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Tectonosedimentary evolution related to extreme crustal thinning ahead of a propagating ocean: Example of the western Pyrenees

Suzon Jammes,¹ Gianreto Manatschal,¹ Luc Lavier,^{2,3} and Emmanuel Masini¹

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[1] In this paper we describe the tectonosedimentary evolution and its subsequent inversion of a basin that underwent extreme crustal thinning in a transtensional setting ahead of a propagating ocean in the western Pyrenees. The Labourd-Mauléon area situated in the western Pyrenees, at the termination of the V-shaped Bay of Biscay, is an ideal natural laboratory to study how such complex basins evolve in time and space. Because of a mild inversion of the basin during Pyrenean compression, the rift structures and their relations to basement rocks and sediments are exposed and can be directly studied in the field. The basin shows a complex polyphase evolution that starts with left-lateral dominated transtension in latest Jurassic–early Aptian time. This event is overprinted by a late Aptian–early Albian extension that is related to the counterclockwise rotation of Iberia away from Europe leading to the opening of the Bay of Biscay. During this stage, the Late Triassic to Jurassic carbonate platform was stretched, salt migrated, and detachment faults exhumed upper and lower crustal and mantle rocks to the seafloor. The final structure of the basin resembles a sag basin floored by exhumed rocks overlain by extensional allochthons and compartmentalized by N40° to N60° transfer faults. The sedimentary architecture is characterized by late Aptian synrift sediments (e.g., Urgonian limestones) that were deposited in fault-bounded basins and are overlain by thick latest Aptian to Albo-Cenomanian sediments (e.g., Flysch noir) that define a sag sequence. The complex tectonosedimentary evolution of the basin is associated with salt tectonics and overprinted by a major magmatic/thermal event that postdates mantle exhumation. **Citation:** Jammes, S., G. Manatschal, L. Lavier, and E. Masini (2009), Tectonosedimentary evolution related to extreme crustal thinning ahead of a propagating ocean: Example of the western Pyrenees, *Tectonics*, 28, TC4012, doi:10.1029/2008TC002406.

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1. Introduction

[2] The acquisition of refraction and reflection seismic profiles, combined with deep sea drilling results from deep magma-poor rifted margins changed the way to think about how the lithosphere extend and oceans form. The major discoveries were (1) the occurrence of subcontinental mantle and extremely thinned crust extending over tens to hundreds of kilometers [Boillot *et al.*, 1987; Contrucci *et al.*, 2004] and (2) the observation of top basement detachment faults and extensional allochthons covered by synrift and postrift sediments [Reston *et al.*, 1995; Manatschal *et al.*, 2001]. These systems have been drilled in the Iberia-Newfoundland margins, mapped in the ancient Alpine Tethys margins and inferred for a number of other rifted margins, such as the South Atlantic, the south and west Australian margins and the northern Red Sea. However, in these examples, the rift structures that stretched and thinned the crust to less than 10 km were overprinted and separated during final breakup and are at present covered by thick postrift sedimentary sequences and lie at abyssal depth. In V-shaped rift basins, such as the Woodlark basin [Kington and Goodliffe, 2008], the northern Gulf of California [Nagy and Stock, 2000; Persaud *et al.*, 2003] or Rockall Trough, the various stages of extension leading to final breakup and seafloor spreading are recorded along strike. Thus, in these examples, the stage of rifting that predates continental breakup is recorded in front of the propagating ocean.

[3] In this paper, we focus on the Labourd-Mauléon area located in the western Pyrenees, which is located at the eastern termination of the Bay of Biscay in SW France (Figure 1). Previous studies based on refraction and reflection seismic and gravity surveys suggested that the continental crust was thinned in this area to less than 10 km [Daignières *et al.*, 1981; Grandjean, 1994]. Evidence for extreme crustal thinning exists also for the Parentis and Cantabrian basins (Figure 1) [Tomassino and Marillier, 1997; Pulgar *et al.*, 1996; Pedreira *et al.*, 2007]. These basins are filled by a thick Albo-Cenomanian sedimentary sequence indicating that major crustal thinning had to occur during the Early Cretaceous period. During the Pyrenean compression, the Mauléon basin was inverted and thrust south and northward over its cover units. As a consequence, rift structures and their relations to upper and lower crustal and mantle rocks and the prerift, synrift and postrift sedimentary sequences are exposed in the field. This enables to describe the tectonosedimentary evolution of these extensional basins that form ahead of a propagating ocean. In this paper we will discuss the importance of detachment faults for the thinning of the crust and their control on the basin

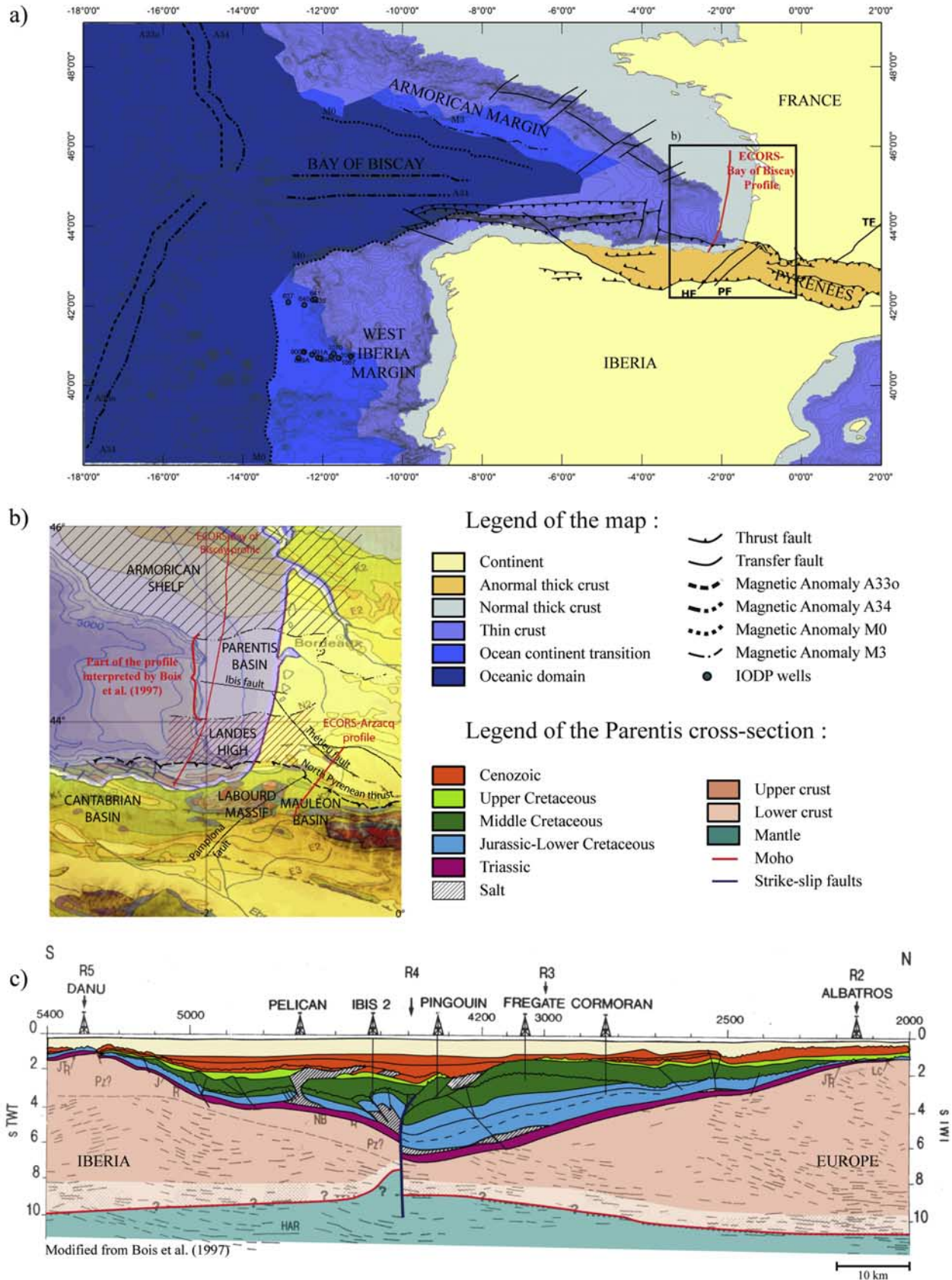


Figure 1

architecture and sedimentary evolution during a final stage of rifting within a transtensional setting.

2. Western Pyrenees: Bay of Biscay

2.1. Tectonic Evolution

[4] The Labourd Massif and Mauléon basin described in this paper are located in the northwestern Pyrenees at the eastern termination of the Bay of Biscay in SW France (Figure 1). The study area records a long and complex Paleozoic history, initiating with Devonian basins that were partly reactivated during Variscan compression [Arthaud and Matte, 1975] and overprinted by an extensional or transtensional phase during Permian time [Burg et al., 1994a, 1994b]. The stacking of Devonian rift basins, Carboniferous foreland and Permian intracontinental rift basins resulted in a weak crustal domain within the Pyrenean domain, which may explain why this zone became the locus of Mesozoic extension. During the Triassic, most of the Alpine realm was either shallow marine or subareal. Locally, more subsiding intracontinental basins might have formed as indicated by thick siliciclastic and carbonate sediments and evaporites. Curnelle [1983] suggested that these basins reactivated and overprinted Paleozoic basins that were mainly bounded by N40° to N50° trending faults. During the Jurassic a carbonate platform extended over most of the Aquitanian and Pyrenean domains. The precise lateral extent and tectonic setting in which this platform formed is still a matter of debate. In Late Jurassic time, an important reorganization of the depocenters occurred. The main basins within the Aquitanian and Pyrenean domains became E-W trending, and deep marine facies were deposited in the western Bay of Biscay [Bureau de Recherches Géologiques et Minières et al., 1974]. This change was concurrent with a widespread Jurassic rifting event in the North Atlantic. In late Aptian to early Albian time a major event, related to the opening of the Bay of Biscay, affected the Aptian platform in the present-day northern Pyrenean domain. This event resulted in the exhumation of crustal and mantle rocks. Henry et al. [1998] dated the crustal emplacement of the mantle rocks at 110–105 Ma. Mantle exhumation was accompanied by major subsidence resulting in the deposition of deep marine sediments [Ducasse and Velasque, 1988]. These sediments were intruded by magmatic rocks dated at 110–100 Ma [Montigny et al., 1986]. To the south, in the present-day Axial Zone of the Pyrenees, major uplift resulted in the erosion and reworking of upper crustal rocks, as documented in the Albian to Cenomanian Mendibelza conglomerate [Boirie and Souquet, 1982]. A high-temperature/low-pressure metamorphic phase occurs around 95 Ma and postdates the major Albian event [Montigny et al., 1986; Golberg and

Maluski, 1988]. In the past, different tectonic settings, ranging from back arc [Sibuet et al., 2004] to transtensional setting with pull-apart basins [Choukroune and Mattauer, 1978] were proposed to explain the various observations. In this paper we propose an alternative model that is able to explain the observed relation between the structures observed in the basement and the overlying prerift, synrift and posttectonic sedimentary sequences and the magmatic and metamorphic overprint observed in the Albian and Cenomanian sequences. The onset of deformation is clearly documented in the southern Pyrenees by the presence of a significant unconformity and the first occurrence of growth sequences resulting from the inversion of previous extensional early Cretaceous basins [Garrido-Megías and Rios, 1972; McClay et al., 2004]. The major collision occurred during Eocene time coinciding with the uplift of the entire chain and the formation of a major foreland basin to the south. On the scale of the Pyrenean Cantabrian orogen, a transition from an embryonic subduction to the west, to a continental collision to the east can be observed, indicating an increase of convergence from west to east. Transfer faults are observed along both the northern and southern margins and segment the Cantabrian-Pyrenean chain as well as the Armorican margin to the north. They are oriented NE-SW in the Armorican margin and NW-SE in the northern Iberia margin [Derégnaucourt and Boillot, 1982]. These fault systems played a major role during both extensional and subsequent compressional deformation.

2.2. Plate Kinematic Framework

[5] The fact that the Mauléon basin and Labourd massif are located along the Iberian-European plate boundary ask for a clarification of the larger-scale plate kinematic framework before focusing on a more regional scale. The palaeogeographic reconstruction of the Iberian plate remains a subject of major debate. Olivet [1996] proposed a reconstruction that was obtained by fitting the magnetic anomalies of the M series of the North Atlantic between Iberia and Newfoundland. In his reconstruction (Figure 2a), Olivet [1996] assumed that the breakup occurred at the J anomaly (M3–M0, 126 to 118.5 Ma) and considered that prebreakup extension was minor. On the basis of the results of ODP Legs 103, 149, 173, and 210 and seismic reflection and refraction surveys [e.g., Sibuet et al., 2007; Péron-Pinvidic and Manatschal, 2008], the prebreakup extension, which also led to the exhumation of subcontinental mantle, was estimated to be in the order of 300 to 400 km. These new results imply that most of the displacement accommodated along the Iberia/Europe plate boundary had to predate continental breakup along the Iberia-Newfoundland margin, dated as late Aptian to early Albian (about 110 Ma) [Tucholke et al., 2007]. Therefore, we suggest that most of the E-W directed movement, estimated to be in the order

Figure 1. (a) Map of the Bay of Biscay and Pyrenees displaying the major structures identified in the area and the different domains situated between the continental and the oceanic domains in the Bay of Biscay and western Iberia margin. (b) Location map of the Parentis basin and the Labourd-Mauléon area. Red lines show the location of the ECORS-Bay of Biscay reflection seismic profile. (c) ECORS-Bay of Biscay reflection seismic profile as interpreted by Bois et al. [1997].

