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Crustal structure and orogenic material budget in the west central Pyrenees

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Abstract. Surface and subsurface data are combined to construct a crustal-scale cross section of the western central Pyrenees (France and Spain) at the boundary between the European and Iberian plates. The position of Moho reflections in the ECORS-Arzacq reflection profile suggests a tectonic wedge of European crust and upper mantle had indented the Iberian plate at lower crustal levels. The European wedge is overlain by an upper, Iberian wedge thus constituting a double (stacked) wedge geometry. The upper wedge was delaminated and deformed giving rise to the Pyrenean orogenic prism, manifested as a bivergent fan in upper crustal levels. The underthrust lower Iberian plate has been imaged to depths of 55-60 km, but crustal budget considerations based on a palinspastic reconstruction require that this continental root subducted to depths up to 90 km. Total orogenic contraction calculated from surface structures is about 75-80 km, which was accomplished between the latest Cretaceous and the early Miocene at an averaged rate of 1.2 mm/yr. Consistent with these moderate values, exhumation of the orogen is much less than in the more shortened eastern parts of the range. Paleozoic basement and preorogenic Mesozoic rocks are little eroded, and much of the exhumation involved cannibalization of early foreland basins, which once covered the entire, poorly emergent orogen at this transect. This resulted in a continuous process of sediment recycling and, coupled with a considerable lateral arrival of material, a bulk negative erosion-sedimentation budget.

1. Introduction

The understanding of the deep structure of collisional mountain ranges has improved in the past years as a result of extensive seismic reflection profiling [e.g., *Ando et al.*, 1984; *Allmendinger et al.*, 1987; *Bayer et al.*, 1987; *Cook et al.*, 1988; *Choukroune et al.*, 1989; *Pfiffner et al.*, 1990; *Meissner et al.*, 1991, and references herein]. This wealth of data has spurred discussion on orogenic aspects like subduction of continental lithosphere and crustal delamination [e.g., *Roure et al.*, 1989; *Laubscher*, 1989; *Pfiffner et al.*, 1990; *Bois*, 1991; *Muñoz*, 1992; *Cook and Varsek*, 1994; *Marchant and Stampfli*, 1997].

The Pyrenees are a mountain range that formed in Late Cretaceous to Tertiary times at the collisional boundary between the European and Iberian plates [*Choukroune et al.*, 1989]. They are an east-west trending, bivergent orogen flanked by two foreland basins, the Ebro basin in the south and the Aquitanian basin in the north (Figure 1). Pyrenean contractional deformation involved an old Hercynian (Paleozoic) basement, a series of Mesozoic preorogenic basins, and synorogenic latest Cretaceous to Tertiary sediments of the proximal foreland basins. The northern part of the orogen is characterized by north vergent thrusting and a thick Mesozoic succession ("North Pyrenean Zone" of *Choukroune and Séguret* [1973]). The southern side of the orogen is characterized by a wide south vergent belt that incorporates thick Tertiary synorogenic successions and includes a basement-involved thrust stack called the Axial Zone (Figure 1).

Seismic reflection profiles have been acquired in various parts of the Pyrenean orogen (Figure 1), namely, the Etude Continentale et Océanique par Reflexion et Refraction Sismique (ECORS)-Pyrenees line, across the eastern part of the central Pyrenees, the ECORS-Bay of Biscay and the Estudios Sísmicos de la Corteza Ibérica (ESCIN)-2, offshore and onshore in the western Pyrenees and Cantabrian mountains, and the ECORS-Arzacq in the west central North Pyrenean Zone [*Choukroune et al.*, 1989; *Pinet et al.*, 1987; *Daignières et al.*, 1994; *Pulgar et al.*, 1996]. In spite of these data, several doubts concerning the deep structure still remain, and different models, emphasizing the role of subduction, wedging or crustal imbrication, are in debate [e.g., *Roure et al.*, 1989; *Mattauer*, 1990; *Muñoz*, 1992]. In addition, there seem to be significant lateral variations in the structure of the orogen. The purpose of this paper is to present a new crustal transect of the west central part of the Pyrenees (Figure 1), based on surface geology [*Teixell*, 1996] and on published information of the recently acquired ECORS-Arzacq reflection profile [*Daignières et al.*, 1994] (see location in Figure 1). The resultant crustal-scale section (Ansó-Arzacq section) illustrates the importance of tectonic wedging at different levels of the crust as a thickening mechanism. The section serves as a basis for a discussion on material balance in the Pyrenean orogeny, which addresses both the entire crust and the near surface. This permits us to evaluate crucial aspects as crustal subduction and the budget of erosion and sedimentation during growth of the orogen.

2. South Pyrenean Thrust Belt

The South Pyrenean thrust belt includes the Axial Zone basement massif and imbricated Mesozoic and Tertiary rocks to the south and west of it (Figure 1). Details of the stratigraphy and structure along the well-exposed study transect (named "the Ansó transect") are given by *Teixell* [1990,

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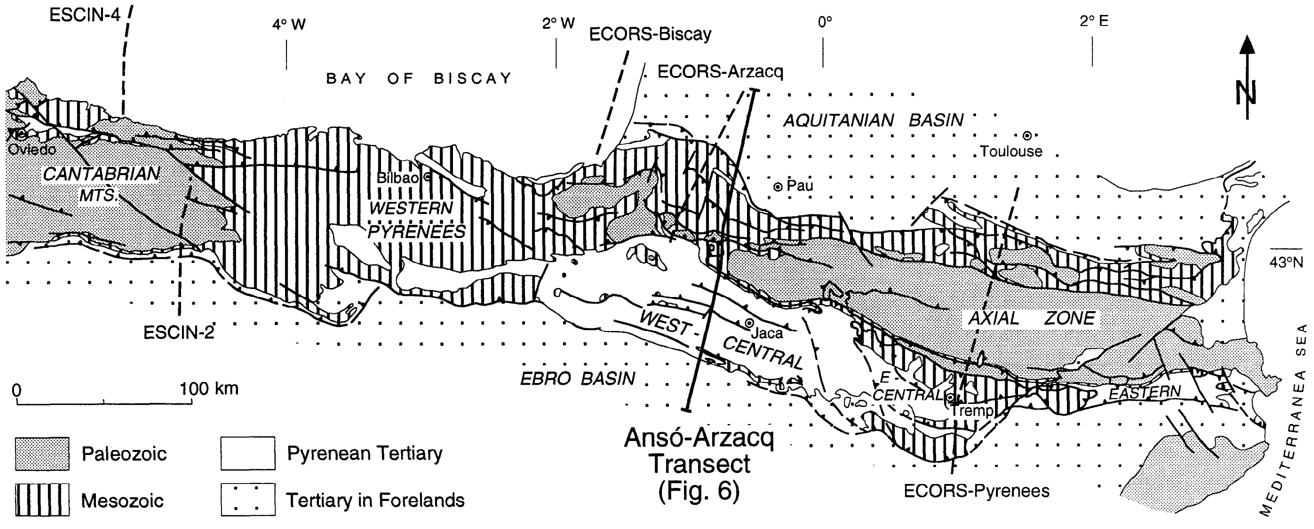

Figure 1. Tectonic map of the Pyrenees and Cantabrian mountains, showing the location of the study transect (Ansó-Arzacq section) and the trace of deep seismic reflection profiles that have been acquired across the orogen (dashed lines).

