Journal of the Virtual Explorer, 2002
Volume 08
Paper 4
http://virtualexplorer.com.au/

# The Pyrenean orogen: pre-, syn-, and post-collisional evolution

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Keywords: Pyrenees, Alpine-Himalayan belt, Ebro foreland basin, thrust timing

**Abstract:** The Pyrenean Mountains represent the westernmost end of the long Alpine-Himalayan collisional system. The excellent preservation of foreland basin deposits in conjunction with folds and thrusts has been the basis for the numerous papers on the syn-tectonic evolution of the Pyrenees. Many of these papers quantified the geological processes: inversion tectonics, fold-and-thrust development, foreland and hinterland sequences of thrusting, growth strata, and control of stratigraphy on tectonics as well as tectonics on sedimentation. Geophysical data also constrain the crustal and lithospheric structure. The pre-orogenic Mesozoic rift basins exerted a significant influence on the Pyrenean thrust system. Later, the opening of the València trough was also important for the late development of the Eastern Pyrenees. Both, the pre- and post-orogenic evolution deserve more attention.

In this paper we present an integrated synthesis of the Pyrenees from the middle Cretaceous to the present showing the pre-, syn- and post-collisional evolution ranging from plate tectonics to single anticlines and thrusts. Special emphasis is given to the timing of deformation related to both compression during collision and the later extension related to the opening of the València trough.

A lithospheric section across the Central Pyrenees and another along the strike of the Eastern Pyrenees show the present-day structure at depth. The present-day crustal structure of the Western Pyrenees almost reflects the final stage of the Pyrenean orogenic growth, since there have not been major post-collisional events in the region. The eastern Pyrenees, however, show a relatively rapid thinning of the crust and lithosphere towards the E due to the strong overprinting of Neogene and Quaternary extensional events. Most of the easternmost Pyrenean landscape is related to block uplift related to normal faulting.

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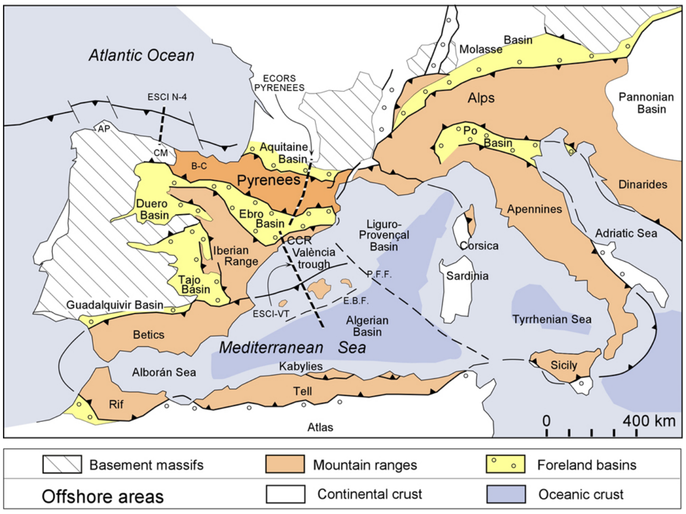
## Introduction

The Iberian Peninsula constitutes the westernmost segment of the 12,000-km long Alpine-Himalayan Belt originated by the Tertiary closure of the Tethys during the collision of India, Arabia and Africa against Asia and Europe (e.g., Dercourt et al., 1986). The Iberian Peninsula, constituted a separated microplate between Africa and Europe. The continuous motion of Africa towards the north and northwest concluded with the Pyrenean continental collision between Iberia and Europe before the opening of the western Mediterranean basins in Oligocene times (Fig. 1). Deformation propagated intraplate producing the inversion of previous Mesozoic rifted basins with different orientations: NE-SW trend for the Catalan Coastal Ranges, and NW-SE trend for the Iberian Range. The Betic Cordillera, showing an ENE-WSW direction, also corresponds to the inversion of the southern Iberian Margin together with oceanic fragments related to the former Africa-Iberia oceanic transform boundary.

**Figure 1. Map of western Europe**




Map of western Europe with location of principal orogenic chains related to the Africa-Europe collision (from Vergés and Sàbat, 1999). The Pyrenean Range corresponds to the westernmost limit of the about 12,000-km long Alpine-Himalayan Belt. The ECORS Pyrenees, the ESCI Valencia Trough and the ESCI N-4 Iberian Margin are shown. CCR: Catalan Coastal Ranges; B-C: Basco-Cantabrian thrust belt; CM: Cantabrian Mountains; and AP: As Pontes.

The Pyrenean orogen constitutes a well-know orogenic system because its relative small size and well-constrained syntectonic deposits. In its foreland basins, particularly in the Ebro Basin where it is possible to determine the timing of shortening of individual structures as well as the sequences of deformation both perpendicular and parallel to the strike of the chain. However, total inversion of Mesozoic basins permits the observation of both extensional and compressional geometries, which are important for oil industry. Finally, a large amount of geophysical data mostly assembled along the ECORS profile in the Central Pyrenees together with a youth topography and river drainage development permit to investigate the recent rise of the Pyrenean Mountains, as we know them today.

We present in this paper a summary of major geodynamic events that took place between Iberia and Europe since the middle Mesozoic starting with the Mesozoic rifting and formation of the Gulf of Biscay in the Western Pyrenees. The syn-collisional evolution of the Pyrenees shows the geometry and timing of the Pyrenean fold-and-thrust belt. The paper terminates with the present-day crustal and lithospheric structures of the Pyrenees, which provide the final stage representative of the sum of the entire evolution.

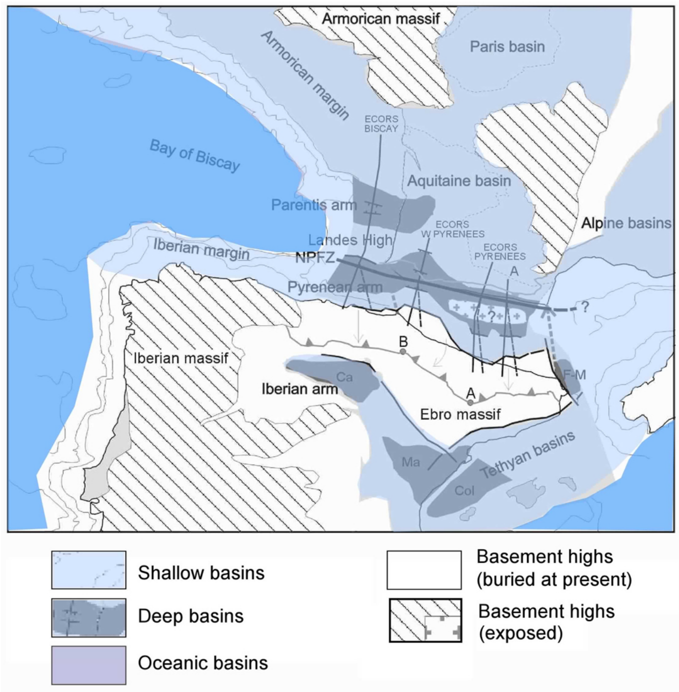
## Pyrenees evolution

The evolution of the Iberian and European plate boundary evolved since the early Mesozoic as: a) a rifted margin during the extensional and transtensional Mesozoic episodes, b) a collisional margin during the Tertiary, and c) a large-scale passive margin during most of the late Miocene and Quaternary (e.g., Ziegler, 1988; Srivastava et al., 1990; Olivet, 1996), (Fig. 2).

