



HAL
open science

Syn-tectonic sedimentation and thrust-and-fold kinematics at the intra-mountain Montalbán Basin (northern Iberian Chain, Spain)

Antonio Casas, Albert Casas, Antonio Pérez, Sylvia Tena,, Laurie Barrier, Denis Gapais, Thierry Nalpas

► To cite this version:

Antonio Casas, Albert Casas, Antonio Pérez, Sylvia Tena,, Laurie Barrier, et al.. Syn-tectonic sedimentation and thrust-and-fold kinematics at the intra-mountain Montalbán Basin (northern Iberian Chain, Spain). *Geodinamica Acta*, 2015, 13 (1), pp.1-17. <10.1080/09853111.2000.11105358>. <insu-05202728>

HAL Id: insu-05202728

<https://insu.hal.science/insu-05202728v1>

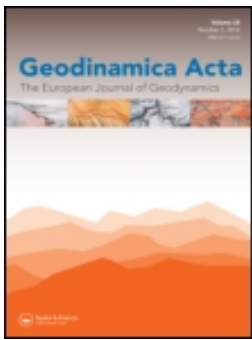
Submitted on 7 Aug 2025

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



HAL Authorization



Syn-tectonic sedimentation and thrust-and-fold kinematics at the intra-mountain Montalbán Basin (northern Iberian Chain, Spain)

Antonio M. Casas, Albert Casas, Antonio Pérez, Sylvia Tena,, Laurie Barrier, Denis Gapais & Thierry Nalpas

To cite this article: Antonio M. Casas, Albert Casas, Antonio Pérez, Sylvia Tena,, Laurie Barrier, Denis Gapais & Thierry Nalpas (2000) Syn-tectonic sedimentation and thrust-and-fold kinematics at the intra-mountain Montalbán Basin (northern Iberian Chain, Spain), *Geodinamica Acta*, 13:1, 1-17, DOI: [10.1080/09853111.2000.11105358](https://doi.org/10.1080/09853111.2000.11105358)

To link to this article: <https://doi.org/10.1080/09853111.2000.11105358>



Published online: 24 Mar 2015.



Submit your article to this journal [↗](#)



Article views: 121



Citing articles: 1 View citing articles [↗](#)

Syn-tectonic sedimentation and thrust-and-fold kinematics at the intra-mountain Montalbán Basin (northern Iberian Chain, Spain)

Antonio M. Casas^{a*}, Albert Casas^b, Antonio Pérez^a, Sylvia Tena^a,
Laurie Barrier^c, Denis Gapais^c, Thierry Nalpas^c

^a Departamento de Geología, Universidad de Zaragoza, 50009 Zaragoza, España

^b Department de Petrología, Geoquímica i Prospecció Geològica, Universitat de Barcelona, 08008 Barcelona, España

^c Géosciences Rennes, campus de Beaulieu, 35000 Rennes, France

Received 23 July 1999; accepted 3 December 1999

Abstract – The Montalbán Basin (30 × 15 km wide) is located within the Iberian Chain (N Spain), and filled with syn-tectonic Tertiary (Eocene to Lower Miocene) deposits, with a cumulated thickness of about 2 000 m. The depth to the Palaeozoic basement is maximum at the western part and gradually shallows toward the east, as inferred from gravimetric data. The Montalbán Basin is surrounded by an E–W, N-verging, shallow-dipping thrust to the south and a NW–SE-trending anticline, involving the Palaeozoic, to the north. The southern thrust shows a minimum displacement of 8 km and results from the inversion of Mesozoic normal faults. The northern anticline is asymmetric, its southern limb being vertical in most of its length. Mesozoic extensional faults and Variscan thrusts have acted as controls on the location of the frontal limb of this anticline. The sedimentary, syn-tectonic filling of the Montalbán Basin, can be divided into five (M1 to M5) tectono-sedimentary (unconformity-bounded) units, each with a fining upwards-coarsening upwards vertical evolution. Their sedimentary environment corresponds to alluvial fans, with conglomerates at the basin margins grading to evaporites and limestones at the basin centre. The geometry and kinematics of the structures limiting the basin strongly controlled its sedimentary evolution: the Montalbán Basin was wider during M1 and M2, with a northward provenance of alluvial fans, and closed to its present-day dimensions from M3 to M5, coinciding with the largest displacement and uplift of the surrounding structures, which became the main source areas. © 2000 Éditions scientifiques et médicales Elsevier SAS

compressional basin / thrusting / syn-tectonic sedimentation / inversion tectonics / Tertiary / Iberian Chain

Résumé – Sédimentation syntectonique et cinématique de plis et chevauchements dans le bassin compressif de Montalbán (nord de la chaîne Ibérique, Espagne). Le bassin de Montalbán (30 × 15 km) est une dépression intramontagneuse située à l'intérieur de la chaîne Ibérique. Il est rempli avec des sédiments syntectoniques du Tertiaire continental (de l'Éocène au Miocène inférieur), qui ont plus de 2 000 m d'épaisseur. À partir de l'étude des anomalies gravitaires, on a déterminé que la profondeur du « socle » paléozoïque est maximale dans la partie occidentale du bassin et qu'elle diminue progressivement vers l'est. Le bassin de Montalbán est limité au sud par un chevauchement à vergence nord, et au nord par un anticlinal de direction NW–SE dont le cœur est constitué par des argiles et des grès du Carbonifère. Le chevauchement de la limite sud, de direction E–W, a un déplacement de 8 km vers le bassin et il est interprété comme résultat de la réactivation de failles normales mésozoïques, renversées pendant la compression Tertiaire. L'anticlinal de la bordure nord est déversé vers le sud, avec des couches verticales ou renversées tout au long de son flanc sud. La localisation du flanc sud est en rapport avec des failles normales mésozoïques et des chevauchements hercyniens. Dans les sédiments syntectoniques du bassin de Montalbán, on a identifié cinq unités tectosédimentaires limitées par des discordances en bordure du bassin (M1 à M5). Ces unités, sédimentées par des cônes alluviaux, montrent une évolution verticale du type *fining upwards-coarsening upwards*. Près des bordures du bassin, les roches plus abondantes sont des conglomérats, qui passent à des grès, argiles, calcaires lacustres et évaporites vers le centre du bassin. La géométrie et la cinématique des structures ont contrôlé fortement l'évolution sédimentaire du bassin : pendant la sédimentation de M1 et M2, le bassin était plus large (en direction N–S) et pendant M3, M4 et M5, ses dimensions se rapprochaient progressivement des actuelles, avec le soulèvement et déplacement des structures des deux bordures. Les paléocourants dans les premières unités montrent une provenance nord, en-dehors des limites actuel-

* Correspondence and reprints: acasas@posta.unizar.es

les, tandis que dans les dernières unités les structures des bordures nord et sud étaient les principales sources de sédiments. © 2000 Éditions scientifiques et médicales Elsevier SAS

**bassin compressif / chevauchement / sédimentation
syntectonique / inversion tectonique / Tertiaire / chaîne
Ibérique**

1. Introduction

Intra-plate sedimentary basins develop as a result of tectonic loading due to large-scale folds and thrusts. They can be asymmetric, linked to a single structure or symmetric, with folds and thrusts at both margins [1–4]. In this second case the dynamics of sedimentation within the basin are determined by the relationships between the kinematics of the different structures limiting the basin [5, 6].

The kinematics of particular structures and of the whole basin can be determined from the analysis of vertical and horizontal variations of syn-tectonic sedimentary units. Definition of unconformity bounded units or tectono-sedimentary units is useful to determine the main episodes of basin filling and their relationships with structures located at the basin margins [6–9].

Within the northern Iberian plate there are several Paleogene continental, internally drained basins, with sizes ranging from several hundreds of kilometres (as the Ebro Basin) to a few kilometres (most basins located within the Iberian Chain). Many of them underwent a common evolution during the Paleogene, with (i) a first stage of sedimentation over wide areas during the Late Eocene and (ii) a second stage, with separation of smaller, internally drained, basins during the Middle–Late Oligocene [10–14]. The uplifting of the basin margins during this second stage is outlined by the deposition of conglomerates. During the Middle–Late Miocene sedimentation areas became larger, and the formerly separated basins were again connected [16]. The analysis of the geometry and sedimentary evolution of sedimentary units within Tertiary basins is an essential tool for understanding of the kinematics of Iberia during the Cainozoic [12–15, 17]. The Montalbán Basin is the largest of these intramontane basins, with more than 2 000 m of syn-tectonic sediments. Although neither seismic nor borehole data are available, the good outcrop conditions of the pre- and syn-tectonic sequences allow its subsurface geometry to be inferred.

The objectives of this work are to determine the geometry of the Montalbán Basin, to analyse the evolution of its sedimentary filling during the Paleogene and the kinematics of structures at its margins, and to establish its relationships with other Paleogene basins located in the northern part of the Iberian plate. The methodology used included aerial photography and field studies to determine the geometry of the basin and its margins, sedimentological analysis to determine the horizontal and vertical evolution of syn-tectonic

units, balanced cross-sections, and a gravimetric study to constrain the subsurface geometry of the basin.

2. Geological setting

The Iberian Chain is located at the northeastern part of the Iberian plate (*figure 1*). It constituted a wide area of intra-continental deformation within the Iberian plate during the Mesozoic and the Tertiary [18, 19]. Its limits are Tertiary molasse basins, filled with large thicknesses (up to 5 000 m) of terrestrial deposits: the Ebro basin forming the main foreland basin of the Pyrenean orogen to the north, the Tagus basin to the south, and the Duero basin to the west. At the eastern margin of the Iberian peninsula, the Iberian Chain disappears at the Mediterranean coast, due to the opening of the Valencia Trough during Neogene extension [20].

During the Mesozoic the northeastern part of the Iberian plate underwent extension, with two episodes of continental rifting (Early Triassic and Early Cretaceous) each followed by marine deposition linked to thermal subsidence [19, 21]. By the Late Cretaceous (Cenomanian) a stage of tectonic quiescence maintained for 40 My. The main Mesozoic extensional structures are normal faults oriented NE–SW and NW–SE, corresponding with the main directions of Variscan folds and faults, and in some places N–S and E–W. Jurassic and Cretaceous normal faults show listric geometries, with detachment levels in the Upper Triassic, and in slaty units of the Palaeozoic series.

Compressional deformation of the Iberian Chain during the Paleogene was strongly conditioned by pre-existing structures, in general oblique to the main Tertiary shortening direction: (i) Variscan and late-Variscan faults, folds and thrusts (most of them with NW–SE direction) and (ii) Mesozoic faults. The overall shortening direction during the Paleogene is considered to be NNE [22], approximately perpendicular to the northern border of the Iberian plate. There are several detachment levels, the most important of which are the Precambrian and Silurian shales and the Middle–Upper Triassic (Muschelkalk and Keuper facies) shales and evaporites [22, 23]. The latter separates the Mesozoic–Tertiary cover (Jurassic–Cretaceous) from the Palaeozoic. The main folds in the northern part of the Iberian chain strike NW–SE to E–W and have a northward vergence [22]. The southern part of the Iberian chain is characterized by westward-verging thrusts, positive flower structures and forced folds of the Mesozoic sedimentary cover over the Variscan rocks [24].