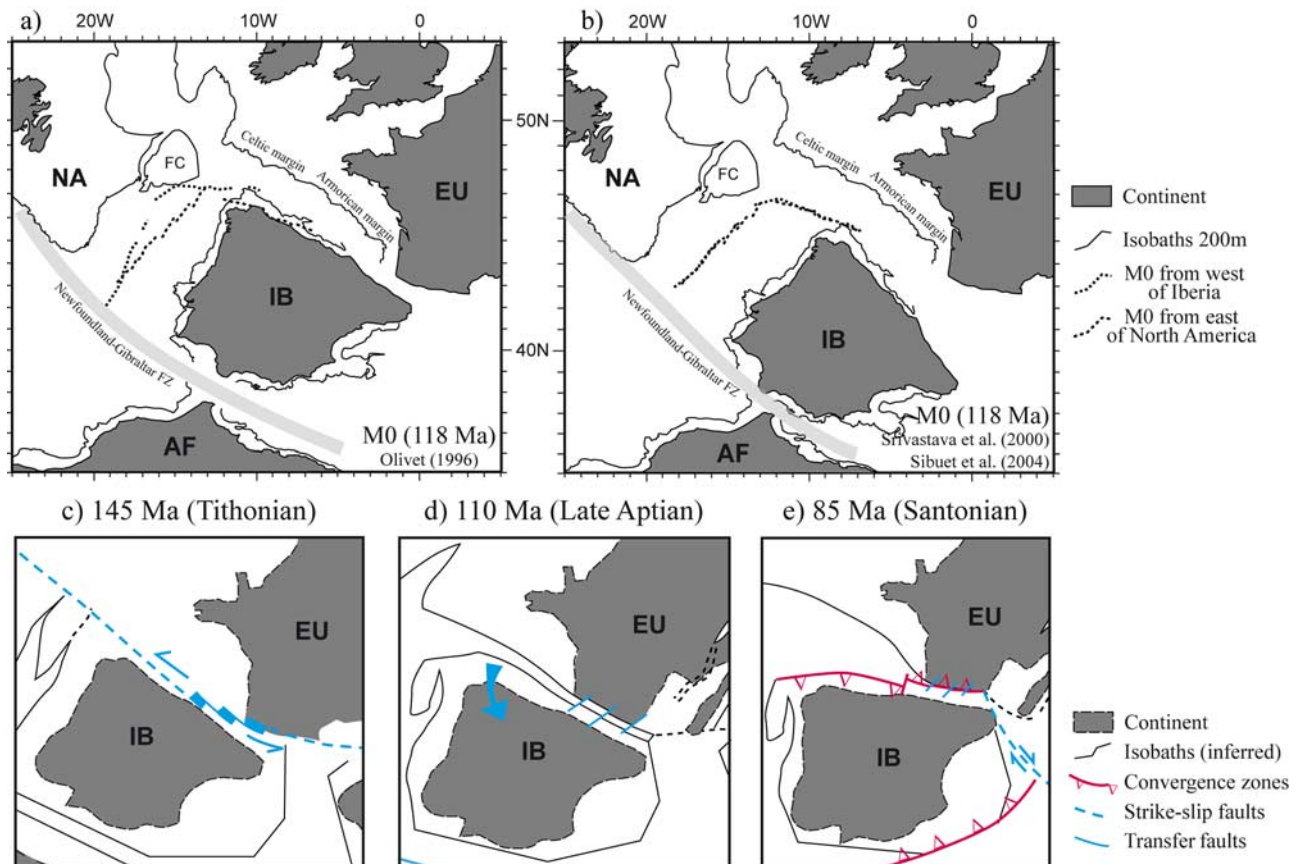


Figure 2. Paleokinematic reconstruction of the southern North Atlantic showing the position of Africa (AF) North America (NA), Europe (EU) and Iberia (IB) at chron M0. from (a) Olivet [1996] and (b) Srivastava *et al.* [2000] and Sibuet *et al.* [2004]. (c, d, e) Plate kinematic interpretation for the Europe-Iberia plate evolution as discussed in this paper. The proposed position of the Iberia plate relative to the European plate is shown for end of Tithonian (Figure 2c); late Aptian (Figure 2d); and Santonian (Figure 2e). For further discussion, see text.

of 300 to 500 km [Rowley and Lottes, 1988; Srivastava *et al.*, 1990a, 1990b; Olivet, 1996], had to occur sometime between latest Jurassic to late Aptian time. This interpretation, which differs from existing models, has major consequences for the geology of the study area, which will be discussed below.

[6] A second major point that resulted from the study of the Iberia-Newfoundland margins is related to the interpretation of the nature and age of the magnetic anomalies [Sibuet *et al.*, 2007; Norton, 2007]. Sibuet *et al.* [2004] discovered magnetic anomalies in the Bay of Biscay and interpreted them as M0 and M3 anomalies. The reconstruction of these anomalies (Figure 2b) results in more than 600 km of extension in the eastern Pyrenees, a value that is incompatible with the regional geological and geophysical observations. This led Norton [2007] to conclude that the M0 anomaly of Sibuet *et al.* [2004] might not represent an isochron and therefore, it cannot be used for plate kinematic reconstructions. In Figure 2 we propose an alternative reconstruction that accounts for the prebreakup deformation observed between Iberia and Newfoundland. This recon-

struction takes into account the global movements of the European and African plates relative to the North American plate and favors geological observations that come mainly from the Iberia-Newfoundland margins [Péron-Pinvidic and Manatschal, 2008] rather than the fit of the M series magnetic anomalies. In this reconstruction, the movement of Iberia relative to Europe was accommodated within a wide, diffuse plate boundary along which E-W directed transtensional basins formed (Figure 2c). A major change in the plate kinematic framework occurred in Aptian time [Gong *et al.*, 2008]. The rotation of Iberia away from Europe resulted in orthogonal extension that localized and overprinted the former domain that was affected by transtensional deformation (Figure 2d). Extension results in major crustal thinning and local mantle exhumation in the east and the opening of an oceanic domain in the present-day Bay of Biscay. The extensional domains were strongly segmented along SW-NE directed transform faults. Examples for such faults are, from west to east, the Hendaya fault, the Pamplona fault (also named the Estella-Dax fault [Larrasoña *et al.*, 2003]) and the Toulouse fault [Souquet

and Mediavilla, 1976]. This new interpretation is compatible with the observed orthogonal extension and segmentation observed in the Armorican margin [Thinon, 1999] and the observation that the Pamplona and other faults of Albian age crossed the Iberian/European plate boundary [Razin, 1989; Claude, 1990]. Thus, the Labourd Massif and the Arzacq-Mauléon Basin might have formed within a complex strain field in which extension and left-lateral strike-slip motion were partitioned along a complex and probably diffuse plate boundary separating Iberia from Europe [Mathieu, 1986].

3. Labourd-Mauléon Area

3.1. General Overview

[7] The Labourd Massif and the Mauléon Basin are exposed in the northwestern Pyrenees between Biarritz and Pau (Figures 1 and 3). In this part of the Pyrenees the classical subdivision into an “Axial Zone” and a “northern Pyrenean Zone” is obscured by the occurrence of thick Cretaceous sediments. In the Labourd Massif Middle to Late Cretaceous sediments cover Paleozoic upper crustal rocks and remnants of midcrustal granulites. In the Mauléon Basin these sediments overlie east-west trending ridges; the “Châinons Béarnais” (Mail Arrouy, Sarrance, Layens), constituted of Triassic to Lower Cretaceous sediments that locally are associated with remnants of mantle rocks (Figure 3). Razin [1989] suggested that the limit between the Labourd Massif and the Mauléon basin is formed by a major NNE-SSW crustal discontinuity, the Pamplona fault. To the south, in Spain, this fault is indicated by an alignment of Triassic salt diapirs and a change in the depth of the top of the basement. However, further to the northern the trace of this fault is not well constrained. Indeed, Razin [1989], Claude [1990], Larrasoña *et al.* [2003], and Pedreira *et al.* [2007] suggested that this fault is situated to the east of the Labourd massif, while for Schoeffler [1982], Vergés [2003], and Vergés and García-Senz [2001] this fault cut across the Labourd massif. We, therefore, suggest that this fault could present several branches in its northern parts. Because the eastern branch of the fault also affects the Albian sediments, Ducasse *et al.* [1986] and Claude [1990] interpreted this structure as a Variscan fault that was reactivated first during Albian rifting and later during the Pyrenean compression as an intercontinental transfer fault [Larrasoña *et al.*, 2003]. In the Mauléon area, a restoration of the ECORS-Arzacq deep seismic profile [Daignières *et al.*, 1994] suggests that major crustal thinning occurred beneath the Mauleon basin during Lower Cretaceous time. The gravimetric data show a strong positive anomaly above the Mauleon basin and the Labourd Massif which has been explained by the occurrence of high-density body at upper crustal level [Grandjean, 1994; Corpel and Casas, 1996; Pedreira *et al.*, 2007].

3.2. Labourd Massif

[8] The Labourd Massif is constituted of three “massifs,” named Iparla-Artzamendi, Baygoura-Jara, and Ursuya

(Figure 4). The Ursuya Massif in the north is essentially composed of aluminous paragneiss with biotite, sillimanite, garnet, and cordierite and biotite, garnet and sillimanite bearing micaschists, representing retrogressed metagranulites. Vielzeuf [1984] determined maximum temperatures of $775 \pm 50^\circ\text{C}$ and a pressure of 6 ± 0.5 kbar for these rocks. Along the Louhossoa lineament (Figure 4) these midcrustal rocks are separated from upper crustal Paleozoic metasediments and Lower Triassic sediments exposed in the Iparla-Artzamendi and Baygoura-Jara massifs. The Ordovician to Carboniferous metasediments are constituted by an alternation of quartzites and schists that are overlain by a Permo-Triassic cover formed by claystones, sandstone, and limestones belonging to the Buntsandstein and Muschelkalk lithostratigraphic units [Boissonnas *et al.*, 1974]. The entire Labourd Massif is surrounded by Albian to Santonian sediments, essentially constituted by marls or calcareous turbiditic sequences. The tectonic position of the Labourd Massif and its relationship to the Cretaceous sedimentary cover was a matter of debate. Viennot [1927] suggested that the Labourd Massif represented a klippe of basement rocks floating on Cretaceous sediments, whereas Le Pochat [1982] and Flamand and Curnelle [1982] propose that it represents a deeply rooted basement horst. Claude [1990] suggested, on the basis of the discovery of clasts derived from the middle crust in the sediments surrounding the Ursuya Massif, that the Cretaceous sediments were deposited onto the already exhumed granulites of the Labourd Massif. Vielzeuf [1984] showed that in the same massif Variscan metamorphic isograds are cut by north vergent shear zones that do not affect Cretaceous sediments. Consequently these shear zones are post-Variscan but pre-Pyrenean in age and might be related to the exhumation of middle crustal rocks in Early Cretaceous time. In the following, we describe some key outcrops that document the relationship between middle and upper crustal rocks and their relationship with the overlying sediments.

3.2.1. Contact Between Upper and Middle Crustal Rocks: Louhossoa Lineament

[9] The contact between the granulites of the Ursuya Massif and the upper crustal rocks of the Iparla-Artzamendi and Baygoura-Jara massifs is marked by the Louhossoa lineament. On the Iholdy geological map of the BRGM [Boissonnas *et al.*, 1974], this contact is sealed by Cretaceous sediments. Although this relationship cannot be confirmed in the field because of lack of exposures, the observations suggests that the Louhossoa lineament represents a pre-Pyrenean contact. The contact between the upper and midcrustal rocks is formed by foliated amphibolites (outcrop in the railway cutting near Itxassou) and carbonate rich quartzo-feldspatic metasediments. In the Bidartéa quarry (Figure 4), the foliation is well developed and dips with 20° to the SE (150/20), the lineation plunges with 10° to 16° to the SW (210/10 and 228/16), and the sense of shear determined in the field on the basis of sigma clasts and shear bands shows a top-to-the-S sense of shear. In thin sections, the rocks show recrystallized and partially annealed calcite and well-aligned quartz ribbons testifying dynamic recrystallization of quartz. In contrast, feldspar does not