**Figure 2. Map of the Pyrenees combining topography and geology**


The Pyrenean Range consists of the North Pyrenean thrust system (in green), basement Axial zone (in brown), and the South Pyrenean thrust system (in green for upper thrust sheets and yellow for lower thrust sheets). The Aquitaine and Ebro basins constitute the foreland basins of the Pyrenees.

**Figure 3. Restored map**




Restored map at the end of Late Cretaceous times to show the distribution of principal sedimentary basins along the Pyrenean rift system. This reconstruction combines the plate reconstruction by Olivet (1996) and results of crustal-scale transect reconstruction by Vergés and García Senz (2001). Abbreviations: Ca: Cameros Basin, Ma: Maestrat Basin, Col: Columbretes Basin, F-M: Figueres-Montgrí Basin. Position and extend of Columbretes Basin after (Roca, 1996a). Sardinia is shown in its restored position prior to Neogene opening of the Gulf of Lyons (Olivet, 1996). The Balearic Islands are shown in their restored position, prior to Neogene opening of the Valencia Trough (Vergés and Sàbat, 1999).

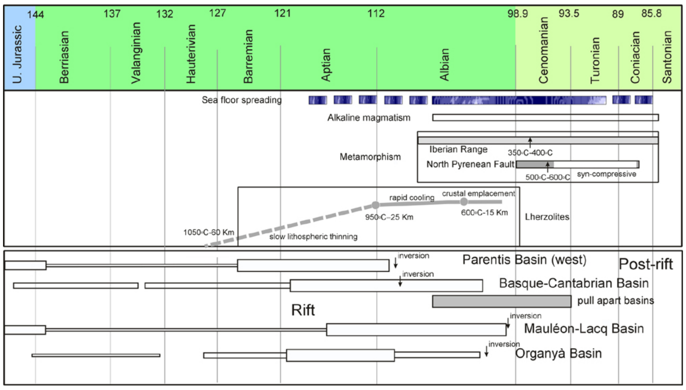
## Mesozoic pre-collisional history

Extension was the predominant mechanism of deformation in the Iberian Plate during the northern propagation of the opening of the Atlantic Ocean during Mesozoic times as well as in the rest of Western Europe. The Iberian Plate moved independently from Africa and Europe along the Azores-Gibraltar plate boundary in the S and the North Pyrenean Fault Zone in the N (e.g., Srivastava et al., 1990; Olivet, 1996). Rift systems and final continental break-up developed along the western margin of the Iberian Plate (offshore Galicia and Portugal; e.g., Malod and Mauffret, 1990), within the continental plate (Iberian and Catalan rifts; e.g., Salas et al., 2001), and along the two plate boundaries (Betics and Pyrenean rifts in the S and N, respectively), (Fig. 3).

In this large-scale plate tectonics framework, the Pyrenean rift took place in an ESE-WNW trending branch and culminated with the continental separation between Iberia and Europe and the opening of the Bay of Biscay along its western segment (e.g., Le Pichon and Barbier, 1987; Pinet et al., 1987). The Pyrenean rift connected the Bay of Biscay with the Tethys Ocean to the E (Fig. 3).

The initiation of the Pyrenean rift took place synchronously to the opening of the North Atlantic starting in Triassic times at about 250 Ma (Ziegler, 1990). Two periods of rifting (late Jurassic-Early Cretaceous and late Barremian-Albian times) have thinned the crust between Iberia and Europe controlling the formation of most important Pyrenean extensional basins: (Fig. 4), (e.g., Vergés and García Senz, 2001).

**Figure 4. Major extensional geodynamic events**




Major extensional geodynamic events developed during the Early and Late Cretaceous. (from Vergés and García Senz, 2001). Time scale after Gradstein et al. (1995).

Several major concurrent geodynamic events took place from middle Albian to the end of Cenomanian along the Pyrenean rifted region (Fig. 4):

(a) end of extension in all sedimentary basins,

(b) opening of the Bay of Biscay (García-Mondéjar, 1996; Le Pichon and Barbier, 1987),

(c) anticlockwise 35¼ rotation of the Iberian Plate,

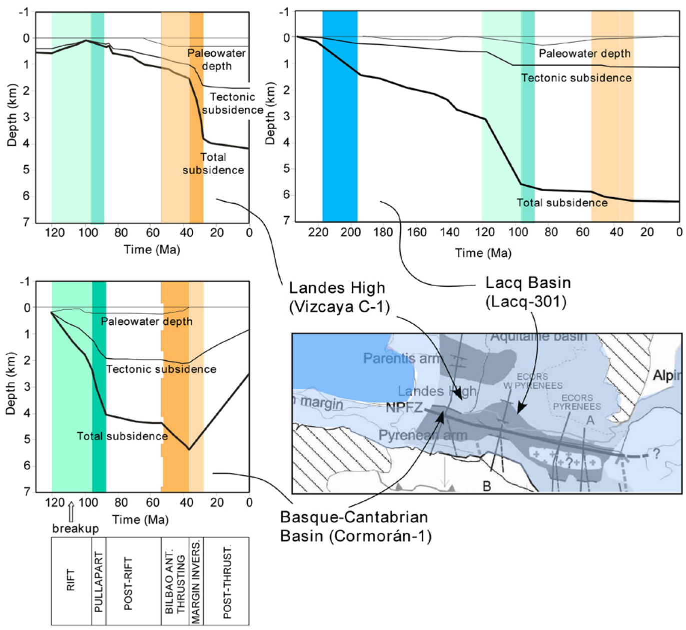
(d) development of pull-apart basins linked to the transtensional motion of the Iberian Plate boundary (the present-day North Pyrenean Fault Zone; Choukroune and Mattauer, 1978),

(e) magmatic events, metamorphism and emplacement of upper mantle slices into the pull-apart basins (Fabriès et al., 1998; Montigny et al., 1992).

Away from the transcurrent North Pyrenean Fault Zone, post-rift development was characterised by the thermal relaxation of the lithosphere widening the former rift basins with opposed fault systems. These syn-rift faults were later inverted during compression becoming the Pedraforca-South Central and the Basco-Cantabrian units to the S and the NW Pyrenean thrust system to the S of the Lacq-Mauleon basins.

