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# Role of structural inheritance and salt tectonics in the formation of pseudosymmetric continental rifts on the European margin of the hyperextended Mauléon basin (Early Cretaceous Arzacq and Tartas Basins)

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## Abstract

Arzacq and Tartas were two Cretaceous basins developing in the Bay of Biscay as secondary depocentres in the larger Aquitaine Basin. They belong to an Albian rift system, where recent studies have stressed the role of simple-shear thinning on the genesis of regional asymmetric basins. However, the two basins differ from recent models in having a pseudo-symmetric morphology. Here, we address the Early Cretaceous tectono-sedimentary evolution of the Arzacq and Tartas rift basins and the lithospheric processes associated with their genesis. These basins did not suffer major brittle deformation during rifting stage, but nevertheless record a major change in their configuration between the Aptian and the Albian. The Arzacq Basin shifted from a symmetric to a slightly asymmetric configuration. This change was controlled by gravity sliding of the pre-rift sedimentary cover in the eastern Arzacq Basin moving its depocenter south, and by salt diapirism in the western Arzacq Basin moving its depocenter north. Several inherited Paleozoic structures were reactivated as transfer zones and appear to be responsible for this depocenter shift, the emplacement of salt diapirs, at same time regionally limiting gravity sliding. The Tartas Basin maintained a symmetric regime throughout the Early Cretaceous, except along the Barlanès transfer zone where the Lussagnet salt diapir originated. Two drivers of subsidence are thus envisaged in the Arzacq Basin: a Neocomian-Aptian crustal thinning stage, followed by reactivation of Paleozoic faults in Albian time accompanied by salt diapirism and gravity cover sliding. The Mauléon North Pyrenean Basin and its north adjacent Tartas and Arzacq basins thus formed part of a series of rift basins that progressed in maturity southward, from a simple sag basin (Tartas) to a slightly asymmetric basin (aborted detachment, Arzacq) to a hyperthinned basin (Mauléon). Our results offer new insights on the role of: (1) structural inheritance in partitioning extensional strain, (2) transfer zones as able to influence the sedimentary record of basins during crustal thinning, and (3) pre-rift salt décollements as able to separate the structural styles of sub- and supra-salt successions.

## Key-words

Rifting; Symmetric basin; Salt Tectonic; Inheritance; Early Cretaceous; Southwest France

## 1. Introduction

Models of continental crust thinning have grown in complexity from their original pure-shear geometry, which results in the development of symmetric rifts (McKenzie, 1978), to the newer simple-



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shear models, capable of producing asymmetric margins (Wernicke, 1981; Lister et al., 1986). Recent work on magma-poor Atlantic margins and fossil margins of the Alps have led to a better understanding of the geodynamic evolution of asymmetric margins, which ultimately evolve as regions of hyperthinned continental crust characterized by a β factor > 2 (Manatschal et al., 2004; Lavier et Manatschal, 2006; Péron-Pinvidic et al., 2009, 2015; Unternehr et al., 2010; Masini et al., 2011, 2012; Haupert et al., 2016). Similarly, it is well established that the Early Cretaceous reorganization of the Iberian and Eurasian plates (Roest and Srivastava, 1991; Olivet, 1996; Rosenbaum et al., 2002; Sibuet et al., 2004; Gong et al., 2008) led to the development of the Pyrenean rift system (Fig 1). As a result, the Iberia-Eurasia plate kinematic has been widely debated under the scope of two models: a) scissor-type opening (e.g Srivastava et al., 2000), versus b) left-lateral strike slip of Iberia with respect to Eurasia (e.g. Olivet, 1996). The first model relies on palaeoreconstructions of the Bay of Biscay and Central Atlantic seafloor magnetic anomalies, while the second model is based on onshore geological data (Gong et al., 2008). The major difference between both models is that a scissor-type opening implies an Early Cretaceous (Berriasian to Aptian) northward subduction of the Neo-Tethys below Eurasia, followed by back-arc development of the North-Pyrenean Zone and associated basins (Sibuet et al., 2004 ; Vissers and Meijers, 2012 ; Vissers et al., 2016). In this model, slab break-off would be responsible for asthenosphere mantle upwelling and high temperature metamorphism of the syn-rift series. In both scenarios, plate reorganization between Iberia and Eurasia leads to the opening of the V-shaped Bay of Biscay margin and proposed exhumation of sub-continental mantle at the ocean-continent transition (Thinon, 1999; Ferrer et al., 2008; Roca et al., 2011; Tugend et al., 2014), the formation of the North Pyrenean Basins (Jammes et al., 2009; Lagabrielle et al., 2010; Masini et al., 2014; Clerc and Lagabrielle, 2014; Corre et al., 2016; Teixell et al., 2016; Hart et al., 2016, 2017; Lagabrielle et al., 2019), and the formation of the Parentis Basin along the Atlantic margin (Pinet et al. 1987; Bois and ECORS Scientific team, 1990; Bois, 1992; Ferrer et al., 2008, 2012; Tugend et al., 2014).

In the north Pyrenean domain, the main evidence for a hyperthinning rift history is recorded by ~40 outcrops of exhumed mantle rocks, which occur in several points along the Pyrenean belt (e.g. Fabriès et al., 1991 et 1998 et Debroas., 2011). They were recently studied in details to better constrain their exhumation and precise the modality of the hyperextension stage. Among these outcrops, Lherz is probably one of the most spectacular and it crops out on the most oriental portion of the belt (Minnigh et al., 1980; Vielzeuf and Kornprobst., 1984; Clerc et al., 2012 and 2014, Lagabrielle et al., 2010, 2016; 2019). Similarly, in the western Pyrenees, Urdach and Saraillé Massif are key outcrop (Fortané et al., 1986; Jammes et al., 2009; Debroas et al., 2010; Lagabrielle et al., 2010, Corre et al., 2016). Most of these authors agree on an Albian-Cenomanian exhumation age, partly inferred from reworked mantle clasts within deep-turbidites facies, inferring a syn-rift age to this major stage. Mauléon Basin was recently revisited (Jammes et al., 2009; Masini et al., 2014), and interpreted as a hyperextended basin, bounded on its southern edge by major north-dipping diachronous detachement faults. Such structures control the relative asymmetric shape of the Basin, and are responsible for considerable accommodation space creation. Saspiturry et al. (2019a) propose a different hyper-thinning history, but fully agree on the existence of diachronous detachement faults leading to crustal thinning. Masini et al. (2014) proposed a crustal scale reconstitution considering the Arzacq Basin closely linked to Mauléon as an upper-plate basin probably controlled by a deep-rooted crustal structure on the northern flank of the Grand-Rieu, a structural high inherited from early Mesozoic times (Serrano et al., 2006). Although the development of these domains is well constrained, the sedimentary record of this hyperthinned rift is poorly addressed in the symmetric rift system of the Arzacq and Tartas basins, a closely associated pair of small basins in the southern Aquitaine Basin (Fig 1, Daignières et al., 1994; Bourrouilh et al., 1995; Serrano et al., 2006) (Fig. 1). Consequently, the geometry of these two basins and the mechanisms responsible for their opening are still uncertain, and few studies have addressed the geodynamic evolution and sedimentary

record of hyperthinned rift basins with a symmetric geometry (Etheve et al., 2018). Similar studies have never been conducted in “continental” to slight hyperthinned rift basins.

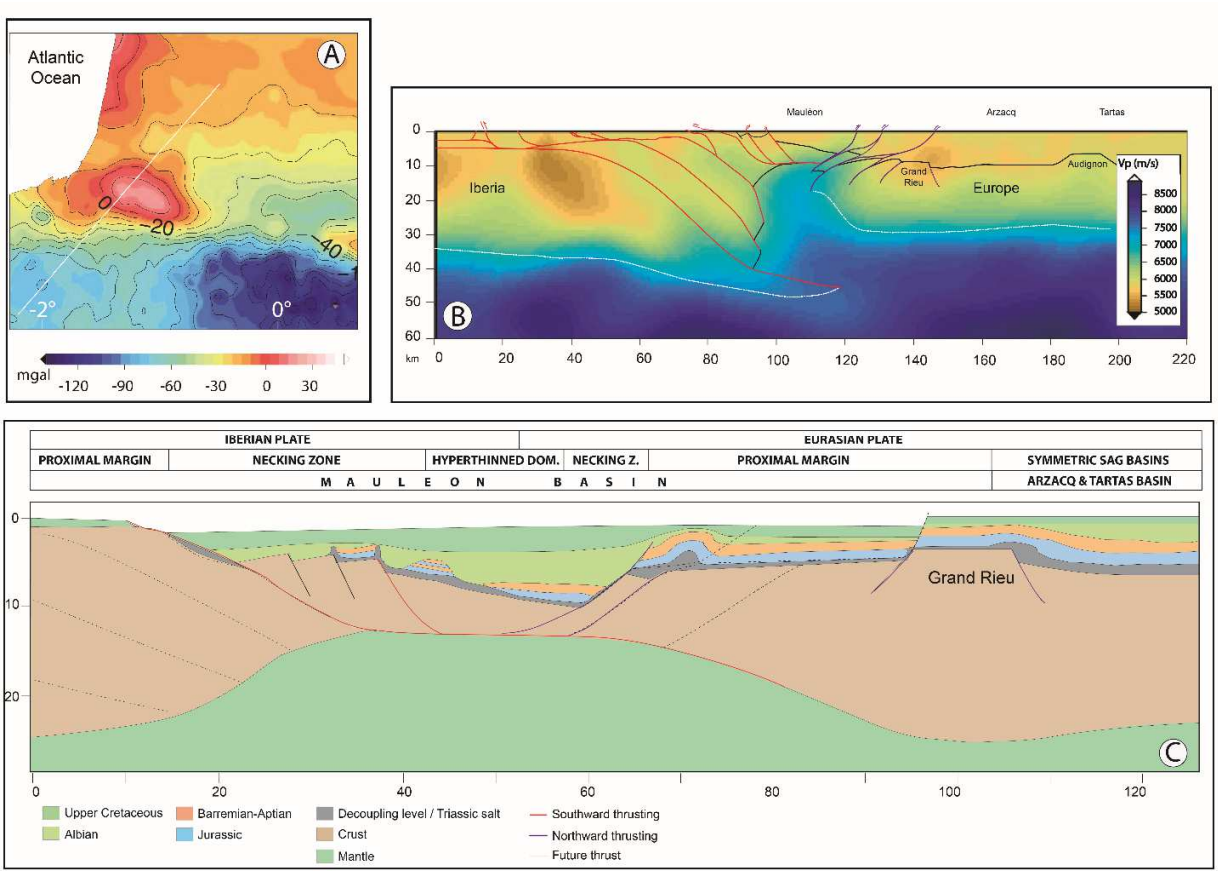


**Fig. 1 : (a) Bouguer gravity map of the western Pyrenees and Aquitaine Basin showing a strong positive anomaly centred upon the Mauléon Basin (modified from Chevrot et al, 2018). Contour interval, 10mgal. (b) Vp model showing the relative high position of the Moho below Mauléon Basin and a nearly normal position below the Eurasian Plate (modified after Wang et al., 2016 and Saspiturry et al., 2020). (c) Iberian-Eurasian cross-section before the Pyrenean orogeny (modified after Saspiturry et al., 2020). It illustrates an inner margin position of Arzacq and Tartas Basins. Main rift axis (Hyper-extended domain) is located much southward within the Mauléon Basin.**

Numerical models (Karner et al., 2003) have highlighted the role of lower crustal thinning processes in the development of synrift sag basins. These rifted basins are not affected by distributed extension in the upper crust, as a result of decoupling beneath the upper crust along a layer in the middle crust. The resulting rift is characterized by the absence of brittle deformation and by the development of a symmetric trough-shaped basin. This thinning mechanism has been proposed to explain the symmetric geometry of the Mauléon rift basin located to the south of the Aquitaine Basin (Saspiturry, 2019; Saspiturry et al., 2019a). As a consequence, the Tartas and Arzacq Basins are a promising site for studying the evolution of synrift sag basins located on the periphery of hyperthinned rifted basins in a warm thermal regime. In this paper we combine interpretation of seismic reflection profiles and borehole data to reconstruct the tectono-sedimentary evolution of these basins and their crustal thinning mechanisms.

# 2. Geological setting

## 2.1. Structural framework of the Arzacq and Tartas Basins

The Aquitaine Basin lies between the North Pyrenean Frontal Thrust, the Massif Central and the Bay of Biscay (Fig. 2a). The basin developed throughout Mesozoic and Cenozoic times above inherited Hercynian structural trends; among these is the N110° Celtaquitaine Flexure (BRGM et al., 1974), which separates the Arzacq and Tartas Basins from the North Aquitaine platform (Serrano et al., 2006). These two basins, the Arzacq to the south and the Tartas to the north, are separated by the Audignon-Pécorade-Antin-Maubourguet salt structures (Mauriaud, 1987; Serrano et al., 2006). They first developed as rift basins during Latest Jurassic to Albian time in an extensional context and then were reactivated by convergence during the Pyrenean orogenesis (Mauriaud, 1987; Mediavilla, 1987; Serrano et al., 2006).

The Grand Rieu domain (Fig. 2a) accommodated major relative displacement between the Early Cretaceous Mauléon Basin to the south (Souquet et al., 1985; Canérot, 2008; Masini et al., 2014) and the rifted Arzacq Basin to the north (Daignières et al., 1994; Bourrouilh et al., 1995). The north flank of the Grand Rieu is bounded by a normal fault with significant offset in the Triassic and earliest Jurassic (Hettangian), accommodating rapid subsidence and anhydrite deposition to its north (Curnelle, 1983). The Grand Rieu thus is an inherited structural high that accumulated carbonate deposits throughout the Jurassic (Serrano et al., 2006).

## 2.2. Tectono-sedimentary evolution of the Aquitaine Basin

The Aquitaine Basin first formed in the Late Permian with extension related to the fragmentation of Pangea (Burg et al., 1994). Extension continued throughout the Triassic and into the Hettangian, leading to an early rift basin characterized by clastic rocks, carbonates, up to 1000m thick evaporites and bodies of diabase with ophitic structure (ophites) (Curnelle, 1983; Curnelle et Dubois, 1986; Rossi et al., 2003). Extensional tectonics stopped after the Hettangian, and the overlying Jurassic was a tectonically stable period marked by the development of a widespread carbonate platform (Delfaud and Henry, 1967; Delfaud, 1969; Peybernès, 1976). At the end of the Jurassic, the entire platform was confined, as suggested by the deposition of restricted dolomite and anhydrite facies (BRGM et al., 1974) that correspond to the Dolomie de Mano Formation (Serrano et al., 2006). In the same time, the Pyrenean carbonate platform was uplifted, weathered (creating bauxite deposits) and partly eroded (Combes et al., 1998; James, 1998; Canérot et al., 1999). The Cretaceous sedimentary sequence rests unconformably upon these Jurassic deposits (Serrano et al., 2006).

The Early Cretaceous was a structurally active time in which the Aquitaine Basin evolved into different sub-basins characterized by very rapid subsidence (up to 130 m/My, Désaglaux and Brunet, 1990), including the Arzacq and Tartas basins. The onset of transgression after the Late Jurassic gave rise to poorly preserved sedimentary breccias (the Breche Limite Formation) that reworked the underlying Jurassic deposits (Peybernès, 1976). These grade upward into shallow marine to continental carbonate and clastic deposits (Bourroulec and Deloffre, 1970). They correspond to brackish facies characterized by units of limestone (with ostracods and algae), dolomite and reddish sandstone (Bourroulec and Deloffre, 1970; Calcaires de Ger Formation, Argiles du Gamma Ray Formation). These facies give way upward to black sandy shale with characea, ostracods and coprolites. The transgression continued in the Barremian with the development of limestone with oolites, annelids, chofatellas and coprolites (Calcaire à Annélides Formation, Delfaud, 1969; Peybèrnes and Combe, 1987). In the near field, the Bay of Biscay initiated its rifting stage (Montadert et al., 1979; Boilot, 1984; Brunet, 1994;

Thinon et al., 2001) at the same time continental breakup developed in west Iberia (Alves et al., 2009; Alves et Cunha, 2018).

In detail, the upper Neocomian and Barremian lagoonal deposits are subdivided from base to top into the Calcaires à Algues Formation, Lower Calcaires à Annélides Formation, Argiles du Latéolog Formation, and Upper Calcaires à Annélides Formation (Biteau and Canérot, 2008). For the sake of simplicity, they are all referred to here as the Calcaires à Annélides Formation.

A major flooding episode resulted in the deposition of the Sainte Suzanne Marls Formation (Delfaud, 1969), which represents a relatively deep open marine facies rich in cephalopods, and marls continued to spread across the entire area of the Pyrenees. A subsequent regression starting in the middle to late Aptian led to the development of the Pyrenean Urgonian facies (e.g. Bouroullec et al., 1979; Peybernès, 1979, 1982). These facies are contemporary of the early rifting in the North Pyrenean Zone (Canérot, 2008), while West Iberia records the onset of the Breakup Sequence B (Alvès and Cunha, 2018). It is characterized by limestone rich in algae, rudists and Iraqia (Mailh-Arrouy–Brassempouy Formation, Serrano et al., 2006). These rocks reflect the development of widespread inner-ramp depositional environments, and they grade locally to argillaceous limestone (Lower Clèdes Formation, Serrano et al., 2006). In the late Aptian and early Albian, the edges of the Arzacq and Tartas Basins saw the development of shallow carbonate facies (Gaujacq Formation and Brassempouy Formation) while the central basin significantly subsided, as evidenced by the deposition of argillaceous limestone (Geaune and Upper Clèdes Formations). In a distal position is the marl facies of the Marnes d'Assat Formation (Serrano et al., 2006), known in the North Pyrenean Zone as the Marnes de Saint Palais Formation or Spicules Marls Formation (Delfaud and Henry, 1967; Souquet et al., 1985). The Aquitaine Basin also hosted halokinesis from the latest Jurassic (Mauriaud, 1987; Mediavilla, 1987) to the Albian. An unconformity separates the Cenomanian and Albian sequences (Fig. 1c), the origin of which is uncertain although previous authors have interpreted it as representing a stage of compressive deformation (Biteau al., 2006). This question is addressed in the present study.

### 2.3. Deep structure of the Arzacq and Tartas Basins

Gravimetric studies have identified a strong positive gravity anomaly associated with the Mauléon Basin (Grandjean, 1992, 1994; Casas et al., 1997). Formerly interpreted as a dense intracrustal body (Grandjean, 1994), it is now thought to represent the presence of lithospheric mantle at shallow depths (Masini et al., 2014). This interpretation is supported by a recent seismic velocity model that places the current mantle-crust contact at around 10 km depth (Wang et al., 2016; Wang, 2017). This model shows the absence of similar gravity anomalies in the Arzacq and Tartas Basins suggesting that their history involves less significant Early Cretaceous thinning. Moreover, these basins became a single wide flexural basin related to the Pyrenean exhumation during Campanian to late Eocene time. Still, the 22 km depth of the current subcontinental mantle (Wang et al., 2016) remains as a sign of upper crustal thinning during the Albian rifting stage.

## 3. Methodology

This paper relies on the interpretation of 2D and TWT seismic reflection profiles within the Arzacq and Tartas Basins to address two topics in detail: the origin and evolution of Early Cretaceous depocenters and their depositional environments inferred from well analysis. A database of 35 hydrocarbon exploration wells was established to constrain correlations among these profiles (Supplementary material 1). These wells contain lithology, well logs (gamma ray, resistivity, sonic or density), lithostratigraphy interpretation, and in rare case biostratigraphy markers. A first task consisted

in the lithostratigraphy harmonization to ensure a coherent dataset. Wells were then short-distance (500 m) projected to ensure the best possible seismic reflection profile calibration. In this paper we discuss six profiles, equivalent to more than 300 km of interpreted data (Fig. 2b).