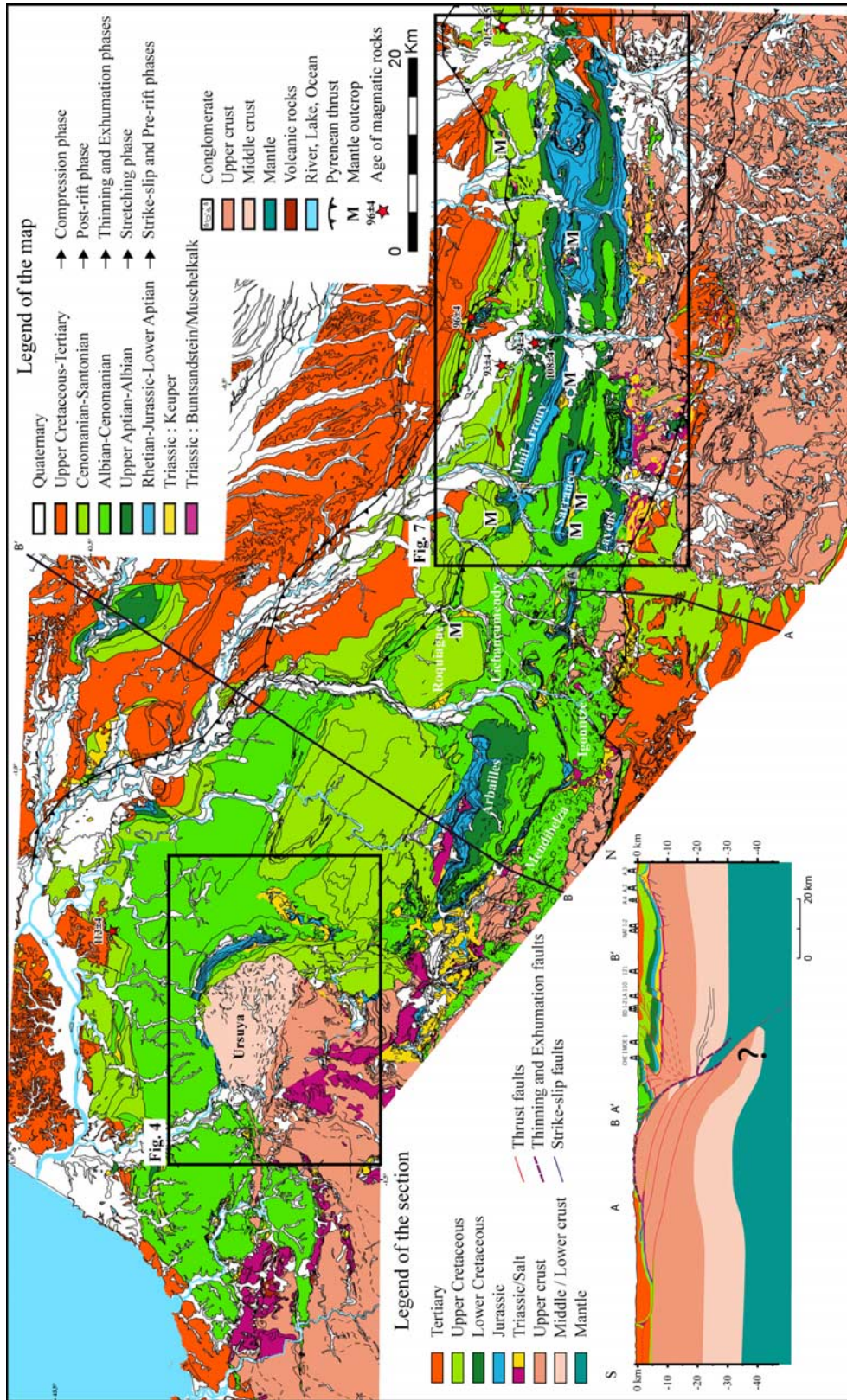


Figure 3. Simplified geological map of the Labourd-Mauléon area modified after the BRGM 1/50,000 geological maps of France (maps of Bayonne (1001) (where numbers refer to the references of the 1/50 000 geological map in BRGM classification), Hasparren (1002), Orthez (1003), Espelette (1026), Iholdy (1027), Mauléon-Licharre (1028), Pau (1029), Saint Jean Pied-de-Port (1049), Tardets-Sorholus (1050), Oloron-Ste-Marie (1051), Lourdes (1052), Larrau (1068), Laruns-Somport (1069), Argelès-Gazost (1070), Gavarnie (1082)). The map shows the distribution of mantle rocks, middle, and upper crustal rocks; sediments and magmatic rocks; conglomerates; and ages of magmatic rocks discussed in the text. The cross section shown is based on the ECORS-Arzacq reflection seismic experiment [Daignières *et al.*, 1994]: the external parts of the orogen have been modified after Teixell [1996] and Schellart [2002] for the Spanish part and after *Ducasque and Velasque* [1988] and *Serrano et al.* [2006] for the French part. The two boxes show the location of the Labourd area (Figure 4) and the Mauléon basin (Figure 7).

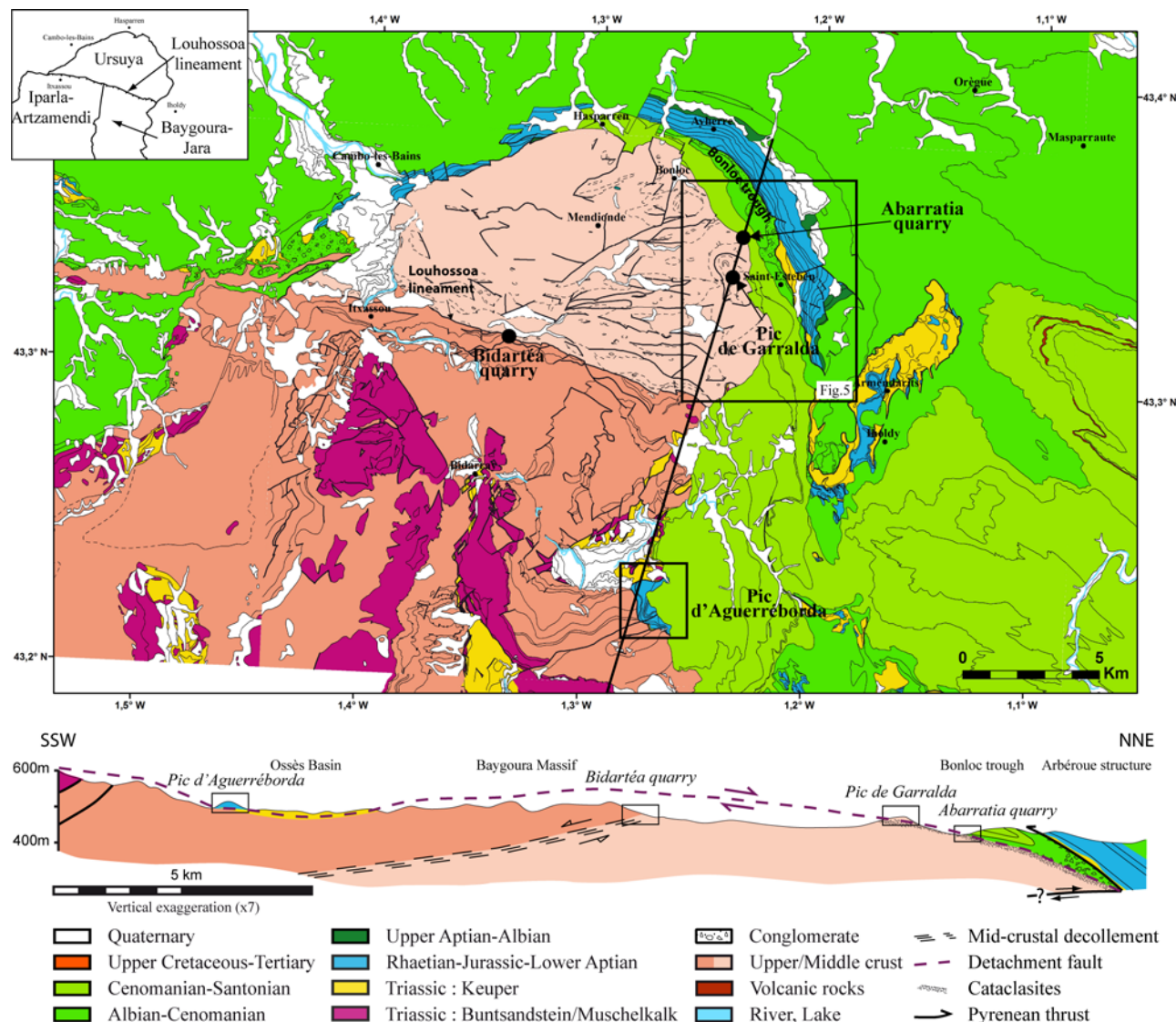


Figure 4. Geological map and cross section across the Massif de Labourd (map modified after the BRGM 1/50,000 geological map of Iholdy); cross section modified after *Boissonnas et al.* [1974]. Positions of the outcrops described in the paper are indicated on the map and the cross section. For location of the map, see Figure 1.

show evidence for dynamic recrystallization, indicating that the deformation observed in this section occurred under greenschist facies conditions.

3.2.2. Contact Between Upper Crustal Rocks and Its Triassic to Jurassic Cover: Pic d'Aguerréborda

[10] On the Iholdy geological map of the BRGM [*Boissonnas et al.*, 1974] in the Baygoura-Jara massif, the Paleozoic metasediments are locally overlain by Upper Triassic to Jurassic sediments. An example can be observed on the Pic d'Aguerréborda, near Ossès. In this location Upper Triassic to Jurassic sediments are separated along a brittle tectonic contact formed by tectonic breccias from the underlying Paleozoic basement. On the BRGM map (Figure 4), both the basement and the overlying Triassic

and Jurassic rocks are sealed by Upper Cretaceous sediments. Whether this contact is stratigraphic or tectonic could not be confirmed in the field, because of a lack of exposures.

3.2.3. Relation Between Middle Crustal Rocks and Cretaceous Sediments: Pic de Garralda and Abarratia Quarry

[11] As described above, the nature of the contact between the granulites forming the Ursuya Massif and the surrounding Albian to Santonian deep marine sediments was a matter of debate. In this paper, we describe two new key outcrops that confirm the idea that the granulites of the Ursuya Massif were exhumed to the seafloor prior to the Pyrenean compression. The major outcrop observations are illustrated in Figure 5, and the relations between the

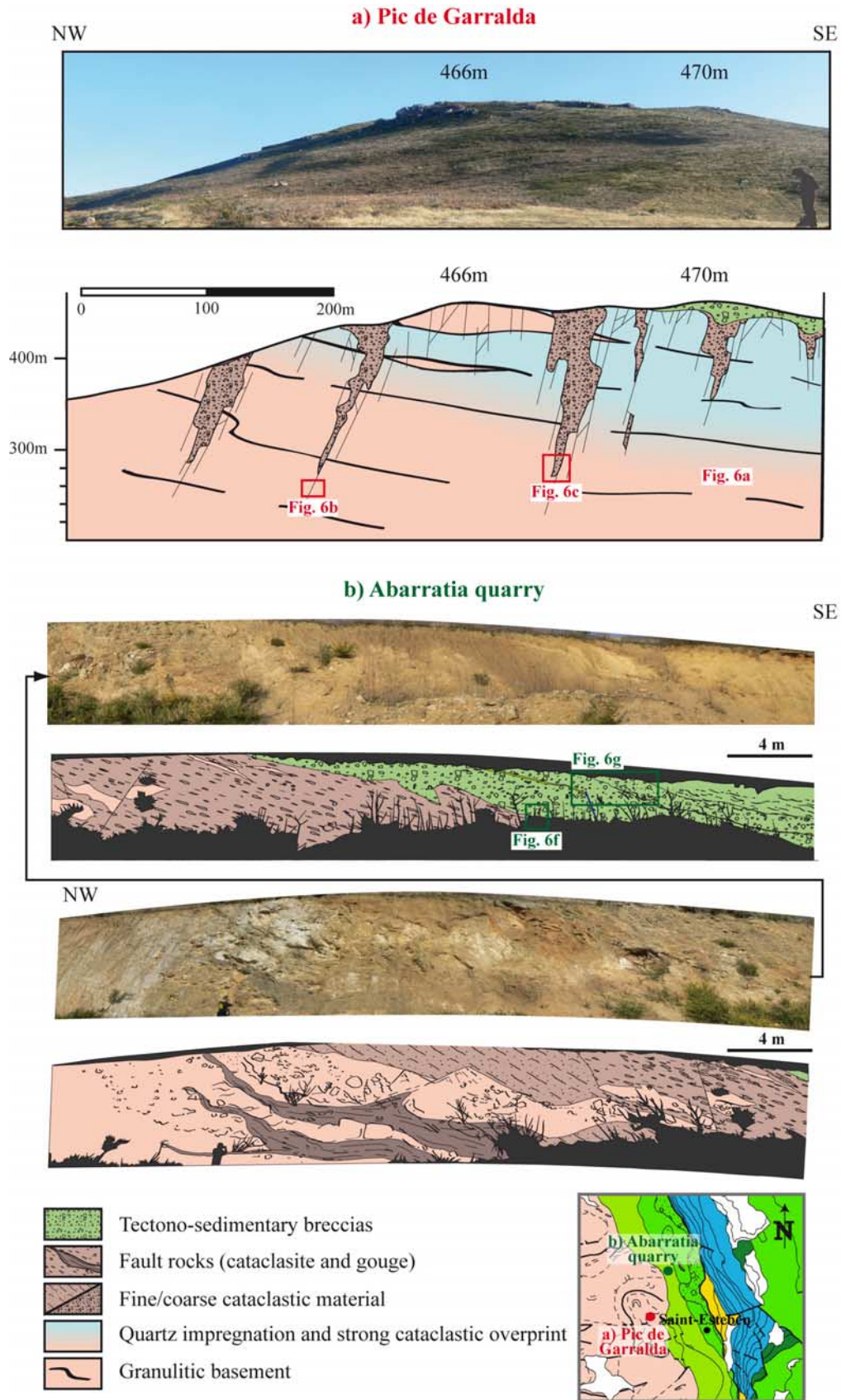


Figure 5

basement and sediments and deformation are summarized in Figure 6.

3.2.4. Pic de Garralda

[12] The Pic de Garralda was mapped on the Iholdy geological map sheet [Boissonnas *et al.*, 1974] as an outcrop of Ordovician schists and quartzite with a tectonic contact with middle crustal rocks and interpreted as a klippe that was thrust onto the Ursuya Massif. A detailed field study shows that the Pic de Garralda is formed by an alternation of massive well-foliated quartzo-feldspathic rocks interleaved with leucocratic Al-rich rocks that are reminiscent of former metasediments equilibrated at granulite facies conditions during or prior to the Variscan orogeny (Figure 6a). The rocks show a penetrative foliation that dips with 25° toward the east (100/25) and are affected by steep ($\pm 80^\circ$) fractures that dip toward the west to northwest. The major observations, on an outcrop scale, are the strong penetrative foliation, the upward increase in brittle deformation that is accompanied by the occurrence of breccias and an impregnation/cementation of quartz (Figure 5a). Although in the field the foliation appears to be locally overprinted by mylonitic shear zones, resulting in very massive, fine-grained, well-foliated rocks, in thin section, all quartz and feldspar microstructures are annealed and mask the deformation history taking place at higher temperatures occurring at middle to lower crustal levels. The foliation is cut by veins and fissures filled by quartz. Upsection, the presence of quartz becomes more dominant, and the host rocks are increasingly more impregnated by siliceous cherts near the summit of Pic de Garralda (shown by the blue in Figure 5a near the top of the basement). Locally this overprint is so pervasive that the primary metamorphic structures are completely erased. Near the top, the veins and fissures are affected by fracturing and formation of breccias that overprint and rework the impregnated rocks (Figure 6d). At the base of the outcrop, breccias are localized and occur along subvertical fractures (Figures 5a, 6b, and 6c). Toward the summit, the breccias as well as the fractures and veins become more abundant and wider. The clasts within the breccias consist mainly of granulites at the base, upsection of impregnated quartz-rich host rocks, suggesting that the clasts in the breccias are derived from the adjacent fractured host rock. The matrix is fine-grained and red. On a macroscopic scale, it is, however, evident that it is composed of the same material as the clasts and surrounding rocks. Only at the very top, the breccias become more massive, polygenic and a sedimentary origin is very likely, mainly also because the rocks do not show a deformation fabric (Figure 6e).

