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Sedimentation and base level in an endorheic basin: the early Miocene of the Ebro Basin, Spain

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ABSTRACT

During the Oligocene and early Miocene the Ebro Basin was an endorheic basin, a basin of internal drainage without a hydrological connection to either the Atlantic Ocean or the Mediterranean Sea. In the central-western part of the basin, around Huesca and north of Zaragoza, the basin deposits of this period were the products of sedimentation on alluvial fans, fluvial systems and in lakes. Small (<5 km radius) alluvial fans along the northern margin of the basin formed conglomeratic deposits 300-400 m thick that show some coarsening- and fining-up trends, but overall show an aggradational pattern. There is no evidence of deep incision within the fan successions. The bulk of the clastic deposition in the basin at this time was by the Luna and Huesca fluvial distributary systems which formed terminal fans 40 to 60 km radius. The proximal and medial parts of the systems do not show any evidence of incised valley fill and the distal parts interfinger with lacustrine facies. Small fluctuations in lake level occurred, but overall the base level appears to have been rising throughout this period. Conglomerate beds on top of the External Sierras at Peña del Sol indicate that the fluvial deposition occurred at over 1400 m above present sea level. This rise in base level of at least 1000 m in the Ebro Basin during this period can be attributed to the sedimentary filling of the basin, which continued until the late Miocene when an external drainage was established to the Mediterranean. It is possible the basin reached its spill-point, initiating the drainage system that is now the Río Ebro and its tributaries. This drainage system has incised deeply into the Oligo-Miocene foreland basin deposits to expose them today.

Key words: base level controls, Ebro Basin, endorheic basins, fluvial distributary systems, Miocene

Sedimentación y nivel de base en una cuenca endorreica: el Mioceno inferior de la Cuenca del Ebro, España

RESUMEN

Durante el Oligoceno y el Mioceno inferior la Cuenca del Ebro constituyó una depresión endorreica, con un drenaje interno desconectado hidrológicamente tanto del Océano Atlántico como del Mar Mediterráneo. En la parte centro-occidental de la cuenca (sector de Huesca y norte de Zaragoza), el relleno de la depresión para este periodo es el producto de la sedimentación en abanicos aluviales, sistemas fluviales y lagos. Pequeños abanicos aluviales, de menos de 5 km de radio, desarrollados a lo largo del margen septentrional de la cuenca dieron lugar a depósitos de 300-400 m de espesor, que muestran algunas tendencias estrato y grano decrecientes hacia arriba y, en conjunto, un patrón de tipo agradacional. No existen evidencias de incisión profunda dentro de estas sucesiones aluviales. La mayor parte de la sedimentación clástica en la cuenca en ese momento se originó en los sistemas fluviales distributarios de Luna y de Huesca, que formaron abanicos terminales de 40 a 60 km de radio. Las partes proximales y medias de los sistemas no muestran ninguna evidencia de relleno de valle encajado, en tanto que las partes distales se interdigitan con facies lacustres. La tendencia general del nivel de base durante este periodo parece haber sido ascendente, si bien tuvieron lugar pequeñas fluctuaciones en el nivel lacustre. La existencia de capas de conglomerado sobre las Sierras Externas en Peña del Sol es indicativo de que la sedimentación fluvial tuvo lugar a unos 1400 m sobre el nivel del mar actual. Este ascenso del nivel del mar de al menos 1000 m en la Cuenca del Ebro durante este periodo puede ser atribuido al relleno sedimentario de la cuenca, que continuó hasta el Mioceno superior, cuando se estableció un drenaje externo hacia el Mediterráneo. Es posible que la cuenca alcanzase su punto de escape, iniciándose el sistema de drenaje que constituyen actualmente el Río Ebro y sus afluentes. Este sistema de drenaje ha incidido profundamente en los depósitos oligo-miocenos de la cuenca de antepaís, que de esta manera afloran actualmente.

Palabras clave: controles del nivel de base, cuencas endorreicas, Cuenca del Ebro, Mioceno, sistemas fluviales distributarios

Introduction

Endorheic basins are areas of sediment accumulation that do not have a hydrological connection to the sea. These basins of internal drainage can be important sites of accumulation of continental sediment because all of the detritus eroded from the surrounding catchment areas is deposited in fluvial and lacustrine environments within the confines of the basin. Unlike most sedimentary basins, endorheic basins are not subject to the effects of global or regional sea level change. In humid climatic settings, fluctuations in lake level will result in progradational and retrogradational patterns, but in a drier environment without deep, permanent lakes, the alluvial plain will act as a base level. Changes to that base level will occur as sediment fills the basin, and through time base level will rise. This continuous rise in base level will affect deposition throughout the basin and can be predicted to give rise to predominantly aggradational facies patterns.

In the north central part of the Ebro Basin, near the city of Huesca (Fig. 1), there is excellent exposure of continental facies deposited in late Oligocene to early Miocene times in an endorheic basin setting. These units belong to the Uncastillo and Sariñena formations and they consist of alluvial fan, fluvial channel and overbank and lacustrine facies. Some of the alluvial fan deposits form prominent pinnacles of conglomerate along the basin margin (Fig. 2) whilst the fluvial and lacustrine deposits are exposed in river valleys and on the flanks of mesas which rise above the plain. In this paper the depositional facies and their stratigraphic architecture is considered in the context of deposition in a basin of internal drainage, and the subsequent change to external drainage through the Río Ebro discussed as a major factor in generating the exposure seen today.