The Montalbán anticline is located at the zone of intersection between the northern part of the Iberian Chain, constituted by two NW–SE Palaeozoic-cored anticlines of the Aragonian Range and the E–W folds and thrusts that form the Linking zone between the Iberian Chain and the Catalan Coastal Range [22]. The two anticlines that form the

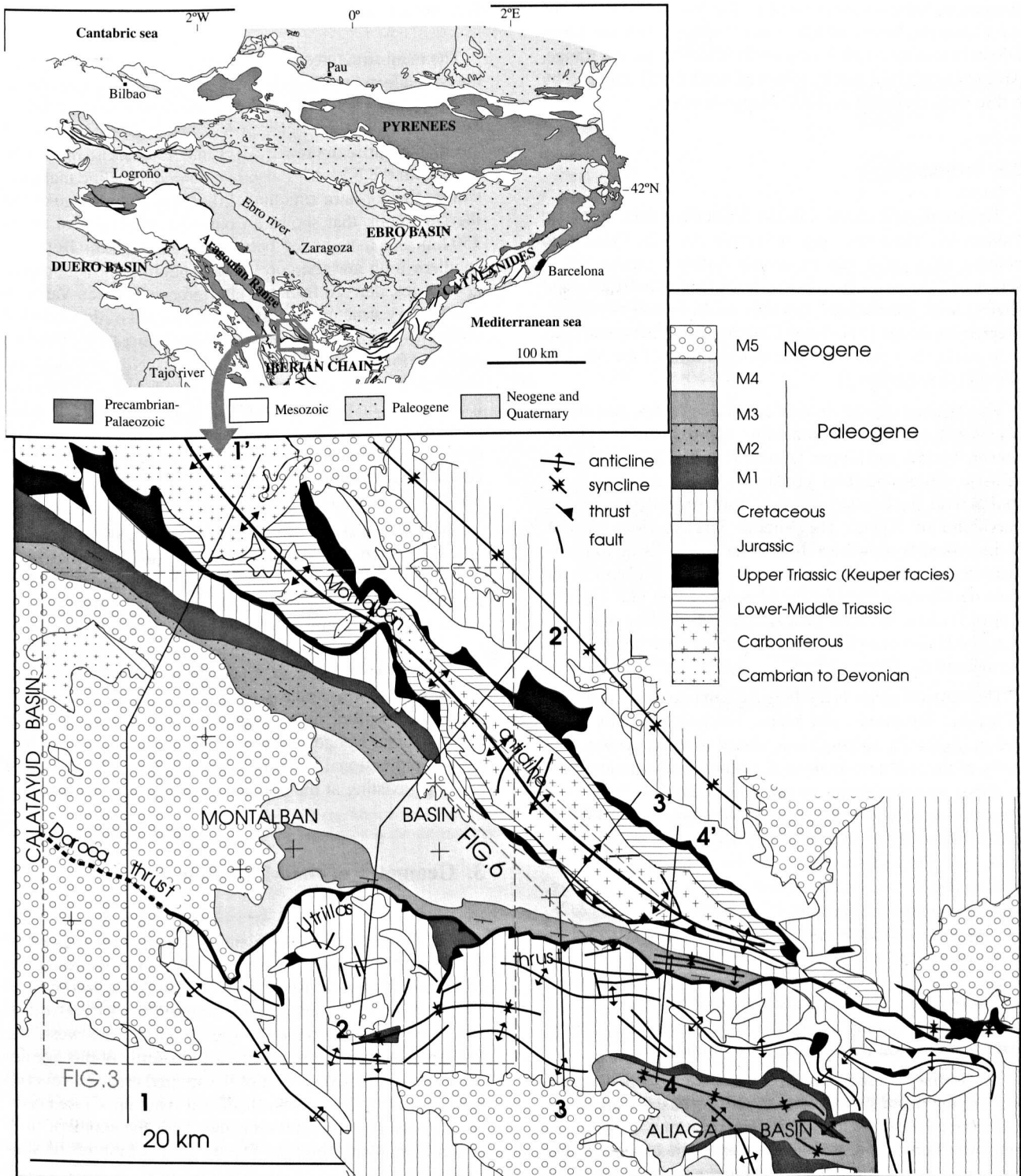


Figure 1. Geological sketch of the Montalbán Basin (modified from [21]). The location of cross-sections of figure 4 and the maps of figures 3 and 6 are shown. Inset shows the location of the Montalbán Basin within the Iberian Chain.

Aragonian Range are separated by the Neogene outcrops of the Calatayud basin, which is in continuity with the Montalbán Basin (*figure 1*). To the north of the Aragonian Range, Mesozoic outcrops can be followed northwards, covered by a thin (less than 500 m thick) Neogene cover.

2.1. Stratigraphy

The stratigraphic series in the Montalbán area comprise Palaeozoic, Mesozoic, and Tertiary rocks. The Palaeozoic consists of a thick (up to several hundred metres thick) series of Lower Carboniferous turbidites (sandstones and shales) with interbedded volcanic rocks (alkali rhyolites), Stephanian in age [21]. Some Cambrian and Devonian beds crop out in the core and on the western limb of the Montalbán anticline (*figure 1*).

The Triassic can be divided into three facies, two continental and one marine, coinciding approximately with the Lower, Middle and Upper Triassic [19, 25, 26]. The Lower Triassic (Buntsandstein) consists of red sandstones and shales with thicknesses varying from several metres to a maximum of 300 m. The Middle Triassic (Muschelkalk facies) consists of two levels of dolostones with an intermediate level of clays and gypsum, that in many places is the main décollement level for the Mesozoic cover [22, 27]. The Upper Triassic (Keuper facies) consists of clays and gypsum and is also one of the most important detachment levels throughout the Iberian Chain.

The Jurassic series is a relatively homogeneous sequence of marine limestones and marls, reaching a thickness of 600 m (*figure 2*), although it is absent in many areas, especially at the southern limb of the Montalbán anticline, due to either non-deposition or pre-Albian erosion (*figure 2*). The Lower Cretaceous consists of continental (Weald facies) and marine (Urgon facies) sequences, up to 600 m thick [28]. Deposition during the Early Cretaceous in the Iberian Basin was strongly controlled by normal faulting, with two dominant directions: NW–SE and NE–SW [22, 28, 29]. Albian sandstones unconformably overlie other terms of the series, due to erosion after the main extensional stages (*figure 2*). The Upper Cretaceous (Cenomanian–Maastrichtian) calcareous beds constitute the upper terms of the pre-compressional series, the latter terms being deposited in lagoon and shallow marine environments.

The Tertiary is represented by alluvial continental deposits, varying from conglomerates at the basin margins to sandstones and shales in intermediate positions and to lacustrine limestones and gypsum at the basin centre. In the Paleogene, coarse clastic deposits are dominant, whereas in the Neogene lutites, limestones and gypsum are the most widespread deposits. The Middle Miocene shows a deposition area larger than that of the Paleogene and covers unconformably many Paleogene compressional structures (*figure 1*).

2.2. Structures

The main structures surrounding the Montalbán Basin are the Montalbán anticline, to the north and the Utrillas thrust to the south (*figures 1* and *2*). The Montalbán anticline involves Palaeozoic rocks, previously folded and thrustured during the Variscan orogeny. It is in continuity, to the northwest, with the NW–SE Palaeozoic-cored anticline that constitutes the northern anticline of the Aragonian Range of the Iberian Chain, that shows an outcropping length of about 150 km and a width of between 5 and 30 km. Both the southern limb and the core of the anticline show complex geometries, derived from the interference between Variscan and Tertiary structures, and the development of thin-skinned thrusts with opposite vergence. At the Montalbán anticline, Variscan folds and thrusts show a N–S to NE–SW direction and Tertiary folds and thrusts are NW–SE to E–W. Variscan folds show a first phase of isoclinal folds associated to axial-plane cleavage and a second phase of gentle folds [21]. The detailed geometry and orientation of the two folding stages cannot be determined due to the lack of outcrops in the central part of the anticline.

The Utrillas thrust is an E–W structure that continues eastward within the Portalrubio-Vandellós thrust system [30]. This thrust system is the main compressional structure at the northern part of the Iberian Chain. To the west, the Utrillas thrust probably dies out against a strike-slip reverse fault (Daroca thrust, [31]). Although most of this margin is covered by Upper Miocene unconformable sediments, in some places it can be seen that the Lower Cambrian overthrusts the Aragonian sediments [31]. Under the horizontal Neogene of the Calatayud basin some Paleogene compressional structures can be inferred from several outcrops existing at the boundary between the two basins.

3. Geometry of the Montalbán Basin

The Montalbán Basin is triangle-shaped, with a length of more than 50 km and a maximum width (in its western part) of 25 km. Toward the east the Montalbán Basin narrows and finally closes at the intersection between the Utrillas thrust and the Montalbán anticline (*figure 1*). To the west, the Paleogene must also disappear, since deposits of this age are not thicker than 500 m west of the studied area. The overall geometry of the Montalbán Basin is a syncline whose northern, steeply-dipping limb coincides with the southern limb of the Montalbán anticline. The horizontal limb of the syncline is overthrust by the Utrillas thrust. In some places the Tertiary beds forming the horizontal limb of the syncline show a shallow dip toward the south, giving a footwall flat geometry below the south-dipping thrust surface. In other places along the Utrillas thrust, vertical Tertiary beds can be recognised, forming a footwall ramp.

