Temporal and spatial controls on the alluvial architecture of an axial drainage system: late Eocene Escanilla Formation, southern Pyrenean foreland basin, Spain

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ABSTRACT

In young or currently active foreland basins of the world, along-orogen variations in structural deformation and/or depositional environments are common elements of the later phases of basin development. The late Eocene Escanilla Formation of the South–Central Pyrenean foreland basin represents an ancient drainage system in which such variability can be studied in detail using high-resolution magnetostratigraphy combined with a more traditional field-based approach. Downstream changes in the nature of the alluvial system were strongly influenced by the on-going Eocene structural partitioning of the foreland basin as it began to become incorporated into the southward-advancing South Pyrenean thrust system. Lower subsidence rates within these allochthonous 'piggy-back' sub-basins served to increase channel-body interconnectedness of sheet-like alluvial conglomerates, to inhibit the preservation of significant volumes of fine-grained overbank material, and to promote the extensive development of pedogenic calcretes.

During the phase of coastal progradation along the subsiding basin axis, a number of N–S-trending anticlines impeded the westward progradation of the alluvial system, producing a strong diachrony in the age of a Lutetian–Priabonian-aged deltaic system along the orogen. Fold growth across the western oblique ramp of the South–Central Unit thrust system dramatically influenced middle to late Eocene drainage patterns and lithofacies distributions. Within the portions of the drainage system upstream of these active folds, the alluvial deposits were periodically ponded, allowing the deposition of micritic lacustrine limestones. Fluctuations in regional base-level exerted control on the drainage system upstream into the alluvial drainage basin. Base-level rises caused short reversals in the longer-term westward regression of marine environments across the foreland basin, whereas base-level falls produced widespread sheet conglomerate deposition.

INTRODUCTION

The middle to late Eocene sediments of the South Pyrenean Foreland were deposited in an internally deforming system of 'piggy-back' basins. The depositional systems active at this time showed great lateral variability and diachrony along the length of the orogen. Along-strike variations in structural deformation or depositional environments, while being important aspects of the later history of foreland basins, are not addressed or incorporated within most quantitative synthetic models concerning the stratigraphy of such sedimentary systems (Angevine, Heller & Paola 1990; Flemings & Jordan 1989, 1990). The late Eocene Escanilla Formation of the South–Central Pyrenean foreland basin offers a chance to study such variability in great detail. Fortuitous preservation of the important geometric relationships has allowed the description of the thrust deformation through the effects it exerted on the coeval depositional systems within the basin (Garrido-Megías 1973; Puigdefàbregas 1975; Mutti, Séguret & Sgavetti 1988; Burbank *et al.* 1992).

This paper addresses this late phase of Pyrenean foreland history, when the previous flexural basin deposits began to be incorporated into the southward-advancing south Pyrenean thrust wedge as plate convergence continued. We will describe the internal stratigraphy and large-scale architecture of the Escanilla Formation from two areas exposed across the western oblique ramp of the South–Central Pyrenean thrust system, in the Ainsa and Tremp basins. A three-fold subdivision of the Escanilla Formation based upon these observations is constructed for the Ainsa

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Basin, and this is carried to other parts of the drainage network in order to reconstruct the nature of this Eocene river system. Our Escanilla Formation reference stratigraphies will then be contrasted with work by other authors in the downstream equivalents of the alluvial system preserved within the Jaca Basin (Puigdefàbregas 1975; Jolley 1988; McElroy 1990; Hogan 1992). Such regional correlations have been made possible by the use of magnetic polarity stratigraphy, a method that has proven useful for constraining the tectono-stratigraphic development of this region within an absolute temporal framework (Hogan, Burbank, & Puigdefàbregas 1988; King Powers 1989; Burbank *et al.* 1992).

EOCENE STRUCTURAL AND STRATIGRAPHIC FRAMEWORK OF THE SOUTH-CENTRAL PYRENEES

Structural development

The Pyrenees are an E–W-trending mountain system developed at the NE corner of the Iberian Peninsula, separating Spain from the rest of Europe. Formed during a phase of late Cretaceous–Miocene convergence and limited northward underthrusting of the Iberian plate beneath Eurasia (Muñoz 1991), the onset of thrust deformation associated with the Pyrenean collision was strongly diachronous from east to west. In the southern Pyrenees, basins developed during Palaeocene to early Eocene times, ahead of the southerly translating thrust sheets, partly in response to thrust wedge loading, and partly due to subduction-related flexure of the down-going Iberian Plate (Muñoz 1991). Collectively referred to as the South Pyrenean Basin (Puigdefàbregas 1975), this region began to partition or compartmentalize during the early Eocene epoch in response to the incorporation of proximal parts of the foreland into the developing thrust wedge.

The South–Central Unit (SCU) of the southern Pyrenees (Fig. 1) represents a linked system of southward-directed cover-involved thrust sheets and associated piggy-back basins. Thrust motions show a complex pattern of forward- and hindward-imbrication, as well as significant phases of out-of-sequence fault reactivation (Puigdefàbregas, Vergés & Muñoz 1991). Three main thrust sheets are present, the Bóixols, the Montsec, and the Sierras Marginales, and they link along their eastern boundary into the Segre Fault Zone oblique ramp (Fig. 1) (Vergés & Muñoz 1990). Along their western boundary, a more poorly defined, diffuse oblique ramp system is seen, with the development of a number of transport-oblique anticlines (Boltaña and Mediano). This study is concerned mainly with the later development of this western oblique ramp and with the controls that its growth exerted on the middle–late Eocene syntectonic depositional systems. The Mediano and Boltaña oblique ramp folds initiated during early Eocene time, at the onset of thrust motion and piggy-basin formation, and both have long protracted histories (Cámara & Klimowitz 1985;

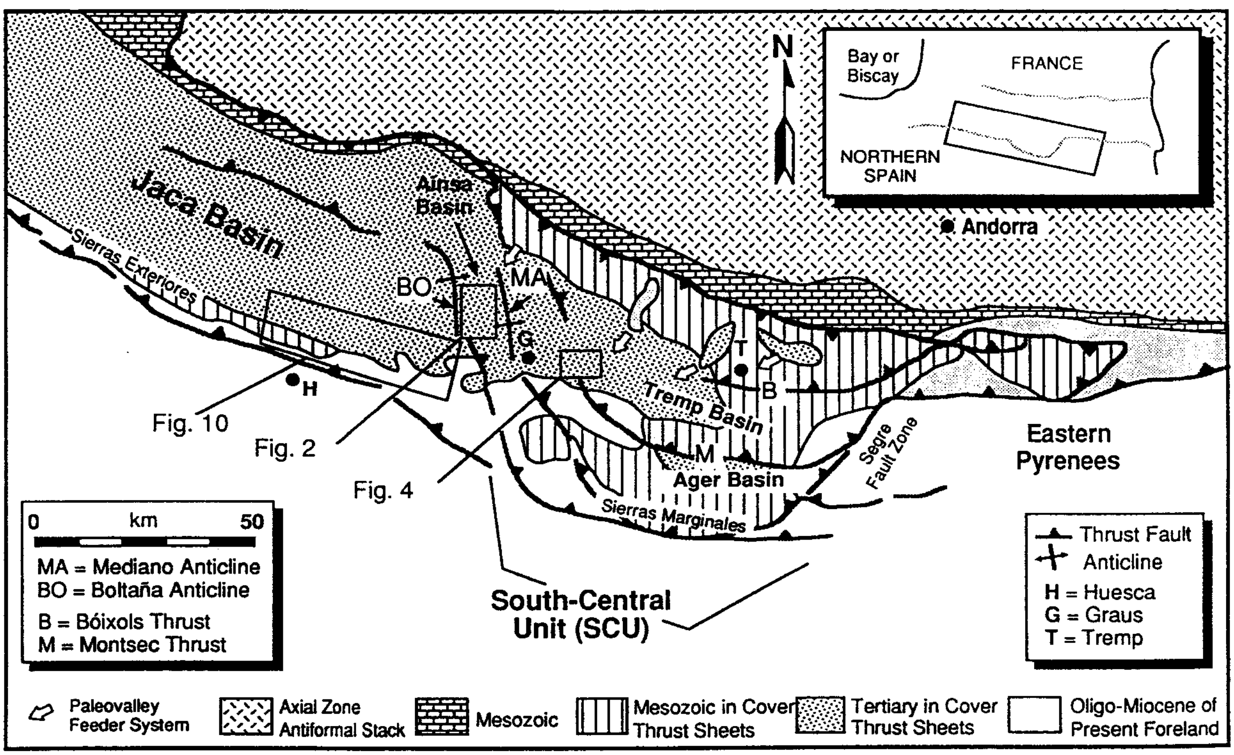


Fig. 1 The South Pyrenean Foreland Basin. As well as showing the general configuration of the South Pyrenean basins, the map also indicates the location of other figures and detailed maps referred to in the text. The small inset shows the approximate position of the study area within the Pyrenean Chain.

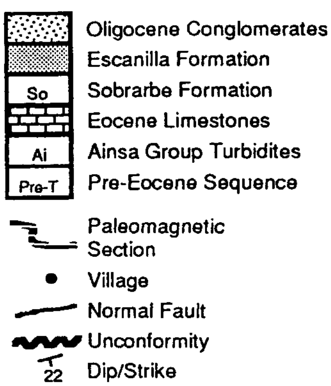
Farrell, Williams & Atkinson 1987; Reynolds 1987; Nijman 1989; McElroy 1990). The main focus of this study, the Ainsa Basin, is located between these two structures (Fig. 2).

Across the Boltaña anticline to the west, the Jaca Basin records a two-phase history. Prior to the growth of the Sierras Exteriores and to the structural definition of the southern margin of the Jaca Basin, a flexural foreland basin existed that experienced largely deep-marine turbidite deposition during most of Eocene time. During and prior to thrust detachment in late Eocene and early Oligocene time and the formation of the piggy-back Jaca Basin (McElroy 1990; Hogan 1992), regional sedimentary systems were being strongly modified by ongoing structural deformation (Puigdefàbregas, 1975). This deformation continued through into Miocene time when discrete thrust motion largely ceased within this region (Crusafont, Riba & Villena 1966; Soler & Puigdefàbregas 1970), and the current basin configuration was established.

Stratigraphy

The stratigraphic framework of the southern Pyrenean basins has become particularly complex and confused, showing little or no standardization across research groups. Here we adopt a modified version of the system used by Cuevas Gozalo (1990) for the Tremp Basin (Fig. 3). For the region west of Mediano Anticline in the Ainsa and Jaca basins, we slightly modify the terminology of Puigdefàbregas (1975), and Nijman & Nio (1975) (Fig. 3).