Tectonic and stratigraphic setting

The Pyrenees (Fig. 1a) is Cenozoic orogenic belt that formed as a result of approximately north-south crustal shortening between the Iberian sub-plate and the Eurasian plate (ECORS-Pyrenees Team 1998; Choukroune *et al.* 1989; Muñoz 1992; Teixell 1996). Southward thrust movement in the early Eocene (Puigdefàbregas and Souquet 1984) resulted in a foreland basin forming by the loading of the Iberian crust by thrust sheets in the southern Pyrenean zone. During the early stages of the evolution of the area, the southern Pyrenean foreland basin was connected to the Atlantic in the Bay of Biscay (Coney *et al.* 1996). From the onset of Pyrenean compressional tectonics in the Maastrichtian to the Middle Eocene, depositional environments in the foreland basin were either marine or were hydrologically connected to marine base level (Puigdefábregas and Souquet 1986). Deposits during this period in the central and western parts of the Pyrenean foreland basins (the Tremp-Graus, Ainsa and Jaca Basins) show westerly palaeoflows and facies trend that show a deepening towards the west (Vergés *et al.* 1995; Coney *et al.* 1996).

In the late Eocene (Priabonian) evaporitic facies in the western part of the southern Pyrenees (Puigdefábregas 1975; Millán *et al.* 1995) mark the blockage of the connection to the Atlantic Ocean. In the middle Oligocene the Guarga Thrust formed the External Sierras (Millán *et al.* 1995; Hogan 1996; Teixell 1996), the northern boundary in the central western part of the Ebro Basin. By late Oligocene time, the Ebro Basin (Fig. 1a) was a site of foreland basin flexural subsidence bound to the north by the external zones of the Pyrenees, and to the south and southwest by the Iberian Range and the Catalan Ranges respectively (Vergés *et al*. 1995). Catchment areas from these high areas around the basin provided water and sediment supply to the Ebro Basin, but there was no external outlet to either the Atlantic or the Mediterranean during the deposition of late Oligocene to early Miocene continental facies which are the subject of this study.

The outcrop of Ebro Basin deposits in the Huesca area is mainly the upper part of the Uncastillo Formation and within Tectonostratigraphic Unit 3 (TSU 3) of the Arenas and Pardo (1996) and Arenas *et al.* (2001) correlation scheme. Only the lower, deformed parts of the conglomerate bodies at Agüero, Murillo and Riglos and some exposures in the valley of the Río Gállego near Murillo (Fig. 1b) belong to lower units. Deformation in TSU 3 is slight: over most of the area the bedding is within a degree of horizontal (Hirst 1983; Nichols 1984), with the exception of a zone 4-8 km from the basin margin where beds are folded into broad, low amplitude folds with limb angles of less than 10° (Nichols 1984; Arenas *et al.* 2001).

Syn-sedimentary folds and faults in some of the basin margin deposits provide evidence of faulting and deformation within the External Sierras thrust front, but these features are all preserved in late Oligocene parts of the succession (Arenas and Pardo 1996; Arenas *et al.* 2001; Nichols *in press*). Along most of the basin margin the unconformity contact between the early Miocene basin margin facies and the thrust front has been preserved with little or no evidence of deformation. Differential vertical movement between the southern parts of the south Pyrenean thrust units and the Ebro Basin can therefore be ruled out as a factor controlling the relative base level in the basin.

The facies distributions in these strata (Fig. 1b) are summarised in Hirst and Nichols (1986), Nichols and Hirst (1998), Arenas *et al*. (2001) and Luzón and González (2003). Basin margin alluvial fan deposits formed from the erosion of the adjacent thrust front are petrographically distinct from the fluvial channel

