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Basement-cover decoupling during the inversion of a hyperextended basin: insights from the Eastern Pyrenees

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Abstract

Deformation processes related to early stages of collisional belts, especially the inversion of rifted systems remain poorly constrained, partly because evidence of these processes is usually obliterated during the subsequent collision. The Pyrenean belt resulting from the inversion of a Cretaceous hyperextended rifted margin associated with a HT/LP metamorphism in the Internal Metamorphic Zone (IMZ), is a good example for studying the early stage of orogenic deformation. This study is focused on the Eastern Pyrenees where the relation between inverted Mesozoic rifted basins and their basement are well-preserved. By using maximum temperatures (T_{\max}) estimated by the Raman Spectroscopy of Carbonaceous Materials geothermometer and structural data, we describe the spatial distribution of the various tectono-metamorphic units. T_{\max} recorded in the sedimentary cover exposed to the north and to the south of a Paleozoic basement block (Agly massif), exceed 550°C, while the Paleozoic metasediments and their autochthonous Mesozoic cover show $T_{\max} < 350^\circ\text{C}$. The metamorphic sedimentary cover is affected by ductile deformation, while the basement is only affected by brittle deformation.

Post-metamorphism breccias are observed between the basement and the metamorphic

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sedimentary cover, which are interpreted as a decollement level in the Upper Triassic evaporites. Unlike previous models suggesting that the basement block separated two metamorphic basins (Boucheville and Bas Agly) during rifting, we propose a large displacement of a single metamorphic basin by a large thrust above the basement block. This novel interpretation emphasizes the general allochthonous position of the former hyperextended rift basin (IMZ) thrust along a decoupling layer.

1. Introduction

It is commonly accepted that the major part of collisional orogens often results from the inversion and contraction of former continental rifted margins. However, the early stages of orogenic processes, corresponding to the inversion of the rifted system, usually affected by hyperextension, remains poorly constrained. The lack of knowledge on the early orogenic processes stems from the obliteration of the hyperextended part of former rift systems, during collision, by a strong metamorphic and tectonic overprint or because this domain is now buried in the crustal root of belts. Therefore, the inherited rift-related geometries and thermal-mechanical structure of the pre-orogenic crust and lithosphere play important roles in the structural style of collisional orogens (e.g. [Lemoine et al., 1986](#); [Watts et al., 1995](#); [Mouthereau et al., 2013](#); [Jammes & Huisman, 2012](#); [Manatschal et al., 2015](#)). Reconstructing the evolution of collisional belts and especially quantifying the finite shortening requires a precise understanding of their overall structure and kinematics, including the pre-orogenic position of the thrust packages. Recent studies have shown that the occurrence of salt tectonics during the pre-orogenic period can lead to significant overestimation of finite orogenic shortening (e.g. [Jourdon et al., 2020](#); [Izquierdo-Llavall et al., 2020](#); [Labaume & Teixell, 2020](#)). The timing of deposition of weak layers (salt-bearing rocks or shales), pre-, syn- or post-rift, is thus one of the main factors that controls the overall architecture and the structural patterns of rifted basins (e.g. [Jackson and Vendeville, 1994](#); [Rowan, 2014](#); [Duretz et al., 2019](#); [Jourdon et al., 2019](#),

2020). When the decoupling layer is pre-rift, it may act as a decollement layer leading to the partitioning of the deformation between the basement and overburden units during rifting (e.g. Jammes *et al.*, 2010; Rowan, 2014; Ducoux *et al.*, 2019; Coleman *et al.*, 2019; Izquierdo-Llavall *et al.*, 2020; Labaume & Teixell, 2020). During contractional deformation, pre-rift weak layers control the geometry of the thrust belt by favoring strain propagation toward the foreland thin-skinned tectonics (e.g. Letouzey *et al.*, 1995; Jourdon *et al.*, 2020).

The Pyrenean orogen (Fig. 1) results from the inversion and integration of a Lower Cretaceous hyperextended rift system with a pre-rift Triassic evaporitic layer (Lagabriele and Bodinier, 2008; Jammes *et al.*, 2009; Lagabriele *et al.*, 2010; Clerc *et al.*, 2012, 2013; Clerc and Lagabriele, 2014; Masini *et al.*, 2014; Tugend *et al.*, 2014; Lagabriele *et al.*, 2016; Clerc *et al.*, 2016; Duretz *et al.*, 2019; Jourdon *et al.*, 2019, 2020). This crustal thinning episode was associated with a high-temperature and low-pressure (HT/LP) metamorphic event observed within narrow stripes on the south edge of North Pyrenean Zone (NPZ), forming the so-called Internal Metamorphic Zone (IMZ), where pre- to syn-rift sediments display a HT/LP metamorphism up to 600°C and below 4kbar (Bernus-Maury, 1984; Golberg and Leyreloup, 1990; Vauchez *et al.*, 2013; Clerc *et al.*, 2015). The NPZ domain is limited by major crustal faults, the North Pyrenean Frontal Thrust in the north and the North Pyrenean Fault along the southern rim, considered as a major discontinuity between two lithospheric plates and assumed to be active since the end of the Variscan orogenic cycle (Mattauer, 1968; Choukroune, 1976; Choukroune and Mattauer, 1978; Choukroune and ECORS Team, 1989).

Several studies investigated the tectonic evolution of Pyrenean belt and proposed estimates of the finite shortening based on N-S balanced geological sections (Choukroune and ECORS-Pyrenees Team, 1989; Roure *et al.*, 1989; Muñoz, 1992; Teixell, 1998; Vergés *et al.*, 2002; Martinez-Peña and Casas-Sainz, 2003; Beaumont *et al.*, 2000; Mouthereau *et al.*, 2014; Teixell *et al.*, 2016; Ternois *et al.*, 2019) but the role of decoupling layer and the early orogenic

processes were not assessed in details in these reconstructions. Only a few previous works described the early orogenic stages, suggesting the formation of an accretionary prism by the inversion of the former distal part of the rift system (Mouthereau et al., 2014; Ford et al., 2016). A recent study in the Western Pyrenees demonstrated that the early orogenic stage was associated with the inversion of the hyperextended rift system, reactivating rift-related extensional structures (Gomez-Romeu et al., 2019). In addition, the thick pre-rift Triassic evaporites, which had induced salt-tectonics during the Cretaceous rifting and gravity-driven post-rift deformation (e.g. Lopez-Mir et al., 2014; Saura et al., 2016; Teixell et al., 2016) acted as a decollement during the subsequent Pyrenean shortening (Canérot, 1988; Canérot et al., 1993; James & Canérot, 1999; Canérot, 2008; Ferrer et al., 2009; Jammes et al., 2009; 2010; Ducoux et al., 2019; Labaume & Teixell, 2020; Izquierdo-Llavall et al., 2020). The geometry of syn-rift structures is then difficult to assess because the former Cretaceous hyperextended rift basins were strongly overprinted by collisional deformation, except in the western and eastern Pyrenees. In particular, in the eastern Pyrenees, extension led to intense crustal boudinage and decoupling of the sedimentary cover from the basement (Clerc and Lagabrielle, 2014; Clerc et al., 2016). In this area, we have access to a complete section across basins which belonged to the former distal portion of the rift system, making this region a good candidate to study early orogenic processes corresponding to the inversion of the hyperextended rift basins.

By using new maximum temperature (T_{\max}) reached by sedimentary rocks and structural data, the aim of this study is to reconsider the bulk structure of the NE portion of the eastern Pyrenees and investigate the role of a pre-rift weak evaporitic layer in the partitioning of the deformation during contractional deformation. In the eastern Pyrenees, published rift restorations suggest that the Agly massif was a high separating two basins (Vauchez et al., 2013; Clerc et al., 2015; 2016; Ternois et al., 2019; Odum and Stockli, 2019); (1) the Boucheville basin sits on the rift

axis above exhumed lithospheric mantle, and (2) the Bas-Agly/St-Paul-de-Fenouillet basin sits on hyperthinned to thinned continental crust. This architecture is questionable, because it does not explain the HT/LP metamorphism observed in the present-day Bas-Agly syncline with temperatures similar to the Boucheville Basin, nor the low-temperature recorded in the St-Paul-de-Fenouillet syncline. We propose that the IMZ is allochthonous on top of the Agly North Pyrenean massif and its sedimentary cover and that the Bas-Agly syncline is a northern klippe of the IMZ. This interpretation suggests that the amount of Mesozoic sedimentary unit displacement in the eastern Pyrenees may be larger than classically proposed. In this work, we describe the succession of events that produce the present-day Pyrenean geometries, from the Late Cretaceous rifting stage to the Cenozoic main horizontal shortening, showing how the syn-rift geometry was reworked and how it controlled the finite structure of the belt.

2. Geological setting

2.1. The Pyrenean belt

The Pyrenean belt results from the collision between the Eurasian and Iberian plates from late Cretaceous to Miocene time. The present structure of the Pyrenean belt shows an asymmetric double-verging tectonic wedge above the northward underthrusting Iberian continental lithosphere (Choukroune and ECORS Team, 1989; Roure *et al.*, 1989; Muñoz, 1992; Vergés *et al.*, 1995; Teixell, 1998; Teixell *et al.*, 2016; Chevrot *et al.*, 2018). Across a maximum width of 150 km, the Pyrenees are traditionally divided into five distinct structural domains (Bertrand, 1940; Mattauer, 1968; Choukroune & Séguret, 1973; Castéras, 1974; Mattauer & Henry, 1974; Mirouse, 1980; Boillot, 1984) (Figure 1). (1) The Ebro and (2) the Aquitaine basins respectively correspond to the foreland and retro-foreland basins (e.g. Ford *et al.*, 2016; Angrand *et al.*, 2018). (3) The NPZ is a WNW-ESE elongated ribbon made of thrusts and folds deforming the Mesozoic sedimentary succession of Cretaceous basins and locally associated with basement blocks (North Pyrenean massifs). The NPZ is limited by the North Pyrenean Frontal Thrust

(NPFT) and the North Pyrenean Fault. (4) The Axial Zone, the topographic backbone of the Pyrenees, is mainly composed of Paleozoic rocks deformed during the Variscan and Alpine orogenic cycles (Mattauer, 1964; Mattauer and Seguret, 1966; Debat, 1969). Finally, (5) the South Pyrenean Zone (SPZ) consists of Mesozoic to Eocene sedimentary rocks transported southward over the Ebro basin above the South Pyrenean Frontal Thrust (SPFT) localized within the Triassic evaporites (Séguret, 1972; Vergés and Muñoz, 1990; López-Mir *et al.*, 2014).

The architecture of the Pyrenees results from the inversion and integration in the orogen of early Aptian to early Cenomanian rifted basins (Lagabriele and Bodinier, 2008; Jammes *et al.*, 2009, 2010; Lagabriele *et al.*, 2010; Clerc *et al.*, 2012, 2013; Masini *et al.*, 2014; Tugend *et al.*, 2014; Lagabriele *et al.*, 2016). Rifting has then evolved to hyperextension and mantle exhumation in the NPZ and the Basque-Cantabrian Basin as suggested by several mantle exposures, then to drifting further west in the Bay of Biscay (e.g. Fabries *et al.*, 1991, 1998; Lagabriele and Bodinier, 2008; Jammes *et al.*, 2009; Clerc *et al.*, 2012, 2013; Masini *et al.*, 2014; Tugend *et al.*, 2014; Lagabriele *et al.*, 2016). It is commonly accepted that hyperextension and mantle exhumation are responsible for a high-temperature and low-pressure (HT/LP) metamorphism (Ravier, 1959; Bernus-Maury, 1984; Azambre and Rossy, 1976; Golberg and Leyreloup, 1990; Dauteuil and Ricou, 1989; Clerc and Lagabriele, 2014; Clerc *et al.*, 2015; Ducoux, 2017; Ducoux *et al.*, 2019). This HT/LP metamorphic event affecting the southern NPZ it is mainly evidenced by marbles of the IMZ issued from pre-rift to syn-rift sediments, with peak conditions up to 600°C and below 4kbar (Bernus-Maury, 1984; Golberg and Leyreloup, 1990; Vauchez *et al.*, 2013; Clerc *et al.*, 2015). Available T_{\max} , obtained with the Raman Spectroscopy of Carbonaceous Materials (RSCM) method along the IMZ, first suggested the existence of a temperature gradient from west to east (Clerc *et al.* 2015), but more recent studies of the westernmost orogen (i.e. Basque-Cantabrian Basin) showed otherwise with equally high

maximum temperatures in the east and west (Ducoux *et al.*, 2019). Published geochronological data indicate ages ranging from Albian to Santonian (110–85 Ma) for this HT/LP metamorphic event, demonstrating a short delay (10 My) between the end of rifting event (Cenomanian) and the end of the HT/LP metamorphism (Santonian) (Albarède and Michard-Vitrac, 1978a; Albarède and Michard-Vitrac, 1978b; Montigny *et al.*, 1986; Golberg and Maluski, 1988; Golberg *et al.*, 1986; Bandet and Gourinard in Thiébaud *et al.*, 1988; Clerc *et al.*, 2015; Chelalou *et al.*, 2016).

The end of rifting was rapidly followed by the onset of convergence across the Pyrenean belt during the Late Santonian, as suggested by tectonic and sedimentological data (Garrido-Megias & Rios 1972; Muñoz, 1992; Vergés *et al.*, 1995; Teixell, 1998; Vergés & García-Senz, 2001; García-Senz 2002; McClay *et al.*, 2004; Biteau *et al.*, 2006; Mouthereau *et al.*, 2014). After a quiet tectonic period during the Paleocene (Danian to early Selandian, Ford *et al.*, 2016), the main collisional phase occurred in Eocene-Oligocene times (Muñoz 1992, 2002; Vergès *et al.* 2002; Mouthereau *et al.*, 2014), ultimately leading to the present-day structure. The collisional phase ended during the Chattian in the NPZ (Ortiz *et al.*, 2020) but remained active in the southern Pyrenees until the early Miocene (Muñoz *et al.*, 1992; Hogan and Burbank, 1996; Teixell, 1996; Millán Garrido *et al.*, 2000; Millán Garrido, 2006; Jolivet *et al.*, 2007; Oliva-Urcia *et al.*, 2015; Labaume *et al.*, 2016). Finally, after the main collisional event, since the middle Oligocene, the Eastern Pyrenees were affected by extensional deformation associated with the opening of the Valencia Trough and Gulf of Lion (e.g. Gorini *et al.*, 1993; Gorini *et al.*, 1994; Mauffret *et al.*, 1995; 2001; Roca *et al.*, 1999; Vergés and Garcia-Senz, 2001; Roca, 2001; Wehr *et al.*, 2018; Etheve *et al.*, 2018; Jolivet *et al.*, 2020).

2.2. The eastern North Pyrenean Zone

The architecture of the eastern NPZ consists of the Agly Massif, the easternmost North Pyrenean massif (Fig. 1), bounded by the Boucheville Basin to the south and the St-Paul-de-Fenouillet and Bas-Agly synclines to the north (Fig. 2). The Agly massif, which represents a condensed crustal section, is composed of plutonic and metamorphic rocks affected by a Variscan HT/LP metamorphism (granulite to greenschist facies) (Barnolas *et al.*, 1996; Guille *et al.*, 2018; Olivier *et al.*, 2008; Wickham & Oxburgh, 1986). This metamorphic event is characterized by a strong geothermal gradient, locally higher than 100°C/km (Fonteilles 1976; Vielzeuf 1984; Delay 1990, Berger *et al.*, 1993). The upper parts of the massif are composed by thick Ediacarian to Devonian metasediments and by granitoids (Fonteilles, 1970; Berger *et al.*, 1993; Casas and Palacios, 2012). The deepest parts contain thin sheets of paragneisses and orthogneisses derived from granitic sills emplaced at ca. 540 Ma (Guille *et al.*, 2019). Deformation and late Variscan HT/LP metamorphism that affect these para and ortho-derived series have been variably interpreted as distributed mylonitic shear zones during the Variscan orogeny between 305 and 296 Ma (e.g Olivier *et al.*, 2004, 2008; Wickham & Oxburgh, 1986; Vanandois *et al.*, 2020) or during a late Variscan extensional event related to a major detachment fault in the middle crust (Bouhalier *et al.*, 1991). Part of this high-strain mylonitic deformation has alternatively been attributed to the Cretaceous rifting event (Passchier, 1984; Costa and Maluski, 1988; St Blanquat *et al.*, 1990; Delay, 1990; Delay & Paquet, 1989; Paquet and Mansy, 1991; Vauchez *et al.*, 2013; Clerc *et al.*, 2016; Odlum and Stockli, 2019). Low-grade Ordovician to Devonian metasediments (mainly metapelites, shales and carbonates) compose the northeastern part of the Agly massif. They were weakly metamorphosed in the chlorite zone of the regional HT/LP metamorphism (Berger *et al.*, 1993), while high-grade gneissic and granulitic rocks are observed in the southwestern domain (Fig. 2). The Agly basement was also affected by hydrothermal alteration during the rifting episode, as revealed by 98±2 Ma albitization within the St. Arnac pluton (Poujol *et al.*, 2010). This massif is finally crosscut by

198 numerous N110°E-striking faults displaying down-dip slickenlines attributed to Pyrenean
199 collision (Olivier *et al.*, 2004).

200 The Mesozoic sedimentary sequence of the area is exposed in the St-Paul-de-Fenouillet and
201 Bas-Agly synclines, and in the Boucheville basin. It starts with unconformable continental
202 Permian to Middle Triassic deposits, only observed in the southern margin of the Mouthoumet
203 massif. These sediments are missing over the Agly massif and the northern margin of the Axial
204 Zone (Fig. 2). Shallow marine Upper Triassic sediments are carbonates, clays and evaporites
205 (Keuper facies) passing upward to Liassic to late Aptian shallow marine limestones. The Albian
206 period is then marked by the opening of the large and interconnected basins Albian to
207 Cenomanian “Flysch Noir” basin (Debroas & Souquet 1976; Debroas, 1990; Berger *et al.*,
208 1997), later dismembered during convergence and now preserved in the St-Paul-de-Fenouillet,
209 Boucheville and Bas-Agly synclines (Fig. 2). Post-rift late Cenomanian-Turonian flysch
210 deposits are transgressive on underlying older syn-rift sequences (Debroas 1990; Debroas in
211 Ternet *et al.*, 1997), and were continuously deposited until the early-Coniacian, onlapping the
212 northern part of Axial Zone and the North Pyrenean massifs (Debroas, 1987; 1990). The
213 Pyrenean convergence was responsible for the positive inversion of the rifted basins from the
214 Santonian to the Eocene (Bessière *et al.*, 1989). From Miocene to Present, the eastern part of
215 the Pyrenean range was characterized by the development of extensional structures due to the
216 opening of the Gulf of Lion (Berger *et al.*, 1993).