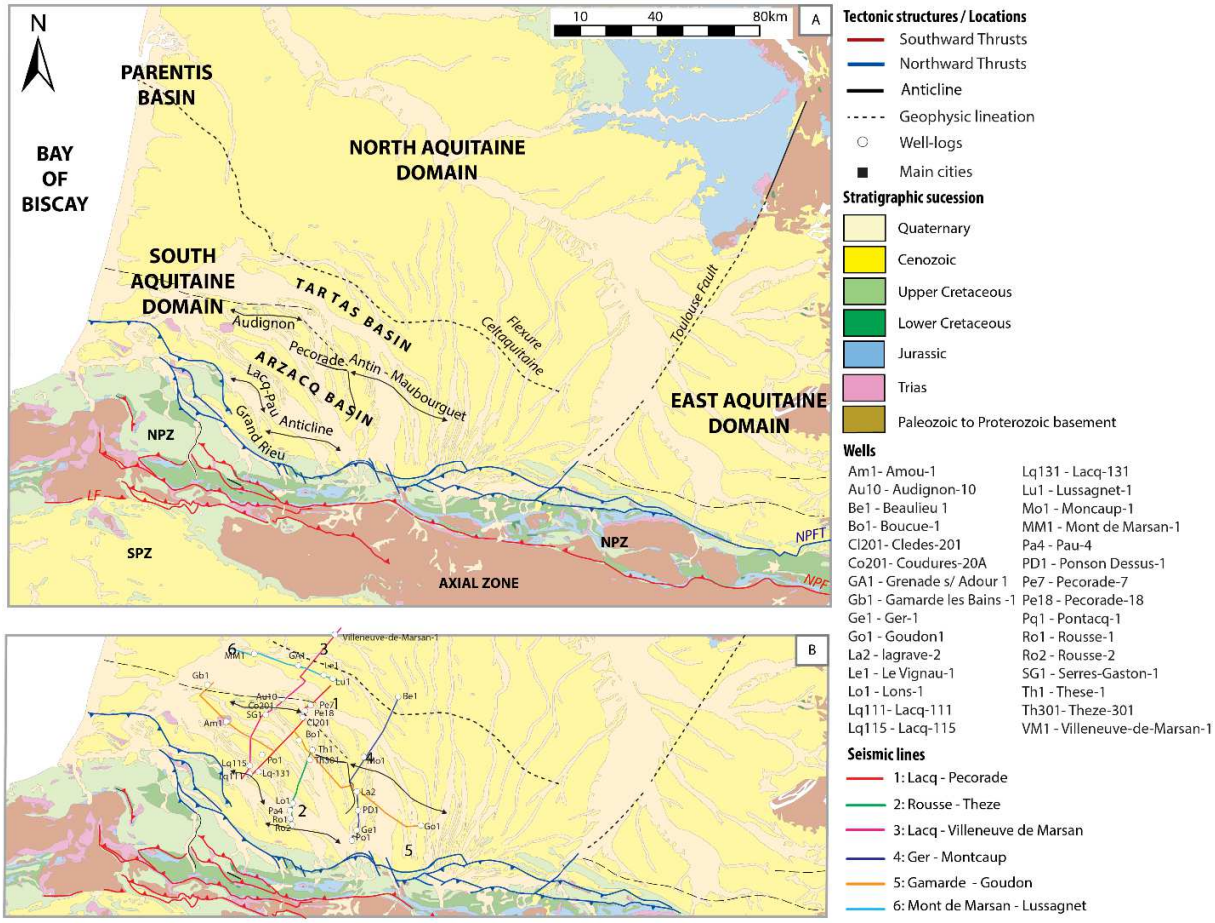


Fig. 2. Geologic maps of the Aquitaine-Pyrenees area. (2A) Major structures and domains. (2B) Locations of seismic reflection profiles.

Our interpretation relies on the seismic stratigraphy method of Mitchum et al. (1977) and is based on correlating onlaps, toplaps and downlaps. We recognized five Cretaceous tectono-sedimentary sequences in the wells that were used to interpret the composite seismic reflection profiles: Neocomian-Barremian, lower Aptian, upper Aptian, Albian, and Cenomanian-Turonian. Three Jurassic and Triassic lithostratigraphic sequences were also considered: Triassic-Hettangian evaporites, Hettangian carbonates- Oxfordian, and Kimmeridgian.

The Neocomian-Barremian sequence condenses a great deal of geologic history in a small stratigraphic thickness. The Neocomian (Berriasian to Hauterivian) was a long and complex period that encompassed bauxite development in the Pyrenees and the onset of shallow and narrow basins characterized by the Calcaire de Ger and Argiles du Gamma Ray Formations. Yet, the thickness of these formations rarely exceeds 20 m, and they cannot be distinguished in seismic reflection profiles. Consequently, the Neocomian sequence was combined with the Barremian sequence in our seismic interpretation, but we differentiated the two sequences in the well lithostratigraphy for greater insight into the basin's sedimentary dynamics.

# 4. Seismic profiles and well calibration

The following section aims at detailing the seismic reflection profiles and the wells used to calibrate them. For each of these profile, a short description of the major structural unit is provided, as well as thicknesses of the formation further constraining the seismic interpretation. Depth of the stratigraphy markers and formation thicknesses were directly measured on the boreholes, while the tectono-sedimentary sequence thicknesses are measured in two-way traveltime (TWT) on the seismic reflection profiles.

## 4.1. Lacq-Pécorade profile

The Lacq-Pécorade seismic reflection profile is 35 km long and oriented north-south (Fig. 2 and Fig. 3 It is calibrated by the Lacq-131, Clèdes-201, Pécorade-18 and Pécorade-7 wells (Supplementary Material 1). The northern part of the profile corresponds to the southern edge of the Pécorade ridge (Figs. 2b and 3) as evidenced by the progradations visible within the Campanian-Maastrichtian sequence (Issautier et al., in prep.).

The Lacq-131 well reaches a depth of 4300 m within Tithonian dolomite (Dolomie de Mano Formation). This is overlain by the Neocomian-Barremian sequence, beginning with 60 m of Berriasian-Valanginian black shale (Argiles du Gamma Ray Formation) that grades into a relatively thick shallow carbonate sequence of Barremian age (Calcaires à Annélides Formation). The Lower Aptian sequence appears relatively thick with 500 m of marl (Sainte Suzanne Marls Formation) passing upward into nearly 2000 m of undifferentiated Albian-Aptian limestone (no well cuttings). The Clèdes-201 well penetrated Tithonian dolomite (Dolomie de Mano Formation) down to a depth of 3543 m. This facies is overlain with 50 m of restricted-marine deposits of the Berriasian-Hauterivian and nearly 200 m of Barremian shallow limestone (Calcaires à Annélides Formation). The lower Aptian sequence measures 275 m and consists of marl (Sainte Suzanne Marls Formation). The upper Aptian corresponds to 400 m of alternating shale and shallow limestone (Brassempouy–Mail d'Arrouy Formation) grading upward into 1000 m of Albian marl (Assat Formation). Both the Pécorade-18 and Pécorade-7 wells penetrate shallow Barremian deposits resting on Kimmeridgian-Tithonian dolomite (Dolomie de Mano Formation). The rest of the Lower Cretaceous section consists of lower Aptian marl (Saint Suzanne Marls Formation), upper Aptian argillaceous limestone (Clèdes Formation) and Albian argillaceous limestone (Geaune Formation) and marl (Assat Formation).

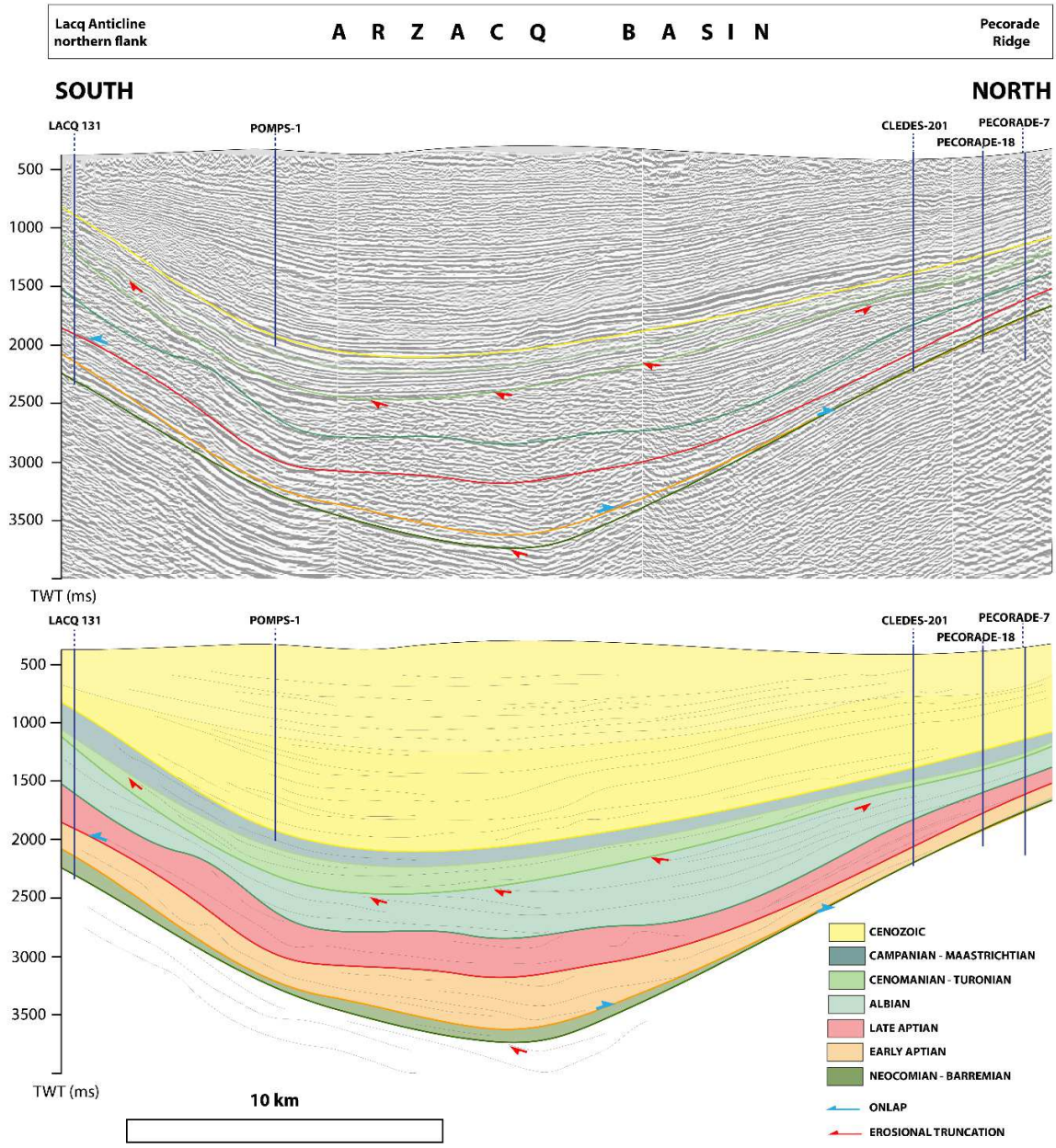


Fig. 3. Lacq-Pécorade seismic reflection profile. All Lower Cretaceous sequences define a symmetric basin. Onlaps are clearly visible within the early infill (Neocomian to Aptian). Subsidence increases during Albian time, and the Cenomanian sequence partly erodes the Albian deposits.

## 4.2. Rousse-Theze profile

The Rousse-Theze seismic reflection profile is oriented north-south and is located 20 km east of the Lacq-Pécorade profile (Figs. 2b and 4). It is calibrated by the Rousse-2, Rousse-1, Pau-4, Lons-1, Theze-301 and Theze-1 wells (Supplementary Material 2). The major structure on this seismic section is the Lacq-Pau Anticline (Fig. 2b), characterized by steeply dipping reverse faults that favored the pop-up of this anticline during Eocene compression (Fig. 4 ; Serrano et al., 2006). The Rousse-2 well reaches Liassic-Triassic deposits directly overlain by an Aptian sequence, no more than 50 m in total thickness,

consisting of very thin lower Aptian marl (Saint Suzanne Marls Formation) and upper Aptian shallow carbonate rocks (Brassempouy–Mail d'Arrouy Formation). Subsequently, the entire Middle and Upper Jurassic and much of the Lower Cretaceous are unrepresented in this well. The upper Aptian sequence is capped by a thin Albian sequence of shallow carbonates (Gaujacq Formation). The Upper Cretaceous sequence is represented by nearly 3000 m of turbidites and base-of-slope breccias at the Lower-Upper Cretaceous transition. The Rousse-1 well penetrates Oxfordian dolomite (Dolomie de Meillon Formation) capped by Kimmeridgian-Tithonian dolomite (Dolomie de Mano Formation). These Upper Jurassic rocks are unconformably overlain by 2500 m of Upper Cretaceous turbidites; thus, this well lacks the entire Lower Cretaceous. The Pau-4 well penetrates 300 m into marly limestone of Albian age (Upper Clèdes Formation) overlain by a 1700 m Upper Cretaceous sequence. The Lons-1 well, roughly 6000 m deep, reaches lower Kimmeridgian dolomitic limestone (Dolomie de Belair Formation). The uppermost Jurassic is represented by dolomite and breccia of Tithonian age (Dolomie de Mano Formation). It is directly overlain by 250 m of Barremian restricted-marine limestone (Calcaire à Annélides Formation), thus Neocomian rocks are absent. This grades upward to 500 m of lower Aptian marl (Saint Suzanne Marls Formation) and 800 m of argillaceous limestone (Lower Clèdes Formation). The uppermost Lower Cretaceous rocks are a 1500-m-thick Albian marly sequence (Assat Formation), and Campanian to Maastrichtian turbidites rest upon them. The Theze-301 and Theze-1 wells both penetrate Oxfordian marl (Marnes à Ammonites Formation) that grades upward to Kimmeridgian-Tithonian dolomite (Dolomie de Mano Formation). The Lower Cretaceous sequence is characterized by marginal to continental facies (Calcaire de Ger Formation and Gamma Ray Formation) in the Theze-1 well, whereas these facies are absent in the Theze-301 well, where Barremian restricted-marine shallow limestone (Calcaires à Annélides Formation) rests directly upon Tithonian dolomite. The overlying sequences are common to both wells and consist of lower Aptian marl (Sainte Suzanne Marls Formation), upper Aptian shallow to argillaceous limestone (Mailh Arrouy - Brassempouy Formation and Lower Clèdes Formation), and 1300 m of Albian limestone (Gaujacq Formation) and marl (Assat Formation).

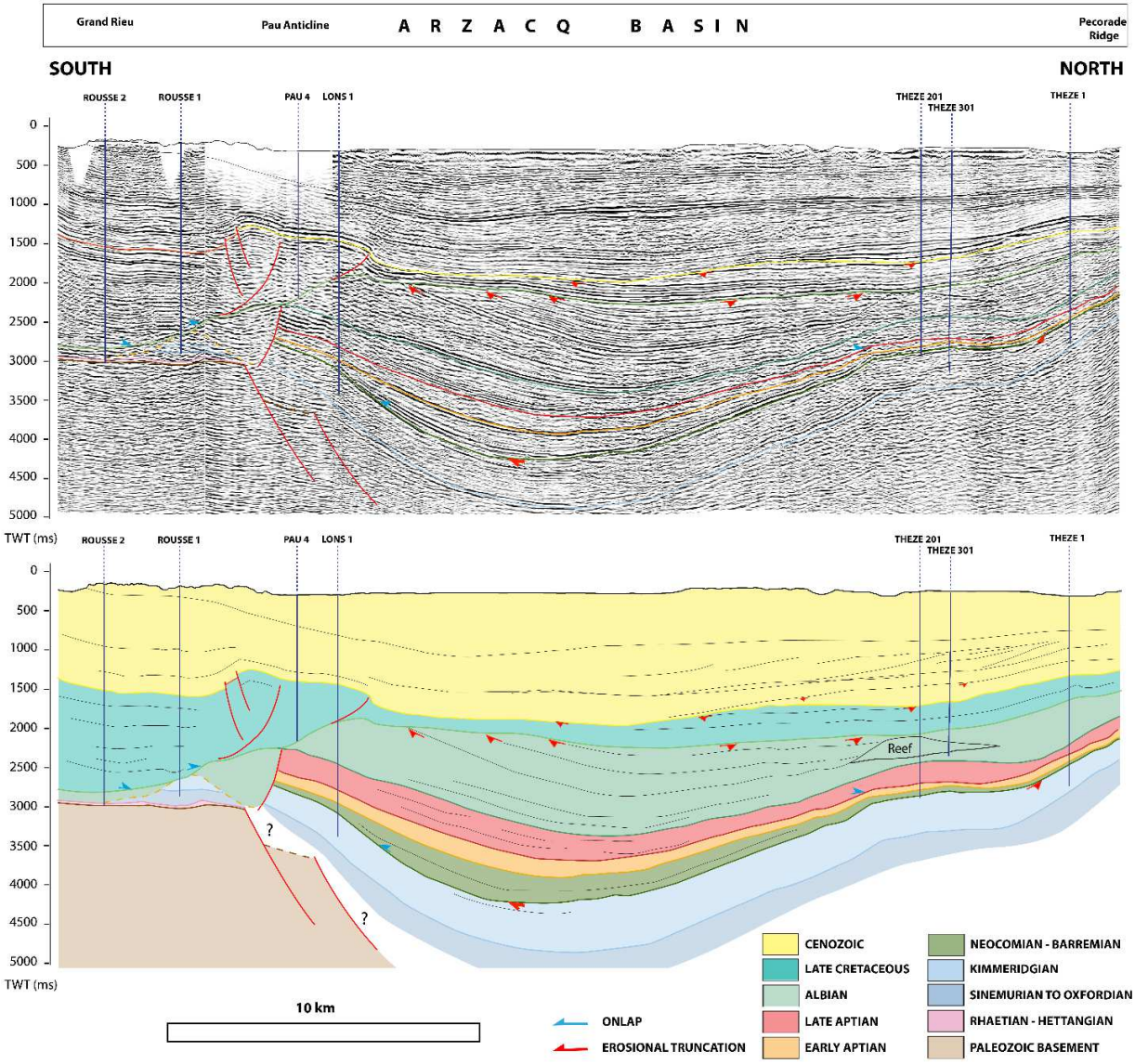


Fig. 4. Rousse-Theze seismic reflection profile, showing the Grand Rieu domain between the Mauléon and Arzacq Basins. The depocenter of the Albian sequence in the Arzacq Basin migrates south from its position in underlying Lower Cretaceous sequences.