3.2.5. Relation Between Basement and Sedimentary Cover: Abarratia Quarry

[13] The Abarratia quarry about 1 km to the northeast of Pic de Garralda (for location, see Figure 5) shows a complete section from the top of the basement into its undeformed Middle to Late Cretaceous sedimentary cover (Figure 5b). The section initiates in a highly fractured and altered basement that is constituted of stretched and discontinued melanocratic slices inside cataclastically deformed leucocratic rocks, in which some nondeformed pegmatite lithons with feldspar, quartz and muscovite are conserved (Figure 5b). The progressive cataclastic overprint together with a strong alteration masks the primary nature of the basement. The basement is capped by tectonic breccias that pass gradually into tectonosedimentary breccias that are composed of clasts of the underlying basement (Figure 5b). The transition to true sediments is marked by the absence of fractures, veins and a foliation and by the first occurrence of sedimentary structures and sedimentary bedding (Figures 6f and 6g). The transition between tectonic and sedimentary breccias is difficult to define, because of the concordant transition and the invariable composition of the reworked material. Upsection, the sediments, described as flysch in the Iholdy geological map [Boissonnas *et al.*, 1974] develop into blue marls and gray beds of clay rich micritic limestones. The lowermost sediments are affected by high-angle faults, which are sealed by the overlying sediments (Figure 6g). This suggests that the sediments were deposited onto an active fault plane that exhumed midcrustal rocks to the seafloor.

[14] Tectonosedimentary breccias similar to those described in the Abarratia quarry were described from the nearby Bonloc syncline. These breccias, referred to as the Bonloc Breccias, contain angular fragments of granulites and pegmatites inside a clay rich sandy matrix. *Viennot* [1927] interpreted these breccias as “frictional tectonic breccia” formed along a major thrust. *Lamare* [1950], *Le Pochat et al.* [1978], *Muller and Roger* [1977], and *Richard* [1986] described a stratigraphic contact between the Bonloc Breccia and the Ursuya metamorphic basement. *Hall and Johnson* [1986] stated that the angle between the sedimentary bedding and the underlying contact is incompatible with an onlap of the sediments onto the exhumed basement. *Claude* [1990] suggested, however, on the basis of the occurrence of clast of granulite derived from the Ursuya Massif in the Bonloc Breccia, that the Albian to Cenomanian sediments [Boissonnas *et al.*, 1974] were deposited onto previously exhumed granulite facies rocks derived from midcrustal levels.

Figure 5. Overview of the two major outcrops in the Massif de Labourd discussed in this paper (for location of the two outcrops see map in the lower right corner as well as Figure 4). (a) View of Pic de Garralda with the major outcrop shown in the line drawing. Line drawing shows the relationships between the basement rocks (granulites) and the tectonosedimentary cover. Pictures and line drawings of the detailed relationships are shown in Figure 6 and discussed in the text. (b) Abarratia quarry view of the contact between exhumed midcrustal metagranulites (completely tectonized) to the NW (at bottom left), its tectonosedimentary cover (at bottom right and its continuation on the top left) and the overlying sedimentary cover to the SE (at top right). Line drawings show the main relations between the different lithologies observed in the quarry. Details of the relationships observed in the outcrop are shown in Figure 6.

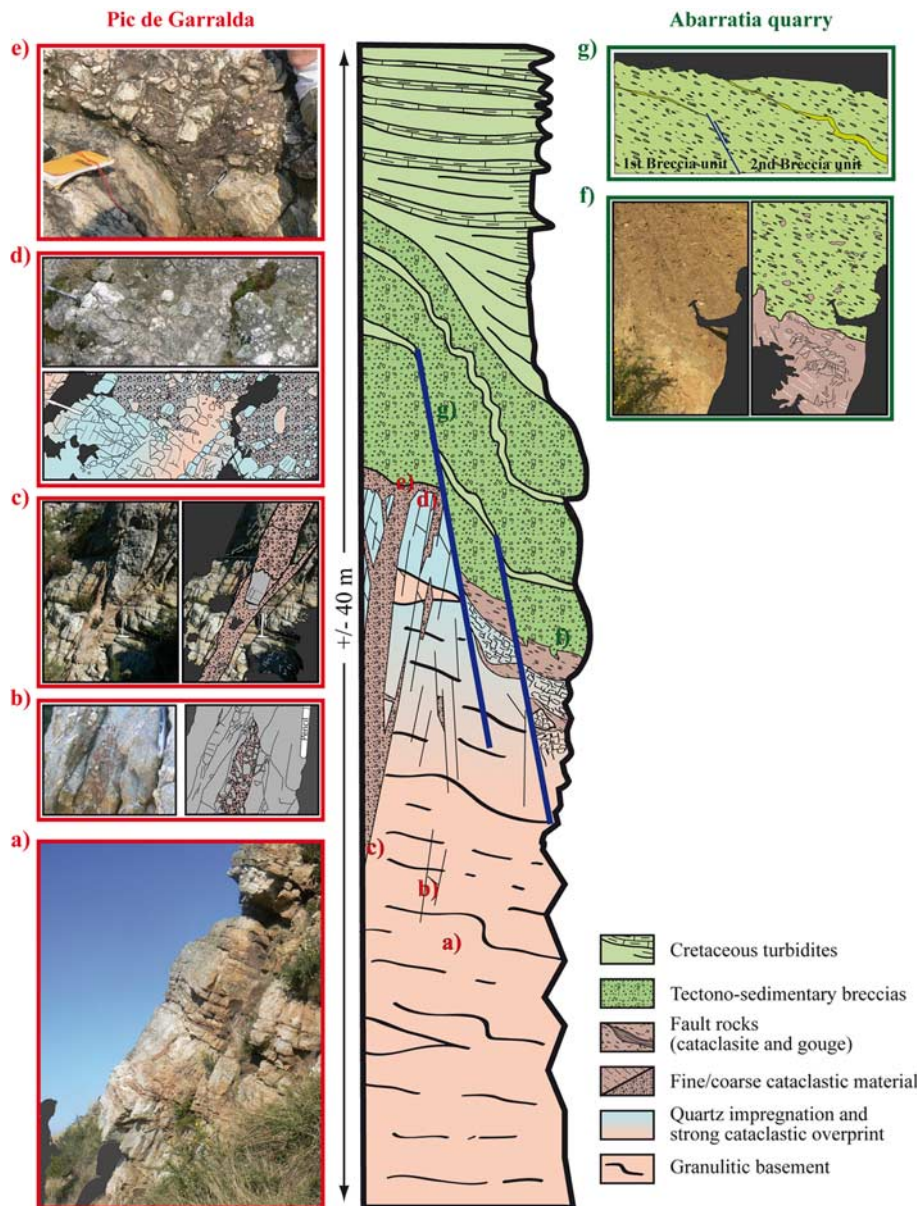


Figure 6. Schematic cross section summarizing the field relations observed on the Pic de Garralda and the Abarratia quarry showing the relationship between the exhumed and tectonized metagranulites and the overlying tectonosedimentary and sedimentary cover. Pictures and line drawings shown in Figures 6a to 6e are from Pic de Garralda (see Figure 5a) and those shown in Figures 6g and 6f are from the Abarratia quarry (see Figure 5b). (a) Alternation of massive well-foliated quartzo-feldspatic rocks interleaved with leucocratic Al-rich rocks. (b) Cataclastic material infiltrating into the basement. (c) Larger vein filled with material derived from the surrounding basement. (d) Contact between cataclastically deformed basement rocks and tectonosedimentary breccias infilling the vein. (e) Sedimentary breccias sealing the exhumed tectonized basement. (f) Contact between exhumed cataclastically deformed basement and its tectonosedimentary cover. (g) Sealed syndepositional normal fault in the basal tectonosedimentary unit.

3.3. Mauléon Basin

[15] The Mauléon basin is situated in the western Pyrenees between Pau and Dax and belongs to the northern Pyrenean zone (Figure 3). This basin overthrusts the Arzacq basin to the north along the Sainte Suzanne thrust, which is

a part of the northern Pyrenean frontal thrust system. To the south, the Mauléon basin is limited by the Paleozoic Igoutze and Mendibelza massifs. As a consequence of the Pyrenean compression, the basin was inverted and deeper parts of the basin were exhumed along north and

south vergent thrust faults resulting in a large-scale pop-up structure. The occurrence of thrust sheets containing deeper parts of the basin thrust onto postrift sediments enables to have direct access to the basal parts of the basin and its related structures. Drilling and geophysical surveys, in particular, the Arzacq–western Pyrenees ECORS profile [Daignières *et al.*, 1994], permitted the determination of the overall architecture and nature of the basin and the underlying crust. On the basis of a refraction seismic investigation, Daignières *et al.* [1981, 1982] identified the position of the Moho to be located at around 40–45 km under the Pyrenean Axial Zone and described a northward dip of the deep crustal structures in this part of the orogen. To the south, the Moho was identified to lie at 30–33 km depth under the Ebro foreland basin [Teixell, 1998]. Beneath the Mauléon basin, the Moho is identified at 28–29 km depth. To balance the surface of the pre-Triassic crust evidenced by the ECORS profile and refraction studies, Daignières *et al.* [1994] proposed a restored section at the end of Cretaceous time in which the crust was thinned to 5 km in the central part of the Mauléon basin. The extreme crustal thinning is compatible with the up to 5 km thick Albo-Cenomanian sedimentary sequence observed in the northern part of the basin. On the basis of a palinspastic reconstruction and assuming a 32 km thick prerift crust, Vergés and García-Senz [2001] estimated the amount of extension with 60.5 km ($\beta = 1.49$). Moreover gravimetric data and teleseismic delays imply high density (at least 2900 kg m^{-3}) and high velocity (7 km s^{-1}) in the crustal block between 7 and 27 km depth beneath the Mauléon basin [Grandjean, 1992]. This high-velocity, high-density block is interpreted to represent either lower crust and/or mantle-derived material [Daignières *et al.*, 1994]. Apart from the extreme crustal thinning, two other observations are remarkable in the Mauléon basin: (1) the occurrence of mantle derived rocks within the basal units of the basin and (2) the existence of a synextensional to postextensional magmatic system. A third point, less evident but not less important, is the complex sedimentary and isostatic evolution observed in the basin (Figure 7).

[16] In the past, each of these points has been studied in detail; however, how these observations are interlinked, remained unclear. This is mainly due to the fact that the underlying tectonic system was not understood. In the following, we describe some key outcrops/observations that document the relation between crustal thinning and the sedimentary evolution documented in the basin. These observations may also help to better understand the relation between the subsidence history, the thermal history and the magmatic evolution of this basin.

3.3.1. Mantle-Derived Rocks in the Mauléon Basin

[17] In the Mauléon basin a number of outcrops showing mantle derived serpentized peridotites can be found, among which the most important are, from east to west Montaut, Moncaut, Turon de Tecouère, Sarailié, Pédaing, and the Col d’Urdach (see Figure 3 for distribution of mantle rocks). In contrast to the mantle rocks exposed in the eastern Pyrenees (e.g., Lherz) the mantle rocks in the western Pyrenees are not associated with North Pyrenean Variscan massifs (Saint Barthelemy, 3 Seigneurs, Milhas)

[Fabriès *et al.*, 1998] nor with the North Pyrenean fault zone. The outcrops range from a few meters to 3 km in diameter, and are commonly found at the base of east-west trending ridges composed of Upper Triassic to Lower Cretaceous sediments. The serpentized mantle peridotites are mainly derived from foliated lherzolites associated with spinel websterite microlayers [Fabriès *et al.*, 1998]. The metamorphic foliation can be very strong as for example in the Turon de Tecouère Massif. Moreover these massifs have undergone hydrothermal alteration with different degrees of serpentization ranging between less than 10% in Turon de Tecouère to up to 80% in Col d’Urdach [Fabriès *et al.*, 1998]. In the past, various scenarios have been proposed for their emplacement, ranging from purely tectonic mechanisms, such as solid intrusion of hot or cold mantle rocks into sediments during strike-slip events [Vielzeuf and Kornprobst, 1984], to tectonosedimentary processes in which mantle rocks were exhumed during Variscan time [Mattauer and Choukroune, 1974; Fortane *et al.*, 1986] and reworked in a middle Cretaceous wild flysch [Fortane *et al.*, 1986]. More recently, Lagabrielle and Bodinier [2008] proposed, on the basis of a reexamination of the Lherz massif in the eastern Pyrenees, that these rocks were exhumed during Albian time to the seafloor before they were reworked and deposited in Albian sediments.

[18] A key area to understand the processes that are related to mantle exhumation in the western Pyrenees is the “Col d’Urdach” (Figure 8). In this area, a remnant of serpentized mantle peridotite is exposed over 2 km^2 . The mantle rocks overlay strongly deformed and foliated Cenomanian flysch sediments. Since the basal contact crosscut a steep foliation within the Cenomanian sediments, the contact has to be younger than Cenomanian. Therefore, we interpret the basal contact of the Col d’Urdach body as a thrust fault and its present position as the results of Pyrenean compressional tectonics. In contrast, Duée *et al.* [1984] interpreted the mantle body as an olistholites within Cenomanian sediments. The mantle rocks in the Urdach outcrop are composed of massive serpentized peridotites that are capped locally by ophicalcites (Figure 8b). These ophicalcites are associated with brittle structures reminiscent of structures found over exhumed mantle in the Alps and drilled off Iberia [Manatschal, 2004]. The mantle derived rocks are overlain by sedimentary breccias (Figure 8a), which were mapped on the Oloron Ste Marie geological map [Castéras *et al.*, 1970] as basal Cenomanian breccias containing clasts of Paleozoic basement. A detailed study of these breccias show that they contain also clasts derived from the mantle and the middle to lower crust.