Differential vertical motions across the boundaries of these Mesozoic basins are determined by subsidence analysis from the Lacq Basin (Brunet, 1984), and the Landes High and the Basco-Cantabrian Basin (Gómez et al., 2002), (Fig. 5). The late Barremian-Albian rift and post-rift tectonic subsidence curves of the Lacq and Basco-Cantabrian basins show a similar evolution. On the contrary, the Landes High experienced uplift during the same period. The Basco-Cantabrian Basin was affected by renewed subsidence during early stages of compression and then was uplifted above the thrust system, which produced flexural subsidence in the Landes High foreland basin to the N. The Lacq Basin experienced moderate subsidence in the early stages of basin inversion. The initial hydrocarbons generation started during Cenomanian times (e.g., Bourrouilh et al., 1995; Le Vot et al., 1996). However, the tectonic inversion and uplift of the Basco-Cantabrian Basin produced the total exhumation of the petroleum systems after Paleocene-Eocene times (Vergés and García Senz, 2001; Gómez et al., 2002), whereas they were preserved in the Lacq Basin.

**Figure 5. Subsidence curves**



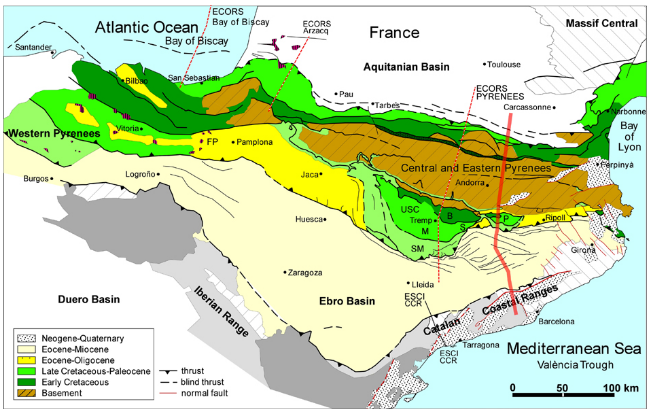

Subsidence curves for the Lacq Basin (from Brunet, 1984), the Landes High and the Basco-Cantabrian Basin (from Gómez et al., 2002), showing differential tectonic evolutions, which controlled the petroleum generation and preservation.

## Tertiary collisional history

The continental collision of Iberia and Europe produced the formation of the Pyrenean orogen with a partial subduction of the Iberian lithosphere to the north (Choukroune and team, 1989; Roure et al., 1989; Muñoz, 1992; Beaumont et al., 2000), (Fig. 6). The South-Pyrenean flexural foreland basin developed as underfilled and marine from 55 to 37 Ma and then overfilled and continental from deposition of the Cardona evaporitic level (~37 Ma) to the end of shortening during the Oligocene (Puigdefàbregas and

Souquet, 1986; Puigdefàbregas et al., 1992; Vergés et al., 1995; Vergés et al., 1998), (Fig. 7).

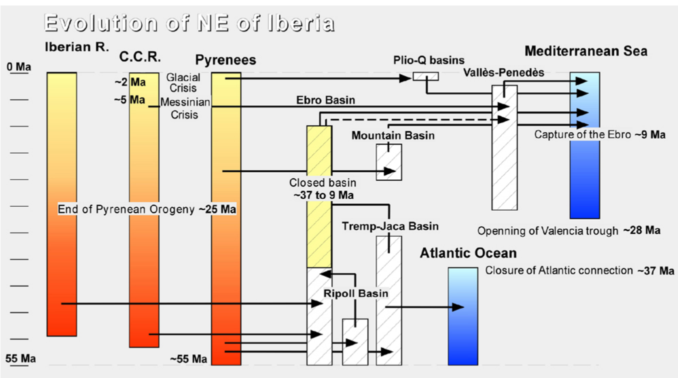
### Figure 6. Deep crustal-scale reflection profiles




Map of the Pyrenees showing the location of deep crustal-scale reflection profiles across the Pyrenees and Catalan Coastal Ranges (red discontinuous lines are deep seismic reflection profiles). Red continuous line shows the location of both the crustal-scale cross-section in Fig. 8 and the balanced geological section in Fig. 10.

At the middle-late Eocene boundary (~37 Ma), the uplift of the Western Pyrenees triggered the end of the foreland basin stage and originated an intermontane basin limited by the Pyrenees, the Catalan Coastal Ranges and the Iberian Range (Burbank et al., 1992a; Vergés and Burbank, 1996). An internal fluvial network delivered sediments to the Ebro Basin characterised by a large central lake (e.g., Anadón et al., 1979; Arenas and Pardo, 1999).

### Figure 7. Sediment flow diagram




Sediment flow diagram for the Cenozoic evolution of NE Iberia between the mountain ranges (Pyrenees, Iberian Ranges (Iberian R.) and Catalan Coastal Ranges (C.C.R.), and the basins (see Fig. 6 for location). Active tectonics in mountains is depicted in reddish whereas the post-orogenic phase after about 25 Ma is depicted in yellowish. Ebro foreland basin and Ripoll and Tremp-Jaca piggyback basins were opened towards the Atlantic Ocean during initial stages of foreland development. Subsequently, the Ebro basin remained closed from ~37 Ma to ~9 Ma when it opened to the Mediterranean Sea. This opening occurred by the capture of the internal Ebro basin drainage by the Vallès-Penedès rift related rivers (García-Castellanos et al., 2001).

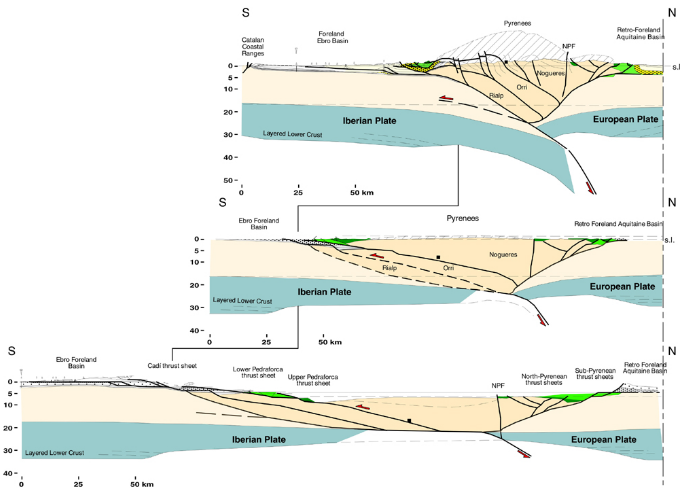
The end of deformation determined by magnetostratigraphy on growth strata attached to the front of the Pyrenean fold-and-thrust belt occurred during late Oligocene times (~24.7 Ma) (Meigs et al., 1996) although major basement uplift determined from fission track cooling ages ended at about 30 Ma (Fitzgerald et al., 1999).

