, magnetostratigraphy and geophysics of the Gállego alluvial deposits. Our aim is to provide a better understanding of the dynamics of fluvial systems in subsiding areas not controlled by active tectonics. The study of thickness variations, sedimentological characteristics and internal structure of the alluvial deposits will provide information about the spatial distribution and temporal evolution of the subsidence areas and the river response to subsidence. The magnetostratigraphy of the terrace deposits will bound the chronology of the subsidence periods and will allow estimation of the total subsidence. In addition, the evolutionary model of river systems in subsiding areas due to solution can also be applied to fluvial valleys affected by long-term human-induced subsidence caused by removal of fluid or solid materials.

2. Geological setting

The studied reach of the Gállego river, a Pyrenean tributary of the Ebro river, is located in the central sector of the Ebro Basin near the city of Zaragoza (Fig. 1). The Ebro Basin corresponds to the southern foreland basin of the Pyrenees, an alpine orogen generated in a continental collision zone. From the Upper Eocene, following the Priabonian regression, the Ebro Basin was no longer occupied by the sea and became an individual endorheic basin surrounded by mountain ranges (Riba et al., 1983). During this endorheic stage, the unroofing by tectonic uplift and erosion of the surrounding reliefs provided detritus (molasse) deposited in alluvial fans, distally related to shallow lacustrine environments with evaporitic (playa-lake) and carbonate sedimentation. The continental sedimentary infill of the basin is composed of conglomerates and sandstones at the margins grading into clays, marls, evaporites and carbonate facies towards the depocentre of the basin. Throughout the tecto-sedimentary evolution of the basin the evaporitic formations have occupied the most subsiding depocentres which have migrated from north to south (Ortí, 1990) as a consequence of continued convergence and forebulge translation. The 40 km lower reach of the Gállego river cuts through the Zaragoza Gypsum Formation (Quirantes, 1978;

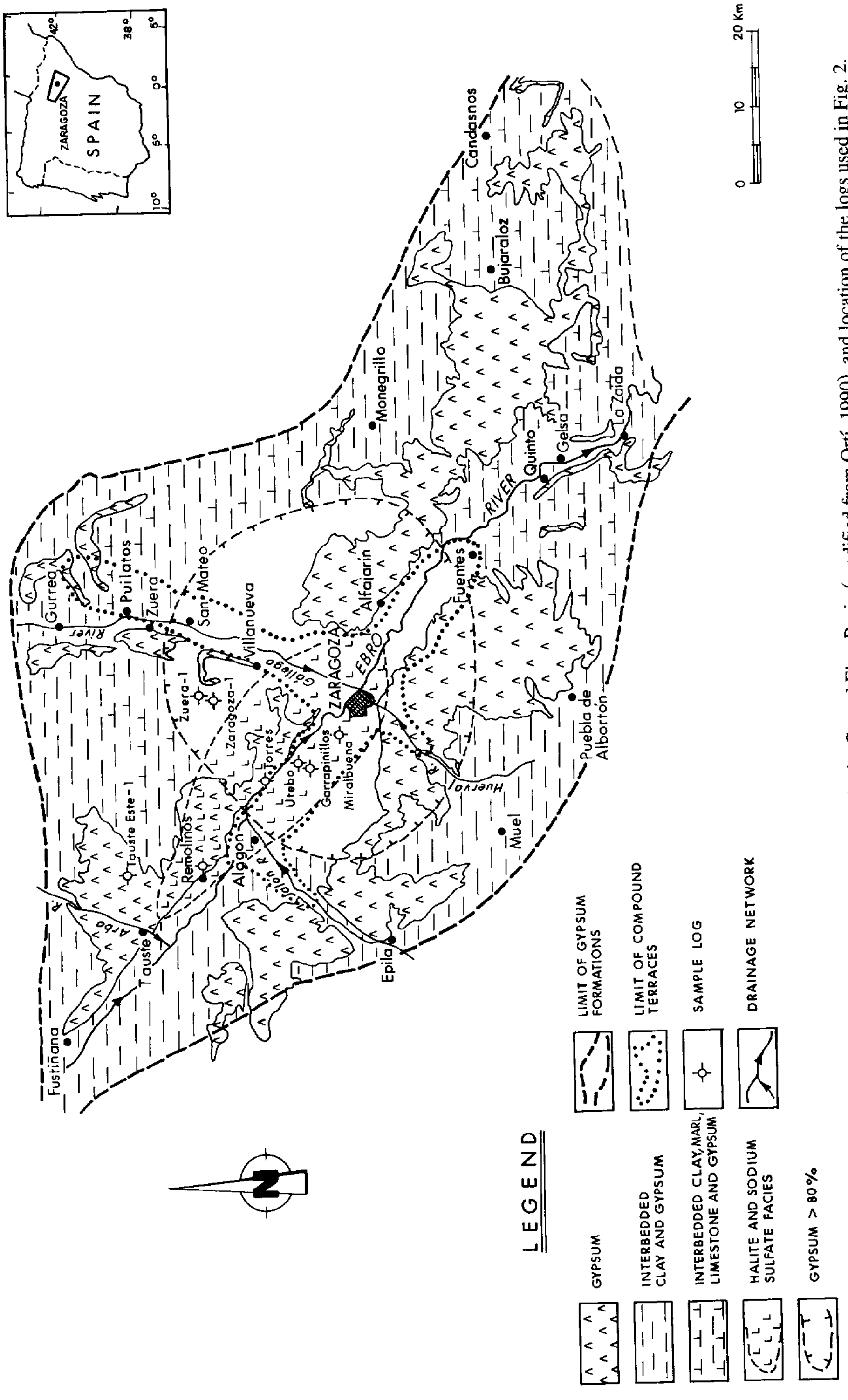

Fig. 1. Distribution of the Zaragoza Formation Tertiary facies within the Central Ebro Basin (modified from Ortí, 1990), and location of the logs used in Fig. 2.

Riba et al., 1983; Ortí, 1990), which constitutes the evaporitic sediments deposited in the Miocene depocentre of the basin (Fig. 1). From the structural point of view, these evaporitic sediments show a general subhorizontal structure and deformation is restricted to slight tilting and subvertical joints.

