Evolution of a salt-rich transtensional rifted margin, eastern North Pyrenees, France
— **Source link** ⧉

Mary Ford, Jaume Vergés

Institutions: University of Lorraine, Spanish National Research Council

Related papers:

- Mantle exhumation, crustal denudation, and gravity tectonics during Cretaceous rifting in the Pyrenean realm (SW Europe): Insights from the geological setting of the lherzolite bodies

- Placing limits to shortening evolution in the Pyrenees: Role of margin architecture and implications for the Iberia/Europe convergence

- The crustal evolution of the west-central Pyrenees revisited: Inferences from a new kinematic scenario

- Thermochronological Evidence of Early Orogenesis, Eastern Pyrenees, France

- Evolution of salt structures of the Pyrenean rift (Chaînons Béarnais, France): From hyper-extension to tectonic inversion

Evolution of a salt-rich transtensional rifted margin, eastern North Pyrenees, France

M. Ford[1]* and J. Vergés[2]

[1] Université de Lorraine, CNRS, CRPG, F-54000 Nancy, France
[2] Group of Dynamics of the Lithosphere, Institute of Earth Sciences Jaume Almera, ICTJA-CSIC, Barcelona 08028, Spain
MF, 0000-0002-8343-188X; JV, 0000-0002-4467-5291
*Correspondence: mary.ford@univ-lorraine.fr

Abstract: In this field study we reinterpret the narrow eastern North Pyrenean Zone, France, as an inverted salt-rich transtensional rift system based on identification of halokinetic depositional sequences across rift platform to distal rift margin domains with a cumulative throw of >2.8 km on steep Cretaceous faults. The rift platform records extension on detached rotational faults above Triassic evaporites from Jurassic to Aptian with uplift and erosion during the Albian. Transtensional Aptian–Albian minibasins align along the salt-rich rift margin fault zone. In the Aptian–Albian main rift large en echelon synclinal minibasins developed between salt walls, although Jurassic diapiric evolution is likely. Upper Cretaceous units locally record continuing diapirism. The Boucheville and Bas Agly depocentres, altered by synrift HT metamorphism, form the distal rift domain terminating south against the North Pyrenean Fault. The narrowness of the Pyrenean rift, shape of minibasins, en echelon oblique synclinal depocentres and folds coupled with a discontinuous distribution and intensity of HT metamorphism support a transtensional regime along the Iberia–Europe plate margin during late Early and early Late Cretaceous. In this model, the distal European margin comprises deep faults limiting laterally discontinuous crustal domains and 'hot' pull-apart basins with mantle rocks directly beneath sedimentary cover.

Evaporites can play a major role in controlling the architecture of external orogenic belts, during both pre-collisional extension and subsequent compressional phases. However, salt can 'hide' deformation because of its ability to flow and dissolve. Compressional overprinting can further mask halokinetic structures by squeezing and eventually obliterating diapirs and other salt bodies (e.g. Rowan and Vendeville 2006; Graham et al. 2012; Saura et al. 2014, 2016). High-quality seismic imaging of salt-rich basins over the last 20 years has revolutionized salt tectonic concepts, particularly on rifted margins (e.g. Rowan 2014). This new knowledge is now stimulating a reassessment of the evolution of inverted salt-rich margins preserved in fold-and-thrust belts (e.g. Graham et al. 2012; Espurt et al. 2019; Dooley and Hudec 2020). The challenge is to recognize the imprint of the presence of salt and its influence in both rift and subsequent fold belt evolution. Identifying salt-related stratigraphic architectures, facies distributions and structures holds the key. In this way we can often resolve decades-long controversies and incoherencies in tectonic interpretations and geological histories. In addition, recognition of salt-related stratal geometries can lead to new insights into the distribution and true amount of shortening in inverted salt-rich margins and rifts.