217 The Boucheville unit is a large synclinorium (Choukroune, 1970, Chelalou *et al.*, 2016)
218 showing evidence of early extensional ductile deformation coeval with the rifting event
219 (Chelalou *et al.*, 2016). The Boucheville syncline and the eastern part of the Agly massif are
220 separated from the Axial Zone by the sub-vertical North Pyrenean Fault (Fig. 2). To the
221 northeast of the Agly massif, the Bas-Agly syncline overthrusts the eastern part of the St-Paul-
222 de-Fenouillet syncline (Fig. 2) that is limited, to the north, by the south-dipping NPFT (Fig. 2).

The northern border of the Agly massif, corresponding to the southern Bas-Agly syncline, shows the remains of a décollement of the pre-rift cover (Durand-Delga, 1964; Légier *et al.*, 1987; Clerc and Lagabriele, 2014; Clerc *et al.*, 2016) with tectonic lineations and drag folds indicating a top to the NNE displacement (Légier *et al.*, 1987; Vauchez *et al.*, 2013). The Bas-Agly/St-Paul-de-Fenouillet and the Boucheville synclines are interpreted in most restorations, as two separate rifted basins on either side of the Agly massif, the latter corresponding to a tilted basement block (Vauchez *et al.*, 2013; Clerc *et al.*, 2015; 2016; Ternois *et al.*, 2019; Odum and Stockli, 2019). In these rift restorations, the Boucheville syncline sits on the rift axis above exhumed lithospheric mantle, while the Bas-Agly and St-Paul-de-Fenouillet synclines sit on hyperthinned to thinned continental crust.

3. Materials and Methods

To determine the distribution of the HT/LP metamorphism and then compare with the deformation pattern, we sampled 9 Mesozoic rocks of the Bas-Agly and the St-Paul-de-Fenouillet synclines for determining the maximum recorded temperatures with the RSCM method (Beyssac *et al.* 2002a; Lahfid *et al.* 2010). This data set completes the previous works focused on the HT/LP metamorphism (Clerc *et al.*, 2015; Chelalou, 2015). This analytical method allows characterizing the structural evolution of carbonaceous material (CM), reflecting a transformation from disordered to well-ordered CM during metamorphism (Wopenka and Pasteris, 1993). The relation of this increasing graphitization with temperature was quantified, leading to a tool to determine peak temperatures attained by metamorphic rocks (Beyssac *et al.*, 2002a). Since graphitization is an irreversible process, the RSCM method gives the temperature peak (Pasteris and Wopenka, 1991; Beyssac *et al.*, 2002a). This is the basis of the RSCM geothermometer, which was calibrated in the range between 330 and 650°C by Beyssac *et al.* (2002a) and extended to the range between 200 and 320°C by Lahfid *et al.* (2010). In this study, we applied these two calibrations to estimate paleotemperatures in carbonates and pelitic

metasedimentary rocks from the Paleozoic and Upper Cretaceous series of the study area. Raman analysis protocol is described in supplementary material. The entire results are presented in Table SM1 in supplementary materials and Figures 2 and 3 (T_{\max} values of this study are display in red) with the details of the data acquisition protocol.

4. Thermal pattern of the eastern NPZ

4.1. Distribution of the HT/LP metamorphism

The eastern part of NPZ has been extensively studied and numerous studies propose temperature estimates for the HT/LP Pyrenean metamorphic event with different methods including the RSCM approach (e.g Golberg, 1987; Golberg and Leyreloup, 1990; Clerc *et al.*, 2015; Chelalou, 2015; Chelalou *et al.*, 2016). The Boucheville syncline is largely affected by this HT/LP metamorphism and has recorded rather homogeneous peak temperatures comprised between 530 and 580°C (Golberg et Leyreloup, 1990; Chelalou *et al.*, 2016) (Figs. 2 and 3). Locally, near the southern edge of the basin, within pre-rift Jurassic sediments, T_{\max} are below 500°C (Chelalou *et al.*, 2016). According to Clerc *et al.* (2015), the eastern part of the Agly massif, made of Ordovician to Devonian metasediments, experienced T_{\max} 351±3°C measured in Silurian metasediments and close to the contact with the south margin of the Bas-Agly syncline (Fig. 2). Our data confirm this trend, with a T_{\max} of 351±12°C measured a few kilometers westward. This range of T_{\max} shows that the thermal event has not affected or has not exceeded 350°C in the upper part of the Agly massif.

Remnants of the metamorphic Mesozoic cover lying on the central-western part of Agly basement (Berger *et al.*, 1993; Fonteilles *et al.*, 1993), more precisely in the Serres de Verges area, correspond to Jurassic and Lower Cretaceous brecciated metasediments. We measured in this unit a T_{\max} of 424± 32°C obtained in foliated clasts (Fig. 2). This value of T_{\max} shows high-grade metamorphic conditions of the Mesozoic sedimentary cover, located above high-grade

Variscan metamorphic rocks of the Agly massif. Thus, there is no observed metamorphic gap between the breccia and the basement. Measured T_{\max} in the Mesozoic metasediments of the eastern Agly massif are instead higher than in Paleozoic rocks, the latter being only affected by low-grade metamorphism under low greenschist-facies conditions.

We measured T_{\max} higher than 550°C in the Cretaceous core of the Bas-Agly syncline. The highest T_{\max} estimated in this syncline correspond to respectively $570 \pm 27^{\circ}\text{C}$ and $566 \pm 15^{\circ}\text{C}$ in Valanginian and Aptian metacarbonates. A T_{\max} of $534 \pm 19^{\circ}\text{C}$ is recorded in black Albian marbles in the central part of the syncline (Fig. 2). In a previous study (Chelalou, 2015), a similar range of T_{\max} comprise between 530 to 559°C was characterized. In the southern Bas-Agly syncline, close to the contact with the Agly massif and documented by previous studies, T_{\max} decreases around 350°C with a local value of $494^{\circ}\text{C} \pm 7^{\circ}\text{C}$ in anhydrite-rich Upper Triassic sediments (Clerc et al., 2015). Intermediate temperatures comprised between 450 and 400°C (Golberg and Leyreloup, 1990) indicate a progressive southward decrease of metamorphic grade (Fig. 2). In the Bas-Agly, the highest temperatures are thus recorded in the central part of the syncline.

In the Albian marls of the St-Paul-de-Fenouillet syncline, we measured a local T_{\max} value of 246°C and two T_{\max} lower than 200°C. These temperatures corresponding to low-grade metamorphism, are in agreement with previous data obtained in this syncline, which are comprised between 200 and 290°C (Chelalou et al., 2016). In the eastern part of this basin, close to the contact with the Bas-Agly syncline, we also obtained T_{\max} lower than 200°C (Fig. 2) confirming that the whole basin has not been heated, which marks a major difference with both the Bas-Agly and Boucheville synclines.

A map of Cretaceous HT/LP metamorphism distribution has been interpolated from the available T_{\max} and field geological data in the eastern part of the ZNP (Fig. 3). It shows a clear

thermal contrast between the Boucheville and the Bas-Agly synclines on the one hand, and the St-Paul-de-Fenouillet syncline on the other hand. Both the Bas-Agly and Boucheville synclines show lateral temperature gradients within the sediments that cannot be attributed to differential burial. Actually, the highest temperatures are observed in the syn-rift sediments, while pre-rift sediments experienced only moderate temperatures (~400°C for the Boucheville syncline and between 350 and 400°C for Bas-Agly syncline) (Fig. 3). Consequently, HT/LP metamorphic isograds are oblique on the bedding in those basins and on different structures observed in this area. A thermal gap (>250°C) is observed across the Tautavel thrust fault bounding the Bas-Agly and St-Paul-de-Fenouillet synclines, connecting northward with the NPFT (Figs. 2 and 3).

To summarize the distribution of the thermal imprint of the Cretaceous HT/LP metamorphism, the Boucheville and Bas-Agly synclines show the highest grade of metamorphism with T_{\max} exceeding 500°C. The underlying eastern Agly massif experienced T_{\max} never exceeding 350°C, a peak-temperature colder than these two metamorphic Mesozoic synclines. Furthermore, this contrast of T_{\max} between basement and metamorphic Mesozoic sedimentary cover is attested by remnants of Mesozoic sediments located above the Agly massif, where T_{\max} exceeds 400°C. Thermal contrast is most significant between the Boucheville/Bas-Agly-synclines and the St-Paul-de-Fenouillet syncline where T_{\max} does not exceed 250°C.

4.2. Deformation of basement versus Mesozoic sedimentary cover

Below the basal contact of the Bas-Agly syncline, the north-eastern margin of the Agly massif is made of low metamorphic grade sediments (Fig. 4). Silurian sandstones and feldspathic shales that composed the Paleozoic basement of the northeastern Agly massif still show graptolites and preserved turbiditic sedimentary figures. This upper part of the basement is only affected by a series of N110°E localized metric-scale shear bands (Fig. 5), some of which corresponding to N-verging normal faults (Fig. 5a). We also observe reverse faults with a top-

to-the S sense of shear, suggested by folding and reverse offset of sandstone layers (Fig. 5b). The northeast Agly massif is thus affected by various brittle and brittle-ductile shears, but no pervasive ductile deformation is observed (Fig. 5), in agreement with the measured low T_{\max} . Our observations are in agreement with previous studies (Légier *et al.*, 1987; Vauchez *et al.*, 2013). Only the contact between low-grade metasediments and high-grade metamorphic rocks underneath are associated with ductile deformation previously attributed to the Variscan event (Berger *et al.*, 1933 and references therein).

In contrast with the Paleozoic low-grade metasediments of the Agly Massif affected by brittle deformation, the Rhaetian and Liassic sediments of the Bas-Agly syncline show an intense ductile deformation with stretching lineation and plurimetric-scale boudinage (Figs. 4 and 6), with a NNE-ward sense of shear (Vauchez *et al.*, 2013). The base of this sedimentary cover is associated to the development of north-verging recumbent metric folds as well (Fig. 6a and b). It is worth noting the presence of Upper Triassic evaporites at the base of the sedimentary pile. The contrasted deformation observed in the different units confirmed the distribution of T_{\max} with higher temperature in the cover than in the basement.

As for the Bas-Agly, this ductile deformation is also observed in the Boucheville syncline equally affected by the HT/LP metamorphism. This syncline is strongly overprinted by Pyrenean-related compressional deformation responsible for the development of N110°-striking cleavage (Fig. 4). This cleavage is coeval with the development of the main faults (as the North Pyrenean Fault) which bound the Boucheville syncline, attributed to the late convergence (Berger *et al.*, 1993). Concerning the Bas-Agly syncline, only its southern margin is folded and associated to the late subvertical cleavage. This deformation zone is located along the extension of the Latour-de-France Fault, responsible of the late thrusting of the Agly massif over the Bas-Agly. This cleavage is not clearly expressed in the rest of the Bas-Agly syncline. However, this subvertical cleavage extends into the St-Paul-de-Fenouillet syncline until the

NPFT (Fig. 4). No cleavage is observed to the north of the North Pyrenean Frontal Thrust. Only salt tectonics-related structure is preserved (Fig. 4).

The contact between the Mesozoic sediments and the crystalline/metamorphic basement (orange faults in Fig. 4) is mainly observed in the eastern Boucheville syncline and along the southern margin of the Bas-Agly syncline. This flat-lying contact is characterized by the presence of breccia recognized on the top of the Agly Massif and at the base of Jurassic series in the Bas-Agly. Furthermore, the surface of this contact is subsequently deformed and truncated by a fault (Durand-Delga, 1964). The contact between the Bas-Agly and the St-Paul-de-Fenouillet corresponds to the Tautavel fault which consist to a low angle thrust connected to the NPFT (Fig. 4).

The Boucheville and Bas-Agly syncline are always limited by tectonic contacts with the basement. On the opposite, the St-Paul-de-Fenouillet syncline is lying over the northern margin of the Agly massif without any significant deformation (Fig. 4), suggesting that it could be the autochthonous Mesozoic sedimentary cover of the Agly massif.

5. Discussion and interpretation: tectonic consequences of the IMZ thermal structure

5.1. Architecture of the eastern North Pyrenean Zone

The geological cross-sections of figure 7 show the structure of the eastern part of the IMZ and its relationships with NPZ and the Agly massif (Fig. 7). The Boucheville Basin corresponds to an asymmetric synclinorium (e.g. Choukroune, 1976; Chelalou *et al.*, 2016) bounded by two steeply-dipping major faults, including the North Pyrenean Fault to the south. These faults affect both the basement and the IMZ (Figs. 4 and 7a) and can be extended eastward within the Agly massif where they offset Variscan metamorphic isograds (Fig. 7a). These steeply-dipping faults are intersected by late normal faults linked to the formation of grabens filled by Miocene-

Quaternary sediments (Figs. 4 and 7b). Variscan structures within the Agly massif have been deformed during the Pyrenean compression, and are affected by WNW-ESE striking reverse faults (Olivier *et al.*, 2004).

West of Latour-de-France, the contact between the Bas-Agly syncline and the Agly massif is overturned and faulted (Latour-de-France Fault) while, further east, the Bas-Agly cover is flat-lying on the top of Paleozoic series with a tectonic contact (Figs. 2 and 4). The northern limb of the Bas-Agly syncline overthrusts the St-Paul-de-Fenouillet syncline through the Tautavel Fault that extends and connects with the NPFT further north (Fig. 4). West of Maury, the low-temperature Mesozoic sequence of the St-Paul-de-Fenouillet syncline, which is the cover of the Paleozoic basement of the Agly massif, is still present, only partly detached thanks to the Triassic evaporites.

Isograds of metamorphism are represented on the geological cross sections and show the distribution of HT/LP Cretaceous metamorphism in the eastern NPZ (Fig. 7). In the Boucheville Basin, temperature isograds are clearly intersected by steeply-dipping faults that bound the basin (Fig. 7a). Moreover, a large gap of temperature across the Tautavel Fault is evidenced on both cross sections (Fig. 7). Folding observed in the Mesozoic sedimentary cover results partly from the late compressional event, but some folds may result from the halokinesis active during the rifting event. Temperature isograds are overturned, intersected and shifted by late deformational structures and faults. However, the distribution of metamorphism in these synclines is rather heterogeneous and shows lateral temperature gradients within the basin. Isograds in the Bas-Agly syncline clearly intersect bedding. This observation was already made in the Western Pyrenees, especially in the Basque-Cantabrian Basin and in the Chaînons Béarnais area, where the obliquity of isotherms on the structure is due to a pre-metamorphic folding related to salt tectonics (Ducoux *et al.* 2019; Izquierdo-Llavall *et al.*, 2020).

5.2. Significance of temperature and deformation contrasts across tectonic contacts.

The central parts of the Bas-Agly and Boucheville synclines show significantly higher temperature $>450^{\circ}\text{C}$, while the St-Paul-de-Fenouillet syncline shows temperatures $<250^{\circ}\text{C}$. The temperature gap between the Bas-Agly and St-Paul-de-Fenouillet synclines is abrupt and corresponds to the Tautavel thrust fault. On the other hand, the metamorphic contrast is significant between Paleozoic shales with low-grade greenschist facies conditions (HT/LP Variscan metamorphism) of the northern Agly massif and Mesozoic sediments with higher T_{max} . Consequently, the Bas-Agly and Boucheville synclines were affected by Cretaceous HT-metamorphism, coeval with mantle exhumation, but not the overlying northern Agly massif which never experienced temperature exceeding 350°C . T_{max} measured in the Paleozoic metasediments of the northern Agly massif can either date back to the Paleozoic or to the Cretaceous rifting event, but the measured temperature shows that the basement has seen lower temperatures than the overlying cover. Note that we do not discuss here the southern part of the Agly massif where the HT/LP metamorphism has been attributed to the Variscan event (Vielzeuf and Kornprobst, 1984) or to the Cretaceous HT/LP episode (Odum and Stockli, 2019). It is commonly admitted that the regional HT/LP that affects the NPZ is coeval with the Lower Cretaceous crustal thinning event (Ravier, 1959; Bernus-Maury, 1984; Azambre and Rossy, 1976; Golberg and Leyreloup, 1990; Dauteuil and Ricou, 1989; Clerc and Lagabrielle, 2014; Clerc *et al.*, 2015). In the Boucheville synclinorium, the paleogeothermal gradient during this HT/LP metamorphic event has been estimated between 70 and $80^{\circ}\text{C}/\text{km}$ (Chelalou *et al.*, 2016). Recent low-temperature thermochronological study indicates that the Agly block cooled below 250°C during the syn- to post rifting (117-90 Ma) (Odum & Stockli, 2019; Ternois *et al.*, 2019), indicating significant lower temperatures than bounding metamorphic sedimentary basins that recorded temperatures $>500^{\circ}\text{C}$ during the post-rift period (95-90 Ma) (Clerc *et al.*,

2015) . Thus, the HT/LP metamorphism during the Cretaceous would have been confined to the southern Agly massif, like further west in the Aulus Basin for instance.

With reference to the distribution of HT-metamorphism, the deformation in the different units is also contrasted. Intense ductile deformation is observed in the Bas-Agly and Boucheville synclines that recorded the highest temperatures, while the underlying Silurian strata corresponding to Paleozoic cover of the Agly Massif, where temperature are lower, are much less deformed and certainly not mylonitized. Remnants of a Mesozoic cover are locally preserved on top of the Agly Massif, such as cataclastic breccias containing clasts of HT ductilely deformed marbles sealed by unmetamorphic cement. These observations and the temperature higher than 400°C in marble clasts in the Serre de Vergés area confirm that the breccia is a post-metamorphic event.