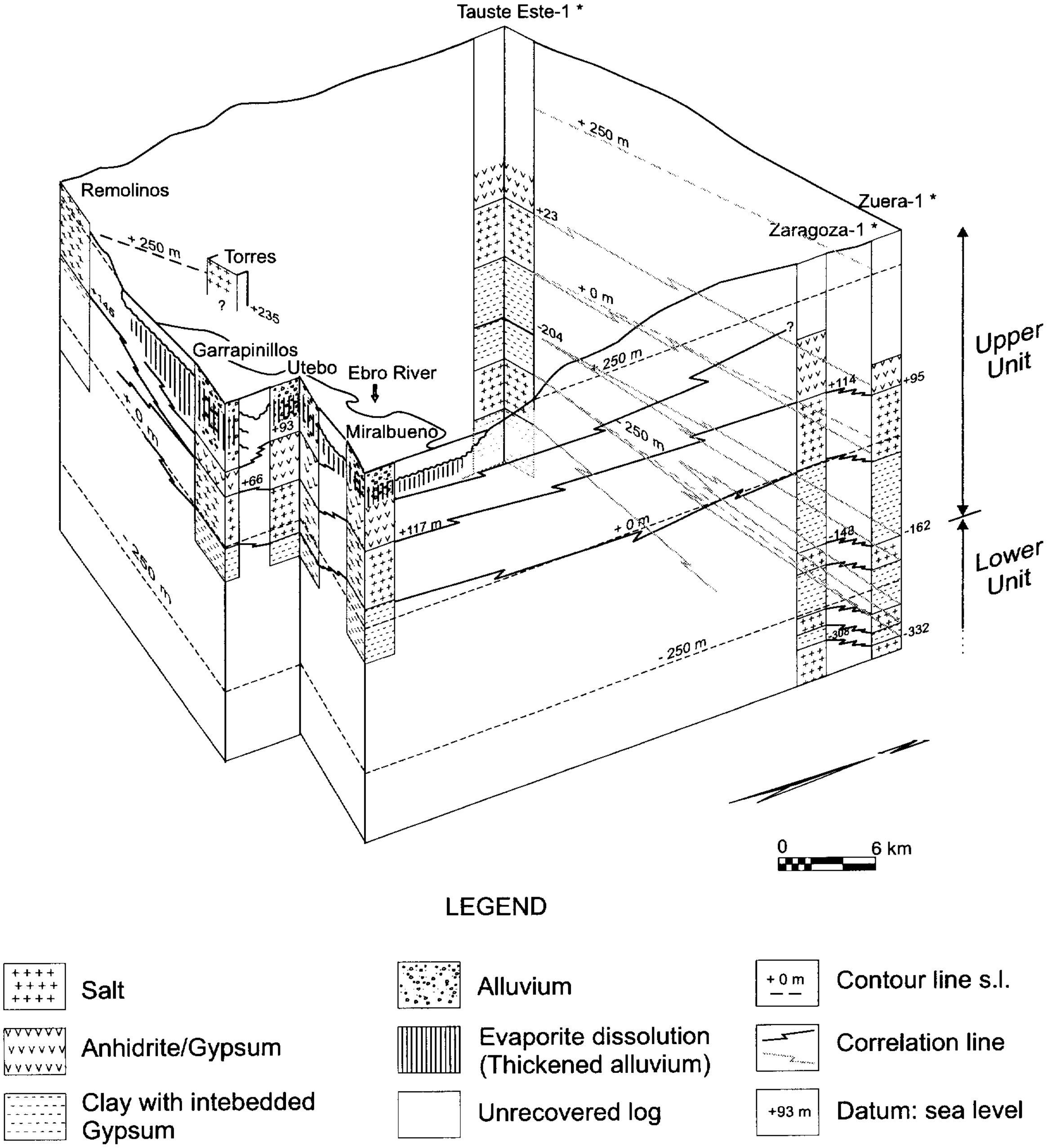

Fig. 2. Fence diagram based on the stratigraphical relationships delineated by Torrescusa and Klimowitz (1990), using gamma-ray logs in Tauste Este-1, Zaragoza-1 and Zuera-1, and by Esnaola et al. (1995), using the strip logs performed by Tosla S.A. in Remolinos, Torres, Utebo, Garrapinillos and Miralbueno.

Torrescusa and Klimowitz (1990) have described two major lithostratigraphic units within the Miocene evaporites (Fig. 2). The Lower Unit, up to 270 m thick, has its upper boundary at around −162 m (sea level datum) in Zuera and Zaragoza, and at −204 m in Tauste. This unit is composed of three sedimentary sequences, each consisting of a lower body of clay interbedded with anhydrite and limestones and an upper body of halite interbedded with clay and anhydrite. The Upper Unit (Fig. 2) reaches 600 m in thickness and is composed of a lower 140 m thick clay–marl subunit, an intermediate 120 m thick halite subunit (its upper boundary ranges from +95 m in Zuera to +23 m a.s.l. in Tauste) and an upper anhydrite–gypsum subunit. In the Remolinos–Torres area, 15–20 km to the west of the confluence of the Gállego and the Ebro (Figs. 1 and 2), a 12-m-thick halite layer is mined near the ground surface at about 250 m a.s.l. (Fig. 2). The detailed distribution of the different lithological bodies of the Upper Unit is not well known, since facies show abrupt lateral and vertical changes, and most of this information has been obtained from the interpretation of four petroleum logs (Torrescusa and Klimowitz, 1990) and three logs performed by Tolsa, S.A. for halite exploration (described in Esnaola et al., 1995). The intermediate halite subunit of the Upper Unit and the Remolinos mined layer may correspond to two different subunits (Fig. 2). Halite beds have been found underlying the Quaternary alluvium in Puilatos (Fig. 1); however, the distribution of halite in the Gállego valley area is not well known. Probably, if halite beds were present in this area they have been removed by solution and the subsequent accommodation space, created by subsidence, has been occupied by the thickened alluvial deposits of the Gállego valley.

3. General features and deformations of the stream terrace deposits in the central sector of the Ebro Basin

In the central sector of the Ebro Basin, the Quaternary alluvial deposits, overlying Tertiary evaporitic formations, show anomalous thickenings generated by synsedimentary subsidence (Benito, 1989; Benito and Pérez-González, 1990). Furthermore, the boundary between the alluvial cover and the soluble bedrock generally shows a very irregular geometry (Benito, 1989; Gutiérrez and Gutiérrez, 1996). These thickened alluvial deposits fill multiple solution-induced depressions of variable sizes, with bedding planes fanning out at the depression margins and with an overall basin-type of structure. As a consequence of the thickening in the terrace deposits, the sedimentary units corresponding to different terrace levels may be overlapped and bounded by angular or parallel unconformities. On the other hand, the alluvial cover shows abundant brittle and ductile deformation, whereas the adjacent and underlying evaporites remain undeformed. This fact rules out tectonics and corroborates the karstic origin for the subsidence recorded in the Quaternary alluvium (Gutiérrez and Gutiérrez, 1996). At particular sites postsedimentary deformations are superimposed on synsedimentary structures revealing solution and subsidence reactivation. Generally, ductile structures are synsedimentary deformations that formed in loose sediments soon after deposition, whereas brittle structures are mainly postsedimentary deformations which formed in sediments that have been lithified to some degree. The sediments deformed by postsedimentary collapse show cylindrical normal faults with clast reorientation at the outer rims. In the central parts of these collapses, the sinking and sagging of sediments leads to horizontal compression giving rise to tight folds and antithetic reverse faults. A similar scheme has been reported from recent subsidence processes triggered by fluid withdrawal (Holzer, 1980). In addition, the thickened alluvial deposits show marl–clay diapiric structures up to several metres in diameter (Benito and Casas, 1987). The rapid loading caused by the high sedimentation rate in subsiding areas leads to excess fluid pressure conditions in low-permeability fine-grained sediments, and to gravitational instability. Overpressuring reduces the strength of the unconsolidated sediments and the plastic sediment–fluid mixture intrudes into the overlying deposits causing these marl–clay diapirs. In the study area, the synsedimentary deformation is associated with these diapirs indicating that intrusion took place during, or very soon after, deposition. These loose sediment deformational structures are similar to mud diapirs described in deltaic environments (Morgan et al., 1968).