## 4.3. Lacq–Villeneuve de Marsan profile

The Lacq–Villeneuve de Marsan seismic reflection profile is parallel to and west of the Lacq-Pécorade profile and extends farther north, covering both the Arzacq and Tartas Basins, along a section more than 60 km long (Figs. 2b and 5). Six wells constrain the interpretation: Lacq-129129, Lacq-115, Serres-Gaston-1, Coudures-201, Audignon-10 and Villeneuve de Marsan-1 (Supplementary Material 3). The main structures along this profile are the Lacq-Pau Anticline and the Audignon ridge (Fig. 2b). The Lacq-129129 well reaches Tithonian dolomite (Dolomie de Mano Formation), which is overlain by a Lower Cretaceous sequence that begins with 100 m of Berriasian-Valanginian limestones (Calcaire de

Ger Formation). This grades into 300 m of Barremian shallow carbonates (Calcaire à Annélides Formation), 550 m of lower Aptian marl (Sainte Suzanne Marls Formation) and 1000 m of upper Aptian shallow carbonates (Mailh Arrouy–Brassempouy Formation). The Lower Cretaceous sequence ends with 500 m of Albian marl (Assat Formation). The Lacq-115 well shows the same succession). The Serres Gaston-1 well, on the south side of the Audignon ridge, reaches Tithonian rocks at 5300 m depth that are directly overlain by 200 m of Barremian shallow marine carbonates (Calcaire à Annélides Formation), suggesting that Berriasian to Hauterivian rocks are absent. Overlying these is 200 m of lower Aptian marl (Sainte Suzanne Marls Formation) and roughly 600 m of upper Aptian argillaceous limestone (Lower Clèdes Formation). The well is topped by nearly 2500 m of Albian marly rocks (Assat Formation).

The Coudures-201 well reaches Oxfordian dark marl (Ammonite Marls Formation), partly intruded with salt (tectonic injection or "diapir" origin), overlain by 20 m of Barremian shallow carbonates (Calcaires à Annélides Formation); the intervening interval of the Upper Jurassic and most of the Neocomian is absent . The rest of the Lower Cretaceous sequence consists of 60 m of lower Aptian marl (Sainte Suzanne Marls Formation), 500 m of upper Aptian shallow carbonates (Mailh Arrouy–Brassempouy Formation) and 2700 m of Albian marl (Assat Formation). The Audignon-10 well is emplaced on a structural high which controls the emplacement of the Audignon diapir structure (Mauriaud, 1987). The well intersects a fault at 2500m and it crosses both an allochthonous unit in the hanging-wall that was north-thrusted and the underlying autochthonous unit in the footwall. The base of the well lies in Kimmeridgian and Tithonian dolomite (Dolomie de Mano Formation) that is overlain by 10 m of Barremian restricted-marine facies (Calcaire à Annélides Formation) and 30 m of lower Aptian open-marine marl (Sainte Suzanne Marls Formation). This is succeeded by a 300 m sequence of shallow limestone and dolomite (Mailh Arrouy–Brassempouy Formation) that grades upward to Albian spicule-bearing marls picular marl (Assat Formation). The allochthonous unit, above a decollement at 2500 m depth, consists mainly of Triassic salt and slabs of Lower Cretaceous and Jurassic rocks, not described here, that are overlain by 2000 m of Albian spicular marl (Assat Formation). The Villeneuve de Marsan-1 well constrains the sedimentary record of the Tartas Basin and North Aquitaine platform. It penetrates a condensed Cretaceous sequence, resting conformably upon Tithonian dolomite (Dolomie de Mano Formation), in which the Albian is absent. The Lower Cretaceous sequence consists of 150 m of Berriasian to Hauterivian shallow carbonates (Calcaire de Ger Formation) grading upward to a similar facies 120 m thick with Barremian fauna (Calcaires à Annélides Formation). Lower Aptian marly limestone (Sainte Suzanne Marls Formation) ends this succession, which is unconformably overlain by Cenomanian deposits.

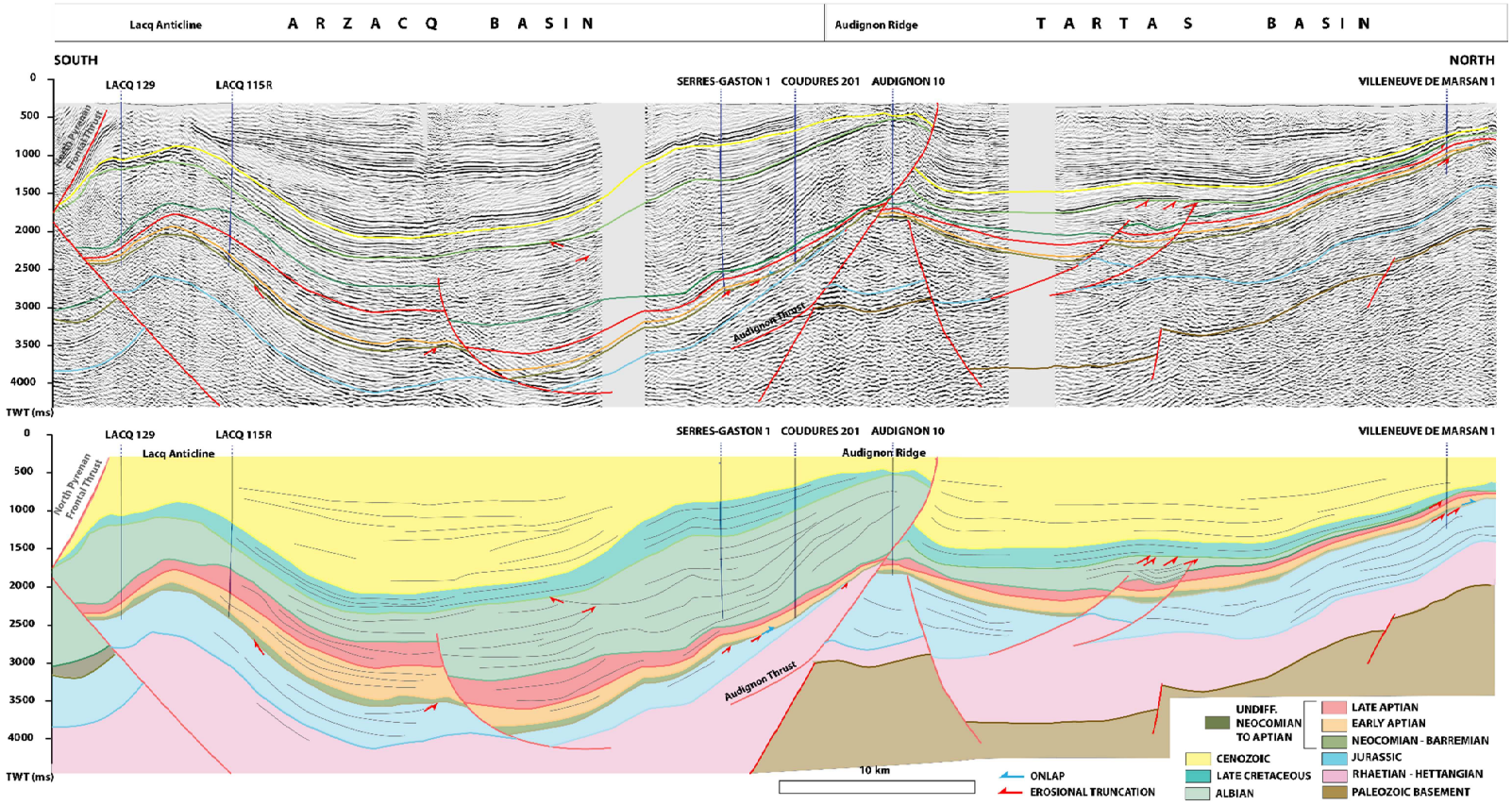
Lacq Anticline
A R Z A C Q B A S I N
Audignon Ridge
T A R T A S B A S I N
SOUTH
NORTH
LACQ 129
LACQ 115R
SERRES-GASTON 1
COUDURES 201
AUDIGNON 10
VILLENEUVE DE MARSAN 1
North Pyrenean Frontal Thrust
Audignon Thrust
0
500
1000
1500
2000
2500
3000
3500
4000
TWT (ms)
10 km
ONLAP
EROSIONAL TRUNCATION
UNDIFF. NEOCOMIAN TO APTIAN
CENOZOIC
LATE CRETACEOUS
ALBIAN
LATE APTIAN
EARLY APTIAN
NEOCOMIAN - BARREMIAN
JURASSIC
RHAETIAN - HETTANGIAN
PALEOZOIC BASEMENT

Fig. 5. Lacq–Villeneuve de Marsan seismic reflection profile. The southern part of the profile corresponds to the Lacq anticline, a salt pillow structure (Serrano et al., 2006). In the central part of the profile, the Audignon thrust which is a former salt diapir reactivated during basin's inversion (Mauriaud, 1987 ; Serrano et al., 2006) delimitates the Arzacq Basin from the Tartas Basin. The Neocomian to Barremian sequence shows both the Arzacq and Tartas Basins, which are connected during the early Aptian (Marnes de Sainte Suzanne transgression). The Albian sequence shows clearly differentiated basins: the Tartas Basin remains symmetric and the Arzacq Basin acquires a slight asymmetry as the strata deposition migrates north.

## 4.4. Ger-Beaulieu profile

The Ger-Beaulieu seismic reflection profile is oriented north-south and covers the Grand Rieu domain, Arzacq and Tartas basins (Figs. 2b and 6). In this area, these two basins are separated by the Antin-Maubourguet ridge, materialized here by the Moncaup salt diapir. It is constrained by 5 wells: the Ger-1, Ponton-Dessus-1, Lagrave-2, Moncaup-1, and Beaulieu-1 wells (Supplementary Material 4). The base of the Ger-1 well is in the Oxfordian dolomite of the Meillon Formation, which is overlain by 700 m of Kimmeridgian-Tithonian dolomite and limestone (Dolomie de Mano Formation). The basal Lower Cretaceous deposits consist of 60 m of Berriasian-Valanginian restricted marine carbonates to continental shale (Calcaire de Ger Formation and Argiles du Gamma Ray Formation). They grade upward into 250 m of Barremian shallow carbonates (Calcaires à Annélides Formation) followed by 600 m of lower Aptian marl (Sainte Suzanne Marls Formation) and 500 m of upper Aptian rocks, the shallow Urgonian facies and the deeper argillaceous limestone facies (Gaujac, Brassempouy and Lower Clèdes Formations). The Lower Cretaceous sequence ends with 500 m of Albian marl (Assat Formation). The Ponton-Dessus-1 and Lagrave-2 wells display the same succession, although the Berriasian-Valanginian sequence is thinner (<20 m in Ponton-Dessus-1, 10 m in Lagrave-2), and the Albian sequence is absent in the Lagrave-2 well. In both wells, Lower Cretaceous deposits rest conformably upon Tithonian rocks. The Moncaup-1 well, located at the northern edge of the Arzacq Basin is emplaced on a diapir, located on the prolongation of the Antin-Maubourguet "Ridge" (lateral equivalent to Audignon, Fig. 2 ; Serrano et al., 2006)Moncaup-1 well reaches Triassic-Hettangian evaporites overlain by a lower Aptian reduced marly sequence (50 m of Sainte Suzanne Marls Formation). The upper Aptian sequence is condensed as well (50 m) and consists of a shallow carbonate facies (Mailh-Arrouy-Brassempouy Formation). It is overlain by 500 m of Albian argillaceous carbonates (Geaune Formation and Upper Clèdes Formation, drawing a syncline located to the south of the diapir. This latter observaton attests for the activation of this salt structure during the Albian time (Fig. 6).The Beaulieu-1 well contains Cenomanian rocks onlapping Kimmeridgian carbonate deposits, evidence that the entire Lower Cretaceous is absent here.

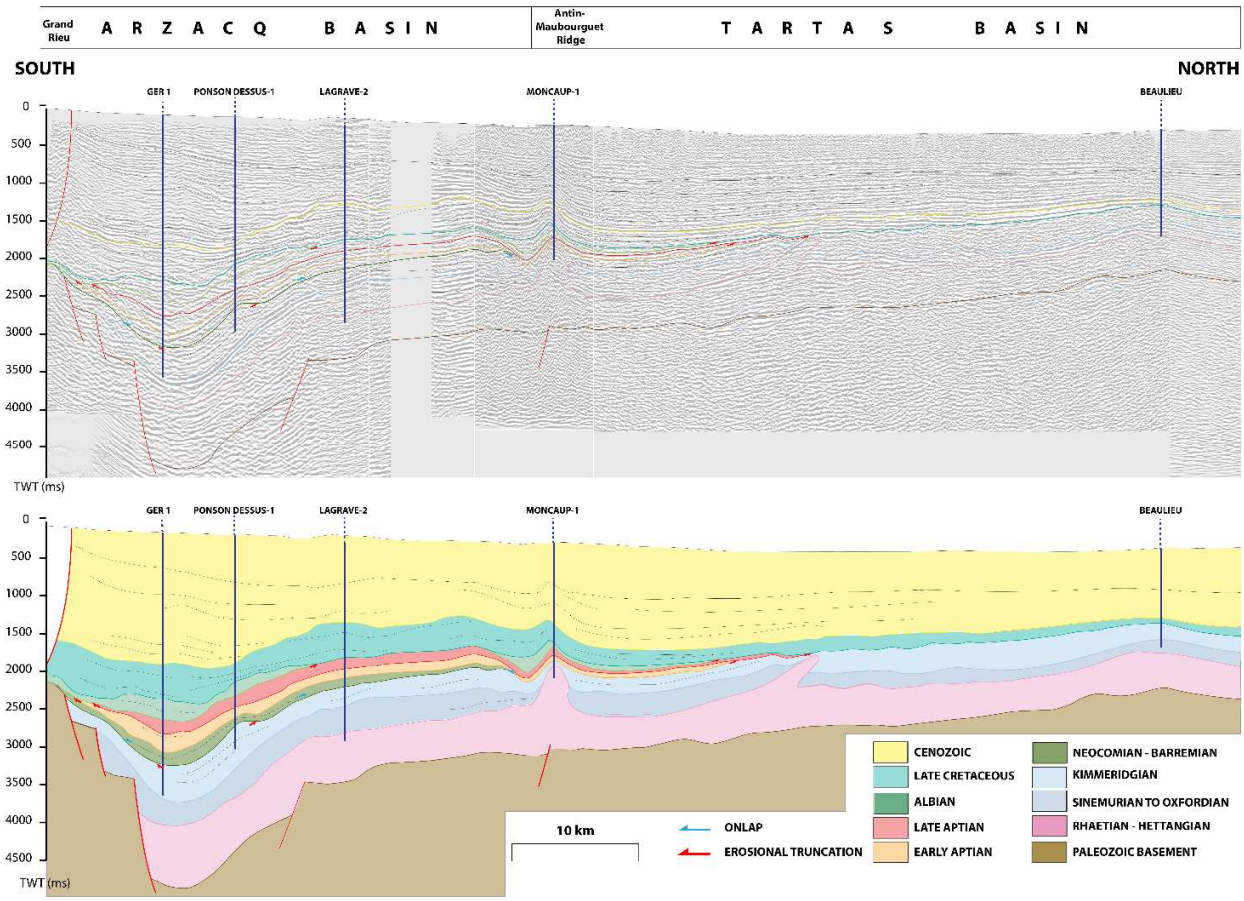


Fig. 6. Ger-Beaulieu seismic reflection profile. Prerift sedimentary cover is absent in the Grand Rieu domain, which is onlapped by the Albian sequence. Basement is significantly offseted by the north Grand Rieu Jurassic faults. The Albian depocenter migrates south, in contrast with the aligned Jurassic and Early Cretaceous depocenters. On the central and northern part of the profile, halokinetic structures developa s evidenced by the Moncaup salt diapir corresponding to a typical diapir controlling a local syncline filled with Albian deposits. This latter seems to be emplaced right above a basement fault.

## 4.5. Gamarde-Goudon profile

The Gamarde-Goudon seismic reflection profile is oriented west-east across the Arzacq Basin (Figs. 2b and 7). It extends from the Landes salt diapirs zone (Gamarde-les-Bains-1 well) to the Tarbes area (Goudon-1 well). It is calibrated by the Gamarde-les-Bains-1, Amou-1, Boucoue-1, Lagrave-2 and Goudon-1 wells (Supplementary Material). The Gamardes-les-Bains-1 well exhibits a reduced Lower Cretaceous sequence that consists of 500 m of upper Aptian shallow carbonates (Mailh-Arrouy--Brassempouy Formation) overlain by 1500 m of Albian marl and argillaceous limestone (Assat Formation). The lowermost Cretaceous and the entire Jurassic are absent in this well, which bottoms out in Triassic-Hettangian anhydrites. The base of the Amou-1 well is in Kimmeridgian and Tithonian dolomite (Dolomie de Mano Formation and Lons Formation) overlain by 200 m of shallow Barremian facies (Calcaire à Annelides Formation), and the Neocomian is absent. Above these is 200 m of Aptian marly facies (Saint Suzanne Marls), 600 m of upper Aptian shallow limestone (Mailh-Arrouy-

Brassempouy Formation), and nearly 2000 m of Albian marl (Assat Formation). The Boucue-1 well does not extend beyond an Albian sequence. The Lagrave-2 well is described as part of the Ger-Beaulieu profile. The Goudon-1 well lacks the entire Lower Cretaceous, as Cenomanian deposits directly overlie Kimmeridgian strata.

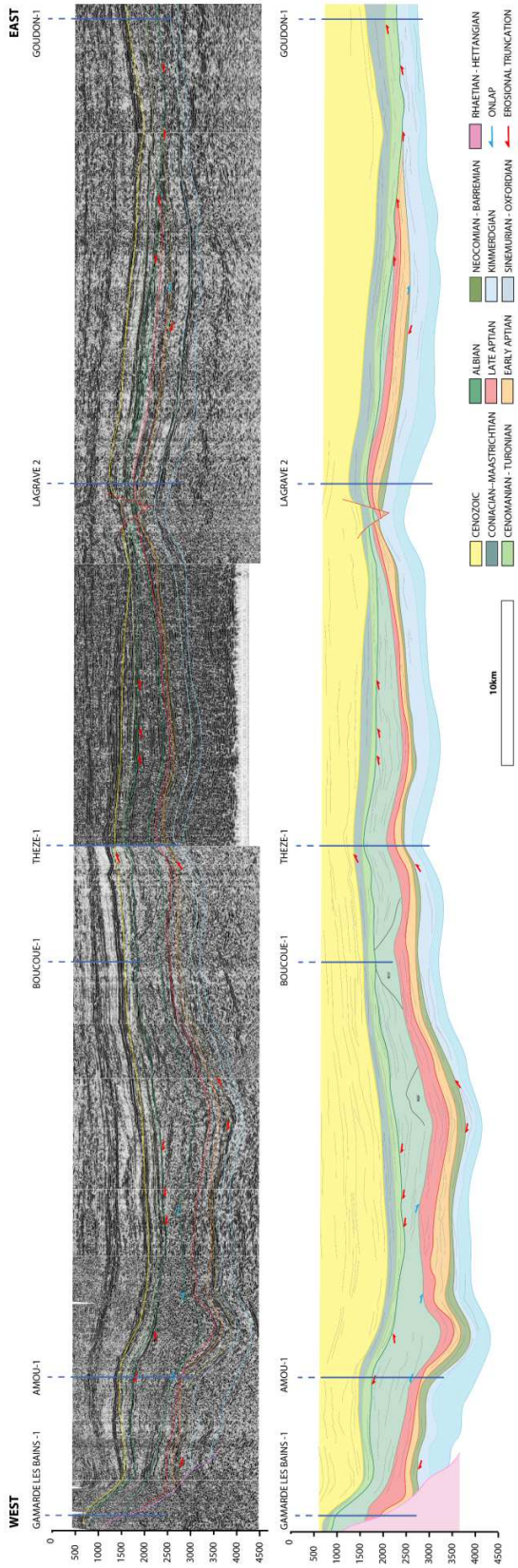
WEST
EAST
GAMARDE LES BAINS -1
AMOU-1
BOUCOUE-1
THEZE-1
LAGRAVE 2
GOUDON-1
0
500
1000
1500
2000
2500
3000
3500
4000
4500
10km
CENOZOIC
CONIACIAN - MAASTRICHTIAN
CENOMANIAN - TURONIAN
ALBIAN
LATE APTIAN
EARLY APTIAN
NEOCOMIAN - BARREMIAN
KIMMERIDGIAN
SINEMURIAN - OXFORDIAN
RHAETIAN - HETTANGIAN
ONLAP
EROSIONAL TRUNCATION

Fig. 7. Gamarde-Goudon seismic reflection profile. This long west-to-east transect displays no visible tectonic activity, as the Albian sequence is relatively isopachous except at the ends of the transect where it is affected by salt diapirism (Gamarde les Bains) and Late Cretaceous erosion (Goudon). Note that a narrow syncline develops within the Albian sequence in the Amou area.