1992, 1996]. Post-Hercynian rocks consist of basal Triassic shale and gypsum followed by a southward tapering prism of Upper Cretaceous carbonates, shales, and sandstones. Tertiary syntectonic rocks include several thousands of meters of deformed Eocene to lower Oligocene flysch and molasse, constituting the Jaca basin [*Puigdefàbregas,* 1975; *Labaume et al.,* 1985; *Barnolas and Teixell,* 1994]. Basement and cover rocks form three major imbricate thrust sheets (Lakora, Gavarnie, and Guarga), all of them with a southern vergence (Figure 2). Also included in the belt are the small cover thrust sheets of the Chaînons Calcaires region, which, though classically included in the North Pyrenean Zone, are still south vergent (Figure 2). The leading edge of the Guarga thrust sheet overrides the autochtonous Ebro foreland at the mountain front of the External Sierras (Figure 2). The Ebro foreland basin contains Oligocene and Miocene sedimentary rocks [*Riba et al.,* 1983].

In the east central and eastern Pyrenees, thrust sheets of basement rocks are arranged in an antiformal stack, creating a high structural relief (Axial Zone) [*Williams and Fischer,* 1984; *Muñoz et al.,* 1986; *Muñoz,* 1992]. However, in the west central Pyrenees, major thrust sheets exhibit less degree of overlap [*Teixell,* 1996] (Figure 2). They constitute crustal ramp anticlines with flat tops at different elevations, separated by monoclinal flexures of the frontal culmination limbs. The Axial Zone culmination can still be recognized, corresponding to the hanging wall anticline of the Gavarnie thrust (Figure 2); the fold shows a westerly plunge of 11° that causes the termination of the Paleozoic outcrops. The geometry and angular relationships of these culminations indicate that the basal thrust faults form low-angle (<20°) ramps in basement that flatten to bedding-parallel décollements at the base of the cover, within the Triassic or the Upper Cretaceous (Figure 2). Comparable gentle ramp angles (about 15°) of Alpine-age

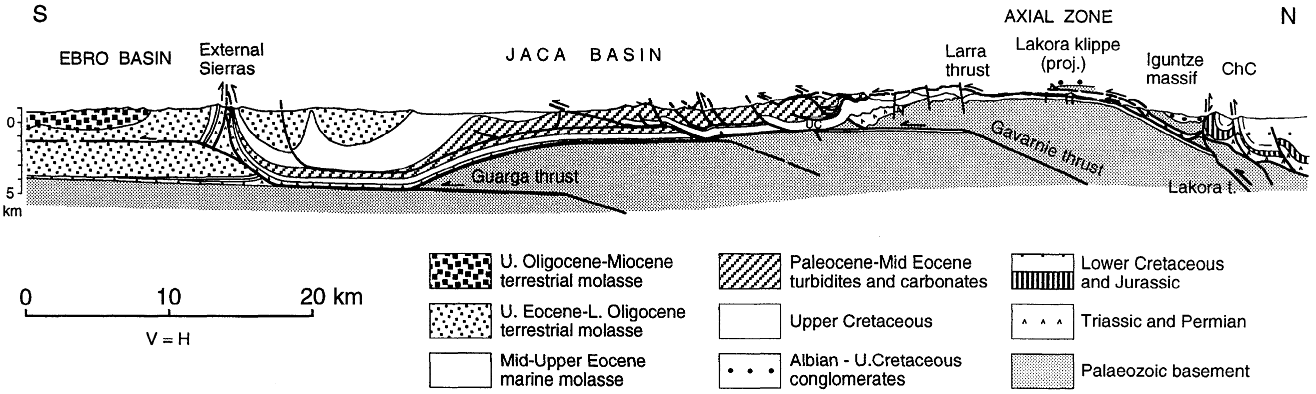

Figure 2. Cross section of the South Pyrenean thrust belt in the west central part of the range (southern part of Ansó-Arzacq section line in Figure 1) (simplified after *Teixell* [1996], see this publication for a geological map and details on the stratigraphy and structure). Note the imbricated pattern of the stacking of basement units, the limited thickness of Mesozoic rocks, and the thick synorogenic Tertiary deposits incorporated in the thrust belt (Jaca basin). The mountain front is at the External Sierras. ChC is Chaînons Calcaires.

thrusts in basement rocks were deduced by *Alonso et al.* [1996] in the Cantabrian Mountains. The basal cover décollements root distinct upper level thrust systems, whose relationships with synorogenic sediments indicate a piggyback sequence of deformation from (latest Cretaceous?) Eocene to early Miocene times. The Lakora thrust probably initiated in the latest Cretaceous, although its main activity was in early to mid-Eocene time, including a footwall splay called the Larra thrust [*Teixell*, 1993, 1996]. The Gavarnie thrust was active during late Eocene to early Oligocene times, whereas the Guarga thrust took up final compressional deformation from the late Oligocene to the earliest Miocene [*Teixell,* 1992, 1996]. The present length of the South Pyrenean thrust belt in the transect, including the Chaînons Calcaires region, is 73 km. The cumulative shortening caused by the thrust system is close to 55 km (about 43%).

3. North Pyrenean Thrust Belt

In the northern part of the range, the principal feature of the north vergent belt of the Pyrenees is a thick Mesozoic succession, which includes several thousands of meters of deep water shales and turbidites of Aptian to Late Cretaceous age. These dominate in outcrop and accumulated in a rapidly subsiding rift or transtensional basin, later inverted during the Pyrenean compression [*Peybernès and Souquet,* 1984; *Séguret and Daignières,* 1986; *Ducasse and Velasque,* 1988]. Underlying these rocks are Triassic shales and evaporites followed by Jurassic and Aptian-Albian carbonates, which are encountered in exploratory and productive oil and gas wells. The margin of the Cretaceous flysch basin is now observed in the Iguntze-Mendibelza massifs (Lakora thrust sheet), where Albian and Upper Cretaceous conglomerates and breccias directly overlap the Paleozoic basement [*Boirie and Souquet,* 1982]. Farther south, the Upper Cretaceous deposits of the southern Pyrenees represent shelf facies of the basin wings. Cretaceous crustal thinning was associated to alkaline magmatism [*Azambre and Rossy,* 1976], and the associated extensional faulting was accompanied by contemporaneous salt tectonics of the Triassic layer [*Canerot,* 1988].

The cross section through the present North Pyrenean thrust belt (Figure 3) has been constructed from geological maps and available subsurface information [*Alimen et al.,* 1963; *Casteras and Paris,* 1971; *Soler,* 1972; *Le Pochat et al.,* 1976; *Societé Nationale Elf Aquitaine Production (SNEAP),* 1991]. The southern limit of the belt, that is, the divergence axis between the south and north vergencies occurs along a synclinal zone (the Roguiague syncline), without a major bounding fault (Figure 3). In more eastern parts of the orogen, the divergence occurs along the so-called North Pyrenean fault, a major vertical structure that is supposed to have been generated as a strike-slip fault in mid-Cretaceous times, defining the southern limit of the flysch basin [*Choukroune,* 1976]. This structure dies out to the west [*Hall and Johnson,* 1986], and at the study transect the margin of the flysch basin is deformed by a system of south vergent thrusts (e.g., Lakora and Licq faults), which derive from inclined, synsedimentary normal or oblique-slip faults [*Teixell,* 1993].