As reviewed by Saura et al. (2016), salt structures are well documented across much of the Pyrenean orogen (Fig. 1). The source layer is the evaporite-rich Middle to Upper Triassic Keuper Group, which is well known as the main decoupling level between crystalline basement and Mesozoic cover. Salt diapirs are widespread offshore and onshore in the Basque–Cantabrian and Basque–Parentis domains (Ferrer et al. 2008, 2012; Roca et al. 2011), in the South Pyrenees (Ríos et al. 1943; Serrano and Martínez del Olmo 1990; Lopez-Mir et al. 2014; Saura et al. 2016; Teixell et al. 2016, 2018; Cámara and Flinch 2017) and in the

northern external zone and foreland, where the evaporite layer thickens westward to up to 2700 m (Henry and Zolnai 1971; Canérot et al. 2005; Biteau et al. 2006; Serrano et al. 2006). Whereas local studies have reported on the role of salt diapirism during rifting in the westernmost (Canérot et al. 2005; James and Canérot 1999; Labaume and Teixell 2020) and central sectors of the North Pyrenees (Ford et al. 2016; Rougier et al. 2016; Grool et al. 2018), there is little detailed work in easternmost regions. Recent publications on the eastern North Pyrenean Zone have represented the pre-shortening template as an isopach Mesozoic succession above the Keuper décollement with no salt diapirs (Berger et al. 1993; Ducoux 2017) or with narrow diapirs (Clerc et al. 2016). Both models require high estimations of Pyrenean shortening in the North Pyrenean Zone (43% according to Clerc et al. 2016; 58% according to Ducoux 2017).

In this paper we present detailed analyses of halokinetic features recognized for the first time in Mesozoic depocentres of the Pyrenean Trough in a 50 km long sector of the easternmost North Pyrenees. The work is based on high-resolution mapping and structural analyses. We document the distribution and style of salt features and clarify the role of salt in the evolution of Jurassic to Cretaceous depocentres and in Pyrenean convergence. We identify contrasting halokinetic tectonic styles on the rift platform, in the rift margin fault zone and in the main rift. We will argue that (1) crustal thinning of the European margin was accommodated on steep basement faults decoupled across Triassic salt from transtensional basins in Mesozoic cover, (2) the diapiric history of the eastern Pyrenees aligns with similar histories and behaviours in adjacent Pyrenean, Iberian and Alpine domains and (3) the documented basin and tectonic history is compatible with an Aptian–Cenomanian transtensional regime along the Iberia–Europe plate boundary.

