SPACE AND TIME ANALYSIS OF RIVER SYSTEMS, ILLUSTRATED BY MIOCENE SYSTEMS OF THE NORTHERN EBRO BASIN IN ARAGON, SPAIN

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SUMMARY

Sediment systems are defined in terms of the transfer of sediment from one area to another, over a specified period of time. River systems can be single or compound, and terminal or transit.

Along the northern edge of the Ebro basin in Aragon, terminal river systems were a feature of Early Miocene times, and are here called "Ebro-type" systems. The size of the depo-areas ranged from small (10 km^2), to large ($10^3 km^2$) depending on the amount of sediment and water being transferred from small and large source areas determined by contemporaneous structures in the southern Pyrenees. In the large Ebro-type systems, ribbon sandstone bodies were formed by the interaction of the dominant extrabasinal system (sourced outside the basin), with more localised intra-basinal, short-lived river systems.

At the present day, the whole of the northern Ebro area in Aragon is part of the source area of the very large ($10^5 km^2$) Ebro river system, that is transferring sediment to the Mediterranean Sea. The contrast in river system patterns between mid Cenozoic and present day times, for north and central Iberia, is the contrast between small to large terminal systems supplying land-locked non-marine basins in the mid-Cenozoic, and small to very large transit systems supplying deltaic and marine depo-areas at the present-day.

Key words: sediment system, river system, alluvial fans, sandstone bodies, Ebro basin, Early Miocene, palaeocurrents.

RESUMEN

Se definen los sistemas sedimentarios en función de la transferencia de sedimento que tiene lugar de un área a otra en un intervalo de tiempo determinado. Los sistemas fluviales pueden ser simples o compuestos, y terminales o de tránsito.

Durante el Mioceno inferior, el borde norte de la Cuenca del Ebro en su sector aragonés, se caracterizó por el desarrollo de sistemas fluviales terminales, que se han denominado de "tipo Ebro".

El tamaño de las áreas de depósito varía desde dimensiones reducidas (10 km^2) a grandes ($10^3 km^2$), dependiendo de la cantidad de sedimento y de agua que hayan sido transferidas desde las áreas fuentes pequeñas o grandes, que se estaban formando en relación con las estructuras contemporáneas que afectan al borde meridional del Pirineo. En los grandes sistemas del tipo Ebro se formaron cuerpos de areniscas lineales ("ribbons") debidos a la interacción de los sistemas del exterior de la cuenca (con área fuente situada fuera de la cuenca) y, en menor escala y más localmente, de los sistemas fluviales efímeros del interior de la cuenca.

En la actualidad la totalidad de este borde norte de la cuenca del Ebro, en Aragón, forma parte del área fuente del sistema fluvial de grandes dimensiones del Ebro ($10^5 km^2$) que transfiere sedimentos al mar Mediterráneo. Esto contrasta con los modelos de sistemas fluviales que se deducen para el Cenozoico medio, los cuales serían sistemas fluviales terminales pequeños y grandes, que alimentaban cuencas endorreicas. Por el contrario los sistemas actuales del Ebro son sistemas fluviales de tránsito pequeños y muy grandes que alimentan áreas de depósito deltaicas y marinas.

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1.-INTRODUCTION TO THE RIVER SYSTEM APPROACH

Although sedimentary geologists generally study a very incomplete rock record, some areas do allow the investigation of relatively complete sedimentary formations. The object of this paper is to review the investigation of some early Miocene river systems in northern Spain, which are complete enough to provide insights into the space and time factors that play a complex part in natural sediment systems.

Sediment systems can be defined in terms of the transport or transfer of sediment from one area to another (Schumm,1979).

A system, therefore can be defined in terms of:
1) a specified source (or production) area. or
2) a specified depositional area (depo-area for short),
3) a specified transfer process (eg river transport), or group of processes, and
4) a time interval.

As we shall discuss further below, natural sediment transport is never uniform (in space), or steady (in time), so the space-time pattern must be specified as fully as possible in any use of this approach.

Fig. 1 illustrates our terminology for sediment systems generally, and river systems particularly. It also illustrates that many depositional areas may be divided into different sub-divisions, by area, environment or process. In the stratigraphic examples in this paper, we shall be concerned entirely with the reconstruction of river systems using the alluvium of the depo-areas. One reason for concentrating on river systems is that they may be expected to reflect the climate, and the geological (tectonic) history of land areas more directly than many other sediment systems.

2.- EARLY MIOCENE RIVER SYSTEMS OF THE NORTHERN EBRO MARGIN IN ARAGON.

2.1 Background stratigraphy and investigations

A comprehensive review of the stratigraphy of the Ebro Basin has been provided by Riba, Reguant and