## 4.6. Mont de Marsan–Lussagnet profile

The Mont de Marsan–Lussagnet seismic reflection profile is oriented east-west within the Tartas Basin (Figs. 2b and 8). The major structure in this profile is the Lussagnet salt diapir. The profile is calibrated by the Mont-de-Marsan-1, Grenade-sur-Adour-1 and Lussagnet-1 wells (Supplementary Material 6). The base of the Mont-de-Marsan-1 well is in Oxfordian black shale (Ammonite Marls Formation) and Kimmeridgian dolomite (Dolomie de Mano Formation). A 200 m sequence of upper Aptian shallow carbonates (Mailh-Arrouy--Brassempouy Formation) rests directly upon the Kimmeridgian, evidence of a significant gap between Tithonian and Lower Cretaceous (Berriasian to lower Aptian) rocks. The Aptian sequence is overlain by 800 m of Albian shallow dolomite (Gaujacq Formation). The base of the grenade-sur-Adour-1 well is in Tithonian-Kimmeridgian dolomites at 3600 m (Lons and Mano formations). These are directly overlain by 700 m of Barremian shallow facies (Calcaire à Annélides Formation), 60 m of lower Aptian marly deposits (Sainte Suzanne Marls Formation), 160 m of upper Aptian rocks , and a 250 m succession of Albian shallow carbonates (Gaujacq Formation). The Lussagnet-1 well was drilled on the Lussagnet diapir (Serrano et al., 2006). It penetrates a 1300 m thick sequence of undifferentiated Albian and upper Aptian carbonates resting upon a Dogger-Liassic sequence, implying a gap that includes most of the Upper Jurassic and much of the Lower Cretaceous. This gap is probably related to the diapir rise which removed the Early and Mid-Jurassic deposits.

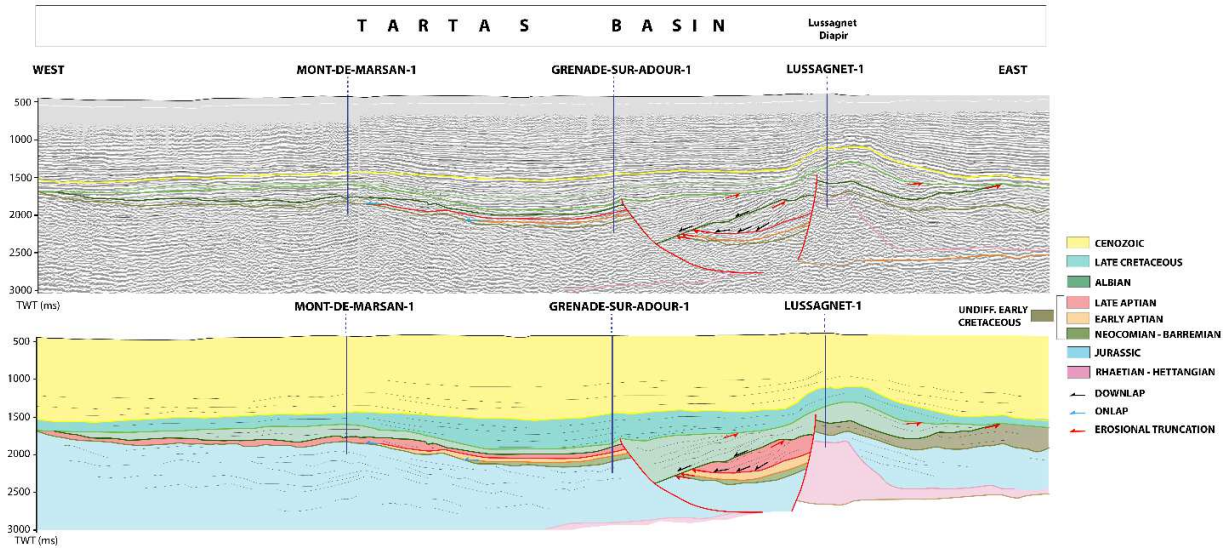


Fig. 8. Mont de Marsan–Lussagnet seismic reflection profile. Salt tectonism affects the Albian sequence, as attested by clear growth strata controlled by growth of the Lussagnet salt diapir.

# 5. Seismic Interpretation

## 5.1. Arzacq Basin

In the Lacq–Villeneuve de Marsan seismic reflection profile (Fig. 5), the key observation is the existence of two inherited steep normal faults bounding the Audignon Ridge—the northern one dipping north, the southern one dipping south, which was reactivated during tectonic inversion as the Audignon Thrust. Audignon northern flank exposes a massive accumulation of Upper Triassic to Lower Jurassic evaporites, twice as thinner in northern Tartas Basin. This pattern defines the Audignon structure as an Early Mesozoic horst. Similarly, the Ger-Beaulieu seismic reflection profile (Fig. 6) is characterized by steep north-dipping normal faults that offset the basement south of the Arzacq Basin. These faults too exhibit thick sections of evaporites that slightly decrease in thickness to the north toward the Tartas Basin's northern edge. Following this Late Triassic-Early Jurassic's asymmetry, the Middle and Upper Jurassic sequences display a much more relative isopachous, and their depocenters do not migrate, so that they have their greatest thickness in the central axis of the Arzacq Basin as visible on the Rousse-Theze, Lacq-Villeneuve de Marsan and Ger-Beaulieu profiles (e.g. Figs. 4 to Fig6).

The base of the Lower Cretaceous is the Neocomian-Barremian sequence, which rests unconformably upon a partly eroded Jurassic surface evident as erosional truncations markers below the Lower Cretaceous basal surface. In the Audignon-10 well on the Lacq–Villeneuve de Marsan profile (Fig. 5), pre-Cretaceous erosion removed the entire Kimmeridgian sequence. On the Rousse-Theze seismic reflection profile (Fig. 4), several basal Cretaceous onlap markers are clearly visible that document onlap in both northward and southward directions. These markers migrate towards the basin's edges, Grand Rieu to the south and Pécorade to the north (Figs. 3 and 5), and the Ger-Beaulieu seismic reflection profile shows the same features in the eastern Arzacq Basin (Fig. 6). To sum up, the Neocomian-Barremian sequence is thickest in the central trough of the Arzacq Basin and thins toward its north and south edges. This thickness variation corresponds to the onlap of the Neocomian (Berriasian and Valanginian) brackish to coastal facies and its replacement by Barremian inner-platform deposits, which barely transgressed the Audignon and Grand-Rieu domains where their thickness is negligible.

Unlike the sequence just described, the Aptian deposits show only a slight reduction in thickness on the basin edges (Fig. 3). The base of the Aptian sequence is a widespread lower offshore marly facies (Sainte Suzanne Marls Formation) that indicates a sudden and general deepening of the depositional profile. The marl onlaps a reduced Neocomian-Barremian sequence on the Pécorade ridge at the north edge of the Arzacq Basin (Fig. 3) and a partly to completely eroded Jurassic sequence on the Audignon ridge (Fig. 5). Several onlap markers are visible within the Marnes de Sainte Suzanne Formation in the Lacq-Pécorade seismic reflection profile (Fig. 3). These onlaps demonstrate the expansion of the area of sedimentation toward the basin's edges. The upper Aptian sequence consists mainly of a shallow carbonate facies (Urgonian facies, representing an inner ramp with rudist bioherms) that passes locally into marl deposits. This sequence is thicker in the central trough and thinner at the northern and southern edges of the Arzacq Basin (Figs. 3&5). This thinning is most visible close to the Audignon ridge (Fig. 5) and towards the Grand Rieu domain, where onlap is visible in the Lacq-131 well (Fig. 3). In the west-east Gamarde-Goudon profile (Fig. 7), a striking point is the absence of Lower Cretaceous deposits in the eastern part of the profile (Goudon-1 well). There the Cenomanian sequence rests unconformably on partly eroded Kimmeridgian deposits, as shown by several erosional truncation markers below the basal Cretaceous surface. Between the Boucue-1 and Theze-1 wells, several erosional truncation are similarly visible below the Neocomian basal surface. Notably, the Neocomian to upper Aptian sequences east of

the Amou-1 well give way to a synform consisting of a large, sharply defined increase in thickness of overlying Albian deposits.

The significant thickness variations of the Albian sequence mark a change in the basin's regime. Several carbonate build-ups appear in the Gamarde-Goudon profile (Fig. 7), and a sharp thickness increase east of the Amou-1 well has numerous onlaps from either side of this synform. Their dipping results from Gamarde salt diapir growth and basin compression during Cenozoic times. A gradual eastward decrease in thickness, associated with erosional truncation markers, includes a pinchout in the Lagrave-2 well. Consequently, preservation of the sequence is poor in the eastern part of the profile, probably related to a latest Albian to pre-Cenomanian erosional stage.

North-south cross sections show that the Arzacq Basin entered a more asymmetric and strongly subsiding stage during Albian time. The Albian sequence (1s TWT) is twice as thick as the underlying upper Aptian and Neocomian-Barremian sequences (0.5s TWT) in the Rousse-Theze profile (Fig. 4) and three times as thick as the Neocomian-to-upper Aptian sequence in the Lacq–Villeneuve de Marsan profile (1.5s TWT ; Fig. 5). Both profiles also show radically different depocenter locations and depositional profiles. The greatest thickness increase is to the north of Grand Rieu f(southern Arzacq Basin) on the Rousse-Theze profile (Fig. 4) and to the south of Audignon ridge (northern edge of the Arzacq Basin) on the Lacq–Villeneuve de Marsan section (Fig. 5). Regarding the depositional profile, the platform-basin transition shifts north with time on the Lacq–Villeneuve de Marsan seismic reflection profile (Supplementary Material .3 and Fig. 5) and south on the Rousse-Theze seismic reflection profile (Supplementary Material & Fig. 4).

A moderate southward migration of the Albian depocenter (3–5 km) is visible in the Ger-Beaulieu profile (Fig. 6) over the Grand Rieu paleo-Jurassic fault(s). This pattern evidences a gradual southward thickness increase of the Albian deposits.

In the Grand Rieu domain, the Jurassic to Triassic sedimentary cover is absent in the Rousse-2 well, where Cretaceous rocks directly overlie the Paleozoic substratum (Fig 4). Here the Albian basin displays a very complex shape, with a thick sequence to the north of Grand Rieu that is partly disconnected from a small and narrow basin to the south (Fig. 4; between the Pau-4 and Rousse-1 wells). Both sequences consist of marly facies of the Assat Formation except in the Rousse-2 well, where a bioclastic carbonate facies (Gaujacq Formation) occupies the southern edge of the Arzacq Basin (Supplementary Material. 2). This more proximal facies on the southern edge is consistent with the southward thickness reduction of the Albian sequence (Figs. 3 & 6).

On the north side of the Arzacq Basin, the Lacq–Villeneuve de Marsan profile shows a massive thickness increase of Albian marly facies on the southern flank of the Audignon structure (nearly 2000m in Coudures-201, Supplementary Material.3 and Fig. 5). Here, deposits are twice thicker than on the vicinity of the Lacq Anticline (1000m in Lacq Profond-115), and four times thicker than in the southern part of the Tartas domain (Fig 5). On this profile, markers within the Albian sequence suggest growth-strata (Coudures-201 and Serres-Gaston 1 wells) with internal erosion, possibly related to tectonic or halokinesis which will be discussed in the next chapter.

In Lacq-Pecorade profile (Fig. 3), Albian deposits tend to be thicker toward Pecorade ridge (south of Cledes-201, ig. 3 *i.e* northern Arzacq basin), suggesting a depocenter migration 5 km to the north. The depositional profile of the basin reflects this asymmetry, with proximal facies on the southern margin (Lacq-131 well, Supplementary Material 1) and more distal marl on the northern margin (Cledes-201, Pecorade-18 and Pecorade-7 wells in (Lacq-131 well, Supplementary Material 1). The Albian gradual northward strata migration recorded during the Albian are very similar to that recorded in salt-detached ramp synclines (Jackson and Hudec, 2005; Pichel et al., 2018).

The Cenomanian sequence overlies the Albian deposits unconformably, as illustrated by the erosional truncation on every seismic profiles interpreted (Figs. 3 to 7). This unconformity is considerable on the south flank of the Audignon structure (Fig. 5), where shallow carbonate deposits (inner ramp facies of Pilo Formation; Serrano et al., 2006) sharply contrast with the underlying deep Albian facies (Fig. 5 & Supplementary Material 3). On Grand Rieu, especially on the Pau Anticline (Fig. 3) this erosive surface lies between the shallow platform deposits of Pilo Formation in the Arzacq Basin –(strong reflective markers to the North of the Lons-1 well, calibrated in the Theze wells) and deep-water turbidites in the northern Mauléon Basin which are intersected in the Lons-1, Pau-4 and Rousse wells (Fig. 3 and Supplementary Material 2). This rapid facies transition is discussed in the next chapter.

To summarize, the Arzacq Basin had two different stages of structural evolution during the Early Cretaceous. Stage 1 (Neocomian to middle Aptian) was characterized by a symmetric basin in which subsidence was greater in the central trough. This difference in subsidence was not accommodated by faults, at least in the sedimentary cover, as witnessed by the absence of synsedimentary wedges on every seismic profiles presented (Figs. 3 to 7). The Barremian to Aptian carbonate facies indicates a uniform, nearly flat depositional profile, yet the maximum thickness of the Barremian-Aptian sequence at the center of the basin (1100m) attests to a relative high subsidence rate at this time, approximately -60 m/My. Stage 2 (late Aptian to Albian) featured the development of slightly asymmetric basins in which the geometry and depositional profile were differently organized in the western and northern parts of the South Aquitaine domain. Numerous strata deposition migration suggests a tectonic or halokinesis control discussed later on the next chapter. This stage was also marked by an increase in the subsidence rate.(>80m/My)

## 5.2. Tartas Basin

The Lacq–Villeneuve de Marsan seismic profile provides a north-south transect of the Tartas Basin, the southern edge of which is delimited by the normal fault at the north edge of the Audignon horst (Fig. 5). As in the Arzacq Basin, a Neocomian-Aptian sequence of shallow carbonates unconformably overlies the Upper Jurassic sequence, including onlap marker indicating an Aptian significant sedimentation area enlargement that progresses towards the basin's edges (Fig. 5). The geometry documents the confinement of brackish inner ramp Neocomian (Berriasian–Hauterivian) facies within a trough (Fig. 5). The Tartas and Arzacq Basins were not connected at this stage, because Neocomian facies are absent in the northern Arzacq Basin (Fig. 5; Serres Gaston-1, Coudures-201 and Audignon-10 in Supplementary material.3); rather, the Neocomian facies shift sharply northward as shown in the Villeneuve de Marsan well (Supplementary material.3). There, upper Aptian is reduced and Albian strata is absent owing to erosion below the Late Cretaceous basal surface (erosional truncation markers in Villeneuve-De-Marsan-1 well in Fig. 5. The Albian sequence is marked by the development of slight salt tectonics in the heart of the basin, illustrated by an intra-Albian unconformity (Fig. 5). Indeed, a small syncline is visible in between two gently south-dipping structures unconformably overlained by flat markers.

In the western part of the west-east Mont de Marsan–Lussagnet seismic reflection profile (Fig. 8), the Neocomian-Barremian and lower Aptian sequences appear relatively isopachous. They clearly onlap towards the Mont-de-Marsan-1 well, where the upper Aptian sequence directly overlies Jurassic deposits and spreads far to the west (Fig. 8 &. 9a). The Albian sequence consists of shallow carbonate facies throughout the profile (Supplementary Material 6). It is consistently about 1000 m thick between the Mont-de-Marsan-1 well and a fault just east of the Grenade-sur-Adour well (Fig. 8), but on the other side of this fault it thickens in a wedge-shaped basin between the fault and the Lussagnet-1 well. The growth of this basin began in the late Aptian (and probably earliest Albian) as witnessed by the large-scale strata growth leaning back on the diapir westward (Fig. 9b). This first sequence, which measures roughly 0.5

in TWT thickness, was largly truncated during a late Albian stage showing a westward tilt and remarkable stratal growth (0.75 TWT thickness). The pre-Albian sequence tilting is related to the onset of the Grenade sur Adour listric normal fault, which probably corresponds to a rapid final stage evaporites flow in the Lussagnet diapir. This pattern implies that the apparent downlap markers within the late Aptian strata corresponds to tilted onlaps (Fig. 9b and 9c) consequently to the onset of the Grenade-Sur-Adour listric normal fault. The Cenomanian sequence regionally overlies the previous sequences, and numerous toplaps appear below its basal surface.

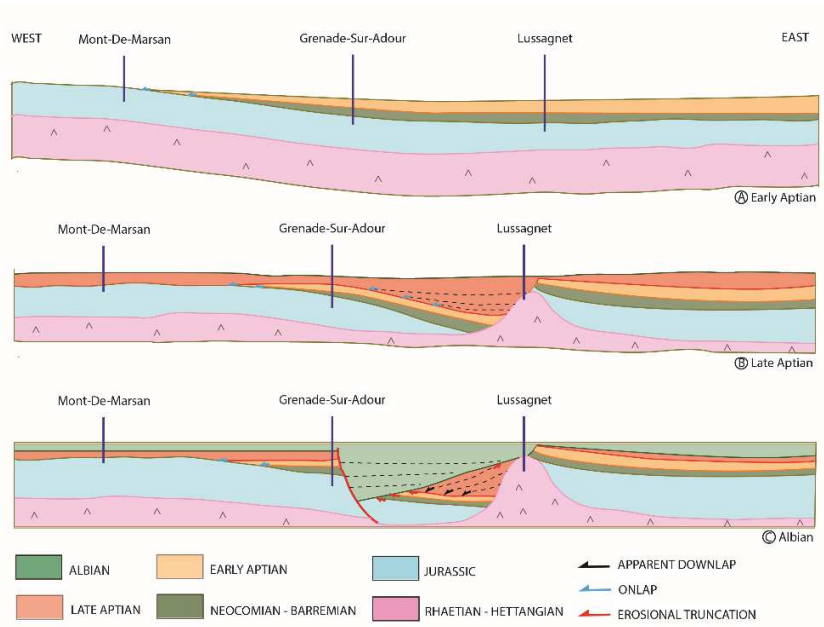


Fig9 : Sequential development of the Lussagnet diapir (not to scale).(a) Neocomian-Early Aptian stage corresponding to to the onset of the Tartas Basin formation as a SAG basin opened toward the north. (b) Late Aptian growth of the Lussagnet diapir with northward onlap and growth strata leaning back on the diapir. (c) Albian stage. Final diapir growth with a sudden and massive Grenade-Sur-Adour evaporites flow yielding to the development of the Grenade-Sur-Adour listric normal fault and the westward tilting of the Pre-Albian deposits.