M. Ford and J. Vergés
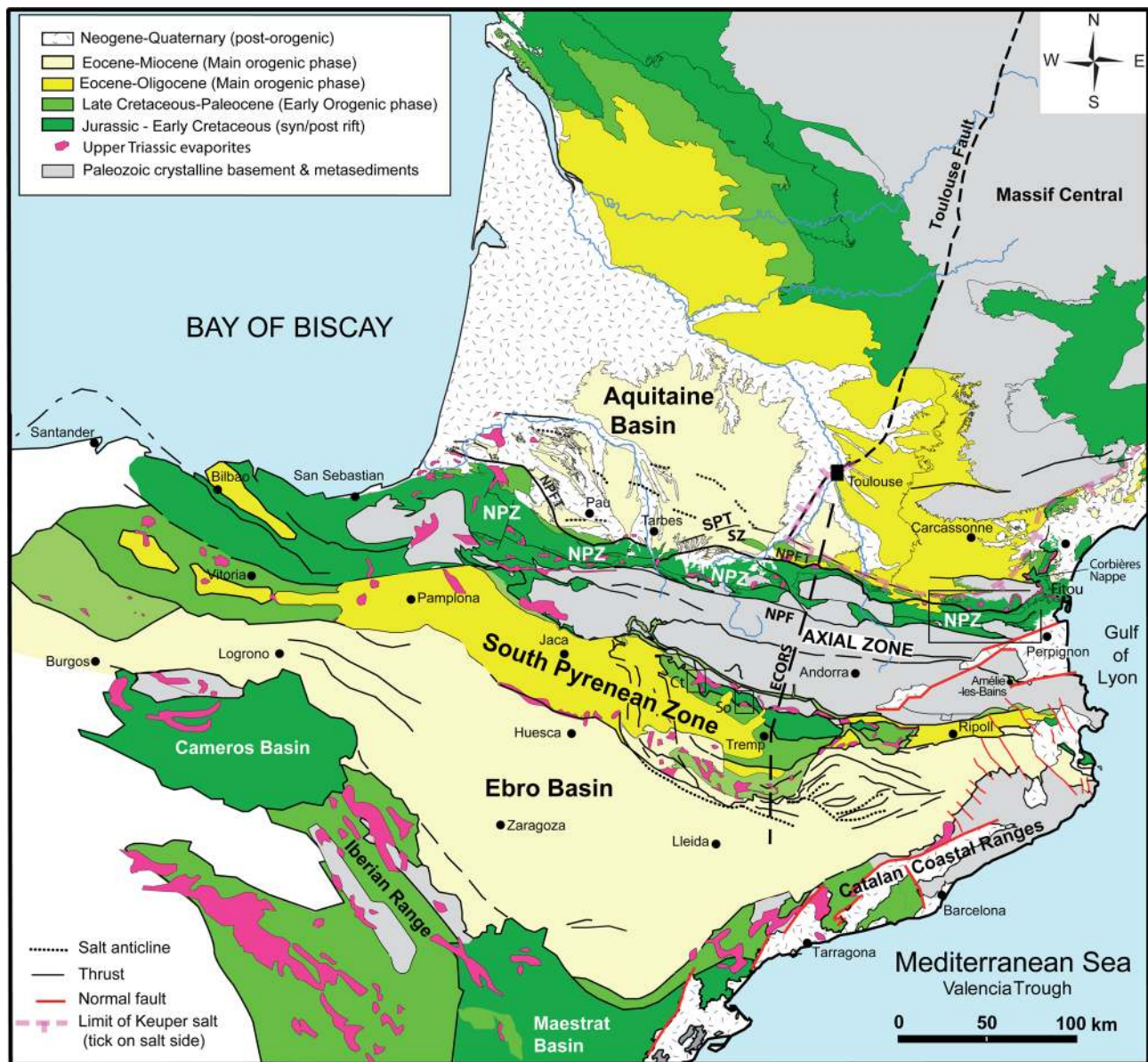
Fig. 1. Tectonostratigraphic map of the Pyrenees and Iberia adapted from Vergés et al. (2002) and Angrand et al. (2018). The small rectangle in the NE Pyrenees indicates the location of the area shown in Figure 3. Along the southern margin of the Axial Zone, Ct represents the location of the Coniacian to early Santonian Cotiella extensional system (Lopez-Mir et al. 2014, 2015) and So represents the location of the earliest Cretaceous to early Santonian Sopeira extensional system (Saura et al. 2016). NPZ, North Pyrenean Zone; NPF, North Pyrenean Fault; SZ, Subpyrenean Zone; SPT, Subpyrenean Thrust; NPFT, North Pyrenean Frontal Thrust.

Salt-related structures and halokinetic sequences

Identifying and interpreting extensional halokinetic sequences and relict salt features that have subsequently been inverted can be challenging. Here we present a summary of key extensional and compressional halokinetic features and terminology following Jackson and Hudec (2017). This paper will demonstrate the occurrence of these characteristic features in outcrop in the study area.

The northern Pyrenees is characterized by pre-rift salt (Middle to Upper Triassic Keuper evaporites). Depending on its initial spatial and thickness distribution and the amount of extension, pre-rift salt can decouple basement extension from deformation in suprasalt cover to varying degrees. Decoupling can continue during the full rifting process or can decrease gradually as extension increases and the salt layer thins (Jammes et al. 2010b; Rowan 2014). Our study is focused on the proximal Pyrenean rift domain where basement and cover appear to have remained mainly decoupled throughout the full

rift history. Extensional basement faults play a key role in creating accommodation in conjunction with halokinetic activity. Salt diapirs tend to develop above deep-rooted basement faults during extension. During inversion the most intense shortening is located in these salt-rich zones near or above basement faults as observed in other inverted rifts (e.g. Dooley and Hudec 2020).