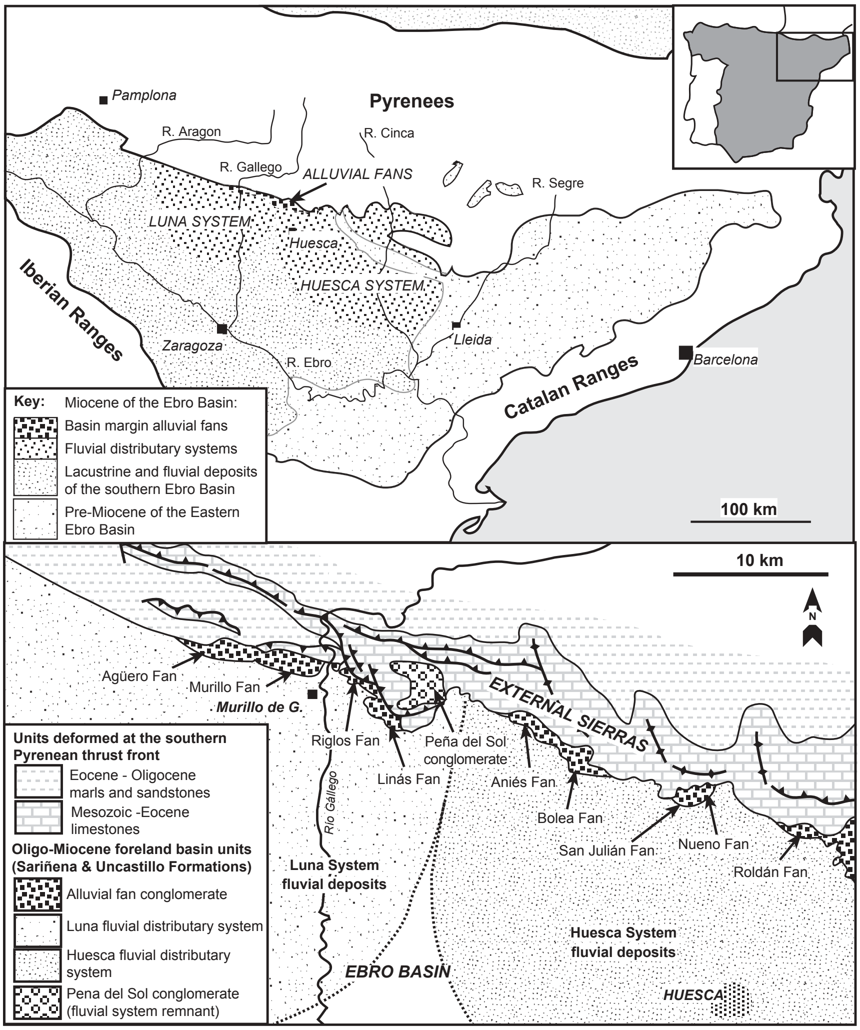

Fig. 1. The Ebro Basin and surrounding area. (a) The Luna and Huesca fluvial distributary systems are stratigraphically within the Uncastillo and Sariñena Formations and most of the exposures are early Miocene in age. (b) The basin-margin alluvial fans north of Huesca are within the same formations, and these deposits range from the late Oligocene to the early Miocene

Fig. 1. La Cuenca del Ebro y sectores adyacentes. (a) Los sistemas distributarios fluviales de Luna y Huesca se sitúan estratigráficamente dentro de las formaciones Uncastillo y Sariñena, siendo la mayor parte de los afloramientos de edad Mioceno inferior. (b) Los abanicos aluviales del margen de la cuenca situados al norte de Huesca pertenecen a las mismas formaciones, oscilando en edad entre el Oligoceno superior y el Mioceno inferior

and overbank facies that are made up of material derived from a larger area of the southern Pyrenees. These fluvial facies were deposited by large fluvial distributary systems, the Huesca System in the east and the Luna System in the west which are partly coeval with each other and with the alluvial fan deposits. The distal fluvial distributary system deposits interfinger with lacustrine facies that dominate the exposure further south towards Zaragoza.

Alluvial fan deposits

The pinnacles or 'mallos' of conglomerate are a striking feature of the geomorphology of the northern margin of the Ebro Basin north of Huesca (e.g at Riglos, Fig. 2). They are the remnants of alluvial fans formed at the northern margin of the Ebro Basin (Puigdefábregas 1975; Hirst 1983; Nichols 1984; 1987a; Hirst and Nichols 1986; Arenas and Pardo

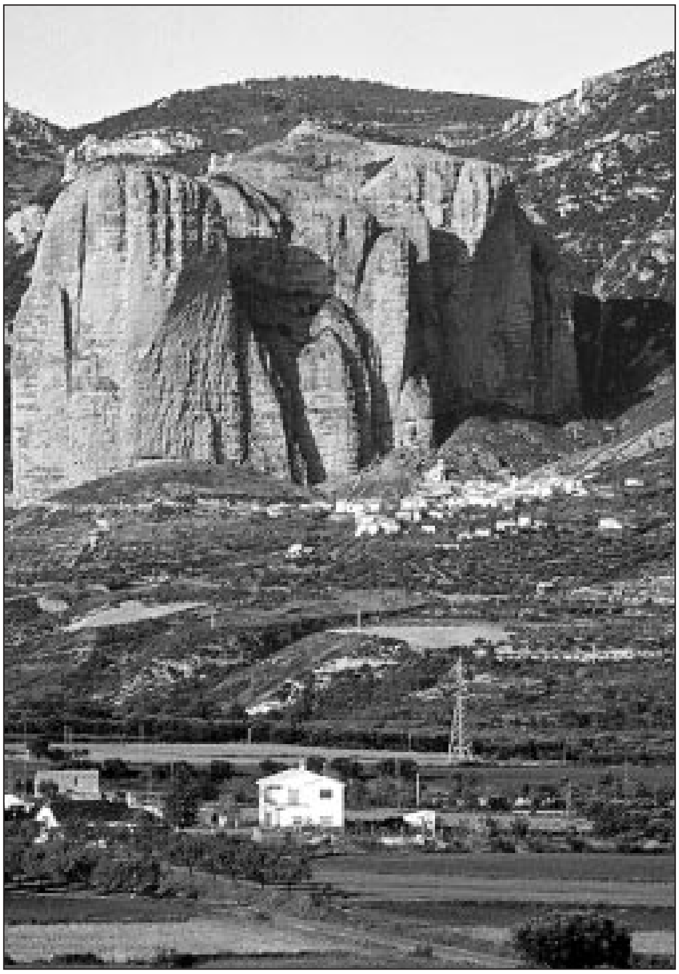

Fig 2. Los Mallos de Riglos, pinnacles of early Miocene alluvial fan conglomerate beds towering above the village of Riglos with Murillo de Gallego in the foreground
Fig. 2. Los Mallos de Riglos, pináculos de capas de conglomerado de abanicos aluviales del Mioceno inferior coronando el pueblo de Riglos, con Murillo de Gállego en primer término

1996; Nichols and Hirst 1998; Lloyd *et al.* 1998; Arenas *et al.* 2001). The tallest and most impressive pinnacles occur at Agüero, where they rise 250 m from their base, Riglos, which has sheer cliffs 330 m high and Roldán, where conglomeratic facies are exposed over a vertical distance of 400 m from the valley floor to the tops of the two pinnacles at Salto de Roldán (Fig. 3).