# 6. Tectono-sedimentary evolution of the Aquitaine Basin

## 6.1. Early Jurassic aborted rift and pull-apart basins

During the latest Triassic and earliest Jurassic, incipient rifting between the modern-day Europe and Iberia plates led to the initiation (or reactivation) of major north-dipping normal faults in the Aquitaine Basin region, along which thick bodies of evaporites accumulated (Fig. 10a). At that time, sedimentation was condensed over the relatively high Grand Rieu and Audignon-Pécorade-Antin-Maubourguet domains, and sediment thicknesses decreased away from the normal faults (Fig. 10a). In the Late Triassic and Hettangian, the Aquitaine Basin region thus consisted of shallow carbonate platforms (Grand Rieu and Audignon domains) bounded by steep normal faults that accommodated rapid deepening of the intervening basins. This horst-basin pattern persisted throughout the Jurassic, during which time the depositional sequence was relatively isopachous (Fig. 10b).

Previous authors (BRGM et al., 1974; Curnelle, 1983; Brunet, 1984, 1991) have attributed these high subsidence rates (100 m/Myr) and initiation of Grand Rieu normal faulting to the accelerated disruption of Pangea in the Late Triassic and Early Jurassic during the initial opening of the Tethys. Still, Audignon, Pécorade and Antin-Maubourguet ridges have been previously interpreted as structures of latest Jurassic to Albian-Aptian age (Bouroullec et al., 1979; Mauriaud, 1997; Serrano, 2001; Serrano et al., 2006) and, we demonstrate here that their origin was part of the earlier opening of the Tethys.

The aborted rift in the Aquitaine region led to the development of an asymmetric substratum, which hosted stable depocenters throughout the Early and Middle Jurassic (Figs. 10a and 10b).Recent plate reconstructions (Torsvik et al., 2012 ; Van Hinsbergen et al;, 2020) suggest a Ladinian-Hettangian roughly E-W extensional direction, which is very oblic to the N110 faults controlling the evaporites accumulation. This pattern combined with the basin's asymmetry suggest that they originated as pull-apart basins opened during an oblic transtensive stage similar to what is described in the Dead Sea (Zak and Freund, 1981; Ben-Avraham and Zoback, 1992; Wu et al., 2009) rather than half-graben in an orthogonal opening.

## 6.2 Latest Jurassic to Neocomian uplift phase

The latest Jurassic and earliest Cretaceous were marked by the emersion and weathering of the Jurassic carbonate platform in the Pyrenean realm. Our interpreted seismic reflection profiles show that the Arzacq Basin was affected as well by this major episode. Its response to this event included both uplifting domains and subsiding domains. Evidence of uplifting domains includes thickness reduction and erosion of the Tithonian sequence over the major structural highs of the Arzacq Basin: the Grand Rieu, Audignon, Pécorade and Antin-Maubourguet ridges (Fig. 10c). In these areas, the Neocomian (Berriasian to Hauterivian) interval is always absent, meaning that the Barremian are the first deposits postdating the event. However, in several logs where Tithonian facies are preserved (Lacq-131, Supplementary Material 1; Thèze-301 ; Supplementary Material 2 ; Lacq-Profond-129 and 115, Villeneuve-De-Marsan-1, Supplementary Material 3 ; Lagrave-12, Supplementary Material 5 ; Mont-De-Marsan-1; Supplementary Material 6), significant thicknesses of Neocomian facies also remain (Calcaire de Ger Formation and Argiles du Gamma Ray Formation), indicating that these wells and associated areas underwent subsidence. Consequently, the Late Jurassic to Neocomian period corresponds to a vast, heterogeneous doming stage that extended far beyond the Pyrenean domain (Canérot, 2008). This general uplift was characterized in the Aquitaine Basin by subemersive to eroded structural highs bounding subsiding domains that held shallow, poorly connected brackish seas (Fig. 10c). This setting suggests that asthenospheric upwelling uplifted domains bounded by inherited Tethyan faults and localised subsiding basins between them.

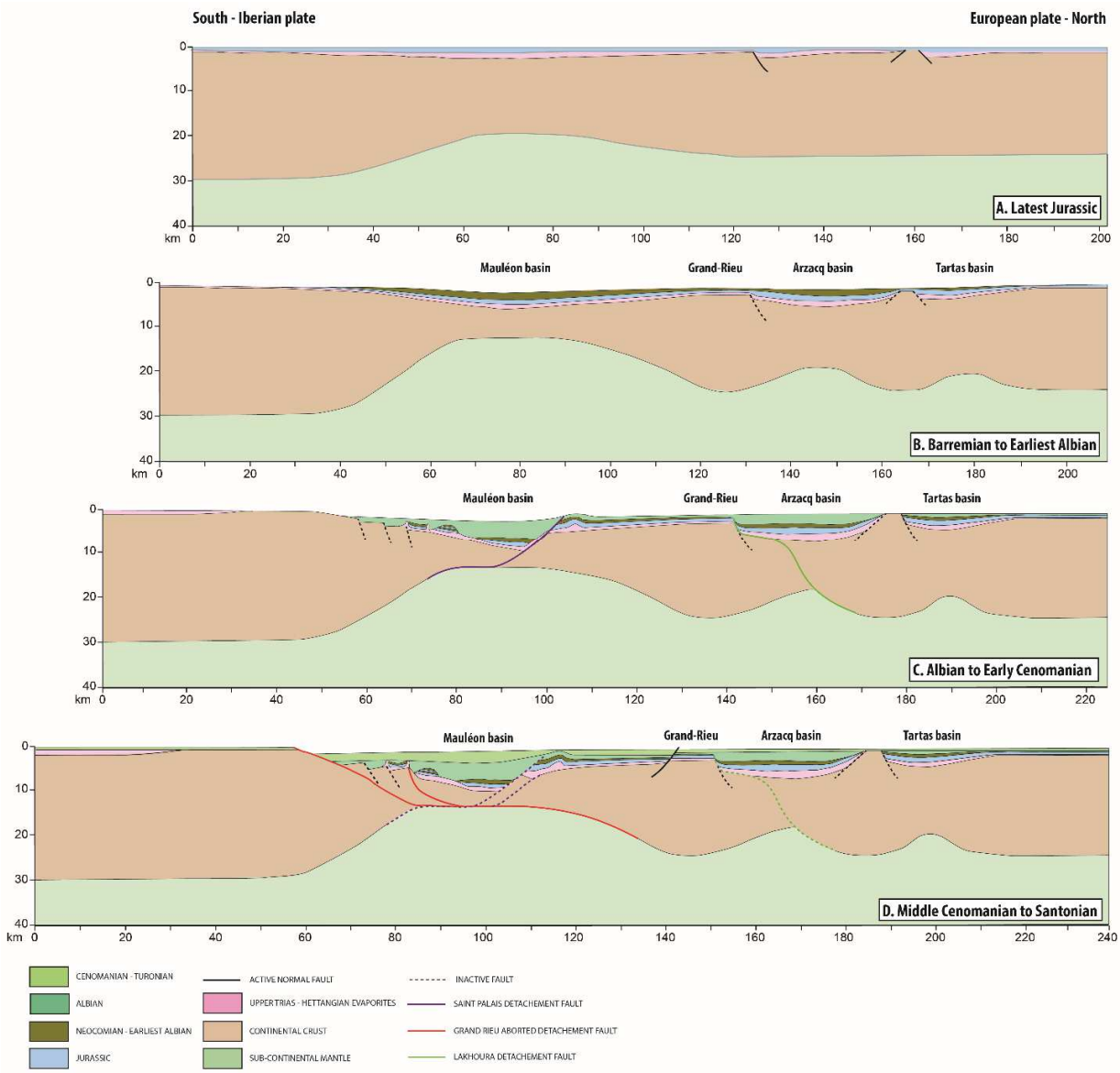


Fig. 10. North-south sections (no vertical exaggeration) showing the evolution of the Aquitaine Basin and North Pyrenean Zone (modified after Saspiturry et al., 2019), including the Arzacq and Tartas Basins. (a) A half-graben developing in Late Triassic to Hettangian time accumulated a thick evaporite sequence , which in turn controlled the emplacement of the Arzacq and Tartas Basins in Berriasian-Barremian time (c). (d)The two basins differentiated during the Albian, the Arzacq Basin acquiring an asymmetric cross section following gravity sliding of the sedimentary cover on the northern Grand Rieu flank. This cover gliding is controlled by the onset of a detachement fault quickly aborted. On the contrary, the Tartas Basin remaining a simple sag basin.

## 6.3. Barremian to early Aptian rifting stage 1: Symmetric rift basins

The thickness of the Barremian sequence indicates that the Early Cretaceous transgression only slightly overspilled the Grand Rieu and Audignon-Pécorade-Antin-Maubourguet domains (Fig. 10c). The transgression did not extend over the Arbailles domain (Mauléon Basin) until the Aptian, as the

Barremian is absent there (Canérot et al., 1978; Martin-Closas and Peybernès, 1987; Combes et al., 1998; Canérot, 2008; Saspiturry et al., 2019a). The fact that the basin's depocenter was the same in Neocomian and Barremian time implies that the subsidence regime was continuous (Fig. 10c). As a result, this period saw the development of a shallow sea flooding small, disconnected structural lows located between the structural high domains inherited from the Late Jurassic doming stage: the Arbailles, Grand Rieu, and Audignon highs and the Celtaquitaine Flexure. The transgression accelerated in the early Aptian, as suggested by the regional extent of the Saint Suzanne Marls Formation and by the regional paleogeographic reorganization. Indeed, widespread marginal-marine deposits of the Calcaire à Annélides Formation grade vertically to these marls, tracing a direct transition to relatively deep open marine conditions. Their extent suggests that the Tartas, Arzacq and Mauléon basins became connected for the first time in the Cretaceous, and they remained connected into the late Aptian with the development of the shallow Urgonian platform.

In this first stage, we interpret the relative lack of brittle deformation affecting the upper crust, the deep subsidence in the basin center and the unchanging depocenter as a response to thinning of the lower crust during Neocomian uplift that did not affect the upper crust. The lower crustal thinning was responsible for the basin subsidence and the progressive onlap of deposits towards the basin margins. This process favors the development of rift basins with a sag geometry. Subsidence of 0.8 s TWT over a 20 My period signifies a subsidence rate of roughly 60 m/My. The constant position of the Barremian and Neocomian depocenters suggests that the Late Jurassic to Neocomian doming was the driver of this crustal thinning stage. It is quite similar to the Barremian-Aptian history of the Mauléon Basin, where a synrift sag basin morphology preceded the development of an asymmetric basin in the Albian and Cenomanian (Saspiturry et al., 2019a).

## 6.4. Late Aptian to Albian stage 2: Widespread rifting and onset of asymmetry

The Tartas and Arzacq basins became separated again during the Albian (Fig. 10d) , and they show different geometries. The Tartas Basin remained symmetric throughout the Albian (Figs. 5 & 10d) except in the Lussagnet area, where the rise of a salt diapir controlled the development of a mini-basin (Figs. 8 & 9). In the meantime, The Arzacq Basin became non-symmetric,. attested on the Rousse-Theze (Fig. 4) and Ger-Beaulieu (Fig. 6) profiles. This latter shows an Albian sequence thickening southward, strata deposition shifts 3 to 5kilometers southward and deep marly facies to the south (Fig. 11). This geometry is much comparable to salt-detached ramp syncline (Jackson and Hudec, 2005; Pichel et al., 2018).On the contrary, Lacq–Villeneuve de Marsan profile (Fig. 5) shows a northward thickening together with a northward shift of the strata deposition, and deep marly facies to the north (Fig. 11).

The Rousse-Theze profile shows remnant of Jurassic deposits below the Rousse-1 well, in the Grand Rieu domain, that is disconnected from the continuous Jurassic cover in the Arzacq Basin (Fig. 4). The intervening space is filled with Albian deposits (age inferred from wells drilled laterally within this syncline), which we interpret as the result of early Albian gravity sliding: northward movement of the sedimentary cover on a detachment over a Triassic-Jurassic salt layer that created accommodation space for Albian sediment (Fig. 11b). Similar gravity sliding is documented in the adjacent Mauléon Basin (Ducasse et al., 1986; Teixell et al., 2016; Saspiturry et al., 2009a). The erosion of the Albian sequence prior to Cenomanian sequence in the neighborhood of Pau anticline suggests that local minor halokinetic movements responded to the uplift of the northern Grand Rieu domain. This inference is supported by recent results (Saspiturry et al., 2019a) that document the generation of an anticline by late Albian and early Cenomanian salt diapirism in the Grand Rieu domain.

The Lacq–Villeneuve de Marsan profile documents the development of significant Albian asymmetry in the Audignon area (Fig. 11b), where a thick marly basin developed on the current Audignon anticline in which the depocenter migration and depositional profile orientation are northward rather than southward. No gravity sliding is evident here, and it is possible that syn-rift salt diapirism marked by internal truncations, prior to the current thrust-piercement of salt geometry was responsible for the development of a salt-controlled basin on the southern flank of the Audignon anticline. The increase in thickness overlies normal faults of Early Jurassic age, suggesting that this major structure was reactivated throughout the Mesozoic, and inverted during Cenozoic times.

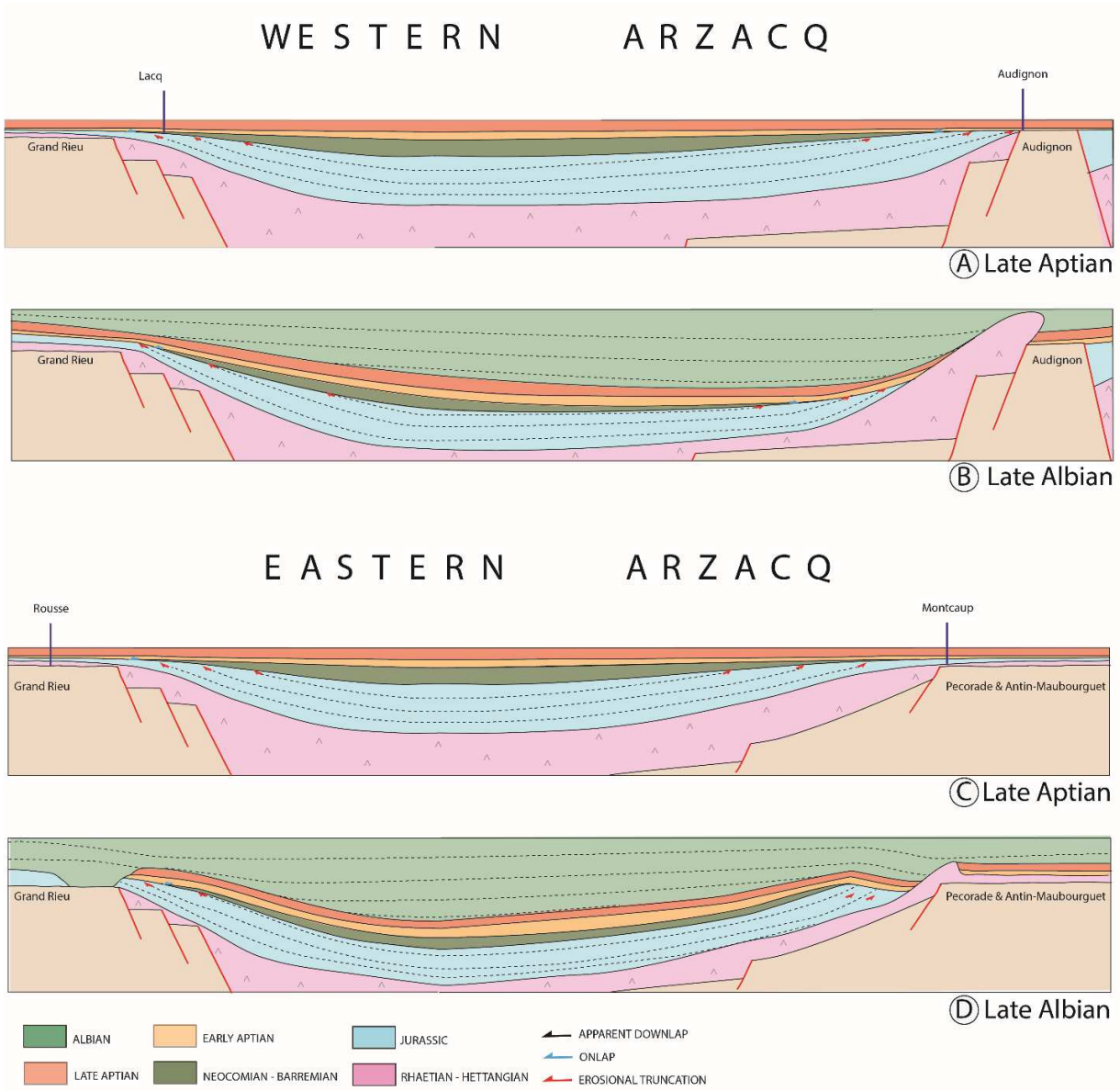


Fig. 11 Halokinesis comparison between western Arzacq (a-b) and Eastern Arzacq (c-d) basin (Not to scale). (a-b) In the western Arzacq basin, the Albian syn-rift sequence is marked by a northward strata deposition migration relative to the onset of the Albian Audignon salt diapir. The southern part of the basin do not undergo salt movement. (c-d) The eastern Arzacq basin spans a massive northward cover-gliding initiating at Early Albian time. This latter translates strata deposition southward in direction of

the grand Rieu Horst. The Northern margin is affected by the formation of the minor Moncaup salt diapir during Albian time.

In this rifting stage, subsidence was more localized and more strongly controlled by brittle deformation than in the previous stage. The strata deposition were offset in different directions, and subsidence rates were approximately 1 s TWT over a 13 My time period, or roughly 115 m/My, double the rate during the previous stage. Two subsiding domains can be distinguished: a western one as shown in the Lacq–Villeneuve de Marsan profile and an eastern one around the Pau area (Fig. 9). In the western domain, strata deposition migrated northward in response to massive salt diapirism on the Audignon-Pécorade ridge, inverted as thrust-piercement of salt during basin's inversion (Cenozoic). In the eastern domain, strata deposition migrated southward consequent to northward gravity sliding upon thick underlying evaporites, which was probably a response to the initiation and abortion of a detachment similar to what is described in the North Pyrenean Basins (e.g Lagabrielle et al., 2019). Recent numerical models by Pichel (2019) on the impact of syn-rift tilting of inherited structures on the localization of salt structures enable a reliable comparison with Arzacq halokinesis. In the case of a horst structure, which is likely to correspond to Grand Rieu and Audignon structural highs, both salt-detached ramp syncline and salt anticline form on the edges of the horst. They might respectively correspond to southern and northern Arzacq edges. Extensional stain was is thus accommodated by salt tectonics localized along major inherited and reactivated structures.

### 6.5. Cenomanian postrift phase

Numerous erosional truncations are visible below the Cenomanian base in every seismic reflection profile in the Arzacq and Tartas Basins, marking a significant unconformity between the Lower and Upper Cretaceous sequences. This pattern is especially visible in the Arzacq Basin, where north- and south-oriented erosional truncations are visible on the southern and northern margins, respectively. These record vertical displacement of the Grand Rieu and Audignon-Pécorade-Antin-Maubourguet domains between latest Albian and early or mid-Cenomanian time. This uplift is likely related to flexural rebound of the rift edges at the beginning of the postrift regime (e.g. Weissel and Karner, 1989; Petit et al., 2007; Nemčok, 2016). In this scope, the unconformity is a break-up unconformity, i.e the onset of the breakup sequence which precedes the post rift stage (Moore, 1992; Soares et al., 2019, Fig. 8).