In the study area, depocentres show a range of distinct halokinetic geometries that can be grouped into two types: extensional minibasins and basement detached extensional structures (Fig. 2a). Extensional minibasins are characterized by synsedimentary folding above mobile salt recorded in dip, thickness and facies variations, numerous local, angular and progressive unconformities and onlap surfaces, with local development of wedges, hooks and flaps (Fig. 2a). The width of synclinal depocentres varies depending on stratigraphic thickness and diapir spacing, both controlled by salt thickness and deeper extension. Basement detached extensional structures are characterized by rotational fault blocks with discordant downward termination of strata onto a primary weld or

Salt-rich transtensional rift margin, Pyrenees
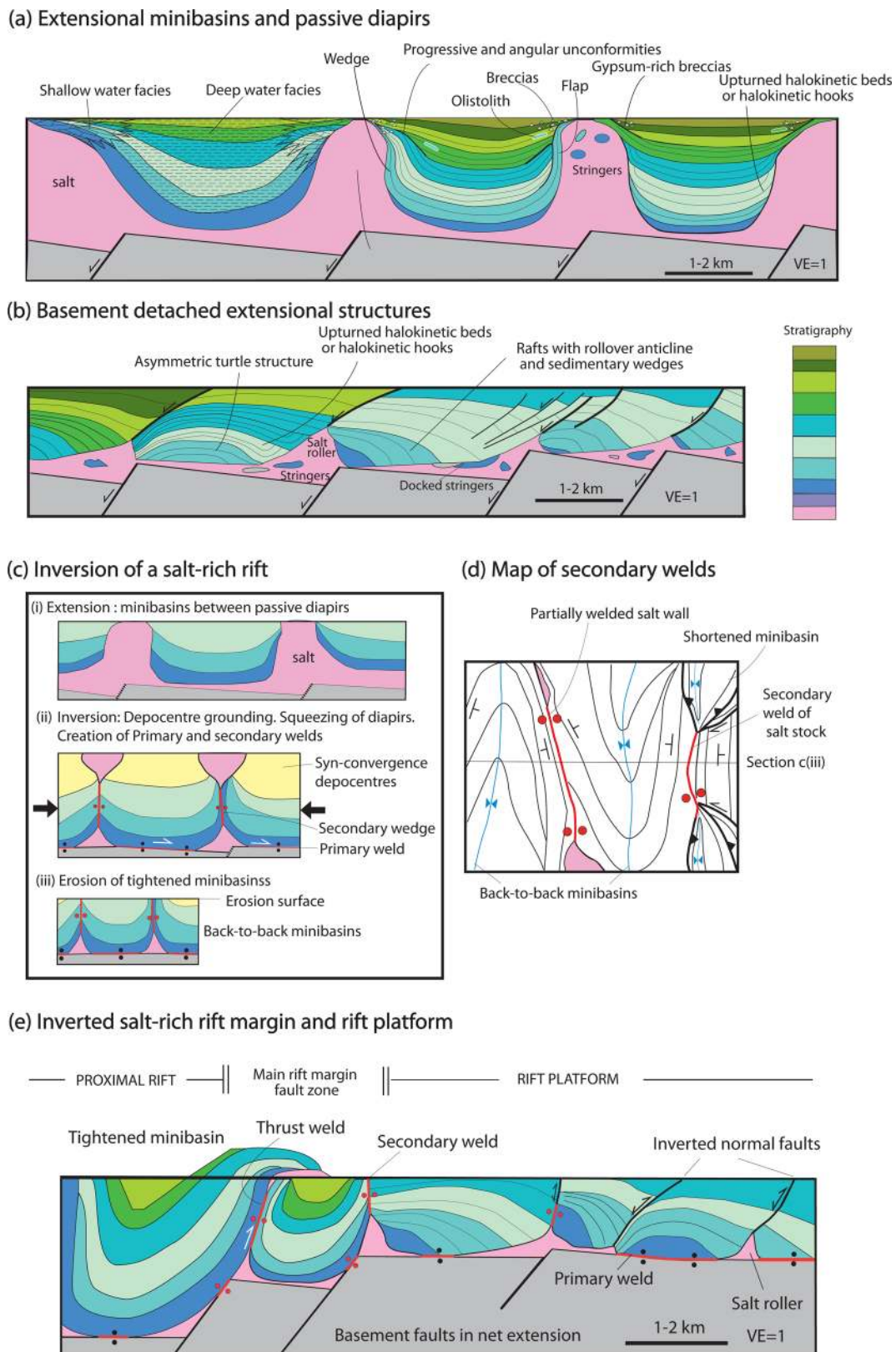
Fig. 2. Schematic illustrations representing halokinetic features and terminology used for both extensional and inversion regimes. (**a**) Salt-based synclinal depocentres. (**b**) Basement detached extensional fault blocks. (**c**) Contractional behaviour of salt diapirs and adjacent depocentres (adapted from Jackson and Hudec 2017): (i) Synclinal depocentres develop between salt diapirs; (ii) during contraction salt diapirs close owing to dissolution or upward extrusion of salt to