To the north of the divergence zone, the Upper Cretaceous flysch succession is deformed into a north directed fold and thrust system (Figure 3), where the individual thrusts can be observed in poor exposures at the surface or in wells and commercial seismic profiles [*Ducasse and Velasque,* 1988; *Daignières et al.,* 1994]. Many thrusts faults are blind with tip lines within the flysch deposits, which show intense deformation (chevron folds and slaty cleavage) above. The

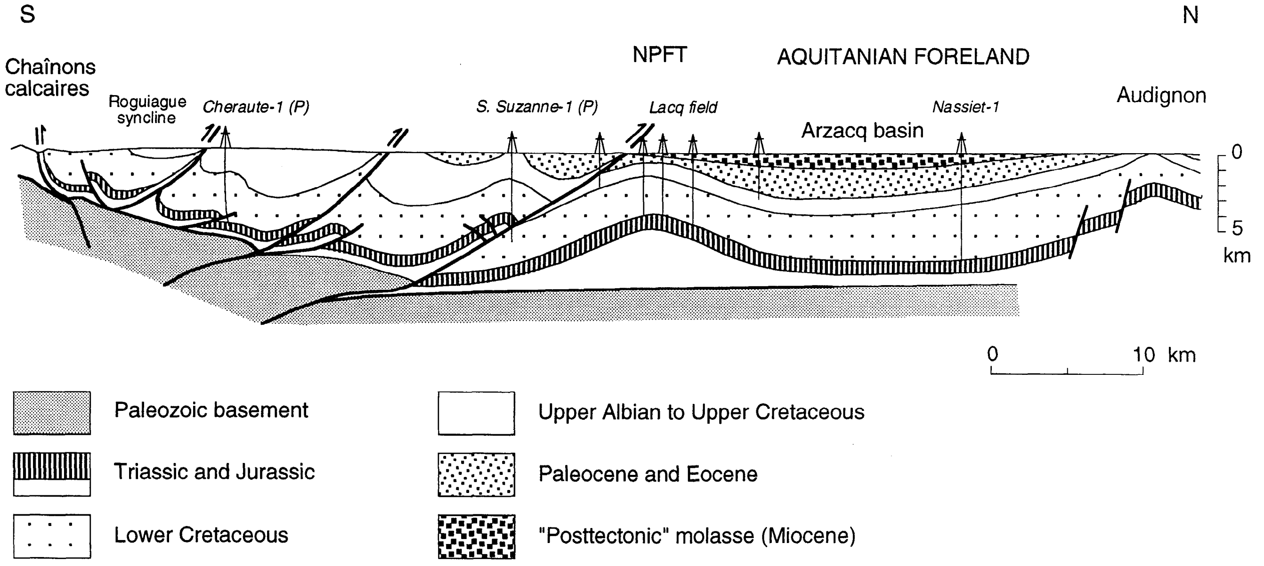

Figure 3. Cross section of the North Pyrenean thrust belt and Aquitanian foreland at the study transect (see location in Figure 1). This section has been constructed on the basis of published geological maps and well information given by *Alimen et al.* [1963], *Casteras and Paris* [1971], *Soler* [1972], *Le Pochat et al.* [1976], and *SNEAP* [1991]. Note the thick Mesozoic successions, which correspond to a preorogenic extensional basin. The divergence axis between south and north vergent compressional structures in this transect of the Pyrenean orogen corresponds to the Roguiague syncline. NPFT is North Pyrenean frontal thrust.

ECORS-Arzacq seismic profile shows that basement deepens progressively to the north under the north Pyrenean thrust belt from its last occurrence at the surface in the hanging wall of the Lakora thrust (Iguntze massif) (Figures 2 and 3).

The North Pyrenean frontal thrust overrides Eocene sediments of the Aquitanian foreland (Figures 1 and 3). The thrust front in the west central Pyrenees developed in the interior of a lower Cretaceous basin, the northern part of which remained in the foreland ("Arzacq basin" [*Curnelle et al.,* 1982; *Daignières et al.,* 1994]). The Arzacq basin contains more than 4 km of Lower Cretaceous rocks (including Neocomian-Barremian), with local thickness variations related to synsedimentary salt rises [*Curnelle et al.,* 1982]. The North Pyrenean frontal thrust does appear to invert the Upper Cretaceous flysch basin margin: 4500 m of northward tapering flysch deposits of the North Pyrenean belt are replaced by a few hundred meters of platform deposits in the thrust footwall [*Curnelle et al.,* 1982; *Ducasse and Velasque,* 1988]. North of the frontal thrust, there are still kilometric-scale folds, such as the Lacq anticline that originates a well-known hydrocarbon field [*Winnock and Pontalier,* 1970; *SNEAP,* 1991] (Figure 3).

Although synsedimentary tectonics are not so well preserved as in the South Pyrenean belt, subsidence analyses indicate that compressional deformation in the northern Pyrenees lasted from the latest Cretaceous to the late Eocene or early Oligocene [*Désegaulx et al.,* 1990]. Thus deformation in the south proceeded, while in the north it had already ceased. The present length of the north vergent belt of the Pyrenees is 36 km (42 km if the foreland Lacq anticline is included), much shorter than the southern belt. Total shortening accommodated by the North Pyrenean thrust system is difficult to calculate because of uncertainties in the geometry and magnitude of the preorogenic extensional configuration, but the length of the sedimentary units suggests it may be close to 20-25 km (32-37%).

4. Constraints for a Crustal Section

Constraints on the deep structure of the west central Pyrenees come from geometric inferences from the near-surface structures and from available geophysical data. (Figures 4 and 5). Acquisition parameters and a velocity model of the ECORS-Arzacq reflection profile have been published by *Grandjean* [1994] and *Daignières et al.* [1994]. Other data taken into account include seismicity [*Haessler et al.,* 1978; *Gagnepain et al.,* 1980], refraction experiments [*Daignières et al.,* 1982], and gravity anomalies [*Casas et al.,* 1997]. In the southern side of the transect, depth to basement of the Ebro foreland basin can be estimated to be some 4 km on the basis of regional contour maps [*Riba et al.,* 1983]. Within the orogen, the basement is raised in a stepped fashion by the main South Pyrenean thrusts up to an elevation of ~2000 m in the Axial Zone top (Gavarnie thrust sheet) (Figure 2). The small interlimb angles and long flat tops of the basement culminations (i.e., Guarga and Gavarnie, Figure 2) indicate that thrust ramps are gently dipping and cannot flatten out at shallow levels but must penetrate into the middle crust [*Teixell,* 1996]. The Lakora thrust appears gently dipping beneath the Iguntze and Mendibelza massifs, but it may steepen northward to follow the Arette seismicity axis (Figure 5). In this region, a group of earthquake foci define a band inclined 60°-70° N up to a depth of some 15 km, constituting

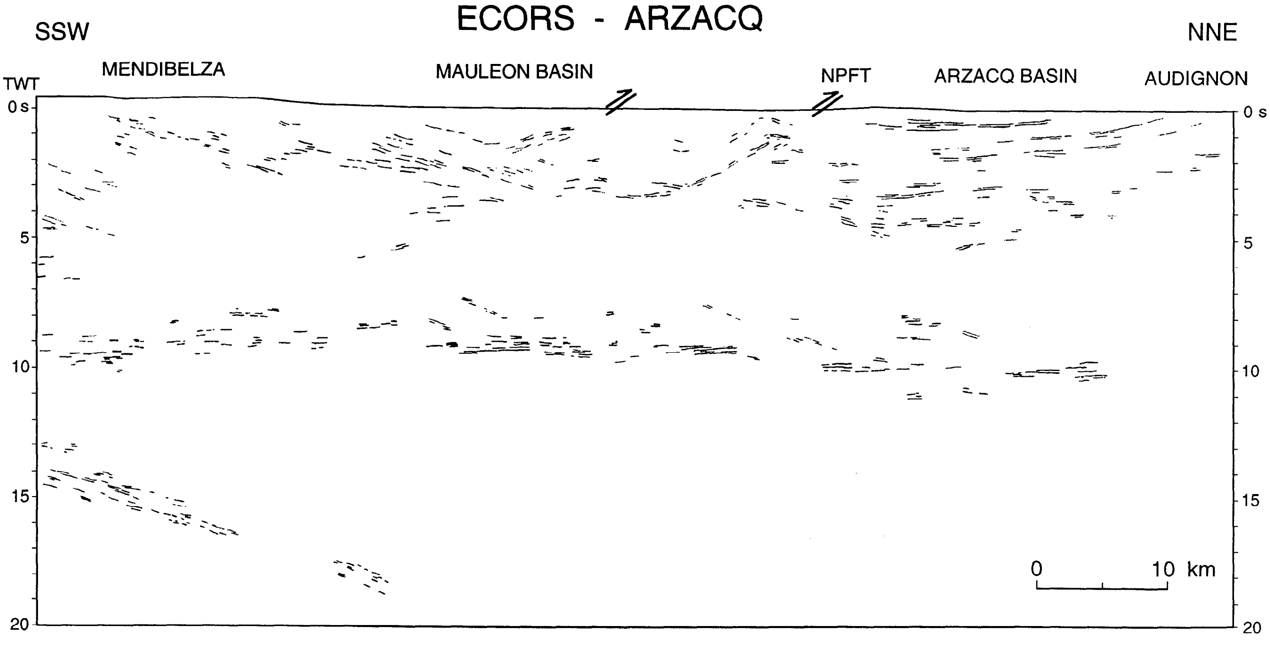

Figure 4. Line drawing of the unmigrated ECORS-Arzacq vertical reflection profile, after the published line given by *Daignières et al.* [1994]. Note subhorizontal reflections at 9-10 s two-way time (TWT) all along the profile, correlatable with the European reflection Moho, and inclined reflections at 15-16 s in the southern part of the profile, attributed to the underthrust Iberian lower crust. NPFT is North Pyrenean frontal thrust.