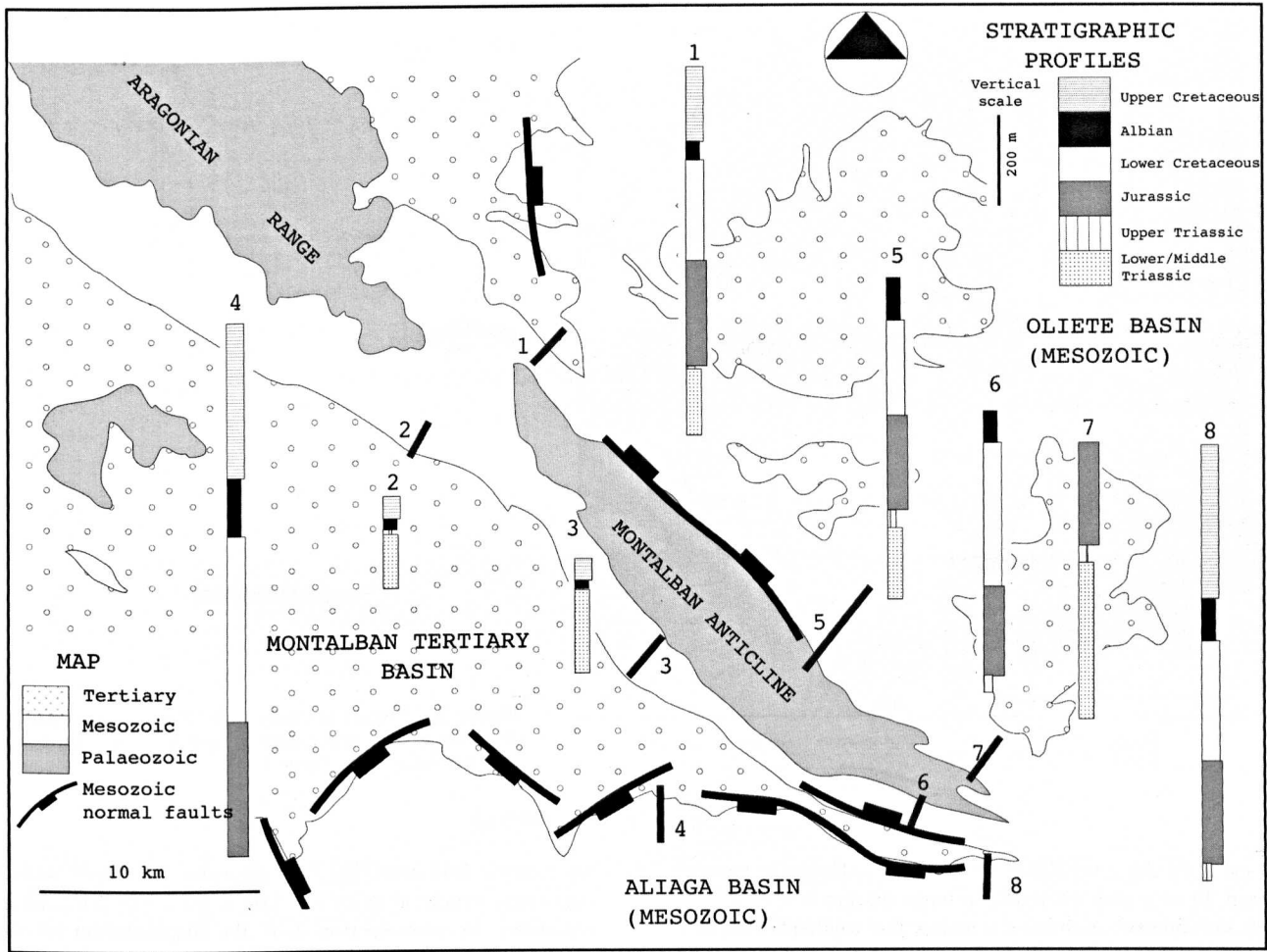


Figure 2. Stratigraphic synthetic profiles of the Mesozoic around the Montalbán Basin. The location of Mesozoic normal faults can be inferred from the differences in thickness and facies between the different profiles and from sedimentary wedges associated to normal faults [28, 35].

3.1. 3-D geometry. Gravimetric data

The geometry in depth of the Montalbán Basin cannot be inferred from seismic reflection or borehole data. Furthermore, the central and western parts of the basin are covered by horizontal Neogene deposits (*figure 1*). To constrain the 3-D geometry of the basin, and the balanced cross-sections, a gravimetric survey was carried out. The results obtained (expressed in the Bouguer anomaly map) allow to determine the overall geometry of the basin in terms of depth to the denser Palaeozoic basement. The distance between contours is also indicative of the dip of the Palaeozoic/Mesozoic unconformity. These two data (depth to the basement and dip of the top of the basement) were used for the construction of the cross-sections shown in this section.

For the compilation of the gravity map about one hundred new gravity measurements using a Lacoste & Romberg

gravity meter were added to the pre-existing data [19], covering an area of 300 km². All the observed gravity values were tied to the IGSN-71 system taking as a reference the Zaragoza base station (9.8022323 m·s⁻²). Bouguer anomalies were computed using a mean value of 2670 kg·m⁻³ for the density and topographic corrections were applied up to 167 km.

The regional anomaly can be considered as a regular surface with a NW–SE trend shallowly dipping to the south (*figure 3*). The Bouguer anomaly map shows a broad absolute minimum at the western limit of the studied area, where only the horizontal Neogene crops out. This absolute minimum spreads to the east reaching the present-day limits of the Montalbán Basin. The northern limit of the latter is well marked by a relative positive anomaly that indicates the uplift of the Palaeozoic rocks. Other minor uplifts to the

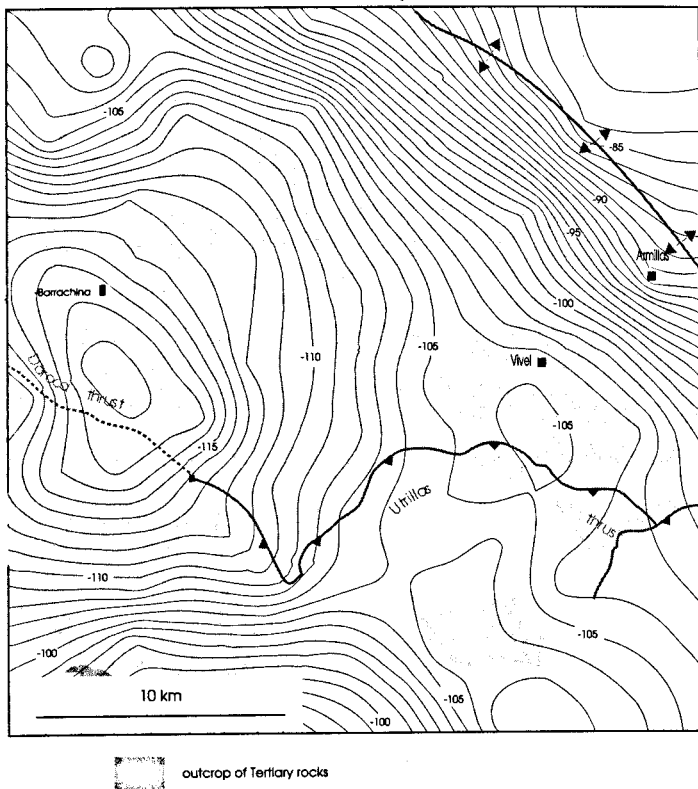


Figure 3. Bouguer anomaly map of the western part of the Montalbán Basin obtained from the gravimetric survey. See location on figure 1.

west have also a regular expression in the Bouguer anomaly map. In summary the northern basin margin is well defined by gravimetric anomalies whereas the southern margin is not, probably because the differences in density between the Tertiary and Mesozoic rocks are negligible. The existence of an important gravimetric minimum some kilometres west of the present-day limits of the Montalbán Basin indicates that the maximum thickness of Tertiary deposits is probably located under the horizontal Neogene, coinciding with the intersection between the southern anticline of the Aragonian Range and the western end of the Utrillas thrust. The fact that this minimum disappears gradually toward the east may be interpreted as a gradual ascent of the base of the Tertiary in this same direction.

3.2. Balanced cross-sections

Three cross-sections (2–2', 3–3' and 4–4' in figure 1) were drawn and restored to interpret the geometry and evolution of the Montalbán Basin. One more cross-section at the western sector of the basin (1–1' in figure 1) is also presented, although due to the lack of outcrops it is not as well constrained as the others. In all of them (figure 4), the overall structure shows common features, as it is a shallow-dipping thrust with horizontal displacement of several kilometres (Utrillas thrust) to the south, and a south-verging

asymmetric fold involving the Palaeozoic basement, with a maximum structural relief of 4 km, to the north (Montalbán anticline). In cross-section 1–1' the displacement of the southern thrust becomes smaller. In this section, the basin floor, larger than in the other sections, is cross-cut by northward-verging thrusts. The Palaeozoic and Mesozoic at the hangingwalls of these thrusts crop out at the western limit of the Montalbán Basin (see figure 1).

3.2.1. The Utrillas thrust

In most cross-sections, the Utrillas thrust shows a hangingwall ramp at the frontal part, in which the thrust surface cross-cuts overturned units, from the Lower Jurassic to the Upper Cretaceous (figure 5). The dip of the thrust surface varies between the horizontal at footwall flats and 25–30° at footwall ramps. In the western sector of the Montalbán Basin (cross-section 2–2', figure 4) the Utrillas thrust can be interpreted as the result of the tectonic inversion of a southward-dipping normal fault because: (1) the Lower Cretaceous in the hangingwall thickens progressively from north to south suggesting that the present-day thrust was active at least during the Early Cretaceous [32]. (2) The orientation of the frontal ramp of the thrust changes along strike, showing segments with NW–SE and NE–SW strikes. These orientations correspond to the directions of the main

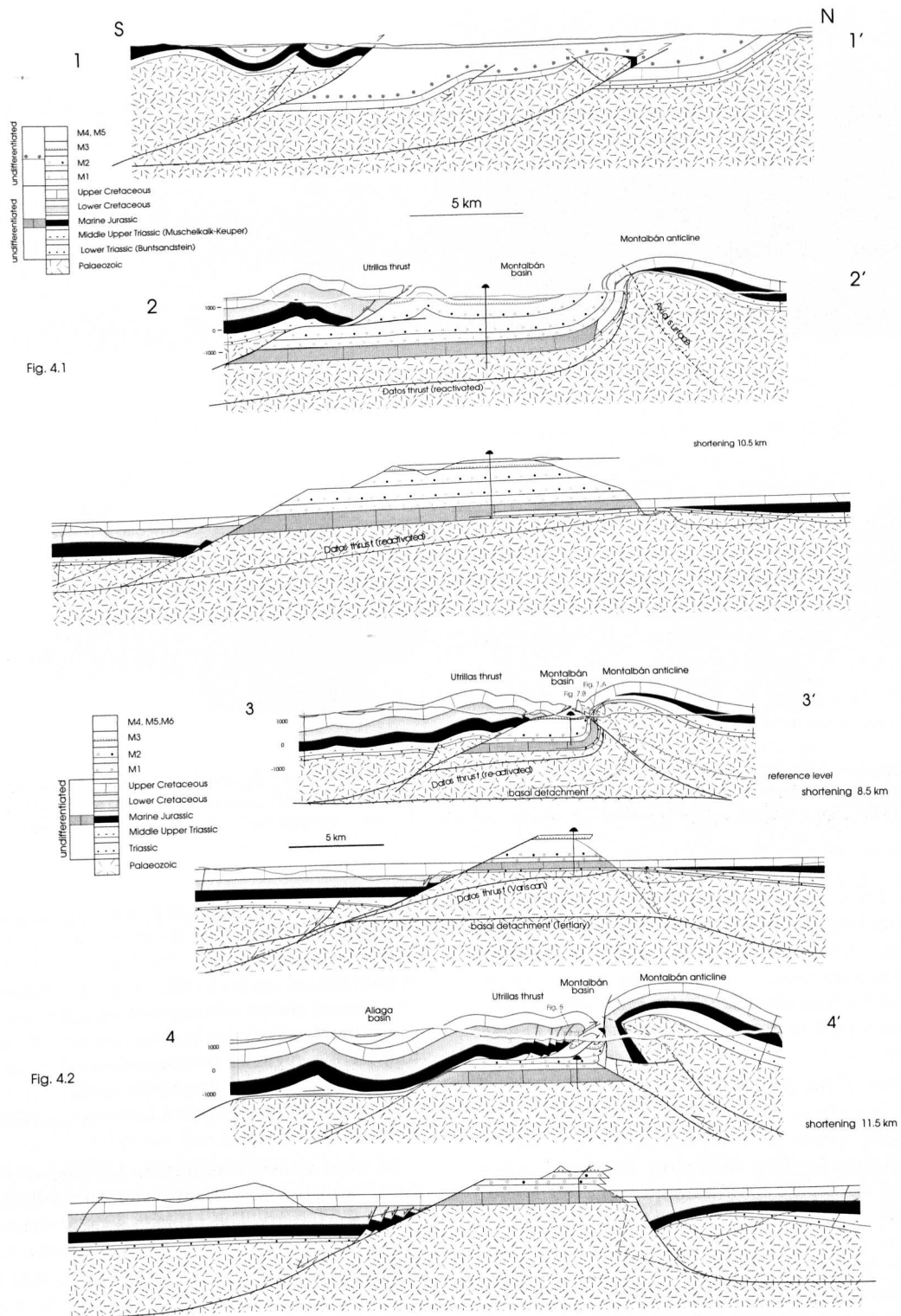


Figure 4. Balanced and restored cross-sections across the Montalbán Basin. See location of cross-sections in figure 1.