As geomorphological features, the 'mallos' along the northern margin of the Ebro Basin are not unique: at Montserrat, 40 km to the northeast of Barcelona, impressive masses of conglomerate tower above the plain and at Meteora, in the Mesohellenic Trough in northwest Greece, conglomerate pinnacles are famous for the isolated monasteries built on top of them. However, these two examples are different from the north Ebro Basin examples in an important way: they are fan-delta deposits, built up into a marine environment that provided the accommodation space for them to accumulate thick successions (Ori and Roveri 1987; López-Blanco *et al.* 2000). In a continental setting, accommodation space is provided by an equilibrium profile to which fluvial deposits can aggrade (Shanley and McCabe 1994; Viseras *et al.* 2003). In the Ebro Basin this profile must have been rising due to an increase in height of the base level within the basin to provide the accommodation space for the accumulation of thick successions of alluvial fan conglomerates.

The Riglos, Nueno and lower part of the Agüero fan conglomerate bodies (Fig. 1b) are predominantly the product of debris-flow processes (Nichols *in press*), whilst the other fans along the margin, including Roldán are dominated by water-lain processes (Nichols 1987a; Nichols and Hirst 1998; Nichols *in press*). The radius of an alluvial fan is limited by the processes of deposition to about 10 km from the basin margin (Blair and McPherson 1994). None of the fans along the northern margin of the Ebro basin near Huesca were that extensive, the largest being Roldán and Linás (Fig. 1b), each of which deposited material up to 3.5 km from the basin margin (Lloyd *et al.* 1998). The fan with the smallest depositional area was Riglos: fan-derived material is limited to about 0.8 km from the thrust front (Lloyd *et al.* 1998).

An alluvial fan will initially build up and out to reach its equilibrium profile. If the base level in a basin remains constant or falls, an alluvial fan at the margin will tend to prograde (Denny 1967; Heward 1978) resulting in incision of channels into the preceding deposits (see Fernández *et al.* 1993). However, if the base level rises the fan will tend to display an aggradational facies architecture. Base level changes affecting alluvial fans can therefore be recognised by the presence of coarsening-up representing fan progradation, fining-up signifying a retrogradation and incision marking base level fall (Heward 1978).

The lower part of the fan succession at Agüero shows trends in clast size and bed thickness which can be related to phases of progradation (Nichols 1987a), but the upper, pinnacle-forming part of the succession (Fig. 4), which is coeval with the bulk of the deposits exposed in this part of the Ebro Basin (Arenas *et al.* 2001), does not display any obvious trend (Nichols 1987a). At Roldán (Fig. 3) the vertical profile through the main pinnacles (Hirst 1983; Lloyd 1994) shows two coarsening-up trends of 100-200 m thickness separated by a fining-up succession of similar thickness which these authors attribute to changes in climate and sediment supply. None of the basin

Fig. 3. The most complete exposure of alluvial fan deposits in the area is at the Salto de Roldán, north of Huesca, where the 'mallos' provide 400 m of vertical exposure and the fan facies can be traced laterally over more than a kilometre
Fig. 3. El afloramiento más completo de los depósitos de abanico aluvial en el área de Salto de Roldán, al norte de Huesca, donde los "mallos" proporcionan una exposición vertical de 400 m y donde las facies de abanico se pueden seguir lateralmente una distancia superior a un kilómetro

Fig 4. The main pinnacles at Agüero are over 200 m high and are made up of conglomerates deposited in youngest phase of fan deposition (Nichols 1987a). The beds at the base of the view are at the top of a coarsening-up succession, but the beds in the pinnacles do not display any clear trends
Fig. 4. Los principales pináculos en Agüero tienen una altura próxima a los 200 m y se componen de conglomerados depositados en la fase más moderna de la sedimentación de los abanicos (Nichols, 1987a). Las capas de la parte inferior de la imagen son el techo de la sucesión grano-creciente; sin embargo, las capas de los pináculos no muestran ninguna tendencia clara

margin fans display any evidence of deep incision: small channels can be identified within the Roldán fan succession, but they are only 1-2 m deep and do not cut down through the underlying sheets (Nichols and Hirst 1998; Fig. 5).

The lack, or limited amount, of progradation displayed in the alluvial fans along the Ebro Basin margin implies a rising base level (Fig. 6). The coarsening-up and fining-up patterns observed within the fan successions may be a result of changes in sediment supply due to climatic or tectonic effects in the hinterland, or they may be a consequence of a change in the balance between base level rise and sediment supply. Incision promoted by base level fall has not been recognised within the fan successions.

Fluvial distributary systems

Away from the basin margin, the Luna and Huesca distributary systems formed two large cones of detritus (Hirst and Nichols 1986) made up of bodies of conglomerate, sandstone and mudstone which are interpreted as the fills of channels scoured into the alluvial plain (Fig. 7) (Nichols 1987b; Friend 1989; Hirst 1993). The architectural stacking of these deposits suggests that lateral migration and avulsion of channels were important processes, but there is no evidence of lateral confinement of channels within a valley (see Hirst 1993). The fluvial distributary systems fed into areas of ephemeral lakes (Hirst and Nichols 1986; Arenas *et al.* 2001) and fluctuations in lake level could have resulted in some fluvial incision. The absence of incised valley patterns which have been recognised in other fluvial systems (Shanley and McCabe 1994) indicates that there were no episodes of deep fluvial incision resulting from a significant fall in base (lake) level.