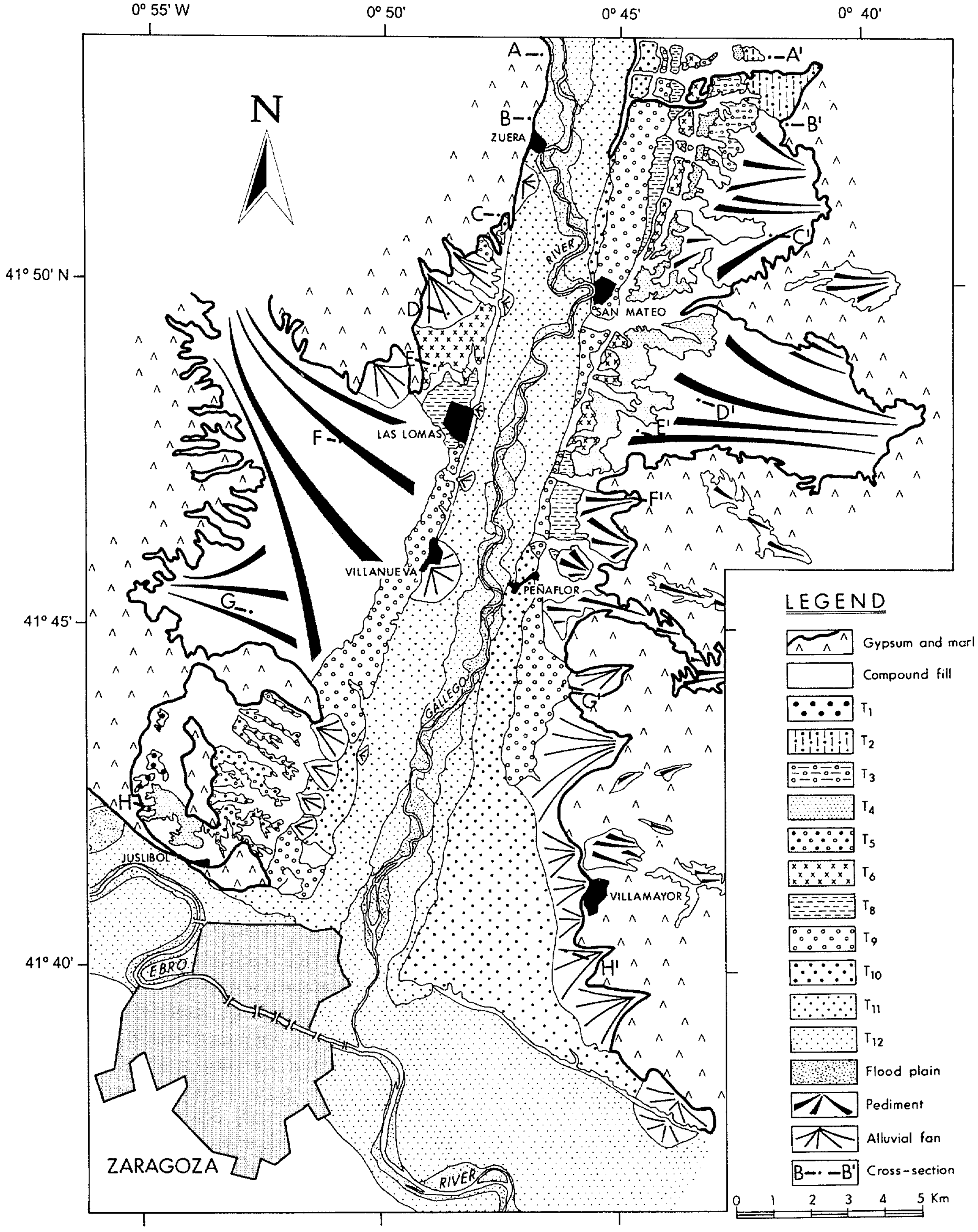

Fig. 3. Geomorphological map of the Quaternary stream terraces and alluvial fans in the lower reach of the Gállego River.

4. Stream terraces of the Gállego river upstream of the main subsidence area

The modern Gállego river has a drainage area of 4000 km^2 and flows in a NNE–SSW direction (sinuosity index (Leopold et al., 1964) ranging between 1.3 and 1.6.). The Gállego channel shows a meandering pattern mixed in some reaches with braided characteristics. This accords with model 4 of the channel morphology classification described by Schumm (1981). In terms of sediment transport, this river can be considered as a gravel-bed river with sand forming the matrix fraction.Terrace surfaces are ubiquitous and nearly continuous along the Gállego river valley. Geomorphological interpretation of aerial photographs (1 : 30,000 in scale) shows up to twelve terrace levels (Fig. 3 and Table 1). Topographic maps at scales of 1 : 25,000 and 1 : 50,000, with additional altitudinal measurements taken with an altimeter, were used to draw the longitudinal profiles of the terrace surfaces (Fig. 4). The most complete sequence of fill terraces was found in the upper reach of the study area north of San Mateo (Fig. 3). The terrace levels can be divided into three groups (Table 1): (a) Sarda terraces or older alluvium (T1 to T6), (b) El Temple terraces or intermediate terraces (T7 to T9), (c) Santa Isabel terraces or lower terrace treads (T10 to T12).

The most upstream local alluvial thickenings are located near Gurrea (44–30 km upstream of the Gallego–Ebro confluence), where the deposits of the fill terraces T3 (130–140 m above the present thalweg; Fig. 1) and T4 (+120 m) increase in thickness from 2–3 m to 20 m showing evidence of synsedimentary deformation. Downstream, at Puilatos (km 30–27, Fig. 4), the Sarda terraces have been tilted by postsedimentary subsidence increasing their long-profile gradient. One of the best outcrops of this postsedimentary deformation is located in the Valdeparadas gully (km 27.5 on Fig. 4), where the 6-m-thick T4 (+85 m) terrace deposit descends 20 m within 300 m. The parallel bedding in the alluvium indicates the postdepositional development of the subsidence. This terrace deposit has been dated by magnetostratigraphic analysis as Matuyama (pre-780,000). At 4 km northeast of Zuera (km 25.5–26;

Table 1
Elevation (in m) above the present thalweg of the alluvial tread terraces at Alcalá de Gurrea and Zuera

					7 km N of Gurrea	3 km NE of Zuera
Holo.		Brunhes	Santa Isabel	T12	2-9	2-6
Pleistocene	Late			T11	12-20	10-12
				T10	20-30	20
	Middle		El Temple	T9	40-50	30
				T8	50	45
				T7	60-70	--
	Early	Matuyama	Sarda terraces	T6	85-90	60
				T5	100	75
				T4	120	85
				T3	130-140	95
				T2	150	105
				T1	175	--

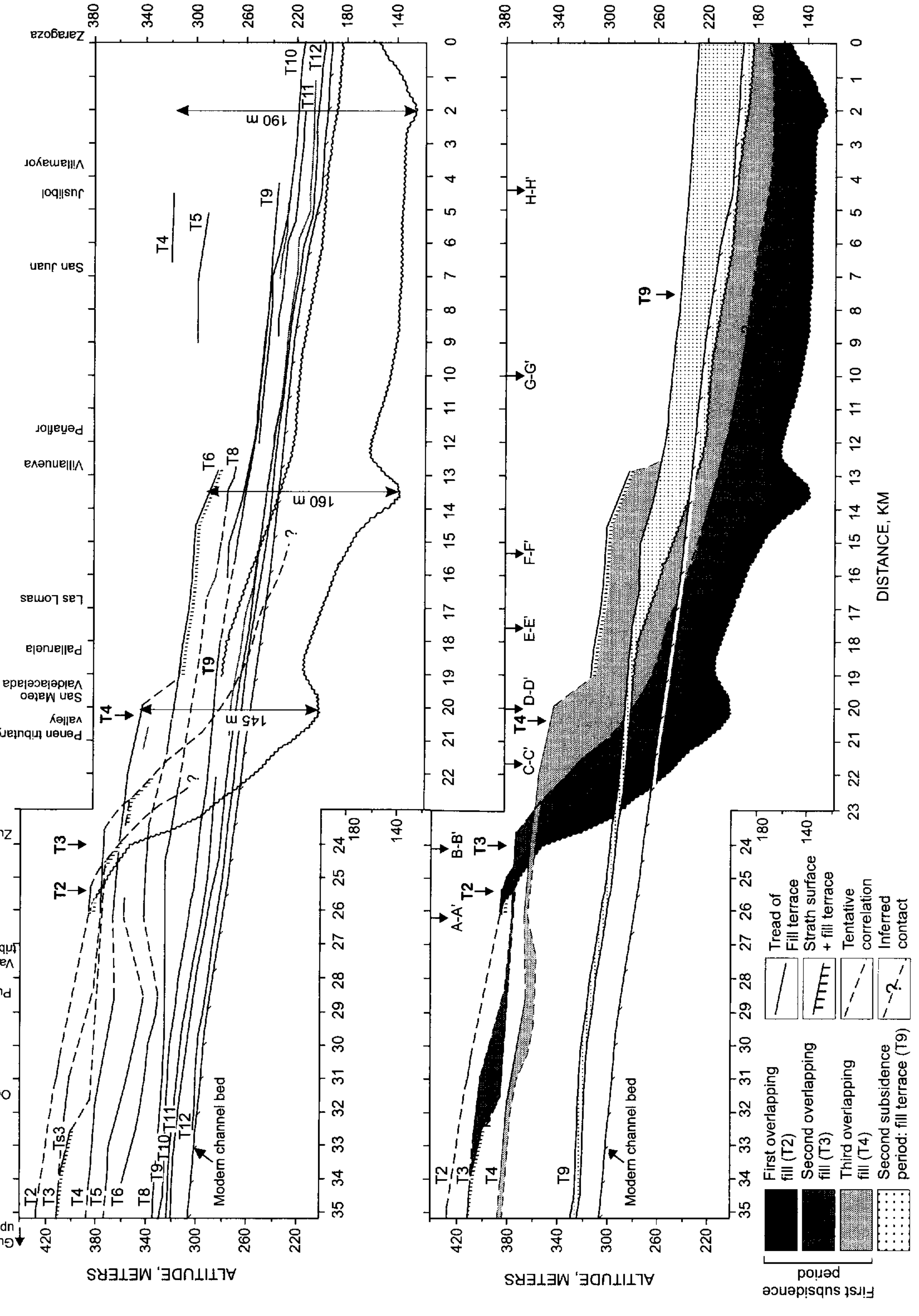
ALTITUDE, METERS
DISTANCE, KM
Gurrea: 10 km upstream
Zaragoza
Villamayor
Juslibol
San Juan
Peñaflor
Villanueva
Las Lomas
Pallaruela
San Mateo
Valdelacelada
Peñen tributary valley
Zuera
Valdeparadas tributary valley
Puilatos
Ontinar
T2
T3
Ts3
T4
T5
T6
T8
T9
T10
T11
T12
190 m
160 m
145 m
Modern channel bed
A-A'
B-B'
C-C'
D-D'
E-E'
F-F'
G-G'
H-H'
First overlapping fill (T2)
Second overlapping fill (T3)
Third overlapping fill (T4)
Second subsidence period: fill terrace (T9)
First subsidence period
Tread of Fill terrace
Strath surface + fill terrace
Tentative correlation
Inferred contact
?