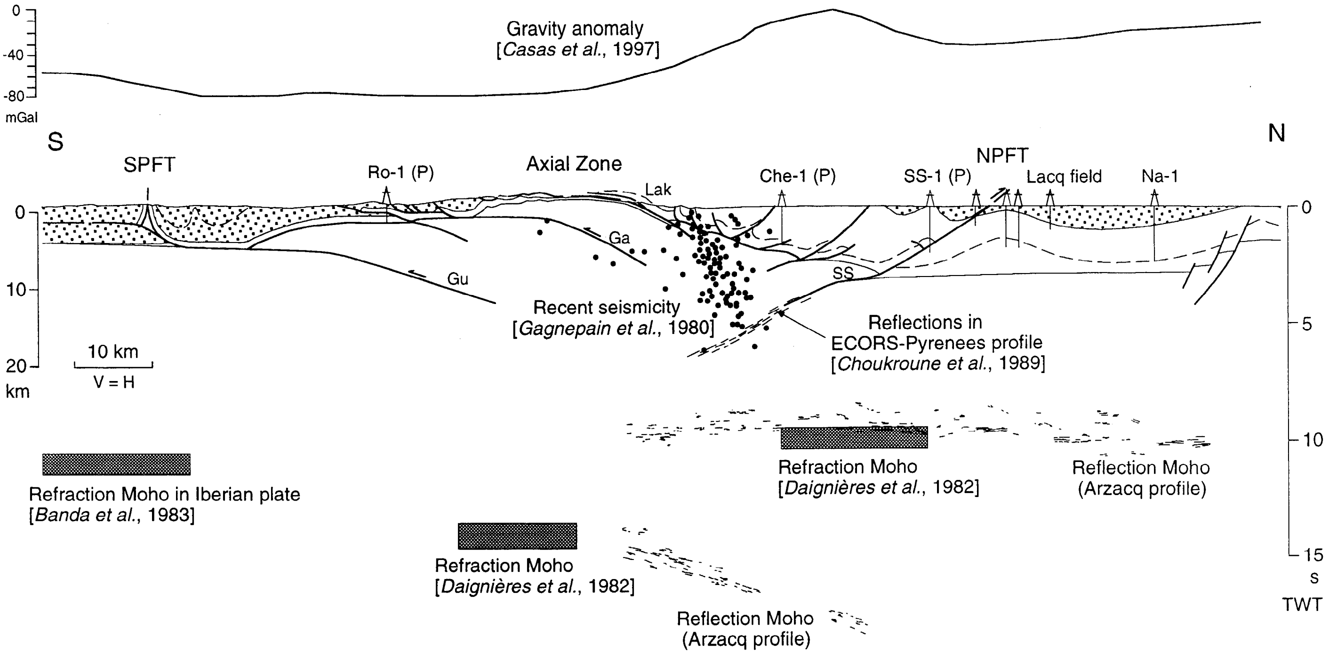

Figure 5. Integration of near-surface geology and subsurface data from different geophysical sources to constrain the deep structure of the Pyrenean range in the study transect. A Bouger gravity profile located some 35 km to the west of the transect was modeled by *Casas et al.* [1997]. SPFT is South Pyrenean frontal thrust; NPFT is North Pyrenean frontal thrust. Dotted pattern indicates Tertiary rocks, and dashed line in northern Pyrenees indicates top of Jurassic.

the most active seismic region of the Pyrenees at present [*Haessler et al.,* 1978; *Gagnepain et al.,* 1980].

Refraction seismics indicate a crustal thickness of 30-33 km beneath the Ebro foreland, a normal value for the Iberian crust outside Alpine mountain ranges [*Banda et al.,* 1983]. As inferred from the ECORS-Pyrenees section (see location in Figure 1), the base of the crust flexes and deepens progressively northward under the mountain range, to be found at a refraction depth of about 42-43 km in the southern Axial Zone at the study transect [*Daignières et al.,* 1982] (Figure 5). A negative gravity anomaly of -80 mGals is related to this crustal root [*Casas et al.,* 1997; *Bayer et al.,* 1998]. From the Axial Zone northward, the lower Iberian crust plunges; the ECORS-Arzacq reflection profile imaged a group of north dipping reflections at 14 to 16 s two-way time (TWT), identifiable as the Iberian reflection Moho [*Daignières et al.,* 1994], directly beneath the northern Axial Zone and Iguntze-Mendibelza massifs (Figure 4). There may be a possible continuation even farther north on a group of short, inclined reflections at around 18 s (Figure 4).

North of the Axial Zone, the deep structure can be projected from the above mentioned ECORS-Arzacq line, which is at a distance of 20 km to the west of the presented section (Figures 1 and 4). In the profile, a group of shallow reflections between 0 and 4 s TWT constrain the geometry of the North Pyrenean thrust belt and the Aquitanian foreland (including the Arzacq basin) [*Daignières et al.,* 1994]. The top of basement under the Arzacq basin was identified by Daignières et al. at a traveltime of 4-4.5 s, indicating depths close to 9-10 km. From this northern foreland southward, top-of-basement reflectors shallow progressively (Figure 4). Much of this northward dip of basement represents the back limb of the Lakora and Gavarnie thrust sheet culminations in addition to north directed basement stacking.

The European reflection Moho is imaged by a group of reflections at a fairly constant travel time of 9-10 s all along the profile (Figure 4). Taking into account lateral variations of velocity, *Daignières et al.* [1994] estimated a homogeneous depth of about 28-29 km. In contrast with the ECORS-Pyrenees profile, a strongly reflective lower crust is not imaged in the Arzacq profile, although discontinuous packets of reflections up to 1.5 s thick are locally traceable (Figure 4).

Reflections of the basal European crust can be traced until almost the southern end of the ECORS-Arzacq line south of the Mendibelza massif (Figure 4), a position that approximately coincides with a sharp inflection of the gravity anomaly profile (Figure 5). This suggests that the Lakora thrust does not continue downward to offset the lower crust (Figure 5). Some 150 km to the east of the transect, the ECORS-Pyrenees profile imaged a strongly reflective continuation of the North Pyrenean frontal thrust plunging southward beneath the northern Axial Zone [*Choukroune et al.,* 1989]. Although such a feature is not evident in the ECORS-Arzacq profile, the interruption at depth of the Arette seismic axis and the lack of continuation of the Lakora to the lower crust suggests the same relationships may apply (Figure 5). The identification of the European reflection Moho at 10 s TWT up to the southern end of the line implies a duplication of the lower crust, with the north dipping Iberian Moho underthrusting the European one with a vertical separation of at least 6 s TWT (Figures 4 and 5). From these features, it follows that the European crust forms a wedge deeply indented into its southern counterpart.