Arenas *et al.* (2001) recognise cycles of progradation of the Luna fluvial distributary system that they attribute partly to variations in sediment supply related to uplift in the Pyrenees and to lacustrine base level changes that were climatically driven. An increase in lake level during a more humid climatic phase would have resulted in a transgression of the lake margin over the distal fringes of the fluvial distributary systems. Thin sheet sandstone and mudstone interbedded with sparse, poorly defined channels dominate in the outer parts of the system (Nichols 1987b) and these facies indicate a very low depositional gradient of the distal parts possibly tending towards horizontal. The distal reaches of terminal fans formed by fluvial ditributary systems are characterised by interfingering of fluvial channel and overbank facies with basinal mudflat areas where the depositional surface is horizontal (Kelly and Olsen 1993). At a relatively steep depositional gradient of 0.1° for the distal fluvial system an increase of lake

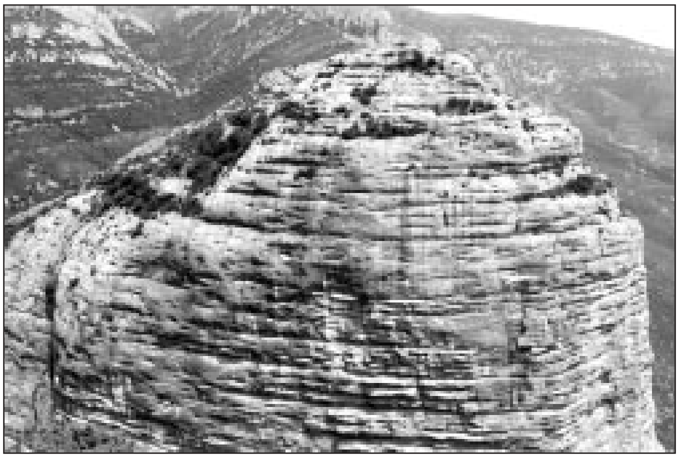

Fig. 5. Beds in the proximal part of the Roldán fan body (exposed here at the top of the western pinnacle) display an overall sheet-like geometry. The beds are thicker and more amalgamated on the left (more proximal) of the view, and there is some local erosion at the base of some of the beds. There is no evidence of deep incision by any channels in either the fan deposits

Fig. 5. Las capas de la parte proximal del cuerpo aluvial de Roldán (expuestas aquí en la parte alta del pináculo occidental) muestran una geometría general laminar. Las capas son más potentes y están más amalgamadas hacia la parte izquierda de la vista (más proximal), donde aparecen rasgos de erosión local en la base de algunas capas. No existen evidencias de incisión profunda por canales en ninguno de los ejemplos de los depósitos de abanicos

level of 10 m would have resulted in a transgression of the lake by over 5 km resulting in the interbedding of thin lacustrine and fluvial facies seen in the outer parts of both the Luna and Huesca systems (Hirst 1983; Nichols 1984, 1987b).

Aggradation within a depositional system requires a balance between accommodation space and sediment supply (van Wagoner *et al.* 1990). During the time of deposition of the Luna system there were fluctuations in this balance which may be attributed to climatic effects, which influenced sediment supply and the level of any basin-centre lake, and tectonic uplift in the Pyrenees resulting in enhanced erosion and sediment supply. Subsidence in the basin may have continued, but the dominant factor controlling the base level in the Ebro Basin was the aggradation of sediment within the basin.

Evidence for aggradation above the alluvial fan bodies: the Peña del Sol conglomerate

To the north of the Linás fan there is an exposure of conglomerate at 1286 m on top of the External Sierras at a peak called Peña del Sol (Fig. 8) (Nichols 1984; Arenas *et al.* 2001). It is very poorly exposed, but conglomerate is found as loose material over an area of about 7 km^2. Clear bedding surfaces are not recognisable, but if it is assumed to be horizontal the lowest (c. 950 m) and highest (1400 m) exposures constrain the thickness to a minimum of 450 m where it filled in topography at the thrust front. The clasts are pebble to cobble grade (occasionally boulders), well-rounded, and moderately well-sorted (Fig. 9). Compositionally they resemble clasts found in conglomerate facies in the Campodarbe Formation and in the Uncastillo Formation in the proximal parts of the Luna System near Biel and Luesia. The structural position of this Peña del Sol Conglomerate lying apparently undeformed on top of the deformed strata of the Guarga thrust front means that it is younger than the last folding/thrusting events in the External Sierras. Arenas *et al.* (2001) map this conglomerate as younger than the uppermost tectonostratigraphic unit of the Uncastillo Formation (TSU3), and therefore younger than all marginal fan deposits.

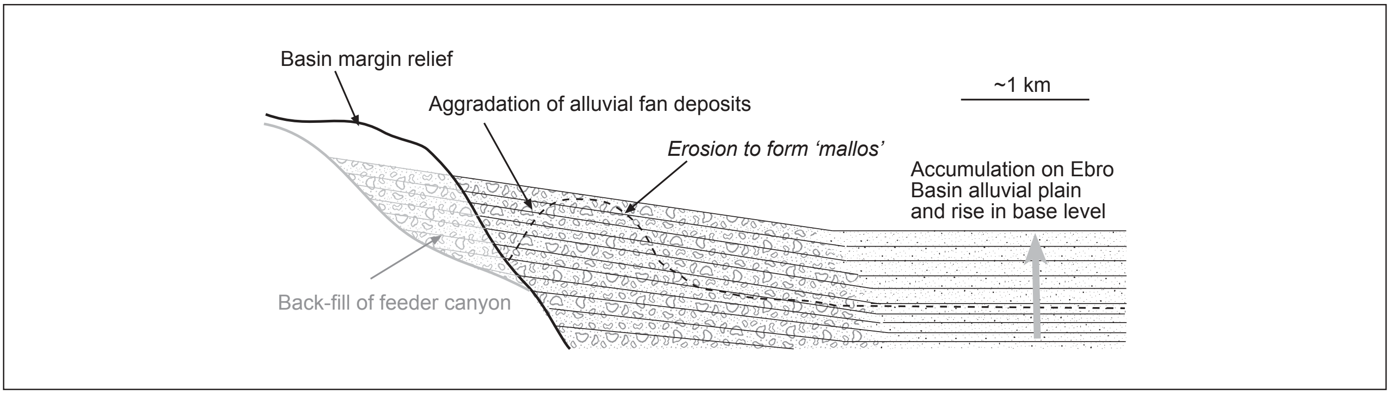

Fig. 6. Aggradation of alluvial fan deposits at the basin margin due to rise in base level: under conditions of falling or constant base level the pattern would be progradational (Heward 1978)