Fig. 4), on the eastern side of the valley, the deposits of the terraces T2 to T12 are inserted into the Tertiary bedrock formed by marl and stromatolitic limestone. In this area, where the terrace deposits overlie a non-soluble substratum, no signs of alluvial thickening have been observed (Fig. 4). The alluvium thickness varies from 7 to 10 m for the Sarda terraces and from 2 to 3 m for the Temple and Santa Isabel terraces. Less than 1 km downstream, where the calcareous bedrock grades laterally into gypsiferous facies, the Sarda terrace deposits are thickened and the alluvium bedrock boundary disappears below the modern floodplain (km 22.5; Fig. 4).

5. Stream terraces in the main subsidence area

5.1. Geometry of the alluvial fill

The geometry of the alluvium–bedrock boundary (isopach map) downstream of Zuera (Fig. 5) has been obtained from geophysical and hydrogeological studies carried out by Sahuquillo et al. (1976) and (Octavio de Toledo, 1986, 1988a,b), and from thickness and texture data from approximately 150 water-well logs. The geophysical interpretation of the electrical logs was supported by drill logs. The textural features of the alluvial deposits have been delineated on the basis of geological cross-sections carried out in the field and water-well log data (Fig. 6).

The Gállego valley alluvial fill is 8 km wide by 30 km long with a maximum preserved thickness of 110 m recorded in a sample log close to Villanueva. The alluvium isopach map (Fig. 5) shows three major depocentres located at San Mateo, Villanueva and between Zaragoza and Villamayor. To the north of San Mateo the thickened alluvial deposits fill an elongated basin with a NNE–SSW trend. The alluvial thickening to the west of Villanueva shows a marked N–S elongation. The third major thickening (2 km to the northeast of Zaragoza) below the valley floor (Fig. 3) seems to be a prolongation of the Villanueva Basin forming a large N–S trough. It seems that karstification and subsidence have been structurally controlled in a N–S direction, which is the strike of the main joint system affecting the Tertiary sediments at the northern margin of the Ebro valley (Arlegui and Simón, 1993). Considering the thickness of terrace deposits below the land surface and the present elevation of the terrace surfaces at the valley margins (Fig. 4), the minimum subsidence in the three depocentres is 145, 160 and 190 m, respectively.

5.2. Subsidence recorded in the Early Pleistocene Gállego river terraces

Northwest of Zaragoza, the deposits of the Ebro river terrace T1 (+160 m) reach up to 50 m in thickness (Figs. 3 and 5) and show synsedimentary and postsedimentary deformations. North of Juslibol (Fig. 3), the entire Quaternary alluvial cover is crossed by subvertical clay-filled cracks. X-ray diffraction analysis carried out to determine the mineralogical composition and origin of the clays suggests that these clay-fillings come from the eluviation of soil horizons developed at the top of the deposits.

In the Gállego valley, the oldest preserved terrace affected by synsedimentary subsidence is T2 (+105 m), followed chronologically by T3 (+95 m) and T4 (+85 m) (Fig. 4). The effects resulting from subsidence are incision and strath terrace generation upstream of the area affected by sinking, and aggradation in the subsidence area with the consequent stacking of the sedimentary units corresponding to different terrace levels. Chronostratigraphically, the thickened alluvial sediments may represent a longer geological time span since aggradation periods in the subsidence area may be correlative to degradation and incision periods upstream. In the area affected by subsidence, the deposits of a certain terrace may be locally superimposed on older alluvium and bounded by angular or parallel unconformity, whereas upstream, the terrace deposits are inset in

Fig. 4. In the upper figure, longitudinal profiles of terrace treads (continuous line), strath surfaces (repeated vertical lines), channel bed (repeated inclined lines) and base of the thickened alluvial deposits (rippled line) from 1 : 50,000 and 1 : 25,000 topographical maps, field surveys with altimeter and geophysical data. Dashed lines indicate tentative correlations. In the lower figure, the stippled patterns indicate the deformation and thickening of the different alluvium fill terraces. The base of those fills within the compound terrace are indefinite (dashed line). Letters *A*–*A*′ etc. refer to Figs. 3–5.

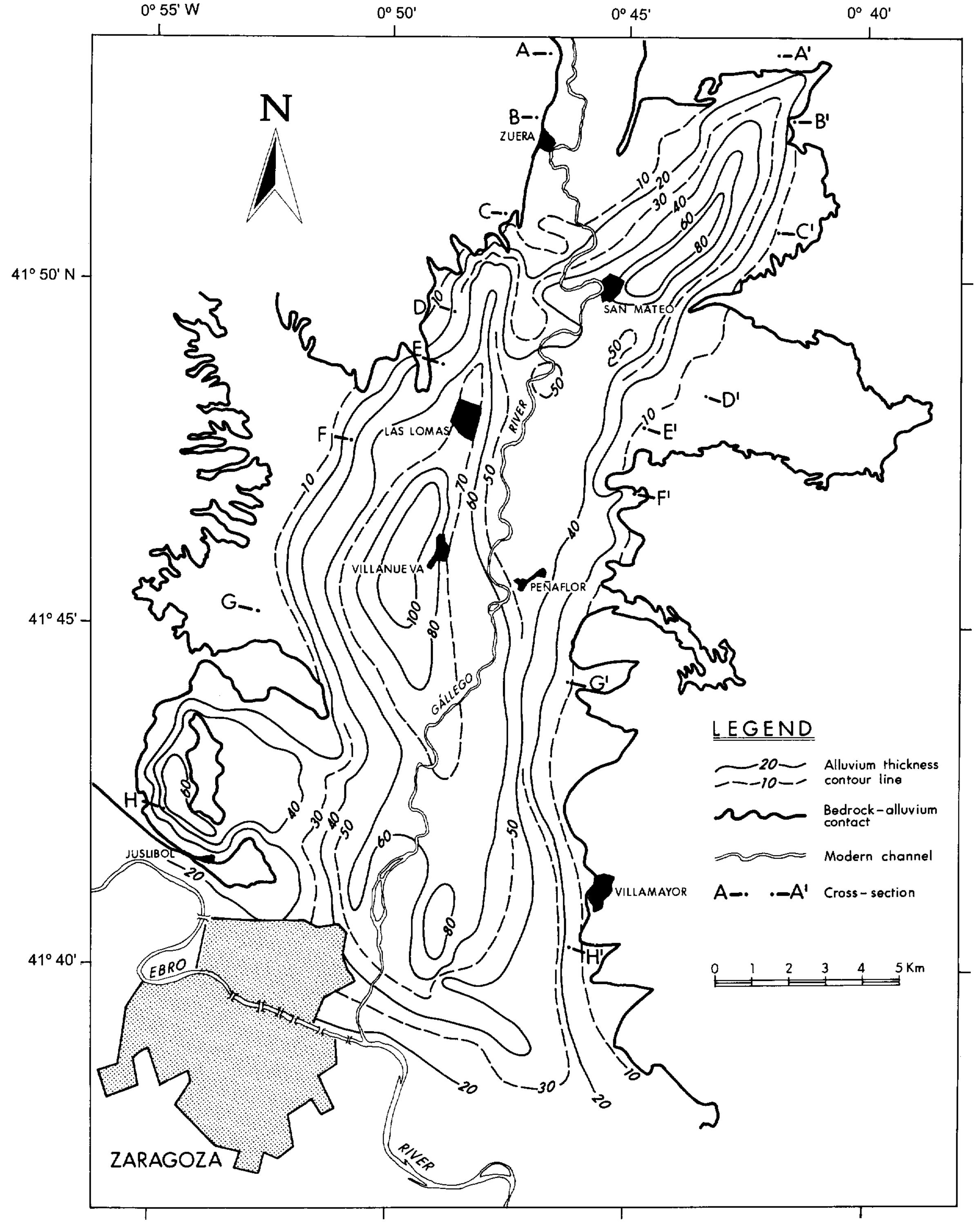

Fig. 5. Alluvium thickness, contour lines in metres (isopachs map).