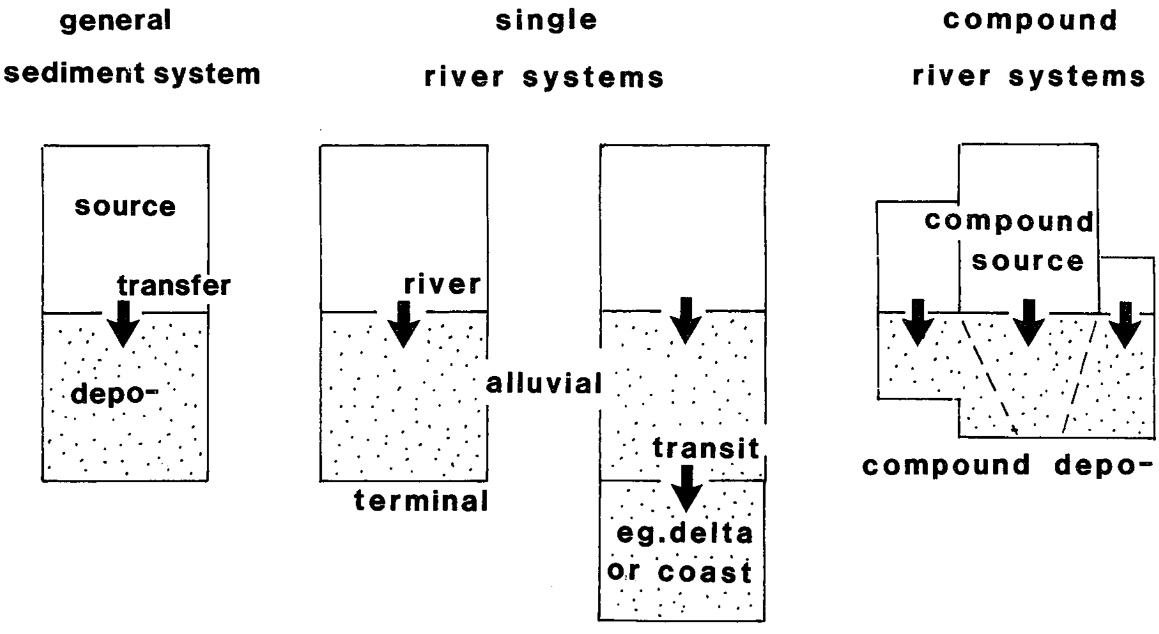


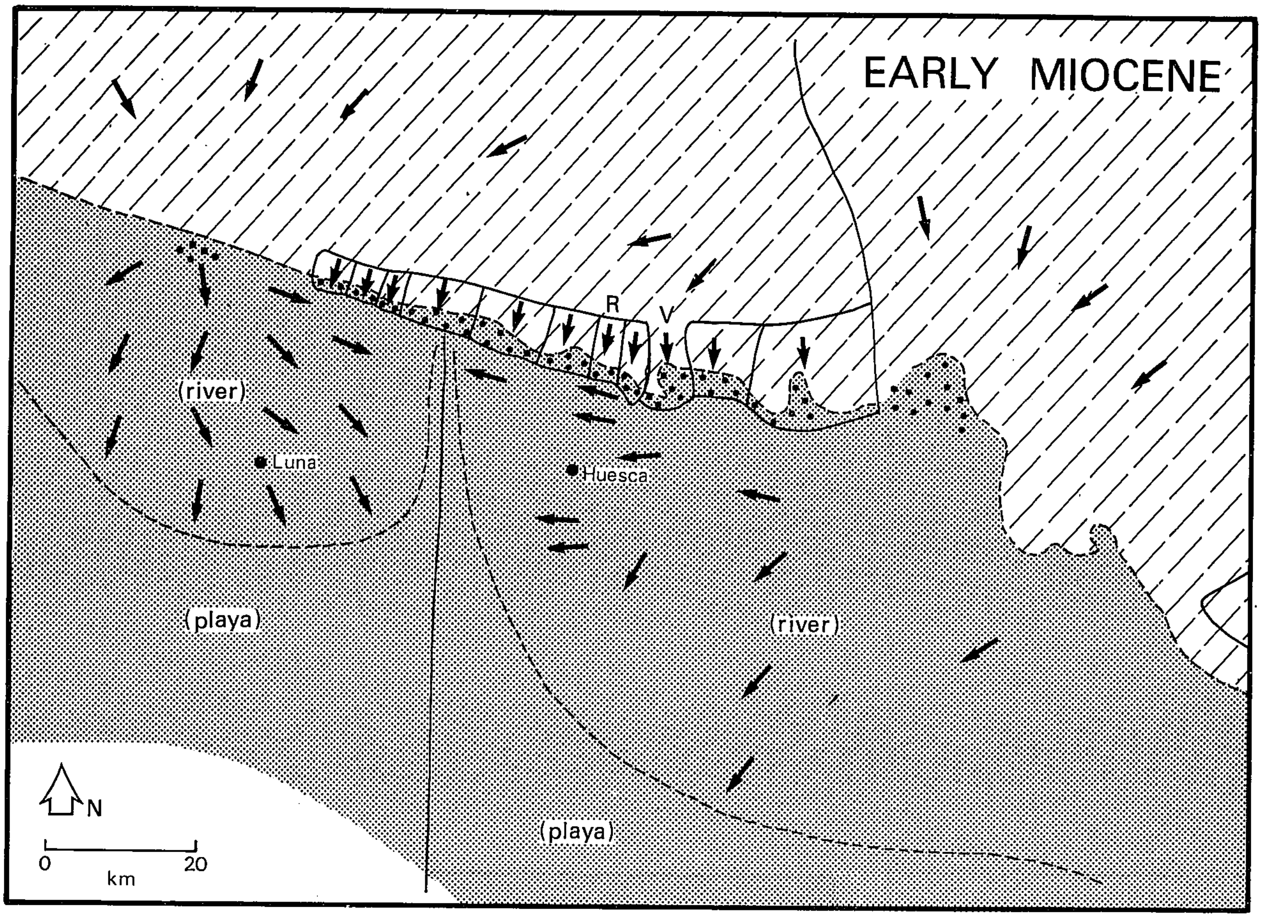
Fig.1.-Cartoon diagrams showing the relationships between *source* and *depo-* areas in sediment systems generally, and the difference between *terminal* and *transit,* and *single* and *compound* river systems.

Fig.1.-Diagramas esquemáticos en los que de manera general se muestran las relaciones entre áreas fuentes y áreas de depósito en sistemas sedimentarios. Se marca la diferencia entre sistemas fluviales terminales y de tránsito, y entre simples y compuestos.

Fig.2.-Maps of the area round Huesca city, northern Spain, outlined on fig. 2a. Fig. 2a shows the river system pattern of Early Miocene times. Two large systems to west and east enclose a series of small river systems, arranged in a west-east row that reflects the contemporaneous emergence of a frontal thrust ramp, now represented by the External Sierras. Fig. 2b shows the different situation at the present-day. The whole area, apart from local spreads of relatively thin Quaternary sediment, is a source area. Present-day river patterns show similarities and differences when compared with their Early Miocene ancestors. H, Huesca city; R. Roldán; V. Vadiello; Z, Zaragoza.