3.3.2. Triassic to Aptian Sedimentary Units

[19] In the Mauléon basin, basement rocks are, with the exception of the Arbailles block, only exposed along the southern border of the basin (Figure 3). The oldest Mesozoic sediments overlying the Paleozoic basement are Triassic sandstones of the Buntsandstein lithostratigraphic unit. It is important to note that in the Mauléon basin the Triassic series cannot be mapped as a continuous horizon. Except for the Arbailles block, where the basal Triassic units are exposed together with the basement, elsewhere the Lower

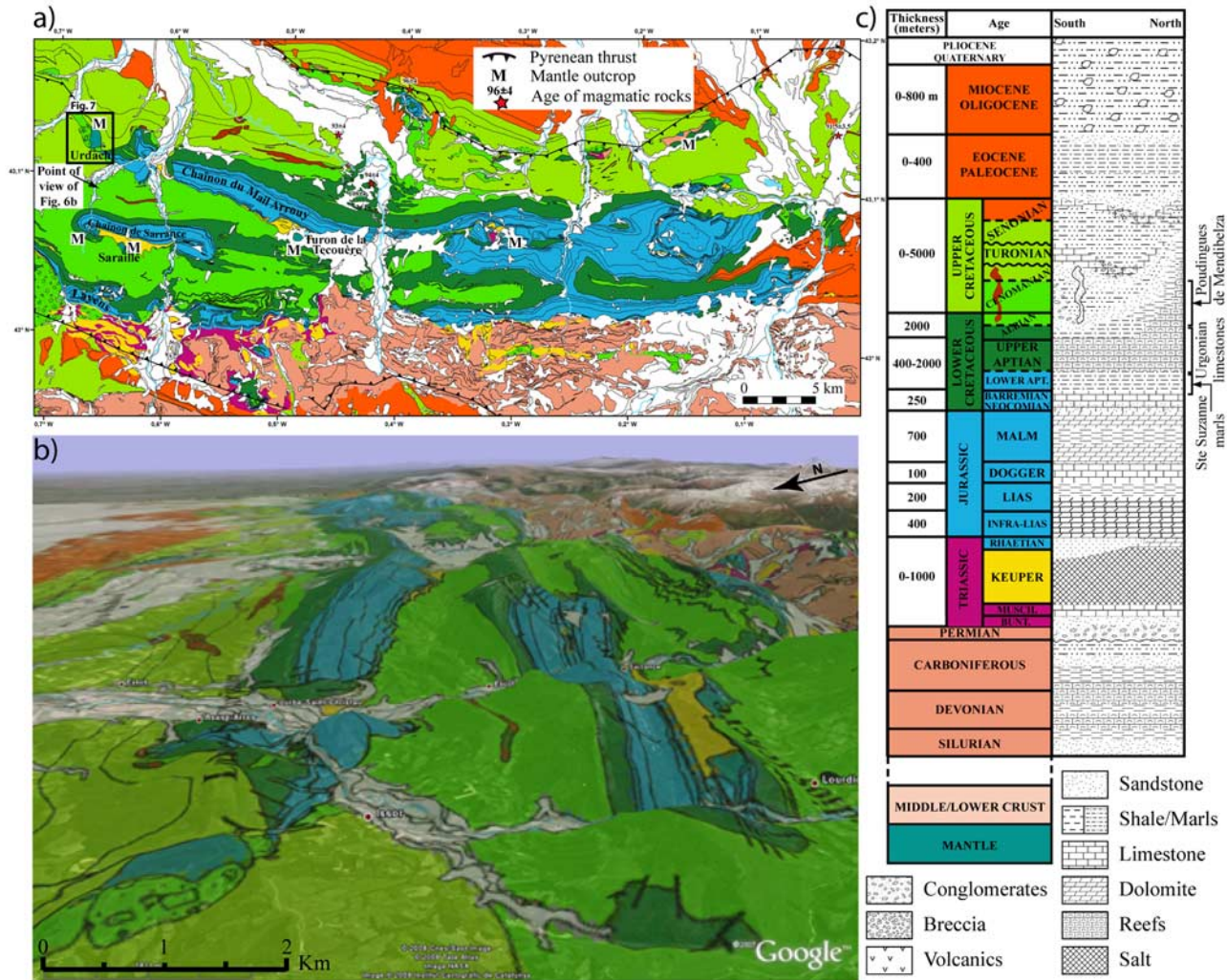


Figure 7. (a) Simplified geological map of the eastern part of the Chaînons Béarnais belonging to the Mauléon basin (map modified after the BRGM 1/50,000 geological map of Tardets-Sorholus, Oloron-Ste-Marie, Lourdes, Larrau, Laruns-Somport); the outcrops described in the paper are identified on the map. (b) Simplified geological map overlain on a 3-D Google map of the Chaînons Béarnais, the map displays the tilted block shape of the Chaînons Béarnais that is infilled by the Albo-Cenomanian sediments. (Google Earth imagery © Google Inc. Used with permission.) (c) Stratigraphic column summarizing the stratigraphic/sedimentary evolution of the Mauléon Basin (south) and Arzacq Basin (north) (modified from Vergés and García-Senz [2001] with permission).

Triassic is missing and only Upper Triassic sediments belonging to the Keuper lithostratigraphic unit (Carnian to Rhaetian) are found. Thus, in the Mauléon basin, the Lower Triassic sediments seem to be associated with basement rocks and decoupled from the Upper Triassic to Cretaceous sedimentary sequence. On the southern border of the basin, in the Axial Zone, Lower and Middle Triassic sediments show stratigraphic contacts to the underlying basement. The Lower Triassic sediments are composed by a quartzite conglomerate and a violet to greyish fluvial sandstone (Buntsandstein lithostratigraphic unit). These sediments are overlain by dark gray or black limestones with dolomitic beds belonging to the Muschelkalk lithostratigraphic unit (Figure 7c). The evaporitic Keuper facies are formed by

multicolored clay and marls, often associated with ophitic extrusive rocks dated as Triassic [Rossi et al., 2003; Canérot et al., 2004]. Within the study area, this evaporitic Keuper facies can be observed in three situations: (1) above upper crustal rocks and Lower Triassic sediment within a stratigraphic context (e.g., Igountze and Mendibelza massifs and in the Axial Zone (Figure 3)), (2) in diapiric structures inside Cretaceous sediments (e.g., Roquiague diapir (Figure 3)), or (3) at the base of a massive Rhaetian to lower Aptian sequence (e.g., Arbailles (Figure 3), Sarrance, Mail Arrouy blocks (Figures 3 and 6)) separated tectonically from mantle derived rocks or Cretaceous sediments. Most of the contacts between the Keuper series and the underlying and overlying units are tectonized.

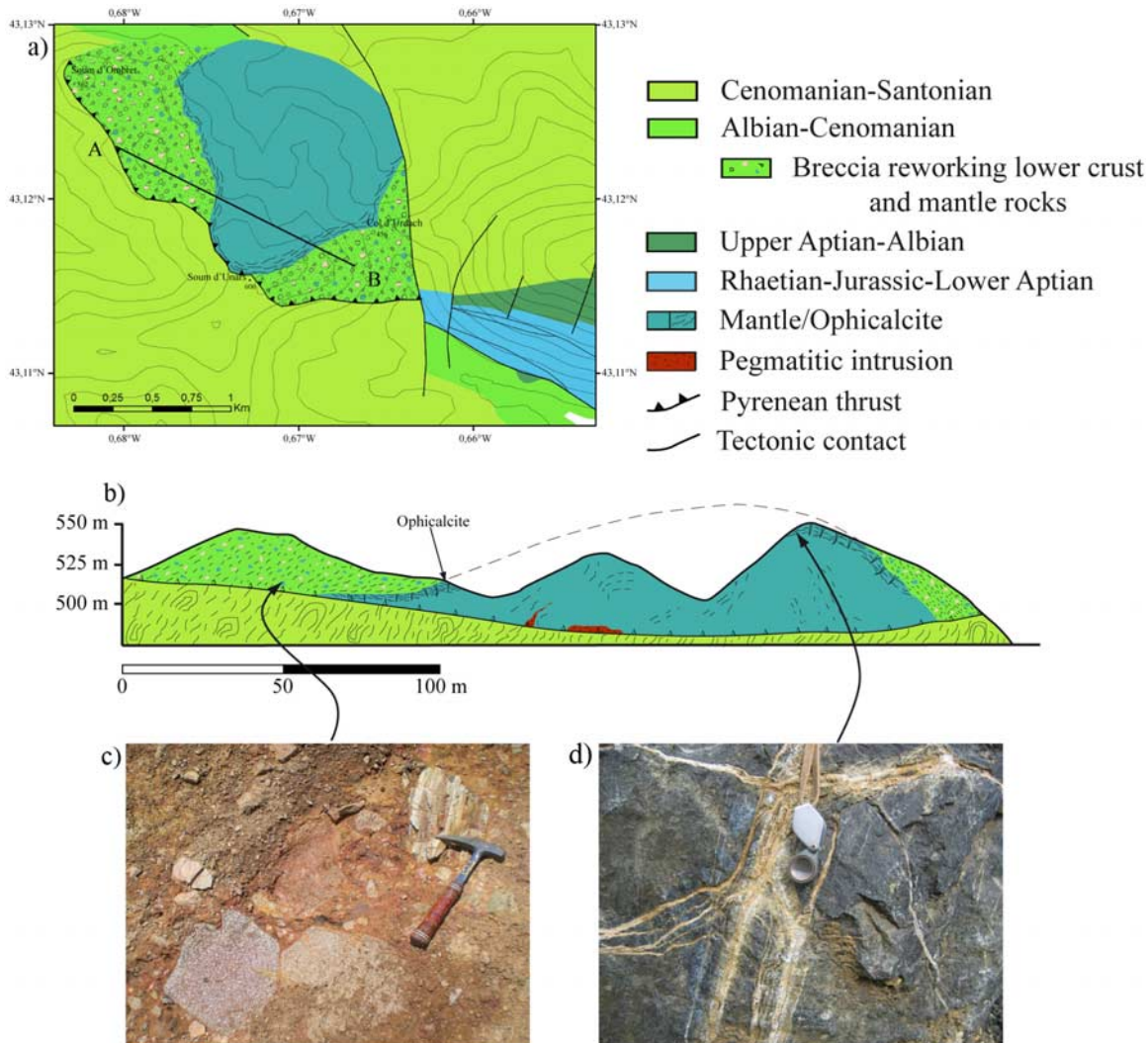


Figure 8. (a) Simplified geological map and (b) cross section across the massif d'Urdach; Photographs showing (c) sedimentary breccia consisting of reworked mantle and crustal rocks overlying exhumed serpentinitized mantle and (d) ophicalcite capping the serpentinitized exhumed mantle rocks.

[20] The massive Rhaetian to Aptian sequence observed in the Mauléon basin is about 1500 m thick and is composed of an alternation of dolomite, limestones, and marls (Figure 7c). These massive limestones dip toward the north (Figure 7b). In the literature, these structures are commonly interpreted as tilted block resulting from Cretaceous rifting, folded and thrust southward during Pyrenean compression [Canérot and Delavaux, 1986; Dubos-Sallée et al., 2007]. In the Massif des Arbailles (Figure 3), for example, a remnant of a tilted block is well exposed. Canérot [1989] showed that the Jurassic and Lower Cretaceous sediments in this block were eroded at the top of the block and overlain by Aptian sediments. In addition, the massive Upper Triassic to Aptian limestones overlie directly mantle rocks. The contacts between the sediments and the mantle rocks are tectonic, but as discussed below, we assume that they predate the Pyrenean compression during which these rocks were thrust, together

with the overlying Rhaetian to Aptian sequence, onto its former cover consisting of Upper Cretaceous sediments. In the Massif des Arbailles, Canérot [1989] showed that there is a direct temporal and spatial relationship between normal faulting and the mobilization and emplacement of salt diapirs. Another example is observed in the Chaînon de Lichançumendy (Figure 3), where Canérot [1989] described diapiric collapse structures that were interpreted to form during outflow of salt and the formation of a salt ridge on the elevated part of the block. Although in this paper we will not focus on the interaction between salt tectonics and exhumation processes, the latter manifested by the occurrence of middle to lower crustal and mantle rocks in direct contact to sediments, it is important to keep in mind that gravitational movements triggered by salt tectonics and tectonic processes are intimately interlinked and result in very complex structures. The preservation of diapiric collapse structures on a map scale also show that

the overall compressional overprint in the study area is limited. Another, interesting detail is the occurrence of pieces of mantle rocks observed in the Roquiague diapir (Figure 3). This observation suggests that the salt might have been in direct contact with the mantle rocks during its diapiric uplift.

[21] A key stratigraphic unit that document the onset of extension is the Sainte Suzanne Formation, dated as early Aptian [Cassou, 1968] (Figure 7c). This formation was deposited conformably across the whole area. It is composed by sandstone rich marls which evolve to the west into limestones and marls containing orbitolines. The Sainte Suzanne Formation has been interpreted to represent a shallow marine depositional system [Cassou, 1968]. Therefore, it can be used as a time marker as well as a bathymetric reference level to estimate the isostatic evolution of the study area. This unit is overlain in the north by thick limestones with Toucasia and black shale dated as latest Aptian whereas in the south it is uplifted and partially eroded. The late Aptian to early Albian sediments, commonly referred to as Urgonian limestones (Figure 7c), show sedimentary wedges thickening into footwall blocks. This is particularly well documented in the Arbailles [Canérot, 1989]. These observations enable to date the onset of major extension, which initiated in late Aptian time. The onset of final extension coincides with rapid subsidence of the basin, uplift of the southern border, and onset of salt migration as documented by Canérot [1989].

3.3.3. Albo-Cenomanian Magmatic, Thermal, and Sedimentary Evolution

[22] During latest Aptian to earliest Albian the subsidence rate increased in the northern part of the Mauléon basin resulting in the deposition of more than 5 km of Albo-Cenomanian sediments (Figure 7c). In the same time interval, the southern border of the basin was uplifted and eroded leading to the deposition of up to 900 m of conglomerates, referred to as the “Poudingues de Mendibelza” (Figure 7c), along the southern margin of the basin. The conglomerates are mainly formed by Paleozoic metasediments that derived from the uplift and erosion of the Axial Zone [Boirie and Souquet, 1982]. The transition from the Albo-Cenomanian conglomerate fan deposits in the south to shales and turbidites in the north suggests the existence of a complete depositional sedimentary system ranging from the platform across the slope into a deep marine fan. However, the existence of blocks composed of Jurassic to Aptian limestone, in this work interpreted as extensional allochthons, seems to control the distribution of the conglomerate fan deposits and its transition/interfingering with the deep marine facies.