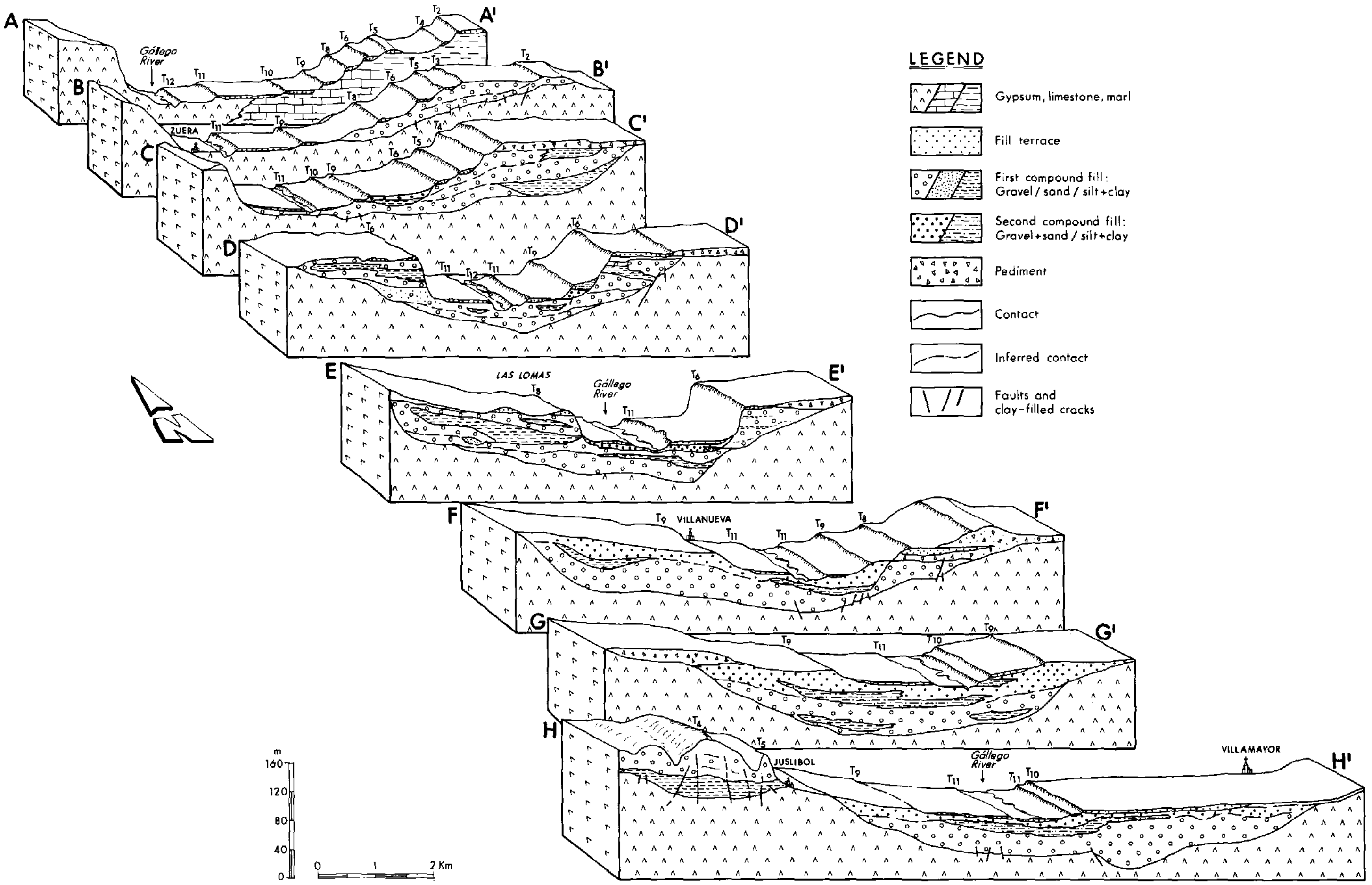

Fig. 6. 3-D geological cross-sections of the lower reach of the Gállego river based on geophysical, water-well logs and stratigraphical field data. Cross-section locations are in Fig. 5.

the bedrock. In the areas of transition it is possible to observe how the deposits of the older thickened terraces plunge under younger terrace deposits and the present floodplain (Fig. 4). The line dividing these different morpho-sedimentary arrangements was named in active tectonic areas by Doornkamp and Mukang (1985) as a pivot line. The deposits of terraces T2, T3 and T4 plunge down progressively downstream at 26, 24.5 and 22.5 km, respectively, indicating that the upstream margin of the subsidence area has migrated downstream through time (Fig. 4). A similar time–space evolution pattern has been described in the Jalón–Jiloca fluvial system (Gutiérrez, 1996).

In the outskirts of Zuera, on the west side of the Gállego valley, the alluvium–bedrock boundary increases in slope angle from 3–4° to local values of 50°, showing a clear alluvial thickening of at least 40 m within a distance of 500 m (Fig. 7). Nonetheless, the surface terrace tread (T5, +75 m) maintains a 1–2° slope and the underlying evaporitic bedrock remains undeformed. This thickening and deformation occurs not only in the longitudinal direction but also across the valley, delineating a solution-induced basin margin. In the Valdelacelada gully, on the west side of the Gallego valley (about 1 km north of cross-section D–D′ in Figs. 3 and 6) the irregular boundary between the bedrock and alluvial cover shows an overall dip of 25° towards the Gállego valley. In this outcrop, two stratigraphic units bounded by angular unconformity can be distinguished. The deformed lower unit dips up to 35° SW and comprises a 20-m-thick gravel and sand facies with intercalations of Fl facies (laminated or cross-laminated fine deposits; overbank or waning flood deposits), Fsc (laminated to massive backswamp deposits), Fcf (massive backswamp pond deposits) and Fm facies (massive overbank fine deposits or drape deposits) (following the lithofacies classification of Miall, 1978, 1985). The backswamp pond deposits are composed of mud with freshwater gastropods and thin layers of limestone. The overbank facies includes sand sheets and crevasse lobes which are related to areas of continuous flooding. The undeformed upper unit comprises a 4-m-thick gravel unit with Gm (massive gravel), Gt (trough cross-bedded framework gravel) and Gp (planar cross-bedded framework gravel) facies. This undeformed upper unit corresponds to fill terrace T5 (+75 m), whereas the deformed lower unit represents an older alluvial fill terrace.

One of the most significant outcrops of fill ter-

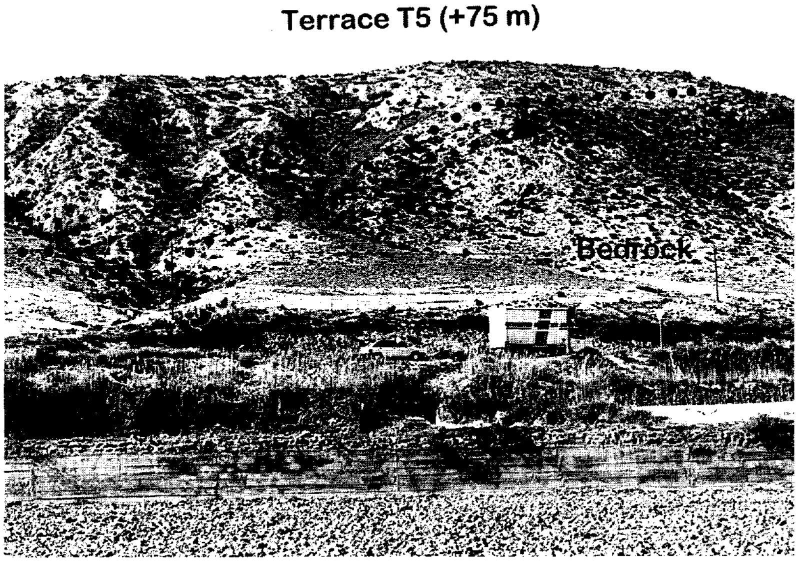

Fig. 7. Bedrock–alluvium boundary plunging downward beneath the floodplain near Zuera.

races deformed by syndepositional subsidence can be found in a tributary valley east of San Mateo (Figs. 3 and 8). The deposits below the surface of terrace T4 (+85 m) show a synsedimentary thickening from N to S and from E to W forming a pericline of a basin structure with a depocentre located to the SW of this tributary valley. The alluvial deposits, 55 m in outcrop thickness, comprise from base to top (Fig. 8): (a) a 13-m-thick gravel unit (Gp, Gt and Gm facies), (b) a 23-m-thick unit of horizontally bedded sand and silt with massive and ripple lamination corresponding to overbank flood deposits (Fm and Fl), (c) a 7-m-thick unit of gravel channel fills with lateral accretion structure and Gt facies, and (d) a 12-m-thick unit of gravel beds 2–3 m in thickness (Gt and Gp facies) interlayered with beds of massive silt and clay overbank deposits of 1–2 m thick (Fm). Four samples were taken through the vertical sequence for magnetostratigraphic analysis giving a reversed magnetic polarity (Matuyama, pre-780,000). On the south margin of this tributary valley the thickened and deformed deposits are unconformably overlain by the 4-m-thick T6 (+60 m) terrace deposit forming an overlapped fill inset terrace (Fig. 3 and km 19 in Fig. 4).