To the east, within the Tremp Basin, the Lutetian tidally influenced alluvial deposits of the Capella Formation are overlain by the Escanilla Limestone and succeeding Escanilla fluvial deposits of the Campodarbe Group (Puigdefàbregas 1975). The upper boundary of the Capella Formation is marked by an abrupt marine transgression (the Biarritzian transgression of Puigdefàbregas 1975). This caused the local drowning of the Capella alluvial plain and the deposition of the Pano Formation barrier-island complex. South of the Isábena Valley (Fig. 4), this transgression is believed to be represented by a laterally extensive lacustrine limestone horizon at the base of the Escanilla Formation (Cuevas Gozalo & De Boer 1989). This 'Escanilla Limestone' lies between the alluvial sediments of the Capella and Escanilla formations (Figs 3 and 4), reaches a thickness of up to 20 m, and may contain up to 16 separate lacustrine intervals (Nickel 1982). It has been suggested that a significant hiatus exists between the



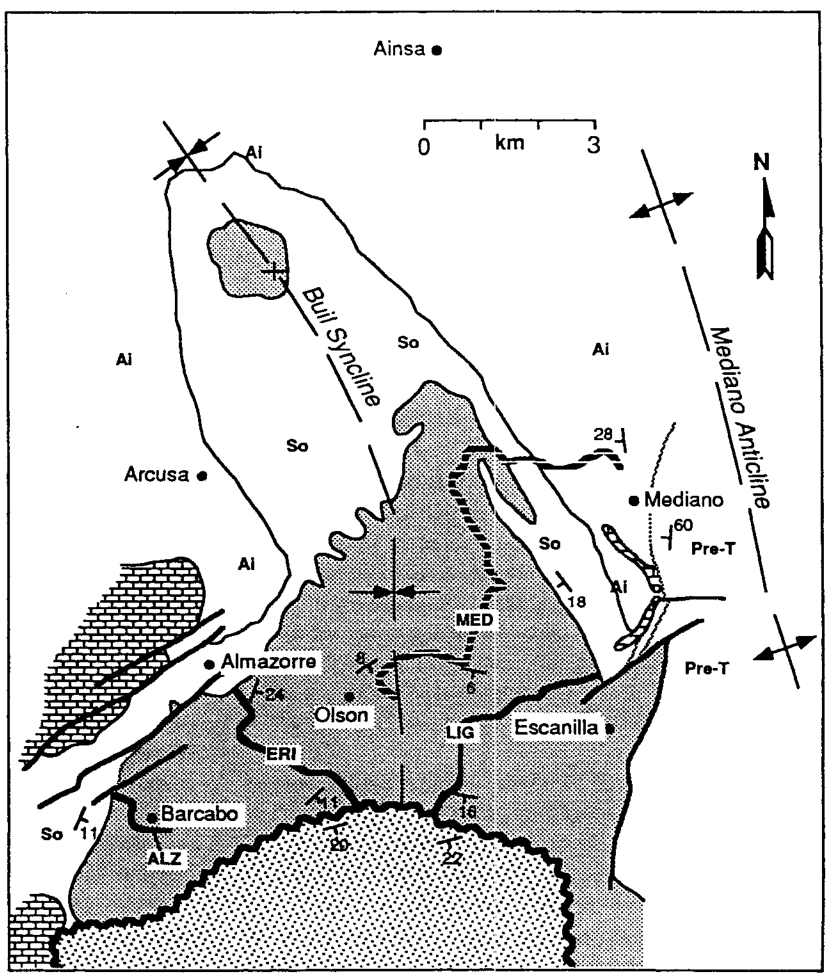


Fig. 2 Simplified geological base-map of the western area, the Ainsa Basin or Buil Syncline, situated along the western oblique ramp of the South–Central Pyrenean thrust system. Important structural features, villages within the study area, and the location of magnetostratigraphic traverses are all shown (ALZ = Almazorre; ERI = Eripol; MED = Mediano; LIG = Liguerre).

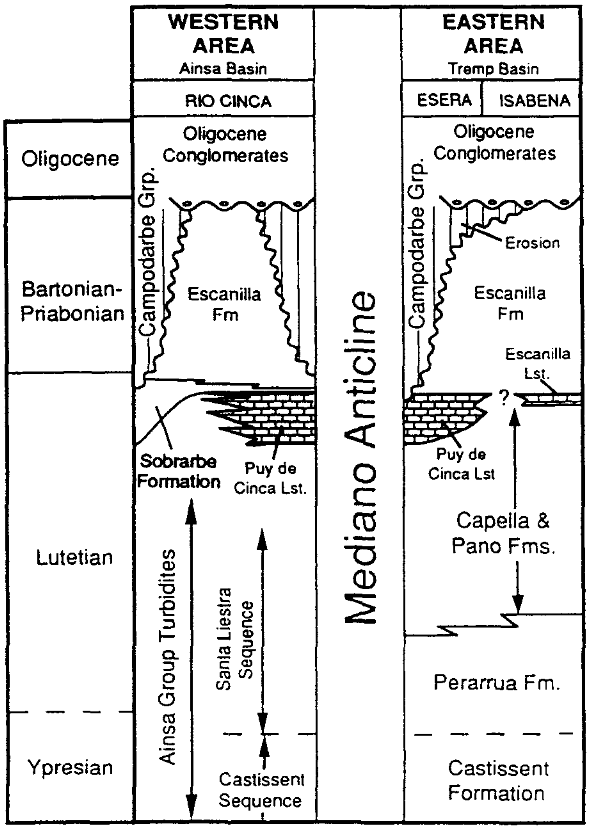


Fig. 3 The lithostratigraphic nomenclature employed during this study. The western area stratigraphic framework is essentially that of Puigdefàbregas (1975), and the scheme for the eastern area is modified after Cuevas Gozalo (1990).

Escanilla Limestone and the overlying fluvial deposits (Cuevas Gozalo 1990). However, angular relationships are not evident and discrete omission or erosion surfaces are absent. Lignites found within the basal limestones of the Escanilla Formation possess a rich vertebrate fauna of Lutetian–early Bartonian age (Crusafont-Pairo 1958). The succeeding Escanilla Formation fluvial deposits were first described by Garrido-Megías (1968), and are interpreted to represent the record of low-sinuosity, braided rivers flowing from east to west along the foreland basin axis. Correlation of these middle to late Eocene units across the Tremp Basin is hampered by incision and erosion at the base of the overlying Oligocene conglomerates. The development of this basal palaeovalley sequence immediately east of the Mediano fold caused the removal of the late Eocene strata, leaving the conglomerates sitting directly upon middle Eocene sediments of the Capella and Puy de Cinca formations.

Correlation across the Mediano anticline is difficult due to lateral facies changes and incomplete exposure. On the fold axis, the Escanilla Formation thins and lies on top of deltaic deposits of the Sobrarbe Formation, and unconformably upon shallow marine platform carbonates of the Puy de Cinca Formation. Within the Ainsa Basin, the Sobrarbe deltaic facies thicken and build a northward-prograding wedge of siliciclastic and carbonate sediments (Figs 2 and 3). In this area, the upward transition into the Escanilla fluvial sequence, although conformable and gradual, is interrupted by a rapid and short-lived marine transgression. The greatest thickness (> 1 km) of Escanilla Formation preserved in the study area is developed within this syncline (Fig. 5A). Due to the presence of post-folding erosion and removal of section prior to the deposition of the succeeding Oligocene conglomerate sequence, the higher parts of the Escanilla Formation are removed along the flanks of the synclinal basin, and wider regional correlation at this stratigraphic level is not possible.

METHODS

In order to provide an absolute temporal framework, five magnetostratigraphic sections were constructed across the SCU western oblique ramp system in regions of good and continuous exposure. Lithological and sedimentological data were collected at the decimetre scale. The presence of mature calcic paleosols, as well as the nature of fine-grained palaeosol profiles within the alluvial sequences were noted. The terms 'immature' or 'mature' were assigned according to criteria given by Bown & Kraus (1987). Palaeocurrent directions were collected from both uni- and bi-directional flow indicators, such as planar cross-beds, trough axes, gutter structures and large clast imbrications. Clast populations were systematically recorded at a number of locations throughout the main exposures of the Escanilla system, and the first appearances of any particularly distinctive clast lithologies were noted.

Mapping was used to correlate sedimentary units spatially, and also relate these units to the important contemporaneous structures. Lateral facies analysis was performed using both land and aerial photography. Lithofacies associations were distinguished, and the three-dimensional spatial arrangement and relative proportions of the main facies types were described.

Oriented block samples were collected for the palaeomagnetic analysis, and the sampled surface and local bedding orientations were recorded, in order to remove any post-depositional tilting or folding. At least four specimens were cut and analysed for a given sample location. Prior to wholesale magnetic analysis, a pilot study employing both thermal and alternating-field (AF) demagnetization techniques was completed. These data suggested that the continental deposits typically yield their characteristic natural remanent magnetic directions between 250°C and 400°C, and the marine lithologies between 200 and 400 Oersteds (after the low temperature removal of a viscous overprint). Bulk sample measurement was completed at three demagnetization levels within these ranges, and a characteristic palaeomagnetic field direction for each specimen was noted. Each site magnetization direction was calculated using the statistical methods of Fisher (1953). The statistical quality of each site was assessed and classified according to the scheme used by Burbank *et al.* (1992).