During late Miocene times the endorheic Ebro fluvial system opened towards the Mediterranean Sea (e.g., Coney et al., 1996; García-Castellanos et al., 2001).

## *Structural units*

The Pyrenean orogen is an asymmetrical, double-wedge continental belt. The southern, and most significant, thrust system developed on top of the subducted Iberian Plate, whereas the northern thrust system developed on top of the European Plate (Fig. 8). From north to south the Pyrenean orogen comprises: 1) the Aquitaine retro-foreland basin, related to the northern Pyrenean wedge, 2) the North Pyrenean Thrust System, 3) the Axial Zone of the chain, formed by basement rock units, 4) the South Pyrenean Thrust System, and 5) the Ebro Foreland Basin associated with the southern Pyrenean wedge (e.g., Muñoz et al., 1986; Muñoz, 1992; Vergés et al., 1995).

**Figure 8. Eastern Pyrenees**




Eastern Pyrenees crustal-scale balanced and two restored sections during middle Lutetian and Early Cretaceous times (see discussion and techniques in text). See location of section in Fig. 6.

From E to W, the chain has been divided into Eastern Pyrenees from the Mediterranean Sea to the Segre Thrust (S in Fig. 6), the Central Pyrenees to the Pamplona Fault (FP in Fig. 6) and the Western Pyrenees. The irregular geometry of the Southern Thrust Sheets (mainly the upper ones) is inherited and corresponds to the boundaries of the Mesozoic extensional basins. The South Central Unit (USC in Fig. 6) has a trapezoidal shape bounded by the Segre thrust in its eastern termination and by a set of ~N-S trending folds and thrusts (such the Mediano and Boltaña anticlines) in its western termination (Séguret, 1972).

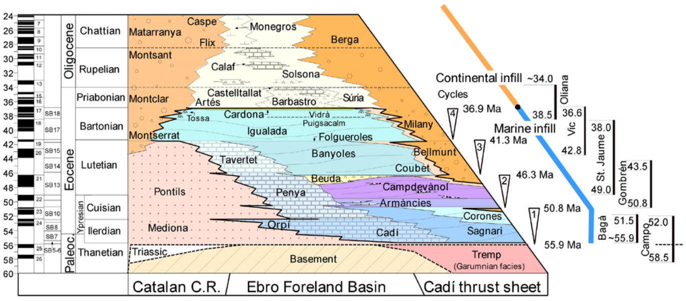
The western continuation of the Pyrenees has been less explored than the eastern and central segments. During the last decade, however, a large effort has been made to study the Alpine component of the mountain ranges aligned with the Pyrenees to the west of the Pamplona Fault (Fig. 1 and Fig. 6). To the west of the wide Basco-Cantabrian system of folds and thrusts (e.g., Cámara, 1997), the Cantabrian Mountains, mainly constituted by Paleozoic rocks, have been interpreted as uplifted above a 30¼ thrust ramp dipping towards the N during the Alpine compression overthrusting lower Miocene deposits of the Duero Basin (Alonso et al., 1996). To the N, the Alpine structure of the Western Pyrenees and Cantabrian Mountains is well imaged in the ESCI N-4 deep seismic profile (Alvarez-Marrón et al., 1995; Pulgar et al., 1996), (see location in Fig. 1). This profile shows a north-directed thrust system involving Tertiary deposits on top of transitional to oceanic crust of the Bay of Biscay.

Towards the western end of the Iberian Peninsula, small transpressional basins (alike As Pontes in Fig. 1) were infilled with alluvial to lacustrine deposits during late Oligocene and earliest Miocene (Cabrera et al., 1996; Huerta et al., 1997).

### A section through the eastern Pyrenees

The Pyrenees consists of the North Pyrenean thrust system, basement Axial Zone (in ruled brown), and the South Pyrenean thrust system (in green for upper thrust sheets and yellow for lower thrust sheets), (Fig. 6). A balanced and two restored sections across the eastern Pyrenees show the complete structure of the Pyrenean orogen (Vergés et al., 1995), (Fig. 8). The upper crustal rocks have been balanced by the length of the strata. Basement units and the lower layered crust have been balanced by area. In the intermediate restored section during middle Lutetian it is assumed that erosion (ruled pattern) is equivalent to the early to middle Eocene clastic basin fill and that the Nogueres basement unit has been internally thickened during its emplacement. The final composite restored section shows the unfolding of all sedimentary basins and basement units. Four different stratigraphic levels have been taken as horizontal reference levels: the Cardona Formation, the top of the Beuda Formation, the top of the Paleocene section and the base of the Late Cretaceous section. Surface and subsurface geometry between the lower Cretaceous basins is speculative (see discussion in Vergés and García Senz, 2001). A lithospheric numerical modelling has been performed along the Central Pyrenees following the ECORS profile (Beaumont et al., 2000). These authors concluded that the formation of the Pyrenees was influenced by the reactivation of Mesozoic and Hercynian structures and that the Iberian lower crust and upper mantle were subducted below the mountain chain.

**Figure 9. Stratigraphic panel across the Eastern Pyrenees and its related foreland basin**




Biostratigraphic data combined with magnetostratigraphic information define the chronostratigraphic framework of the study area (Burbank et al., 1992a; Burbank et al., 1992b; Serra-Kiel et al., 1994; Vergés and Burbank, 1996; Serra-Kiel et al., 1998). Global polarity time scale from Cande and Kent (1995), and larger foraminifera shallow bentic zones (SBZ) from Serra-Kiel et al. (1998).

The southeastern Pyrenean fold-and-thrust belt shows very well preserved coupled tectonic and sedimentation (Fig. 9) permitting to determine rates of geological processes (Fig. 10). From S to N the section shows:

(a) the almost undeformed foreland basin with the SE-sourced Montserrat fan-delta (López-Blanco et al., 2001), (Fig. 10 A);

(b) the Oló, Súria and Cardona detached and thrusted anticlines above the Cardona salt décollement level (Ramírez and Riba, 1975; Vergés et al., 1992; Sans and Vergés, 1995; Sans et al., 1996), (Fig. 10 B);

(c) alluvial and fluvial Upper Eocene-Lower Oligocene sediments show a double syntectonic wedge geometry related to the growth of the Puig-reig anticline;

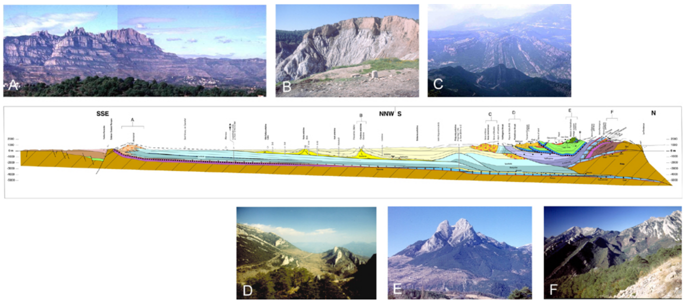
(d) the frontal Vallfogona thrust limits the allochthonous south Pyrenean units (Cadí and Pedraforca thrust sheets); a substantial number of upper Eocene-lower Oligocene growth strata are linked to the emergent front of the Pyrenees alike in Sant Llorenç de Morunys area (Riba, 1976; Ford et al., 1997; Suppe et al., 1997), (Fig. 10 C).