Fig.2. Mapas de los alrededores de la cuidad de Huesca, al norte de la Depresión del Ebro. (a).-muestra la distribución de los sistemas fluviales en el Mioceno inferior. Dos grandes sistemas, uno al este y otro al oeste, que encierran una serie de pequeños sistemas fluviales alineados de oeste a este que reflejan el levantamiento contemporáneo del frente pirenaico cabalgante. (b).-Situación actual que es muy diferente, en la que el conjunto del área, a excepción de pequeños sectores con delgados depósitos cuaternarios, constituye un área fuente. La distribución actual de los rios presenta analogías y diferencias con la red fluvial del Mioceno inferior. H , Huesca; R, Roldán; V, Vadiello, Z, Zaragoza.

(a)


EARLY MIOCENE
R
V
(river)
Luna
Huesca
(playa)
(river)
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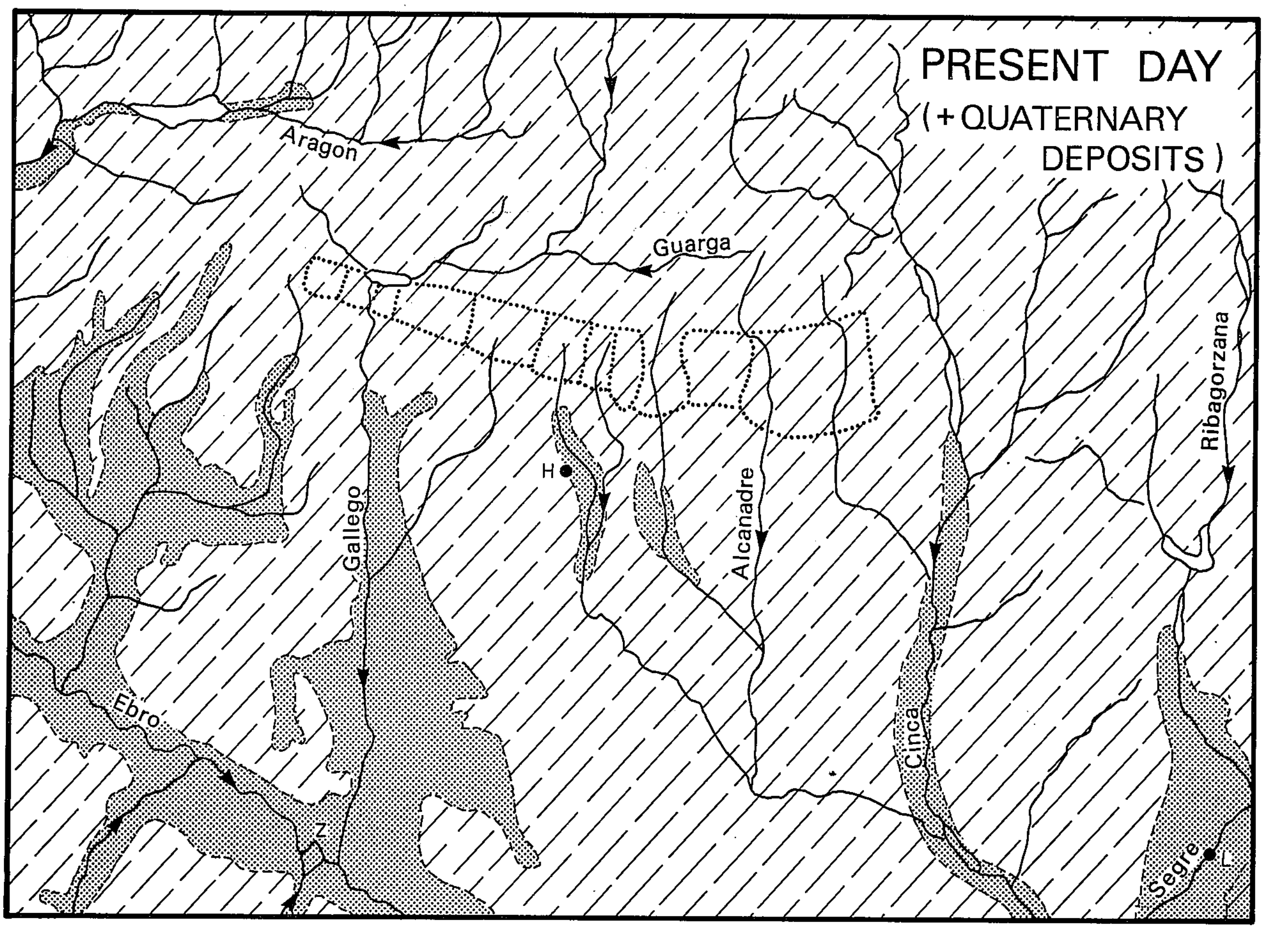
N
0
20
km

(b)


PRESENT DAY
(+QUATERNARY
DEPOSITS)
Aragon
Guarga
Ribagorzana
H
Gallego
Alcanadre
Ebro
Z
Cinca
Segre
L

Villena (1987). In the basin centre, the outcrops are of mudstones, carbonates and gypsums, interpreted as forming under playa-lake conditions, whereas mudstones, sandstones and conglomerates were deposited by rivers to the north and south. The age of these non-marine strata ranges from Oligocene to late Miocene, but most of the river material that will be described below is of early Miocene age. This age has been confirmed by detailed micropalaeontological work on mammal teeth, completed since the above review was written (López-Martínez *et al.*, 1986; Daams *et al.*, 1987; Agustí *et al.*, 1988).

In recent years, a group of us has been examining the outcrops of early Miocene age along the northern margin of the Ebro basin in the Provinces of Huesca and Zaragoza (Aragon) (Turner, Hirst and Friend, 1984; Friend, Hirst and Nichols, 1986; Hirst and Nichols, 1986; Nichols, 1987a,b,c). The measurement of palaeocurrent patterns, and the analysis of the compositions of the sandstones and conglomerates, have revealed a more complex and interesting pattern of river systems than that suggested by earlier workers (eg. Koldewijn and Weber,1969; Reille, 1971). Whereas the earlier workers assumed that the spectacular massifs and needles of conglomerate that occur along the northern margin of the basin, were the proximal deposits of the same rivers that deposited the sandstones nearer the basin centre, it is now clear that this is not the case (fig. 2a).