The sedimentary units forming the thickened alluvial deposits within the subsidence area cannot always be correlated to the flight terrace upstream. On the other hand, certain sedimentary units filling the solution-induced basins may be correlative to incision periods upstream of the subsidence area. Unfortunately, the dating methods for coarse-grained alluvial sediments do not allow a precise differentiation of the terrace fill deposits. In this area, east of San Mateo, the lithostratigraphical sequence and its geometrical relationships with the upstream terrace deposits suggest that the thickened alluvium corresponds to at least two fill terraces (T3 and T4) separated by fine sediments (unit b).

This type of undifferentiated alluvial fill was named as compound terrace by Mukang (1984). Nevertheless, some of these fills within the compound terraces can be separated by the presence of unconformities and by the degree of deformation of the alluvial bodies. The most deformed sediments are the oldest deposits located at the margins of the solution basins. In the area where the alluvium–bedrock boundary disappears below the floodplain (km 22.5 in Fig. 4) the terrace deposits show numerous brittle and ductile deformations. Besides the type and

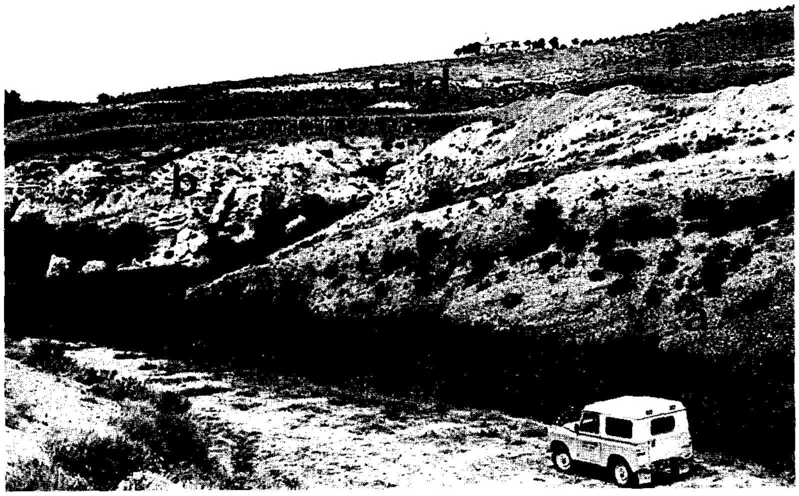

Fig. 8. Subsidence-related facies. 55 m-thick alluvial fill east of San Mateo (a, b, and $c+d$ are units explained in the text) culminating in terrace tread (T4, +85 m above present thalweg).

degree of deformation, the stacked fills comprising the compound terraces may also be differentiated by taking into account the strath surfaces carved in older alluvium, the interbedding of alluvial fan deposits and the sharp changes in texture.

Land subsidence has also influenced the evolution of mantled pediments which were an important source of sediment for the Gállego river (Fig. 3). These pediments up to 11 km in length and 4 km in width developed at the foot of the calcareous structural platforms located on both sides of the Gállego river valley. The relations between the pediments and the terrace deposits can be observed in the Penen tributary valley (3 km NE of San Mateo; km 21, Fig. 4). At this site, the T4 terrace deposits are dipping 26°SE and are overlain by 12- m-thick mantled pediment sediments. Both the terrace deposits and the lateral supply alluvium are affected by postsedimentary deformation and are unconformably covered by loose pediment deposits. Samples taken from each unit of the sequence indicate a reversed magnetic polarity (Matuyama, pre-780,000). The important development of the lateral supply sediments overlying the terrace deposits suggests a progradation of the mantled pediments induced by subsidence at the valley margin.

5.3. Subsidence in Middle and Late Pleistocene stream terraces

Downstream of Zuera, the stream terraces T5 (+75 m), T6 (+60 m) and T8 (+45 m) have a constant thickness of 3–4 m and were built on the thickened alluvial fill. The deposits of stream terrace T6, dated as Lower Pleistocene, upstream of San Mateo are set into the thickened terraces (cross-section C–C′ in Fig. 6), whereas downstream they overlap the sediments of terrace T4 (cross-sections D–D′ and E–E′ in Fig. 6).

The second major subsidence period affected the alluvial deposits of terrace T9 (+30 m) (Figs. 4 and 6). East of Zuera (0°45′W), this fill terrace overlying Tertiary gypsum and marl facies shows frequent changes in thickness from 3 to 7 m (cross-section B–B′ in Fig. 6). The most significant thickening of this terrace deposit occurs 2 km downstream, where

Fig. 9. Deformation of the first compound fill near the bedrock contact. The later fill terrace T11 (+10 m) has developed a strath surface and a 2-m-thick fill terrace.

the alluvial sediments increase in thickness from 1.5 m to more than 15 m over approximately 100 m. At this location, the outcrop underlying bedrock constitutes a gypsum collapse breccia. The T9 (+30 m) stream terrace carved a strath surface levelling the breccia and, downstream, the bedrock–alluvium contact descends and disappears beneath the topographic surface (cross-section E–E′ in Fig. 6). The alluvial fill is composed of cemented gravels forming anastomosed channel fills and clay beds dated as Brunhes (post-780,000, i.e. Middle–Late Pleistocene). Downstream, the sedimentary units corresponding to the Early Pleistocene compound terrace (T2, T3 and T4) and the fill terrace T9 (+30 m) are in many cases very difficult to differentiate.

Between Zaragoza and Villamayor (cross-section H–H′ in Fig. 6), a 15-m-high quarry shows a 10-m-thick lower unit composed of minor non-erosive anastomosed gravel channel fills. An undisturbed clay sample taken 13 m beneath the terrace tread has given a normal magnetic polarity (Brunhes, i.e. a Middle–Late Pleistocene age). The sharp changes in texture beneath this pit recorded in well logs at 20–25 m suggest that subsidence has reached about 25 m during the deposition of fill terrace T9 (+30 m).

The later fill terraces T10 (+20 m) and T11 (+10–12 m) have a constant thickness of 2–3 m and downstream of Zuera are set into the thickened alluvial fills (cross-sections from C–C′ to H–H′ in Fig. 6). North of San Mateo, the undeformed deposits of these terraces unconformably overlie the deformed Early Pleistocene fills (cross-sections C–C′ and D–D′ in Figs. 6 and 9), whereas downstream they are lying over the T9 fill forming bottom cut terraces (cross-sections E–E′ to H–H′ in Fig. 6).

6. Currently active subsidence and sinkholes

At present, evaporite solution and subsidence is an active process causing the continuous modification of the surface landscape by the frequent generation of alluvial dolines (Benito, 1987, 1989; Benito and Gutiérrez, 1988; Benito and Pérez del Campo, 1991; Benito et al., 1995). These correspond to collapse (sinkholes) or bending dolines with a wide range of sizes. In the Jalón valley, Calatayud Graben, it has been observed how the currently active solution subsidence controls the dynamics of the fluvial system (Gutiérrez, 1996).