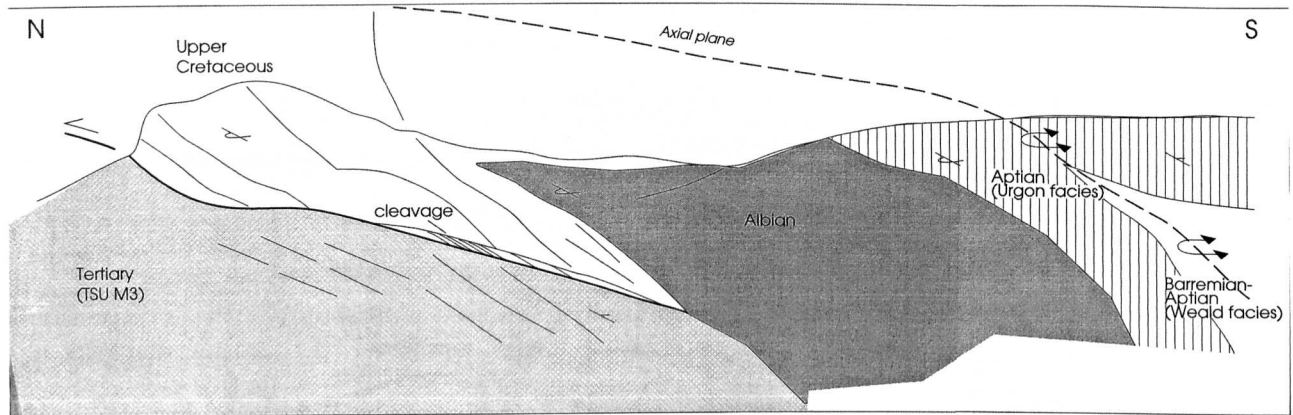
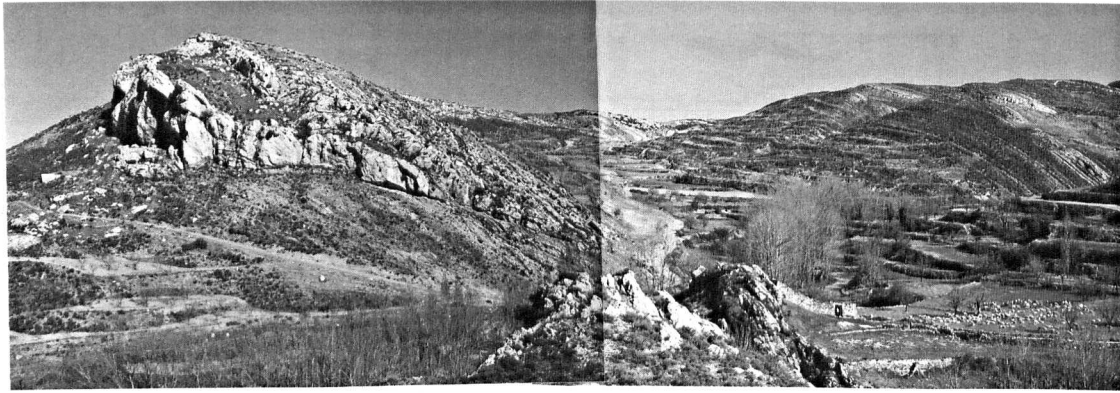


Figure 5. Geometry of the Utrillas thrust in the eastern sector of the Montalbán Basin (see location in *figure 4*). A large anticline with an overturned frontal limb, defined by the Cretaceous units can be seen at the hangingwall. At the footwall the normal, south-dipping Tertiary beds are cross-cut by the thrust surface, probably due to the existence of a gentle fold developed early with respect to the main thrust.

normal faults active during the Early Cretaceous rifting [28, 32, 33]. (3) The Early Cretaceous extensional basin (Aliaga Basin, [28, 34]) located in the hangingwall of the Utrillas thrust was separated from the sedimentary basin located north of the Montalbán anticline (Oliete Basin) and underwent a different tectonosedimentary evolution (*figure 2*) [28, 34, 35].

The geometry of the hangingwall of the Utrillas thrust shows a south-dipping monocline at the eastern part, where the Aliaga Tertiary basin appears (cross-section 4–4', *figure 4*; see also *figure 1*). This monocline has been interpreted [15] as the template for a footwall ramp and would then indicate the location of the footwall cut-off of the Tertiary units of the Montalbán Basin (cross-section 4–4', *figure 4*). This monocline can only be observed in the eastern half of the thrust mapped trace, whereas in the western half, if the thickness of the preserved Tertiary increases, as suggested by gravimetric data, there must be a ramp cross-cutting the Palaeozoic basement at the hangingwall. According to our reconstruction, in its western sector (cross-sections 2–2', 3–3' *figure 4*) the Utrillas thrust is a

basement-involved structure with its surface gradually deepening southward, the thrust surface cross-cutting the basement at shallower depths than the extensional faults. This implies that, as occurs in other structures resulting from the inversion of previous basins [14, 36], the main thrust cuts across the basement and in some segments the thrust surface follows the regional detachment level (Upper Triassic), finally reaching the topographic surface and re-activating some of the Mesozoic normal faults (see cross-sections 2–2' and 4–4', *figure 4*).

In some areas (cross-section 2–2' and 4–4'), the main thrust branches downwards with minor thrusts detached within the Tertiary. This explains some steeply-dipping Tertiary beds outcropping within the Montalbán Basin near its southern margin.

3.2.2. The Montalbán anticline

The basin is limited to the north by the Montalbán anticline (*figures 1* and *6*). The geometry of the latter changes from the northwestern limit of the Montalbán Basin (see *figure 1*), where it shows a northward vergence, to the central

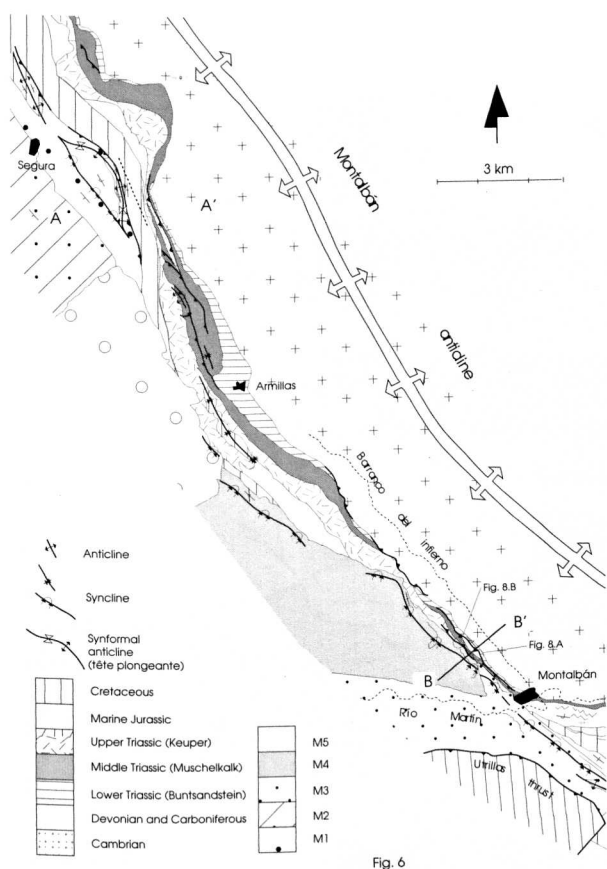


Figure 6. Geological map of the southern limb of the Montalbán anticline. See location in figure 1. The location of cross-sections of figure 7 is shown.

and southern part, where it is asymmetric, with a vertical or overturned (minimum dip 50°) southern limb and a shallow-dipping (between 20° and 30°) northern limb. On the northern limb, the outcropping series consists of Triassic, Jurassic and Cretaceous beds, gradually thickening to the NE (maximum 2 000 m). In some places, it is complicated by the existence of NW–SE normal faults between the Jurassic and the Lower Cretaceous. At the southern limb the outcropping Mesozoic series is relatively thin to the NW, where the Albian lies unconformably on the Upper Triassic. To the SE, the thickness of the Mesozoic increases, reaching 1 000 m at the southernmost sector, where the anticline shows an almost E–W direction (figure 1).

Most of the core of the Montalbán anticline is formed by a large outcrop of Carboniferous flysch (Culm facies). Towards the NW in the Aragonian Range, that is in continuity with the Montalbán anticline, Cambrian and Ordovician sandstones and shales crop out in the cores of the anticlines (figure 1). In the Montalbán anticline Cambrian and Devonian rocks appear in isolated outcrops (see figures 1, 6

and 7). Throughout the Aragonian Range, the Cambrian is separated from the Devonian and the Carboniferous by the Variscan Datas thrust [21, 23] (figures 6 and 7).

A common feature along the southern limb of the Montalbán anticline (cross-sections 2–2' and 4–4', figure 4, and figures 6–8) is the thrusting of the top of the Carboniferous over the Lower and Middle Triassic, that appears with vertical or overturned beds. This geometry can be interpreted as the result of an earlier stage of NE-verging thrusting. These thrusts are presently vertical or overturned (figure 7, cross-section B–B' and figure 8), which indicates that they formed before the whole southern limb of the Montalbán anticline was uplifted and overturned. These early thrusts show an upper décollement in the Upper Triassic. Since in some sections (cross-section A–A', figure 7) the Cambrian crops out in the hangingwall of one of these minor thrusts, they probably correspond to reactivations of the Variscan Datas thrust during the Tertiary (hypothesis proposed in the cross-sections of figure 4). In cross-section 2–2' (figure 4, see detail in cross-section A–A', figure 7), the differential shortening induced by the northeast-verging thrust is balanced at the upper part of the Mesozoic series by a south-verging thrust detached on the Triassic. The late folding of this thrust by the Montalbán anticline gives the geometry of a 'tête plongeante' with a synform anticline defined by sub-horizontal overturned Cretaceous beds (figures 6 and 7).