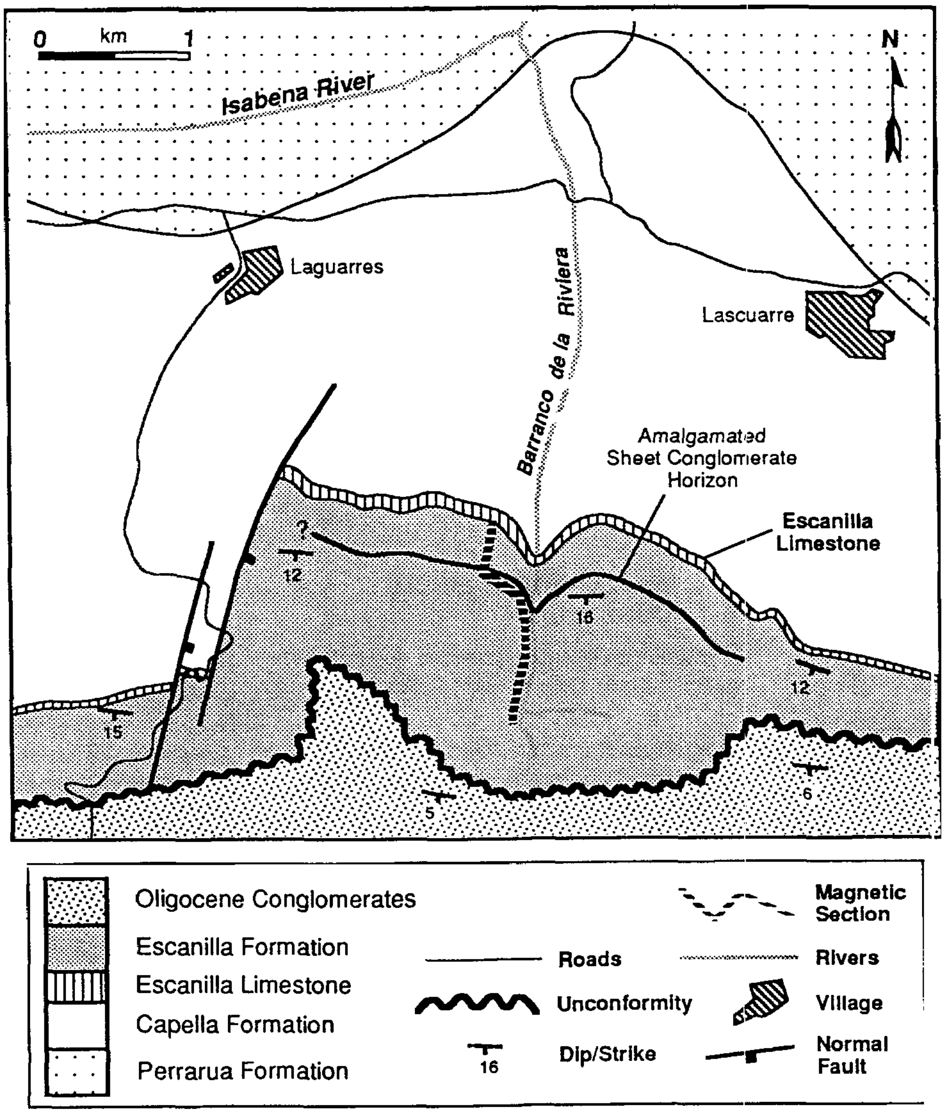


Fig. 4 Geological base-map of the eastern study area within the Tremp 'piggy-back' Basin. The location of the Lascuarre magnetostratigraphic traverse is shown, as is the lacustrine interval represented by the Escanilla Limestone.

Average site magnetic vectors from the Class I and Class II sites were used to calculate virtual geomagnetic pole (VGP) palaeolatitudes, and these were used to classify each site as either normal or reversed polarity. Vector errors were used to calculate α_{95} error envelopes for each VGP palaeolatitude, giving further assessment of the site data quality. Stable magnetozones were defined by two or more adjacent data points of similar polarity, but one point reversals were noted. The erected reversal stratigraphies were correlated with the Magnetic Polarity Time Scale (MPTS) of Harland *et al.* (1990), with the aid of any independent biostratigraphic and magnetostratigraphic age control for the stratigraphic sequence.

Applying the time constraints given by the magnetic chronologies, sediment accumulation rates were calculated across the study area. The data represent undecompacted rates averaged over the interval of a well-defined magnetic polarity chron, because decompaction would only significantly affect the absolute magnitudes of our accumulation data without substantially changing the relative orders of each value.

STRATIGRAPHIC SUBDIVISION OF THE ESCANILLA FORMATION

Ainsa Basin

On the basis of systematic changes in alluvial architecture throughout the 1100 m of Escanilla Formation seen in the Ainsa Basin, we divided the sequence into three distinct units, hereby referred to informally as the 'lower', 'middle', and 'upper' members (Fig. 5).

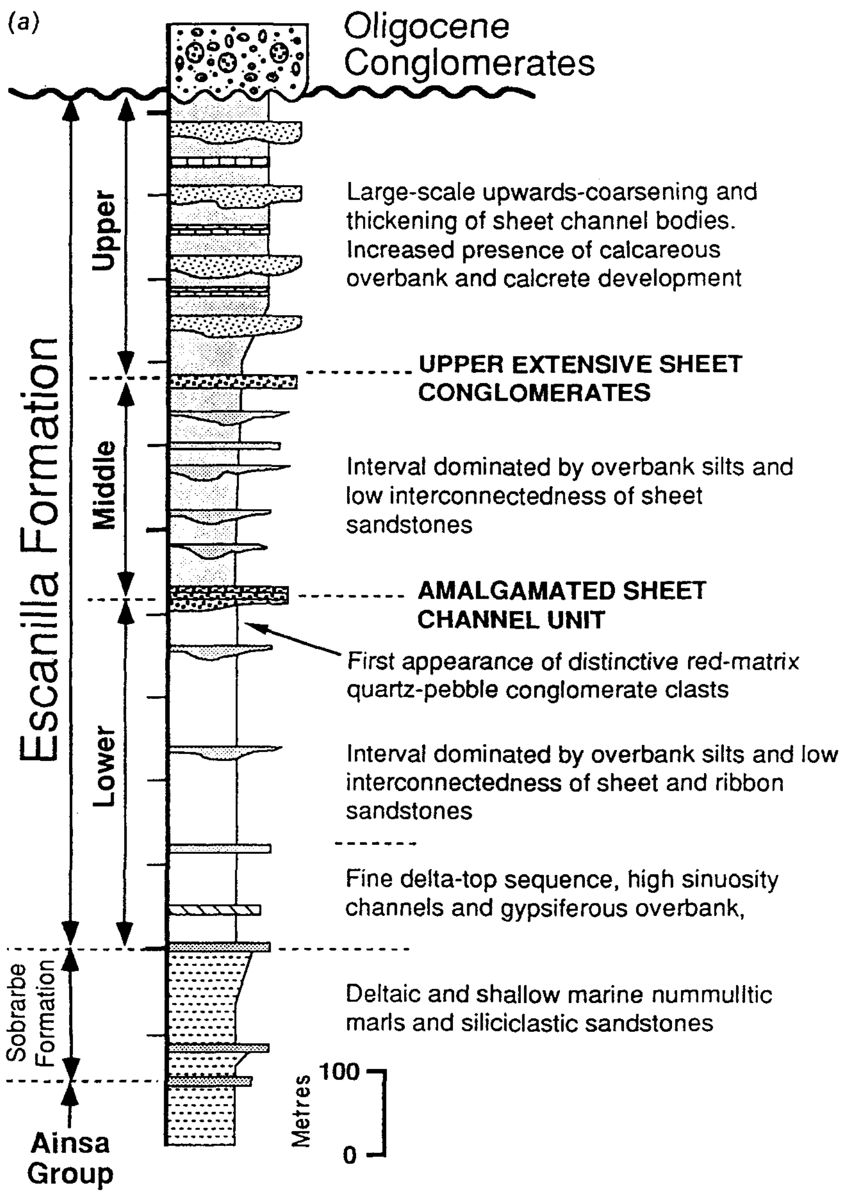


Fig. 5 (a) Stratigraphic subdivision and nature of the lower Campodarbe Group sediments exposed within the Ainsa Basin. The summary magnetic polarity stratigraphy (MPS) constructed within the syncline is shown. Black represents times of normal magnetic field orientation, and white represents reversed field directions. The MPS is correlated with the magnetic polarity time scale (MPTS) of Harland *et al.* (1990) in Fig. 6. (b) Photograph showing the vertical sequence through the lower and middle Escanilla Formation in the position of the Eripol (ERI) traverse. Sandstone and conglomerate sheets can be seen intercalated with comparable volumes of fine grained overbank material. The skyline is made up of the overlying Oligocene conglomerates.

Lower Member (Latest Lutetian–Early Bartonian)

Description. The lower member varies in thickness across the Ainsa Basin (Figs 5A and 6), reaching a maximum thickness of about 400 m in the basin centre before thinning westwards to about 200 m thickness along the eastern limb of the Boltaña anticline. The units lower boundary is defined at the first appearance of reddened mudstones and siltstones, and the subsequent lack of marine fauna. The upper boundary is a thick, laterally extensive horizon of amalgamated sheet sandstone and conglomerate channels.

Basal Escanilla channel sandstones show evidence for channel-scale lateral accretion and intercalated fine-grained sedimentary rocks are commonly gypsiferous. Approximately 25–30 m above the base of the Escanilla Formation is a laterally extensive, planar-based, 3–4 m-thick sandstone horizon. Exposed within the synclinal basin axis, and immediately underlain by gray marls with bivalves, this sandstone shows bi-modal, small-scale ripple and trough cross-stratification and is capped by a horizon rich in shallow marine nummulitic foraminifera.

Above this sandstone, fluvial sediments return and gypsiferous overbank deposits are common within the lower 150 m of this 300 m-thick package. This lower member typically shows a high proportion of massive or crudely bedded reddened siltstones and mudstones relative to the channelized sandstone and conglomerate bodies (>40% of the total volume). Filled by coarse–pebbly sandstones and subordinate volumes of conglomerate, the channels most commonly are of sheet geometry (width:depth ratio of >15:1; Friend, Slater & Williams 1979), although sandstone ribbons (width:depth ratio of <15:1) are also present. The channels exhibit low degrees of vertical interconnectedness or amalgamation, and

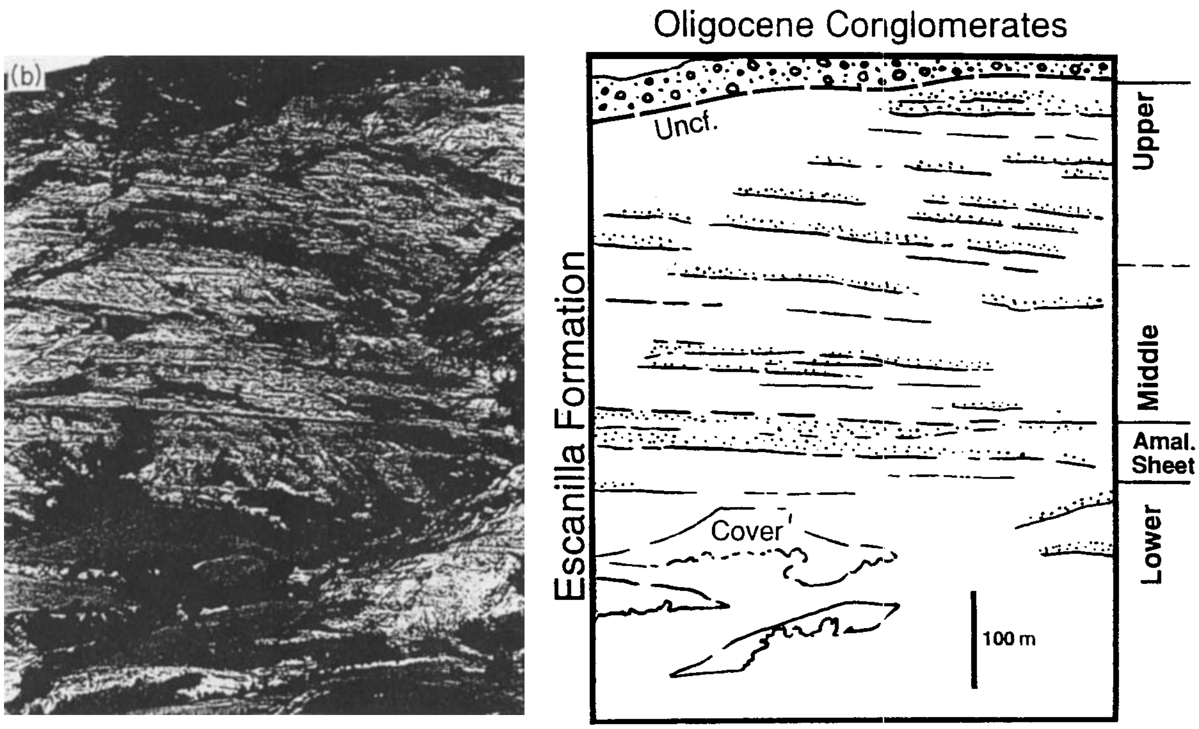


Fig. 5. *continued.*

interfinger at their margins with the enclosing mudstone and siltstone horizons (for a more detailed discussion of the facies architecture within the lower Escanilla, see Bentham, Talling & Burbank 1991, and Bentham, Talling & Burbank 1993). Channel bases are generally strongly erosive, and the succeeding aggradational channel fills occasionally show sandstone or conglomerate lateral accretion surfaces in their lower parts. Subsequent channel deposits are most typically trough and planar cross-bedded coarse sandstones and conglomerates that preserve a general fining-upward trend. Intervening reddened mudstones and siltstones are strongly burrowed by vertical 2–3 cm diameter, tube-like structures, and discoloration ranging from purple to orange or green is often associated with them. Calcic paleosol development was not obvious. These structures are also found on the upper surfaces of channel-fill sequences, and are preserved as siltstone or mudstone-filled tubes within coarse–medium grained sandstones.