form secondary welds; synconvergence depocentres can develop; (iii) further contraction tightens the synclinal depocentres, while erosion removes upper salt and most or all syn-contraction strata. (**d**) Map of two secondary salt welds, one along a former salt wall and the other on a former salt stock (adapted from Jackson and Hudec 2017). Thrusts and folds accommodate equivalent shortening on either side of the stock weld. The location of the schematic cross-section in (**c**, (iii)) is indicated. (**e**) Compendium of main features observed in the study area representing an inverted salt-rich proximal rift margin.
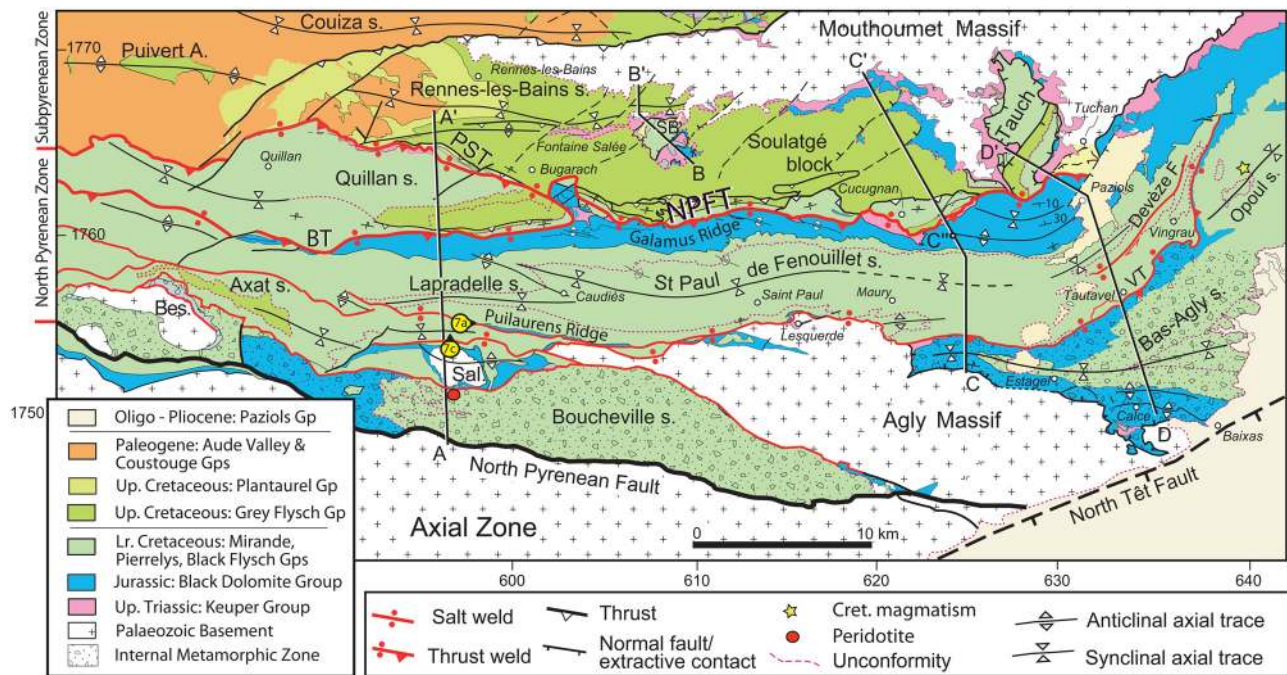
Fig. 3. Tectonostratigraphic map of the eastern North Pyrenees with halokinetic interpretation of major boundaries. Based on BRGM maps (Berger *et al.* 1982, 1993, 1997; Bessière *et al.* 1989) and new field mapping and using lithostratigraphic groups of Ford *et al.* (2016) as detailed in Figure 4 and Supplementary material Table 1). Cross-sections A–A', C–C' and D–D' are presented in Figure 5. Cross-section B–B' and a close-up view onto the north of section C–C' are shown in Figure 9. The locations of field photographs in Figure 7 are indicated with yellow circles. BT, Bougarach Thrust; PST, Pays de Sault Thrust; VT, Vingrau Thrust; Sal, Salvèzines Massif; Bes, Bessède Massif.