The alluvial sediments constitute a source of flowing groundwater that dissolves the evaporites at the bedrock–alluvium contact. In the alluvium aquifer sulphate concentrations reach the highest values (up to 1500 ppm) near the valley margins, where the cover thins and there may be lateral water inflow from the gypsum outcrops (Sahuquillo et al., 1976). These areas coincide with the highest doline density. Average subsidence rates have been measured in sinkholes reaching values of 3–5 cm/year (Benito et al., 1995) and 3–10 cm/year (Soriano and Simón, 1995). In the Gállego valley, the recently built village of Puilatos was abandoned before its occupation due to damage caused by subsidence (Benito and Gutiérrez, 1988).

In areas with anomalously large alluvial thickness, the evaporite dissolution cannot solely explain the generation of collapses on the surface. Besides bedrock karstification, subsurface mechanical erosion of the alluvial cover and migration of the detrital material through the solution voids are processes involved in collapse development (Benito et al., 1995; Gutiérrez, 1996; Gutiérrez and Gutiérrez, 1996). The mechanical transport of detrital particles as well as the subsidence of the alluvial cover are favoured by changes in the water table which can be produced by runoff variations, pumping, irrigation etc.

The response of the contemporary Gállego river to local subsidence is difficult to observe once the channel bed is confined by the Pleistocene terraces. The most outstanding features are the convex longitudinal river profile of the lower reach of 20 km and the increase of the river channel slope in the lower 5 km prior its confluence with the Ebro river. The convex longitudinal profile may be related to diffluent flow from the river into the alluvial aquifer in the thickened area, producing a loss of river competence and deposition of a part of the sediment load.

At the margins of the flood plain, the development of surface subsidence depressions up to several kilometres in diameter has resulted in channel migration into those areas together with an increase in the river sinuosity. This has been observed in several rivers affected by solution-induced subsidence such as the Alframbra, Jalón and Jiloca rivers (Gutiérrez, 1996), as well as the Ebro river upstream of Zaragoza.

7. Interpretation and discussion

Most of the studies dealing with compound terraces are related to tectonic movements (Lensen and Vella, 1971; Brunnacker, 1979; Brunnacker et al., 1982; Mukang, 1984; Markewich, 1984; Doornkamp and Mukang, 1985). Geometric relations among stream terraces vary from areas of faulting to areas of slow crustal warping (Doornkamp and Mukang, 1985). In the central part of the Ebro Basin, only microstructural deformation due to tectonics have been described, but no major deformational tectonic structures exist in the Tertiary and Quaternary sediments related to regional stress fields. The lack of major neotectonic structures and the fact that the deformed alluvial sediments overlie an undeformed soluble evaporitic bedrock corroborate the hypothesis of solution to explain the subsidence recorded in the terrace deposits. The Tertiary substratum composed by gypsum, halite and anhydrite can be easily dissolved by water and produce local subsidence in the alluvial cover. Furthermore, the presence of NaCl in water may enhance the solubility of gypsum up to four times due to the increase in the ionic strength of the solution (Ponsjack, 1940). The water flowing through the alluvial aquifer dissolves the evaporite sediments at the bedrock–alluvium boundary with the consequent development of a covered karst underneath the alluvial sediments (Sweeting, 1972; Jennings, 1985).

Generally, neotectonic subsidence affects both alluvial and bedrock areas, whereas alluvial subsidence induced by the karstification of an evaporitic bedrock is confined to the river valley. This solution-induced subsidence may give rise to multiple basins (Fig. 10) with a complex temporal and spatial pattern. Since evaporite subsidence is litho-structurally controlled, both the distribution of the soluble formations (lithostratigraphy) and their structure would restrain the potential areas of karstification and ground subsidence. Karstification intensity and subsidence rate may be increased by the presence of halite beds or a dense jointing and attenuated by non-soluble layers interbedded in the evaporitic bedrock. On the other hand, runoff variations due to climatic changes will condition the amount of evaporite solution and the subsidence rate.

In the Gállego river valley, the stream terrace deposits have been affected by synsedimentary sub-

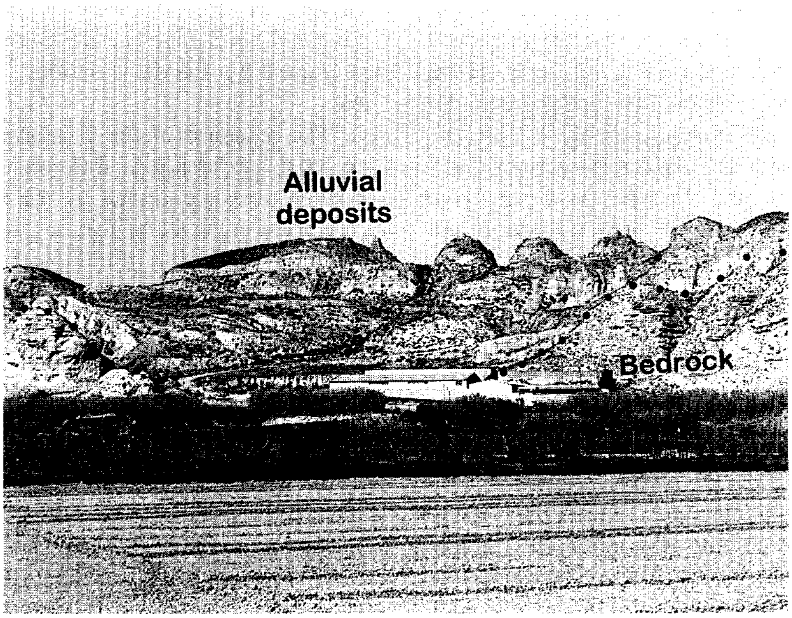

Fig. 10. Subsidence depression 400 m in diameter filled by 90-m-thick Early–Middle Pleistocene alluvial deposits north of Juslibol.

sidence leading to morpho-sedimentary relations similar to the morpho-tectonic model described by Mukang (1984) and Doornkamp and Mukang (1985) in areas of tectonic subsidence. The terrace deposits plunge down in a pivot line producing the successive stacking of younger alluvial fills (Fig. 4). This pivot line changed its position progressively downstream for the stream terraces T2 (+105 m), T3 (+95 m), T4 (+85 m) and T9 (+30 m) at km 26, 24.5, 21 and 18, respectively (Fig. 4). The changes in the location of the upstream thickening margin can be interpreted as the downstream migration of the subsidence zones into the area of thickest evaporite sediments at the confluence with the Ebro river (Fig. 1).

In the proposed model of the fluvial sequence, the rate of accommodation space created by solution subsidence should be balanced by stream aggradation in order to maintain the river equilibrium profile. This equilibrium must be attained by a longitudinal profile adjustment in the river, reaching to upstream of the lowering zone and downstream into the confluence with the Ebro river. The equilibrium would have had dynamic characteristics since the periods of higher subsidence rate would be quickly balanced by aggradation. This synsedimentary subsidence is recorded in the alluvial sediments which show syndepositional deformation and thickening with bedding planes dipping towards the depocentres of the subsidence areas.

The development of subsiding depressions in the alluvial plains leads to local geomorphic changes in the fluvial system, such as the gradient changes in the longitudinal river profile, channel migration and avulsion and the formation of ponded water areas. The main features of the fluvial response to subsidence are aggradation in the central reach of the subsided area, and degradation in the upstream reach. In the upstream reach, the most common architectural elements (Fig. 11) are channels (CH) and gravel bars (GB) with massive (Gm) and stratified (Gt) gravel facies, which fits with model 2 of Miall (1985), interpreted as numerous broad shallow channels of low sinuosity. In the subsided area, two reaches upstream and downstream of the subsidence axis can be differentiated (Fig. 11). In the upstream sector, the longitudinal river profile has a local steepening followed by a reduction in gradient. The depositional sequences are dominated by gravel bars and bedforms (GB) overtopped by fine texture facies (OF), matching with model 3 of large gravel-bed streams of Miall's classification. Downstream of the subsidence axis, a very low-gradient longitudinal profile gives rise to the deposition of gravel bars (GB) and lateral accretion (LA) architectural elements (Fig. 11). Changes in the longitudinal gradient produce aggradation in the channel and frequent flooding of the floodplain areas with crevasse splay and flood deposits. Additionally, in some subsiding areas the water-table can be positioned close to or above the surface developing ephemeral or permanent ponding water areas with backswamp and palustrine facies (Gutiérrez, 1996). These fine deposits frequently display a sheet-like geometry in fining upward cycles. Local base level changes due to subsidence increase degradation and sediment yield not only along the valley floor, but also on the sides of the river valley. In the Gállego river, the terrace deposits are related to extensive mantled pediments and alluvial fans which were also thickened by the synsedimentary subsidence. These alluvial fans are commonly onlapping the contemporaneous stream terraces. In some areas, the lateral migration of the river and alluvial fan progradation and retrogradation during synsedimentary periods have caused alluvial fan units to be 'sandwiched' between stream terrace deposits.