In previous studies, the contact between the Agly massif and the Bas-Agly syncline has been interpreted as the result of basal truncation of a detached Mesozoic cover (Durand-Delga, 1964; Légier *et al.*, 1987) and recently reinterpreted as a north-dipping extensional detachment, the Agly massif being in the position of a metamorphic core complex (Vauchez *et al.*, 2013; Clerc and Lagabriele, 2014) where extensional deformation near the contact in the Mesozoic cover would be expressed by the boudinage and drag folds (Clerc *et al.*, 2016). In this interpretation, the Bas-Agly syncline corresponds to the detached sedimentary cover of the Agly massif, decoupled via a décollement layer in Upper Triassic sediments (Vauchez *et al.*, 2013; Clerc *et al.*, 2016). EBSD and field study in carbonate layers of the base of the Bas-Agly syncline suggest that this N- to NE trending ductile shearing was developed at a temperature around 400°C (Vauchez *et al.*, 2013). In the opposite way, a recent study suggests that the Lower Cretaceous exhumation of the southern part of the Agly massif by extension was accommodated by a top-to-the south detachment (Odlum & Stockli, 2019).

The extensional model and the pre-orogenic restorations of [Vauchez et al \(2013\)](#), [Clerc et al. \(2016\)](#) and more recently the crustal-scale model of [Ternois et al. \(2019\)](#) and [Odum & Stockli \(2019\)](#) do not easily explain the thermal imprint measured in the central part of the Bas-Agly syncline. In particular they do not explain the higher T_{\max} measured in the Bas-Agly syncline. [Figure 8](#) shows two typical situations of a metamorphic core complex and a thrust in terms of deformation and thermal structure. First of all the contrast in T_{\max} is the opposite in the two situations. A detachment with a significant displacement will inevitably lead to cold (superficial) over hot (deep) units, while a thrust will show the opposite arrangement ([Fig. 8a](#)). Then, all detachments show a continuum of ductile-to-brittle deformation within a distinct shear zone that is mostly observed in the lower plate, below the detachment ([Crittenden et al., 1980](#); [Davis and Lister, 1988](#)) and the lower plate display more ductile deformation while the upper plate shows mostly brittle deformation, which is the exact opposite to what is observed in the study area. The deformation observed in the Paleozoic sediments of the top of the Agly massif is weak and certainly does not correspond to a major shear zone.

Then the question arises about the significance of the observed ductile deformation at the base of the Bas-Agly syncline. The N-NE trend of stretching lineations and calcite fabrics near the base of the Bas-Agly syncline described by [Vauchez et al. \(2013\)](#) attests for a northward displacement of the metamorphic unit corresponding to the current Bas-Agly syncline, but it does not prove that it corresponds to an extensional deformation. Here, the large thermal contrast between the hot metamorphic Mesozoic cover and the colder Paleozoic basement underneath is opposite and thus more compatible with a thrust than a detachment ([Fig. 8b](#)).

Finally, models proposed by [Vauchez et al \(2013\)](#), [Clerc et al. \(2016\)](#), [Ternois et al. \(2019\)](#) and [Odum & Stockli \(2019\)](#) describe the Boucheville and Bas-Agly synclines as two narrow disconnected basins on either side of the Agly basement massif, but this assumption conflicts with sedimentological observations indicating that Aptian, Albian and Lower Cretaceous

pelagic sediments (corresponding to “Flysch noirs”) were likely deposited in a unique large basin and not in two narrow separated basins (Olivier, 2013).

The main question then concerns the link between the Mesozoic sedimentary cover and Paleozoic rocks of the Agly massif. A section along the northern margin of the Agly massif further west, near Maury, shows that the St-Paul-de-Fenouillet syncline is the poorly metamorphosed Mesozoic cover of the Agly Paleozoic basement, in agreement with the low temperatures observed in the St-Paul-de-Fenouillet Basin. When moving east, this sedimentary cover is substituted by the Bas-Agly syncline that is more intensely metamorphosed and the contact between the St-Paul-de-Fenouillet syncline and the Bas-Agly corresponds to a well-characterized thrust that connects to the north with the North Pyrenean Frontal thrust. Then, two hypotheses can be proposed: (1) the Bas-Agly syncline may be the eastern equivalent of the St-Paul-de-Fenouillet Basin with a higher metamorphic grade and the two basins were carried along the basal decollement in Upper Triassic evaporites until they got into close contact; (2) alternatively, the Bas-Agly syncline may be the western termination of a rift segment developing eastward, if we consider the eastern termination of Pyrenees as a relay or accommodation zone where the rift axes are shifted. The Boucheville and Bas-Agly synclines may corresponded to V-shaped terminations of two rifted basins, as the western Pyrenees for instance (e.g. Lescoutre & Manatschal, 2020); (3) the Bas-Agly syncline is not the cover of the Agly massif and corresponds instead to a displaced outlier of a more internal and hotter unit where high temperature is due to mantle exhumation as elsewhere in the NPZ.

By combining structural observations and new T_{\max} dataset we then propose an alternative interpretation whereby the Bas-Agly syncline corresponds to a northern klippe of the Boucheville Basin thrust over the Agly massif and a part of St-Paul-de-Fenouillet during the Pyrenean shortening. In this interpretation, the Bas-Agly would connect above the Agly massif with the more internal Boucheville syncline, where high temperatures are recorded.

The top-north detachment described by [Vauchez et al. \(2013\)](#) in the northeastern part of the Agly Massif is then reinterpreted as a top-to-the north thrust instead, assisted by regional-scale well known Upper Triassic evaporites layer. This interpretation explains the distribution of metamorphism, the observed temperature contrasts recorded within the different synclines and the distribution of deformation.

5.3 A 2D crustal-scale geodynamic model

[Figure 9](#) presents a basin-scale restoration model showing a possible evolution of the eastern end of the NPZ from the rifting stage to the end of the Pyrenean orogeny. Based on the model of [Ternois et al. \(2019\)](#) for the crustal architecture, we propose a different interpretation for the sedimentary cover, in which the Bas-Agly syncline represents an allochthonous unit initially connected with the Boucheville syncline above a body of exhumed mantle during the Cretaceous rifting, where both formed a single basin and then transported northward by a thrust. The first step represents the rift template before the onset of the convergence during the Santonian with the inversion of the hyperextended rifted margins formed a span of 30 Myrs between early Aptian to early Cenomanian stages ([Fig. 9a](#)). Rifting was associated to hyperthinning of the lithosphere accommodated by the development of a large-scale top-to-the-south detachment fault located at the base of the basin which induced mantle exhumation and HT/LP metamorphism in the pre- and syn-rift sediments. Such model of crustal boudinage was already proposed by [Clerc et al. \(2016\)](#), but we show here that the northern side of the Agly massif was not affected by ductile deformation during rifting. On the opposite, the Cretaceous basin was affected by intense ductile deformation during this episode, especially in the northern part of the Boucheville Basin ([Chelalou et al., 2016](#)). The syn-rift geometry supposes that the Boucheville, Bas-Agly and St-Paul-de-Fenouillet basins are connected and are filled mainly by Albian-Cenomanian deposits. The Agly massif represents a paleo-topographic high, but it was never significantly eroded before the Late Cretaceous, because there is no evidence of Paleozoic

clasts in Aptian to Cenomanian deposits (Olivier *et al.*, 2013). It is only covered by a thin succession of syn-rift sediment (Fig. 9a). We suggest that the Agly massif separates two basins probably interconnected laterally farther west and probably farther east. There is no argument to bury the Agly paleo-high beneath a thick pile of syn-rift sediments. On the contrary, there is a possibility that this paleo-high was only buried beneath post-rift successions. This assumption is supported by recent thermochronological data (Odlum & Stockli, 2019; Ternois *et al.*, 2019). The eastern NPZ consist in rift and salt architecture with salt pillows, diapirs and raft of the syn-rift sediment further north, driven by gravity gliding of the Mesozoic cover. In this model, syn-rift sediments were deposited over the pre-rift sediments that experienced gravity gliding and were juxtaposed above exhumed mantle and a thin continental crust corresponding to the future Boucheville and Bas-Agly basins where HT/LP metamorphism developed (Fig. 9a). We assume a juxtaposition of pre- and syn-rift sediments and exhumed mantle; but we cannot exclude the possibility that the Mesozoic basin was sitting on a very thin continental crust and not directly on the exhumed mantle, because there is no evidence of mantle clast and/or volcanism in this area. During the onset of convergence, the hyperextended domain is firstly reactivated and inverted up to collision of both margins Gómez-Romeu *et al.* (2019).

The second step corresponds to the Late Cretaceous convergence with the inversion of the two hyper-extended margins after underthrusting of the exhumed mantle and reactivation of the necking domain associated to the development of the south-verging thrusts located in the Axial Zone and the NPFT (Fig. 9b). A major thin-skinned flat-lying thrust rooted in the Upper Triassic decollement level allowed the northward displacement of the metamorphic part of the basin on top of the St-Paul-de-Fenouillet Basin that recorded only low-grade metamorphism. We hypothesize that the inherited detachment at the base of the basin associated to the decollement layer has been reactivated as a thrust. Early salt pillows and diapirs could be responsible for the localization of the major thin-skinned thrust, corresponding to the current Tautavel fault. In

addition, this thrust is probably responsible for the development of breccias at the base of the pre-rift cover. Indeed, these breccias may be a witness of the decollement level localized between the basement and the Mesozoic sedimentary cover (Clerc *et al.*, 2016). It is more difficult to estimate the amount and the direction of this general displacement. The displacement and the thermal contrast seem to decrease toward the east, and Bas-Agly syncline seems to be interconnected with the St-Paul-de-Fenouillet syncline. It may be possible that the deformation softened eastward, especially as this area corresponding to a well-known transfer zone corresponding to the Corbières virgation (Tugend *et al.*, 2014). In the rest of the Pyrenees, the IMZ where higher T_{\max} are recorded, is always interconnected with non-metamorphic basins to the north where North Pyrenean massifs are missing or not outcropping (Clerc *et al.*, 2015). Recent study indicates that the thermal imprint of the metamorphism gently decreases when moving away from the former distal part of the rift system (Ducoux *et al.*, 2019).

The Paleocene corresponds to a period of tectonic quiescence, the convergence rate strongly decreasing (Desegaulx and Brunet, 1990; Ford *et al.*, 2016; Rougier *et al.*, 2016; Machiavelli *et al.*, 2017; Grool *et al.*, 2018; Dielforder *et al.*, 2019; Ternois *et al.*, 2019), as emphasized by the absence of cooling at that age in the Agly blocks (Ternois *et al.*, 2019) and by a minimal deposition of clastic sediments in the Aquitaine retro-foreland basin (Desegaulx and Brunet, 1990, Ford *et al.*, 2016). This tectonic quiescence could be attributed to the transition period between the closure and inversion of both hyperextended domain and the beginning of crustal thickening related to the collision strictly speaking.

The third step corresponds to the onset of the main collision phase and the beginning of crustal thickening involving thick-skinned tectonic style and the development of crustal-scale thrust faults in the pro-wedge domain (Ternois *et al.*, 2019) (Fig. 9c). A major part of the deformation is then accommodated within the basement by the reactivation of former normal faults in the retro-wedge and by the neoformation of thrusts in the pro-wedge. The progressive crustal

thickening is responsible for basement exhumation, especially the Agly massif and sedimentary cover as well (Fig. 9c). Recent thermochronological data indeed indicate a rapid exhumation of the Agly massif near the surface during the Eocene, while the NPZ continues to shorten and deformation migrates northward (Ternois *et al.*, 2019). These recent data are in agreement with other published thermochronological data which consistently suggest such a timing: 49 ± 4 to 35 ± 3 Ma in Mauléon Basin (Western Pyrenees) (Vacherat *et al.*, 2014); 50 to 35 Ma for North Pyrenean massifs in the central Pyrenees (Vacherat *et al.*, 2016); 44 to 35 Ma in the Axial Zone (Fitzgerald *et al.*, 1999). In our model, the exhumation of the Agly block along the main thrust caused a shift of the primary thrust (i.e. Tautavel fault, Figs. 2, 4 and 6), and a folding of the Mesozoic cover that generated the current shape of the Bas-Agly syncline.

The last step corresponds to the end of collision with nappe stacking of the Axial Zone (Fig. 9d). The shortening is mainly localized on the future SPFT at depth and on the NPFT. From the middle Eocene to the early Oligocene, the Axial Zone records higher exhumation rates (Whitchurch *et al.*, 2011; Rushlow *et al.*, 2013; Mouthereau *et al.*, 2014; Bosch *et al.*, 2016; Labaume *et al.*, 2016), while the exhumation of the Agly massif ceases (Gunnell *et al.*, 2009; Ternois *et al.*, 2019). The NPZ is finally tilted and uplifted by the exhumation of the Axial Zone related to crustal stacking. Consequently, the Boucheville and Bas-Agly synclines are now separated by the Agly Massif (Fig. 9d). Only small remnants of sedimentary cover are observed on the top of Agly massif. In this configuration, the North Pyrenean Fault corresponds to an inherited structure related to the rifting event and was only reactivated as a reverse fault during the end of collision. The main part of the deformation was accommodated by thick-skinned deformation expressed by the stacking of basement nappes, corresponding to the present-day Axial Zone. Thin-skinned deformation of the sedimentary cover was accommodated by the Upper Triassic decoupling layer. Consequently, the distribution of the deformation is drastically different between the basement and the sedimentary cover when an efficient decoupling layer

is present (e.g. [Jammes et al., 2010](#); [Jourdon et al., 2020](#)). The presence of the Triassic evaporite layer thus has considerably impacted the tectonic history of the eastern Pyrenees. First during the rifting stage and then during the Pyrenean shortening.

After the main collision, the eastern Pyrenees was affected by normal faults associated with the opening of Valencia Trough since the middle Oligocene (e.g. [Roca et al., 1999](#); [Roca, 2001](#); [Etheve et al., 2018](#); [Jolivet et al., 2020](#)).

5.4 Rift inheritances control the finite orogenic architecture

Classical models describing the geodynamic evolution of the Pyrenean range do not address the early convergence and the onset of the collision of the two hyper-extended margins. Before the two last decades, the Pyrenean rift was described as a narrow rift and hyperextension and mantle exhumation were thus not considered in geodynamic models (e.g. [Choukroune et al., 1990](#); [Munoz, 1992](#); [Beaumont et al., 2000](#); [Canérot, 2016](#)). Some recent models suggested that the distal part of the rift system, corresponding to deep basins sitting on the exhumed mantle, formed an accretionary prism during the subsequent early inversion (e.g. [Mouthereau et al., 2014](#); [Ford et al., 2016](#)). The early convergence setting is characterized by thin-skinned tectonics in the sedimentary pile which corresponded to the former hyperextended domain (mantle exhumation) ([Fig. 9](#)). A decollement propagates at the interface between Mesozoic sediments and the basement (Paleozoic rocks and subcontinental mantle) within the Upper Triassic evaporites. We further suggest that most of the distal rifted basin is transported over the former necking domain along the former Cretaceous south-dipping detachment ([Fig. 9](#)). This tectonic process is in agreement with recent studies promoting large displacements of rifted basins along inherited decoupling layer ([Gomez-Romeu et al., 2019](#); [Labaume & Teixell, 2020](#)). Rift-related inheritances (crustal structures and rheology) may fundamentally control the development and the finite structure of orogens by controlling the depth of the decoupling layer and its propagation (e.g., [Tugend et al., 2014](#); [Lacombe & Bellahsen, 2016](#); [Gomez-Romeu et](#)

al., 2019; Tavani et al., 2020; Lescoutre & Manatschal, 2020). Inversion of the hyperextended domains depends of the depth of the efficient decoupling layer. The positioning of the decoupling layer is variable and can be located at the interface between the basement and the sedimentary units (e.g. Bellahsen et al., 2012; Muñoz et al., 2013; this study) or in the serpentinized exhumed mantle which corresponds to the weakest part of rifted margins (Pérez-Gussinyé et al., 2001; Péron-Pinvidic et al., 2008), where deformation may preferentially initiate during the contractional deformation (Péron-Pinvidic et al., 2008; Lundin and Doré, 2011; Tugend et al., 2014 and 2015a; Gomez-Romeu et al., 2019). In the necking and proximal domains, the continental crust is thicker, and the decoupling layer consequently develops in the middle-lower crust (e.g. Pfiffner, 2017; Jourdon et al., 2019; Tavani et al., 2020). Therefore, during contractional deformation thick-skinned tectonics is prevailing, and inherited rift-related crustal structures may be reactivated (e.g. Froitzheim et al., 1988; Letouzey, 1990; Mitra et Mount, 1998; Brown et al., 1999; Domènech et al., 2016) or intersected by syn-tectonic structures (e.g. Bellahsen et al., 2012 ; Bellanger et al., 2014; Branellec et al., 2016). The tectonic history of the eastern Pyrenees as discussed in this paper thus shows the succession of two periods of the contractional deformation that led to the full inversion of the rifted margins. Other sections, further west, except for the Basque-Cantabrian basin with the Nappe des Marbres (Ducoux et al. 2019; Lescoutre and Manatschal, 2020), show a narrower IMZ where most units are pinched and vertical, thus obliterating the details of the shortening history. The Agly section and the Nappe des Marbres sections are thus key to unravel the early stages of the Pyrenean shortening with two stages, a first thin-skinned episode with decollement of the basin above the Triassic evaporites and a second thick-skinned episode leading to the present-day structure.

Conclusions

The eastern North Pyrenean Zone is thus an ideal locality to study the tectonic inversion and integration of hyperextended rifted system (Internal Metamorphic Zone), associated with a pre-rift decoupling layer, in an orogenic belt. By applying structural data and measured maximum temperatures (T_{\max}) estimated with the Raman Spectroscopy of Carbonaceous Materials (RSCM) method, we show that a pre-kinematic decoupling layer has strongly impacted the architecture of the Pyrenean belt, as well as the disposition of its sedimentary basins.

Concerning the thermal pattern, the Agly massif corresponded to a basement block separating two metamorphic areas, the Boucheville syncline to the south and the Bas-Agly syncline to the north. The Bas-Agly and Boucheville synclines are both affected by the Cretaceous HT/LP metamorphism with T_{\max} exceeding 550°C. Remnants of Mesozoic sediments observed on top of the Agly massif is also affected by the HT/LP Pyrenean metamorphism with temperature higher than 400°C but lower than in the Bas Agly syncline. A strong thermal contrast exists between the Bas-Agly/Boucheville synclines and the St-Paul-de-Fenouillet syncline located to the north. A thermal gap is also observed between Bas-Agly/Boucheville synclines and the northeastern part of the Agly massif.