onto top salt. Rotational fault blocks can show dip fans and thickness variations, rollover anticlines or turtle structures and the local development of halokinetic upturned beds or hooks (Fig. 2b). A raft is an extensional fault block that has been completely separated from its footwall and lies entirely on the décollement. The basal salt layer typically forms salt rollers below each normal fault. Salt can contain blocks and debris (blocks, stringers or floaters) of lithologies originally interbedded within the salt or from the base of the suprasalt succession or from subsalt units. The contact between salt and overlying extensional blocks can be lined with docked stringers of varying sizes and lithologies (Fig. 2b). Both minibasins and basement detached fault blocks can record basinward migration of subsidence as represented in Figure 2a and b.

Evidence of uplift, erosion and shedding of material from rising diapirs can be found within synrift sediments. This includes the presence of debris flows rich in gypsum debris, euhedral quartz crystals and clasts of older lithostratigraphic units (Fig. 2a). Gypsum is a mechanically and chemically unstable material and therefore gypsum clasts must have been shed from an adjacent emergent diapir. Euhedral bipyramidal quartz crystals of diagenetic origin are ubiquitous in Keuper gypsum throughout the Pyrenees, and they are a useful indicator of where gypsum has been eroded (e.g. Charrière *et al.* 2004). Clasts of other lithologies in debris flows can derive from stringers or from steep diapir walls. Large (>100 m) olistoliths of older strata with Keuper along their base are found lying parallel to bedding within synrift strata adjacent to Keuper bodies. These are interpreted to have been emplaced as slide blocks shed off the side of an adjacent emergent diapir (Fig. 2a). Harrison and Jackson (2014) describe similar phenomena in minibasins of Arctic Canada.

During shortening, deformation tends to focus on weak diapirs. Consequently, secondary welds are preferentially developed in salt-rich fold-and-thrust belts (Rowan and Vendeville 2006; Jackson and Hudec 2017). If squeezed diapirs or secondary welds accommodate inverse displacement they are referred to as thrust welds. Secondary

welds and thrust welds are the most common contractional features in the North Pyrenean Zone, with locally preserved pockets of salt along their traces. Typically, secondary welds separate back-to-back minibasins (mapped as synclines) with oppositely younging steep limbs (sometimes flaps) juxtaposed across the weld (Fig. 2c and e). Extensional minibasins can contain different stratigraphies in terms of age, facies and thickness. Juxtaposed rock units can also change rapidly along the weld (Fig. 2d). Figure 2c is adapted from Jackson and Hudec (2017) to show the following evolution. (1) Pre-shortening extensional minibasins lie between passive diapirs. (2) Shortening causes upward and lateral migration of salt to create secondary welds, as minibasins tighten. Minibasins can continue to subside to create young depocentres. (3) Erosion later removes upper levels, preserving tightened minibasins juxtaposed across secondary welds. An example of a characteristic map view of this final configuration is shown in Figure 2d (adapted from Jackson and Hudec 2017). These examples illustrate the difficulty in distinguishing early halokinetic folding from later shortening.