In early Miocene times, the pattern of river systems (fig. 2a) consisted of a series of small (10 km^2) systems, enclosed in two large (10^3km^2) systems. The small systems were arranged west-east along the front of what are now the External Sierras of the Pyrenees, and were sourced from the early Miocene ridge that is now represented by the Sierras. In contrast the large systems transferred sediment round the ends of this ridge and distributed it across most of the basin floor south of the ridge. These two types of systems will be described and discussed next.

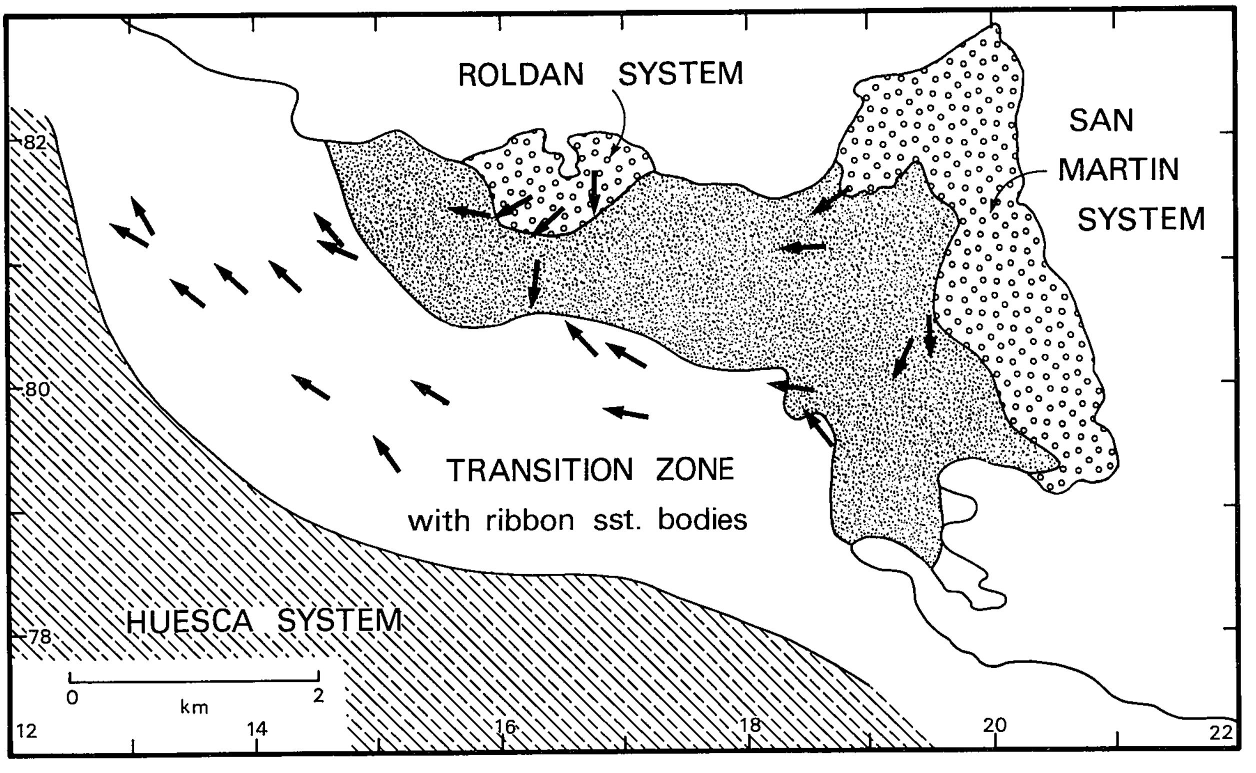


Fig.3.-Outline geological map of the Early Miocene sediments of an area, some 15 km. north of Huesca city (National Grid reference numbers are shown round the frame). The mapping is the work of Dr. J.P.P.Hirst. Sediments with more than 80% conglomerate (shown by small-circle shading), and the local palaeocurrent pattern (based on clast imbrication), mark the positions of the depo-areas of the small Roldan and San Martin systems. Grey shading marks a zone of outcrops of sediment with less than 80% conglomerate, and less th an 5% mudrock. Stipple shading in the south-west marks outcrops of sediments of the large Huesca system (see fig. 3a), and the unshaded zone north of this contains outcrops of transitional sediments with more than 5% mudrock, and also ribbon sandstone bodies from the Huesca system. Palaeoflow directions along the ribbon bodies are indicated, generally perpendicular to the Roldan and San Martin progradation directions.

Fig.3.-Mapa geológico esquemático de los sedimentos del Mioceno inferior de un área localizada unos 15 km al norte de la ciudad de Huesca (en los bordes del esquema se marcan las coordenadas del mapa topográfico nacional). El mapa ha sido elaborado por el Dr. J.P.P.Hirst. Los sedimentos con más del 80% de conglomerados (marcados con trama de círculos) y las direcciones de las paleocorrientes (medidas a partir de la imbricación de cantos) indican la posición de las áreas de depósito de los sistemas de San Martín y Roldán. El entramado de puntos finos corresponde a los afloramientos con menos de 80% de conglomerados y menos de 5% de lutitas. La trama con rayas oblicuas en el suroeste marca los afloramientos de sedimentos del gran sistema de Huesca (ver fig 2a) y la zona en blanco, sin trama, marca los afloramientos de los sedimentos de transición con mas del 5% de lutitas y con cuerpos arenosos lineales ("ribbons") del sistema de Huesca. Se indica la dirección de las paleocorrientes a lo largo de los cuerpos arenosos, que generalmente es perpendicular a las direcciones de progradación de los sistemas de Roldán y San Martín.