Fig. 6. Agradación de los depósitos de abanico aluvial en el margen de la cuenca, debida a un ascenso en el nivel de base; bajo condiciones de nivel de base en descenso o estable el patrón sería progradacional (Heward, 1978)

Fig. 7. Exposures of fluvial channel-fill sandstone bodies from the Huesca fluvial system in the Canal de Cinca, 10 km south of Huesca. Throughout the Luna and Huesca distributary systems there is no evidence of incised valleys from the stacking patterns of the channel and overbank facies

Fig. 7. Afloramientos de los cuerpos de areniscas de relleno de canal fluvial pertenecientes al sistema fluvial de Huesca en el Canal de Cinca, 10 km al sur de Huesca. En toda la extensión de los sistemas distributarios de Luna y Huesca, los patrones de apilamiento de facies de canal y de desbordamiento no muestran evidencias de la existencia de valles encajados

The Peña del Sol conglomerate is here interpreted as a remnant of a fluvial system which deposited at a level which would have covered most of the External Sierras and buried the marginal alluvial fan deposits north of Huesca. As the conglomerate is exposed at 1400 m above sea level, the thickness of this blanket of material can be constrained to being at least 900 m above the present level of the ground near Huesca (at about 500 m). The northern limit of the area of deposition may have been some distance north of the External Sierras, and the only expression of the topography at the thrust front would have been isolated inselbergs.

It seems likely that this fluvial system was similar to the Luna System in that it was supplied from the reworking of the Campodarbe Formation and deposited gravel, sand and mud over an area of many hundreds of square kilometres. There must therefore have been distally equivalent fluvial sandstone and mudstone deposited further south in the Ebro Basin. At a maximum depositional gradient for a river of 0.3° (Blair and McPherson 1994), the distal fringe of a 40 km radius distributary system (the radius of the Luna System: Nichols 1987b) would have been 200 m lower at an altitude of around 1100 m above present sea level. Using a lower, more realistic gradient of 0.1° for the fluvial system, the distal fluvial and lacustrine deposits would have been at about 1300 m above present sea level.

However, this estimate of the altitude of the distal Peña del Sol fluvial deposits does not take into account any relative vertical movement between the

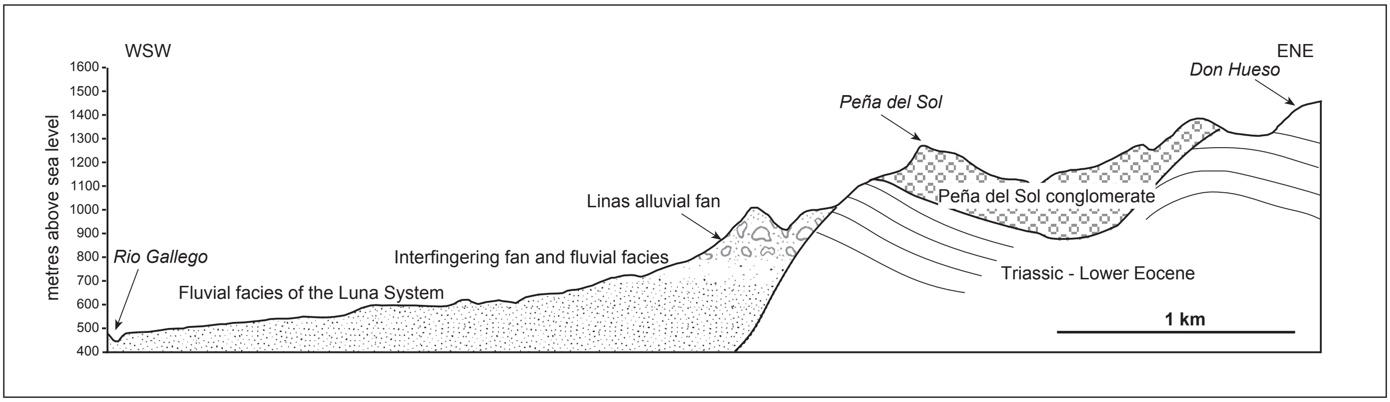

Fig. 8. A cross-section WSW-ENE from the valley of the Río Gállego south of Murillo de Gallego to one of the higher points in this part of the External Sierras, Don Hueso. Fluvial deposits of the Luna fluvial distributary system interfinger with distal deposits of the Linas alluvial fan body. This fan body is made up of material derived from the Triassic to Lower Eocene strata which form the External Sierras. The clasts in the Peña del Sol conglomerate are not locally derived, and the body locally covers the thrust front strata, filling in palaeotopography. It represents the remnant of a fluvial system derived from further north which formed at a time (in the early Miocene) when the base level in the Ebro Basin was up to 1300 m above present sea level