In the southeastern part of the Montalbán anticline, steeply-dipping south-verging thrusts cut across its vertical southern limb (figures 6 and 7, and cross-section 3–3' in figure 4), with the result that this limb is tectonically thinned with respect to other transects. These thrusts are usually arranged in break-back sequences, as can be inferred from the relationships between Tertiary units and the asymmetric south-verging synclines associated to these thrusts: (i) south of Armillas (figure 6), unit M5 lies unconformably on a syncline defined by M4 which, in turn, is folded by a syncline whose axial trace is shifted to the NE with respect to the former; (ii) NW of Montalbán (figure 6, see also point 6 in figure 10) the same relationship is observed between units M4 and M3; M3 shows a geometry of progressive unconformity, associated to the uplifting of the southern limb of the Montalbán anticline and M4 lies unconformably on the folded beds of M3.

In the southernmost part of the Montalbán anticline (cross-section 4–4', figure 4) the Triassic deposits are very reduced or absent, which probably indicates an unconformity between the Lower Jurassic and the Palaeozoic, similar to other areas of the Iberian Chain [37]. The upper part of the Mesozoic series (Albian sandstones) shows steeper dips (practically vertical) than the lower part (marine Jurassic, dipping 50° N, overturned). This relationship can be interpreted as a consequence of thickness changes in the Mesozoic series, that would form a southward-opening wedge. This sedimentary wedge would be the result of deposition associated to a syn-sedimentary southward-dipping

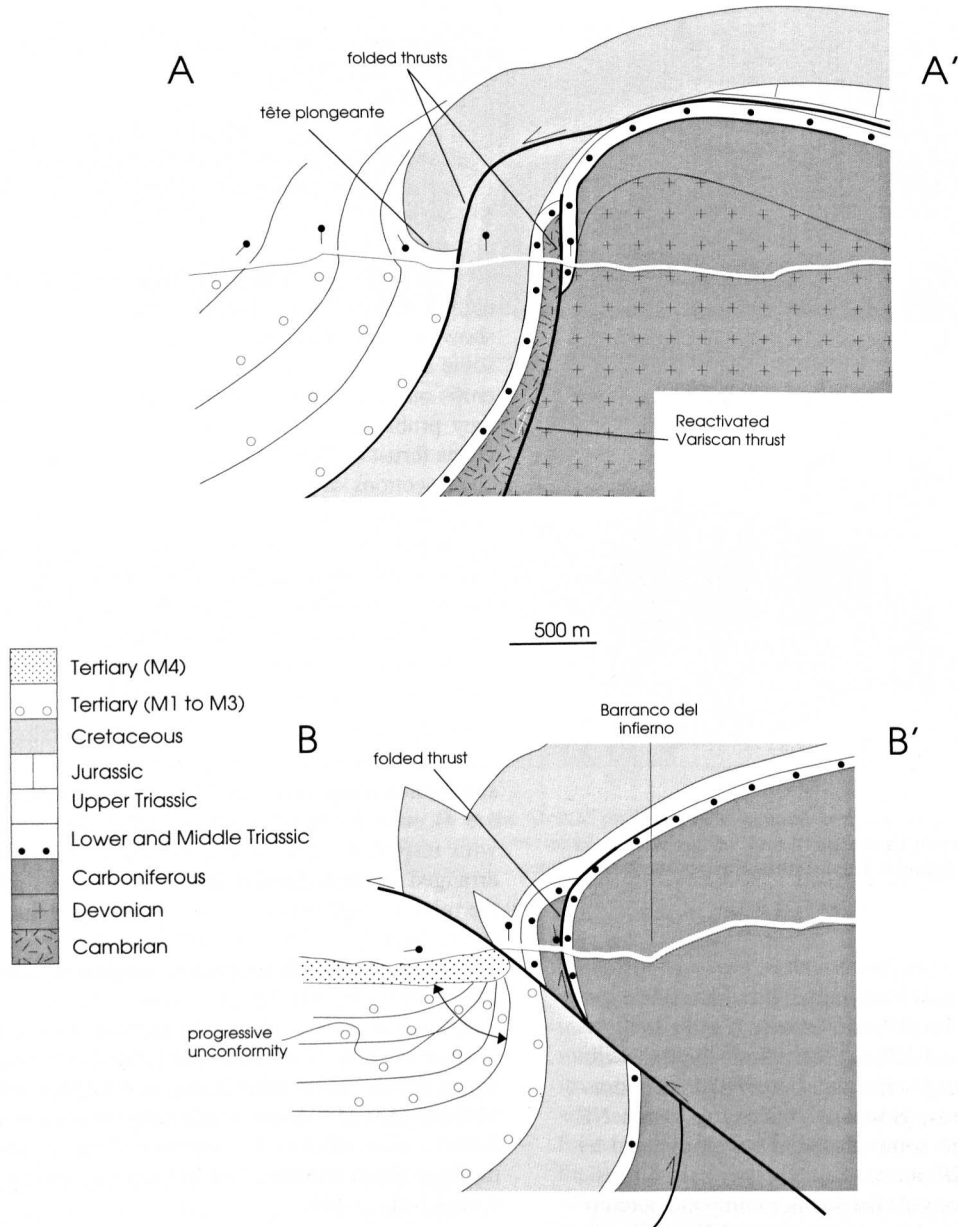


Figure 7. Detailed cross-sections of the southern limb of the Montalbán anticline. See location in figure 6.

listric normal fault during the Early Cretaceous (cross-section 5–5', restored, figure 4). This interpretation agrees with the palaeogeographical reconstructions of Early Cretaceous sedimentary basins [28, 34, 35]. In our interpretation, the Cretaceous normal fault would be now in a horizontal position below the surface (cross-section 5–5', figure 4),

with an angular relationship with beds different from the pre-deformational state. This would be due to reverse shear at the fold limb during flexural-slip folding. Nevertheless, the compressional structure can also be interpreted as the result of the reactivation of the normal fault as a reverse fault, without a shortcut in the Palaeozoic basement.

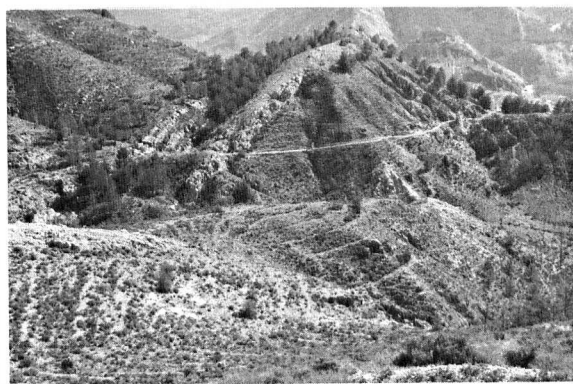
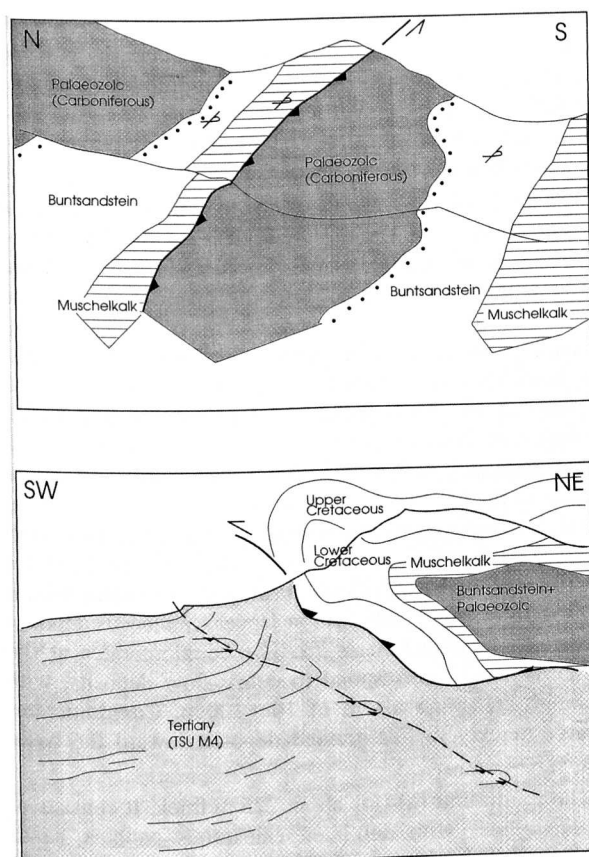


Figure 8. Geometry of the southern limb of the Montalbán anticline. A. Folded north-verging back-thrust involving the upper part of the Palaeozoic, the Lower and Middle Triassic (Buntsandstein and Muschelkalk facies, respectively). The thrust surface was overturned together with the Palaeozoic and Triassic beds during the development of the Montalbán anticline. B. Thrusted southern limb of the Montalbán anticline involving the Upper Cretaceous beds at the hangingwall and the M4 unit, defining a south-verging syncline, at the footwall. See location of photographs in figure 4.

4. The syntectonic Tertiary units

The Tertiary filling of the Montalbán Basin can be divided into five units (unconformity-bounded units or tectono-sedimentary units, TSU), bounded by unconformities at the basin margins and their equivalent conformities (identified by sedimentary breaks, that is sudden shifts and/or changes in their vertical trends) at the basin centre. Recognition and characterization of TSU is based on fieldwork, and in particular determining the vertical trend of stratigraphic series on the basis of lithological and textural data (figures 9, 10). Correlation between sedimentological profiles was done by means of photo-geological study with identification of bed contours.

Five tectonosedimentary units (labelled M1 to M5, figure 2) were differentiated within the Montalbán Basin. Each unit is characterized by its vertical trend, which appears to be uniform throughout the basin. This vertical trend usually contains a fining-upwards and a coarsening-upwards

sequence (figure 9). Unit M4 is the most widespread and occupies almost all the central and western parts of the Montalbán Basin (figure 1). The other units crop out only at basin margins. The constraints on the lateral evolution of the first and second units are poor, since they have relatively small outcropping areas (figure 1). For units M3 and M4 a 3-D reconstruction can be made since they are horizontal or shallow-dipping and they crop out along wide areas within the basin (figure 10). Unit M5 crops out only in a small area near the northern margin, but farther west it occupies most of the Calatayud Basin (figure 1).