(e) the Lower Pedraforca thrust sheet is constituted by several tectonic units describing a break-back sequence of thrusting dated by different units of lower and middle Eocene growth strata (Martínez et al., 1988; Ramos et al., 2002), (Fig. 10 D).

(f) the Upper Pedraforca thrust sheet is constituted mainly by lower Cretaceous rocks forming a positive inversion along the southern margin of the lower Cretaceous extensional basin. Alluvial and fluvial Paleocene deposits overlap the basal thrust recording the latest emplacement of the thrust sheet (Vergés and Martinez, 1988; Vergés, 1999), (Fig. 10 E).

(g) the present gentle south dipping position of the Upper Pedraforca basal thrust is due to the general southern tilting of thrust sheets during the emplacement of lower and younger basement thrust sheets (Muñoz et al., 1986), (Fig. 10 F).

**Figure 10. Balanced section across the southeastern Pyrenees**




Balanced section across the southeastern Pyrenees with selected pictures from different tectonic units (from Vergés, 1999). Views of the southern margin of the Ebro Basin with the fan delta conglomerates of Montserrat (A), of the Cardona detachment anticline (B), of the Sant Llorenç de Morunys growth strata (C), of the front of lower Pedraforca thrust sheet front -N is to the left of the picture- (D), of the upper Pedraforca thrust sheet (E), and of the basement-cover contact dipping to the S (F). See location of section in Fig. 6.

Total shortening between points A and B is 69.2 km or 54% (Vergés, 1999), whereas the total shortening in this transect is about 125 km (Vergés et al., 1995).

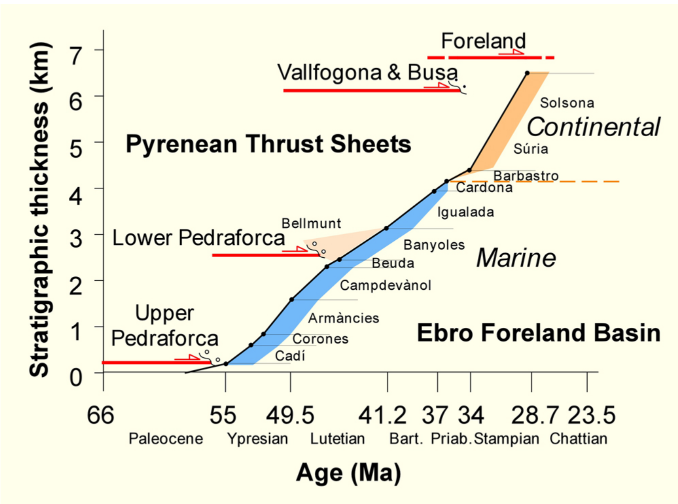
Along the ECORS profile, the comparison of balanced and restored crustal sections results in 149 km of shortening (Muñoz, 1992) and 165 km according to modelling (Beaumont et al., 2000). Shortening decreases from the Central Pyrenees towards the W. A transect to the E of the Pamplona Fault accounts for 80 km of shortening (Teixell, 1998), whereas only 50 km is accounted for the Basco-Cantabrian fold-and-thrust belt. To the W, the Cantabrian Mountains display more than 26 km of shortening (Alonso et al., 1996).

Area balancing using balanced and restored sections along the ECORS profile determined that the amount of lower crust and upper mantle missing is of about 90 km, which could be due to subduction of the Iberian plate underneath Europe (Muñoz, 1992). This possibility was confirmed by the magnetotelluric survey along the same profile (Pous et al., 1995; Vacher and Souriau, 2001). These studies shows a steep north-dipping, high conductivity body, which reaches a depth of about 90 km and has been interpreted as subducted partly melted lower crust and lithospheric mantle.

## *Timing and rates of shortening*

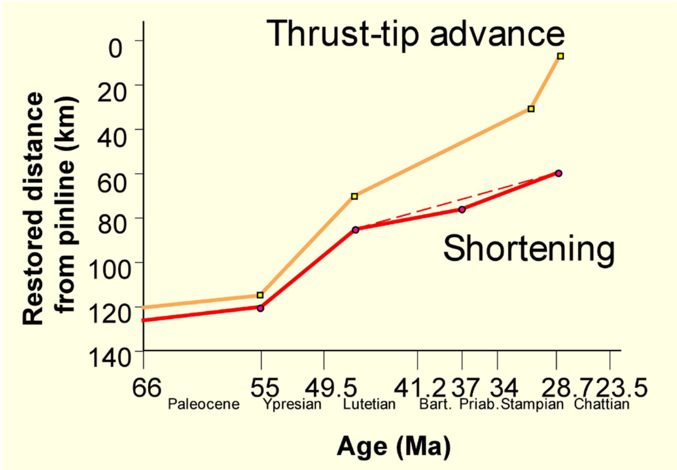
The Eastern Pyrenean sections permit to calculate the timing of thrust sheet emplacement and rates of shortening and thrust tip advance as depicted in Fig. 11 and Fig. 12. However, the good preservation of growth strata along the strike of the Pyrenean Range (Vergés et al., 2002) permits the calculation of rates of shortening in selected transects covering more than 410 km.

**Figure 11. Syntectonic foreland sediments**




Undecompacted stratigraphic thickness of syntectonic foreland sediments from Paleocene to Oligocene time and age of cover and basement thrusting along the Eastern Pyrenees cross-section depicted in Fig. 10 (from Vergés et al., 1995).