5. A Double Wedge Model for the West-Central Pyrenees

The section of Figure 6 integrates the above mentioned data and represents the proposed model for the crustal structure of the Pyrenean orogen. The European crust appears indented into the Iberian crust between the lower north dipping thrust zone offsetting the Moho and an upper retrovergent structure that continues to the basal North Pyrenean thrust (Figure 6). As mentioned above, the European Moho reflections beneath the northern Axial Zone make unlikely a continuation of the lower north dipping zone to the Lakora thrust, or to the gently dipping Guarga thrust ramp (Figures 5 and 6). In the proposed model, these south Pyrenean thrusts root in the upper, north vergent thrust of the wedge thus defining a second, upper wedge of Iberian crust at middle to upper crustal levels. The geometry described can be synthetically referred to as a double (stacked) wedge, in comparison with the small-scale analogues reported by *Martínez-Torres et al.* [1994] (Figure 7). The upper wedge was delaminated at the North Pyrenean frontal thrust, and material from the wedge was progressively accreted into the orogenic prism by the piggyback rupture of the Lakora, Gavarnie, and Guarga thrusts until the early Miocene (Figure 8).

Below the southern Axial Zone, the crust is thickened by more than 10 km with respect to the Ebro foreland, a value that, as we have seen, increases farther north. However, the structural relief caused by the south Pyrenean basement thrusts is only about 6 km. Hence a highly penetrating tectonic wedge represents an efficient thickening mechanism, without the need to invoke intense ductile thickening at deep crustal levels. Mesozoic thinning of the European crust is preserved under the Arzacq basin (Figure 6), where there are less than 20 km of continental basement [*Daignières et al., 1994*]. This value is in contrast to the almost 30-km-thick "normal" Iberian basement of the southern foreland, and it is due to the remarkable fact that the North Pyrenean thrust belt did not invert the entire lower Cretaceous basin but left a portion of it (Arzacq basin) in the foreland (Figure 6).

The position of the leading edge of the European lithospheric mantle adopted in the model is also consistent with the distribution of the negative Bouger anomaly, which is slightly off the deepest root. In the study transect, the anomaly was detected in the northern Jaca basin and the southern Axial Zone, flanked to the north by a strong positive gradient toward the northern Axial Zone and Lakora thrust sheet [*Casas et al.,* 1997; *Bayer et al.,* 1998]. This is a regional feature of the Pyrenees, in addition to localized maxima that do occur in the North Pyrenean Zone and that have been attributed to different local causes (slices of granulitic basement or basic intrusions [see *Torné et al.,* 1989; *Grandjean,* 1994]).

The cross section presented here (which will be called the Ansó-Arzacq section) shows some similarities but also some remarkable differences with respect to the models presented for other crustal transects of the Pyrenees and Cantabrian mountains (Figure 1). In comparison with the ECORS-Pyrenees section of the east central part of the orogen [*Roure et al.,* 1989; *Muñoz,* 1992], there are not many differences in terms of deep seismic structure and magnitude of thickening. This is so in spite of more pronounced differences in surface geology: in the ECORS-Pyrenees transect, the Axial Zone is modeled with a much larger amplitude because of antiformal stacking of basement thrust sheets, and the sections proposed imply a very large exhumation. By contrast, the Ansó-Arzacq transect shows the top of the Axial Zone basement in the subsurface (Figures 3 and 6); the exhumation of the orogen is

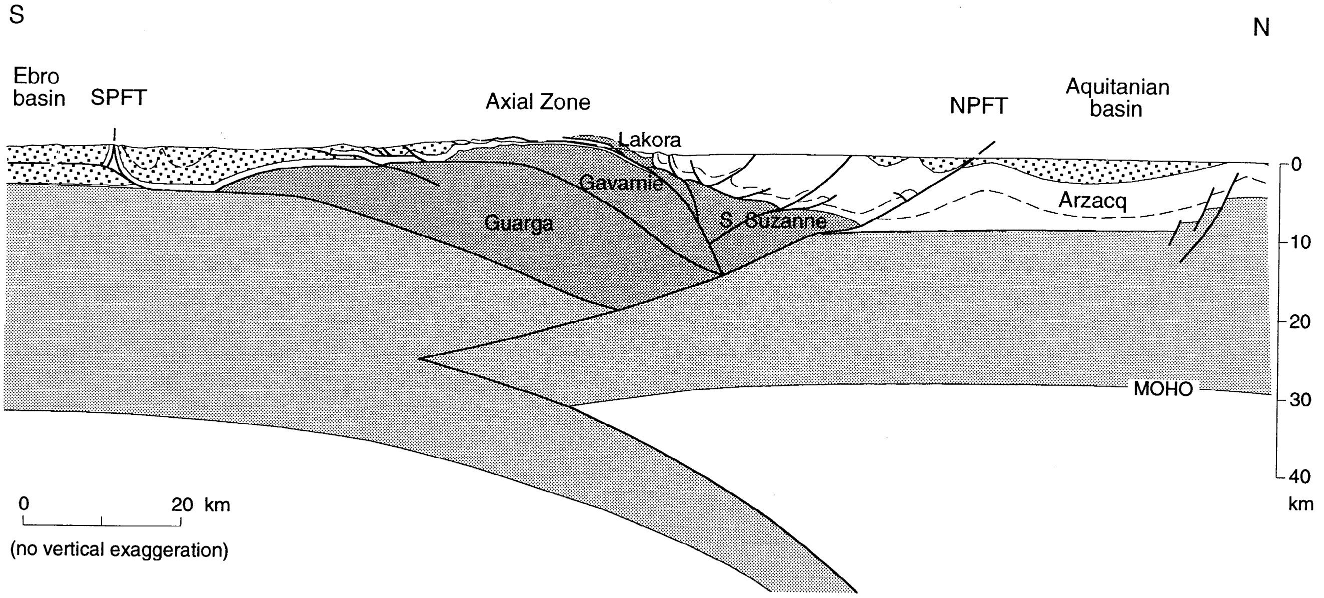

Figure 6. Crustal section of the west central Pyrenees (Ansó-Arzacq transect). The section shows stacked tectonic wedges at different levels of the crust, with an underthrust Iberian lower crust and a delaminated, upper level orogenic prism. The crustal root is drawn to the depth imaged by the ECORS-Arzacq profile. SPFT is South Pyrenean frontal thrust, NPFT is North Pyrenean frontal thrust, dotted pattern indicates Tertiary rocks, and dashed line in northern Pyrenees indicates top of Jurassic.

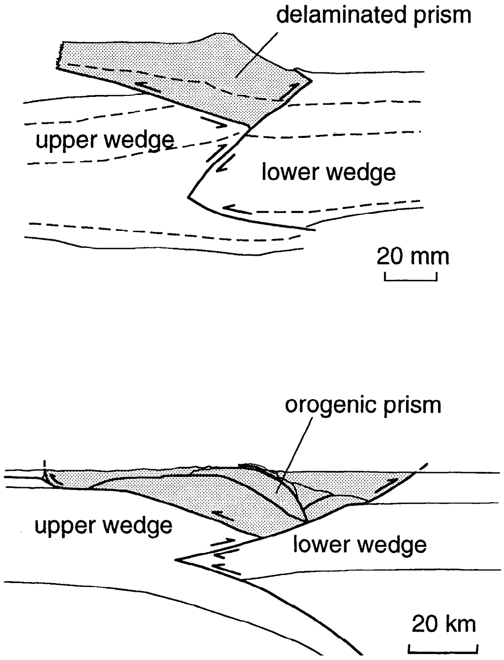

Figure 7. Comparison of the west central Pyrenean double wedge with a small-scale analogue from a turbiditic bed of the Pyrenean basque coast. Sketch of turbiditic bed modified after *Martínez-Torres et al.* [1994].

much lower. This fact, together with its related sedimentary record, will be analyzed later in more detail.