Structural observations confirm the T_{\max} distribution measured in the Agly massif and Bas-Agly syncline. The northeast part of the Agly massif composed by Silurian to Devonian shales exposed various brittle and brittle-ductile shears without no pervasive ductile deformation, while the Mesozoic sediments of the Bas-Agly syncline show an intense ductile deformation with metric-scale boudinage and recumbent metric folds.

To explain thermal and structural gaps and the similarities between the Boucheville and Bas-Agly synclines, we propose that the Bas-Agly syncline may correspond to an allochthonous unit thrust northward on top of the Agly massif and the St-Paul-de-Fenouillet syncline during early stages of horizontal shortening (thin-skinned tectonics). The pre-orogenic Upper Triassic

evaporites decoupling layer and the low-angle normal faults inherited from the early Cretaceous rifting allowed the transport of the Mesozoic cover above a north-verging thrust and the substitution of the normal cover of the Agly massif by the metamorphic Bas-Agly syncline. Consequently, the Boucheville and Bas-Agly basins were initially parts of a single basin during the hyperextension rifting phase.

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References

- Angrand, P., Ford, M., & Watts, A. B. (2018). Lateral variations in foreland flexure of a rifted continental margin: The Aquitaine Basin (SW France). *Tectonics*, 37(2), 430-449.
- Azambre, B., Rossy, M., 1976. Le magmatisme alcalin d'âge crétacé, dans les Pyrénées occidentales et l'Arc basque; ses relations avec le métamorphisme et la tectonique. *Bull. Soc. Geol. Fr.* S7–XVIII, 1725–1728. doi:10.2113/gssgfbull.S7-XVIII.6.1725
- Barnolas, A., Chiron, J. C., & Guérangé, B. (Eds.) (1996). *Synthèse géologique et géophysique des Pyrénées: géophysique: cycle hercynien*. Orléans, France: BRGM.

- 692 Beaumont, C., J. A. Muñoz, J. Hamilton, and P. Fullsack (2000), Factors controlling the Alpine
693 evolution of the central Pyrenees inferred from a comparison of observations and
694 geodynamical models, *J. Geophys. Res.*, 105(B4), 8121–8145,
695 doi:10.1029/1999JB900390.
- 696 Bellahsen, N., Jolivet, L., Lacombe, O., Bellanger, M., Boutoux, A., Garcia, S., Mouthereau,
697 F., Le Pourhiet, L., Gumiaux, C., 2012. Mechanisms of margin inversion in the external
698 Western Alps; implications for crustal rheology. *Tectonophysics* 560–561, 62–83.
699 doi:10.1016/j.tecto.2012.06.022
- 700 Bellanger, M., Bellahsen, N., Jolivet, L., Baudin, T., Augier, R., Boutoux, A., 2014. Basement
701 shear zones development and shortening kinematics in the Ecrins Massif, Western Alps.
702 *Tectonics* 33, 84–111. doi:10.1002/2013TC003294
- 703 Berger, G.M., Bessière, G., Bilotte, M., Viallard, P., 1997. Carte géologique de la France (1/50
704 000), feuille Tuchan (1078), Bureau de recherches géologiques et minières, Orléans.
- 705 Berger, G.M., Fontelles, M., Leblanc, D., Clauzon, G., Marchal, J.-P., Vautrelle C., 1993.
706 Notice explicative de la carte géologique de la France au 1/50.000, feuille de Rivesaltes
707 (1090), 119 pp., BRGM, Orléans.
- 708 Bernus-Maury, C., 1984. Etude des paragenèses caractéristiques du métamorphisme
709 mésozoïque dans la partie orientale des Pyrénées (French). Paris 6.
- 710 Bessière, G., Bilotte, M., Crochet, B., Peybernès, B., Tambareau, Y., Villate, J., 1989. Notice
711 explicative de la carte géologique de la France au 1/50.000, feuille de Quillan (1077),
712 98 pp., BRGM, Orléans.
- 713 Beyssac, O., Goffé, B., Chopin, C., Rouzaud, J.N., 2002. Raman spectra of carbonaceous
714 material in metasediments: a new geothermometer. *J. Metamorph. Geol.* 20, 859–871.
715 doi:10.1046/j.1525-1314.2002.00408.x
- 716 Beyssac, O., Rouzaud, J.-N., Goffé, B., Brunet, F., Chopin, C., 2002. Graphitization in a high-
717 pressure, low-temperature metamorphic gradient: a Raman microspectroscopy and
718 HRTEM study. *Contrib. Mineral. Petrol.* 143, 19.
- 719 Bles, J.L., Berger, G.M., 1982. Carte géologique de la France (1/50 000), feuille Leucate
720 (1079), Bureau de recherches géologiques et minières, Orléans.
- 721 Bosch, G., Teixell, A., Jolivet, M., Labaume, P., Stockli, D., Domènech, M., & Monié, P.
722 (2016). Timing of Eocene–Miocene thrust activity in the Western Axial Zone and
723 Chaînons Béarnais (west-Central Pyrenees) revealed by multi-method
724 thermochronology. *Comptes Rendus Geoscience*, 348(3–4), 246–256.
725 <https://doi.org/10.1016/j.crte.2016.01.001>
- 726 Bouhallier, H., Choukroune, P., Balleve, M., 1991. Evolution structurale de la croûte profonde
727 hercynienne : exemple du massif de l'Agly (pyrenees orientales, france). *Comptes*
728 *Rendus Académie Sci. Sér. 2 Mécanique Phys. Chim. Sci. Univers Sci. Terre* 312, 647–
729 654.
- 730 Branellec, M., Niviere, B., Callot, J. P., & Ringenbach, J. C. (2016). Mechanisms of basin
731 contraction and reactivation in the basement-involved Malargüe fold-and-thrust belt,
732 Central Andes (34–36 S). *Geological Magazine*, 153(5-6), 926-944.
- 733 Brown, D., Alvarez-Marron, J., Perez-Estaun, A., Puchkov, V., Ayala, C., 1999. Basement
734 influence on foreland thrust and fold belt development; an example from the Southern
735 Urals. *Tectonophysics* 308, 459–472.

- 736 Canérot, J., 2016. The Iberian Plate: myth or reality? *Bol. Geológico Min.* 127, 563–574.
- 737 Canérot, J., 2008. Les Pyrénées: histoire géologique et itinéraires de découvertes, Atlantica-
738 BRGM éditions. ed.
- 739 Canérot, J., 1988. Manifestations de l'halocinèse dans les chaînons béarnais (zone Nord-
740 Pyrénéenne) au Crétacé inférieur. *Comptes Rendus Académie Sci. Sér. 2 Mécanique*
741 *Phys. Chim. Sci. Univers Sci. Terre* 306, 1099–1102.
- 742 Canérot, J., Lenoble, J.L., 1993. Diapirisme cretace sur la marge iberique des Pyrenees
743 occidentales; exemple du pic de Lauriolle; comparaisons avec l'Aquitaine, les Pyrenees
744 centrales et orientales. *Bull. Société Géologique Fr.* 164, 719–726.
- 745 Casas, J. M., & Palacios, T. (2012). First biostratigraphical constraints on the pre-Upper
746 Ordovician sequences of the Pyrenees based on organic-walled microfossils. *Comptes*
747 *Rendus Geoscience*, 344(1), 50-56.
- 748 Chelalou, R., 2015. Formation et évolution du bassin de Boucheville, implication sur
749 l'évolution tectonique, métamorphique et sédimentaire des bassins sédimentaires
750 mésozoïques du Nord-Est des Pyrénées (phdthesis). Université Rennes 1.
- 751 Chelalou, R., Nalpas, T., Bousquet, R., Prevost, M., Lahfid, A., Pujol, M., Ringenbach, J.-C.,
752 Ballard, J.-F., 2016. New sedimentological, structural and paleo-thermicity data in the
753 Boucheville Basin (eastern North Pyrenean Zone, France). *Comptes Rendus -*
754 *Géoscience* 348, 312–321. doi:10.1016/j.crte.2015.11.008
- 755 Chevrot, S., Sylvander, M., Diaz, J., Martin, R., Mouthereau, F., Manatschal, G., ... & Ruiz, M.
756 (2018). The non-cylindrical crustal architecture of the Pyrenees. *Scientific reports*, 8(1),
757 1-8.
- 758 Choukroune, P., 1976. Structure et évolution tectonique de la zone nord-pyrénéenne: analyse
759 de la déformation dans une portion de chaîne à schistosité sub-verticale. Société
760 géologique de France, Paris.
- 761 Choukroune, P., 1970. Contribution a l'étude structurale de la zone metamorphique nord-
762 pyreneenne; tectonique et metamorphisme des formations secondaires de la foret de
763 Boucheville (P.-O.); feuille au 1/50 000 Saint-Paul-de-Fenouillet. *Struct. Metamorp* 4,
764 49–63.
- 765 Choukroune, P., ECORS Team, 1989. The ECORS Pyrenean deep seismic profile reflection
766 data and the overall structure of an orogenic belt. *Tectonics* 8, 23–39.
- 767 Choukroune, P., Pinet, B., Roure, F., Cazes, M., 1990a. Major Hercynian thrusts along the
768 ECORS Pyrenees and Biscay lines. *Bull. Soc. Geol. Fr.* 6, 313–320.
- 769 Choukroune, P., Mattauer, M., 1978. Tectonique des plaques et Pyrenees: sur le fonctionnement
770 de la faille transformante nord-pyreneenne; comparaisons avec des modeles actuels.
771 *Plate Tecton. Pyrenees Action North. Pyrenean Transform Fault Comp.* 20, 689–700.
- 772 Clerc, C., Boulvais, P., Lagabrielle, Y., de St Blanquat, M., 2013. Ophicalcites from the
773 northern Pyrenean belt: a field, petrographic and stable isotope study. *Int. J. Earth Sci.*
774 103, 141–163. doi:10.1007/s00531-013-0927-z
- 775 Clerc, C., Lagabrielle, Y., 2014. Thermal control on the modes of crustal thinning leading to
776 mantle exhumation: Insights from the Cretaceous Pyrenean hot paleomargins. *Tectonics*
777 33, 2013TC003471. doi:10.1002/2013TC003471
- 778 Clerc, C., Lagabrielle, Y., Labaume, P., Ringenbach, J.-C., Vauchez, A., Nalpas, T., Bousquet,
779 R., Ballard, J.-F., Lahfid, A., Fourcade, S., 2016. Basement – Cover decoupling and

- 780 progressive exhumation of metamorphic sediments at hot rifted margin. Insights from
781 the Northeastern Pyrenean analog. *Tectonophysics* 686, 82–97.
782 doi:10.1016/j.tecto.2016.07.022
- 783 Clerc, C., Lagabriele, Y., Neumaier, M., Reynaud, J.-Y., de Saint Blanquat, M., 2012.
784 Exhumation of subcontinental mantle rocks: evidence from ultramafic-bearing clastic
785 deposits nearby the Lherz peridotite body, French Pyrenees. *Bull. Soc. Geol. Fr.* 183,
786 443–459.
- 787 Clerc, C., Lahfid, A., Monie, P., Lagabriele, Y., Chopin, C., Poujol, M., Boulvais, P.,
788 Ringenbach, J.-C., Masini, E., de St Blanquat, M., 2015. High-temperature
789 metamorphism during extreme thinning of the continental crust: a reappraisal of the
790 North Pyrenean passive paleomargin. *Solid Earth* 6, 643–668. doi:10.5194/se-6-643-
791 2015
- 792 Costa, S., Maluski, H., 1988. Use of the ^{40}Ar - ^{39}Ar stepwise heating method for dating
793 mylonite zones: An example from the St. Barthélemy massif (Northern Pyrenees,
794 France). *Chem. Geol. Isot. Geosci. Sect.* 72, 127–144. doi:10.1016/0168-
795 9622(88)90061-9
- 796 Coleman, A. J., Duffy, O. B., & Jackson, C. A. L., 2019, Growth folds above propagating
797 normal faults. *Earth-Science Reviews*, 102885.
- 798 Crittenden, M.D., Coney, P.J., Davis, G.H., 1980. Cordilleran metamorphic core complexes.
799 *Geol. Soc. Am.* 490.
- 800 Crochet, B., Villate, J., Tambareau, Y., Bilotte, M., Bousquet, J.-P., Kuhfuss, A., Bouillin, J.-
801 P., Gélard, J.-P., Bessière, G., Paris, J.-P., 1989. Carte géologique de la France (1/50
802 000), feuille Quillan (1077), Bureau de recherches géologiques et minières, Orléans.
- 803 Dauteuil, O., Ricou, L.E., 1989. Une circulation de fluides de haute-temperature a l'origine du
804 métamorphisme crétacé nord-pyrénéen. *Circ. High-Temp. Fluids Orig. North Pyrenean*
805 *Cretac. Metamorph.* 3, 237–250.
- 806 Davis, G.A., Lister, G.S., 1988. Detachment faulting in continental extension; Perspectives
807 from the Southwestern U.S. Cordillera. *Geol. Soc. Am. Spec. Pap.* 218, 133–160.
808 doi:10.1130/SPE218-p133
- 809 De Saint Blanquat, M., Lardeaux, J.M., Brunel, M., 1990. Petrological arguments for high-
810 temperature extensional deformation in the Pyrenean Variscan crust (Saint Barthélémy
811 massif, Ariège, France). *Tectonophysics* 177, 245–262. doi:10.1016/0040-
812 1951(90)90284-F
- 813 Debroas, E.J., 1990. Le flysch noir albo-cénomane témoin de la structuration albienne a
814 senonienne de la Zone nord-pyrénéenne en Bigorre (Hautes-Pyrénées, France). *Bull.*
815 *Société Géologique Fr.* 6, 273–285.
- 816 Debroas, E.J., 1987. Le flysch à fucoides d'Uchentein témoin d'un escarpement turono-
817 senonien inférieur de la paleofaïlle nord-pyrénéenne, Pyrénées centrales, France.
818 *Fucoidal Flysch Uchentein Indic. Turonian-Low. Senonian Escarpment.* Of 3, 77–93.
- 819 Delay, F. (1990). Etude structurale du massif de l'Agly (Pyrénées orientales). *Mémoires de la*
820 *Société Géologique du Nord*, 17.
- 821 Delay, F., & Paquet, J. (1989). Tectonique ductile en extension dans le massif hercynien de
822 l'Agly (zone nord-pyrénéenne): *Comptes Rendus de l'Académie des Sciences* (Vol.
823 308, pp. 1637–1643).

- 824 Desegaulx, P., & Brunet, M. F. (1990). Tectonic subsidence of the Aquitaine basin since
825 Cretaceous times. *Bulletin de la Société géologique de France*, 8, 295-306.
- 826 Domènech, M., Teixell, A., Stockli, D.F., 2016. Magnitude of rift-related burial and orogenic
827 contraction in the Marrakech High Atlas revealed by zircon (U-Th)/He
828 thermochronology and thermal modeling. *Tectonics* 35, 2016TC004283.
829 doi:10.1002/2016TC004283
- 830 Ducoux, M. (2017). Structure, thermicité et évolution géodynamique de la Zone Interne
831 Métamorphique des Pyrénées (Doctoral dissertation).
- 832 Ducoux, Maxime; Jolivet, Laurent (2021): Peak metamorphic temperatures (Tmax) from the
833 eastern Pyrenees. PANGAEA, <https://doi.pangaea.de/10.1594/PANGAEA.930199>
834 (DOI registration in progress)
- 835 Ducoux, M., Jolivet, L., Callot, J-P., Aubourg, C., Masini, E., Lahfid, A., Homonnay, E.,
836 Cagnard, F., Gumiaux, C., & Baudin, T., 2019. The Nappe des Marbres unit of the
837 Basque-Cantabrian Basin: the tectono-thermal evolution of a fossil hyperextended rift
838 basin. *Tectonics*, ...
- 839 Durand-Delga, M., 1964. Remarques sur la stratigraphie et la structure du Mésozoïque situé
840 entre Estagel et Perpignan (Pyrénées-Orientales). *C. R. Acad. Sci. Paris* 259, 837–840.
- 841 Duretz, T., Asti, R., Lagabriele, Y., Brun, J. P., Jourdon, A., Clerc, C., & Corre, B. (2019).
842 Numerical modelling of Cretaceous Pyrenean Rifting: The interaction between mantle
843 exhumation and syn - rift salt tectonics. *Basin Research*.
- 844 Etheve, N., Mohn, G., Frizon de Lamotte, D., Roca, E., Tugend, J., & Gómez-Romeu, J., 2018.
845 Extreme Mesozoic Crustal Thinning in the Eastern Iberia Margin: The Example of the
846 Columbrets Basin (Valencia Trough). *Tectonics*, 37(2), 636-662.
- 847 Ferrer, O., Roca, E., Jackson, M.P.A., Muñoz, J.A., 2009. Effects of Pyrenean contraction on
848 salt structures of the offshore Parentis Basin (Bay of Biscay). *Trab. Geol.* 29.
849 doi:10.17811/tdg.29.2009.%p
- 850 Fitzgerald, P.G., Muñoz, J.A., Coney, P.J., Baldwin, S.L., 1999. Asymmetric exhumation
851 across the Pyrenean orogen: implications for the tectonic evolution of a collisional
852 orogen. *Earth Planet. Sci. Lett.* 173, 157–170. doi:10.1016/S0012-821X(99)00225-3
- 853 Fonteilles, M. (1970). Géologie des terrains métamorphiques et granitiques du massif hercynien
854 de l'Agly (Pyrénées orientales). *Bulletin de la Bureau de Recherches Géologiques et*
855 *Minéralogiques*, 2, 21-72.
- 856 Fonteilles, M., Leblanc, D., Clauzon, G., Vaudin, J.-L., Berger, G.M., 1993. Carte géologique
857 de la France (1/50 000), feuille Rivesaltes (1090), Bureau de recherches géologiques et
858 minières, Orléans.
- 859 Froitzheim, N., Stets, J., Wurster, P., 1988. Aspects of Western High Atlas tectonics, in: In:
860 Jacobshagen, V. (Ed.), *The Atlas System of Morocco*, Lecture Notes in Earth Sciences.
861 Springer, Berlin, Heidelberg, pp. 219–244. doi:10.1007/BFb0011595
- 862 Garrido-Megias, A., Rios Aragües, L.M. (super a), 1972. Sintesis geologica del Secundario y
863 Terciario entre los rios Cinca y Segre (Pirineo Central de la vertiente sur pirenaica,
864 provincias de Huesca y Lerida). *Summ. Mesoz. Tert. Geol. Cinca Segre Rivers Souther*
865 83, 1–47.