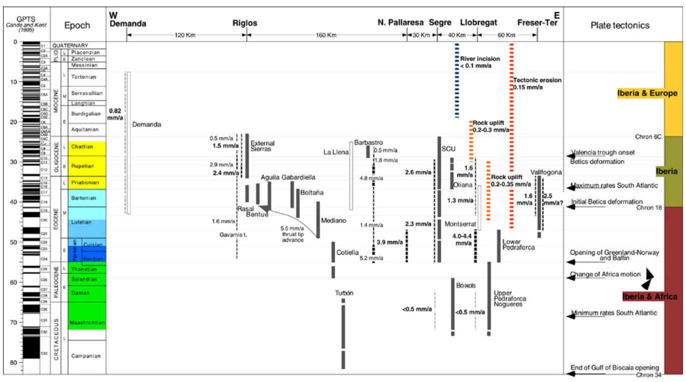
**Figure 12. Rates of shortening**




Rates of shortening along Eastern Pyrenees cross-section depicted in Fig. 10 (from Vergés et al., 1995). Rock uplift rates during Pyrenean shortening are based on cross-section reconstructions (Vergés et al., 1995). Tectonic erosion of 0.15 mm/yr is based on crustal-scale reconstructions across the Eastern Pyrenees (Vergés et al., 1995). This calculation, however, assumes a simple approach with a constant rate of uplift and erosion during both the collision and post-collision stages. Maximum rates of erosion took place during the Pyrenean orogen (Fitzgerald et al., 1999), and during the dissection of the Pyrenees and Ebro Basin after its opening towards the Mediterranean at ~9 Ma (see Fig. 7). River incision rate was also calculated to give a minimum amount. If we use the same numbers but starting at about 9 Ma we obtain almost 0.2 mm/yr.

The distribution of the rates of shortening for the southern part of the Pyrenees shows 3 different periods roughly related with the emplacement of different thrust sheets (Fig. 13), (based on Vergés, 1999).

**Figure 13. Timing of deformation**



Timing of deformation along the strike of the Pyrenees (see details in text).

The first period (older than 55 Ma) was characterised by very low shortening rates of less than 0.5 mm/a and related to the emplacement of the uppermost thrust sheets as a result of the positive tectonic inversion of pre-existing rifted Mesozoic basins (upper Pedraforca, Bóixols and Turbón thrust sheets). The second period (from 55 to 47 Ma), which corresponded to the highest rates of shortening between 4.0 and 4.4 mm/a, was correlated to the motion of the intermediate units (lower Pedraforca and South Central Unit thrust sheets). The front of these thrust sheets had a submarine emplacement during the consumption of previously thinned Iberian crust. A third period (from 47 Ma to the middle Oligocene), in which rates varied from 1.5 to 2.6 mm/yr. Deformation during this period affected the transition zone between thinned and undeformed crusts.

The combination of the southern Pyrenees shortening rates with a constant shortening rate of 1 mm/yr for the northern side of the orogen supports a convergence rate between the northeastern part of the Iberian plate (the present Ebro Foreland Basin) and Europe of almost 6 mm/yr during the most rapid period of continental plate collision during the early-middle Eocene (Vergés et al., 1995).

Rates to the west of the Noguera Pallaresa river are deduced from Meigs and Burbank (1997). The Mediano, Boltaña, Gabardiella, Pico del Aguila, Bentué and Rasal anticlines consitute a set of N-S oriented anticlines developed following an oblique-lateral propagation of deformation at the western termination of the South Central Unit. The rate of oblique-lateral propagation of deformation was 5.5 mm/yr (data from Millán et al., 1994; Poblet and Hardy, 1995; Poblet et al., 1997). Rates along the Riglos transect include results from Hogan and Burbank (1996) and Teixell (1996). The la Demanda thrust sheet shortening rates are from Muñoz-Jiménez and Casas-Sainz (1997). Other cross sections, which provide timing information, are constructed along the Noguera Ribagorçana river (Teixell and Muñoz, 2000) and to the east of the Pamplona Fault (Teixell, 1998).

Although the shortening data related to the Catalan Coastal Ranges are less reliable growth strata close to its front provide a good indication of deformation time. The Montserrat fan-delta conglomeratic section (López-Blanco et al., 2001) and the La Llena alluvial-fluvial system (Colombo and Vergés, 1993) indicate the timing of thrusting in the southeastern margin of the foreland Ebro basin.

The end of thrusting was diachronous, migrating from east to west (this interpretation could be modified by the lack of younger deposits in the eastern Ebro Basin due to the important exhumation processes, which occurred after the cessation of thrusting during Oligocene times. Between the Freser-Ter and and Segre transects the migration rate for the end of thrusting was 11 mm/yr. and from this transect to the west was 20 mm/yr.

Major plate tectonic events related to the Iberian Plate during the Tertiary are shown in Fig. 13. Although their close relationship with Pyrenean events may be conjectural, there is a remarkable coincidence between high rates of thrusting in the Pyrenees and both the abrupt change of the Africa convergence vector (Srivastava and Tapscott, 1986) and the initiation of the opening of Greenland, Baffin and Norway Seas at early Eocene times (Ziegler, 1992). The end of this period of rapid deformation coincides with the initiation of deformation on the Betics, documented by field data (e.g., Lonergan and Mange-Rajetzky, 1994). The end of Pyrenean thrusting roughly corresponds with important deformation in the Betics (Banks and Warburton, 1991) and with extension of the westernmost Mediterranean Sea related with the formation of the Gulf of Lions and the València Trough (e.g., Roca, 2002).

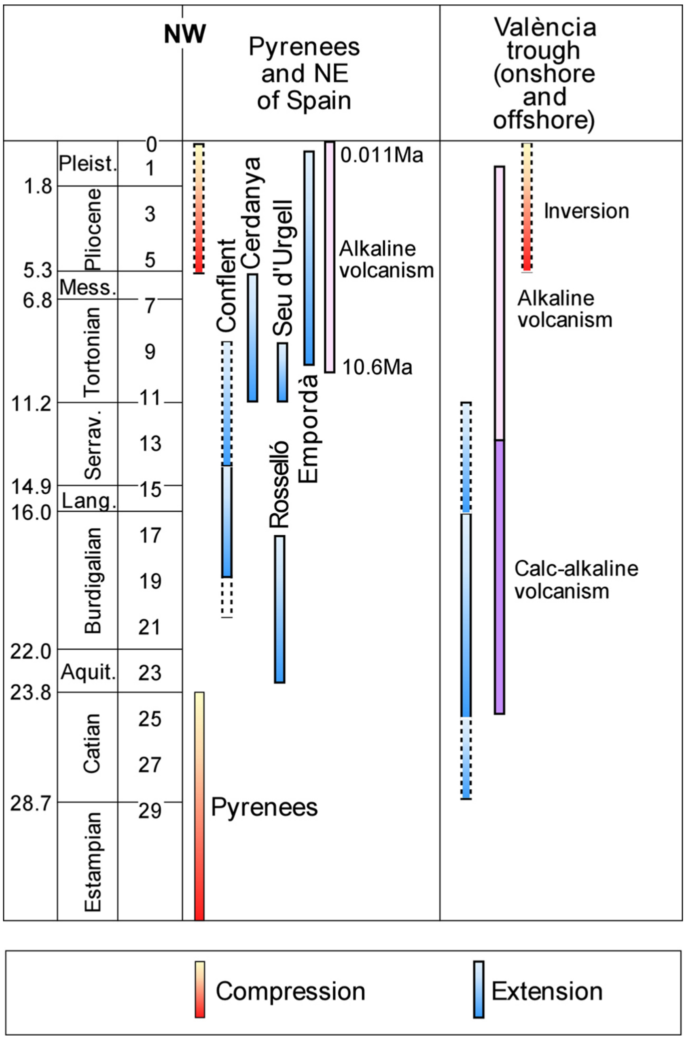
## Cenozoic post-collisional history of the Pyrenees

The transfer of tectonic activity from the Pyrenees to the Betics took place at the Oligocene-Miocene transition forcing important geodynamic changes around and inside the Iberian plate (Fig. 13). Major variations along the Pyrenean chain occurred at its eastern termination whereas a slight compression remained to the W.