In the interpretation of the east central ECORS-Pyrenees profile, *Roure et al.* [1989] and *Muñoz* [1992] traced the basal, north dipping thrust zone of the overriding European plate all the way to the frontal South Pyrenean thrust. As an alternative, in the west central Pyrenees the European crust seems to show a high degree of indentation, and its tip remained not delaminated under the southern Pyrenees. Unfortunately, crocodile patterns of reflections [*Meissner,* 1988] have not been imaged as the ECORS-Arzacq line does not extend sufficiently to the south, but diverging reflections indicating such a geometry have been imaged 300 km to the west in the ESCIN-2 line [*Pulgar et al.,* 1996] (see location in Figure 1), and *Coward and Dietrich* [1989] proposed a comparable interpretation for the ECORS-Pyrenees profile.

Conversely, *Désegaulx et al.* [1990] and *Muñoz* [1992] proposed that lower crustal subduction had occurred in the ECORS-Pyrenees transect to balance the restored lengths of the upper and lower crust. The viability of subduction has also been sustained by teleseismic and magnetotelluric data [*Souriau and Granet,* 1995; *Pous et al.,* 1995], thermomechanical modeling [*Chery et al.,* 1991], and finite element modeling [*Beaumont and Quinlan,* 1994]. In principle, a highly penetrating wedge in the west central Pyrenees would accommodate some extra deep-level shortening in addition to that of subduction. Therefore, in light of the smaller orogenic shortening of the Ansó-Arzacq transect (75-80 km, much less than the 147 km proposed by [*Muñoz,* 1992] for the ECORS-Pyrenees transect), it is interesting to test how much, if any, subduction had occurred there. A simple material budget evaluation will yield an idea about the amount of crust that may have been subducted or underthrust to mantle depths, an exercise that is discussed in section 6.

6. Crustal Budget

A consideration of the budget of crustal material involved in the formation of the Pyrenees serves as a check for cross-section validity and may give an idea of the fate of the Iberian lower crust, that is, the amount of crustal material subducted into the mantle. A similar exercise has been done in other orogens such as the Alps [*Ménard et al.,* 1991; *Marchant and Stampfli,* 1997]. In principle, two-dimensional material balance during deformation requires that orogenic shortening multiplied by the original thickness of the shortened crust equals the area of structural relief plus that of the crustal root. More directly, one can compare the cross-sectional area of a tentative palinspastic reconstruction with that of the present section, as shown in Figure 9. The little exhumation of the continental basement in the Ansó-Arzacq transect allows a precise reconstruction of the structural relief, and hence the volume (area) of the subducted root can be estimated.

In a palinspastic reconstruction to late Cretaceous times (Figure 9), the crustal thickness outside the Mesozoic basin

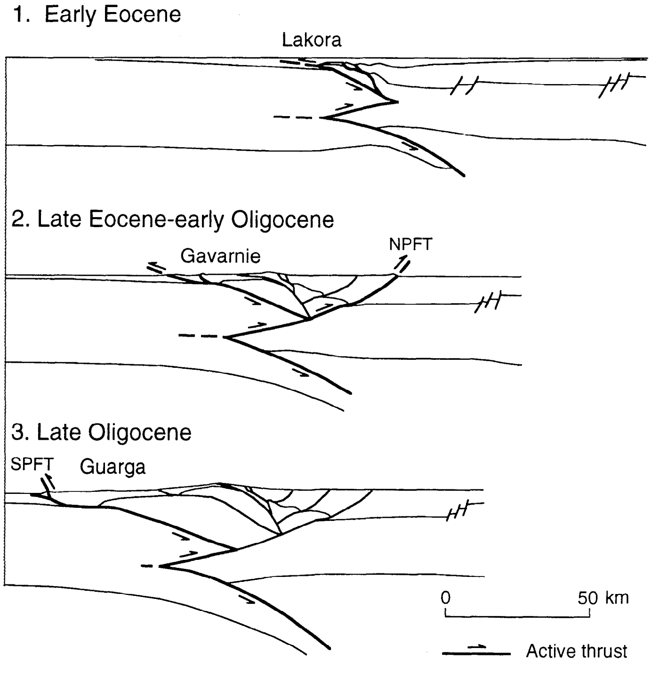

Figure 8. Chronological development of the west central Pyrenean thrust system at crustal scale. Stage 1, corresponding to the inversion of the southern margin of the North Pyrenean mesozoic basin, is characterized by the initiation of a double- or stacked-wedge geometry. The orogen is below sea level at this stage. Stage 2 involves delamination (North Pyrenean frontal thrust, NPFT) and accretion from the upper wedge (Gavarnie thrust), causing marked surface uplift and emergence of the orogen. Stage 3 involves further accretion from the upper wedge, giving rise to the Guarga thrust sheet and the present South Pyrenean thrust front (SPFT).

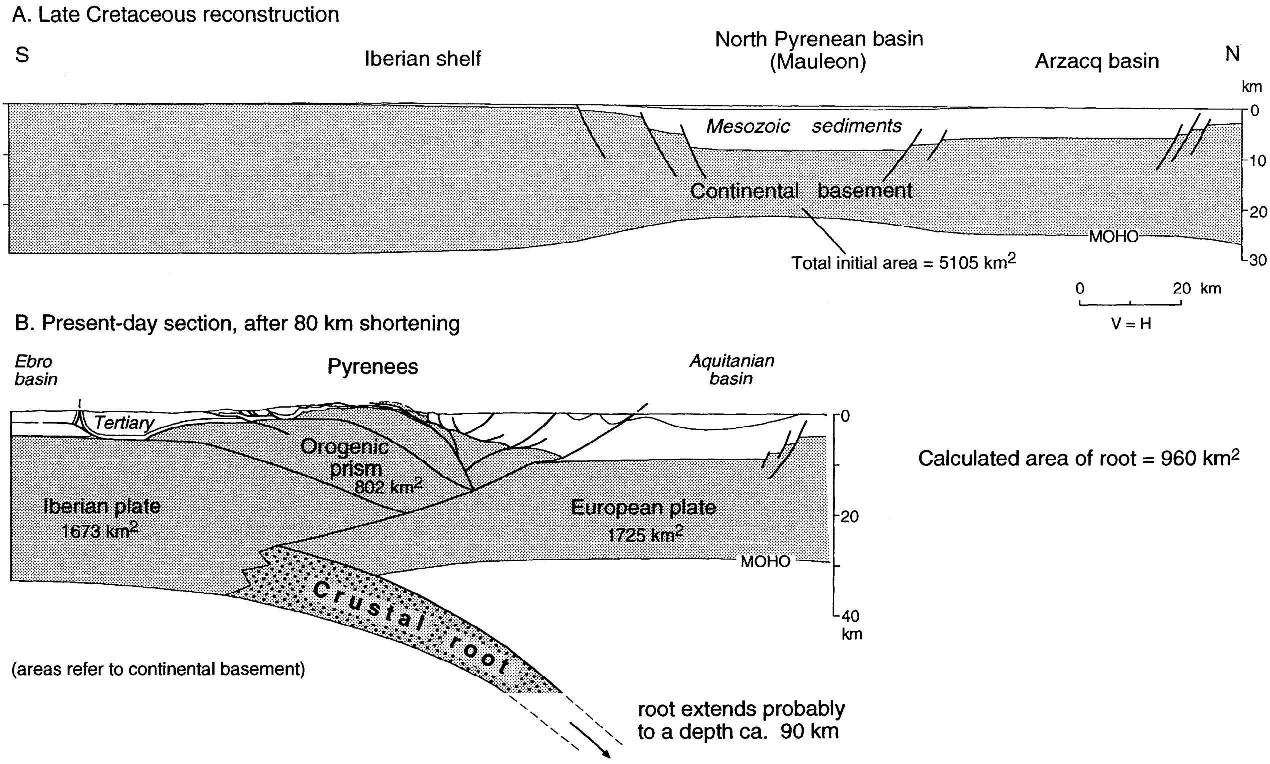

Figure 9. Comparison of a palinspastic reconstruction to preorogenic times and the present-day cross section of the west central Pyrenees as a basis to evaluate the two-dimensional budget of crustal material during Pyrenean orogeny. The palinspastic section is schematic, and a detailed interpretation or model of the precise deep fault structure at this stage is not intended.

has been taken from the present thickness of the continental basement in the far forelands, that is, close to 30 km. Much of the Cretaceous basin was floored by ~19-km-thick basement, as preserved in the Arzacq basin, a value that has been assumed to go down to some 13 km beneath the precursor of the North Pyrenean belt (Mauleon basin) in order to account for thicker and deeper-water Upper Cretaceous sediments there. No evidences of formation and subsequent consumption of oceanic crust have ever been presented for the inland Pyrenees east of the Bay of Biscay. A shortening value of 80 km has been used in the reconstruction. Precise geometry of the Mesozoic extensional structures is not intended, as the objective is merely an evaluation of the area of the preorogenic crustal material.