The top of this unit is defined immediately below a very prominent horizon some 30–40 m thick, made of both laterally and vertically amalgamated coarse sandstone and conglomeratic sheet channel-bodies. This unit can be followed laterally from east to west across the entire Ainsa Basin (Figs 6 and 7). Fine-grained material is much less voluminous within this interval, and the degree of channel body interconnectedness is much higher than in the units either above or below. Approximately 20–30 m below this laterally continuous horizon, clast composition studies show the first appearance of a rather distinctive clast lithology (Fig. 5A). These red matrix, quartz-pebble conglomerate clasts are seen in varying quantities throughout the remaining Escanilla sequence.

Palaeocurrents within this lower unit vary considerably, but systematically through time. Initial channels show flow directed off the top of the Sobrarbe Delta towards the NW–NNW (Fig. 7). These directions are superseded by palaeocurrents that define a broad sweeping arc, flowing westwards from the Mediano anticline then progressively rotating SW and SSW as one traverses the Ainsa Basin (Fig. 7). Palaeocurrent data from channels preserved in the isolated Escanilla exposures to the north, in the region of Santa Maria del Buil indicate flow to the SSE. The lowest channels along the western flank of the syncline show flow dominantly directed towards the SSW approaching parallelism with the axis of the Boltaña anticline.

Interpretation. Based on our magnetostratigraphic correlations (Bentham 1992), this interval (Fig. 6) ranges in age from ~42.7 Ma to 41.4 Ma (latest Lutetian–early Bartonian), and is typified by low-sinuosity channels developed on a low-gradient coastal alluvial plain. This distal alluvial environment was invaded by a brief marine transgression at ~42.5 ± 0.2 Ma, which led to deposition of the shoreface sandstone sequence with an associated shallow marine fauna. The internal geometries within the sandstone and conglomerate channels are strongly suggestive of braided stream deposition (Bentham *et al.* 1991); however, the large quantities of enclosing contemporaneous overbank material is considered rather atypical for such a low-sinuosity fluvial system. Rates of sediment accumulation

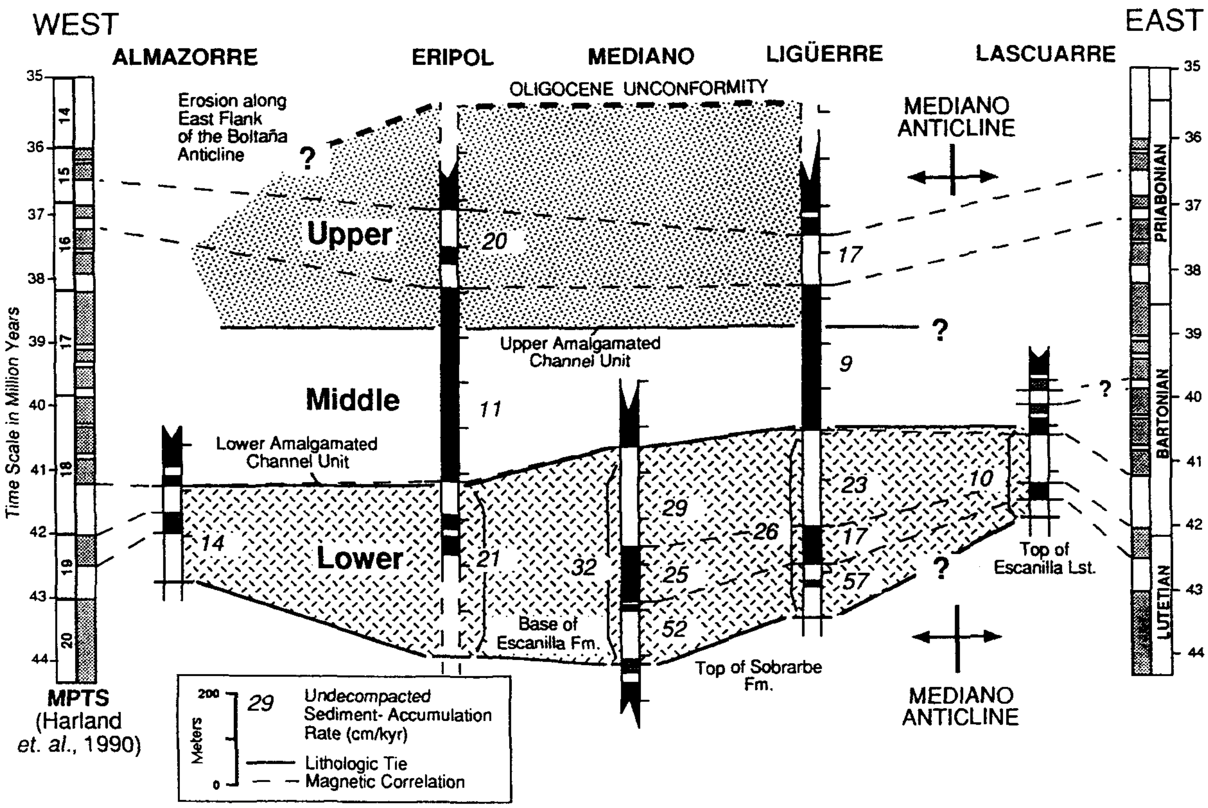


Fig. 6 Magnetostratigraphic correlation of the Escanilla Formation across the study area. Lithological correlations confirmed in the field are shown as solid lines linking the magnetostratigraphic traverses. Correlations based on the comparison of the MPSS with each other and with the MPTS, are shown as dashed lines. Average undecompacted sedimentation rates within each member of the Escanilla system are shown, and are calculated using the ages of chron boundaries taken from Harland *et al.* (1990).

(undecompacted) during this interval vary spatially across the Ainsa Basin and lie in the range ~ 14–57 cm kyr^{-1}. Such figures are in agreement with long-term rates described from rapidly aggrading modern systems (Bridge & Leeder 1978). The high proportions of the enclosing fine-grained fluvial overbank sediments, combined with the lack of mature calcic paleosol development within the lower member, suggests that rates of sediment accumulation remained high during fluvial deposition.

Initial palaeocurrents within the basal Escanilla Formation, prior to the brief marine transgression, are in agreement with the progradational advance of the Sobrarbe delta along the axis of the actively subsiding synclinal basin. The presence of southerly directed palaeocurrents within the northern Ainsa Basin during Lower Escanilla time suggests initiation of a northern fluvial source area, which interacted with rivers flowing westwards across the Mediano anticline out of the Tremp Basin. This strong reversal in the Lower Escanilla drainage pattern, from the NW to SSW during latest Lutetian time ($\sim$42 Ma) is interpreted by Farrell *et al.* (1987) to result from out-of-sequence reactivation of the Peña Montañesa thrust system at the northern margin of the Ainsa Basin. However, this interpretation is not unique as the folding and tilting of the Ainsa channels could alternatively have occurred by tilting of the western limb of the Mediano anticline.

Middle Member (Bartonian)

Description. Above the laterally continuous level of sheet sand and conglomerate channels, there is a return to fluvial facies similar to those immediately below. Coarse conglomerate-filled sheet channels and rarer ribbon sandstone channels are seen wholly enclosed within fine-grained reddened siltstones (Fig. 5A). This middle member appears to thicken slightly to the west reaching a maximum thickness of $\sim$300 m (Fig. 6). The member's upper limit is defined on the basis of upward-coarsening and thickening trends at the next laterally continuous level of conglomerates that may be traced across the core of the syncline. This member shows a general coarsening-up sequence, and nodular calcic paleosol horizons were occasionally observed. Intervening fine-grained sediments remain strongly colour mottled, and much finer-grained than the adjacent channellized material. Thin (<11 cm-thick) micritic limestones are occasionally preserved within the fine-grained sediments, but these are rare and are not laterally extensive ($<$ few 100s of metres wide).