## 7. Discussion

### 7.1. Crustal thinning: The role of prerift salt

The Aquitaine Basin is an immature rift basin in the sense that it did not evolve into a truly brittle and asymmetric rifted basin. Whereas the Tartas Basin remained a sag basin throughout the Early Cretaceous, the Arzacq basin went through an intermediate stage between a sag basin and a hyperthinned basin like the Mauléon rift (Jammes et al., 2009; Lagabrielle et al., 2010; Masini et al., 2014; Saspiturry et al., 2019a), the Parentis rift (Jammes et al., 2010; Ferrer et al., 2012; Tugend et al., 2014) and the Bay of Biscay continental margin (Ferrer et al., 2008; Roca et al., 2011; Tugend et al., 2014). In detail, the slightly asymmetric Arzacq Basin was not affected by the significant detachment faults that led to the pronounced asymmetry seen in adjacent hyperthinned basins. Accommodation was instead controlled by salt tectonic induced by extensional stain localization on inherited structures, including large-scale salt diapirism in northern Arzacq (Audignon-Pécorade and Antin-Maubourguet Horts) and salt-detachement

synclines in Southern Arzacq (Grand Rieu Horst). Such tectonic setting has been recently reproduce by numerically modeling based on the example of the North-Pyrenean synrift sag basin geometries (Duretz et al., 2019). In the adjacent Mauléon Basin, salt-lubricated sliding on its Iberian margin (Ducasse et al., 1986; Bouquet, 1986; Lagabrielle et al., 2010; Teixell et al., 2016) has been interpreted as the stage preceding the early Albian initiation of the south-dipping Saint-Palais detachment (Saspiturry et al., 2019a).

However, the Arzacq Basin differs from its neighboring basins in the magnitude of crustal thinning. For instance, several areas in the North Pyrenean Zone are characterized by a denudated subcontinental mantle, the origin of which is strongly debated but is generally considered to have included a rifting stage that caused the hyperthinned crust to delaminate and lead to the presence of mantle rocks at very shallow depths (Vissers et al., 1997; Jammes et al., 2009; Lagabrielle et al., 2010; Masini et al., 2014; Saspiturry et al., 2019a). However, the present-day Moho in the Arzacq Basin is interpreted at 22 km depth (Wang et al., 2016), which is not compatible with extreme crustal thinning. For these reasons, we suggest that an aborted detachment fault controlled the slight asymmetry of the Arzacq Basin, and that decoupling focused within thick evaporites insulated the sedimentary cover, with its lack of visible brittle structures, from crustal thinning below the salt layers. Nevertheless, recent numerical models (Pichel et al., 2019) suggest that tilting of an inherited horst structure could favor the development of salt-detachement synclines, and we thus could question the existence of what we interpret as an aborted detachement on the location of salt tectonics.

The unconformity below the Cenomanian sequence is highly pronounced near the Grand Rieu and Audignon-Pécorade-Antin-Maubourguet domains. In some areas (Sainte Suzanne area, Saspiturry et al., 2019a), it is associated with the growth of small salt anticlines. Such deformation on the basin borders implies that these borders underwent late uplift, probably related to thermal equilibration at the end of the rift stage (Fig. 8e). This interpretation strongly contrasts with previous studies that have linked this unconformity to a poorly constrained compressive stage (Biteau et al., 2006). In the Mauléon Basin, postrift deposits do not predate the mid to late Cenomanian, after a flip-flop detachment directed extension onto the Iberian margin on the Lakhoura detachment fault and beheaded the previous detachment (Saint-Palais detachment fault) on the European margin (Saspiturry et al., 2019a). Consequently, the postrift stage is diachronous between the Arzacq and Mauléon Basins.

## 7.2. Transfer zones of the Arzacq Basin

In the North Pyrenean Zone, few studies have addressed the effect of transfer zones on the opening of the Cretaceous basins. Nevertheless, a major structure, the Pamplona fault, is believed to offset the axis of the Early Cretaceous rift (Razin, 1989; Claude, 1990; Larrasoaña et al., 2003; Vergès, 2003). This major transfer zone is responsible for the duplication of the Early Cretaceous rift axis towards the west. The Mauléon Basin was also affected by three N20° transfer zones within the North Pyrenean Zone (Peybernès and Souquet, 1984; Canérot, 2008, 2017; Saspiturry., 2019). From east to west these are the Ossau, Barlanès and Saison transfer zones (Canérot, 2017). Recent work interprets this network of faults as inherited from the late Paleozoic Hercynian collapse stage (Saspiturry et al., 2019b).

These three major transfer zones also appear to account for the east-west segmentation within the Arzacq and Tartas Basins (Fig. 12). The Ossau transfer zones controls the N110° southward offset of the Antin-Maubourguet Ridges with respect to the Pécorade anticline. The Barlanès transfer zone controls the eastern termination of the Pécorade anticline, and in the Tartas basin, it appears to control the position and elongation of the Lussagnet salt diapir. The most striking impact of the Barlanès transfer zone is in the Audignon area, where it governed the position of the massive Audignon salt diapir along the

Audignon structural high, prior to its Cenozoic thrust reactivation. This major structure is also responsible for a proximal and distal margin inversion across the fault (Fig. 12). Indeed, in the western part of the Arzacq basin, depositional profile opens toward the Audignon ridge (Lacq being occupied by inner ramp/reef carbonates and Audignon by marls); and in the eastern part of the Arzacq basin, depositional profile opens toward the south (Garlin area being occupied by inner ramp limestone and Pau Anticline by marly limestones). The Saison zone fault may appear in the Gamarde-Goudon seismic reflection profile (Fig. 7) where an abrupt increase in the thickness of the Albian sequence east of the Amou-1 well may correspond to Albian activity on the transfer zone.

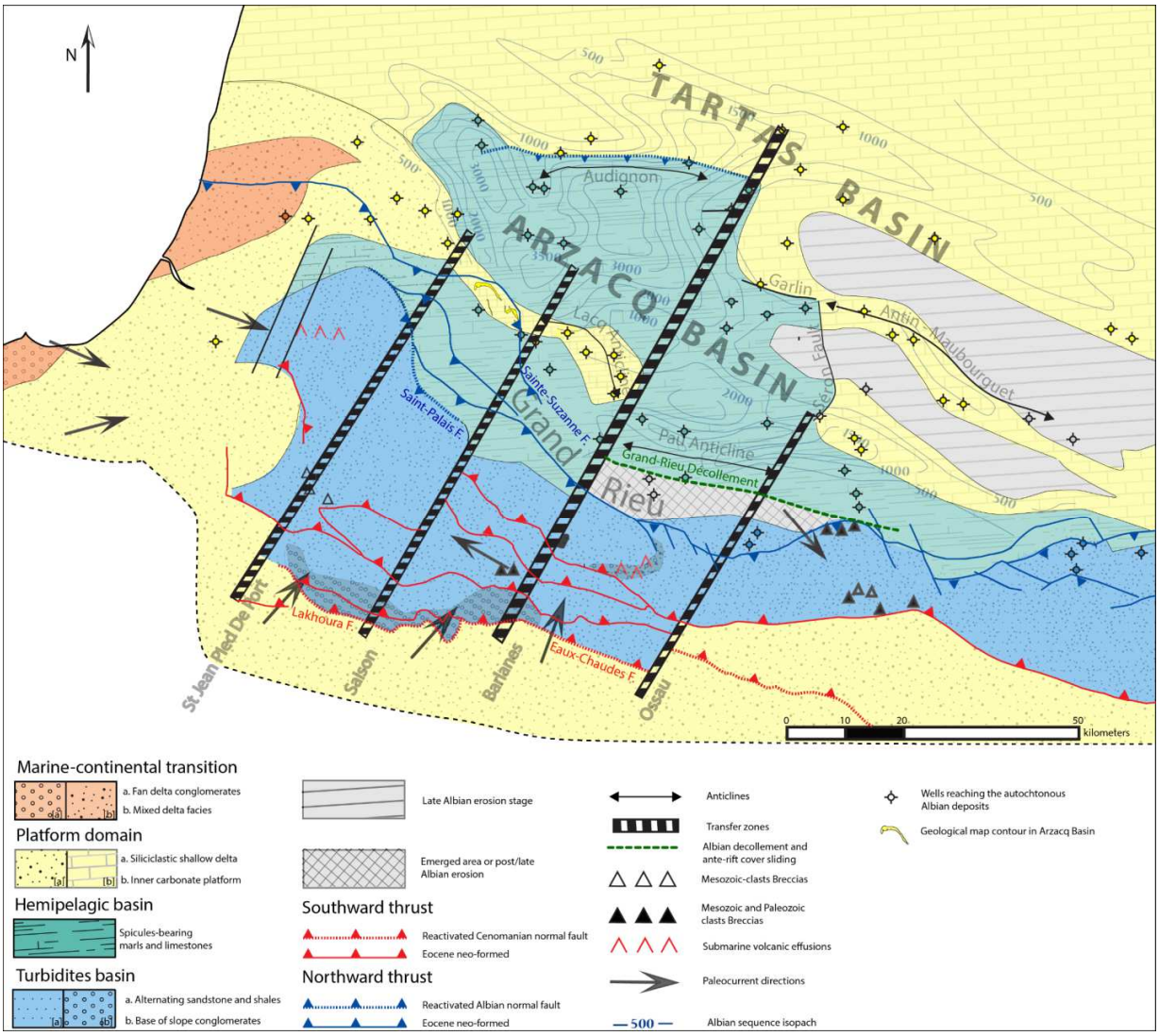


Fig. 12. Albian paleogeography in the Pyrenees-Aquitaine domain (modified after ; Canérot et al., 2017; GSO, and BRGM, 2019; Saspiturry et al., 2019). The N110 and N20 structural trends largely govern facies transitions. These inherited structures account for salt tectonics in the Audignon area (northward deepening) and the eastern Arzacq Basin (southward deepening). Transfer zones control the lateral inversion of the proximal-distal orientation within the Arzacq Basin as well as the emplacement of the Lussagnet diapir in the Tartas Basin.

In our interpretation, then, inherited late Hercynian structures (Saspiturry et al., 2019b) control, through the N110 faults, the emplacement of gravity slides and salt diapirs, while N20 faults act as

transfer zones segmenting the Arzacq and Tartas Basins from east to west). The concept of transfer zones inverting the orientation of proximal and distal domains in adjacent basin segments has been invoked elsewhere on Atlantic margins (Lister et al., 1986; Péron-Pinvidic et al., 2015; Péron-Pinvidic and Osmundsen, 2018).

## 7.3. The Arzacq and Tartas basins within the Pyrenean rift system

Many studies describe the development of sedimentary basins associated with the opening of the Bay of Biscay, marked by significant hyperthinning structures. Most of them highlight the existence of detachment faults that accommodate this crustal thinning. We suggest here that similar structures formed but were curtailed early in the rifting history of the Arzacq Basin, while the Tartas Basin never underwent hyperthinning. In a north-south section that restores spreading between the Mauléon Basin and the North Aquitaine Platform, we propose that the maturity of rifting decreases away from the main rift axis in the North Pyrenean basins (Fig. 10). The Mauléon and Parentis Basins, in the heart of the Albian-Cenomanian rift zone, underwent the greatest crustal thinning. The Arzacq Basin was only moderately thinned, as shown by the relatively deep Moho there (see Fig. 1; Moho at 22 km); nevertheless, its rifting stage included intense tectonic activity marked by salt diapirism and salt-detached ramp syncline. We propose that halokinesis initiation could be related to an aborted detachment. On the Iberia plate, the Columbrets and Cameros Basins show features of a similar history (Casas et al., 2009; Omodéo Salè et al., 2014; Etheve et al., 2018; Roma et al., 2018; Omodeo Salè et al., 2019; Rat et al., 2019), referred to as salt-detached ramp-synclines (Roma et al., 2018) or extensional synclines (Casas et al., 2009). In these basins, crustal thinning was controlled by detachment faults, by which an upper-crust ramp generated large-scale roll-over structures in the pre-rift series, and syn-rift strata deposition migration toward the footwall.. Like the Arzacq Basin, the Columbrets and Cameros Basins are located on the periphery of the Cretaceous rifting and did not evolve in a mature rift system. Arzacq is probably more immature than the Iberian Columbrets and Cameros basins as the asymmetry is mainly governed by salt-detachement The Tartas Basin represents the common initial state of all these basins.

To sum up, the Pyrenean-Biscay rift can be described as a four-part combination consisting of an oceanic domain where complete loss of continental crust led to development of oceanic crust (Bay of Biscay), a mature rift system in which detachments favored crustal thinning and development of nonsymmetric basins (North Pyrenean Basins, Parentis Basin), an immature rift system affected by salt-detached ramp syncline deeply controlled by an aborted detachment (Arzacq Basin, Columbrets Basin, Caméros Basin), and a symmetric sag basin without brittle structures where crustal thinning was accommodated by ductile crustal flow (Tartas Basin).

## 7.4. Comparison between southern inner European Margin and Iberia plate

The North-Pyrenean Zone and a significant part of the Aquitaine Basin were part, at broader scale,of the North Atlantic Mesozoic rifting stage (Fig. 13). In the nearfileld, Bay of Biscay rifting initiates in the Early Cretaceous (our stage 1), it accelerates from Barremian to Aptian with mantle exhumation is recorded in Albian time (our stage 2) and culminates in Albian time with first oceanic crust accretion (Montadert et al., 1979 ; Boilot, 1984 ; Brunet, 1984 ; Thinon et al., 2001). Diachronism is pretty clear with the North Pyrenean Basins (Basque Cantabrian and Mauléon Basin) in which rifting stage accelerates in Albian time with mantle-exhumation(Garcia-Mondéjar et ak., 1996 and 2005; Pedrera et al., 2017 ; Debroas 1987, 1990 and Saspiturry et al., 2019) while oceanic crust is already created in Bay of Biscay. The Arzacq and Tartas basins share a similar timing, in a less mature fashion, as we discussed above. Westward, recent work document a complex pattern of rift propagation in West Iberia (Alves et

al., 2009; Alves and Cunha 2018 ; Soares et al., 2012) and the diachroneity in both continental and lithospheric breakup (sensu Soares et al., 2012). In this domain, four rifting stages are described ranging from (1) Trias, (2) Lias, (3) Oxfordian-Kimmeridgian and (4) Early Cretaceous. Only the Triassic and Early Cretaceous events are evidenced in the Aquitaine-Pyrenean domain, probably due to its relative far position compared to the Neo-Tethys and the Atlantic opening. Nevertheless, the West Iberia margin spans a major rifting stage initiating in the Late Jurassic time (Fig. 13; Srivastava et al., 2000; Alves et al., 2009), This first rifting stage (wide rift) culminates with the lithosphere break up in the southernmost West Iberia Margin during lowermost Cretaceous time (Pinheiro et al., 1992 ; Fig. 13). From lowermost Cretaceous to uppermost Aptian, the continental break up does not cease to migrate northward, culminating in the Aquitaine area with the lithosphere break up in the Latest Aptian to Albian (Fig. 13 ; Montadert et al., 1979; Boillot, 1984).

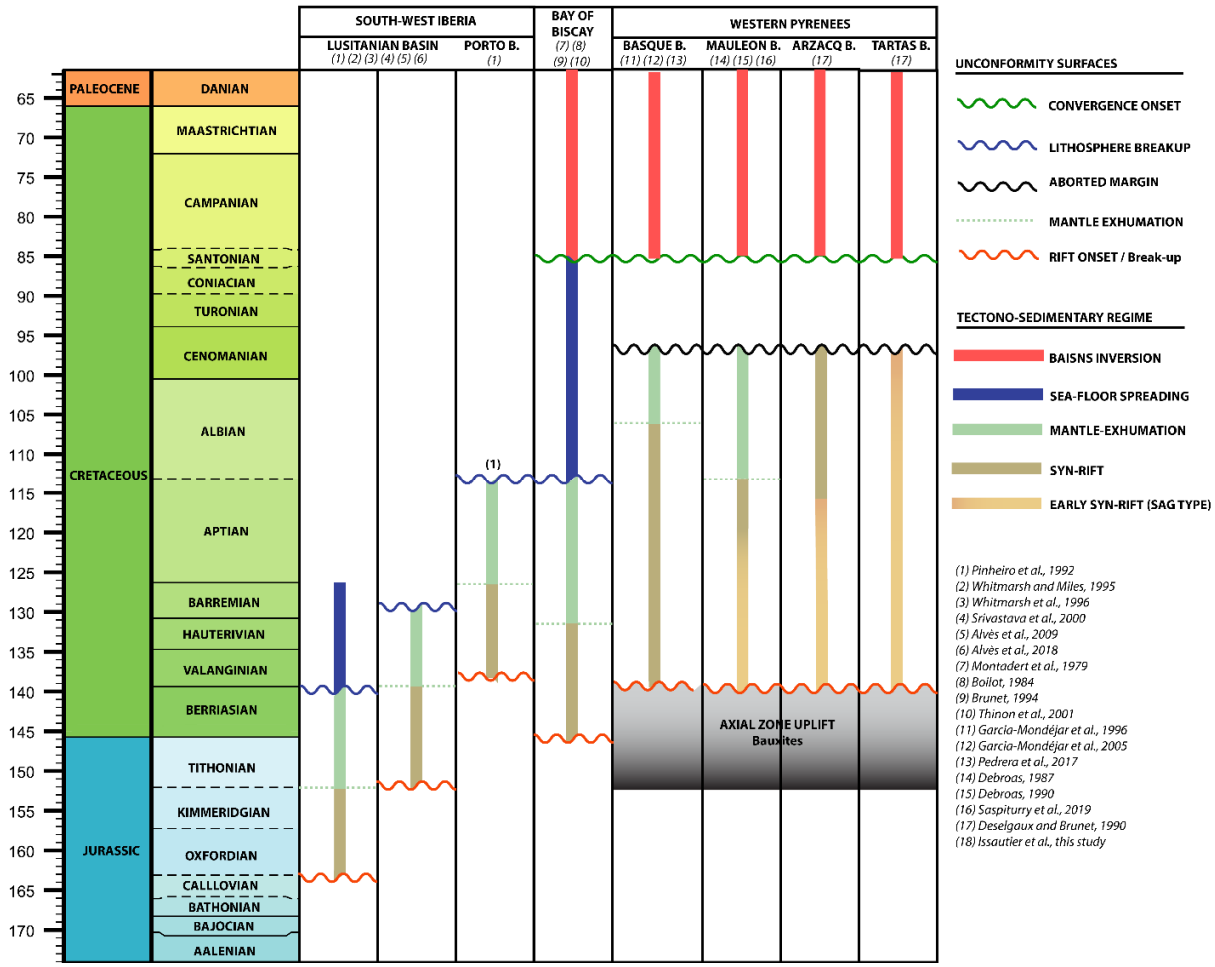


Fig. 13 : Event chart between south-west Iberia, Bay of Biscay and Western Europe. The chart illustrates the diachronism of the rifting onset and lithosphere break up, which occurs only in southwest Iberian and bay of Biscay. Furthermore, the chart illustrates the evolution in Western Europe from a rift reaching oceanization (Bay of Biscay) to a rift basin maintained in a SAG regime (Tartas Basin).

The definition of a break-up sequence (Moore, 1992 ; Soares et al., 2012) within the North Pyrenean zone is extremely complex since inversion of the rift basin might occur rapidly after the lithosphere break up (Issautier et al., 2018). The following unconformity within the basin is probably related to the onset

of Iberia-Europe convergence and for this reason, no break-up sequence might properly identified. However, there is a notable change in the sedimentary profile since syn-rift sequence is dominated by deep marly facies, and the unconformity is capped by very shallow to marginal littoral facies. This pattern is relatively consistent with Soares et al. (2012) and Alves and Cunha (2018) observation of a regressive interval at the base of breakup sequences. Still, the Arzacq-Tartas basins and in a minor way Mauléon Basin remained as continental rifts at this time (Fig. 13) which might explain the lack of isostatic rebound described in much more evolved rifts or margins.