[23] A magmatic system constituted of submarine lava flows and numerous sills and dikes of variously fractionated basic alkaline rocks developed in the deepest parts of the basin in the Albo-Cenomanian sediments that overlie locally exhumed mantle rocks. In detail, this magmatic system is complex, as indicated by the observation that in one and the same sill a succession of picrite, teschenite, and analcite syenites can be observed [Azambre and Rossy, 1976]. K-Ar ages on minerals extracted from these volcanic and intrusive

rocks gave ages between 110 Ma and 85 Ma [Montigny *et al.*, 1986]. In the surrounding sediments, metamorphic assemblages of Ca-plagioclase, orthoclase, biotite, muscovite, scapolite, and actinolite are observed and show a high-T/low-P mesozonal metamorphic overprint. Younger sediments (Albian to Coniacian) show an anchizonal to epizonal metamorphic event that gave rise to crystallization of muscovite, chlorite, and albite [Montigny *et al.*, 1986]. It is yet unclear if the sediments were affected by one or by two distinct metamorphic events [Golberg and Maluski, 1988]. Ages dating the metamorphic overprint range between 95 and 85 Ma [Montigny *et al.*, 1986]. Thus, magmatic and thermal peak outlasted mantle exhumation and predate the onset of Pyrenean compression.

[24] The postextensional sedimentary system is well exposed in the “Gorge de Kakoueta” on the southern border of the Mauléon basin. In this area, 300 to 400 m thick Turonian to Campanian limestones overlie Paleozoic metasediments. In the Ossau valley in the Axial Zone, Late Carboniferous batholiths of the Eaux Chaudes massif are also overlapped by Cenomanian-Turonian limestones. In both areas Triassic to Lower Cretaceous rocks are not observed, suggesting that they were either not deposited, or that they were deposited and then removed either by erosion or tectonic processes. Evidence that material had to be removed is supported by the occurrence of up to 900 m of conglomerates in the Mendibelza system, as well as the observation that the post-Variscan batholiths were not yet exposed at the surface in Late Permian time. Thus, the southern border had to be uplifted and eroded before Turonian time. However, in contrast to ample evidence for erosion of basement, Jurassic to Lower Cretaceous sediments could not be found as clasts in the conglomerates indicating that they were either not deposited or that they were tectonically removed. In a later part, we will discuss how far the uplift and erosion of the southern margin might be related to the extreme crustal thinning observed in the basin to the north and the emplacement of the magmatic rocks and the high-T/low-P event recorded there.

3.3.4. Late Santonian to Eocene Syncompressive Sedimentary Record

[25] A major change in the depositional environment occurred during Santonian time. Up to 150 m of calcarenites containing rounded gravels of quartz or schist are deposited unconformably over a karstic substratum showing a transport direction from S-SW to N-NE. This system terminates the Cenomanian transgression toward the south. The calcarenites are overlain by up to 300 m of Santonian packstones, wackstones, and mudstones interpreted to be deposited in a deeper marine environment [Bourrouilh and Al Hamawi, 1993]. The Campanian is characterized by the deposition of terrigenous sediments that are sourced from the emerging Pyrenees to the south. During this stage, the Santonian carbonate platform was uplifted, eroded and redeposited in the flysch basin to the north. Flysch-type sedimentation prevailed during the remainder of the Cretaceous and persisted into the Eocene [Vergés and García-Senz, 2001]. In the Mauléon Basin the compressional deformation ceased in late Eocene or early Oligocene [Déségaulx *et al.* 1990;

Teixell, 1998]; meanwhile, it continued until late Oligocene to earliest Miocene in the southern Pyrenees [*Teixell*, 1996, 1998], indicating the migration of the deformation from north to south and the formation of a strongly asymmetric double vergent mountain belt. In the Mauléon basin a change in the vergence from north to south directed thrusting occurs along a synclinal zone (the Roquiague syncline). *Teixell* [1998] showed that this system is not associated with major bounding faults. To the south, in the area of the “Chaînons Béarnais,” a south verging thrust system prevails consisting of thrust faults that override the Axial Zone (e.g., the Lakora thrust). *Teixell* [1993, 1996, 1998] proposed that this system accommodated a shortening of up to 22 km. To the north, the Upper Cretaceous flysch succession is deformed into a north directed fold and thrust system where the individual thrusts, poorly exposed at the surface, were observed in wells and seismic profiles [*Ducasse and Velasque*, 1988; *Daignières et al.*, 1994]. The most important north vergent thrust systems are formed by the Saint Palais and Sainte Suzanne thrust faults along which the Mauléon Basin is thrust onto the Arzacq Basin [*Ducasse and Velasque*, 1988]. *Daignières and ECORS Team* [1992] and *Teixell* [1998] estimated that the total shortening accommodated by the North Pyrenean thrust system is in the order of 20 to 30 km.

4. Discussion

[26] The present-day Pyrenean/Cantabrian–Bay of Biscay system results from the opening of a V-shaped basin during latest Jurassic to early Albian time within a left-lateral transtensive strike-slip system. This system was reactivated during latest Cretaceous to Oligocene time by N-S directed compression. In this paper we focus on the Labourd-Mauléon area located at the eastern tip of the Bay of Biscay in the western Pyrenees (Figure 1). Although the Pyrenean compressional overprint resulted in the inversion of the Lower Cretaceous basins and reactivated most of the rift-related structures, it has the advantage that it uplifted and exhumed the basal parts of a former rift basin. As a consequence, in the Mauléon-Labourd area there is direct access to mantle, middle and upper crustal rocks as well as to the complete stratigraphic record including prerift, synrift and postextensional sediments. These rocks form a unique archive that record the evolution from initial stretching to thinning to final exhumation of mantle rocks at the seafloor, including a major post extensional thermal and magmatic event. This event might be related with the complex uplift and subsidence history observed in the basin and its southern border during Early Cretaceous time. In the following discussion, we start with an overview of the large-scale kinematic evolution and propose a three-dimensional reconstruction of the Mauléon Labourd area at the end of rifting in Albian time. In a second part, we discuss the tectonic evolution of this highly extended area on the basis of the observed relations between structures, basement rocks and the sedimentary record. The aim of the discussion is to understand how the observed extreme crustal thinning was accommodated ahead of a propagating ocean and how

this deformation is recorded in the sedimentary system. We believe that this work has major implications for the understanding of how continents rupture and how this process is documented in the structural and stratigraphic record.

4.1. Plate Kinematic Context

[27] From a plate tectonic point of view the major questions related to the understanding of the Pyrenean Cantabrian system are related to the timing, location, and amount of left-lateral displacement between the Iberian and European plates. The reconstruction proposed by *Olivet* [1996] (Figure 2a) did not take into account mantle exhumation and crustal thinning, which is today well documented by deep sea drilling and refraction and reflection seismic experiments along the Iberia-Newfoundland margins. The reconstruction of *Sibuet et al.* [2004] (Figure 2b), which proposes 600 km of extension in the eastern Pyrenees, is clearly in conflict with the local geological observations made in the Pyrenees. Two major new results that need to be taken into account in paleogeographic reconstructions of the Iberia plate are (1) the much larger prebreakup extensions observed in the Iberia-Newfoundland margins inferred to be in the order of 300 to 400 km [*Péron-Pinvidic and Manatschal*, 2008] and (2) the problem of understanding the nature and significance of the magnetic anomalies in the Iberia-Bay of Biscay system [e.g., *Sibuet et al.*, 2007; *Norton*, 2007]. The two major consequences for the paleogeographic reconstruction are that Iberia had to move for up to 400 km eastward relative to stable Europe before continental breakup, i.e., before late Aptian time, and that the pre-M0 rotation of Iberia is much less important. Indeed, *Gong et al.* [2008] recently concluded, on the basis of new paleomagnetic data that the rotation of Iberia occurred predominantly in Aptian time, between M0 and the Aptian-Albian boundary, i.e., between 125 and 112 Ma according to the time scale of *Ogg et al.* [2004]. These two changes have major implications for the geological evolution of the Mauléon-Labourd area. As shown in Figure 2c, most of the left-lateral movement is suggested to occur between Late Jurassic and late Aptian time and predates the anticlockwise rotation leading to the opening of the Bay of Biscay. During the opening of the Bay of Biscay in early Albian time, extension localized along previously formed strike-slip systems and overprinted and obscured the Late Jurassic to Aptian structures. This process resulted in a highly thinned crust and exhumed middle crust (Labourd) and mantle rocks (Mauléon). Evidence for major Late Jurassic to Aptian strike-slip movements are, also strongly overprinted by the late Aptian to Albian extension, the formation of E-W directed depocenters of Late Jurassic to Aptian age and the local occurrence of deep marine facies in the Bay of Biscay. Moreover, the occurrence of thick Upper Jurassic to Lower Cretaceous sequences in the Cameros basin [*Platt*, 1990; *Casas-Sainz and Gil-Imaz*, 1998; *Mata et al.*, 2001] in northern Spain clearly demonstrates a transtensive tectonic activity prior to the late Aptian. In the study area, the onset of major extension associated with crustal thinning and mantle exhumation initiates after the

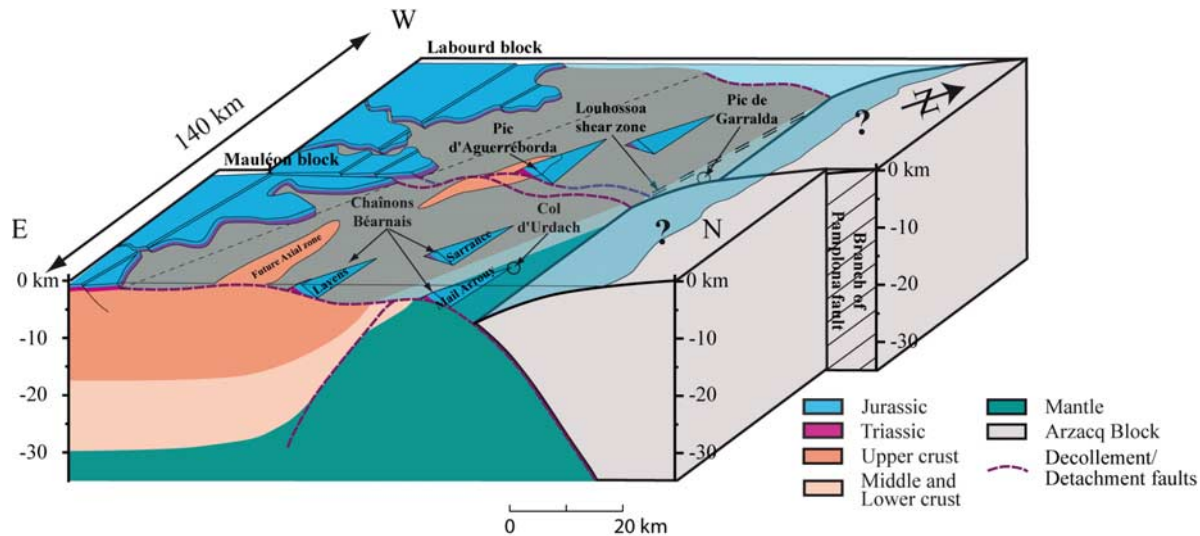


Figure 9. Restoration of the 3-D architecture of the Labourd-Mauléon area prior to onset of compression. Only the preextensional sedimentary cover is represented. In the reconstruction, the two major blocks (Mauléon block to the east and the Labourd block to the west) are separated by the Pamplona fault interpreted to represent an Albian SW-NE striking transfer fault. The major structure in the Labourd block is a detachment fault that exhumes midcrustal rocks at the seafloor. In the Mauléon block, extensional allochthons are interpreted to overlie in the deep distal domain directly exhumed mantle rocks (e.g., Chainons Béarnais).

deposition of the shallow marine early Aptian Sainte Suzanne formation.

4.2. Restorations of a Regional 3-D Rift Architecture Prior to Onset of Compression

[28] A prerequisite to restore the precompressional architecture of the study area is the understanding of the plate kinematics and compressional structures within the overall area (Figure 9). In this paper we assume, as previously discussed, that the major left-lateral displacement between the Iberian and European plates occurred before Aptian anticlockwise rotation of the Iberian plate [see also *Gong et al.*, 2008]. As a consequence, the major late Aptian to Albian extensional event and the later compression are inferred to be much more orthogonal and to overprint a previously formed E-W trending diffuse plate boundary. This is supported by the observation of a strongly segmented margin as indicated by the occurrence of NE-SW trending transfer/transform faults active since Lower Cretaceous time and reactivated during Pyrenean compression. Examples for such fault systems are from west to east: the Hendaya fault, the Pamplona fault [*Larrasoña et al.*, 2003] and the Toulouse fault [*Souquet and Mediavilla*, 1976]. The more orthogonal extension and compression justifies the study of the local evolution of the extensional and compressional evolution in two-dimensional, N-S directed sections (Figure 10). However, on the scale of the study area, which is 120 km in E-W and 40 km in N-S direction, the geometries are more complex and clearly 3-D. Therefore, before we start to describe the temporal evolution of the study area, we propose a 3-D restoration of the Labourd-Mauléon area prior to onset of compression.