Since middle Oligocene times the opening of the Valencia Trough created an extensional fault system paralleling most of the eastern coast of NE Spain (e.g., Roca et al., 1999; Roca, 2001), (Fig. 6). However, towards the NE the fault system cut obliquely across the Catalan Coastal Ranges. Concomitant differential crustal-mantle thinning produced the uplift of segments of the Catalan Coastal Ranges as well as of the SE margin of the Ebro Basin (e.g., Morgan and Fernàndez, 1992; Lewis et al., 2000; López-Blanco et al., 2001), recently quantified by apatite fission track studies (Juez-Larré and Andriessen, 2001). This uplift of more than 1.5 km is responsible for the significant dissection of this margin from which the more resistant Eocene, SE-derived conglomeratic fan deltas and alluvial fans of Montserrat and Sant Llorenç del Munt constitute the present-day maximum altitude along this area (Lewis et al., 2000), (Fig. 10 A).

The Pyrenean belt was also affected by extension with the development of Neogene and Quaternary grabens (e.g., Cabrera et al., 1988; Roca, 1996b), (Fig. 14). From middle Miocene to Recent, NW-SE trending faults developed at an almost right angle to the eastern Pyrenean structures (Fig. 6). This extensional system is related to the extrusion of basaltic lavas sourced in the asthenospheric mantle at about 55-60 km of depth (e.g., Martí et al., 1992; Neumann et al., 1999).

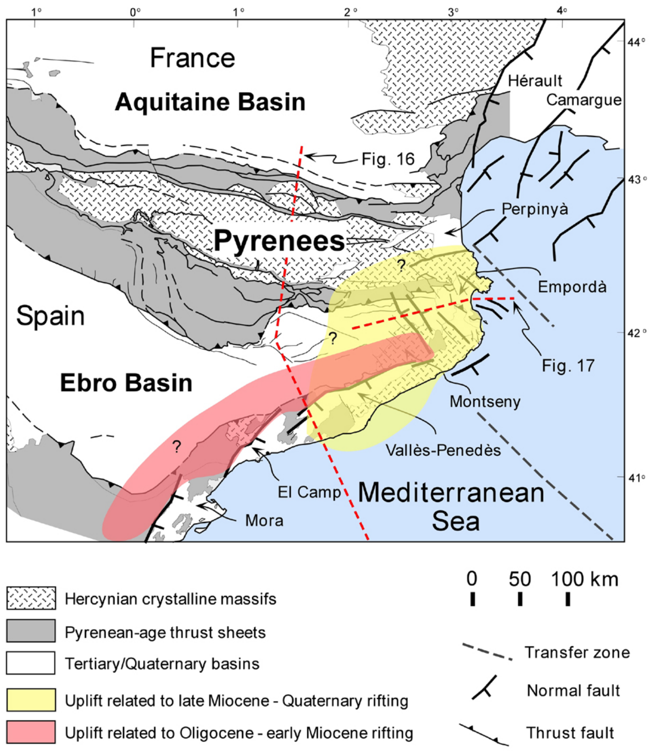
**Figure 14. Post-collisional history of Eastern Pyrenees and Valencia Trough**




Timing of deformation of post-collisional history of Eastern Pyrenees and Valencia Trough from Oligocene to Recent. A system of normal faults cut the eastern end of the Pyrenees forming graben basins (modified from Vergés and Sàbat, 1999).

Increasing topography towards the E along the axis of the Ebro Basin (towards the footwall of the youngest Amer-Brugent normal fault) constitutes the Transverse Range parallel to the fault itself. This eastward increasing of the mean elevation and local relief together with the large-scale tilt of the NE Ebro Basin produced significant uplift related to a combination of lithospheric thinning and crustal faulting since middle Miocene times (Lewis et al., 2000). This younger uplift affected a much broader area than Oligocene-early Miocene uplift and overprinted it (Fig. 15). This uplift has been related to the general westwards migration of normal fault activity and extrusion of volcanics and interpreted as produced by the progressive lithospheric thinning in the same direction (Cabal and Fernàndez, 1995; Lewis et al., 2000).

**Figure 15. NE corner of Iberian Peninsula**




Map of NE corner of Iberian Peninsula displaying two uplifted areas related to late syn- and post-collisional Cenozoic extension: redish for Oligocene to early Miocene and yellowish for middle Miocene to Recent (modified from Lewis et al., 2000).

The recent history of the Pyrenees is dominated by slight compression as determined from instrumental earthquake focal mechanisms (Goula et al., 1999; Souriau and Pauchet, 1998). An important cluster of seismic activity has been recorded along the western segment of the North Pyrenean Fault Zone suggesting the reactivation of Pyrenean structures.

## Crustal and lithospheric present-day structure

The crustal structure across and along the strike of the Pyrenean mountains show well preserved crustal thicknesses derived from its thickening during the Tertiary continental collision and only modified in the eastern Pyrenees by late Neogene and Quaternary extension.

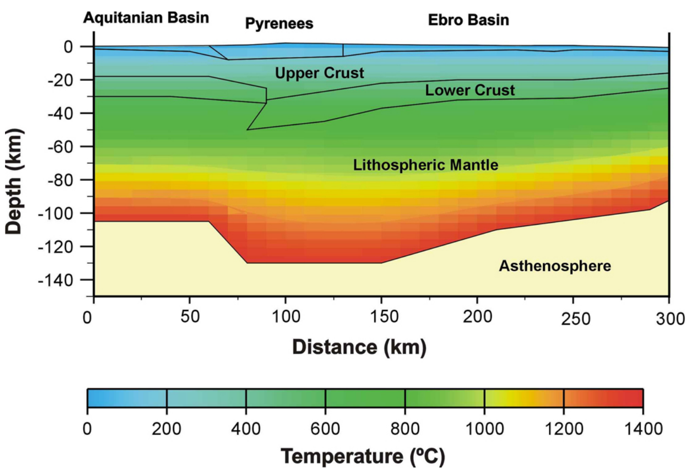
The Iberian crust shows thickening towards the N reaching maximum values of about 50 km below the northern Pyrenees (Gallart et al., 1981). The European crust also thickens towards the south reaching maximum values of about 40 km in the central Pyrenees. The geometry of the Iberian and European crusts beneath the Pyrenees was determined from the ECORS deep seismic reflection survey across the centre of the mountain chain (Choukroune and team, 1989; ECORS Pyrenees Team, 1988)]. This profile shows a highly reflective lower crust gently dipping towards the north in the Iberian side and towards the south in the French side. North-dipping Iberian reflectors however reach the northern part of the Pyrenees and are located underneath the European crust, indicating subduction to the north. The base of this reflective unit was identified as the Moho at 32 km beneath the stable Iberian plate and at 30 km beneath the external part of the Aquitaine basin. Gravity modelling based on gravity data collected along the ECORS profile reproduces the basic crustal geometry below the Pyrenean orogen (e.g., Torné et al., 1989).