The fluvial metamorphosis inferred from the sedimentological analysis fits with the experimental results of the braided channel response to subsidence carried out by Ouchi (1985), although in our case study there is a wider range of sedimentary facies. In Ouchi's model, the increase in the longitudinal profile slope and in sediment load were manifested by the development of a strongly braided channel pattern in the upstream reach of the subsidence area. Downstream, where the slope was reduced, transverse bars and overbank fine textured sediments were deposited.

Considering the difference in altitude between the bottom of the three major alluvial thickenings recognized by geophysical studies (Fig. 5) and the elevation of the nearby highest terrace tread affected by synsedimentary subsidence, the minimum total subsidence produced for the two periods in these solution-induced basins is 145, 160 and 190 m, from north to south, respectively (Figs. 4 and 12). The

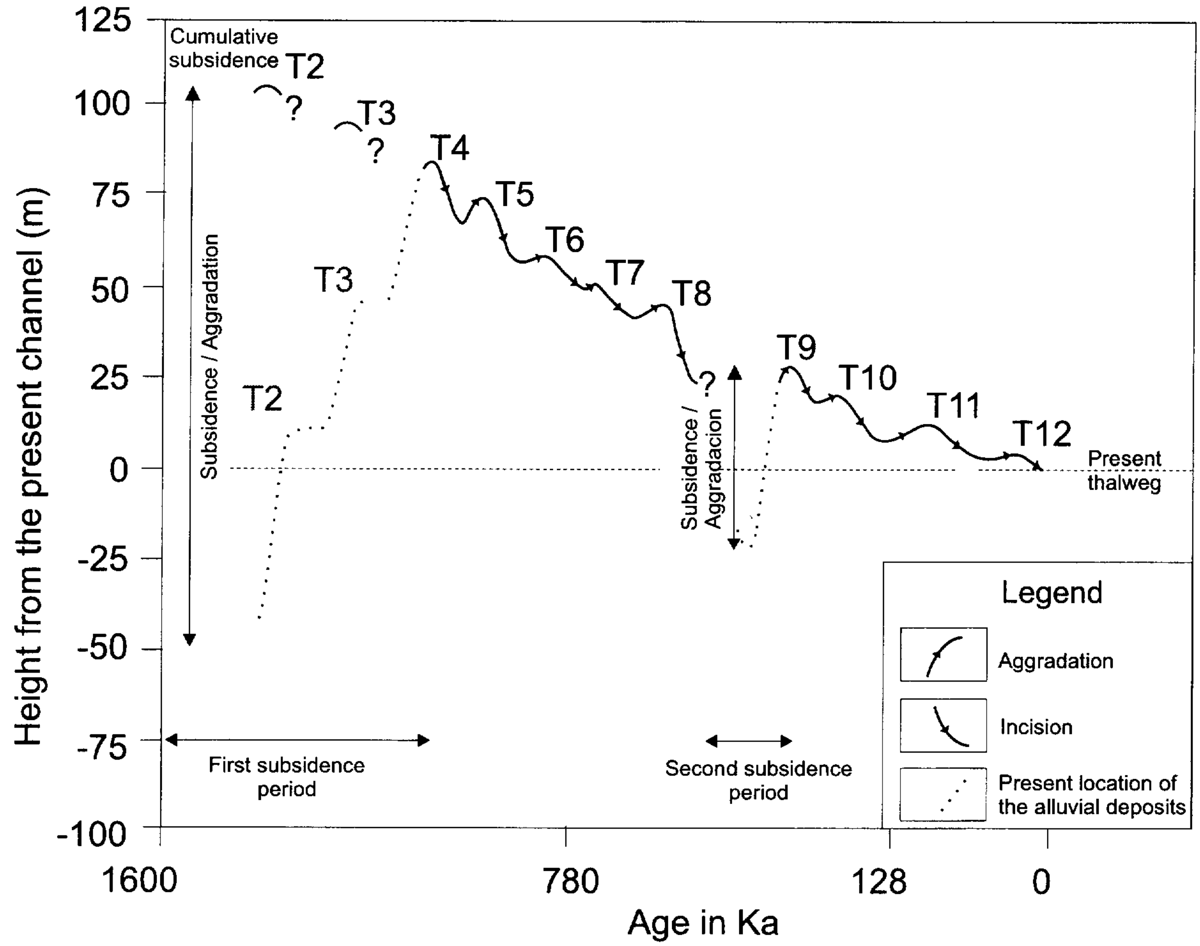

Fig. 11. Channel response to solution-induced subsidence in the lower reach of the Gállego river. *GB* = gravelly bars and bedforms; *CH* = channels; *OF* = fine texture facies; *LA* = lateral accretion deposits; *SB* = sandy bedforms; *Gm* = massive or crudely bedded framework gravel; *Gt* = trough cross-bedded framework gravel; *Gp* = planar cross-bedded framework gravel; *St* = trough cross-stratified sand; *Sl* = laminated or low angle stratified sand; *Fl* = laminated fine deposits; *Fm* = massive fine deposits; *Fsc* = laminated to massive backswamp deposits; *Fcf* = massive backswamp pond deposits.

second major subsidence period occurred during the Middle–Late Pleistocene with a maximum subsidence of about 25 m. The rates and location of the subsidence have changed through time in the Gállego river valley. Probably, the minimum time spans necessary to produce the synsedimentary subsidence recorded in the studied alluvial sediments would take from tens to a few thousand years. The concentration in time of the evaporite solution and subsidence processes may result from the coincidence of positive feedback processes. As indicated above, the evaporite solution is controlled by litho-structural factors like the presence of evaporitic formations of variable solubility underlying the river valley (halite, gypsum, anhydrite), thickness and structure. The nature of the substratum underlying the alluvial sediments may change with the progressive entrenchment of the fluvial system into the Tertiary bedrock. On the other hand, the alluvial karstification of the bedrock and the consequent subsidence were probably enhanced during periods of high water supply related to the Quaternary cold phases. The Gállego River headwater is in the Pyrenees Mountain Range where, during those cold periods, it is likely that the

CHANNEL RESPONSE TO SUBSIDENCE

ZONE	A	B	C
	Flow direction ⇢	← SUBSIDED AREA	↓ axis →
DOMINANT PROCESS	DEGRADATION	AGGRADATION	
ARCHITECTURE	GB, CH	GB → OF	GB LA →(SB) → OF
FACIES	Gm, Gt	Gm, Gp, Gt Fl	Gm, Gp, Gt St, Sl Fl, Fm, Fsc, Fcf
MAIN CHARACTERISTICS		Multiple channels Thick overbank deposits Lateral pedimentation and alluvial fans	Sinuosity increase Flooding Backswamp and pond areas
MODEL (after Miall's 1985 classification)	Model 2: Numerous broad shallow channels of low sinuosity	Model 3: Larger gravel-bed stream (trunk rivers)	Model 4: Gravelly rivers of higher sinuosity

Fig. 12. Sketch of the changes in synsedimentary subsidence and streambed altitude through time.

mean water discharge of the Gállego river was increased due to a higher precipitation and snow-melt. In these conditions, a higher sediment supply can be expected because of the severe climatic conditions and the increase in the river's stream power. Unfortunately, there is not a chronological knowledge about glaciations prior to 60,000 years ago.

In areas of evaporite bedrock, solution-induced subsidence processes have received little attention as a cause of terrace deformation. Moreover, diapirism has been claimed to be the source of Quaternary alluvium deformation. In areas of evaporitic substratum terrace deformation and subsidence due to dissolution should be considered for understanding the evolution and morpho-sedimentological features of the fluvial systems. However, difficulties in separating the origin of subsidence may arise in regions with both neotectonic activity and evaporitic substratum. Nevertheless, some criteria can be given for identifying bedrock dissolution as the main cause of land subsidence: (1) irregular geometry of the alluvium–bedrock contact; (2) selective deformation of the alluvial cover; (3) basin structure of the alluvial deposits along the area affected by dissolution; (4) chaotic deformation of the alluvial deposits; (5) cylindrical and concentric open cracks and fractures and lack of linear faults affecting the alluvium and the bedrock.

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