[29] The existing reconstructions of the Cretaceous basins in the north Pyrenean domain typically propose palinspastic reconstructions in which basins are separated from each other by N40° to N60° transfer faults (e.g., system of hexagonal basins proposed by *Peybernès and Souquet* [1984] or diamond-shaped basins proposed by *Choukroune and Mattauer* [1978]). In the geological map of the Mauléon-Labourd area, transfer NE-SW striking faults are not observed; however, *Claude* [1990] described a major transform fault, the Pamplona fault, separating the Massif de Labourd from the Arbaillies. *Claude* [1990] showed that this fault was active during the deposition of the Lower Cretaceous to Albian sediments and concluded therefore that this fault had to be active during Albian time. *Larrasoña et al.* [2003] agreed with an Albian age of the Pamplona fault and interpreted this fault as a transfer fault that separated two segments of the Pyrenean rift. In our reconstruction, we assume that we deal with two major blocks, the Mauléon block to the east and the Labourd block to the west that are separated by a northern branch of the Pamplona fault (Figure 9).

[30] Within the Labourd block, *Razin* [1989] and *Claude* [1990] demonstrated that Albian to Cenomanian sediments contain reworked middle crustal clasts next to the exposed granulites of the Ursuya Massif (Figure 4). Along strike of the present massifs, P. Razin (personal communication, 2007) observed that the change from upper crustal to middle crustal rocks is mirrored in the sedimentary detritus. While in front of upper crustal basement only upper crustal detritus can be found, in places where middle crustal rocks are observed in the outcrop, clasts of middle crustal rocks are also found in the Cretaceous sediments. Therefore, P. Razin

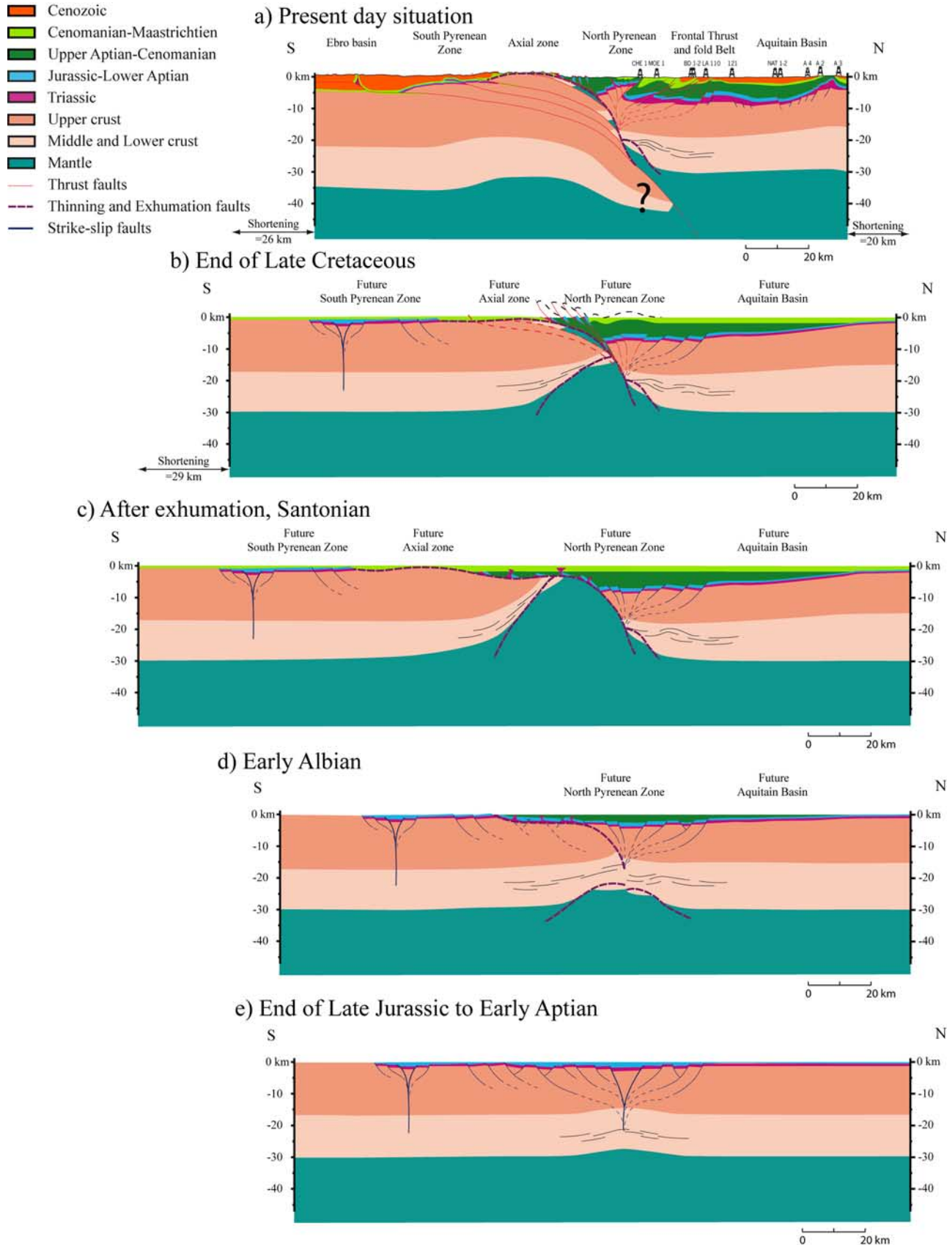


Figure 10

(personal communication, 2007) suggested that the dome shaped body, as observed today on the map (Figure 4), composed of middle and upper crustal rocks, existed already in Albian time. This suggests that the Louhossoa fault, which separates upper and middle crustal rocks, is pre-Pyrenean in age (older than Late Cretaceous). This is compatible with the regional map, on which the Cretaceous sediments are not affected by this fault. Further evidence for this interpretation is the discovery of sediments infiltrating deformed and exhumed middle crust observed at Pic de Garralda (Figures 4 and 5) and the occurrence of a brittle detachment fault in the quarry of Abarratia overlain by tectonosedimentary breccias and Middle to Late Cretaceous sediments (Figures 4 and 5). These observations suggest that the granulites were capped by a brittle top basement detachment fault. Erosion of the brittle fault rocks, as indicated by the reworking of middle crustal rock in the sediments found in the Bonloc conglomerates, is a further evidence to show that this structure was exhumed at the seafloor. Although the detachment fault is not exposed everywhere, the occurrence of blocks containing Jurassic and Lower Cretaceous sediments, interpreted as extensional allochthons, suggests that the detachment capped also the upper crustal rocks (compare cross section in Figure 4). However, the breakaway zone of the detachment fault could not be identified. Because the Lower and Middle Triassic Buntsandstein and Muschelkalk lithostratigraphic units preserve primary contacts to the upper crustal rocks, a possible interpretation is that the detachment faults rooted into the evaporites of the Keuper lithostratigraphic unit. At this point it is important to mention that the top basement detachment fault observed in the Labourd area is clearly a tectonic and not a gravitational structure, as indicated by the observation that this structure cuts into basement. The late top basement detachment fault also postdates the Louhossoa fault that separates upper and middle crustal rocks.

[31] The Mauléon block to the east is covered over most of the area by Cretaceous sediments. Therefore, its basement structure is more difficult to interpret. It can be subdivided in three domains: (1) a proximal, little extended domain in the south (Axial Zone), (2) a transitional domain

(southern margin of the Mauléon basin), and (3) a deep distal domain to the north, where crustal thinning was locally complete. The subdivision into these three units became effective in early Aptian time, after the deposition of the Sainte Suzanne formation.

4.2.1. Proximal Domain

[32] In this zone, Cenomanian sediments directly onlap onto basement. The discovery of clasts of upper crust in the Mendibelza conglomerates [Boirie and Souquet, 1982] suggests that the proximal zone was exposed above sea level and subject to erosion. The lack of clasts of Jurassic and Cretaceous sediments suggests that within the source area, these sediments did not exist. Either they were not deposited, or, they were deposited and eroded or tectonically removed. The observation that late Carboniferous granites such as the pluton of “Eaux chaudes” that were intrusive into Paleozoic metasediments [Ternet *et al.*, 2004] are overlapped by Cenomanian sediments suggests either major erosion, and/or, the existence of exhumation faults that exhumed these rocks tectonically to the surface. Despite the fact that the crustal thickness of this domain cannot be determined directly, the fact that this basement was uplifted above sea level and then overlapped by Cenomanian shallow marine limestones suggests that (1) either the crustal thickness remained in the order of ± 30 km or (2) the thinning of the crust was balanced thermally by the uplift of hot mantle underneath extended and thinned crust. In the latter hypothesis, a subsequent thermal subsidence would have been recorded, which is not observed.

4.2.2. Transitional Domain

[33] The transitional domain is affected by south vergent thrust faults and folds (e.g., Lakora thrust, [Teixell, 1993, 1996, 1998]), which strongly overprint the pre-Pyrenean Lower Cretaceous structures. Therefore, it is difficult to estimate the extent and nature of the precompressional structures. However, this zone is characterized by up to 900 m thick conglomerates. These conglomerates, referred to as the Igountze and Mendibelza massifs (conglomerates), represent a very characteristic feature of this domain. The aggradation of 900 m of conglomerates suggests that this zone had a strong subsidence. In the Mendibelza Massif, it

Figure 10. Palinspastic evolution of a N-S directed section across the Pyrenees from Late Jurassic to present. (a) Present-day situation. Reconstruction based on the ECORS-Arzacq reflection seismic survey [Daignières *et al.*, 1994]: the external parts of the orogen have been modified after Teixell [1996] and Schellart [2002] for the Spanish part and after Ducasse and Velasque [1988] and Serrano *et al.* [2006] for the French part. (b) End of Upper Cretaceous: situation after onset of N-S compression showing the reactivation of the Early Cretaceous, rift-related detachment system and the formation of pro and retro thrust faults forming a large-scale pop-up structure over the previously thinned crust. (c) Early Cenomanian. Situation after the exhumation phase showing a detachment system that cut across thinned middle and lower crust into mantle leading to the exhumation of mantle rocks at the seafloor. This evolution is related with the deposition of thick Albian sedimentary sequence. (d) Early Albian. Situation at the onset of thinning showing a stage when upper and lower crustal deformation is decoupled along midcrustal decollements (e.g., Louhossoa lineament in Figure 4). Near the surface, the detachment faults are soling out in the Triassic evaporites which makes that upper crustal rocks are exhumed beneath tilted blocks consisting of Late Triassic to Early Cretaceous carbonates. During this stage the deformation is controlled by two major decoupling horizons; one in the middle crust and one in the Triassic Keuper lithostratigraphic unit. (e) Late Jurassic to early Aptian. Major distributed strike-slip phase during which the plate boundary between Iberia and Europe will be established. During this stage, obscured by later extension, localized pull-apart basins form along the former Iberia-Europe plate boundary. For simplicity, previous Paleozoic to Triassic basins are not shown, despite the fact that they may be important in localizing the rift-related structures.

can be observed that these conglomerates onlap onto a chaotic breccia (Ithurramburu breccias) [Boirie and Souquet, 1982] that is formed by angular clasts of various size that derive from the underlying basement. Basinward, the conglomerates are interfingered with turbidites; however, on a map view, it looks as if the conglomerates terminate against a block consisting of Upper Triassic to lower Aptian sediments (e.g., Arbailles blocks and Chainons du Layens (Figure 3)). Locally, it can be observed that this block was eroded and filled with upper Aptian sediments, suggesting that this block was tilted, uplifted and eroded before it subsided during latest Aptian to earliest Albian time. This suggests that the transitional zone had a complex morpho–tectonic and isostatic evolution.

4.2.3. Distal Domain

[34] This zone is the most enigmatic, since E-W trending ridges of Upper Triassic to Lower Cretaceous sediments are associated with exhumed mantle rocks, Cretaceous sediments, salt diapirs, magmatic rocks and a local high-T/low-P metamorphic overprint, dated as 95–85 Ma [Montigny *et al.*, 1986]. Thus, this metamorphic overprint postdates extension and predates the Pyrenean collision. On the basis of the stratigraphic record, extensional deformation leading to crustal thinning seems to occur during early Aptian time, after the deposition of the Sainte Suzanne shales. Onset of major deformation in the sedimentary cover is characterized by block tilting and formation of sedimentary wedges, migration of salt and a rapid subsidence. How this deformation is linked to crustal thinning and mantle exhumation is not clear in the Mauléon block, because, in contrast to the Labourd block, basement rocks are only locally exposed. However, where basement rocks are exposed, in this case mainly mantle rocks, they show ophicalcites, which are characteristic for top basement detachment faults overlying exhumed mantle [Desmurs *et al.*, 2001; Manatschal, 2004]. The occurrence of sedimentary breccias over these mantle rocks containing clasts of crustal and mantle rocks is a further evidence for direct exhumation of mantle rocks at the seafloor. Therefore, we suggest that in the Mauléon basin mantle rocks were exhumed at the seafloor and then covered by sediments. The occurrence of clasts of mantle rocks in salt diapirs (e.g., Roquiague structure (Figure 3)) confirms the existence of mantle rocks in the footwall of the Mauléon basin. This observation indicates that the salt had to be allochthonous and had to move out over the exhumed mantle. Therefore, most of the Triassic to Jurassic sediments may be interpreted as extensional allochthons that were emplaced over a detachment system that exhumed mantle and midcrustal rocks at the seafloor. Since the tilted blocks are bounded by sedimentary wedges showing thickening into the footwall, this would imply that deformation might have initiated at the surface along high-angle faults resulting in fault bounded basins. This deformation predates the formation of detachment faults that truncated the previously tilted blocks resulting in the formation of extensional allochthons. These allochthons overlie today thinned crust and locally also exhumed mantle (e.g., mantle outcrop of Sarailié, Urdach and Turon de la Tecouère). Thus, mantle exhumation had to occur after the deposition of the upper

Aptian–lower Albian sediments, which formed in the earlier fault bounded basins (e.g., Arbailles), and before the deposition of the Albo-Cenomanian sediments, which overlie exhumed mantle. It is also important to note, that magmatic rocks are intrusive into sediments that overlie exhumed mantle rocks and are overprinted by a high-T/low-P metamorphic event. Thus, the peak metamorphic and magmatic event, dated as 110 to 85 Ma [Montigny *et al.*, 1986], had to postdate mantle exhumation.