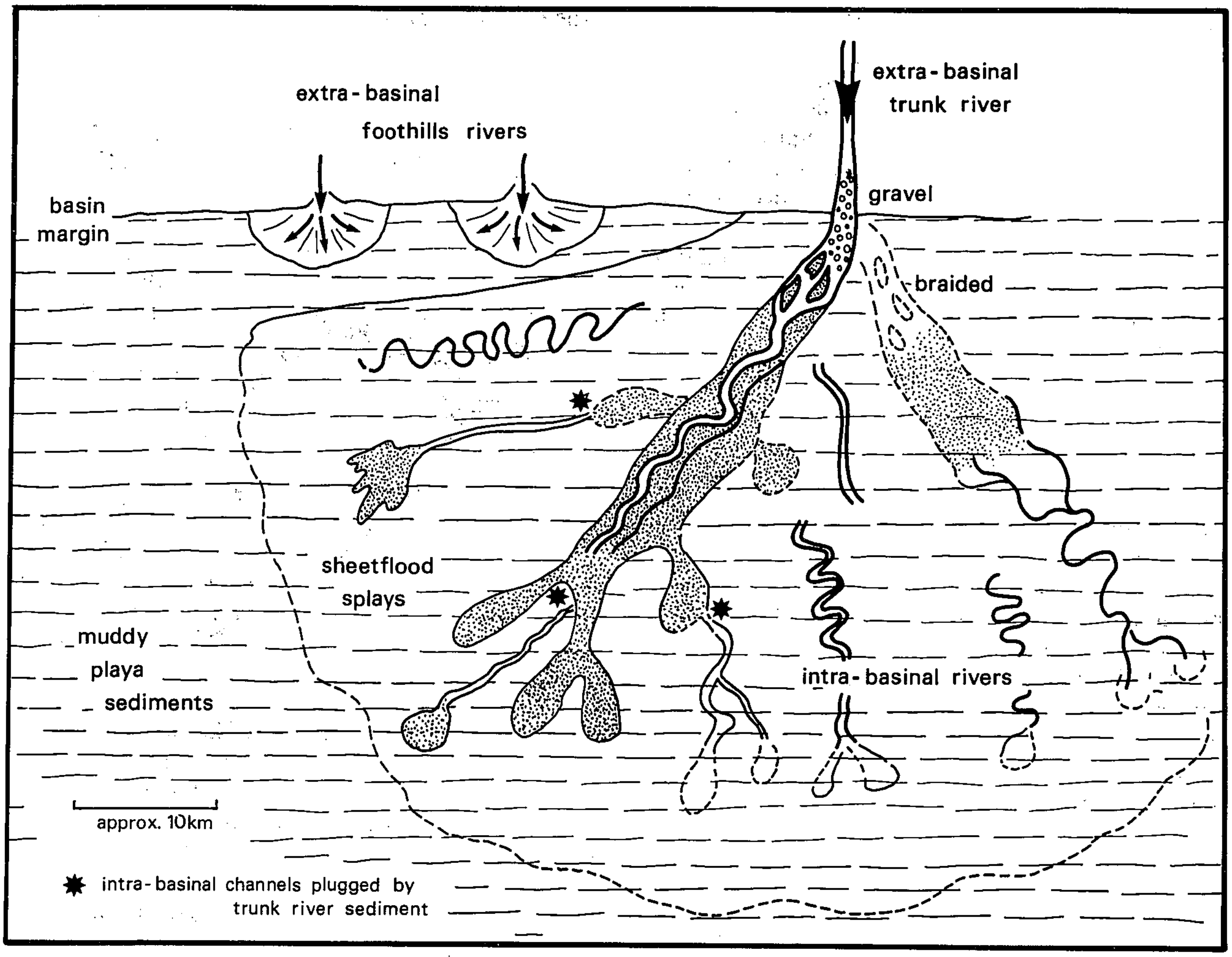


Fig.4.-Cartoon sketch showing small and large Ebro-type systems. Channel patterns are shown on the large system diagrammatically, and not to scale, illustrating downstream changes in the extra-basinal trunk river morphology, and the formation of ribbons by plugging of intra-basinal channels by sediment from the trunk rivers.

Fig.4.-Esquema en el que se representan los grandes y los pequeños sistemas fluviales del tipo Ebro. En el sistema grande se muestra el trazado de los canales de forma esquemática y sin escala, representando los cambios morfológicos que muestra aguas abajo el rio principal que procede del exterior de la cuenca, así como la formación de cuerpos arenosos lineales ("ribbons") ocasionados por el relleno de canales internos a la cuenca con sedimento que procede de los rios principales.

2.2. Small Ebro-type systems

One of these small systems has recently been described by Nichols (1987a). Fig. 3 illustrates two other small systems further east along the front of the External Sierras. These were first examined sedimentologically by M.J.Slater (unpublished Cambridge University thesis), and then studied in greater detail by J.P.P.Hirst. More information from Hirst's study is being included in another publication (Friend, Hirst and Nichols, in prep.).

In the area of fig. 3, distinct conglomerate bodies (Roldan and San Martin) appear to have formed as separate gravel fans at the mouths of two valleys. Palaeocurrent measurements, using cross-stratification and clast imbrication, show that the streams radiated out, fan-like, from these mouths. Between one and three km downstream from the most proximal conglomerates, sandstones and then mudstones rapidly become predominant, and it is clear that the river systems were terminal, ending in a mud rich transition zone. In this zone, the sandstone bodies have the external form of ribbons (Friend, Slater and Williams, 1979), and were formed as part of the large Huesca system that locally transported material to the west-north-west, more or less perpendicular to the progradation direction of the small Roldan and San Martin systems.

2.3. Large systems of northern Aragon

Fig. 2a summarises the location, size and palaeocurrent data of the two large alluvial systems of northern Aragon. Both systems have been reviewed by Hirst and Nichols (1986), and Jupp *et al.,* (1987), and detailed discussion on the Luna system has been provided by Nichols (1987b). More detail on the Huesca system is being published elsewhere (Friend, Hirst and Nichols, in prep.), so here my intention is merely to draw attention to some aspects that are relevant to the recognition and understanding of systems of this sort generally.

Fig. 4 is a diagrammatic interpretation of some aspects of the Huesca river system depo-area. Like the smaller systems, this system, was terminal, in that the rivers terminated in the river depo-area, presumably due to evapo-transpiration and/or soaking in of the river waters. The Ebro basin centre was occupied by playas or lakes (Cabrera, Colombo and Robles, 1985), which must have received their supply of suspended sediment at times of rare flood discharge of the river systems. The river-controlled part of the depo-area had a low-enough gradient to accumulate fine-grained sediment between episodes of river channel activity, so the phrase 'alluvial-plain fan' is suggested to make clear the contrast with the gravel-dominated higher-gradient parts of the depo-areas.