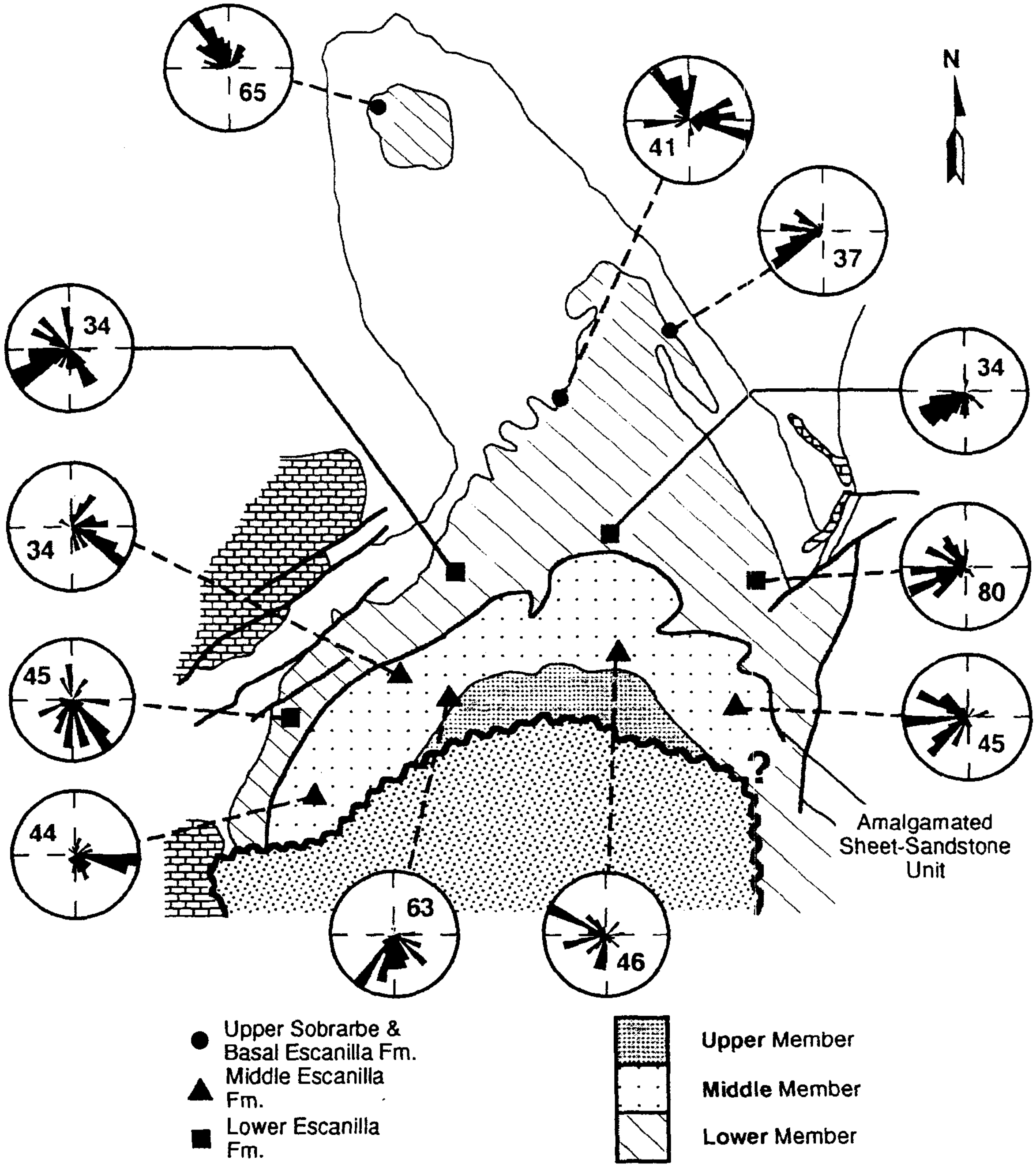


Fig. 7 Palaeocurrent data from the upper Sobrarbe and lower two members of the Escanilla Formation. Figures within the palaeocurrent roses show the total number of measurements taken at a particular location. Additionally, the base-map shows the spatial distribution of the three members of the Escanilla Formation, and the amalgamated channel unit that marks the boundary between the lower and middle members.

Flow within the middle member defines a sweeping arc crossing the Ainsa Basin, with the change from west-directed to south-directed flow being more dramatic than before. However, on the eastern flank of the Boltaña anticline sandstone channels suggest flow to the E and SE, into the centre of the Ainsa Basin.

Interpretation. The middle member ranges in age from 41.4 Ma to ~39.0 Ma (Bartonian) and records a time of slowed average deposition (Fig. 6). Rates of sediment accumulation are ~10 cm kyr^{-1}, less rapid than within the underlying lower member. Facies architecture is similar to the lower member, although a general coarsening upward trend was observed. While the presence of calcic paleosols is consistent with the assertion of slowed rates of sediment accumulation, the overall dominance of fine-grained overbank material is not.

In general, palaeocurrent data within the middle member is similar to information from the lower member. Flow seems to be strongly focused within the subsiding basin axis, with Escanilla rivers being diverted to the south. Additionally, there is an indication that the Boltaña anticline was active at this time as some channels preserved flow away from the rising, or already emergent structure. No direct evidence of the northerly derived fluvial system is preserved within the Ainsa Basin, but it was probably still active at this time.

Upper Member (largely Priabonian)

Description. The upper member is only extensively preserved within the centre of the Ainsa Basin. It is characterized by thick (> 5 m), coarse, wide (100s of metres) sheet sandstone and conglomerate channels interbedded with subordinate thicknesses of calcareous, finer-grained red and tan siltstones (Fig. 5A). The larger scale architecture shows increased channel body interconnectedness both vertically and laterally. Internally the conglomerate channels preserve poorly defined sedimentary structures, such as planar and trough cross-bedding, and often show laterally extensive scour surfaces. Within the reddened siltstones nodular and bedded calcic paleosols are more commonly developed.

The total thickness of this unit is unknown due to erosional truncation below the basal Oligocene unconformity (Fig. 6). This unit coarsens upwards, with maximum clast diameters increasing from about 20 cm to 40 cm. Uppermost clast compositions preserved within the Escanilla Formation are very similar to the overlying Oligocene sequence. Within the centre of the Ainsa Basin, the unconformity is marked by a slight angular discordance in southerly dip between the upper Escanilla sheets and the basal Oligocene sediments. However, along the western flank of the syncline, an extremely strong angular unconformity exists with the lower Escanilla, Sobrarbe, and Guara Limestone formations (Fig. 2).

The few palaeocurrents that were collected from the upper member are consistent with the patterns described for the middle member (Fig. 7).

Interpretation. Based upon the preferred MPS correlation, upper Escanilla time also experienced slowed sediment accumulation, with calculated rates of sediment accumulation in the range of ~15–20 cm kyr^{-1}. Sedimentological evidence, such as mature paleosol development, preferential channel amalgamation, and increased proportions of coarse gravels may all reflect this continued slowing trend (Bown & Kraus 1987).

The strong angular unconformity between the early Oligocene and middle–late Eocene units along the western side of the Ainsa Basin can be related both to continued growth of the Boltaña anticline and to uplift and emergence of the eastern Sierras Exteriores during Priabonian and early Oligocene times. Conglomerate clast populations within the units straddling this unconformity suggest that similar source areas and clast provenance existed during this phase of tectonic development.

Western Tremp Basin

Description. South of the Isábena Valley the Escanilla Formation reaches a thickness of only ~500–550 m (Fig. 8). Overlying the basal Escanilla limestone, the terrestrial alluvial deposits of the Escanilla Formation show a similar upwards-coarsening and -thickening, regressive megasequence as observed in the Ainsa Basin. Here, however, the presence of micritic limestone horizons (generally < 1.5 m thick) throughout the section is striking. The limestones occur with greater frequency in association with both the coarse sheet conglomerate channels and the intervening siltstones. Approximately 170 m above the base of the Escanilla Formation is a very prominent, laterally amalgamated sheet of wide conglomeratic channel bodies. This unit may be traced easily across the Escanilla exposure front, south of Lascuarre, until it dives westwards below the overlying Oligocene unconformity south of the village of Laguarres. As within the Ainsa Basin, 20 m or so below this laterally extensive interval, one sees the first appearance of reworked, red matrix quartz–pebble conglomerates as clasts within the sheet conglomerate channels (Fig. 8). Conglomerate channels in this area are comparable to, although somewhat coarser and thicker than those within the Ainsa Basin. The sequence in the Tremp Basin also shows that the channel-fill coarsens upwards more rapidly, and wholly sand-filled channels are extremely rare. Ribbon sandstones are less evident than in the west, and wider sheets dominate the hillside exposures. Intervening fine-grained sediments, most commonly reddened siltstones, are less voluminous and much more calcareous, and nodular calcic paleosol horizons are more common than within the Ainsa Basin.

Interpretation. Correlation of the Escanilla Limestone with other units, even in the light of the magnetostratigraphic data from Lascuarre, remains inconclusive. Nijman & Nio (1975) suggested that the lacustrine limestone sequence, with its associated coals, would correlate to the west with a marine transgression during Puy de Cinca limestone sedimentation (Middle Lutetian, ~45–44 Ma). This transgression would have induced a rise in the regional water table and formed limestones and coals within the alluvial regions of the Tremp Basin. Ponded facies within the lower parts of the Cis and Gurp palaeovalley feeder systems to the north and north-east of the Lascuarre region are believed to have been deposited at this time also (S. Vincent, pers. comm.). A second interpretation is that the ponding and stagnation of the fluvial system occurred as a result of continued development and uplift of the Mediano fold as data from the Ainsa basin suggests that this structure was still growing during middle–late Lutetian time (De Federico 1981; Bentham 1992).

Based on the preferred magnetostratigraphic correlation (Fig. 6), fluvial facies comparisons, and the first appearance of the quartz–pebble conglomerate as clasts within Escanilla channels, the amalgamated unit exposed within the Tremp Basin is interpreted as the same laterally consistent horizon

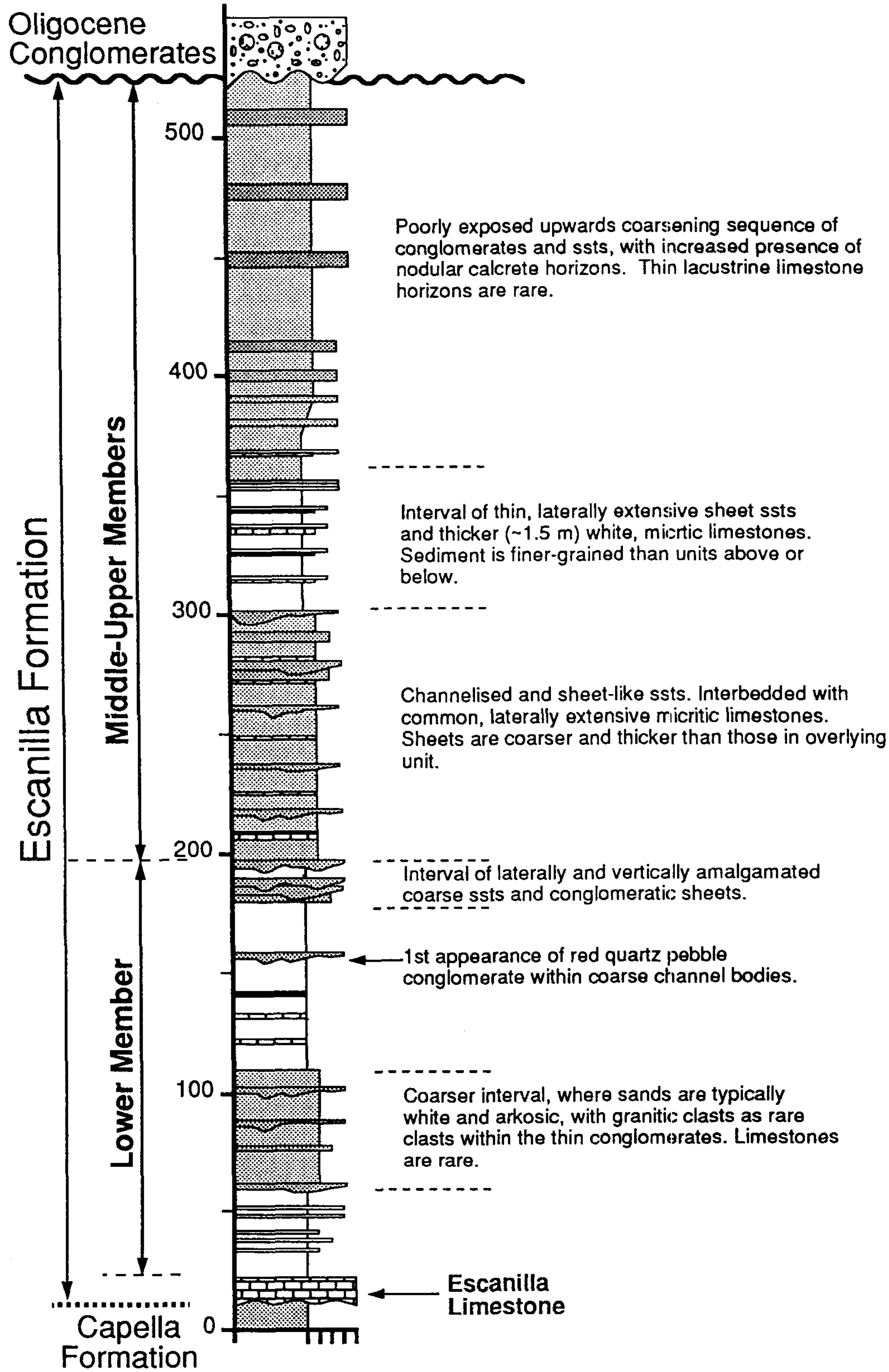


Fig. 8 Stratigraphic subdivision and nature of the lower Campodarbe Group sediments exposed south of the Isábena Valley. Note the gross coarsening-up trend, and the regular occurrence of thick lacustrine limestone units throughout the vertical sequence.