- 866 Golberg, J.M., 1987. Le metamorphisme mesozoique dans la partie orientale des Pyrenees;
867 relations avec l'evolution de la chaine au cretace. Universite des Sciences et Techniques
868 du Languedoc, Centre Geologique et Geophysique : Montpellier, France, France.
- 869 Golberg, J.M., Leyreloup, A.F., 1990. High temperature-low pressure Cretaceous
870 metamorphism related to crustal thinning (Eastern North Pyrenean Zone, France).
871 *Contrib. Mineral. Petrol.* 104, 194–207. doi:10.1007/BF00306443
- 872 Gómez-Romeu, J., Masini, E., Tugend, J., Ducoux, M., & Kusznir, N. (2019). Role of rift
873 structural inheritance in orogeny highlighted by the Western Pyrenees case-study.
874 *Tectonophysics*.
- 875 Gorini, C., Le Marrec, A., Mauffret, A., 1993. Contribution to the structural and sedimentary
876 history of the Gulf of Lions (western Mediterranean), from the ECORS profiles,
877 industrial seismic pro-files and well data. *Bull. Geol. Soc. France* 164,353–363.
- 878 Gorini, C., Mauffret, A., Guennoc, P., Le Marrec, A., 1994. Structure of the Gulf of Lions
879 (Northwestern Mediterranean Sea): a review. In: Mascle, A. (Ed.), *Hydrocarbon and*
880 *Petroleum Geology of France*. Springer-Verlag, pp. 223–243.
- 881 Grool, A. R., Ford, M., Vergés, J., Huismans, R. S., Christophoul, F., & Dielforder, A. (2018).
882 Insights into the crustal-scale dynamics of a doubly vergent orogen from a quantitative
883 analysis of its forelands: A case study of the eastern Pyrenees. *Tectonics*, 37, 450–476.
884 <https://doi.org/10.1002/2017TC004731>
- 885 Guille, B. T., Olivier, P., Paquette, J. L., Bosse, V., & Guillaume, D. (2019). Evolution of the
886 middle crust of the Pyrenees during the Paleozoic: new data on the plutonic rocks from
887 the North Pyrenean Agly massif. *International Journal of Earth Sciences*, 108(1), 245-
888 265.
- 889 Gunnell, Y., Calvet, M., Brichau, S., Carter, A., Aguilar, J.-P., Zeyen, H., 2009. Low long-term
890 erosion rates in high-energy mountain belts: Insights from thermo- and biochronology
891 in the Eastern Pyrenees. *Earth Planet. Sci. Lett.* 278, 208–218.
892 doi:10.1016/j.epsl.2008.12.004
- 893 Hogan, P. J., and K. D. W. Burbank (1996), Evolution of the Jaca piggy-back basin and
894 emergence of the External Sierras, southern Pyrenees, in *Tertiary Basins of Spain*,
895 edited by P. F. Friend and C. J. Dabrio, pp. 153–160, Cambridge Univ. Press,
896 Cambridge, U. K.
- 897 Izquierdo - Llavall, E., Menant, A., Aubourg, C., Callot, J. P., Hoareau, G., Camps, P., ... &
898 Lahfid, A. Pre - orogenic folds and syn - orogenic basement tilts in an inverted
899 hyperextended margin: the northern Pyrenees case study. *Tectonics*, e2019TC005719.
- 900 Jackson, M. P. A., & Vendeville, B. C. (1994). Regional extension as a geologic trigger for
901 diapirism. *Geological society of America bulletin*, 106(1), 57-73.
- 902 James, V., Canerot, J., 1999. Diapirisme et structuration post-triasique des Pyrénées occidentale
903 et de l'Aquitaine méridionale (France). *Eclogae Geol. Helvetiae* 63. doi:10.5169/seals-
904 168647
- 905 Jammes, S., Manatschal, G., Lavier, L., 2010. Interaction between prerift salt and detachment
906 faulting in hyperextended rift systems: The example of the Parentis and Mauléon basins
907 (Bay of Biscay and western Pyrenees). *AAPG Bull.*, 2010b 94, 957–975.
908 doi:10.1306/12090909116

- 909 Jammes, S., Manatschal, G., Lavier, L., Masini, E., 2009. Tectonosedimentary evolution related
910 to extreme crustal thinning ahead of a propagating ocean: Example of the western
911 Pyrenees. *Tectonics* 28, TC4012. doi:10.1029/2008TC002406
- 912 Jolivet, L., Romagny, A., Gorini, C., Maillard, A., Thion, I., Couëffé, R., Ducoux, M.,
913 Séranne, M., 2020. Fast dismantling of a mountain belt by mantle flow: late-orogenic
914 evolution of Pyrenees and Liguro-Provençal rifting. *Tectonophysics* 776, 228312,
915 doi.org/228310.221016/j.tecto.222019.228312.
- 916 Jolivet, M., Labaume, P., Monié, P., Brunel, M., Arnaud, N., Campani, M., 2007.
917 Thermochronology constraints for the propagation sequence of the south Pyrenean
918 basement thrust system (France-Spain). *Tectonics* 26, TC5007.
919 <https://doi.org/10.1029/2006TC002080>.
- 920 Jourdon, A., Le Pourhiet, L., Mouthereau, F., & Masini, E. (2019). Role of rift maturity on the
921 architecture and shortening distribution in mountain belts. *Earth and Planetary Science*
922 *Letters*, 512, 89-99.
- 923 Jourdon, A., Mouthereau, F., Le Pourhiet, L., & Callot, J. P. (2020). Topographic and tectonic
924 evolution of mountain belts controlled by salt thickness and rift architecture. *Tectonics*,
925 39(1), e2019TC005903.
- 926 Labaume, P., Meresse, F., Jolivet, M., & Teixell, A. (2016). Exhumation sequence of the
927 basement thrust units in the west-central Pyrenees. Constraints from apatite fission track
928 analysis. *Geogaceta*, 60, 11–14.
- 929 Labaume, P., Teixell, A., 2020. Evolution of salt structures of the Pyrenean rift (Chaînons
930 Béarnais, France): From hyper-extension to tectonic inversion. *Tectonophysics*,
931 <https://doi.org/10.1016/j.tecto.2020.228451>.
- 932 Lacombe, O., and Bellahsen, N., 2016, Thick-skinned tectonics and basement-involved fold–
933 thrust belts: insights from selected Cenozoic orogens: *Geological Magazine*, v. 153, p.
934 763–810, doi:10.1017/S0016756816000078.
- 935 Lagabriele, Y., Bodinier, J.-L., 2008. Submarine reworking of exhumed subcontinental mantle
936 rocks; field evidence from the Lherz peridotites, French Pyrenees. *Terra Nova* 20, 11–
937 21. doi:10.1111/j.1365-3121.2007.00781.x
- 938 Lagabriele, Y., Clerc, C., Vauchez, A., Lahfid, A., Labaume, P., Azambre, B., Fourcade, S.,
939 Dautria, J.-M., 2016. Very high geothermal gradient during mantle exhumation
940 recorded in mylonitic marbles and carbonate breccias from a Mesozoic Pyrenean
941 palaeomargin (Lherz area, North Pyrenean Zone, France). *Comptes Rendus Geosci.*,
942 From rifting to mountain building: the Pyrenean Belt 348, 290–300.
943 doi:10.1016/j.crte.2015.11.004
- 944 Lagabriele, Y., Labaume, P., de Saint Blanquat, M., 2010. Mantle exhumation, crustal
945 denudation, and gravity tectonics during Cretaceous rifting in the Pyrenean realm (SW
946 Europe): Insights from the geological setting of the lherzolite bodies. *Tectonics* 29,
947 TC4012. doi:10.1029/2009TC002588
- 948 Lahfid, A., Beyssac, O., Deville, E., Negro, F., Chopin, C., Goffe, B., 2010. Evolution of the
949 Raman spectrum of carbonaceous material in low-grade metasediments of the Glarus
950 Alps (Switzerland). *Terra Nova* 22, 354–360. doi:10.1111/j.1365-3121.2010.00956.x
- 951 Légier, C., Tempier, C., Vauchez, A., 1987. Tectoniques tangentielle ductile synmétamorphe
952 d'âge Crétacé supérieur dans la couverture du massif de l'Agly (zone Nord-pyrénéenne
953 orientale). *C. R. Acad. Sci. Paris* 305, 907–911.

- 954 Lemoine, M., bas, T., Arnaud-Vanneau, A., Arnaud, H., Dumont, T., Gidon, M., Bourbon, M.,
955 de Graziansky, P.C., Rudkiewicz, J.L., Mégard-Galli, J., 1986. The continental margin
956 of the mesozoic tethys in the western alps. *Marine and petroleum geology* 3, 179-199.
- 957 Lescoutre, R., & Manatschal, G. (2020). Role of rift-inheritance and segmentation for orogenic
958 evolution: example from the Pyrenean-Cantabrian system Rôle de l'héritage associé au
959 rift et à sa segmentation pour l'évolution orogénique: exemple du système pyrénéo-
960 cantabrique. *Bulletin de la Société Géologique de France*, 191(1).
961 <https://doi.org/10.1051/bsgf/2020021>
- 962 Letouzey, J., 1990. Fault reactivation, inversion and foldthrust belt, in *Petroleum and tectonics*
963 in Mobile Belts, edited by J. Letouzey. Tech. Paris 101–128.
- 964 Lopez-Mir, B., Muñoz, J. A., & Senz, J. G. (2014). Restoration of basins driven by extension
965 and salt tectonics: Example from the Cotiella Basin in the central Pyrenees. *Journal of*
966 *Structural Geology*, 69, 147-162.
- 967 Lundin, E.R., Doré, A.G., 2011. Hyperextension, serpentinization, and weakening: a new
968 paradigm for rifted margin compressional deformation. *Geology* 39, 347–350.
969 <https://doi.org/10.1130/G31499.1>.
- 970 Manatschal, G., Lavier, L., & Chenin, P. (2015). The role of inheritance in structuring
971 hyperextended rift systems: Some considerations based on observations and numerical
972 modeling. *Gondwana Research*, 27(1), 140-164.
- 973 Martinez-Peña, M., and A. Casas-Sainz (2003), Cretaceous–Tertiary tectonic inversion of the
974 Cotiella Basin (southern Pyrenees, Spain), *Int. J. Earth Sci. (Geol. Rundsch.)*, 92(1), 99–
975 113, doi:10.1007/s00531-002-0283-x.
- 976 Masini, E., Manatschal, G., Tugend, J., Mohn, G., Flament, J.-M., 2014. The tectono-
977 sedimentary evolution of a hyper-extended rift basin; the example of the Arzacq-
978 Mauleon rift system (western Pyrenees, SW France). *Int. J. Earth Sci. Geol. Rundsch.*
979 103, 1569–1596. doi:10.1007/s00531-014-1023-8
- 980 Mattauer, M., 1968. Les traits structuraux essentiels de la Chaîne des Pyrénées. *Essent. Struct.*
981 *Traits Pyrenees* 10, 3–11.
- 982 Mauffret, A., Pascal, G., Maillard, A., Gorini, C., 1995. Tectonics and deep structure of the
983 north-western Mediterranean basin. *Mar. Pet. Geol.* 12, 645–666.
- 984 Mauffret, A., Durand de Grossouvre, B., Dos Reis, A.T., Gorini, C., Nercessian, A., 2001.
985 Structural geometry in the eastern Pyrenees and western Gulf of Lion (Western
986 Mediterranean). *J. Struct. Geol.* 23, 1701–1726.
- 987 McClay, K., Munoz, J.-A., Garcia-Senz, J., 2004. Extensional salt tectonics in a contractional
988 orogen; a newly identified tectonic event in the Spanish Pyrenees. *Geol. Boulder* 32,
989 737–740. doi:10.1130/G20565.1
- 990 Michard, A.V., Allègre, C.J., 1975. A study of the formation and history of a piece of
991 continental crust by 87Rb-87Sr method: The case of the French oriental Pyrénées.
992 *Contrib. Mineral. Petrol.* 50, 257–285. doi:10.1007/BF00394853
- 993 Millán Garrido, H. (2006), Estructura y cinemática del frente de cabalgamiento surpirenaico en
994 las Sierras Exteriores aragonesas, in *Colección de Estudios Altoaragoneses*, vol. 53,
995 Instituto de Estudios Altoaragoneses, Huesca, Spain.
- 996 Millán Garrido, H., E. L. Pueyo Morer, M. Aurell Cardona, A. Aguado Luzón, B. Oliva Urcia,
997 M. B. Martínez Peña, and A. Pocoví (2000), Actividad tectonica registrada en los

- 998 depósitos terciarios del frente meridional del Pirineo central, *Rev. Soc. Geol. Esp.*, 13,
999 279–300.
- 1000 Mouthereau, F., Watts, A.B., Burov, E., 2013. Structure of orogenic belts controlled by
1001 lithosphere age. *Nat. Geosci.* 6, 785–789. doi:10.1038/ngeo1902
- 1002 Mouthereau, F., Filleaudeau, P.-Y., Vacherat, A., Pik, R., Lacombe, O., Fellin, M.G.,
1003 Castelltort, S., Christophoul, F., Masini, E., 2014. Placing limits to shortening evolution
1004 in the Pyrenees: Role of margin architecture and implications for the Iberia/Europe
1005 convergence. *Tectonics* 33, 2014TC003663. doi:10.1002/2014TC003663
- 1006 Mitra, S., Mount, V.S., 1998. Foreland Basement-Involved Structures. *AAPG Bull.* 82, 70–109.
- 1007 Muñoz, J.A., 1992. Evolution of a continental collision belt; ECORS-Pyrenees crustal balanced
1008 cross-section. In: MCCLAY, K. R. (ed) *Thrust tectonics*. Chapman & Hall : London,
1009 United Kingdom, pp. 235–246.
- 1010 Muñoz, J.A., 2002. The Pyrenees. In: GIBBONS, W. & MORENO, M. T. (eds) *The geology*
1011 *of Spain*. Geological Society, London, p. 370–385.
- 1012 Muñoz, J.A., Beamud, E., Fernández, O., Arbués, P., Dinarès-Turell, J., and Poblet, J., 2013,
1013 The Ainsa Fold and thrust oblique zone of the central Pyrenees: Kinematics of a curved
1014 contractional system from paleomagnetic and structural data: *Tectonics*, v. 32, p. 1–34,
1015 doi:10.1002/tect.20070.
- 1016 Odlum, M. L., & Stockli, D. F. (2019). Thermotectonic evolution of the North Pyrenean Agly
1017 massif during Early Cretaceous hyperextension using multi-mineral U-Pb
1018 thermochronometry. *Tectonics*, 38, 1509–1531.
1019 <https://doi.org/10.1029/2018TC005298>
- 1020 Oliva-Urcia, B., E. Beamud, M. Garcés, C. Arenas, R. Soto, E. L. Pueyo, and G. Pardo (2015),
1021 New magnetostratigraphic dating in the Palaeogene syntectonic sediments of the west-
1022 central Pyrenees: Tectonostratigraphic implications, in *Palaeomagnetism in Fold and*
1023 *Thrust Belts: New Perspectives*, edited by E. L. Pueyo, *Geol. Soc. Spec. Publ.*, 425,
1024 doi:10.1144/SP425.5.
- 1025 Olivier, P., Gleizes, G., Paquette, J.L., 2004. Gneiss domes and granite emplacement in an
1026 obliquely convergent regime: New interpretation of the Variscan Agly massif (Eastern
1027 Pyrenees, France). *Geol. Soc. Am. Spec. Pap.* 380, 229–242. doi:10.1130/0-8137-2380-
1028 9.229
- 1029 Olivier, P., Gleizes, G., Paquette, J.-L., Sáez, C.M., 2008. Structure and U–Pb dating of the
1030 Saint-Arnac pluton and the Ansignan charnockite (Agly massif): a cross-section from
1031 the upper to the middle crust of the Variscan Eastern Pyrenees. *J. Geol. Soc.* 165, 141–
1032 152. doi:10.1144/0016-76492006-185
- 1033 Olivier, P. (2013), Comment on “Preorogenic exhumation of the North Pyrenean Agly massif
1034 (Eastern Pyrenees-France)” by A. Vauchez *et al.*, *Tectonics*, 32, 821–822,
1035 doi:10.1002/tect.20049
- 1036 Ortiz, A., Guillocheau, F., Lasseur, E., Briais, J., Robin, C., Serrano, O., & Fillon, C., 2020,
1037 Sediment routing system and sink preservation during the post-orogenic evolution of a
1038 retro-foreland basin: The case example of the North Pyrenean (Aquitaine, Bay of
1039 Biscay) Basins. *Marine and Petroleum Geology*, 112, 104085.
- 1040 Paquet, J., Mansy, J.-L., 1991. La structure de l’Est des Pyrénées (transversales du massif de
1041 l’Agly) : un exemple d’amincissement crustal. *Comptes Rendus Académie Sci. Sér. 2*
1042 *Mécanique Phys. Chim. Sci. Univers Sci. Terre* 312, 913–919.