The first unit, M1, crops out both at the northern and southern margins, only at the western part of the Montalbán Basin (figure 1). It is 250 m thick and consists of fine to medium grain-sized siliceous sandstones and shales in strata up to 20 m thick. Its depositional environment corresponds to middle and distal parts of alluvial fans, more than 50 km long [38, 39]. Palaeocurrents indicate a northward provenance, probably from the northern anticline of the Arago-

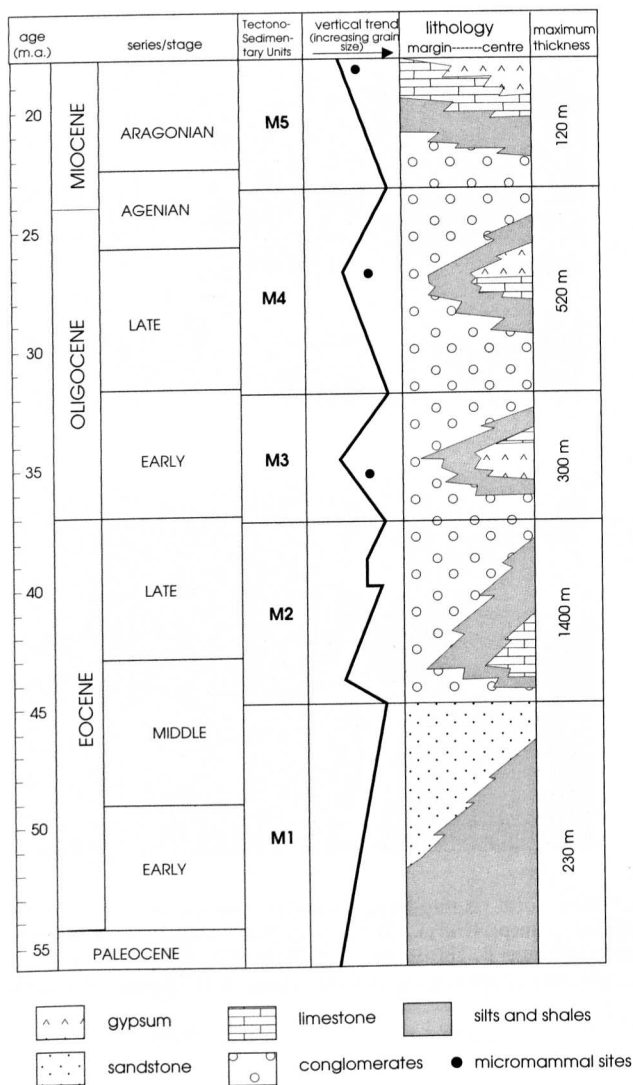


Figure 9. Stratigraphic synthetic profile showing the vertical evolution and composition of the tectono-sedimentary units defined in the Montalbán Basin.

nian Range [21, 38; 43]. The vertical evolution of the unit can be considered as gently coarsening-upwards (figure 9).

The second unit, M2, crops out at the northwestern basin margin (southern limb of the Montalbán anticline). It lies conformably on unit M1, being separated by a sharp change in grain size (figure 9). Its maximum outcropping thickness is about 1 100 m (figure 1). It consists of conglomerates, siliceous sandstones, shales and limestones. At the lower part of the unit, pebbles within conglomerates are exclusively calcareous (Mesozoic source area), whereas the rest of the unit contains calcareous and siliceous pebbles (Mesozoic and Palaeozoic source areas). The depositional envi-

ronment is that of braided streams with channels up to 10 m thick and flood plain deposits [38]. Palaeocurrents indicate a northward provenance for the outcropping part of this unit [21, 38, 43]. Its vertical trend is a fining-upward coarsening-upward sequence, with the inflection point located within the lower part of the unit.

The third unit (M3) crops out all along the southern basin margin, close to the Utrillas thrust. It is the only unit cropping out in the eastern sector of the Montalbán Basin, between the Utrillas thrust and the Montalbán anticline (figure 10). Its thickness is about 350 m. It consists of conglomerates with calcareous pebbles and shales at the northern basin margin, changing to lacustrine limestones and gypsum at the basin centre. Palaeocurrents and facies arrangement indicate provenance from both basin margins, which indicates uplifted margins to the north and south, similar to the present-day geometry (figure 10). Its vertical trend is fining-upward coarsening-upward. M3 unit is overthrust by the Utrillas thrust to the south and locally it lies unconformably on M1. To the north, east of Montalbán, it lies unconformably on Albian or Upper Cretaceous deposits (figure 4, cross-section 4–4'). The conglomerates at the northern margin correspond to debris-flow deposits, with olistoliths reaching a size of 10 × 100 m. Conglomerates change quickly to fine-grained deposits toward the basin centre.

The fourth unit (M4) is about 225 m thick. It consists of conglomerates with dominant calcareous pebbles, sandstones and shales (figure 10). Towards the basin centre some limestone beds also appear. Its vertical trend is fining-upward coarsening-upward. It crops out at both walls of the Utrillas thrust (Tertiary Aliaga and Montalbán basins, figure 1). Palaeocurrents indicate provenance from the present-day basin margins. Its depositional environment corresponds to short alluvial fans. The preserved thickness of the fifth unit (M5) in the studied area is 70 m and it consists of conglomerates with siliceous, calcareous, and sandstone pebbles.

The age of the tectono-sedimentary units can only be determined from six micromammal sites located within the basin. They indicate an Early Oligocene age for M3 and a Late Oligocene to Early Miocene age (Agenian) for M4 [21, 34, 38, 40, 41]. The age of M2 and M1 remains uncertain, and they must be comprised between the Paleocene and the Early Oligocene. By correlation with other basins, they could be Late Eocene–Early Oligocene in age [21, 42].

5. Palaeogeographic evolution of the Montalbán Basin. Tectonics–sedimentation relationships

The meaning of syntectonic unconformities and the vertical trend of tectono-sedimentary units within continental, internally drained, sedimentary basins, closed to marine

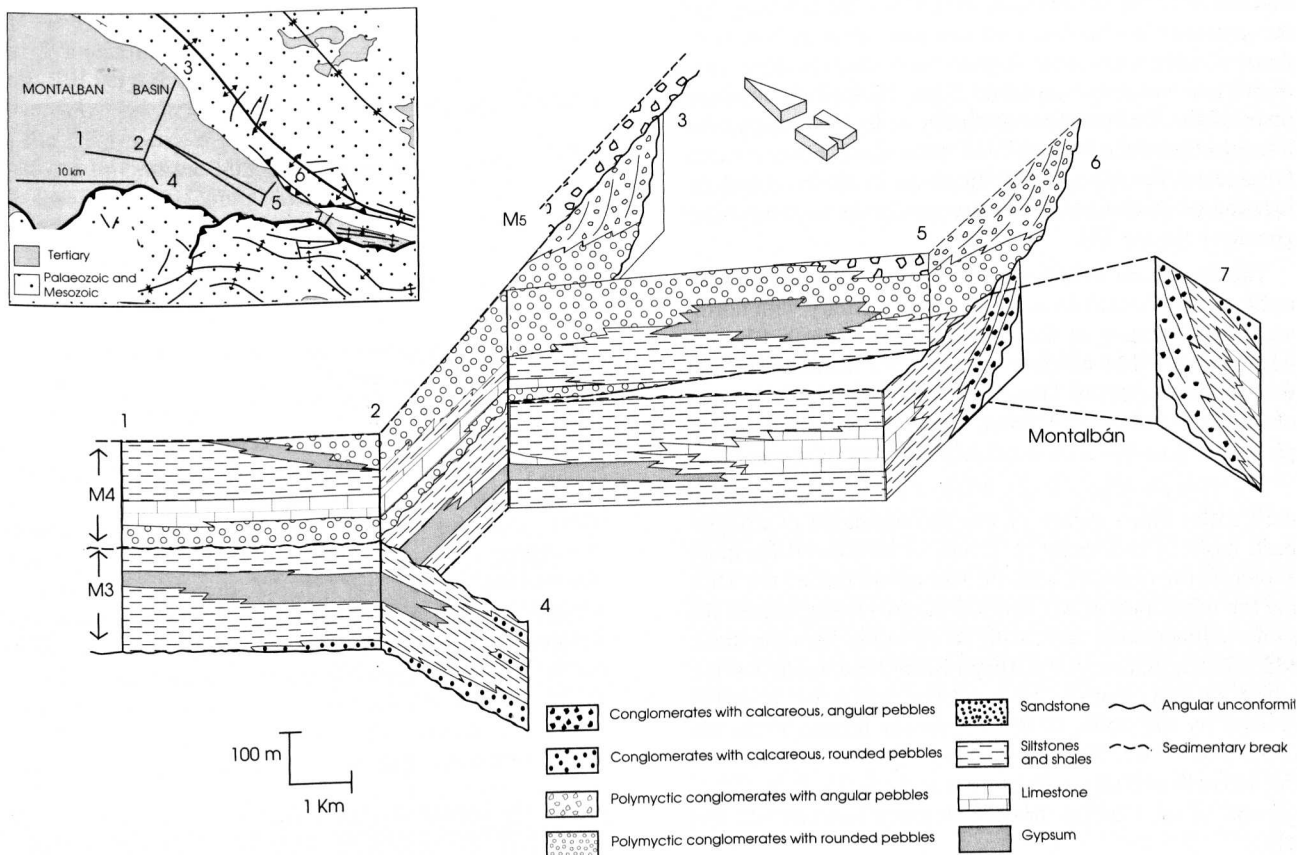


Figure 10. 3-D reconstruction of the Montalbán Basin for units M3 and M4.

influence, has been widely discussed [12–14, 18, 39, 44]. In the Montalbán Basin, unconformities and changes of the vertical trend can only have a tectonic origin, since the facies uniformity of deposits indicates that no strong climatic variations took place during the Paleogene and the Early Neogene on the inner part of the Iberian Chain. The unconformities found within the sedimentary filling of the Montalbán Basin must then correlate with major changes in the tectonic and palaeogeographic evolution of the surrounding areas.

Deposition of M1 was controlled by large structures located northwest of the studied area, probably the uplift of the Palaeozoic of the Aragonian Range. Since similar, distal facies are found in the Aliaga Basin [15] (figure 1), its depositional area was much larger than the present-day Montalbán Basin. East of the Montalbán Basin palaeocurrents in deposits equivalent to M1 show a southward provenance [44], indicating that the Montalbán anticline was not yet elevated and that deformation within the Aragonian Range progressed from the NW to the SE.

During the deposition of M2, the source area was closer to the Montalbán Basin. The occurrence of siliceous, Palaeozoic clasts, indicates an uplift of the eastern part of the Aragonian Range of more than 1 500 m (considering that the Mesozoic cover should be broadly eroded to expose the Palaeozoic in some areas). Nevertheless, the actual geometry of the basin is difficult to constrain, due to the lack of outcrops towards the south.

The deposition of M3, with conglomerates at both north and south margins (figure 10), indicates a coeval movement and uplift of the Utrillas thrust and the Montalbán anticline. The hangingwall anticline of the Utrillas thrust was also the source area for southward-directed alluvial fans, filling the piggy-back Tertiary Aliaga Basin (figure 1) [15]. In the footwall of the Utrillas thrust, there are distal facies of alluvial fans, belonging to M3, sourced in the hangingwall of this thrust. This implies that the movement of the Utrillas thrust continued after the deposition of M3. Nevertheless, in the western sector of the Montalbán Basin, conglomerates appear along the southern basin margin [38]. This fact,

together with the preservation of the hangingwall ramp and the geometry of the thrust surface (see cross-section 2–2', figure 4) indicate that the displacement after the deposition of this unit was not larger than 1.5 km. Most of the displacement of the Utrillas thrust probably took place during the transition between M2 and M3 units (Late Eocene–Early Oligocene). For M3 and M4, the shape of the basin and the location of its margins were very similar to its present-day geometry (figure 10).