that may be traced across the Ainsa Basin, and as such represents a regionally significant depositional surface. The lower 170 m of the Escanilla section of this region would, therefore, be the eastern expression of the 'lower' member described between the Mediano and Boltaña anticlines. The remaining Escanilla strata would then represent the 'middle' and 'upper' members, but no attempt is made to differentiate the two, because of the uncertainty concerning the amount of section that has been removed in this area by erosion. A general summary of the re-interpreted stratigraphic and geometric relationships preserved across the study area is shown in Fig. 9.

CORRELATION WITH THE JACA BASIN

Combining the mapping and facies descriptions of earlier studies (Puigdefàbregas 1975; Jolley 1988; McElroy 1990) with the chronological control of Hogan (1992), it is possible to correlate and compare units down the alluvial system, across the Boltaña anticline, into the eastern Jaca Basin (Fig. 1). Puigdefàbregas (1975) described a rapid drowning of the Guara Limestone platform carbonates, and subsequent deposition of the Arguis Marls unconformably above a series of small, N–S-trending anticlines (Fig. 10). Hogan (1992) dated this event as occurring immediately prior to normal magnetic polarity chron 19 ($\sim$42.6 Ma after Harland *et al.* 1990), and correlated it with a short-term sea-level rise close to the Lutetian–Bartonian boundary shown on the Haq *et al.* (1987) sea-level curve. We suggest that the marine transgression observed at the base of the Escanilla Formation within the Ainsa Basin could represent the coastal expression of this eustatic event (dated at 42.7 ± 0.1 Ma in the Ainsa Basin).

West of the Boltaña anticline, the continental deposits of the Campodarbe Group sit conformably upon the shallow marine and deltaic facies of the Belsue–Atares Formation. In contrast, however, along the western flank of the Boltaña fold, the basal Campodarbe sediments lie in strong angular unconformity against early Eocene sediments, independently documenting the earlier phase of fold growth during early–middle Lutetian times (De Federico 1981) (Fig. 10).

Close to Nocito, west of the Balces and Alcanadre anticlines, interfingering of deltaic and continental deposits reflects small, short-term variations in relative sea-level that appears analogous to the significant marine transgression identified within the Ainsa Basin at $\sim$42.6 Ma. The facies boundary separating the Belsue and lower Campodarbe sediments clearly migrates about 5 km eastwards, reversing the longer-term, westerly directed regressive trend. Near Bara (Fig. 10), the Belsue–Campodarbe boundary appears to have been stabilized for a significant time, possibly in response to the growth of the N–S-trending Alcanadre anticline (Fig. 10). Such fold growth may serve to localize facies belts for long periods of time (De Boer, Pragt & Oost 1991), preventing the seaward migration or retrogression of depositional environments. As a result, the transition from deltaic to continental sedimentation is strongly diachronous. Hogan (1992) constrains the age of the uppermost Belsue deltaic strata in the region of Arguis (Fig. 10) to be 5 Myr younger than

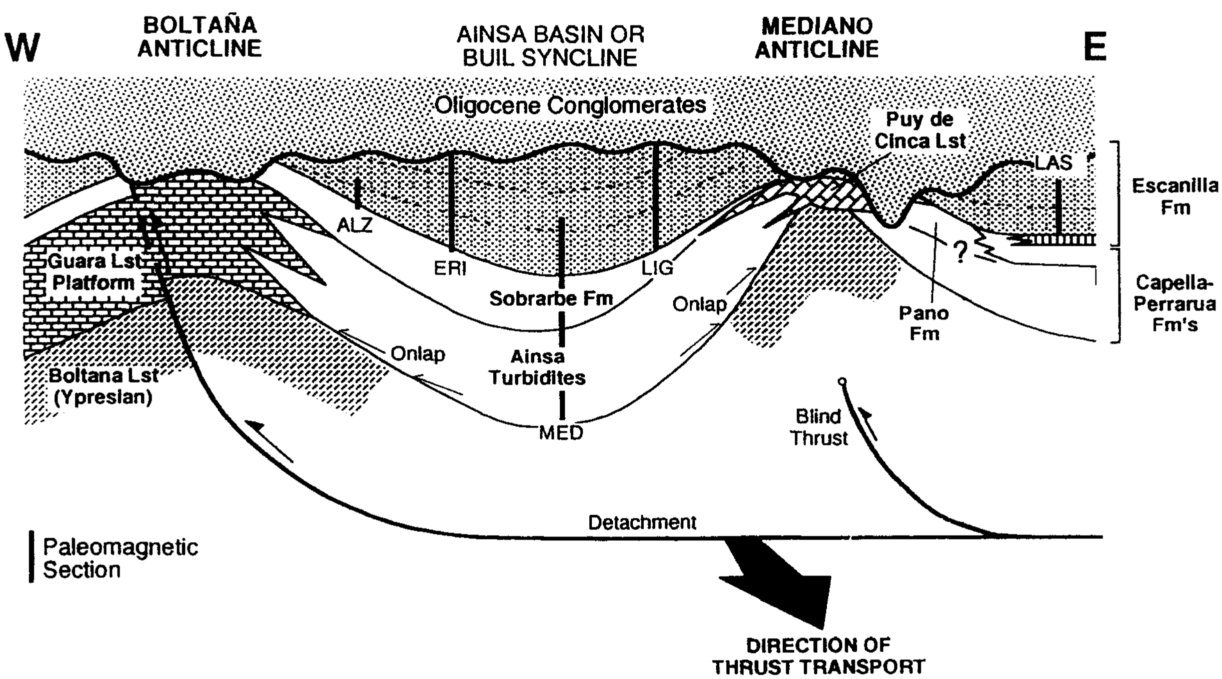


Fig. 9 Regional W–E cross-sectional summary of the inferred stratigraphic relationships discussed within this study. The spatial relationships of the magnetostratigraphic sections are shown (LAS refers to the Lascuarre section shown on Fig. 3). The simplified structural configuration is also presented.

within the Ainsa Basin. The delta, therefore, can be shown to change from Lutetian age in the region flanking the Mediano anticline, to wholly Priabonian age in the central Jaca Basin, across a horizontal distance of less than 100 km. The Eocene shoreline moved at an average progradation rate of about 1000 cm kyr^{-1}, and although this is strongly dependent on factors including sea-level variation and sediment supply, the most important control seems to have been the continued growth of a number of N–S-trending folds (Almela & Ríos 1951; Puigdefàbregas 1975; McElroy 1990), blocking the westward regression of marine environments. The spatial distribution of the syndepositional folds probably resulted in a rather episodic, stepwise migration of the shoreline, as the shoreline would abut against a growing structure until sediment supply outstripped local subsidence (Puigdefàbregas 1975). The coastline would then prograde rapidly westwards until it met the next structural barrier (Fig. 11).

Because of this diachrony, correlation of time-equivalent packages of sediment downstream from the Escanilla Formation within the Ainsa Basin into the deltaic system and the succeeding lower Campodarbe Group is not simple. In the region of the Sierras Exteriores and the Jaca Basin (Fig. 10), the Campodarbe Group is commonly subdivided using a tripartite system into lower, middle, and upper members (Puigdefàbregas 1975; Jolley 1988). Higher parts of the Escanilla are only time equivalent to the lower Campodarbe member within the Jaca Basin (This study; Hogan 1992). The lower and middle Escanilla deposits would correlate with times of marine Arguis Marl deposition and Belsue–Atares delta progradation. Hogan (1992) suggests that average undecompacted sediment accumulation rates near Arguis were of the order of ~ 35 cm kyr^{-1} within the basal 500 m of the Campodarbe. This would then correlate with the upper Escanilla Formation within the Ainsa Basin. The alluvial architecture in the Jaca Basin was described in detail by Jolley (1988). Jolley's Arguis sequence consists of mainly ribbon channels with low degrees of interconnectedness, preserved in association with high proportions of overbank fines showing immature paleosol development. Above this, Jolley (1988) describes a shift to more laterally extensive thick conglomeratic sheets that are very similar to the uppermost sheets further to the east. Although developed later in time than