The total area of crustal basement in the restored section is of 5105 km^2 (Figure 9). In the present-day section, the area of the two plates and orogenic prism is about 4200 km^2, which implies a crustal root of 905 km^2. We have seen that the crustal root of Iberian plate seems to be imaged to 18 s TWT (55-60 km), but, if the slab thickness is considered constant, the estimated area suggests that the Iberian lower crust may have been underthrust to depths up to 90 km (Figure 9). One arrives at this conclusion in spite of the failure to detect a *P* wave velocity anomaly in a teleseismic study by *Souriau and Granet* [1995], although a subducted crust at the study transect is consistent with recent magnetotelluric data provided by *Pous et al.* [1997]. Permissible shortening variations do not alter much the conclusion reached: a minimal shortening estimate of 75 km will yield an initial area of 5040 km^2, by which we obtain a root of almost 840 km^2, implying depths close to 85 km. In any case, material budget considerations require subduction of a considerable amount of crust. These values are still moderate in comparison to those in the easterly ECORS-Pyrenees transect. Larger structural relief and erosion there implies larger subduction, although the amount of crustal material removed by erosion is difficult to ascertain. *Muñoz* [1992] estimated a 130 km-long subducted slab in restoration.

In the Ansó-Arzacq transect, part of the subducted root derived from slightly thinned Iberian crust, originally overlain by the reduced Mesozoic succession of the South Pyrenean belt (Iberian shelf in Figure 9). The positive buoyancy was probably balanced by the fact that only the lower, possibly more dense, crust was subducted. The thinner crust underlying the northern Pyrenees subducted first, and as progressively thicker crust attained the underthrust zone, it probably activated intense deformation and creation of relief from late Eocene/lower Oligocene times (emergence of the North Pyrenean frontal thrust and accretion of Gavarnie and Guarga thrusts sheets). In spite of this deformation, we have already seen that the orogenic prism of the west central Pyrenees did not create much structural relief, and little crustal material has been removed by erosion (Figure 6). Then, if one looks at the volume of syntectonic sedimentary rocks in foreland basins (i.e., Figures 2, 3, and 10), it calls attention to how slight is the exhumation of the orogen, and comparatively how large is the amount of sediments present. This fact demands a more careful analysis, which is partly undertaken in section 7.

7. Erosion-Sedimentation Budget

An estimation of the eroded material in the orogen is obtained by reconstructing the structure above the present surface, using sediment thicknesses (Figure 10). Conversely, the volume (area) of Tertiary sediments derived from the rising orogen can be calculated by integrating the Aquitanian and the entire Ebro foreland basins and also by taking into account the eroded proximal basin sediments in the external parts of the range (Figure 10). The total amount of eroded material, including Tertiary synorogenics, has a reconstructed cross-sectional area of about 575 km^2, while the whole foreland sediments account for some 893 km^2 in the transect. Apart from the effect of material recycling, it is clear that there is a negative erosion-sedimentation budget which, not surprisingly, contrasts with the large sediment deficit that was estimated in eastern transects of the orogen [*Vergés et al.,* 1995]. However, to understand the meaning of these values, it is necessary to track the erosion/sedimentation history through time and, when possible, to treat separately the southern and northern sides of the orogen.

The erosion/sedimentation history can be deduced from well preserved syntectonic sediments, especially in the southern Pyrenees and foreland. Tertiary sediments begin with a turbidite and carbonate wedge of Paleocene to middle Eocene age [*Mutti,* 1984], exposed in the Jaca basin and in isolated synclines in the North Pyrenean thrust belt. These rocks are still recognized in boreholes in the Aquitanian basin, but they pinch out near the South Pyrenean frontal thrust (Figures 2 and 10). The maximum thickness of the turbidite wedge is attained in the Jaca basin, reaching up to 4500 m [*Teixell,* 1992]. Upper Eocene to lower Oligocene first marine and then terrestrial shales, sandstones, and conglomerates overlie the turbidites in the Jaca basin [*Puigdefàbregas,* 1975] (marine and terrestrial molasse in Figure 10). The proximal, northern part of these sedimentary systems has been largely eroded (Figures 2 and 10). The Ebro basin is filled with Oligocene and Miocene terrestrial sediments, whose thickness is controlled by exploration wells and contour maps [*Riba et al.,* 1983]. The Ebro basin is flanked to the south by another Alpine mountain chain, the Iberian range (Figure 10). In the central part of the basin, there is a lacustrine and evaporite facies belt that permits us to separate the sediments of Pyrenean source from those of Iberian source [see *Riba et al.,* 1983; *Arenas,* 1993] (Figure 10). In the Aquitanian basin, lower Eocene rocks are directly overlain by unconformable Miocene alluvial sediments (the "posttectonic molasse" of French authors) (Figures 3 and 10).

The Pyrenees form the watershed between the Iberian peninsula and France. The present drainage divide in the study