The deposition of M4 was largely controlled by the final uplift of the Montalbán anticline, contemporary with northward displacement of the Utrillas thrust, indicated by the occurrence of M4 conglomerates at the hangingwall and footwall of the thrust. These were probably the final stages of movement along this thrust, although some authors [15] propose a post-M4 northward displacement of about 1 km.

The Tertiary Aliaga Basin, located at the hangingwall of the Utrillas thrust (figure 1), can be considered as a piggyback basin of this thrust [15], and its tectono-sedimentary evolution runs parallel with the Montalbán Basin [44]. During the deposition of M1 and M2 the two basins shared the same sedimentation area, with no elevation between them. M2 is much thinner in the Aliaga Basin (maximum 300 m), which suggests that the accommodation space was probably created by the uplift of the Aragonian Range. From the upper part of M2, the Tertiary Aliaga Basin separated from the Montalbán Basin, indicating that the uplift of the hangingwall of the Utrillas thrust took place between M2 and M3.

6. Discussion

6.1. Influence of inversion structures

According to our interpretation of the geometry of the Montalbán Basin and its margins (see cross-sections in figure 4), the Mesozoic faults inherited from the Triassic and Early Cretaceous rifting stages controlled the location, and partly the geometry, of the Tertiary compressional structures. From the arguments given above (see section 3.2.1.) the Utrillas thrust can be interpreted as a result of the reactivation of a system of southward-dipping normal faults (figure 11). This system would be formed by NE–SW and NW–SE-striking faults, preserved at present as the changes in direction of the Utrillas thrust (which are not the result of an outcrop effect of a south-dipping surface, see for example [22, 45]). To the north there was a sedimentary high during the Early Cretaceous, separating the Cretaceous Aliaga Basin to the south from the Oliete Basin to the north (figure 11, see also figure 2). This high was located partly over the Montalbán Basin and the Montalbán anticline [22, 28, 34, 35, 46–48].

During Tertiary thrusting, the Cretaceous Aliaga Basin was in the hangingwall of the Utrillas thrust and the sedi-

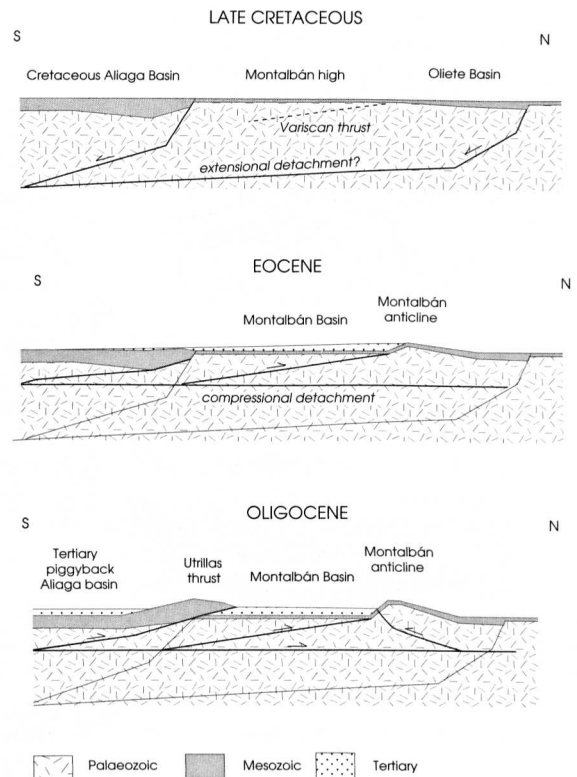


Figure 11. Conceptual sketch showing the geometry of the Mesozoic–Tertiary tectonic inversion in the Montalbán Basin.

mentary high located northward became the Tertiary-filled Montalbán Basin, and the western part of the Montalbán anticline (figure 11). The throw of the normal fault (equivalent to the complete thickness of the Mesozoic, about 2 500 m) was similar to the throw of the Tertiary thrust, but the heave of the Tertiary thrust was larger than the heave of the Cretaceous extensional faults, resulting in the complete inversion of the basin. This geometry of inversion is common throughout the Iberian Chain [13, 49] (figure 11), in contrast with other kinds of inversion in which the uplifted block during extension remains uplifted during compression [50, 51].

At the northern basin margin the change in strike of the front limb of the Montalbán anticline, from NW–SE to E–W, can be interpreted as the result of the existence of a normal fault at depth in the E–W segment (interpretation shown in cross-section 4–4', figure 4) that probably controlled the location and orientation of the front limb in its southern part.

6.2. Kinematics of the Montalbán anticline

The kinematics of the Montalbán anticline can be determined from (i) the geometry of the syn-tectonic deposits and

(ii) the thrust sequences inferred from the structural analysis. Syn-tectonic deposits indicate a break-back sequence, with SW-verging thrusts cross-cutting M3, unconformably covered by M4. In its turn, M4 is cross-cut by thrusts shifted to the NE (*figures 6 and 10*). This thrust sequence in the southern limb of the Montalbán anticline developed during the late stages of folding. Since thrusts cross-cut an overturned limb, they are the reason for some Mesozoic units missing on this limb at the present-day topographic level in some sections and produce an overall brittle thinning of the front limb of the Montalbán anticline (see cross-section 3–3', *figure 4*).

From the geometrical point of view the Montalbán anticline can be considered as a detachment anticline (hypothesis proposed in cross-sections of *figure 4*), or a fault-propagation anticline [53], compatible in both cases with a flat basal detachment located 3 km below the bottom of the Montalbán Basin (*figures 4 and 11*). This geometry can be explained by the existence of a thick series of Carboniferous shale-dominated flysch, which at the scale of Tertiary folding could behave as an incompetent level with respect to the Mesozoic cover. The Variscan structure of the Carboniferous flysch, with a much shorter wavelength, and probably a N–S trend (as inferred from the scarce outcrops, [21]), would have little influence in the development of the anticline. Only the Variscan, NW–SE striking, Datos thrust, with Cambrian sandstones in its hangingwall [21], could be responsible for nucleating small Tertiary NE-verging thrusts in the front limb of the Montalbán anticline. The location of this southern limb could be controlled by the Variscan thrust (*figure 11*).

6.3. Relationship with the shortening direction

The Montalbán Basin shows a triangular shape, limited by structures with different orientations: the Montalbán anticline trends NW–SE and the Utrillas thrust shows an overall E–W strike. From the relationships between structures and syn-tectonic units (*figure 10*) it can be seen that both structures were active during the same period (mainly the Late Eocene–Early Oligocene). The beginning of uplift was probably earlier in the Montalbán anticline (section 5 and *figure 11*).

Since the shortening direction during the Paleogene in the Iberian Chain was probably NNE–SSW (perpendicular to the northern plate margin, [22, 28, 54]), the Utrillas thrust formed perpendicular to this direction, the thrust surface within the Mesozoic cover resulting from the reactivation of NW–SE and NE–SW striking Mesozoic normal faults. The Montalbán anticline is oblique to the main shortening direction, and its orientation and location were probably controlled by pre-existing Variscan structures, as is the Datos thrust, that can be followed all along the northern anticline of the Aragonian Range [23]. The obliquity between the Montalbán anticline and the shortening direction may

explain the change in vergence along strike of the south-verging Montalbán anticline with respect to the rest of the north-verging Aragonian Range, since in transpressional regimes these changes are relatively common, the zones with opposite vergence being separated by strike-slip faults oblique to the main structure [52]. In the Montalbán anticline these faults, striking NNW–SSE, are outlined by a N–S transverse syncline involving the Mesozoic cover [21].

7. Conclusions

The Montalbán Basin is one of the most important compressional Tertiary basins within the Iberian Chain, with a thickness of syn-tectonic terrestrial sediments of about 2 000 m. Both margins of the basin, with NW–SE and E–W directions, were active during the Tertiary, giving a total shortening comprised between 8.5 and 11.5 km. The depocenter of the Montalbán Basin during the Tertiary was a relatively uplifted area during the Mesozoic, bordering to the south on an Early Cretaceous sedimentary basin inverted during the Tertiary. The normal faults limiting the Cretaceous basin were partly reactivated as reverse faults and partly cross-cut by the newly formed thrusts. The localisation and orientation of the Montalbán anticline, located at the northern basin margin, was partly controlled by Variscan thrusts. The analysis of syn-compressional sedimentary units indicates that the basin was much wider during the Eocene and the Early Oligocene (sedimentation of M1 and M2 units) and close to its present day shape by the end of the Oligocene (M3 unit), with active structures at both margins. Sedimentation along the southern limb of the Montalbán anticline influenced the geometry of minor thrusts cross-cutting this limb in break-back sequence.

Acknowledgements. This work was supported by projects PB97-0997 (Spanish Ministry of Education), "Parque cultural del río Martín" (Aragón government) and Spanish-French Integrated Action (Picasso program) HF1997-0167.

References

- [1] Jordan T.E., Flemings P.B., Beer J.A., Dating thrust-fault active by use of foreland-basin strata, in: Kleinspehn K.L., Paola C. (Eds.), *New perspectives in Basin Analysis*, Springer-Verlag, New York, 1988, pp. 307–330.
- [2] Snyder D.B., Ramos V.D., Allmendinger R.W., Thick-skinned deformation observed in deep seismic reflection profiles in Western Argentina, *Tectonics* 9 (1990) 773–788.
- [3] Cobbold P.R., Davy P., Gapais D., Rossello E.A., Sadybakasov E., Thomas J.C., Tondji Biyo J.J., Urreiztieta M., *Sedimentary basins and crustal thickening*, *Sed. Geol.* 86 (1993) 77–89.
- [4] Cook F.A., Vasek J.L., Orogen-scale decollements, *Reviews of Geophysics* 32 (1994) 37–60.