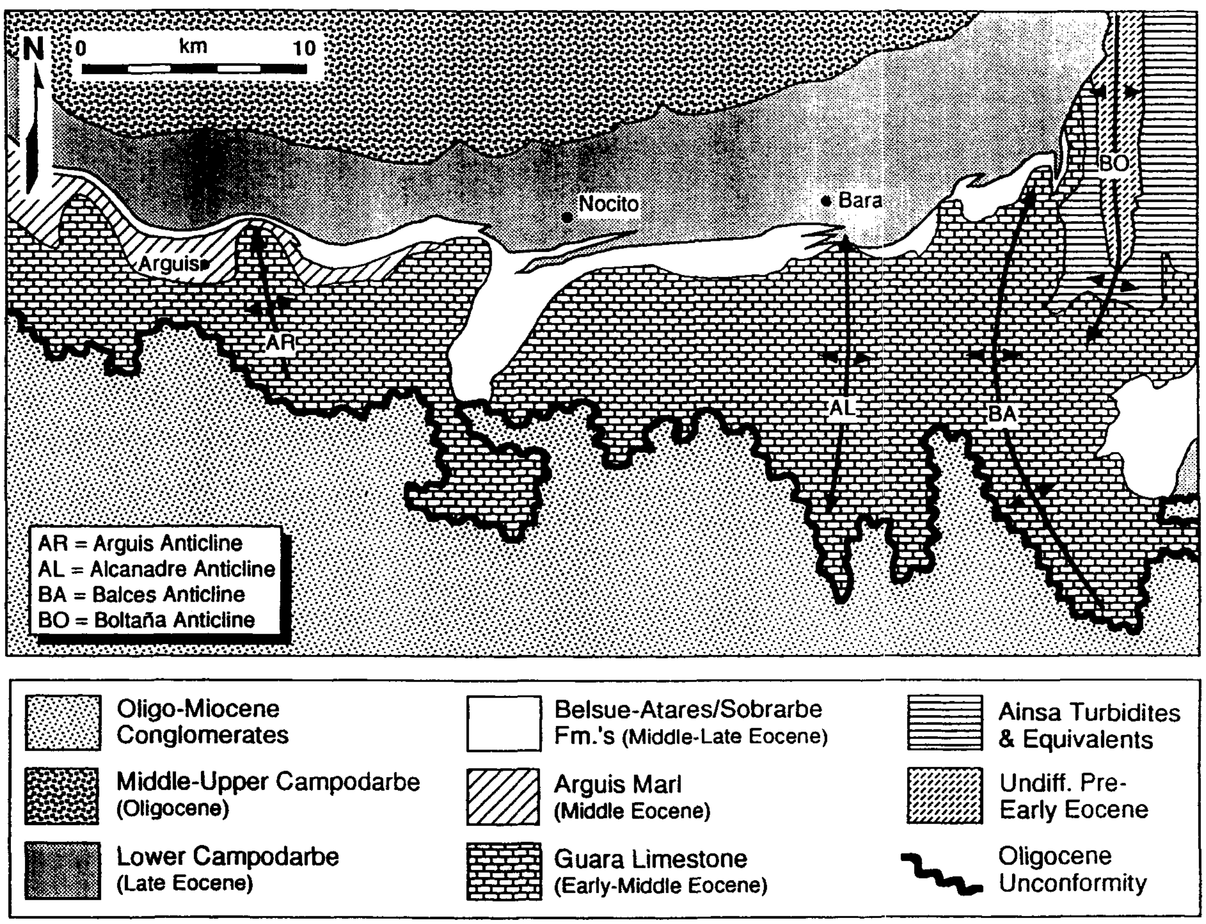


Fig. 10 Simplified geological map of the Sierras Exteriores between the Boltaña Anticline and Arguis (after Puigdefàbregas 1975). Important structural features are shown, and the interfingering relationships of the deltaic facies (Belsue-Atares) and continental facies (Lower Campodarbe) can be seen adjacent to Bara and Nocito (AR = Arguis Anticline; AL = Alcanadre Anticline; BA = Balces Anticline; BO = Boltaña Anticline).

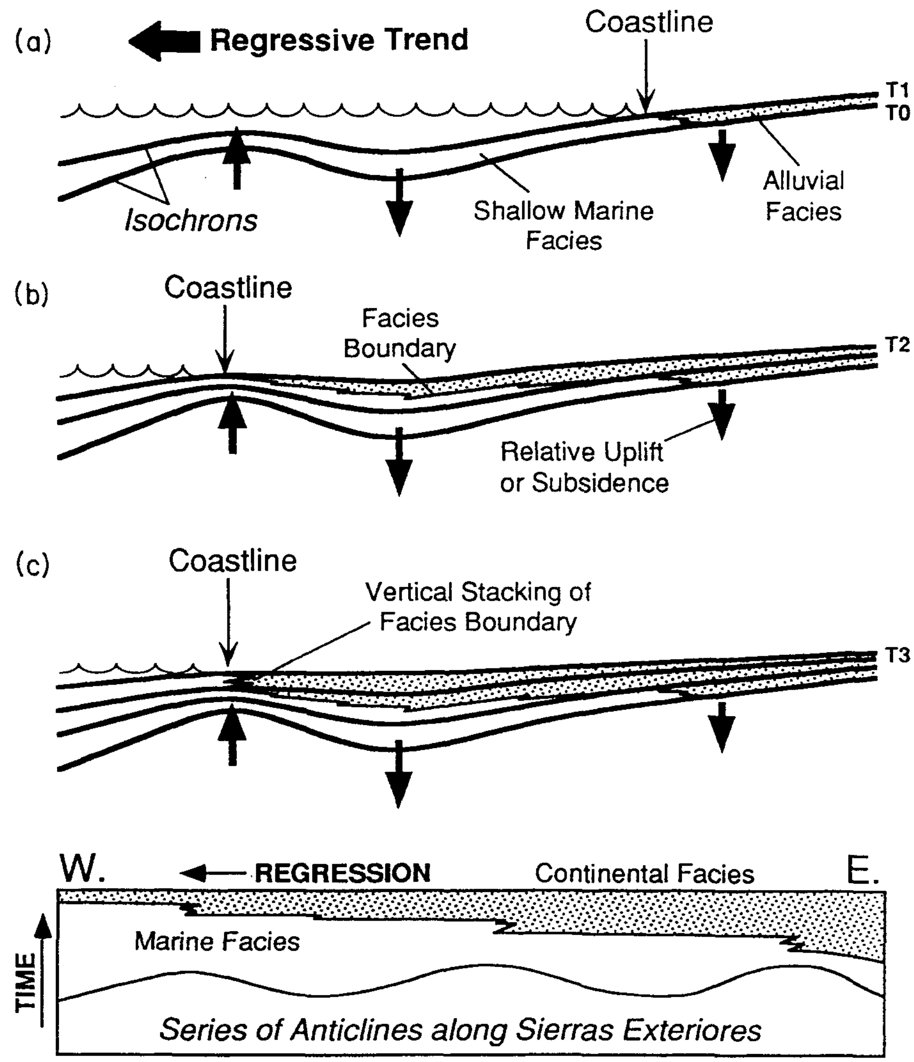


Fig. 11 Illustration describing the interaction of growing folds with a regressive coastline sequence. Facies boundary migration is inhibited as structural relief associated with anticline development serves to balance regional subsidence. Note the strongly diachronous nature of the marine/non-marine facies boundary, especially upon the crests of the developing folds. This is intended to model the 5 Myr diachrony of the Sobrarbe–Belsue–Atares deltaic sediments observed along the axis of the foreland basin system.

the lower Escanilla Formation, the lower Campodarbe Group exhibits very similar alluvial architecture. Both stratigraphic sequences record transitions up-section to wide, coarse sand and gravel sheets, due probably to increased sediment supply, and/or slowing regional subsidence.

DISCUSSION

Alluvial architecture and Eocene drainage patterns

The three-fold lithostratigraphic division of the Escanilla Formation proved to be near coincidental with palaeomagnetic reversal boundaries defined within the erected MPS framework. As such, this provided a better estimate of the ages of member boundaries than might have been anticipated. Escanilla fluvial deposition prograded across the study area at approximately 43–42.7 Ma. Uplift and erosion of the upper Escanilla deposits are believed to have occurred sometime soon after ~36.5 Ma. Palaeocurrents collected from the lower and middle members reflect focusing of the Escanilla rivers by rapid axial subsidence within the Ainsa Basin, as well as a phase of late Eocene growth of the Boltaña anticline. This is supported by observed thickness variations of the lower member within the Ainsa Basin. In the synclinal Ainsa Basin axis, undecompacted sedimentation rates are ~30–40 cm kyr^{-1}, and subsequently decrease westwards to ~15–20 cm kyr^{-1} near the basin margin. Increased proportions of sandstone are present in the more rapidly subsiding region, reflecting a concentration of channel sand-bodies. Nonetheless, rates of subsidence were rapid enough that channel-body vertical interconnectedness remained low (see Bridge & Leeder 1978; Alexander & Leeder 1987).

The anomalous characteristics of the Escanilla deposits within the Ainsa Basin show similarities with a number of examples from the geological literature. For example, Schuster & Steidtmann (1987) report occurrences of low-sinuosity stream channels in association with fine overbank material from the Cretaceous of the Green River Basin. Although the geometry of their stream deposit appears more typical of an anastomosed river system and not braided like the Escanilla rivers, Schuster & Steidtmann suggest that the channels were fixed laterally, unable to migrate across the floodplain because of the rapid local rates of subsidence and sediment accumulation within the subsiding foreland basin. They cite rates of sediment accumulation (undecompacted, ~ 17 cm kyr^{-1}) comparable to the Escanilla Formation.

Based on comparison of alluvial architecture from two sequences formed in differentially subsiding regimes from Idaho and Wyoming, Kraus & Middleton (1987) suggest that rapidly subsiding floodplains prevent the lateral migration of stream channels and subsequent reworking of finer alluvium along the fluvial network. This is due to the dominance of vertical accretion of the channel belt in order to maintain a graded profile as the region actively subsides. Such fluvial systems tend to avulse more frequently, prior to extensive lateral migration or amalgamation of units within the meander belt (Kraus & Middleton 1987). Additionally, the deposition of fine cohesive sediments, primarily along the flanks of the active channel belt can help to confine the system laterally, as the erodibility of the bank material would decrease. The presence of vegetation on these flanks would also significantly inhibit lateral channel migration by bank erosion (Smith 1976).

By analogy, the development of an analogous low-sinuosity fluvial system during Escanilla time, dominated by large volumes of uncharacteristically fine-grained overbank sediments ($>40\%$ silt or clay), seems to have been facilitated by the presence of rapid lateral changes in subsidence rate, which in turn influenced the nature and rate of sediment accumulation. The axially subsiding Ainsa Basin focused the Escanilla fluvial system, and this focusing was expressed both by a peculiar alluvial architecture and by the observed changes in late Eocene palaeodrainage patterns.

Base-level fluctuation

The laterally amalgamated sheet at the top of the lower member of the Escanilla Formation, although not physically traceable downstream into the marine system to the west of the Boltaña anticline, does seem to be a regionally significant interval. Occurring at about ~ 41.4–41.0 Ma, the sheet-like channel unit was interpreted by Cuevas & Puigdefàbregas (pers. comm.) as being generated in response to a regional base-level lowering that caused erosion and reworking within the proximal part of the Tremp Basin. This event does not seem to show any direct correlation to the Haq *et al.* (1987) sea-level curve. Additionally, it has been suggested that the fines-dominated intervals enclosing the lower part of the Escanilla section were deposited during a phase of gradual base-level rise, allowing net vertical aggradation of the alluvial plain (Cuevas & Puigdefàbregas, pers. comm.). Kraus & Middleton (1987) describe a similar strongly amalgamated sheet channel sandstone unit within the Willwood Formation of the north Bighorn Basin, Wyoming. Instead of invoking a regional base-level fall, they use pedological evidence to suggest that this was a time of lowered subsidence and decreased sediment accumulation. Such an interval, within a sequence dominated generally by vertical accretion deposits could be used to invoke a period of foreland basin stability and slowing of basement subsidence. However, the amalgamated unit within the Escanilla Formation does not appear in association with increased soil maturity within the enclosing vertical accretion deposits. Gardner & Cross (1991) suggest that fluvial geometries, especially within the distal reaches of a drainage basin, may be solely modulated by variation in base-level and accommodation space availability. By detailed correlation within the Cretaceous Ferron Sandstone of Utah, they link variations in fluvial architecture directly to changes in base-level and subsequent delta-lobe progradation or retrogression.