Fig. 8. Un corte OSO-ENE desde el valle del río Gállego (al sur de Murillo de Gállego) hasta Don Hueso, uno de los puntos más altos de esta parte de las Sierras Externas. Los depósitos fluviales del sistema distributario de Luna se interdigitan con los depósitos distales del cuerpo de abanico aluvial de Linas. Este cuerpo aluvial está compuesto por material procedente de los estratos de edad Trías-Eoceno inferior que forman las Sierras Externas. Los clastos del conglomerado de Peña del Sol no tienen una procedencia local, y el cuerpo cubre localmente a los estratos del frente de cabalgamiento, rellenando un paleotopografía. Se trata de un remanente de un sistema fluvial procedente de un sector lejano situado al norte, y que se formó en algún momento del Mioceno inferior cuando el nivel de base de la Cuenca del Ebro se encontraba a 1.300 m sobre el nivel del mar actual

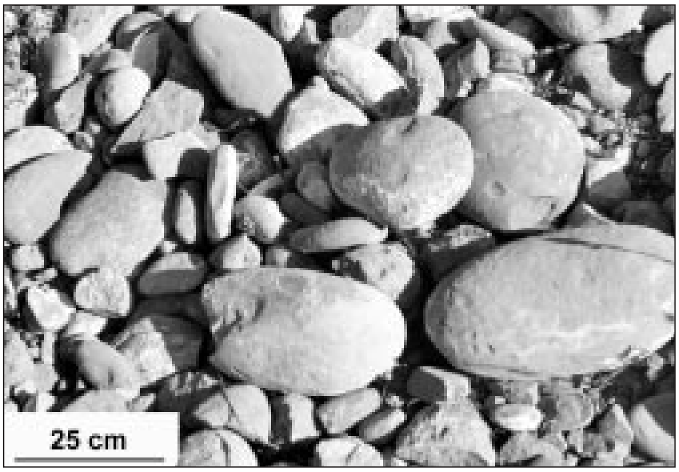

Fig. 9. Clasts from the Peña del Sol conglomerate body: these are compositionally similar to clasts in the proximal part of the Luna fluvial distributary system which are also well-rounded and interepreted as proximal braided river deposits

Fig. 9. Clastos del cuerpo de conglomerado de Peña del Sol; composicionalmente son similares a los clastos de la parte proximal del sistema fluvial distributario de Luna, los cuales también están bien redondeados y se interpretan como depósitos proximales de ríos trenzados. El clasto más grande tiene 40 cm de largo

External Sierras and the basin centre 40 to 60 km to the south. Low amplitude, long wavelength folds have been recognised near the thrust front (Nichols 1984; Arenas *et al.* 2001) and regional dips of approximately 1° S have been recorded within the Luna System (Nichols 1984). It is therefore difficult to determine the amount of fluvial succession that has been eroded, except but it is notable that Arenas *et al.* (2001) consider that there are Miocene lacustrine units in the central Ebro Basin which are younger than TSU3, and these may be presumed to have been fed by fluvial systems such as those found as remnants at Peña del Sol.

Coney *et al.* (1996) recorded late Oligocene conglomerate at over 1700 m above sea level to the northwest of Tremp and there are similar age conglomerate at the top of Peña Oroel in the Jaca Basin north of Huesca (Puigdefàbregas 1975). In both cases these deposits are in piggy-back basin settings which are likely to have undergone post-depositional uplift. However, these are considered to be the remnants of fluvial systems which deposited a broad pediment of material over a large area of the southern Pyrenees, stretching north up on to the axial zone of the orogen and south to cover most of the southern Pyrenean thrust units (Coney *et al.* 1996), including the External Sierras north of Huesca. The remnants exposed at Peña del Sol indicates that the fluvial systems envisaged by Coney *et al.* (1996) persisted until the early Miocene.

Base level in the Ebro basin

The flexural loading of the northern margin of the Ebro Basin by thrust sheets of the southern Pyrenean foreland thrust belt and movements on south Pyrenean thrusts (e.g. the Guarga Thrust which forms the External Sierras) continued until the early Miocene (Arenas and Pardo 1996; Arenas *et al.* 2001). Tectonically driven subsidence, coupled with sediment loading, resulted in a succession of foreland basin strata of which between 3000 and 4000 m thickness are preserved near Huesca (Friend *et al.* 1996). The evidence from the fluvial facies exposed at Peña del Sol indicates that, in early to mid-Miocene time, the total thickness of foreland basin may have been at least 900 m greater than this.

In the absence of any connection to an ocean, the base level in an endorheic basin can continue to rise because of the continued sediment supply filling in the basin. The youngest Miocene continental deposits in the Ebro Basin are middle Miocene in age (Calvo *et al*. 1993; Evans and Arche 2002) which occur at altitudes of over 800 m above present sea level in the Sierra de Alcubierre to the east of Zaragoza.

The rise in base level may have eventually reached the spill-point of the basin (Fig. 10), the lowest point in the watersheds surrounding the basin. It is possible that this occurred at the point where the current Rio Ebro passes through the Catalan ranges, establishing flow from the Ebro basin into the Mediterranean Sea. Evidence from the delta of the Rio Ebro (Evans and Arche 2002) indicates that this may have happened in Tortonian times, as a thick succession of deltaic deposits of this age have been recognised beneath the present day Ebro Delta. A thick succession of terrigenous clastic sediment prograded at the site of the modern Ebro Delta in late Miocene time: it is punctuated by an unconformity that marks the Messinian sea level fall in the Mediterranean (Evans and Arche 2002).