In addition to its terminal structure, the Huesca river system also shows other downstream changes in its sandstone bodies (Friend, Slater and Williams, 1979; Friend, Hirst and Nichols, 1986, in prep.). Gravelly deposits are rapidly replaced by sandstones in a downstream direction, and it is then the geometry and proportion of the sandstone bodies that changes most profoundly. Thick sandstone sheets, often in contact across erosion surfaces with other sandstone bodies, are the commonest upstream form, whereas ribbons and thin sheets, increasingly isolated amongst fine-grained mudstones, are characteristic of the downstream areas, as the lake and playa zone is approached. The thin sheets appear to have formed as lobes, or distal splays, like those typical of some present-day terminal fans on the Indo-Gangetic plains (Parkash, Awasthi and Gohain, 1983).

2.4. Origin of the ribbon sandstone bodies

The downstream changes in the sandstone bodies just described, can be explained partly as results of the downstream decrease in river size, but also reflect the increasing scope downstream for avulsion and lateral shifting of the rivers. But these mechanisms do not offer an obvious explanation for the origin of the ribbon bodies. Each ribbon represents the plugging by sediment, and abandonment, of a channel, in the absence of significant lateral migration of the channel. Dr. B.Parkash (Roorkee University) recently took me on a visit to the Kosi River alluvial plains fan in Bihar, eastern India (Gohain and Parkash, 1985a,b; Wells and Dorr, 1987 a,b), and this experience has suggested an explanation for the Spanish ribbons. On the Indian plains, there is a wide variety of intrabasinal rivers, supplied by run-off and/or ground-water, and deriving their sediment load by reworking the alluvium of their banks. They tend to be less active than the extra-basinal rivers which derive their water and sediment either from the high mountains (trunk rivers), or from the mountain-front foothills. If one of these extra-basinal rivers were to avulse, at time of flood, so that it intersected an intrabasinal river, rapid plugging could take place, and a sandstone ribbon could be the result. The increased probability of this happening downstream, would explain the prevalence of ribbons in the distal parts of the large system depo-area.

3.-COMPARISON BETWEEN EARLY MIOCENE AND PRESENT-DAY SYSTEMS IN NORTHERN ARAGON

It is instructive to compare the early Miocene river system pattern just summarised, with the present-day pattern of the same area (fig. 3b). The main difference is that, whereas the early Miocene Ebro basin was the compound alluvial depo-area for a number of different terminal river systems (fig. 2a), it is today an area of erosion forming part of the source area for the major Ebro river system that carries its sediment eastwards across the Miocene basin centre, through the coastal ranges and to the delta and the Mediterranean sea. Fig. 2b shows some Quaternary alluvial sediment within its area. These Quaternary deposits accumulated during a relatively short-lived episode in the lives of the river systems of the area, and the volume of sediment deposited is small compared with the early Miocene volume, or the amount of material removed by nett erosion between the early Miocene and the present-day.

It is also instructive to compare the present-day locations of the rivers with those of the early Miocene river systems. In the east of the area (fig. 2b), the Cinca and Ribagorzana-Segre systems drain southwards, occupying the same terrain in the north as the source area for the early Miocene Huesca system. Their general incision into the Oligocene and Miocene of the Ebro basin floor seems to have prevented any of the avulsion and outward radiation in direction that characterised the Huesca system in early Miocene times.

In the central part of the area of fig. 2, some of the more easterly rivers (eg Alcanadre) have cut through the External Sierras, and the Gallego has cut a major valley and tapped some of the drainage of the early Miocene Luna system. There is evidence that one of the small early Miocene systems (Vadiello) also derived some of its sediment from the north (granodiorite pebbles occur in the Vadiello conglomerates, as shown me by Ms. E.D.Stroock).

To the west, the River Aragon system drains a northern area that, along with the Gallego catchment, approximates to the source area of the early Miocene Luna system. The Luna system, however, emerged into the basin some 20km east of the present-day Aragon.

4.-OTHER SYSTEMS OF THE SPANISH CENOZOIC BASINS

In the Caspe area of the southern Ebro basin, Cabrera, Colombo and Robles (1985) have distinguished the Guadalupe-Matarranya system. It has provided remarkable exposures of exhumed ribbon sandstone bodies, some of which can be traced for over 1 km along their length. Attention was first drawn to them by Riba, Villena and Quirantes (1967), and some examples have been further illustrated by Friend, Slater and Williams (1979) and Friend, Hirst and Nichols (1986). Although gravel-fill of the ribbons is more common in the Caspe area, the general association of the ribbons with thin sandstone sheets is similar to that of the distal part of the Huesca system depo-area.

In the south-eastern Ebro basin, Cabrera, Colombo and Robles (1985) have presented a model (their Figure 18) for the small alluvial fans (eg. the Gandesa-Horta complex), that are features of their Scala Dei (compound) system, of middle Eocene to late Oligocene age. The scale and terminal character of these small fans are the same as the small systems of northern Aragon, although gravels commonly make up the distal ribbon bodies. In contrast, their Montsant fan appears similar in size and radial pattern (their figure 33) to the Luna and Huesca systems of northern Aragon.

Further north-east along the Catalan (coastal) margin of the Ebro basin are a number of distinct fluvial depo-areas, the best known of which includes the Montserrat conglomerate body. This interdigitates with middle and late Eocene marine deposits, and is clearly a fan delta (Anadon, Marzo and Puigdefabregas, 1985) i.e. a river system that deposited coarse detritus on land and in the sea, with no major depositional break.

Well-defined terminal systems are a feature of other Spanish Cenozoic basins, for example the Tajo or Madrid basin (Diaz Molina and Bustillo, 1985; Junco Aguado and Calvo Sorando, in press; Calvo Sorando *et al.,* in press).

5.-SUMMARY OF EBRO-TYPE ALLUVIAL SYSTEMS

Ebro-type alluvial systems had the following features in common:

1) They were terminal, No water or sediment was carried out of them in a clearly defined river system. They were probably particularly characteristic of inland(land-locked) basins. The disappearance of the defined river channels suggests high rates of evapotranspiration,or soak-in, relative to water supply.