4.3. Tectonosedimentary Evolution

[35] The Labourd and Mauléon areas provide complementary observations that enable to discuss the temporal evolution of crustal thinning and mantle exhumation and its relation to the sedimentary system. Figure 10 represents a palinspastic evolution of a N-S directed section across the study area. Section in Figure 10a shows the present-day situation. It is based on the ECORS-Arzacq seismic data [Daignières and ECORS Team, 1992, 1994]: the external parts of the orogen have been modified after Teixell [1998] and Schellart [2002] for the Spanish part and after Ducasse and Velasque [1988] and Serrano *et al.* [2006] for the French part. For the internal parts, we show a new interpretation, which is based on our observations presented above. The crustal thickness as shown in Figure 10a (present-day situation) is derived from geophysical observations. The crustal thickness for section in Figure 10c (precompression) is based on the stratigraphic record, assuming isostatic equilibrium, and the observation that mantle rocks were exhumed at the seafloor. Figure 10e shows the situation before onset of extension. Although the reconstruction was made backward in time to enable to balance approximately the crustal sections, in the following discussion we discuss the evolution forward in time, beginning with the Late Jurassic.

[36] During Late Jurassic to early Aptian, we assume, on the basis of plate tectonic reconstructions (see Figure 2), that the deformation in the study area was accommodated within a transtensional setting with a strong strike-slip component. This deformation was probably distributed across a wider area within the present-day Pyrenees, as indicated by the local occurrence of Upper Jurassic to Early Cretaceous basins (e.g., the Cameros basin [Platt, 1990; Casas-Sainz and Gil-Imaz, 1998; Mata *et al.*, 2001]). Most of this deformation is, however, masked or overprinted by the latest Aptian to Albian event. Moreover, until early Aptian time, sedimentation was able to keep pace with subsidence, which explains that the whole study area remained at shallow marine conditions. The major change occurred during the Aptian to Albian event, which is recorded in the Mauléon area by the deepening of the basin and the deposition of 1000 m of sediments in the center of the basin, indicating rapid subsidence. Extension was accommodated by block tilting, responsible for the formation of sedimentary wedges and was accompanied by salt migration (Figure 11c). At deeper crustal levels extension is assumed to be accommodated along brittle detachment faults that are exposed in the Labourd area. These structures are responsible for the exhumation of midcrustal rocks at

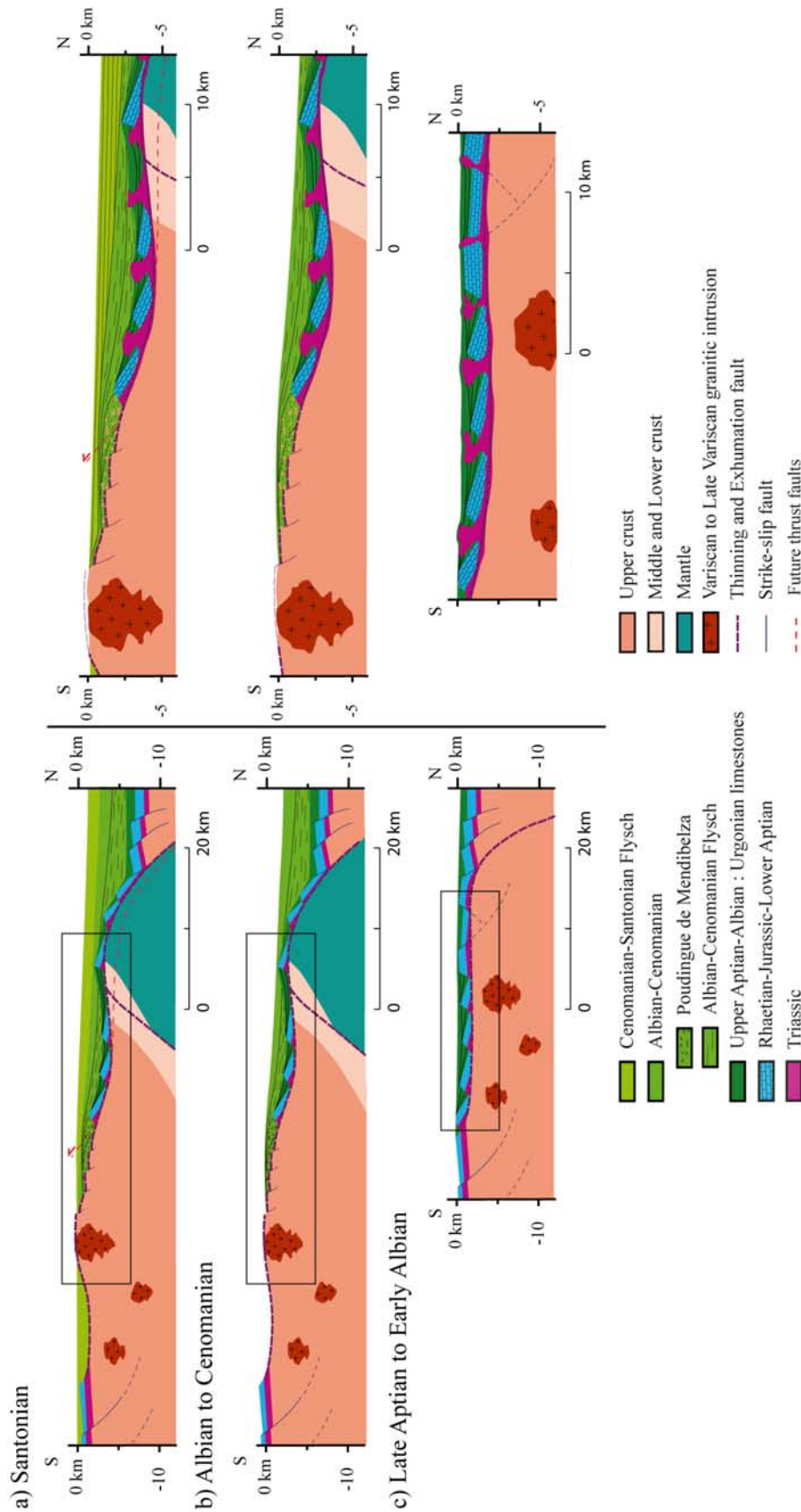


Figure 11. Schematic cross sections documenting the tectonostratigraphic evolution related to extreme crustal thinning and mantle exhumation during Early Cretaceous time. (a) Subsidence resulting in retrogradation and onlapping of the late Cenomanian carbonate platform onto previously exhumed and eroded basement of the Axial Zone. Subsidence is interpreted to be related to thermal equilibration of an Albian magmatic-thermal event. (b) Deposition of the Albian-Cenomanian Mendibelza conglomerates in the southern border of the basin due to the uplift and erosion of the proximal domain. The transition from proximal conglomerates to deep marine facies deposited in more distal parts of the basin seems to coincide and to be controlled by the occurrence of extensional allochthons. (c) Deposition of Urgonian platform carbonates within an extending rift system. The observed growth structures formed by the shallow marine carbonates deposited within the fault bounded basins suggest that extension occurred simultaneous to the deposition and that aggradation was as fast as subsidence. This stage represents the onset of salt migration which is linked to the formation of tilted blocks.

the seafloor and are likely to be of the same generation as those exhuming mantle rocks in the Mauléon basin (e.g., Urdach mantle; Figure 7). The contrasting style of deformation in the cover above the Triassic evaporites (block tilting) and the underlying basement suggests, however, that these two levels were decoupled, at least during an early stage, along the Triassic evaporites. It is also not clear how brittle detachment faults interacted with more ductile layers at depth. In the field, it can be observed that detachment faults truncate foliated midcrustal rocks (e.g., Louhossoa lineament, Figure 4) along a contact separating upper and middle crust. These rocks might form the remnants of a decollement horizon that was active during an earlier stage of crustal thinning. When the crust was thinned to the stage where the whole crust was in the brittle field, detachment faults were able to cut across the embrittled middle crust and to exhume the underlying mantle. The observation that mantle rocks are exhumed at the seafloor implies a large displacement along the final detachment system. Locally these detachment systems were exhumed to the seafloor, forming windows of middle crustal (e.g., Labourd; Figure 4) and mantle rocks (e.g., Urdach, Figure 7) in between allochthons of Upper Triassic to Lower Jurassic sediments forming the hanging wall (see Mail Arrouy, Sarrance, Layens; Figure 7). The occurrence of evaporites belonging to the Upper Triassic Keuper lithostratigraphic unit along the detachment faults suggests that the detachment faults may have used the Triassic evaporites as a decoupling horizon. The half graben basins that formed in the overlying Upper Cretaceous to early Aptian carbonates (e.g., Arbailles block) were, subsequently truncated and pulled apart along detachment faults. This complex evolution is recorded in the change from initially well-confined fault bounded rift basins to the development of supradetachment sag basins. These basins can be mapped over more than 30 km showing a complex sedimentary system with a source that developed as a consequence of exhumation, a transitional zone that formed over an exhumed and highly extended basin, and an active exhumation fault in its frontal part that is responsible for the exhumation of crustal and mantle rocks at the seafloor. Although this system results in lithospheric thinning, the observation that the emplacement of magmatic rocks and the age of the high-T/low-P metamorphic overprint postdate mantle exhumation (because it affects sediments that overlie exhumed mantle), suggest that the magmatic and thermal peak are probably a consequence of crustal thinning, but not directly related to detachment faulting. The thermal event recorded in the basin may be related with the uplift of the southern margin that is documented by the erosion of the basement, the deposition of the Mendibelza conglomerates (Figure 11b) and the subsequent thermal equilibration that may explain the subsequent subsidence and transgression and onlapping of the Cenomanian to Turonian sediments onto previously eroded basement (Figure 11a).

[37] Onset of compression is documented by the reorganization of the sedimentary system. From the structural point of view the detachment system responsible for crustal thinning and mantle exhumation played a key role during

the reactivation of the basins during early Campanian to mid-Eocene time. Thrust faults that reactivated the former detachment faults locally incised into the footwall. This can explain that the former footwall rocks (crustal and mantle rocks) of the extensional detachment faults were sampled, together with the extensional allochthons, in the hanging wall of thrust faults. During convergence, pro and retro thrust faults formed, as indicated by the change in vergence of thrusting and folding across the Mauléon basin. In the southern part of the basin up to 20 km of shortening were accommodated along the south vergent Lakora thrust [Teixell, 1993, 1996], meanwhile to the north of the Arbailles block 20 to 30 km of shortening was accommodated along the north vergent Saint Palais or Sainte Suzanne thrust faults [Daignières and ECORS Team, 1992; Teixell, 1998]. During the final stages of convergence in Oligocene to earliest Miocene time, thrust faults localized within the thick middle crust and ramped across the upper crust toward the surface. These structures resulted in the formation of an antiformal stack that can explain the elevated crustal thickness observed in the Axial Zone and the formation of a south vergent fold and thrust belt and its related foreland basin to the south. About 26 km of shortening were accommodated during this latest phase of compression within the crustal ramps (e.g., Gavarnie ramp, Guarga ramp) [Teixell, 1996].

5. Conclusions

[38] In this paper we propose, on the basis of new results from the Iberia-Newfoundland margins [Norton, 2007; Péron-Pinvidic and Manatschal, 2008] and paleomagnetic investigations [Gong *et al.*, 2008], that most of the left-lateral movement between the Iberian and European plates occurred between latest Jurassic and early Aptian time and predated the Aptian anticlockwise rotation of the Iberian plate leading to the opening of the V-shaped Bay of Biscay. During the left-lateral movement, E-W directed transtensional basins formed along a diffuse plate boundary. These structures had a major control on the subsequent Aptian/Albian rifting and subsequent reactivation of the Pyrenean domain.

[39] In this paper we focus on the Labourd–Mauléon area, where the late Aptian to Albian extreme crustal thinning and local mantle exhumation and the subsequent postextensional thermomagmatic event is well documented. The major result from this study is that we start to see the progressive structural evolution of an extensional system that leads to extreme crustal thinning and mantle exhumation. Moreover, the complete sedimentary record related to this tectonic evolution is well documented in the study area.

[40] The structural evolution related to crustal thinning shows that granulites belonging to the prerift middle crust were exhumed along a detachment system and were partly eroded and deposited in a supradetachment sag basin filled with up to 5 km thick Albo-Cenomanian sediments (e.g., Labourd Massif). In the Mauléon Basin, there is direct evidence that the basin was locally floored by mantle rocks (e.g., Urdach) and extensional allochthons formed by Upper Triassic to Lower Cretaceous rocks (e.g., Chaînons

Bearnais). The occurrence of sedimentary breccias containing clasts of crustal and mantle rocks over exhumed mantle (e.g., Urdach) implies that mantle rocks were exhumed at the seafloor and were reworked similar to the middle crustal rocks in the Labourd area. These observations suggest that in the Labourd-Mauléon area detachment systems are directly related with extreme crustal thinning and exhumation of mantle rocks. How and when extreme crustal thinning occurred is not yet fully understood. Our observations show that a major change occurred in late Aptian to early Albian time when extension changed from strike-slip dominated to more orthogonal extension which coincides with an acceleration of subsidence.

[41] The final lesson that we can learn from the Labourd Mauléon area is how such a hyper-extended basin responds to onset of convergence. The observations suggest that during onset of convergence in late Santonian time, the detachment faults were reactivated and the overlying sag basin was inverted, resulting in the formation of a large, pop-up like structure over previously thinned domains. Moreover, in the area of the Chaînons Béarnais it appears that the former detachment fault has been reactivated as a thrust fault. Indeed, remnants of mantle rocks along the thrust fault (e.g., Urdach, Saraillé, Turon de la Tecouère) are

interpreted to derive from areas where the thrust faults incised into the footwall of the former detachment faults. These pieces were thrust, together with the former allochthons, over Upper Cretaceous sediments.

[42] The new observations together with the existing data enable to reinterpret the regional geological evolution of the northwestern Pyrenees. These results have major implications for the interpretation of both, the Late Jurassic to Albian transtensional and the late Santonian to Oligocene compressional evolution of the Pyrenean domain. It may also serve as a well-documented field analog to study the evolution of V-shaped rift basins, such as the Woodlark basin, the northern Gulf of California or Rockall Trough and may also be used to develop and test numerical models for lithospheric extension.

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