In the light of the Gardner & Cross (1991) study, we suggest that the amalgamated sheet conglomerates deposited across the oblique ramp system and within the piggy-back Tremp Basin during Escanilla time, were the result of a lowering in regional base-level, rather than being primarily due to a period of reduced basin subsidence. It is, however, acknowledged that the unit was deposited during a period of decreasing subsidence rates between lower and middle Escanilla times. Unfortunately, the lack of resolution in our magnetic chronologies at this time prevents the calculation of sediment accumulation rates for the amalgamated interval itself. However, the consistent immaturity of pedogenically modified overbank material suggests that the rates of subsidence remained high during the deposition of the coarse amalgamated sheet, and then subsequently decreased within middle Escanilla time. This eventual decrease in rate could well be related to the same base-level fall that generated the regional amalgamated conglomerate sheet.

Structural development and alluvial facies distribution

Temporal comparison of units across the Mediano Anticline has highlighted striking differences between the Escanilla exposures within the piggy-back basin and those across and outside the western South-Central Unit oblique ramp system. East of the Mediano fold, the Escanilla Limestone represents a protracted lacustrine phase equivalent to deltaic deposition within the oblique ramp system (Fig. 9). Anticline development caused ponding of the alluvial system within the piggy-back basin, slowing down clastic supply to the delta front. The general paucity of these limestones, in both frequency and extent across the Mediano anticline to the west, would suggest they were developed predominantly upstream of this episodically active structural trend. As such, the Escanilla Formation deposition within the piggy-back basin was strongly influenced by the Mediano anticline acting as a temporary local base-level.

The presence of strongly calcareous overbank deposits, a thinner time-equivalent section, and increased volumes and interconnectedness of coarse conglomeratic sheets would all suggest that the region on top of the translating thrust sheet, east of the Mediano Anticline, was subsiding less rapidly than either the region of the oblique ramp or the autochthonous foreland of the Jaca Basin. The differences in alluvial architecture within time-equivalent regions of the Escanilla system were closely related to local structural regimes. Subsidence rates seem to have been the most important control of architectural development at times of stable base-level.

A late Lutetian reconstruction of the SCU western oblique ramp (Fig. 12A) shows the phase of Sobrarbe deltaic progradation along the subsiding Ainsa Basin axis, and the coeval deposition of the Escanilla Limestone to the east of the growing Mediano anticline in the Tremp Basin. During Bartonian time (Fig. 12B), when wide conglomeratic sheet channel-bodies were being deposited within the Tremp 'piggy-back' Basin, 'fines-dominated' sections were being preserved above the more rapidly subsiding oblique ramp system in the Ainsa Basin. Similarly 5 Myr later in Priabonian time (Fig. 12C), when the Ainsa Basin experienced reduced rates of subsidence, the essentially autochthonous flexural foreland of the Jaca Basin was subsiding more rapidly, and predictably the spatial differences in the alluvial deposits across this region reflect this westerly increase in tectonic subsidence.

The final reconstruction (Fig. 12D) shows the post-Escanilla configuration, after further motion of the Boltaña anticline, wholesale translation of the Jaca Basin, and growth of the Sierra Exteriores. No major west-directed fluvial system existed here at this time. Instead, a series of laterally adjacent large alluvial fans developed. These appeared to enter the Oligo-Miocene Ebro foreland basin at significant structural re-entrants (Hirst 1983; Hirst & Nichols 1986) along the Sierras Exteriores and Sierras Marginales thrust fronts.

The changing subsidence rates, when combined with the palaeocurrent information collected within the Ainsa Basin give a remarkably coherent description of the basin history during middle to late Eocene times, just prior to the major influx of coarse conglomerates into the region of the western oblique ramp. The input of these conglomerates was, in part, due to renewed tectonism within the upper

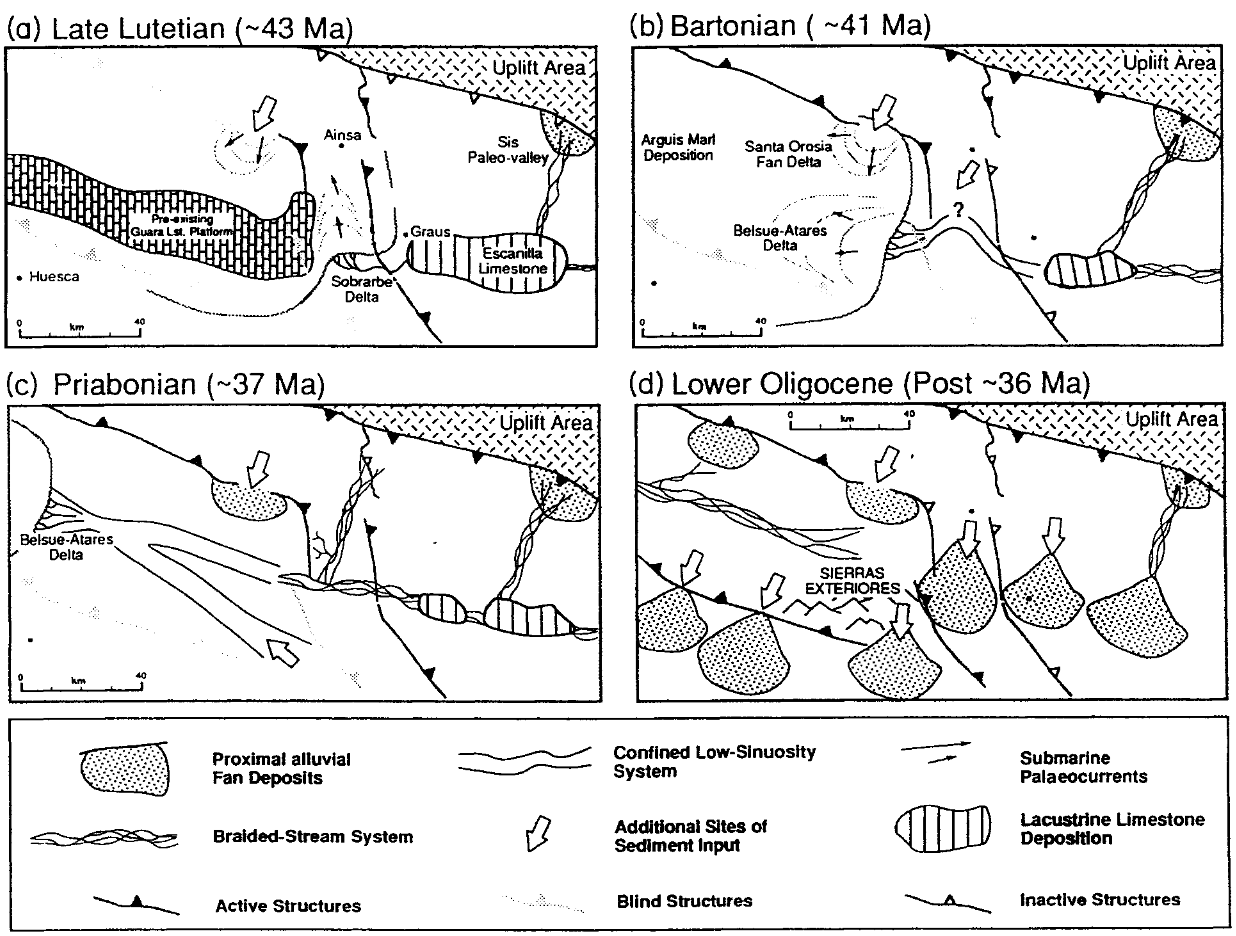


Fig. 12 Four sequential palaeogeographical reconstructions of the South–Central and Western Pyrenees during late Eocene to Oligocene times. Structures active during each interval are shown as solid, whereas inactive structural elements are shown as the lighter dotted pattern. Differences in fluvial style are shown, and can be related to their structural position with respect to active or inactive thrust sheets. Data from Puigdefàbregas (1975), Reynolds (1987), Jolley (1988), McElroy (1990), and Hogan (1992) are incorporated into this summary.

reaches of the Escanilla Formation drainage basin to the east and north in the Pyrenean Axial Zone and in the deforming foreland basin (Burbank *et al.* 1992). This late Eocene–Oligocene deformation represents a major phase of out-of-sequence thrusting and thickening within the central Pyrenees, resulting in significant renewed relief in the uplifted source regions (Puigdefàbregas *et al.* 1991). Vast amounts of conglomerates were shed down the alluvial systems to the south, and were then diverted into the westerly flowing axial system of the Campodarbe Group. However, the presence of a major subregional unconformity at the top of the Escanilla Formation, suggests that the development of the alluvial fill of the basin at this time was also being influenced by spatial variations in structural development along the frontal South Pyrenean thrust system.

CONCLUSIONS

Downstream changes in alluvial architecture within the late Eocene continental depositional system of the southern Pyrenean foreland basin were closely controlled by spatial variations in thrust deformation along the orogenic belt. Variations in local tectonic subsidence rates, related to differences in structural position within the deforming foreland basin affected fluvial channel morphologies, channel-stacking geometries, the exclusion or preservation of fine-grained material, and the development and extent of pedogenic carbonates. Lower subsidence rates within the allochthonous piggy-back Tremp Basin served to increase channel-body interconnectedness of the wide sheet conglomerates, prevent the preservation of significant volumes of fine vertical accretion material, and allow the widespread development of pedogenic calcretes and calcareous fines. Across the actively deforming western oblique ramp, within the intervening synclinal Ainsa Basin, sheet and ribbon channel-bodies were excellently preserved, laterally confined by and entirely enclosed within increased proportions of overbank fines. Calcretes were much less pervasively developed.

The middle–late Eocene partitioning of the linear foreland into a number of structurally distinct sedimentary basins, bounded by oblique ramp tip-line folds such as the Mediano and Boltaña anticlines, also influenced dispersal patterns and facies development. Upstream of the oblique ramp, within the piggy-back basin, the alluvial deposits were periodically ponded or dammed, allowing the deposition of micritic lacustrine limestones. During the phase of deltaic progradation along the subsiding basin axis, these developing folds served to localize the middle–late Eocene shoreline, as local emergence of flanking folds balanced regional flexurally driven subsidence, preventing the oceanward progradation of the delta-front. A number of these N–S-trending anticlines impeded the westward regression of the alluvial system, producing the strong diachrony in the age of the Belsue deltaic system across the oblique ramp into the Jaca Basin (Fig. 11). Additionally, falls in regional base-level induced reworking of portions of the alluvial basin, which delivered increased volumes of coarse alluvial deposits downstream into coastal plain settings. This developed regionally extensive horizons of laterally and vertically stacked channelized sands and conglomerates.

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