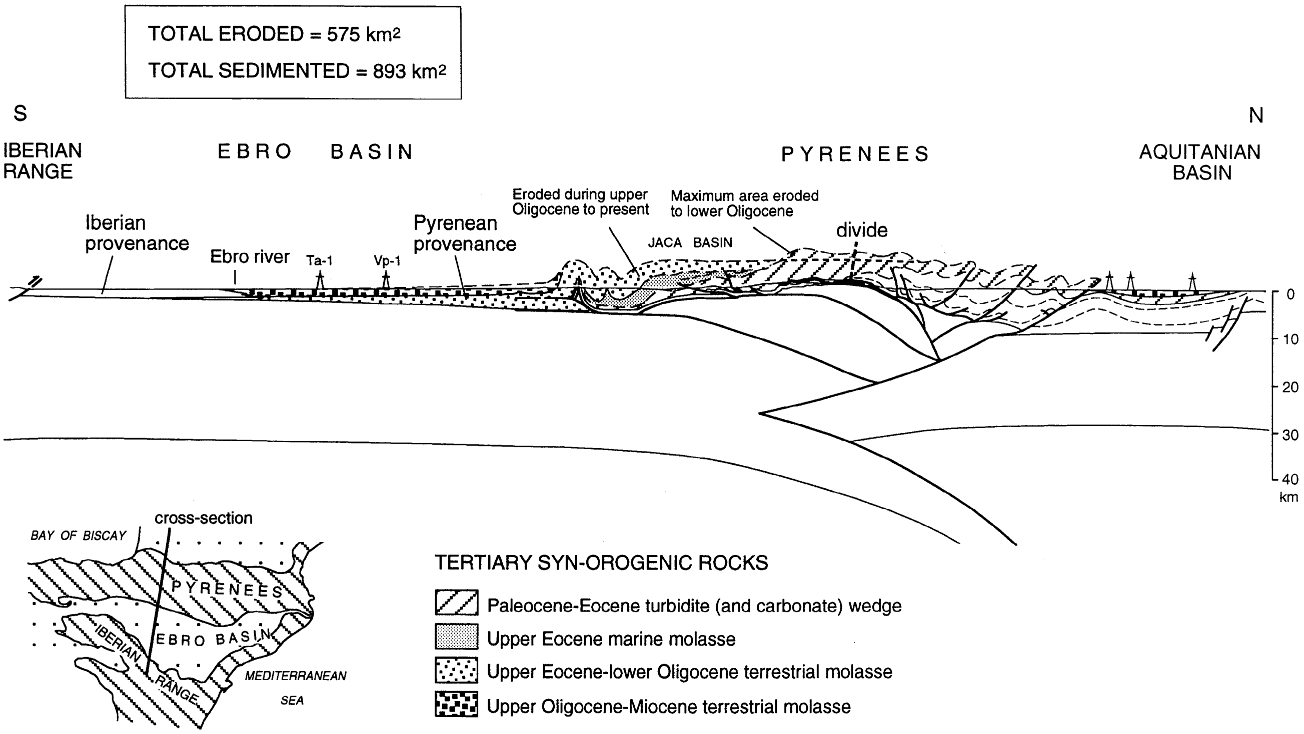

Figure 10. Profile of the west central Pyrenees and adjacent forelands showing eroded material and sedimentary products which are used to evaluate surface material budget during Tertiary growth of the orogen. Although the Pyrenean contraction may have started as early as in the latest Cretaceous, the corresponding sediments are comparatively minor and have not been taken into account in the calculations. Note that much of the eroded material corresponds to uplifted, synorogenic Tertiary rocks. The computation of the total amount of sedimented material includes these eroded volumes (areas), and it should be emphasized that it involves significant sediment recycling.

transect does not coincide with the vergence transition but is located in the Axial Zone, beneath the projected leading edge of the Lakora thrust sheet (Figure 10). Although there is no direct indication of its position in the past, it can be assumed that it has not changed much since the late Eocene or early Oligocene, when the Axial Zone culmination, the area of maximum structural relief of the orogen, was uplifted by the Gavarnie thrust. This assumption is useful in estimating the budget for both sides of the Pyrenees.

The reconstruction of the Eocene turbidite system, coupled with the poorly emergent character of the contemporaneous Lakora thrust, suggests that during the early and middle Eocene the entire transect of the orogen was submarine and covered by deep water turbidites. Hence, although synorogenic, they cannot be considered to represent a foreland basin in the classic sense, that is, in front of a mountain chain. The emergent land was to the east along strike of the orogen, as shown in paleogeographic maps by *Plaziat* [1981]. Some 350 km^2 of turbiditic sediments in cross section came partly from the emerged area, as indicated by westerly paleocurrent patterns, and a contribution from the south eastern craton has also been proposed [*Mutti et al.,* 1985]. Much of the excess sediment when computing the total values arises from this Eocene situation.

During late Eocene to early Oligocene times, greater surface uplift induced by the accretion of the Gavarnie thrust sheet and by some of the North Pyrenean basement thrusts (Figure 8) caused the emergence of the orogen, the retreat of the sea, and the erosional reworking of the Eocene turbidites. Clasts of these rocks dominate in conglomerates of the marine and terrestrial molasses of the Jaca basin. Integrating distal equivalents of these sedimentary units in the Ebro basin, the resulting cross-sectional area is about 388 km^2 (this refers to the southern side of the orogen, as there is little control for sedimentation of this period in the northern side). However, the maximum area eroded at this time, south of the assumed divide, is only about 20 km^2 (Figure 10). Again, there must be much sediment coming from the east along strike, consistent with recorded paleocurrent data [*Puigdefàbregas,* 1975].

Later, during the late Oligocene to early Miocene, final tectonic uplift in the Pyrenees led to new sediment recycling. The emplacement of the Guarga thrust sheet, accreted from the upper wedge of the orogen (Figure 8), terminated sedimentation in the Jaca basin, which was submitted to erosion [*Teixell,* 1996]. Terrestrial molasses of this age are only found in the forelands (Figure 10), where sedimentation continued to late Miocene times [*Riba et al.,* 1983]. In the southern side of the Pyrenees, eroded material from the late Oligocene to present reaches a cross-sectional area of 315 km^2, in contrast with only ~130 km^2 of upper Oligocene and Miocene sediments in the Ebro foreland (Figure 10). A comparable situation is deduced for the northern side: some 200 km^2 of eroded material north of the watershed left a residue in the Aquitanian basin of only 25 km^2. Clearly, there is an inversion of the trend that prevailed in previous stages: there is now a net sediment deficit. Much of sediment escaped along strike, either to the Bay of Biscay and Atlantic Ocean in the north or in the south into the Mediterranean Sea after rivers captured the Ebro basin in late Miocene time [*Riba et al.,* 1983]. This latter process was coupled with isostatically driven rock uplift in the Pyrenean mountains and adjacent foreland margins, although, as *Vergés et al.* [1995] deduced, it was accomplished at markedly slow erosion rates after the end of Pyrenean contraction. In summary, the history of synorogenic erosion and sedimentation in the Ansó-Arzacq transect is that of continuous cannibalization of sediments but also of two-dimensional material unbalance through time. Large lateral sediment influx in the early stages turned to material bypassing in late stages, including the posttectonic isostatic uplift of the orogen.

8. Conclusions

Surface and geophysical data (refraction data and the ECORS-Arzacq reflection profile) suggest that the structure of the west central Pyrenees conforms to a crustal-scale double (stacked) tectonic wedge. In the upper crust, the Pyrenean orogenic prism is bivergent and consists of a system of south directed thrust sheets accreted piggyback from the upper (Iberian) wedge and a smaller, delaminating retrovergent belt. The ECORS-Arzacq reflection profile [*Daignières et al.,* 1994] and refraction data help to interpret the structure at deeper levels. As suggested from these data, a lower, highly penetrating European wedge with a homogeneous Moho depth of about 28-30 km indents into the southern Iberian crust. Wedging explains a crustal thickening that exceeds the well-constrained structural relief caused by major thrusts in the upper crust. The lower Iberian crust is underthrust below the European wedge and plunges from some 30 km in the foreland to at least 55-60 km (and possibly up to 90 km, as required by material balance) beneath the mountain range thus defining a subducted crustal root with a cross-sectional area of some 900 km^2.

Shortening in the Pyrenean orogen in the west central transect is only about 75-80 km, less than that estimated more to the east (i.e., in the ECORS-Pyrenees transect). This value is deduced from surface structures in the orogenic prism. Orogenic convergence rates averaged 1.2 mm/yr from the latest Cretaceous to the early Oligocene (a value accomplished very heterogeneously, probably with very slow rates at the beginning, from the Cretaceous to the Paleocene, and fastest during the late Eocene-early Oligocene [*Teixell,* 1996]). Once deformation in the northern belt of the orogen had ceased, by the beginning of the Oligocene, it continued in the southern belt until the early Miocene at a contraction rate that can be estimated in 1.1 mm/yr. Structural relief and exhumation of the orogen is moderate, and the top of the Pyrenean basement nappe stack is preserved at the near surface. Emergence of the orogen above sea level was not accomplished until late Eocene times, essentially caused by the accretion of the Gavarnie and later the Guarga thrust sheets from the upper wedge. A two-dimensional comparison of the erosional exhumation of this Pyrenean transect with the depositional products reveals a global excess of synorogenic sedimentary material, which is associated to a continuous process of foreland basin recycling and to arrival from source areas located to the east along strike of the orogen. This trend was inverted from late Oligocene times when a deficit of sediments points to bypassing into the Atlantic Ocean (northern side of the orogen) or from the late Miocene into the Mediterranean Sea (southern side of the orogen).

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