- 1043 Passchier, C.W., 1984. Mylonite-dominated footwall geometry in a shear zone, central
1044 Pyrenees. *Geol. Mag.* 121, 429–436. doi:10.1017/S0016756800029964
- 1045 Pasteris, J., Wopenka, B., 1991. Raman-Spectra of Graphite as Indicators of Degree of
1046 Metamorphism. *Can. Mineral.* 29, 1–9.
- 1047 Pasteris, J.D., 1989. In situ analysis in geological thin-sections by laser Raman microprobe
1048 spectroscopy; a cautionary note. *Appl. Spectrosc.* 567–570.
- 1049 Pérez-Gussinyé, M., Reston, T.J., Phipps Morgan, J., 2001. Serpentinization and magmatism
1050 during extension at non-volcanic margins: the effect of initial lithospheric structure.
1051 *Geol. Soc. London, Spec. Publ.* 187, 551–576.
1052 <https://doi.org/10.1144/GSL.SP.2001.187.01.27>.
- 1053 Péron-Pinvidic, G., Manatschal, G., Dean, S.M., Minshull, T.A., 2008. Compressional
1054 structures on the West Iberia rifted margin: Controls on their distribution. In: Johnson,
1055 H. (Ed.), *The Nature and Origin of Compression in Passive Margins*. *Geol. Soc. London,*
1056 *Spec. Publ.* vol. 306. pp. 169–183. <https://doi.org/10.1144/SP306.8>.
- 1057 Pfiffner, O.A., 2017, *Thick-Skinned and Thin-Skinned Tectonics: A Global Perspective:*
1058 *Geosciences*, v. 7, p. 71, doi:10.3390/geosciences7030071.
- 1059 Poujol, M., Boulvais, P., Kosler, J., 2010. Regional-scale Cretaceous albitization in the
1060 Pyrenees: evidence from in situ U–Th–Pb dating of monazite, titanite and zircon. *J.*
1061 *Geol. Soc.* 167, 751–767. doi:10.1144/0016-76492009-144
- 1062 Ravier, J., 1959. Le métamorphisme des terrains secondaires des Pyrénées. *Mémoires Soc.*
1063 *Geol. Fr. Nouv. Ser.* 38.
- 1064 Roca, E., 2001. The Northwest Mediterranean Basin (Valencia Trough, gulf of Lions and
1065 Liguro-Provençal basins): structure and geodynamic evolution, in Ziegler, P. A.,
1066 Cavazza, W., Robertson, A. H. F., and Crasquin-Soleau, S., eds., *Peri-Tethys Memoir*
1067 6: Pery-Tethyan Rift/Wrench Basins and Passive Margins. *Mémoires Muséum National*
1068 *d'Histoire Naturelle*, 186: Paris, 671–706.
- 1069 Roca, E., Sans, M., Cabrera, L., Marzo, M., 1999. Oligocene to Middle Miocene evolution of
1070 the central Catalan margin (northwestern Mediterranean). *Tectonophysics* 315, 209–
1071 229. doi:10.1016/S0040-1951(99)00289-9
- 1072 Roure, F., P. Choukroune, X. Berástegui, J. A. Muñoz, A. Villien, P. Matheron, M. Bareyt, M.
1073 Séguret, P. Camara, and J. Déramond (1989), ECORS deep seismic data and balanced
1074 cross sections: Geometric constraints on the evolution of the Pyrenees, *Tectonics*, 8(1),
1075 41–50, doi:10.1029/TC008i001p00041.
- 1076 Rowan, M.G., 2014, Passive-margin salt basins; hyperextension, evaporite deposition, and salt
1077 tectonics. *Basin Res.* 26, 154–182. doi:10.1111/bre.12043
- 1078 Rushlow, C.R., Barnes, J.B., Ehlers, T.A., Vergés, J., 2013. Exhumation of the southern
1079 Pyrenean fold-thrust belt (Spain) from orogenic growth to decay. *Tectonics* 32, 843–
1080 860. doi:10.1002/tect.20030
- 1081 Saura, E., L. Ardèvol i Oró, A. Teixell, and J. Vergés (2016), Rising and falling diapirs, shifting
1082 depocenters, and flap overturning in the Cretaceous Sopeira and Sant Gervàs subbasins
1083 (Ribagorça Basin, southern Pyrenees), *Tectonics*, 35, 638–662,
1084 doi:10.1002/2015TC004001.
- 1085 Scharf, A., Handy, M.R., Ziemann, M.A., Schmid, S.M., 2013. Peak-temperature patterns of
1086 polyphase metamorphism resulting from accretion, subduction and collision (eastern

- 1087 Tauern Window, European Alps); a study with Raman microspectroscopy on
1088 carbonaceous material (RSCM). *J. Metamorph. Geol.* 31, 863–880.
1089 doi:10.1111/jmg.12048
- 1090 Tavani, S., Camanni, G., Nappo, M., Snidero, M., Ascione, A., Valente, E., Gharabeigli, G.,
1091 Morsalnejad, D., and Mazzoli, S., 2020, The Mountain Front Flexure in the Lurestan
1092 region of the Zagros belt: Crustal architecture and role of structural inheritances: *Journal*
1093 *of Structural Geology*, v. 135, p. 104022, doi:10.1016/j.jsg.2020.104022.
- 1094 Ternet, Y., Colchen, M., Debroyas, E.-J., Azambre, B., Debon, F., Bouchez, J.L., Gleizes, G.,
1095 Leblanc, D., Bakalowicz, M., Jauzion, G., Mangin, A., Soulé, J.-C., 1997. Notice
1096 explicative de la carte géologique de la France au 1/50.000, feuille de Aulus-les-Bains
1097 (1086), 146 pp., BRGM, Orléans.
- 1098 Ternois, S., Odlum, M., Ford, M., Pik, R., Stockli, D., Tibari, B., *et al.* (2019).
1099 Thermochronological evidence of early orogenesis, eastern Pyrenees, France.
1100 *Tectonics*, 38, 1308–1336. <https://doi.org/10.1029/2018TC005254>
- 1101 Teixell, A. (1996), The Ansó transect of the southern Pyrenees: Basement and cover thrust
1102 geometries, *J. Geol. Soc.*, 153, 301–310.
- 1103 Teixell, A. (1998), Crustal structure and orogenic material budget in the west central Pyrenees,
1104 *Tectonics*, 17(3), 395–406, doi:10.1029/98TC00561.
- 1105 Teixell, A., Labaume, P., & Lagabrielle, Y., 2016, The crustal evolution of the west-central
1106 Pyrenees revisited: inferences from a new kinematic scenario. *Comptes Rendus*
1107 *Geoscience*, 348(3-4), 257-267.
- 1108 Tugend, J., Manatschal, G., Kusznir, N.J., Masini, E., Mohn, G., Thion, I., 2014. Formation
1109 and deformation of hyperextended rift systems; insights from rift domain mapping in
1110 the Bay of Biscay-Pyrenees. *Tectonics* 33, 1239–1276. doi:10.1002/2014TC003529
- 1111 Tugend, J., Manatschal, G., Kusznir, N.J., 2015. Spatial and temporal evolution of
1112 hyperextended rift systems: Implication for the nature, kinematics, and timing of the
1113 Iberian- European plate boundary. *Geology* 15–18. <https://doi.org/10.1130/G36072.1>.
- 1114 Vacherat, A., Mouthereau, F., Pik, R., Bellahsen, N., Gautheron, C., Bernet, M., Daudet, M.,
1115 Balansa, J., Tibari, B., Pinna Jamme, R., Radal, J., 2016. Rift-to-collision transition
1116 recorded by tectonothermal evolution of the northern Pyrenees. *Tectonics* 35, 907.
- 1117 Vacherat, A., Mouthereau, F., Pik, R., Bernet, M., Gautheron, C., Masini, E., Le Pourhiet, L.,
1118 Tibari, B., Lahfid, A., 2014. Thermal imprint of rift-related processes in orogens as
1119 recorded in the Pyrenees. *Earth Planet. Sci. Lett.* 408, 296–306.
1120 doi:10.1016/j.epsl.2014.10.014
- 1121 Vanardois J, Trap P, Goncalves P, Marquer D, Gremmel J, Siron G, Baudin T. 2020.
1122 Kinematics, deformation partitioning and late Variscan magmatism in the Agly massif,
1123 Eastern Pyrenees, France, *BSGF - Earth Sciences Bulletin* 191: 15.
- 1124 Vauchez, A., Clerc, C., Bestani, L., Lagabrielle, Y., Chauvet, A., Lahfid, A., Mainprice, D.,
1125 2013. Pre-orogenic exhumation of the north Pyrenean Agly massif (eastern Pyrenees,
1126 France). *Tectonics* 32, 95–106. doi:10.1002/tect.20015
- 1127 Vergés, J., and García-Senz, J., 2001. Mesozoic evolution and Cainozoic inversion of the
1128 Pyrenean rift, in *Peri-Tethyan Rift/Wrench Basins and Passive Margins*, edited by P. A.
1129 Ziegler et al., *mémoire*, pp. 187– 212,

- 1130 Verges, J., Fernandez, M., Martinez, A., 2002. The Pyrenean orogen; pre-, syn-, and post-
1131 collisional evolution. *J. Virtual Explor.* 8, 57–76.
- 1132 Vielzeuf, D., and J. Kornprobst (1984), Crustal splitting and the emplacement of Pyrenean
1133 lherzolites and granulites, *Earth Planet. Sci. Lett.*, 67(1), 87–96, doi:10.1016/0012-
1134 821X(84)90041-4.
- 1135 Watts, A.B., Lamb, S.H., Fairhead, J.D., Dewey, J.F., 1995. Lithospheric flexure and bending
1136 of the Central Andes. *Earth Planet. Sci. Lett.* 134, 9–21. doi:10.1016/0012-
1137 821X(95)00095-T
- 1138 Wehr, H., Chevrot, S., Courrioux, G., Guillen, A., 2018. A three-dimensional model of the
1139 Pyrenees and their foreland basins from geological and gravimetric data.
1140 *Tectonophysics* 734-735, 16-32; <https://doi.org/10.1016/j.tecto.2018.1003.1017>.
- 1141 Whitchurch, A.L., Carter, A., Sinclair, H.D., Duller, R.A., Whittaker, A.C., Allen, P.A., 2011.
1142 Sediment routing system evolution within a diachronously uplifting orogen: Insights
1143 from detrital zircon thermochronological analyses from the South-Central Pyrenees.
1144 *Am. J. Sci.* 311, 442–482. doi:10.2475/05.2011.03
- 1145 Wickham, S. M., & Oxburgh, E. R. (1986). A rifted tectonic setting for Hercynian high -
1146 thermal gradient metamorphism in the Pyrenees. *Tectonophysics*, 129(1-4), 53–69.
1147 [https://doi.org/10.1016/0040-1951\(86\)90245-3](https://doi.org/10.1016/0040-1951(86)90245-3)
- 1148 Wopenka, B., Pasteris, J.D., 1993. Structural characterization of kerogens to granulite-facies
1149 graphite : applicability of Raman microprobe spectroscopy. *Am. Mineral.* 78, 533–557.
- 1150 Yelland, A.J., 1991. Thermo-tectonics of the Pyrenees and Provence from fission track studies.
1151 Ph.D. thesis, University of London.

1152 **Figures captions**

1153 **Figure 1:** Simplified structural map of the Pyrenean belt. Only main “alpine” thrusts and faults
1154 are represented: North-Pyrenean Frontal Thrust (NPFT), South-Pyrenean Frontal Thrust
1155 (SPFT), and North-Pyrenean Fault. The Internal Metamorphic Zone (IMZ, orange in the figure)
1156 is located in the North Pyrenean Zone (NPZ) and crops out along the strike of the belt. The
1157 study area is located in the eastern part of this belt.

1158 **Figure 2:** Geological map of the eastern part of the North Pyrenean Zone (localization on Fig.
1159 1) (after [Crochet *et al.*, 1989](#); [Berger *et al.*, 1997](#); [Bles and Berger, 1982](#); [Fonteilles *et al.*, 1993](#))
1160 with T_{\max} measured with Raman spectrometry ([Chelalou, 2015](#) (in blue); [Clerc *et al.*, 2015](#) (in
1161 black) and this study (in red)) and thermobarometry estimates ([Golberg and Leyreloup, 1990](#)).
1162 Localisation of Mesozoic sequences remnants on the Agly massif are pointed out by numbers:

1163 (1) Serre de Cors; (2) Serre de Verges; (3) Roc de Lansac; (4) Lake Caramany and (5) Agly
1164 dam.

1165 **Figure 3:** Isometamorphic map of the HT/LP metamorphism distribution in the eastern part of
1166 the North Pyrenean Zone.

1167 **Figure 4:** Structural map of the eastern part of the North Pyrenean Zone (localization on Fig.
1168 1) (after [Crochet et al., 1989](#); [Berger et al., 1997](#); [Bles and Berger, 1982](#); [Fonteilles et al., 1993](#)).
1169 This map displays the different tectono-stratigraphic units and the detail of structural framework
1170 (trajectories of foliation and cleavage; lineations and folds). Early convergence-related fault are
1171 drawn in orange and late convergence-related fault in red.

1172 **Figure 5:** field photographs and interpretations of the observed deformation in the Paleozoic
1173 sediments of the Agly massif. a) top-to-the N normal shears. b) top-to-the S reverse shears.

1174 **Figure 6:** field photographs and interpretations of the observed deformation in Mesozoic Bas-
1175 Agly sedimentary cover. a) big picture on Rhaetian and Liassic sediments of the southern Bas-
1176 Agly, modified after [Clerc et al. \(2016\)](#). b) zoom on recumbent fold with top-to-the north
1177 verging. c) pure shear deformation and hectometer-scale boudinaged of Liassic sediments.

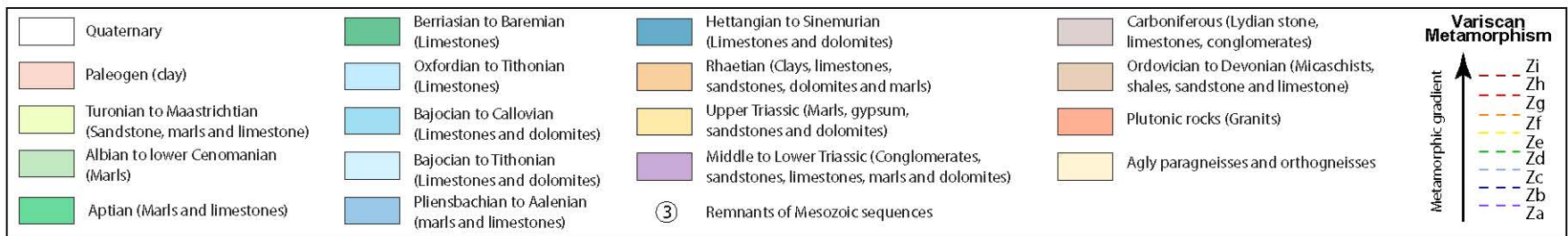
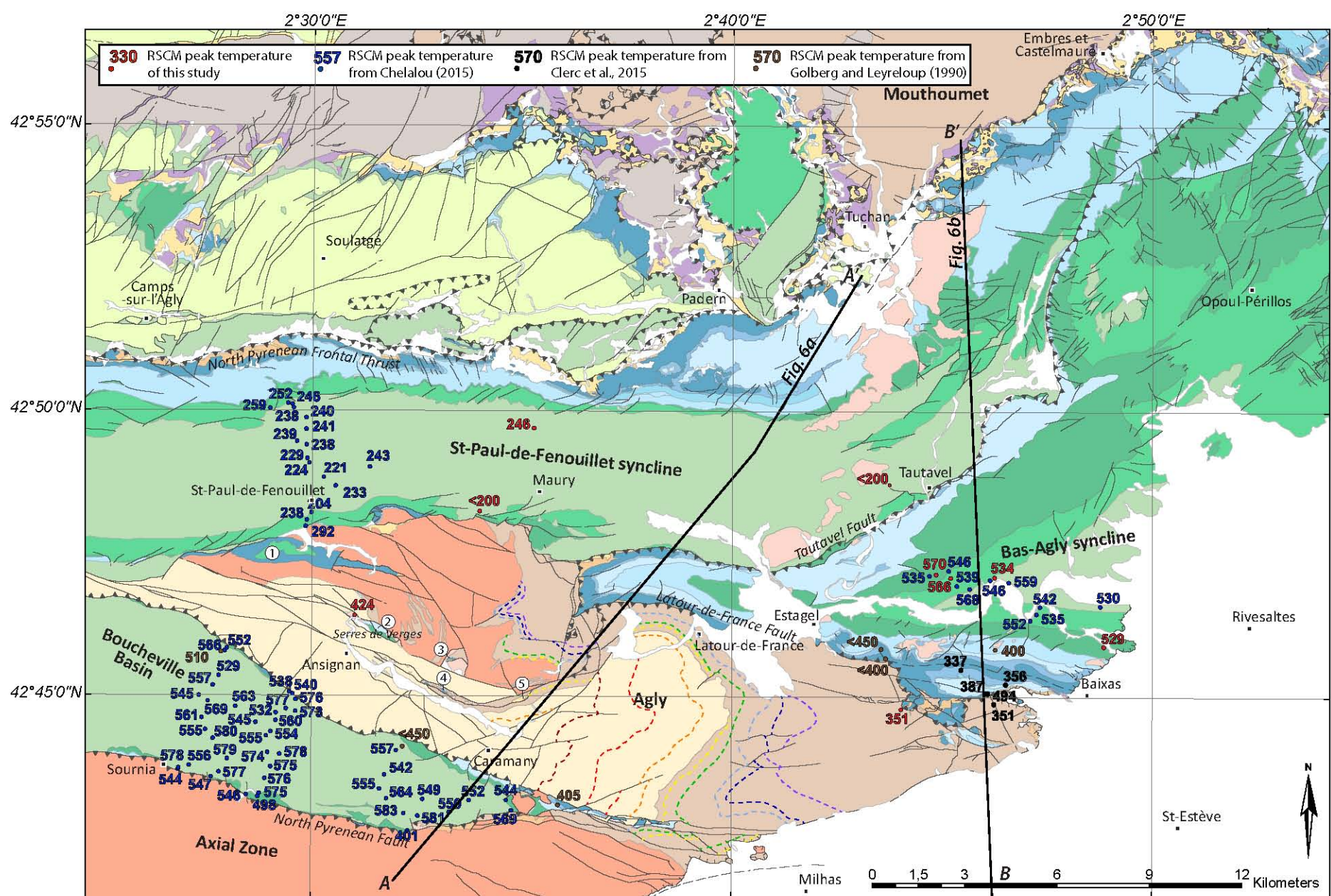
1178 **Figure 7:** Geological cross sections through the eastern part of the IMZ illustrating the
1179 relationships between the Bas-Agly syncline and surroundings units. Legend is similar to Figure
1180 2.