2) They developed river patterns that *radiated outwards* downstream from their point of entry to the basin. This pronounced radiation reflects the change from the source area situation where the rivers were constrained by the morphology and/or structure of the geology, to the depo-area where the river was free to avulse across the alluvial surface. Avulsion can be regarded as the inevitable result of the growth of unstable alluvial topography ,on an unconstrained surface, by deposition of sediment in the channel area.

Other aspects of the systems were that:

3) They varied *in size* from small systems, no more than 2 km in radius (10 km^2), to the Huesca system, more than 50 km in radius (10^{3}km^2). The size reflects the quantity of water and sediment being transferred in each system. This, in turn, must reflect the size of the source area, its rainfall characteristics, its geology and its uplift rate.

4) They contained large volumes of *fine-grained (mud-grade) sediment.* Apart from the gravel accumulations of the proximal areas, these depo-areas must have had very low surface gradients, and the term alluvial-plains fan is suggested.

6.-SPACE AND TIME VARIABLES IN RIVER SYSTEM STUDIES

The object of this final section is to review aspects of the definition of river systems generally .We shall start by considering aspects of the scale of river systems using present-day examples. We shall then use our experience of the Ebro-type systems in Aragon to raise some aspects of the time dependence of features of stratigraphic systems.

Sediment systems can be defined and studied at a variety of scales. At one extreme, there are continent-wide systems, for example the Andean-Amazon system, or the Himalayan-Indo-Gangetic system. At the other extreme of scale are small systems, such as the catchments instrumented and analysed by some geomorphologists, or the metre-scale fans in sand quarries studied by some sedimentologists.

A map of the present-day river pattern of Iberia (fig. 5a) shows most of the larger rivers that are now acting as sediment transfer conduits. The catchments of these rivers are the source areas of the sediment systems that are operating on the land of Iberia today. At the present-time, in contrast with the situation in mid Cenozoic times, the depo-areas of the systems are predominantly restricted to the coast-lines, including the relatively small deltas (eg. the Ebro), and to the offshore areas. In present-day Iberia, the size of the source areas of the systems varies from small ones to intermediate-size ones around the coasts (typically about 10^4 km^2), and to very large ones that drain the interior, for example the Ebro (about 10^5 km^2).

Comparison with the mid Cenozoic situation (fig. 5b) can be conveniently made using a very generalised map of Iberia on the same scale. This map groups together Oligocene to Pliocene sediment outcrops, but serves well to locate several distinct basins, such as the Ebro. As we have already seen in the previous section, the size of the Ebro sediment systems was relatively small in mid Cenozoic times, as well as being radically different in that they were terminal and non-marine, rather than transit to coastal and marine. The early Miocene river systems varied from 10 to 10^{3}Km^2 for the size of their depo-areas, and their source areas were probably of the same order of magnitude. This compares with areas up to 10^{5}km^2 for the present-day very large source areas. Considering the reasons for this increase in size, it seems likely that an important control has been the length of time during which land relief has been evolving since local topography was last strongly modified by local tectonism.

Clearly the time factors, or specifically the rates and durations of episodes of river system activity, are critical in understanding the river system evolution of