Variations of the crustal structure along the strike of the Pyrenean chain are determined from the completion of the gravity anomaly map of the Pyrenees (Casas et al., 1997) as well as using a combination of Bouguer and geoid anomalies (Vacher and Souriau, 2001). Maximum crustal thickness corresponds to the central Pyrenees where topography is higher and decreases towards both the Mediterranean Sea and the Atlantic Ocean in accordance to topography. The reduction in crustal thickness to the west of the chain agrees with the corresponding decrease of the amount of calculated shortening (about 80 km according to Teixell, 1998). The more dramatic reduction in crustal thickness in the easternmost Pyrenees is due to the late overprint of Neogene extension related to the opening of the Valencia Trough in the Western Mediterranean (Vidal et al., 1998; Gallart et al., 2001).

The Pyrenean structure to the W of the Pamplona Fault has been determined by using deep seismic profiling (Fernández-Viejo et al., 2000; Fernández-Viejo et al., 1998). The crustal structure is similar to the Central Pyrenees one with thicknesses increasing towards the N reaching its maximum of 50 km underneath the Mármoles Fault, interpreted as the western continuation of the North Pyrenean Fault (Martínez-Torres et al., 1994). The resultant crustal geometry is interpreted as the product of the moderate subduction of the Iberian Plate to the N.

The lithospheric structure under the Pyrenees is determined by integrating the Bouguer anomaly, the topography and the heat flow in a single model (Zeyen and Fernàndez, 1994), (Fig. 16). The geometry of the lithosphere shows thickening beneath the Pyrenean orogen. The lithosphere thickness roughly mimics the crustal geometry being thicker below the inner part of the mountain. The geometry of this lithospheric root is progressive in the Iberian side with increasing thicknesses from about 105 km in the undeformed part of the Ebro Basin to 130 km below the range. The passage from the undeformed Aquitaine Basin to the French part of the chain is more abrupt.

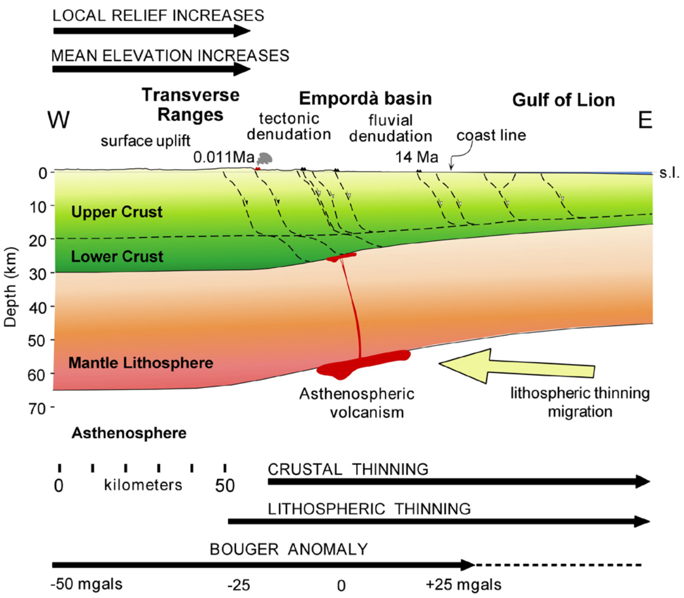
**Figure 16. N-S lithospheric transect**




N-S lithospheric transect along the ECORS profile showing a lithospheric root underneath the Pyrenees. The transect is based on integrating Bouguer anomalies, topography and heat flow data (from Zeyen and Fernàndez, 1994). Location in Fig. 15.

The lithospheric geometry of the Eastern Pyrenees is imaged along the strike of the eastern Ebro Basin (Ayala et al., 1996; Lewis et al., 2000), showing crustal and lithospheric thinning towards the Mediterranean Sea (Fig. 17).

**Figure 17. E-W lithospheric transect**




E-W lithospheric transect to show the present-day geometry of the eastern termination of the Pyrenean Range (location in Fig. 15). The profile integrates surface and subsurface data (modified from Lewis et al., 2000). The colors of the section are not directly related to temperatures as in Fig. 16.

## Conclusions

The convergence between Iberia and Europe started in latest Cretaceous and culminated with the formation of the Pyrenean orogen and the Betic Cordillera at the westernmost end of the Alpine-Himalayan belt. The onset of Pyrenean compression took place about 35 My after the end of major rifting events along the Pyrenean branch in Albian times.

The growth of the Pyrenees was greatly influenced by the former extensional geometry at different crustal and lithospheric scales: from controlling the position of the Tertiary Iberian subduction located in the extremely thinned lithosphere along the North Pyrenean Fault Zone plate boundary to the total tectonic inversion of the irregular Mesozoic basins as the case of the South Central Unit in the southern Central Pyrenees.

Most important Pyrenean shortening lasted for about 40 My and was partitioned along several thrusts describing an overall forelandward propagation of deformation. Maximum shortening occurred across the Central Pyrenees and decreased towards the west. The late Oligocene-early Miocene age of the younger compression in the Western Pyrenees was synchronous to the extensional processes, which affected the Eastern Pyrenees related to the formation of the Western Mediterranean.

Western Pyrenees shows the crustal structure acquired at the end of shortening whereas the present-day crustal and lithospheric structure of the Eastern Pyrenees points out the strong overprinting of the Neogene and Quaternary thinning.

The actual Pyrenean landscape, however, was mainly sculpted after the opening of the endorheic fluvial system of the Ebro Basin towards the Mediterranean in the late Miocene times eroding and incising the smooth overfilling of the southern Pyrenean Ebro Basin.

## Acknowledgements

This work was carried out with the support of project 1999 SGR 00208, funded by the Comissionat per Universitats i Recerca of the Generalitat de Catalunya, Grups de Recerca Consolidats, II Pla de Recerca de Catalunya.

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