# 8. Conclusions

The Arzacq and Tartas Basins, part of the broader Pyrenean-Atlantic rift system, display different records of the Early Cretaceous rifting stage. Whereas the Tartas Basin remained a symmetric sag basin throughout the Early Cretaceous, the Arzacq Basin experienced a first sag stage (Berriasian–Aptian) followed by a rapidly subsiding, slightly asymmetric stage (Albian).

We interpret the sag morphology as linked to thinning of the European lower crust in which normal faulting did not affect the upper crust. The subsidence of the Early Cretaceous basins appears to have been controlled by their inherited Jurassic framework, as the edges of the Early Cretaceous depocenters coincide with major early Mesozoic horsts (Grand Rieu and Audignon). In the Arzacq Basin, Albian salt tectonics was responsible for basin asymmetry, which varies along strike with the influence of transfer zones (the Saint Jean Pied de Port, Saison, Barlanès and Ossau transfer zones). The intersection of these transfer zones and inherited N110 faults led to the development of a giant salt diapir in the Audignon region (in which the asymmetry developed on the north side) and to massive gravity sliding and creation of accommodation space in the Grand Rieu domain (in which the asymmetry developed on the south side).

From a larger regional perspective, the Arzacq and Tartas Basins are in the periphery of the main area of major extension, and they decrease in their degree of crustal thinning with increasing distance from the rifting axis. We propose a multistage scheme for the evolution of basins in this large-scale setting. The first rifting stage is typified by the sag geometry of the Tartas Basin, in which crustal thinning is accommodated by subtractive processes in the ductile crust that are decoupled from the sedimentary cover by the presence of significant evaporite layers. This initial stage might evolve with further crustal thinning into a stage typified by slightly asymmetric basins (such as the Arzacq, Columbrets and Caméros basins) in which large-scale salt tectonics causes brittle deformation accompanying the onset and abortion of a detachment fault. These basins evolve with further thinning into mature rift systems in which well-developed detachment faults lead to efficient crustal thinning (North Pyrenean basins, Parentis Basin) and finally give birth to domains of oceanic crust (Bay of Biscay).

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# References


AGSO and BRGM, 2018, Synthèse géophysique et géologique des Pyrénées - Volume 3 : Cycle alpin : Phénomènes alpins – 2015, Edition AGSO and BRGM, coordinated by A. BARNOLAS (1982-2001), B. GUÉRANGÉ (1982-90) J.C. CHIRON (1991-95) and S. COURBOULEIX (1996-2001), scientific committee : A. AUTRAN, M. DURAND-DELGA and J.M. FONBOTÉ, 480 p., 286 FIGs.

Alves, T., Carlos, M.,Cunha, T., Ullnaess, M., Myklebust, R., Monteiro, J., Manuppella, G., 2009, Diachronous evolution of Late Jurassic–Cretaceous continental rifting in the northeast Atlantic (west Iberian margin). Tectonics. 28. 10.1029/2008TC002337.

Alves, T., Cunha, T, 2018, A phase of transient subsidence, sediment bypass and deposition of regressive–transgressive cycles during the breakup of Iberia and Newfoundland, Earth and Planetary Science Letters, Volume 484, Pages 168-183, ISSN 0012-821X, https://doi.org/10.1016/j.epsl.2017.11.054.

Ben-Avraham, Z., and M. D. Zoback (1992), Transform-normal extension and asymmetric basins; an alternative to pull-apart models, Geology, 20, 423–426, doi:10.1130/0091-7613(1992)020< 0423:TNEAAB>2.3.CO;2

Biteau J.J., and Canérot, J. 2008. La chaîne des Pyrénées et ses avants-pays d'Aquitaine et de l'Ebre, structure, évolution géodynamique et systèmes pétroliers. Revue de l'Union Française des géologuges, n°155.

Bois, C., and ECORS Scientific Party, 1990, Major geodynamic processes studied from the ECORS deep seismic profiles in France and adjacent areas: Tectonophysics, v. 173, p. 397–410.

Boillot, G., 1984, Le Golfe de Gascogne et les Pyrénées, in, Boillot, G., Montadert, M., Lemoine, M., and Biju-Duval, B., eds, Les marges continentales actuelles et fossiles autour de la France, Masson, Paris, p.5–81.

Bouquet, B., 1986, La bordure mésozoïque orientale du Massif du Labourd (Pyrénées occidentales) : Stratigraphie-Sédimentologie-Structure-Implications Géodynamiques: Pau, Université de Pau et des Pays de l'Adour, 219 p.

Bouroullec, J., Deloffre, R. 1970. Interprétation sédimentologique et paléogéographique par microfaciès du Crétacé inférieur basal d'Aquitaine Sud-Ouest. 1970, Bull. Centre Rech. Pau-SNPA, vol 4, n°2, pp. 381-429

Bouroullec, J., J. Delfaud, and R. Deloffre, 1979, Organisations sédimentaire et paléocologique de l'Aptien supérieur à faciès urgonien dans les Pyrénées occidentales et l'Aquitaine méridionale: Géobios, no. 3, p. 25–43.

Bourrouilh, R., J.-P. Richert, and G. Zolnaï, 1995, The North Pyrenean Aquitaine Basin, France: Evolution and Hydrocarbons: AAPG Bulletin, v. 79, no. 6, p. 831–853.

BRGM, Elf, Esso, & SNPA, 1974, Géologie du Bassin d'aquitaine (BRGM Ed). Paris: BRGM Editions.

Brunet, M.F., 1984. Subsidence history of the Aquitaine Basin determined from subsidence curves, Geological Magazine 121(05):421 – 428

Brunet, M. F., 1991, Subsidence et Géodynamique du bassin d'Aquitaine. Relations avec l'ouverture de l'Atlantique. Thèse Sci. Univ. Paris VI, 288p.

Brunet, M. F., 1994, Subsidence in the Parentis Basin (Aquitaine, France): Implications of the Thermal Evolution, ed, in Mascle, A., Hydrocarbon and Petroleum Geology of France: Special Publication of the European Association of Petroleum Geoscientists, Volume 4, p.187–198.

Burg, J.-P., J. Van Den Driessche, and J.-P. Brun, 1994, Syn- to post-thickening extension : mode and consequences: Comptes rendus de l'Académie des sciences. Série 2. Sciences de la terre et des planètes, v. 319, no. 9, p. 1019–1032.

Canérot, J., 2008, Les Pyrénées: Histoire géologique: Atlantica.

Canérot, J., 2017, The pull apart-type Tardets-Mauléon Basin, a key to understand the formation of the Pyrenees, Bull. Soc. géol. Fr. BSGF - Earth Sciences Bulletin 188, 35.

Canérot, J., Peybernes, B., Ciszak, R., 1979, Presence d'une marge meridionale a l'emplacement de la zone des chainons bearnais (Pyrenees basco-bearnaises). Bulletin de la Société Géologique de France; S7-XX (5): 673–676. doi: https://doi.org/10.2113/gssgfbull.S7-XX.5.673

Canérot, J., C. Majesté-Menjoulas, and Y. Ternet, 1999, Le cadre stratigraphique et géodynamique des altérites et des bauxites sur la marge ibérique des Pyrénées occidentales (France): Comptes Rendus de l'Académie des Sciences-Series IIA-Earth and Planetary Science, v. 328, no. 7, p. 451–456.

Casas, A., P. Kearey, L. Rivero, and C. R. Adam, 1997, Gravity anomaly map of the Pyrenean region and a comparison of the deep geological structure of the western and eastern Pyrenees: Earth and Planetary Science Letters, v. 150, no. 1–2, p. 65–78.

Casas, A., Villalaín, J.J., Soto, R., Gil-Imaz, A., Del Río, P., Fernández, G., 2009, Multidisciplinary approach to an extensional syncline model for the Mesozoic Cameros Basin (N Spain), Tectonophysics, Volume 470, Issues 1–2, Pages 3-20, ISSN 0040-1951, https://doi.org/10.1016/j.tecto.2008.04.020.

Claude, D., 1990, Etude stratigraphique, sédimentologique et structural des dépôts Mésozoïques au Nord du Massif du Labourd. Role de la Faille de Pamplona (Pays Basque). Thèse de doctorat, Université de Bordeaux.

Clerc, C ;, Lagabrielle, Y., Neumaier, M., Reynaud, J.Y., De Saint Blanquat; M, 2012; Exhumation of subcontinental mantle rocks: evidence from ultramafic-bearing clastic deposits nearby the Lherz peridotite body, French Pyrenees. Bulletin de la Société Géologique de France ; 183 (5): 443–459. Doi: https://doi.org/10.2113/gssgfbull.183.5.443.

Clerc, C., and Y. Lagabrielle, 2014, Thermal control on the modes of crustal thinning leading to mantle exhumation: Insights from the Cretaceous Pyrenean hot paleomargins: Tectonics, v. 33, no. 7, p. 1340–1359, doi:10.1002/2013TC003471.

Combes, P.-J., B. Peybernès, and A. F. Leyreloup, 1998, Altérites et bauxites, témoins des marges européenne et ibérique des Pyrénées occidentales au Jurassique supérieur—Crétacé inférieur, à l'ouest de la vallée d'Ossau (Pyrénées-Atlantiques, France): Comptes Rendus de l'Académie des Sciences-Series IIA-Earth and Planetary Science, v. 327, no. 4, p. 271–278

Corre, B., Y. Lagabrielle, P. Labaume, S. Fourcade, C. Clerc, and M. Ballèvre, 2016, Deformation associated with mantle exhumation in a distal, hot passive margin environment: New constraints

from the Saraillé Massif (Chaînons Béarnais, North-Pyrenean Zone): Comptes Rendus Geoscience, v. 348, no. 3–4, p. 279–289, doi:10.1016/j.crte.2015.11.007.

Curnelle, R., 1983, Evolution structuro-sédimentaire du Trias et de l'Infra-Lias d'Aquitaine: Bull. Cent. Rech. Explor. Prod. Elf-Aquitaine, v. 7, no. 1, p. 69–99.

Curnelle R., Dubois P., 1986. Evolution des grands bassins sédimentaires français: bassins de Paris, d'Aquitaine et du Sud-Est. Bull. Soc. géol. Fr., 8, 526-546

Daignières, M., M. Séguret, M. Specht, and E. Team, 1994, The Arzacq-western Pyrenees ECORS deep seismic profile, in Hydrocarbon and petroleum geology of France: Springer, p. 199–208.

Debroas, E. J., 1987, Modèle de bassin triangulaire à l'intersection de décrochements divergents pour le fossé albo-cénomanien de la Ballongue (zone nord-Pyrénéenne, France): Bulletin de la Société Géologique de France, v.8, p.887–898.

Debroas, E. J., 1990, Le flysch noir albo-cénomanien témoin de la structuration albienne à sénonienne de la Zone nord-pyrénéenne en Bigorre (Hautes-Pyrénées, France): Bulletin de la société Géologique de France, v.8, p.273–285.

Debroas, E.J., Canérot, J., Bilotte, M., 2010. Les Brèches d'Urdach, témoins de l'exhumation du manteau Pyrénéen dans un escarpement de faille Vraconnien–Cénomanien inférieur (zone nord-pyrénéenne, Pyrénées-Atlantiques, France). Geol. Fr. 2, 53–63

Debroas, E.J., 2011, les massifs de Lherzolite des Pyrénées, 40 monuments historiques du patrimoine géologique mondial à mettre en valeur et à protéger , Les Amis de Moncaut, Bulletin d'information n°6 « Spécial géologie », Août 2011

Delfaud J. 1969. Essai sur la géologie dynamique du domaine Aquitano-pyrénéen durant le Jurassique et le Crétacé inférieur. Thèse doctorat de l'Université de Bordeaux.

Delfaud, J., and J. Henry, 1967, Evolution des bassins jurassiques dans la zone nord-pyrénéenne occidentale: 64ème congrès AFAS Bordeaux, p. 75–80.

Desegaulx, P. and Brunet, M.-F., 1990. Tectonic subsidence of the Aquitaine Basin since Cretaceous times, Bull. Soc. géol. France 8 (VI), pp. 29–306.

Ducasse, L., P.-C. Velasque, and J. Muller, 1986, Glissement de couverture et panneaux basculés dans la région des Arbailles (Pyrénées occidentales): Un modèle évolutif crétacé de la marge nord-ibérique à l'Est de la transformante de Pamplona: Comptes rendus de l'Académie des sciences. Série 2, Mécanique, Physique, Chimie, Sciences de l'univers, Sciences de la Terre, v. 303, no. 16, p. 1477–1482.

Duretz, T., Asti, R., Lagabrielle, Y., Brun, J-P., Jourdon, A., Clerc, C., and Corre, B, 2019, Numerical modelling of Cretaceous Pyrenean Rifting: The interaction between mantle exhumation and syn-rift salt tectonics. Basin Research, doi: 10.1111/bre.12389.

Etheve, N., Mohn, G., Frizon de Lamotte, D., Roca, E., Tugend, J., & Gómez-Romeu, J. ( 2018). Extreme Mesozoic crustal thinning in the eastern Iberia margin: The example of the Columbrets Basin (Valencia Trough). Tectonics, 37, 636–662. https://doi.org/10.1002/2017TC004613

Fabriès, J., Lorand, J.P., Bodinier, J.L.,Dupuy, C., 1991, Evolution of the upper mantle beneath the Pyrenees: evidence from orogenic spinel lherzolite massifs, J. Petrol., Spec. Lherzolites Iss. (1991), pp. 55-76

Fabriès, J., Lorand, J.P., Bodinier, J.L, 1998, Petrogenetic evolution of orogenic lherzolite massifs in the central and western Pyrenees, Tectonophysics, Volume 292, Issues 1–2, 30 June 1998, Pages 145-167

Ferrer, O., E. Roca, B. Benjumea, J. A. Muñoz, N. Ellouz, and MARCONI Team, 2008, The deep seismic reflection MARCONI-3 profile: Role of extensional Mesozoic structure during the Pyrenean contractional deformation at the eastern part of the Bay of Biscay: Marine and Petroleum Geology, v. 25, no. 8, p. 714–730, doi:10.1016/j.marpetgeo.2008.06.002.

Ferrer, O., M. P. A. Jackson, E. Roca, and M. Rubinat, 2012, Evolution of salt structures during extension and inversion of the Offshore Parentis Basin (Eastern Bay of Biscay): Geological Society, London, Special Publications, v. 363, no. 1, p. 361–380, doi:10.1144/SP363.16.

Fortane´, A., Due´e, G., Lagabrielle, Y., Coutelle, A., 1986, Lherzolites and thewestern "Chaînons béarnaise" (French Pyrénées). Structural and paéleogeographical pattern. Tectonophysics 129 (1), 81–98.

García-Mondéjar, J., Agirrezabala, L. M., Aranburu, A., Fernández-Mendiola, P. A., GómezPérez, I., López-Horgue, M., and, Rosales, I., 1996, Aptian–Albian tectonic pattern of the Basque–Cantabrian Basin (Northern Spain): Geological Journal, v.31, p.13–45.

García-Mondéjar, J., López-Horgue, M. A., Aranburu, A., and Fernández-Mendiola, P. A., 2005, Pulsating subsidence during a rift episode: stratigraphic and tectonic consequences (Aptian–Albian, northern Spain): Terra Nova, v.17, p.517–525.

Gong, Z., C. G. Langereis, and T. A. T. Mullender, 2008, The rotation of Iberia during the Aptian and the opening of the Bay of Biscay: Earth and Planetary Science Letters, v. 273, no. 1–2, p. 80–93, doi:10.1016/j.epsl.2008.06.016.

Grandjean, G., 1992, Mise en évidence des structures crustales dans une portion de chaîne et de leur relation avec les bassins sédimentaires. Application aux Pyrénées occidentales au travers du Projet ECORS Arzacq-Pyrénées: Université des Sciences et Techniques du Languedoc, 291 p.

Grandjean, G., 1994, Etude des structures crustales dans une portion de chaîne et de leur relation avec les bassins sédimentaires. Application aux Pyrénées occidentales: Bull. Cent. Rech. Explor. Prod. Elf Aquitaine, v. 18, no. 2, p. 391–420

Hart, N. R., D. F. Stockli, and N. W. Hayman, 2016, Provenance evolution during progressive rifting and hyperextension using bedrock and detrital zircon U-Pb geochronology, Mauléon Basin, western Pyrenees: Geosphere, v. 12, no. 4, p. 1166–1186, doi:10.1130/GES01273.1.

Hart, N. R., D. F. Stockli, L. L. Lavier, and N. W. Hayman, 2017, Thermal evolution of a hyperextended rift basin, Mauléon Basin, western Pyrenees: Thermal evolution of hyperextended rift: Tectonics, doi:10.1002/2016TC004365.

Haupert, I., G. Manatschal, A. Decarlis, and P. Unternehr, 2016, Upper-plate magma-poor rifted margins: Stratigraphic architecture and structural evolution: Marine and Petroleum Geology, v. 69, p. 241–261, doi:10.1016/j.marpetgeo.2015.10.020.

Issautier, B., 2019, Onset of the Convergence between Europe and Iberia: Well correlation and seismic interpretation within the Upper Cretaceous of the Aquitaine Basin, 26eme edition des Réunions de Sciences de la Terre, Lille.

Jackson, M. P., & Hudec, M. R. (2005). Stratigraphic record of translation down ramps in a passive - margin salt detachment. Journal of Structural Geology, 27(5), 889–911. https://doi.org/10.1016/j.jsg.2005.01.010

James, V., 1998, La plate-forme carbonatée ouest-pyrénéenne au jurassique moyen et supérieur stratigraphie séquentielle, stades d'évolution, relations avec la subsurface en aquitaine méridionale: 351 p.

Jammes, S., G. Manatschal, L. Lavier, and E. Masini, 2009, Tectono-sedimentary evolution related to extreme crustal thinning ahead of a propagating ocean: Example of the western Pyrenees: Tectonics, v. 28, no. 4, doi:10.1029/2008TC002406.

Karner, G. D., N. W. Driscoll, and D. H. N. Barker, 2003, Syn-rift regional subsidence across the West African continental margin: the role of lower plate ductile extension: Geological Society, London, Special Publications, v. 207, no. 1, p. 105–129, doi:10.1144/GSL.SP.2003.207.6.

Lagabrielle, Y., P. Labaume, and M. de Saint Blanquat, 2010, Mantle exhumation, crustal denudation, and gravity tectonics during Cretaceous rifting in the Pyrenean realm (SW Europe): Insights from the geological setting of the lherzolite bodies: Tectonics, v. 29, no. 4, doi:10.1029/2009TC002588.

Lagabrielle, Y., Clerc, C., Vauchez, A., Lahfid, A., Labaume, P., Azambre, B., Fourcade, S., Dautria, J.M., 2016, Very high geothermal gradient during mantle exhumation recorded in mylonitic marbles and carbonate breccias from a Mesozoic Pyrenean palaeomargin (Lherz area, North Pyrenean Zone, France), Comptes Rendus Geoscience, Volume 348, Issues 3–4, Pages 290-300, ISSN 1631-0713, https://doi.org/10.1016/j.crte.2015.11.004.Lagabrielle, Y., Asti, R., Duretz, T., Clerc, C., Fourcade, S., Teixell, A., . . Saspiturry, N., 2020. A review of cretaceous smooth-slopes extensional basins along the Iberia-Eurasia plate boundary: How pre-rift salt controls the modes of continental rifting and mantle exhumation. Earth-Science Reviews. 201. https://doi.org/10.1051/bsgf/2019007

Larrasoaña, J. C., J. M. Parés, H. Millán, J. del Valle, and E. L. Pueyo, 2003, Paleomagnetic, structural, and stratigraphic constraints on transverse fault kinematics during basin inversion: The Pamplona Fault (Pyrenees, north Spain): Tectonics, v. 22, no. 6, doi:10.1029/2002TC001446.