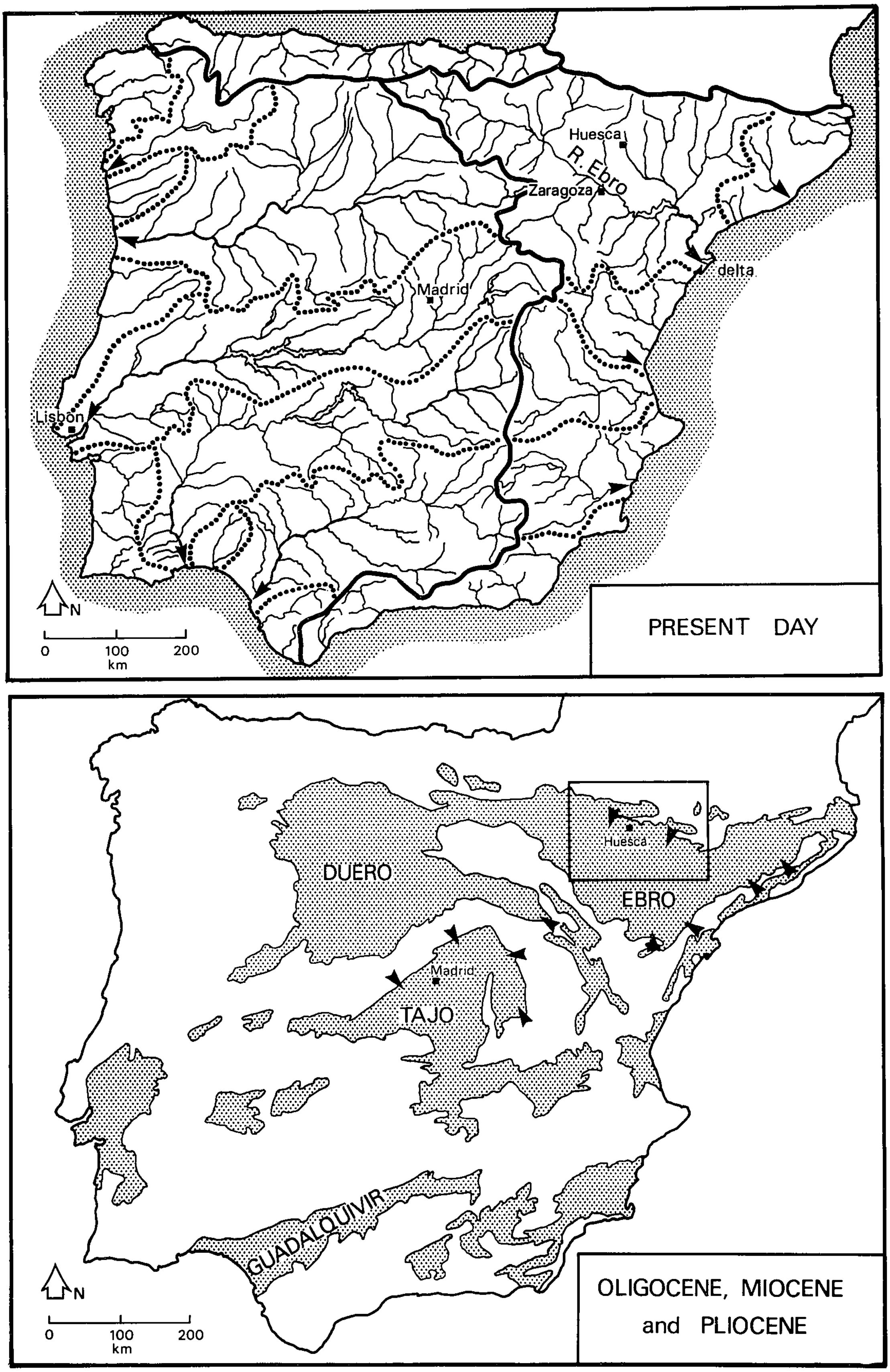


Fig.5.-Maps of the Iberian peninsular showing: a) the main patterns of source area drainage and catchments of the presentday. The depo-areas of these sediment systems are along the coasts and offshore, and b) the distribution of the main outcrop areas of Oligocene to Pliocene sediments with the names of some of the main basins, and some of the sediment transfer directions shown by arrows.

Fig.5.- Mapas de la península ibérica mostrando: a) la distribución de las grandes cuencas fluviales actuales; las áreas de depósito de estos sistemas sedimentarios se localizan en las costas y mares adyacentes, y b) la distribución de los principales afloramientos de sedimentos del Oligoceno al Plioceno, con los nombres de las principales cuencas; se marcan con flechas las direcciones de transferencia de sedimentos.

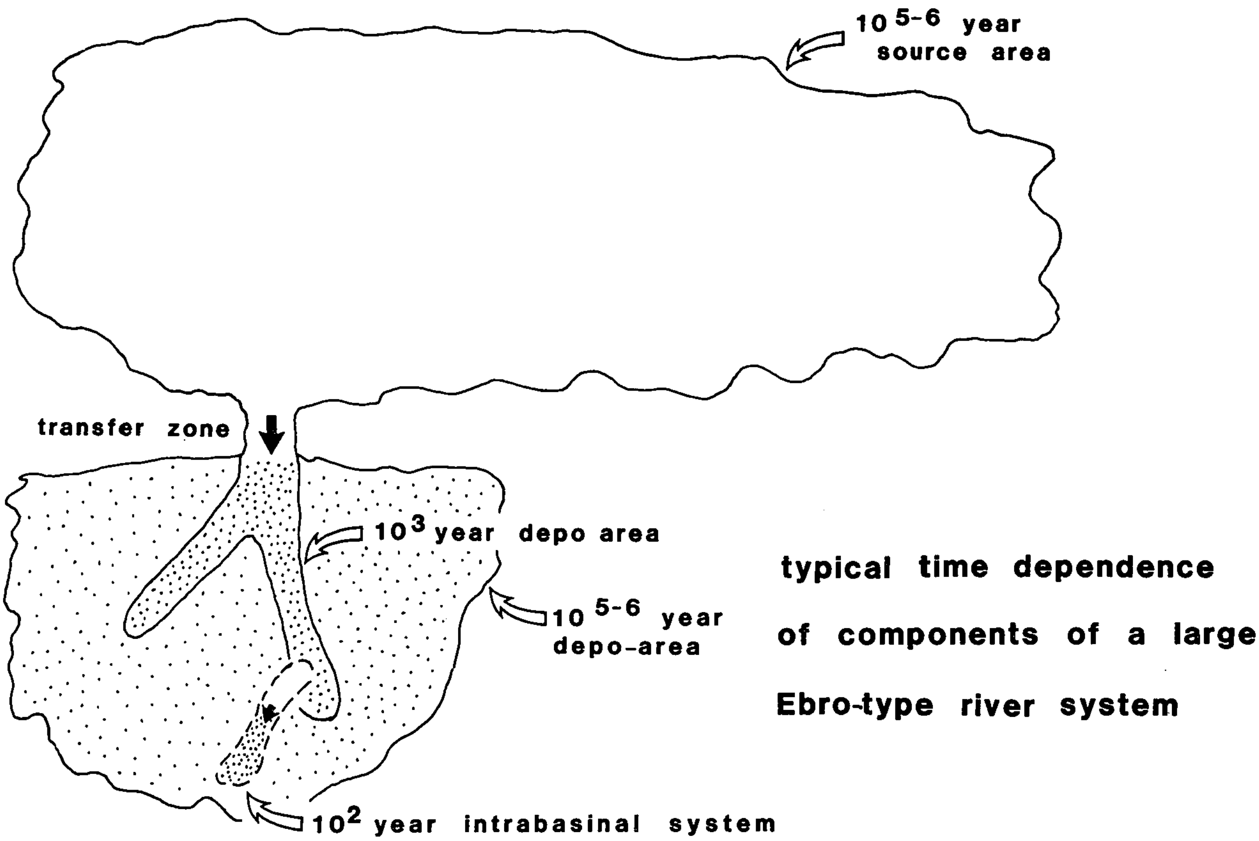


Fig.6.-Sketch illustrating time dependence of extent of the depo-areas of a river system, and the presence of an intrabasinal system within the depo-area of a larger extrabasinal system.

Fig.6.- Esquema en el que se ilustra la relación entre el tiempo y la extensión de las áreas de depósito de un sistema fluvial, así como la presencia de un sistema intracuenca dentro de un sistema extracuenca de mayores dimensiones.

any area. In fig. 5b, we grouped many river system episodes to generalise the $36x10^6$years in which Oligocene to Pliocene sediments accumulated in Iberia. Many different episodes have been generalised to provide this picture, and in Fig. 6, we return to a system similar to one of the large Ebro type systems to illustrate the range of time episodes (from 10^2 to 10^6 years) that can be distinguished in such a system.

My object, in this paper, has been to explore the use of the river system approach, as a means of analysing the morphological and sedimentary evolution of an area. My conclusion is that , if systems are defined and recognised in their hierarchies of scale and time, they can provide a valuable clarity and rigour in our analysis of regional evolution.

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