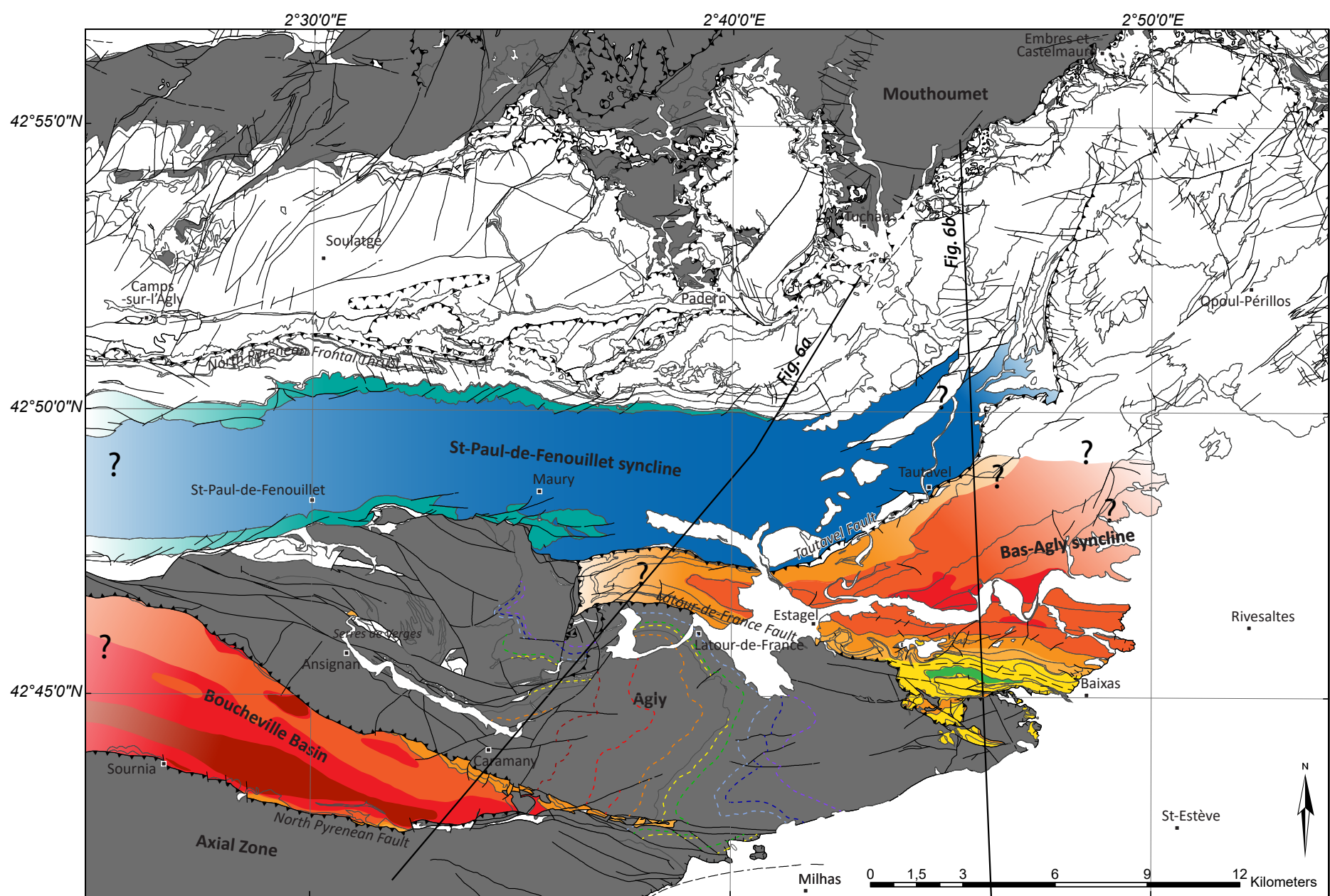
1181 **Figure 8:** Comparison of thermal structure for two endmembers: (a) a detachment system
1182 forming a MCC and (b) a thrust system. Structures are sole in the middle-lower continental
1183 crust and isotherms represent static maximum temperatures reached by rocks.

1184 **Figure 9:** Geodynamical model of the eastern part of the NPZ illustrating a structural evolution
1185 from the rifting event to the present, modified after [Ternois et al. \(2019\)](#). Four steps of

1186 restoration are depicted. SFPT: South Pyrenean Frontal Thrust; NPF: North Pyrenean Fault;
1187 LTFF: La-Tour-de-France Fault; TF: Tautavel Fault; NPFT: North Pyrenean Frontal Thrust.
1188 See text for explanations.

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Legend of structural map

Tectono-stratigraphic Units

Post-rift	Turonian to Maastrichtian
Syn-rift	Albian to Cenomanian
	Late Aptian
Pre-rift	Rhaetian to Aptian
	Upper Triassic and Ophite
	Permian to middle Triassic
Basement	Metasediments
	Metamorphic rocks
	Plutonic rocks

Details of structures

Pyrenean Structures

Structural data

- (S_{0-1}) Direction trajectories of ductile foliation
- (S_2) Direction trajectories of cleavage
- Cleavage front
- Stretching lineations
- Mineral lineations
- ductile lineations (after Clerc et al., 2015)

Salt tectonic-related structures

- Diapiric zones and rafts

Faults

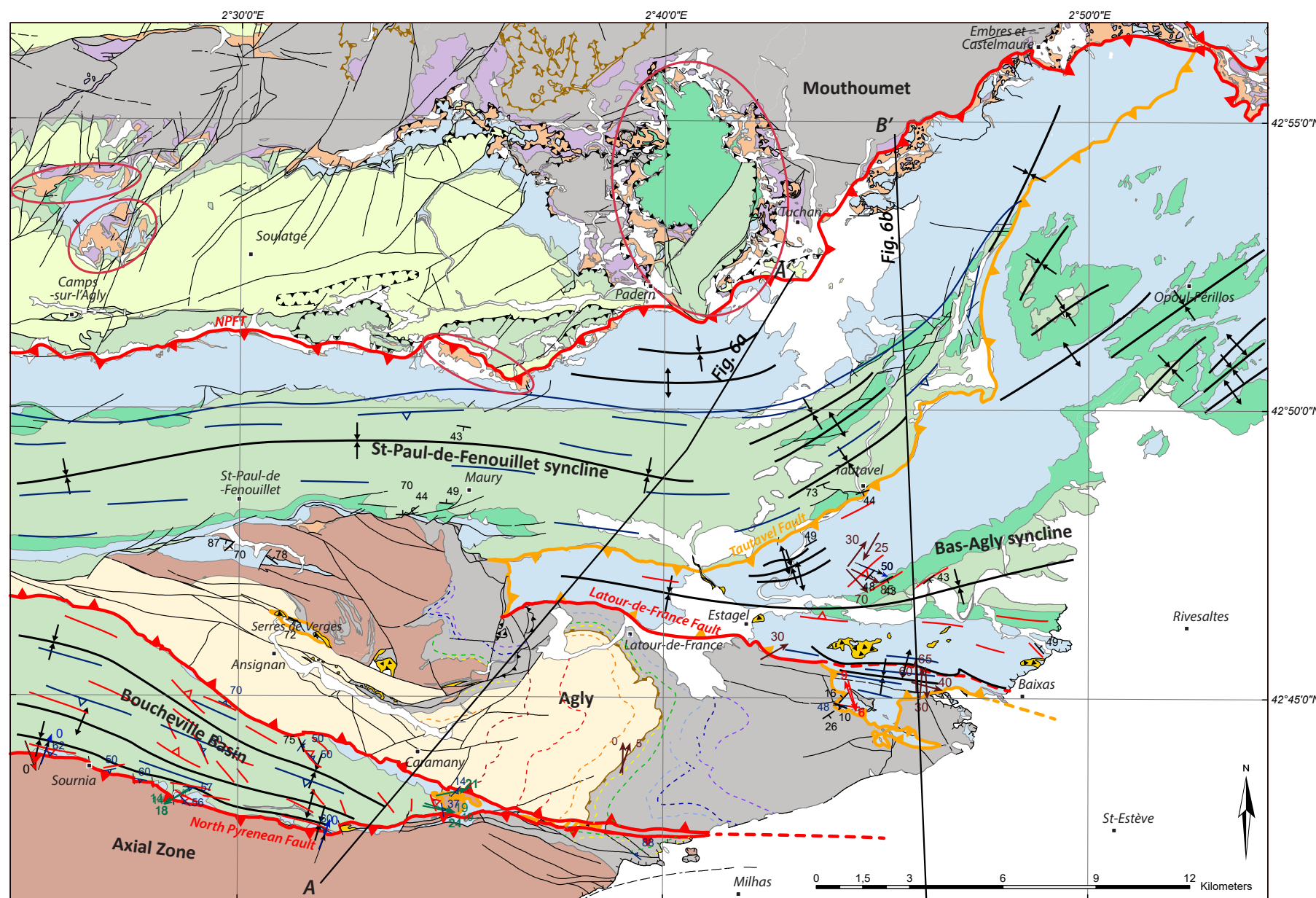
- Main early convergence faults
- Main late convergence faults
- Minor thrusts
- Undifferentiated faults
- Late breccias (décollement plane ?)

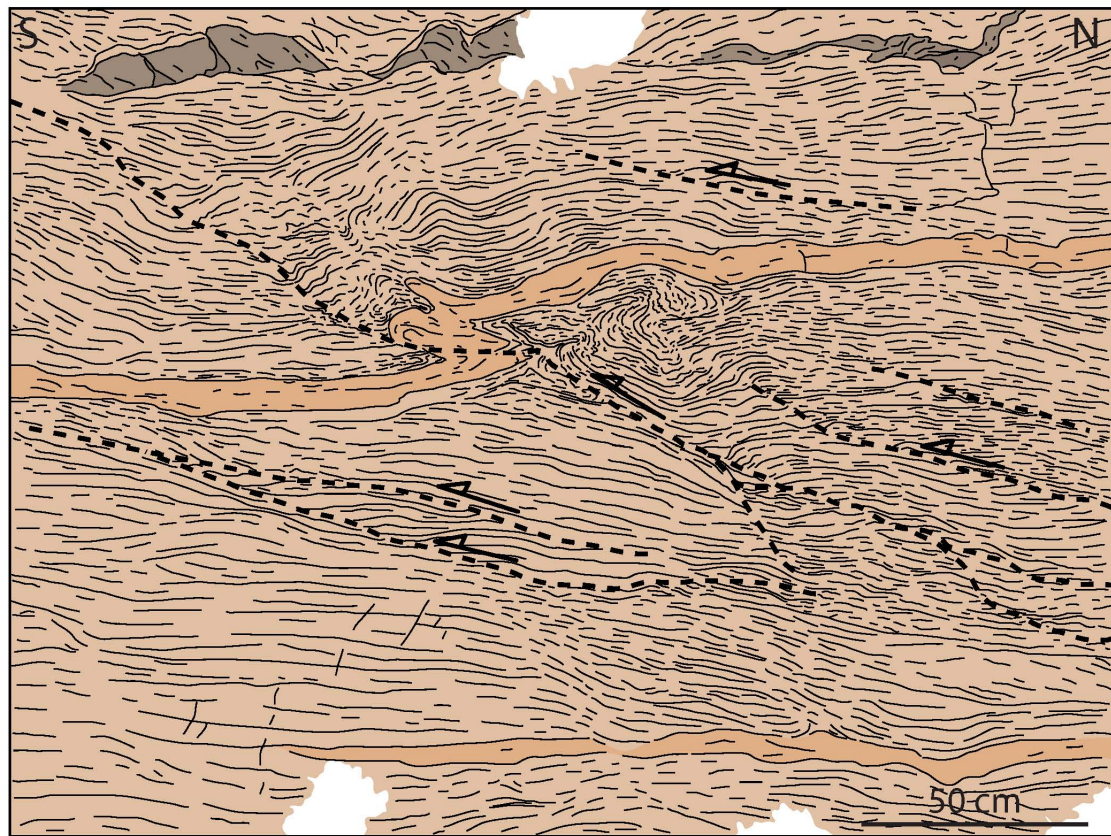
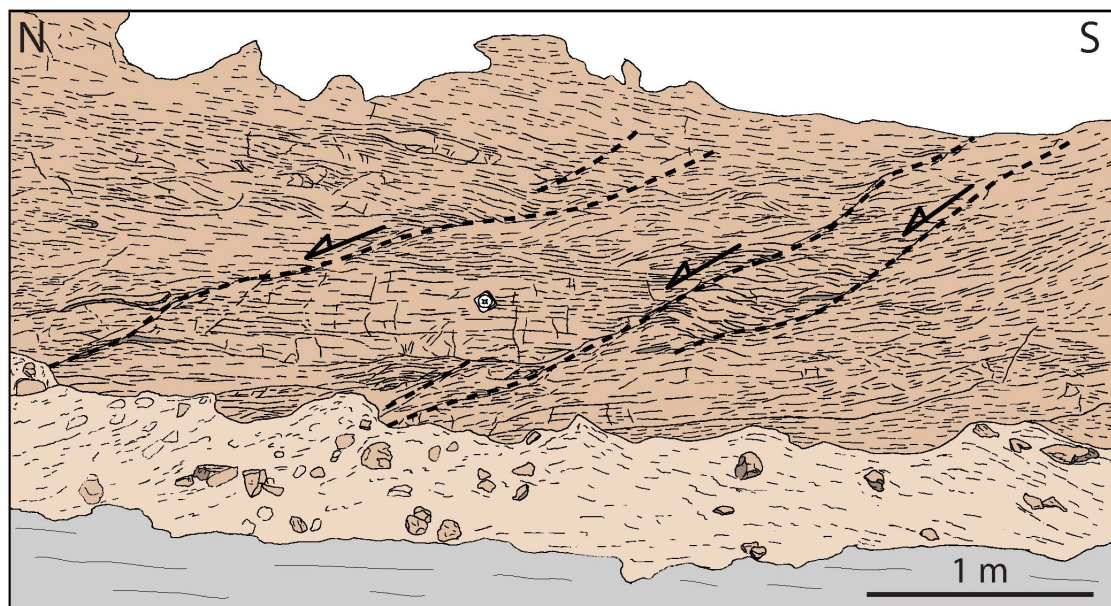
Folds

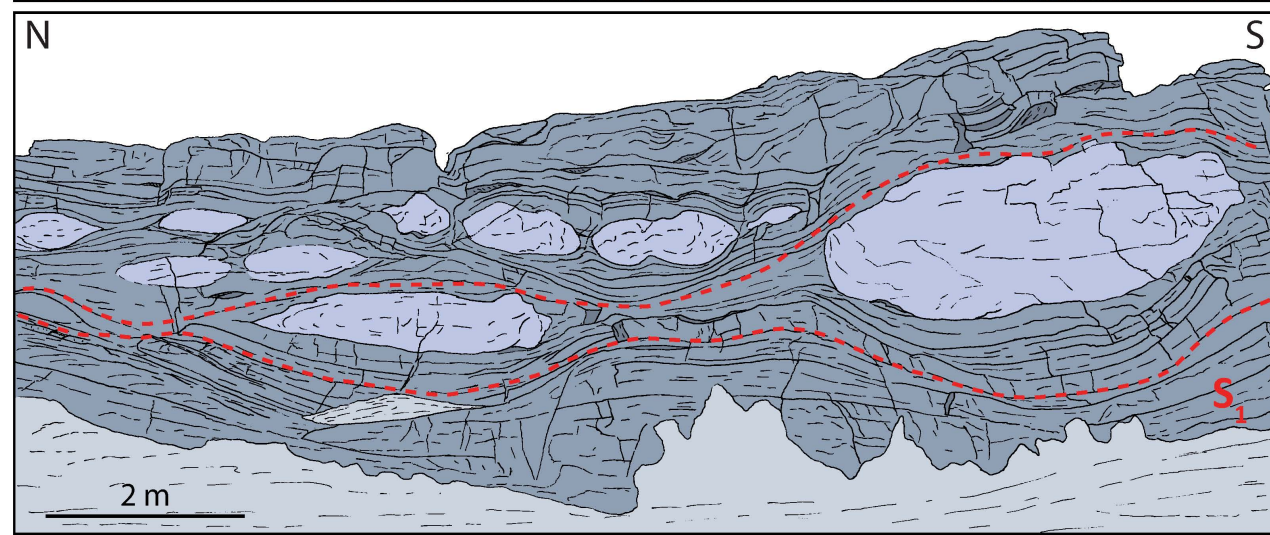
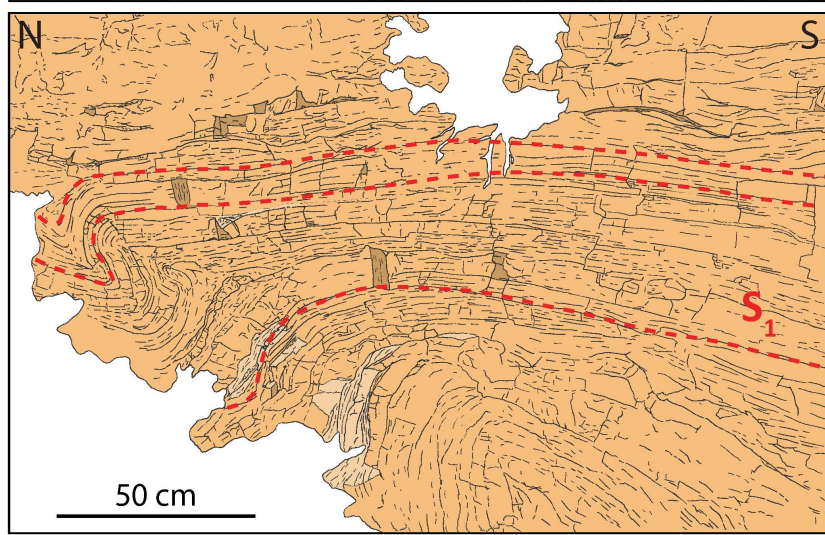
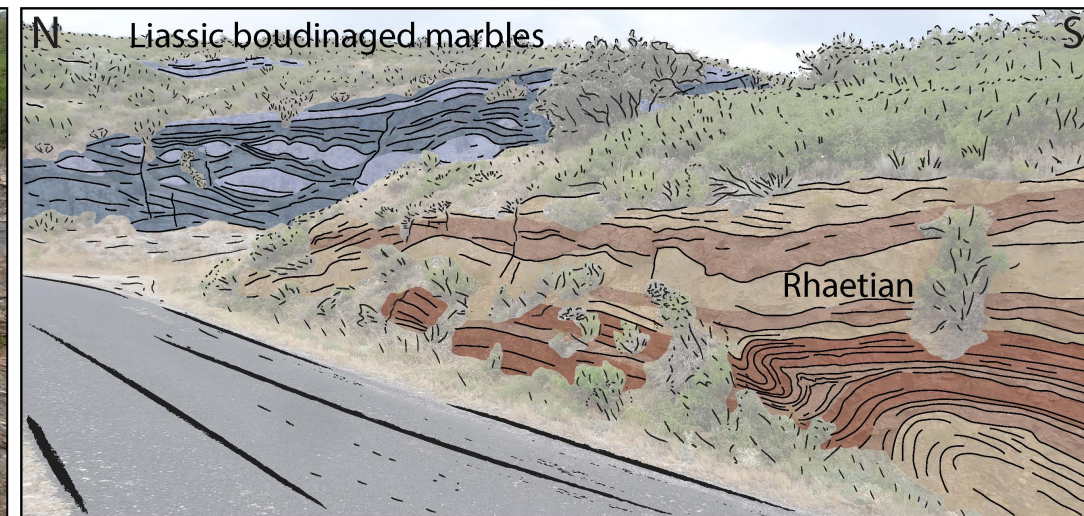
- Large scale Synform
- Large scale Antiform
- Local (dm to m) folds with plunge value of axis