- [5] Jordan T.E., Allmendinger R.W., The Sierras Pampeanas of Argentina: a modern analogue of Rocky Mountain foreland deformation, *Am. J. Sci.* 286 (1987) 737–764.
- [6] Steidtmann J.R., Schmidt J.G., Provenance and dispersal of tectogenic sediments in thin-skinned, thrust terrains, in: Kleinspehn K.L., Paola C. (Eds.), *New perspectives in Basin Analysis*, Springer-Verlag, New York, 1988, pp. 353–366.
- [7] Jordan T.E., Allmendinger R.W., Damanti J.F., Drake R.E., Chronology of motion in a complete thrust belt: the Precordillera, 30–31° S, Andes Mountains, *The Journal of Geology* 101 (1993) 135–156.
- [8] Garrido-Megías A., Estudio geológico y relación entre tectónica y sedimentación del Secundario y Terciario de la vertiente meridional pirenaica en su zona central (provincias de Huesca y Lérida), doctoral Thesis, University of Granada, 1973, 395 p.
- [9] González A., Pardo G., Villena J., El análisis tectosedimentario como instrumento de correlación entre cuencas, II Congreso Geológico de España, Granada, 1988, 175–184.
- [10] Anadón P., Cabrera L., Colombo F., Marzo M., Riba O., Syntectonic intraformational unconformities in alluvial fan deposits, eastern Ebro Basin margins (NE Spain), *Inter. Assoc. Sediment., Spec. Pub.* 8 (1986) 259–271.
- [11] Riba O., Reguant S., Villena J., Ensayo de síntesis estratigráfica y evolutiva de la cuenca terciaria del Ebro, in: Libro Jubilar J.M. Ríos (Ed.), *Geología de España*, vol. 2, IGME, (Madrid), 1983, pp. 131–159.
- [12] Villena J., Pardo G., Pérez A., Muñoz-Jiménez A., González A., Tertiary of the Iberian margin of the Ebro Basin: 1) Stratigraphic synthesis, in: Friend P., Dabrio C. (Eds.), *Tertiary basins of Spain*, Cambridge University Press, 1996, pp. 77–82.
- [13] Muñoz-Jiménez A., Casas-Sainz A.M., The Rioja Trough (N Spain): tecto-sedimentary evolution of a symmetric foreland basin, *Basin Research* 9 (1996) 65–85.
- [14] Casas-Sainz A.M., Cortés-Gracia A.L., Maestro-González A., Intra-plate deformation and basin formation during the Tertiary within the Northern Iberian plate: origin and evolution of the Almazán Basin, *Tectonics* (in press).
- [15] González A., Guimerà J., Sedimentación sintectónica en una cuenca transportada sobre una lámina de cabalgamiento: la cubeta Terciaria de Aliaga, *Rev. Soc. Geol. España* 6 (1–2) (1993) 151–165.
- [16] Armenteros I., Dabrio C.J., Guisado R., Sánchez de Vega A., Megasecuencias sedimentarias del terciario del borde oriental de la Cuenca de Almazán (Soria-Zaragoza), *Stud. Geol. Salmanticensis* 5 (1989) 107–127.
- [17] Sanz de Galdeano C.M., Tertiary tectonic framework of the Iberian Peninsula, in: Friend P., Dabrio C. (Eds.), *Tertiary basins of Spain*, Cambridge University Press, 1996, pp. 9–14.
- [18] Alvaro M., Capote R., Vegas R., Un modelo de evolución geotectónica para la Cadena Celtibérica, *Act. Geol. Hisp. Hom. a Lluís Solé Sabaris* 14 (1979) 172–177.
- [19] Salas R., Casas A., Mesozoic extensional tectonics, stratigraphy and crustal evolution during the Alpine cycle of the eastern Iberian basin, *Tectonophysics* 228 (1993) 33–55.
- [20] Roca E., La evolución geodinámica de la cuenca Catalano-Balear y áreas adyacentes desde el Mesozoico hasta la actualidad, *Acta Geológica Hispánica* 29 (1) (1996) 3–25.
- [21] Ferreiro E., Ruiz V., Lendínez A., Lago M., Meléndez A., Pardo G., Ardevol L., Villena J., Hernández A., Alvaro M., Gómez J.J., Carls P., Mapa y memoria explicativa de la Hoja 40 (Daroca) del Mapa Geológico Nacional a escala 1:200.000, ITGE, 1991, 239 p.
- [22] Guimerà J., Alvaro M., Structure et évolution de la compression alpine dans la Chaîne Ibérique et la Chaîne Cotière Catalane (Espagne), *Bull. Soc. Géol. France* 8 (1990) 339–348.
- [23] Cortés Gracia A.L., Casas Sainz A.M., Deformación alpina de zócalo y cobertura en el borde norte de la Cordillera Ibérica, *Rev. Soc. Geol. España* 9 (1–2) (1996) 51–66.
- [24] Rodríguez Pascua M.A., De Vicente G., González Casado J.M., Cinemática y dinámica de las deformaciones en la zona del Alto Tajo (Guadalajara), *Cuadernos del laboratorio Xeológico de Laxe* 19 (1994) 163–174.
- [25] Sopena A., Virgili C., Arche A., Ramos A., Hernando S., El Triásico, *Geología de España*, vol. 2, in: Libro Jubilar J.M. Ríos, Comba J.A. (Eds.), Instituto Geol. Min. de Esp., Madrid, 1983, pp. 47–63.
- [26] Arche A., López-Gómez J., Origin of the Permian-Triassic Iberian Basin, central-eastern Spain, *Tectonophysics* 266 (1996) 443–464.
- [27] Guimerà J., Paleogene evolution of deformation in the northeastern Iberian Peninsula, *Geol. Mag.* 121 (1984) 413–420.
- [28] Soria A.R., La sedimentación en las cuencas marginales del surco ibérico durante el Cretácico inferior y su control estructural, Doctoral Thesis, Univ. de Zaragoza, Servicio de Publicaciones de la Universidad de Zaragoza, 1997.
- [29] Salas R., Martín-Closas C., Querol X., Guimerà J., Roca E., Evolución tectosedimentaria de las cuencas del Maestrazgo y Aliaga-Penyagolosa durante el Cretácico inferior, in: Salas R., Martín-Closas C. (Eds.), *El Cretácico inferior del Nordeste de Iberia*, University of Barcelona, 1991, pp. 13–94.
- [30] Guimerà J., Cenozoic evolution of eastern Iberia: structural data and dynamic model, *Acta Geol. Hisp.* 29 (1) (1996) 57–66.
- [31] Colomer M., Santanach P., Estructura y evolución del borde sur-occidental de la Fosa de Calatayud-Daroca, *Geogaceta* 4 (1988) 29–31.
- [32] Liesa C.L., Soria A.R., Meléndez A., Estudio preliminar sobre la tectónica sinsedimentaria del Cretácico inferior del borde septentrional de la Cubeta de Aliaga (Cordillera Ibérica), *Geogaceta* 20 (7) (1996) 1707–1710.
- [33] Casas A.M., Cortés A., Liesa C., Soria A.R., Terrinha P., Kullberg J.C., Rocha R., Estudio comparado de la evolución e inversión de distintas cuencas mesozoicas de la Placa Ibérica, *Geogaceta* 24 (1998) 67–70.
- [34] Canérot J., Recherches géologiques aux confins des Chaînes Ibériques et Catalane (Espagne), Doctoral thesis, University of Toulouse, Pub. ENADIMSA, 1974, 517 p.
- [35] Casas A.M., Cortés A.L., Liesa C.L., Meléndez A., Soria A.R., Estructura del borde N. de la Cordillera Ibérica entre la Sierra de Arcos y el anticlinal de Montalbán, *Cuadernos de Geología Ibérica* 23 (1997) 243–268.
- [36] Casas Sainz A.M., Oblique tectonic inversion and basement thrusting in the Cameros Massif (N Spain), *Geodinamica Acta* 6 (2) (1993) 202–216.
- [37] Sanromán J., Aurell M., Palaeogeographical significance of the Triassic-Jurassic unconformity in the north Iberian basin (Sierra del Moncayo, Spain), *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 99 (1992) 101–117.
- [38] Pérez A., Pardo G., Villena J., González A., Estratigrafía y Sedimentología del Paleógeno de la cubeta de Montalbán (prov. de Teruel, España), *Bol. R. Soc. Española Hist. Nat. (Geol.)* 81 (3–4) (1983) 197–223.
- [39] Pardo G., Villena J., González A., Contribución a los conceptos y a la aplicación del análisis tectosedimentario, Rupturas y unidades tectosedimentarias como fundamento de correlaciones estratigráficas, *Rev. Soc. Geol. España* 2 (1989) 199–221.

- [40] Crusafont M., Nuevos datos sobre la edad de los sedimentos terciarios de la zona de Utrillas-Montalbán, *Acta Geol. Hisp.* 5 (1967) 115–116.
- [41] Adrover R., Feist M., Hugueney M., Mein P., Moissenet E., L'âge et la mise en relief de la formation detritique culminante de la Sierra Pelarda (Prov. Teruel, Espagne), *C. R. Acad. Sci. Paris* 295 (1982) 231–236.
- [42] Hernández Samaniego A., Olivé Davó A., Pardo Tirapu G., Villena Morales J., Moissenet E., Mapa Geológico Nacional escala 1:50.000. Hoja nº 491, Calamocha, Instituto Geológico y Minero de España, 1983.
- [43] Pardo G., Villena J., Pérez A., González A., El paleógeno de los márgenes del umbral de Montalbán: relación tectónica-sedimentación, *Publicaciones de Geología, Universidad Autónoma de Barcelona, Homenaje a Luis Sánchez de la Torre, Grupo Español de Sedimentología*, 1984, pp. 355–363.
- [44] González A., Pardo G., Villena J., Pérez A., Estratigrafía y sedimentología del Terciario de la cubeta de Alloza (prov. de Teruel), *Bol. Geol. y Min.* 95 (1984) 407–428.
- [45] Martín Fernández M., Canérot J., Mapa Geológico Nacional escala 1:50.000. Hoja nº 517, Argente. Instituto Geológico y Minero de España, 1977.
- [46] Canérot J., Stratigraphie et paleogéographie du Crétacé inférieur de la région d'Oliete (prov. de Teruel, Espagne), *C. R. som. soc. Géol. Fr.*, fasc. 3 (1970) 119.
- [47] Canérot J., L'évolution paleogéographique du domaine ibérique oriental pendant le Jurassique supérieur et le Crétacé inférieur, *C.R. 96° Cong. Nat. Soc. Savantes, Toulouse*, t.I sect. sc., 1971, pp. 315–320.
- [48] Canérot J., Cugny P., Pardo G., Salas R., Villena J., Ibérica Central-Maestrazgo, *El Cretácico de España, Univ. Complutense Madrid*, 1982, pp. 273–334.
- [49] Casas-Sainz A.M., Gil-Imaz A., Extensional subsidence, contractional folding and thrust inversion of the Eastern Cameros Basin (NW Spain), *Geologische Rundschau* 86 (1998) 802–818.
- [50] Hayward A.B., Graham R.H., Some geometrical characteristics of inversion, in: Cooper M.A., Williams G.D. (Eds.), *Inversion tectonics, Geological Society Special Publication*, 1989, pp. 17–39.
- [51] McClay K.R., Insley M.W., Anderton R., Inversion of the Kechika Trough, northeastern British Columbia, Canada, in: Cooper M.A., Williams G.D. (Eds.), *Inversion tectonics, Geological Society Special Publication*, 1989, pp. 235–257.
- [52] Casas A.M., Cortés A., Gapais D., Nalpas T., Román T., Modelización analógica de estructuras asociadas a compresión oblicua y transpresión, *Ejemplos del NE peninsular, Rev. Soc. Geol. España* 11 (3–4) (1998) 137–150.
- [53] Jamison W.R., Geometric analysis of fold development in overthrust terranes, *J. Struct. Geol.* 9 (1987) 207–219.
- [54] Casas-Sainz A.M., Maestro-González A., Deflection of a compressional stress field by large-scale basement faults. A case study from the Tertiary Almazán Basin (North Spain), *Tectonophysics* 255 (1996) 135–156.