Lavier, L. L., and G. Manatschal, 2006, A mechanism to thin the continental lithosphere at magma-poor margins: Nature, v. 440, no. 7082, p. 324–328, doi:10.1038/nature04608.

Lenoble, J.-L., 1992, Les plates-formes carbonatées ouest-pyrénéennes du dogger à l'Albien, stratigraphie séquentielle et évolution géodynamique: Université Paul Sabatier de Toulouse (Sciences), 395 p.

Lister, G. S., M. A. Etheridge, and P. A. Symonds, 1986, Detachment faulting and the evolution of passive continental margins: Geology, v. 14, no. 3, p. 246–250, doi:10.1130/0091-7613(1986)14<246:DFATEO>2.0.CO;2.

Manatschal, G., 2004, New models for evolution of magma-poor rifted margins based on a review of data and concepts from West Iberia and the Alps: International Journal of Earth Sciences, v. 93, no. 3, doi:10.1007/s00531-004-0394-7.

Martin-Closas, C., Pebernès, B., 1987, Datation de la transgression éocrétacée dans les Pyrénées basco-béarnaises à l'aide des Charophytes, Geobios, Volume 20, Issue 5, Pages 695-700, ISSN 0016-6995, https://doi.org/10.1016/S0016-6995(87)80024-4.

Masini, E., G. Manatschal, G. Mohn, J.-F. Ghienne, and F. Lafont, 2011, The tectono-sedimentary evolution of a supra-detachment rift basin at a deep-water magma-poor rifted margin: the example of the Samedan Basin preserved in the Err nappe in SE Switzerland: Tectono-sedimentary evolution of a supra-detachment rift basin: Basin Research, v. 23, no. 6, p. 652–677, doi:10.1111/j.1365-2117.2011.00509.x.

Masini, E., G. Manatschal, G. Mohn, and P. Unternehr, 2012, Anatomy and tectono-sedimentary evolution of a rift-related detachment system: The example of the Err detachment (central Alps, SE Switzerland): Geological Society of America Bulletin, v. 124, no. 9–10, p. 1535–1551, doi:10.1130/B30557.1.

Masini, E., G. Manatschal, J. Tugend, G. Mohn, and J.-M. Flament, 2014, The tectono-sedimentary evolution of a hyper-extended rift basin: the example of the Arzacq–Mauléon rift system (Western Pyrenees, SW France): International Journal of Earth Sciences, v. 103, no. 6, p. 1569–1596, doi:10.1007/s00531-014-1023-8.

Mauriaud, P. 1987. Le Bassin d'Aquitaine. Pétrole et Techniques, 335, 38–41.

McKenzie, D., 1978, Some remarks on the development of sedimentary basins: Earth and Planetary Science Letters, v. 40, no. 1, p. 25–32, doi:10.1016/0012-821X(78)90071-7

Mediavilla, F. 1987. La tectonique salifère d'Aquitaine. Le Bassin de Parentis. Pe´trole et Techniques, 335, 35–37.

Minnigh, L.D., Van Calsteren, P.W.C. and den Tex, E., 1980. Quenching: an additional model for emplacement of the lherzolite at Lers (French Pyrenees). Geology, 8, 18–21.

Mitchum R.M., Vail, P.R., Thompson, S., 1977. Seismic stratigraphy and global changes of sea level, part 2: The depositional sequence as a basic unit for stratigraphic analysis C.E Payton (Ed.), Seismic Stratigraphy, Am. Assoc. Pet. Geol. Mem., 26, pp. 53-62

Montadert, L., Roberts, D.G., De Charpal, O., and Guennoc, P., 1979, Rifting and subsidence of the northern continental margin of the Bay of Biscay, in: Montadert, L., Roberts, D.G., et al., eds, Initial Reports of the Deep Sea Drilling Project, Volume 48: Washington, DC, US Government Printing Office, p.1025–1060.

Moore, J.G., 1992. A Syn-Rift to Post-Rift Transition Sequence in the Main Porcupine Basin, Offshore Western Ireland, vol. 62. Geological Society, London (Special Publications, pp. 333–349).

Nemčok, M. (2016). Mechanics of rifting and transition to drift phases. In Rifts and Passive Margins: Structural Architecture, Thermal Regimes, and Petroleum Systems (pp. 31-75). Cambridge: Cambridge University Press. doi:10.1017/CBO9781139198844.003

Olivet, J. L., 1996, La cinématique de la plaque ibérique: Bull. Cent. Rech. Explor. Prod. Elf Aquitaine, v. 20, no. 1, p. 131–195.

Omodeo Salè, S., Guimerà, J., Mas, R., 2014, Tectono-stratigraphic evolution of an inverted extensional basin: the Cameros Basin (north of Spain), Int J Earth Sci (Geol Rundsch) 103:1597–1620 DOI 10.1007/s00531-014-1026-5

Omodeo-Salé, S., Ondrak, R., Arribas, J., Mas, R., Guimerà, J. and Martínez, L. (2019), Petroleum systems modelling in a fold-and-thrust belt setting: the inverted cameros basin, north-central spain. Journal of Petroleum Geology, 42: 145-171. doi:10.1111/jpg.12728

Pedrera, A., García-Senz, J., Ayala, C., Ruiz-Constán, A., Rodríguez-Fernández, L. R., Robador, A., & González Menéndez, L.,2017, Reconstruction of the exhumed mantle across the North Iberian Margin by crustal-scale 3-D gravity inversion and geological cross section. Tectonics, 36, 3155–3177. https://doi.org/10.1002/2017TC004716

Péron-Pinvidic, G., and G. Manatschal, 2009, The final rifting evolution at deep magma-poor passive margins from Iberia-Newfoundland: a new point of view: International Journal of Earth Sciences, v. 98, no. 7, p. 1581–1597, doi:10.1007/s00531-008-0337-9.

Péron-Pinvidic, G., Osmundsen, P., 2018, The Mid Norwegian - NE Greenland conjugate margins: Rifting evolution, margin segmentation, and breakup, Marine and Petroleum Geology, Volume 98, Pages 162-184, ISSN 0264-8172, https://doi.org/10.1016/j.marpetgeo.2018.08.011.

Péron-Pinvidic, G., G. Manatschal, E. Masini, E. Sutra, J. M. Flament, I. Haupert, and P. Unternehr, 2015, Unravelling the along-strike variability of the Angola–Gabon rifted margin: a mapping approach: Geological Society, London, Special Publications, v. 438, no. 1, p. 49–76, doi:10.1144/SP438.1.

Petit, C., Fournier, M., Gunnell, Y., 2007, Tectonic and climatic controls on rift escarpments: Erosion and flexural rebound of the Dhofar passive margin (Gulf of Aden, Oman), Journal of geophysical research, vol. 112, B03406, doi:10.1029/2006JB004554, 2007

Peybernès, B. 1976. Le Jurassique et le Crétacé inférieur des Pyrénées franco-espagnoles. Thèse État de l' Université de Toulouse, 459 p

Peybernès, B., 1979, L'Urgonien des Pyrénées, Essai de synthèse: Geobios, v. 12, p. 79–87.

Peybernès, B., 1982, Création puis évolution de la marge nord-ibérique des Pyrénées au Crétacé inférieur: Cuadernos de Geología Ibérica, v. 8, p. 987–1004.

Peybernès, B., Combes, J.P, 1987. Le problème de la limite Jurassique-Crétacé dans les Pyrénées occidentales entre Lourdes et Saint-Jean-Pied-de-Port; cadre stratigraphique et géodynamique des Bauxites Basco-béarnaises, Strata, Série 1, vol°3.

Peybernès, B., Souquet, P., 1984, Basement blocks and tecto-sedimentary evolution in the Pyrenees during Mesozoic times, Geological Magazine, Vol. 121, no. 4, September, pp. 397-539

Pichel, L. M., Peel, F., Jackson, C. A. - L., & Huuse, M. (2018). Geometry and kinematics of salt - detached ramp syncline basins. Journal of Structural Geology, 115, 208–230. https://doi.org/10.1016/j.jsg.2018.07.016

Pichel, L. M., Finch, E., & Gawthorpe, R. L. (2019). The Impact of Pre-Salt Rift Topography on Salt Tectonics: A Discrete-Element Modeling Approach. Tectonics, 38(4), 1466–1488.

Pinet, B., L. Montadert, and ECORS Scientific Party, 1987, Deep seismic reflection and refraction profiling along the Aquitaine shelf (Bay of Biscay): Geophysical Journal International, v. 89, no. 1, p. 305–312, doi:10.1111/j.1365-246X.1987.tb04423.x.

Pinheiro, L., Whitmarsh, R., Miles, P, 1992, The ocean-continent boundary off the western continental margin of Iberia—II. Crustal structure in the Tagus Abyssal Plain, *Geophysical Journal International*, Volume 109, Issue 1, April 1992, Pages 106–124, https://doi.org/10.1111/j.1365-246X.1992.tb00082.x

Rat, J., Mouthereau, F., Brichau, S., Crémades, A., Bernet, M., Balvay, M., et al. ( 2019). Tectonothermal evolution of the Cameros basin: Implications for tectonics of North Iberia. Tectonics, 38, 440– 469. https://doi.org/10.1029/2018TC005294

Roca, E., J. A. Muñoz, O. Ferrer, and N. Ellouz, 2011, The role of the Bay of Biscay Mesozoic extensional structure in the confiuration of the Pyrenean orogen: Constraints from the MARCONI deep seismic reflection survey: Tectonics, v. 30, no. 2, doi:10.1029/2010TC002735.

Roest, W. R., S. P. Srivastava, 1991, Kinematics of the plate boundaries between Eurasia, Iberia, and Africa in the North Atlantic from the Late Cretaceous to the present: Geology, v.19, p. 613–616.

Roma, M., Ferrer, O., Roca, E., Pla, O., Escosa, F., Butillé, M., 2018, Formation and inversion of salt-detached ramp-syncline basins. Results from analog modeling and application to the Columbrets Basin (Western Mediterranean), Tectonophysics, Volume 745, Pages 214-228, ISSN 0040-1951, https://doi.org/10.1016/j.tecto.2018.08.012.

Rosenbaum, G., G. S. Lister, and C. Duboz, 2002, Relative motions of Africa, Iberia and Europe during Alpine orogeny: Tectonophysics, v. 359, no. 1–2, p. 117–129, doi:10.1016/S0040-1951(02)00442-0.

Rossi, P., A. Cocherie, C. M. Fanning, and Y. Ternet, 2003, Datation U-Pb sur zircons des dolérites tholéiitiques pyrénéennes (ophites) à la limite Trias–Jurassique et relations avec les tufs volcaniques dits « infra-liasiques » nord-pyrénéens: Comptes Rendus Geoscience, v. 335, no. 15, p. 1071–1080, doi:10.1016/j.crte.2003.09.011.

Saspiturry, N., 2019. Evolution sédimentaire, structurale et thermique d'un rift hyper-aminci : de l'héritage post-hercynien à l'inversion alpine, Exemple du bassin de Mauléon (Pyrénées). PhD thesis, Bordeaux University, 444p.

Saspiturry, S., Razin, P., Baudin, T., Serrano, O., Issautier, B., Lasseur, E., Allanic, C., Thinon, T., Leleu, S. 2019a. Symmetry vs. asymmetry of a hyper-thinned rift: Example of the Mauléon Basin (Western Pyrenees, France), Marine and Petroleum Geology, Volume 104, 2019, pp. 86-105, ISSN 0264-8172, https://doi.org/10.1016/j.marpetgeo.2019.03.031.

Saspiturry, S., Cochelin, B., Razin, P., Leleu, S., Lemirre, B., Bouscary, C., Issautier, B., Serrano, O., Lasseur, E., Baudin, T., and Allanic, C. 2019b. Tectono-sedimentary evolution of a rift system controlled by Permian post-orogenic extension and metamorphic core complex formation (Bidarray Basin and Ursuya dome, Western Pyrenees), Tectonophysics, Volume 768, https://doi.org/10.1016/j.tecto.2019.228180

Saspiturry, N., Razin, P., Allanic, C., Issautier, B., Baudin, T., Lasseur, E., . . Leleu, S., 2020, Closure of a hyperextended system in an orogenic lithospheric pop-up, Western Pyrenees: The role of mantle buttressing and rift structural inheritance: *Terra Nova*. https://doi.org/10.1111/ter.12457

Serrano, O., 2001, Le Crétacé supérieur- Paléogène du bassin compressif Nord-pyrénéen (Bassin de l'Adour) Sédimentologie, Stratigraphie, Géodynamique: Université Rennes 1, 342 p.

Serrano, O., J. Delmas, F. Hanot, R. Vially, J.-P. Herbin, P. Houel, and B. Tourlière, 2006, Le bassin d'Aquitaine: valorisation des données sismiques, cartographie structurale et potentiel pétrolier: Bureau de Recherche Géologique et minière, 245 p.

Sibuet, J.-C., S. P. Srivastava, and W. Spakman, 2004, Pyrenean orogeny and plate kinematics: Journal of Geophysical Research: Solid Earth, v. 109, no. B8, p. B08104, doi:10.1029/2003JB002514.

Soares, D., Alves, t., Terrinha, P, 2012,The breakup sequence and associated lithospheric breakup surface: Their significance in the context of rifted continental margins (West Iberia and Newfoundland margins, North Atlantic), Earth and Planetary Science Letters, Volumes 355–356, Pages 311-326, ISSN 0012-821X, https://doi.org/10.1016/j.epsl.2012.08.036.

Souquet, P. et al., 1985, Le groupe du Flysch noir (albo-cénomanien) dans les Pyrénées: Bull Cent. Rech Exlpo-Prod Elf-Aquitaine Pau, v. 9, p. 183–252.

Srivastava, S., Sibuet, J.-C., Cande, S., Roest, W.R. and Reid, I.R., 2000, Magnetic evidence for slow seafloor spreading during the formation of the Newfoundland and Iberian margins. Earth and Planetary Science Letters, 182: 61-76

Teixell, A., P. Labaume, and Y. Lagabrielle, 2016, The crustal evolution of the west-central Pyrenees revisited: Inferences from a new kinematic scenario: Comptes Rendus Geoscience, v. 348, no. 3–4, p. 257–267, doi:10.1016/j.crte.2015.10.010.

Thinon, I., 1999,. Structure profonde de la Marge Nord Gascogne et du Bassin Armoricain: PhD thesis, Ifremer-IUEM, Brest, France.

Thinon, I., Fidalgo-González, L., Réhault, J. P. and Olivet, J. L., 2001, Pyrenean deformations in the Bay of Biscay: Comptes Rendus de l'Académie des Sciences, Série IIa, v.332, p.561–568.

Torsvik, T., Van der Voo, R., Preeden, P., Mac Niocaill, C., Steinberger, B., Doubrovine, P., Van Hinsbergen, D., Domeier, M., Gaina, C., Tohver, E., Meert, J., McCausland, P., M. Cocks, L., 2012, Phanerozoic polar wander, palaeogeography and dynamics, Earth-Science Reviews, Volume 114, Issues 3–4, Pages 325-368, ISSN 0012-8252, https://doi.org/10.1016/j.earscirev.2012.06.007.

Tugend, J., G. Manatschal, N. J. Kusznir, E. Masini, G. Mohn, and I. Thinon, 2014, Formation and deformation of hyperextended rift systems: Insights from rift domain mapping in the Bay of Biscay-Pyrenees: Tectonics, v. 33, no. 7, p. 1239–1276, doi:10.1002/2014TC003529.

Unternehr, P., G. Peron-Pinvidic, G. Manatschal, and E. Sutra, 2010, Hyper-extended crust in the South Atlantic: in search of a model: Petroleum Geoscience, v. 16, no. 3, p. 207–215, doi:10.1144/1354-079309-904.

Van Hinsbergen, D., Torsvik, T., Schmid, S., Maţenco, L., Maffione, M., Vissers, R., Gürer, D., Spakman, W., 2020, Orogenic architecture of the Mediterranean region and kinematic reconstruction of its tectonic evolution since the Triassic, Gondwana Research, Volume 81, Pages 79-229,ISSN 1342-937X, https://doi.org/10.1016/j.gr.2019.07.009.

Vergés, J., 2003, Evolución de los sistemas de rampas oblicuas de los Pirineos meridionales: fallas del Segre y Pamplona. Boletín Geológico y Minero, 114 (1): 87-101 ISSN: 0366-0176

Vielzeuf, D. and Kornprobst, J., 1984. Crustal splitting and the emplacement of Pyrenean lherzolites and granulites. Earth Planet. Sci. Lett., 67, 87–96.

Vissers, R.L.M., Drury, M.R., Newman, J.,Fliervoet, T.F., 1997, Mylonitic deformation in upper mantle peridotites of the North Pyrenean Zone (France): implications for strength and strain localization in the lithosphere, Tectonophysics, Volume 279, Issues 1–4, ISSN 0040-1951, https://doi.org/10.1016/S0040-1951(97)00128-5.

Vissers, R.L.M., Meijer, P.Th., 2012, Mesozoic rotation of Iberia: Subduction in the Pyrenees?, Earth-Science Reviews, Volume 110, Issues 1–4, Pages 93-110, ISSN 0012-8252, https://doi.org/10.1016/j.earscirev.2011.11.001.

Vissers, R.L.M., Van Hinsbergen, D.J.J., Van der Meer, D.G., Spakman, W., 2016, Cretaceous slab break-off in the Pyrenees: Iberian plate kinematics in paleomagnetic and mantle reference frames, Gondwana Research, Volume 34, Pages 49-59, ISSN 1342-937X, https://doi.org/10.1016/j.gr.2016.03.006.

Wang, Y., 2017, High resolution imaging of lithospheric structures by full waveform inversion of short period teleseismic P waves: Université Toulouse 3 Paul Sabatier (UT3 Paul Sabatier), 244 p.

Wang, Y. et al., 2016, The deep roots of the western Pyrenees revealed by full waveform inversion of teleseismic P waves: Geology, v. 44, no. 6, p. 475–478, doi:10.1130/G37812.1.

Weissel, J. K., and G. D. Karner (1989), Flexural uplift of rift flanks due to mechanical unloading of the lithosphere during extension, J. Geophys. Res., 94(B10), 13919–13950, doi:10.1029/JB094iB10p13919.

Wernicke, B., 1985, Uniform-sense normal simple shear of the continental lithosphere: Canadian Journal of Earth Sciences, v. 22, no. 1, p. 108–125, doi:10.1139/e85-009.

Whitmarsh, R. B., and Miles, P. R. , 1995, Models of the development of the West Iberia rifted continental margin at 40°30′N deduced from surface and deep-tow magnetic anomalies, J. Geophys. Res., 100( B3), 3789– 3806, doi:10.1029/94JB02877.

Whitmarsh, R.B., Miles, P.R., Sibuet, J.-C., Louvel, V, 1996, Geological and geophysical implications of deep-tow magnetometer observations near sites 897, 898, 899, 900 and 901 on the west Iberia continental margin, in Proc. ODP, Sci. Results, pp.665–674, eds Whitmarsh, R.B., Sawyer, D.S., Klaus, A., Masson, D.G., Ocean Drilling Program, College Station, TX.

Wu, J., McClay, K., Whitehouse, P., Dooley, T., 2009. 4D Analogue modeling of transtensional pull-apart basins, Marine and Petroleum Geology, vol 26, n°8. DOI: 10.1016/j.marpetgeo.2008.06.007

Zak, I., Freund, R., 1981, Asymmetry and basin migration in the Dead Sea rift R. Freund, Z. Garfunkel (Eds.), The Dead Sea Rift, Tectonophysics, 80 (1981), pp. 27-38