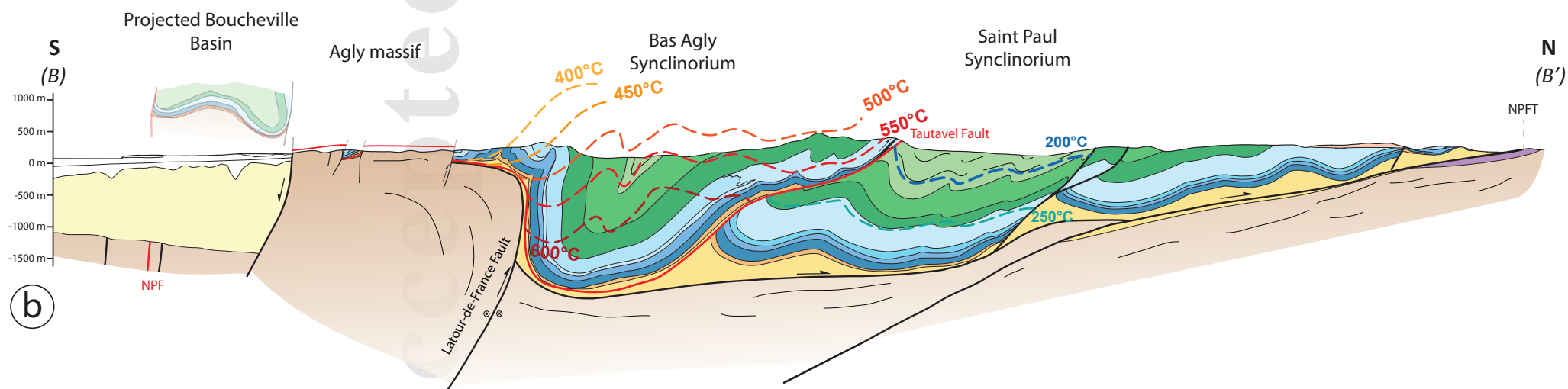
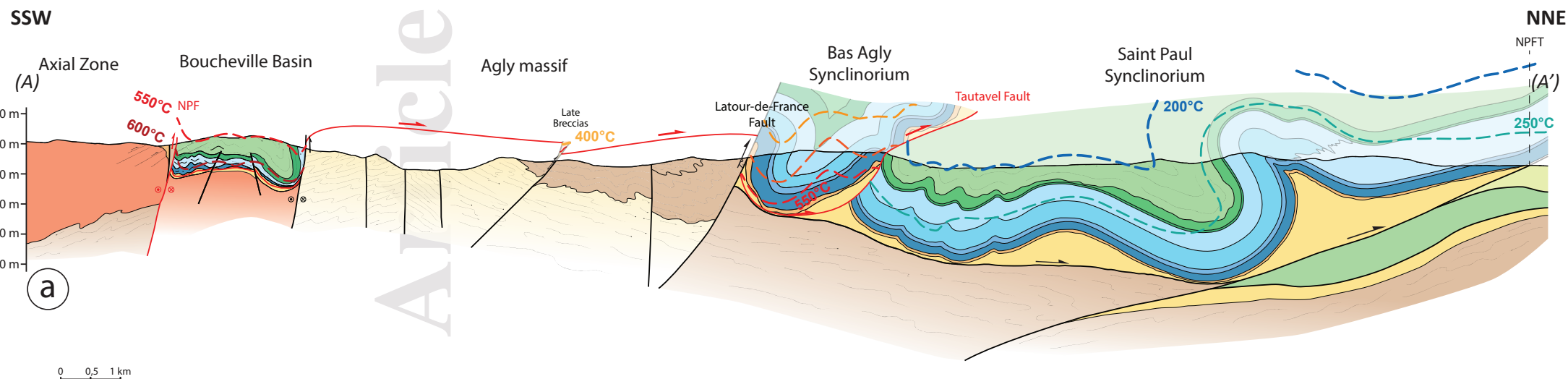
Variscan Structures

- Thrusts and reverse fault
- Extensional fault

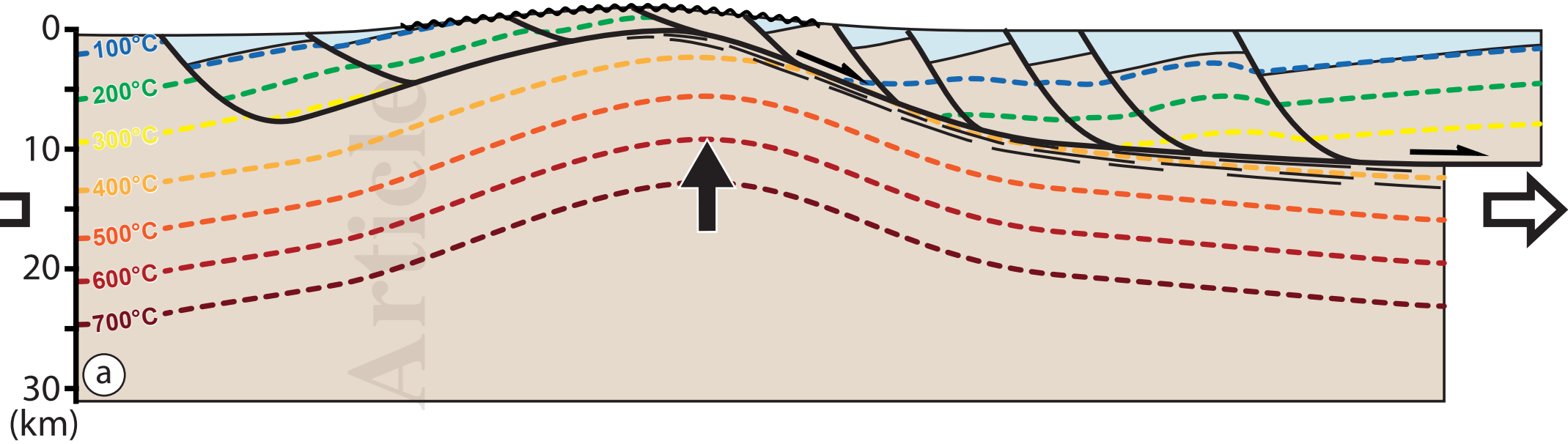




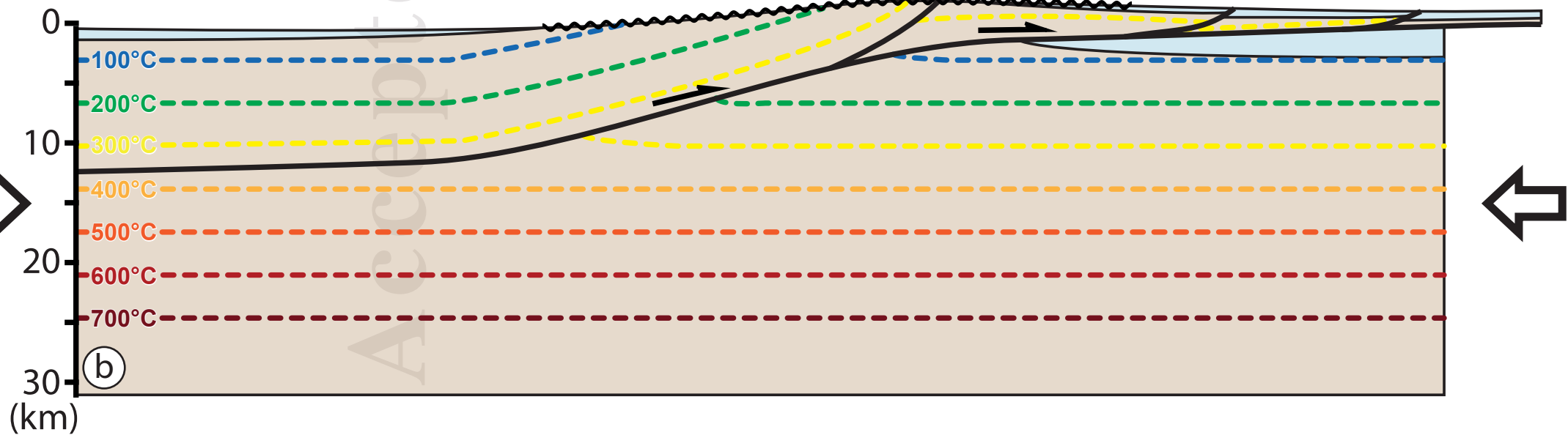




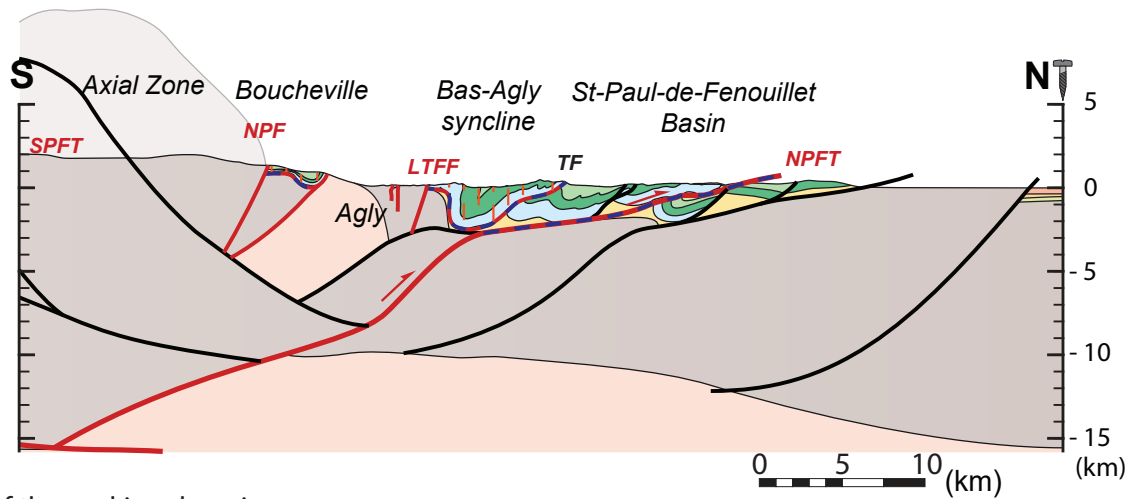
Typical thermal structure related to a Detachment system



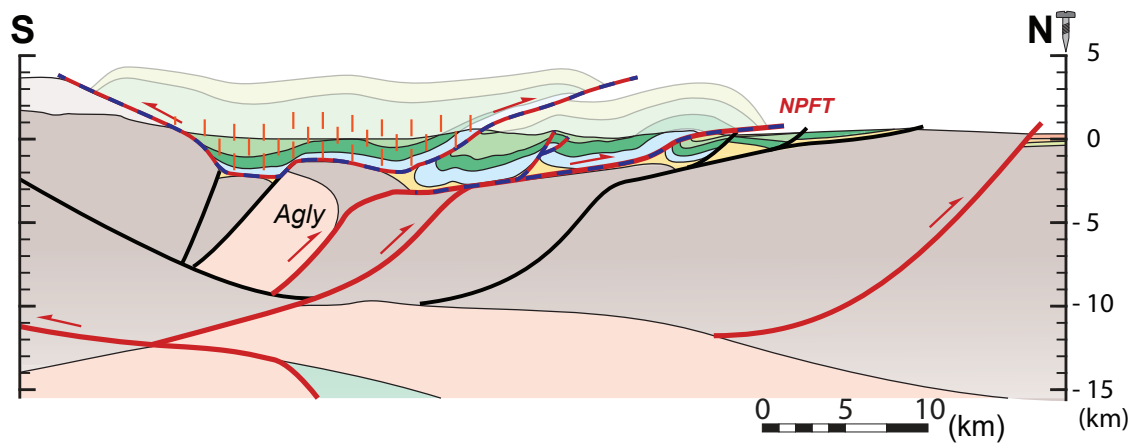
Typical thermal structure related to a Thrust system



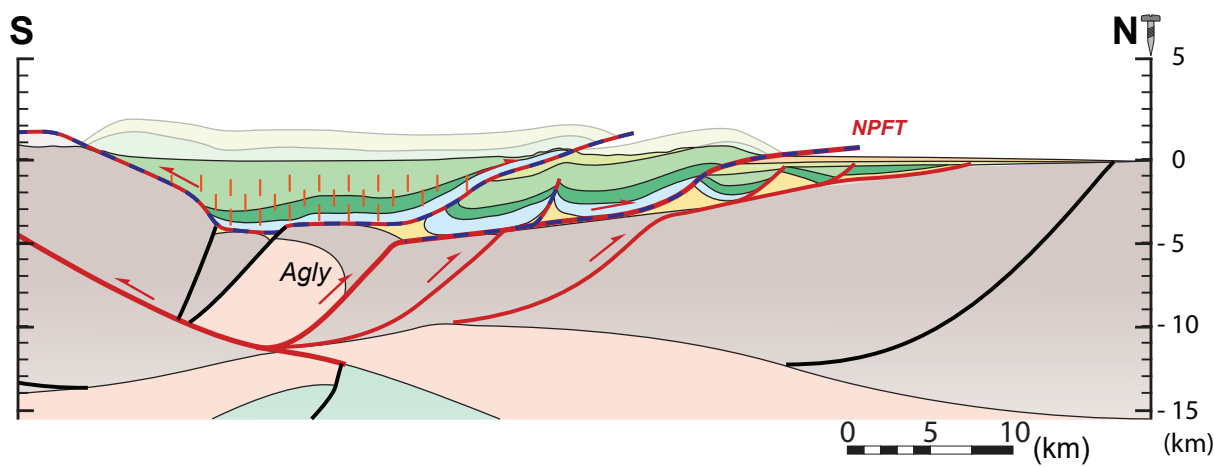
(d) Late Eocene (35Ma) to Present-day - Orogenic crustal thickening



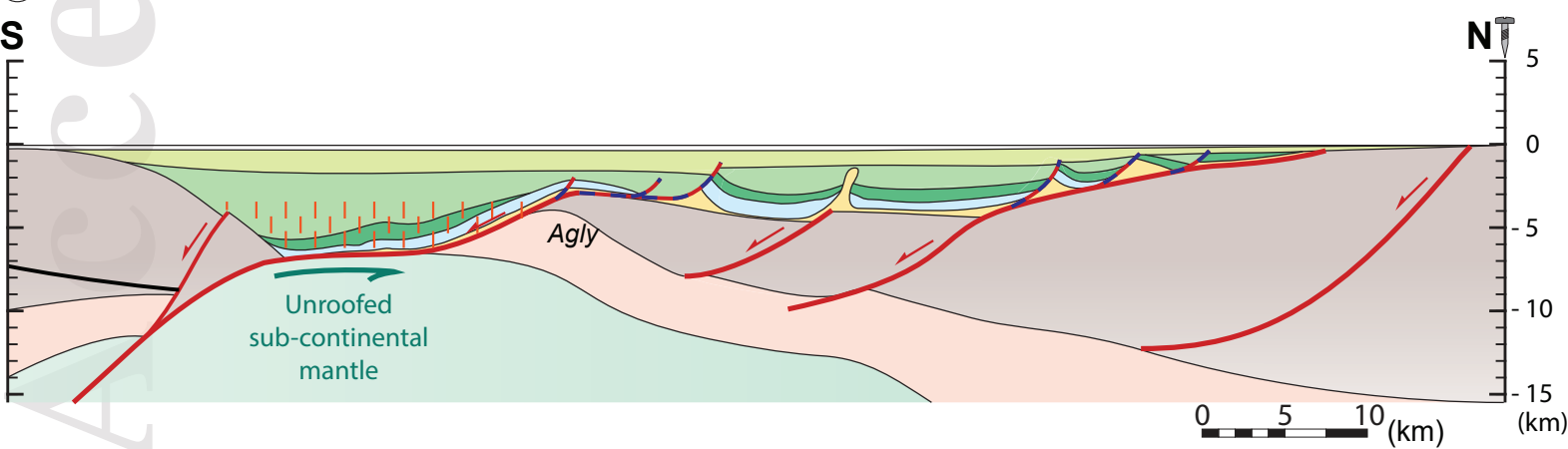
(c) Bartonian (40Ma) - Reactivation of the necking domain



(b) Late Maastrichtian (66 Ma) - Early convergence



(a) Early Santonian (84 Ma) - Rifting templates and onset of the convergence



Lithostratigraphic units

Basement

- Upper crust
- Lower crust
- Lithospheric mantle
- Asthenospheric mantle

Pre-rift

- Jurassic
- Upper Triassic
- Late Albian to mid-Cenomanian
- Early Aptian to early Albian

Post-rift

- Late Cenomanian to late Coniacian
- Syn-orogenic
- Eocene

Metamorphism

- HT metamorphic rocks

Tectonic

- Abandoned faults
- Active faults
- Decollement and salt-assisted faults