The cessation of sedimentation in the Ebro Basin and the onset of deposition at the Ebro Delta indicate that the Ebro Basin changed from being a basin of internal drainage (endorheic) up to the middle Miocene to being drained externally (exorheic) via the Río Ebro in the Late Miocene (Tortonian). This affected a large part of the southern Pyrenees and the Ebro Foreland Basin by lowering the base level. The amount of fall can be partly constrained by the 800 m altitude of the outcrop of middle Miocene strata in the basin centre, although they may have undergone post-depositional deformation and there may have been a greater thickness which has been eroded away.

The effect of the base level fall was for the Río Ebro and its tributaries in the southern Pyrenees to incise along much of their courses and deposit some of the eroded sediment on the Ebro Delta, where over 2000 m of late Miocene and younger strata are recorded (Evans and Arche 2001) and in the Valencia Trough which contains over 3000 m of late Neogene sediment (Batrina *et al.* 1992; Maillard *et al.* 1992). During the late Neogene the rates of fluvial incision have varied and have been punctuated by aggradation in the area of the south Pyrenean thrust belt north of the Ebro Basin (Jones *et al.* 2001). The net effect, however, has been to expose the Pre-mid Miocene foreland basin succession.

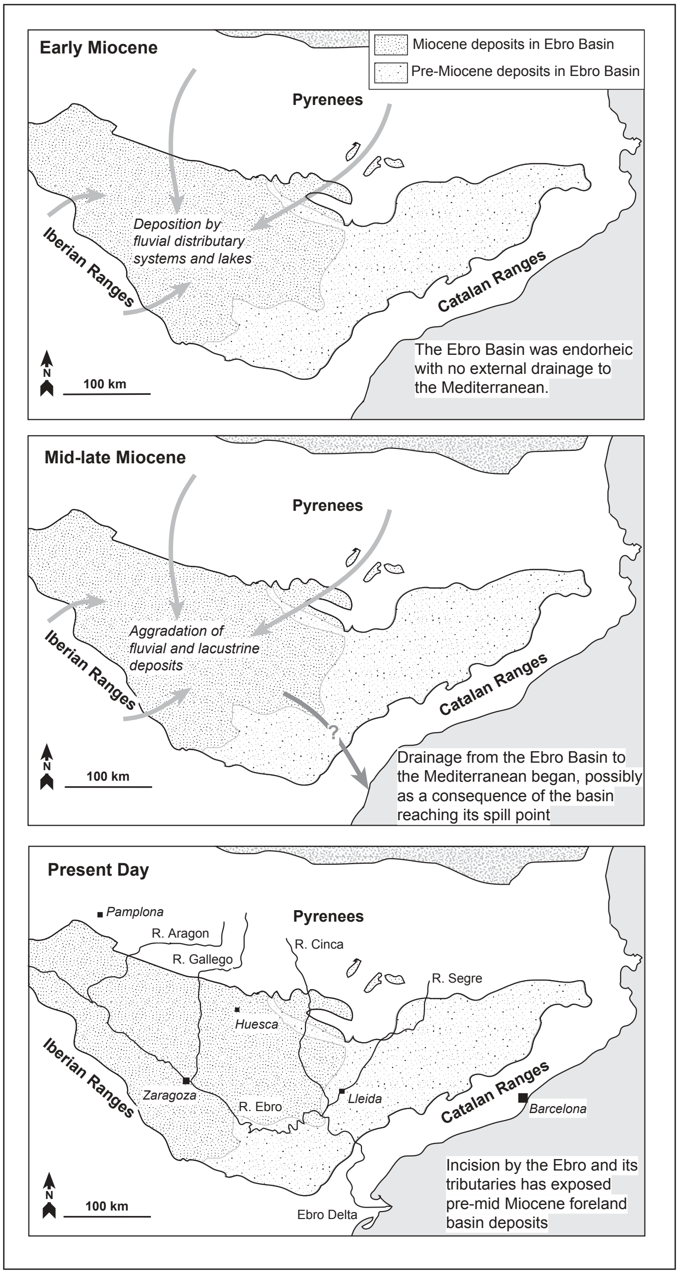

Fig. 10. Schematic reconstructions of the Ebro Basin during the Neogene as fluvial and lacustrine deposits aggraded to fill the basin, possibly to spill point, followed by incision by the Río Ebro and its tributaries to expose the foreland basin succession today
Fig. 10. Reconstrucciones esquemáticas de la Cuenca del Ebro durante el Neógeno, a medida que los depósitos fluviales y lacustres rellenaban la cuenca hasta alcanzar probablemente el punto de derrame, lo cual fue seguido por la incisión del río Ebro y sus afluentes, permitiendo la exposición de la sucesión de cuenca de antepaís

Conclusions

1. The Ebro Basin was an endorheic basin in the Early and Mid-Miocene, and the region between Huesca and Zaragoza was a site of deposition by marginal alluvial fans, large fluvial distributary systems and in lakes.
2. The absence of incised channels in the alluvial fan deposits and of incised valleys within the fluvial successions indicates that there were no periods of base level fall during this time. Fining-up and coarsening-up trends in alluvial and fluvial deposits have been recognised, but are attributed to variations in sediment supply and possible small fluctuations in lake level: overall the trend was aggradational.
3. Endorheic basins are sediment traps and through time the base level will rise relative to the hinterland source area due to the accumulation of sediment in the basin. It is estimated that during the late Oligocene and early Miocene base level in the Ebro Basin rose to approximately 1300 m above present sea level due to sedimentary fill of the basin.
4. Present day exposure of the foreland thrust belt, basin margin facies and the foreland basin stratigraphy has been brought about by incision driven by a base level fall. This occurred with the development of the Río Ebro as a river system draining large parts of the southern Pyrenees in the Tortonian, before the Messinian salinity event.

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