The schematic illustration of an inverted rift margin in Figure 2e integrates most of the features that record past halokinetic activity during extension and subsequent inversion as seen in the study area. They include tightened synclinal minibasins separated by secondary welds, partial welds or thrust welds in the proximal rift and main rift fault zone, and inverted extensional fault blocks with strata terminating downward onto a primary weld or into salt on the rift platform. Gentle to moderate shortening was accommodated in thrust welds, secondary welds and tightening of minibasins. Inversion is not evenly distributed, with the most intense shortening located in salt-rich areas usually above major basement faults. There is little reactivation of basement faults as the top of basement remains in net extension. Other outcropping examples of inverted salt-rich rifts are the Flinders Range, Australia (Rowan and Vendeville 2006) and the Atlas Mountains of Morocco (Saura *et al.* 2014; Martín-Martín *et al.* 2017; Moragas *et al.* 2017; Teixell *et al.* 2018; Vergés *et al.* 2017).
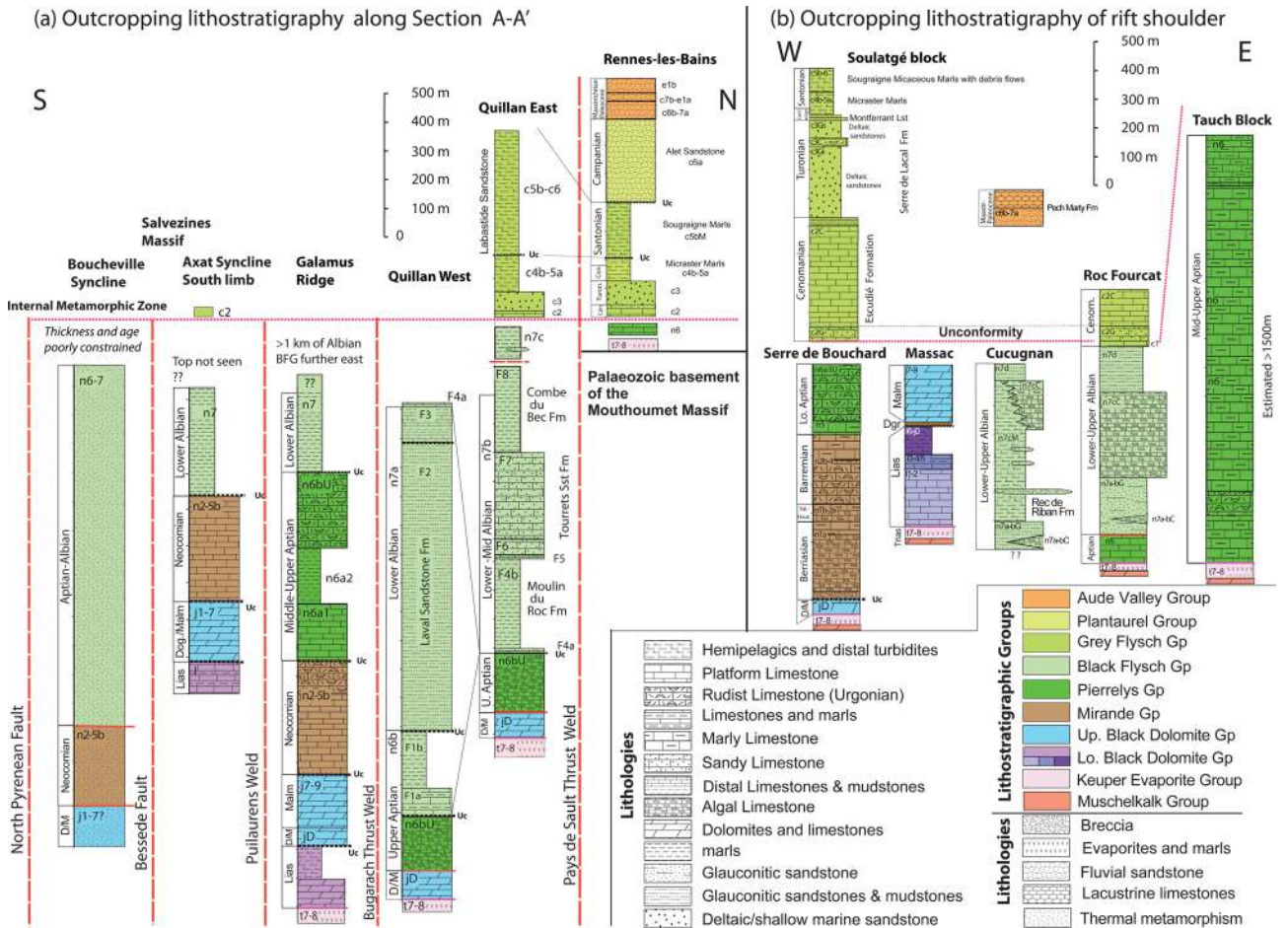
Fig. 4. Outcropping lithostratigraphic units (**a**) along the north–south cross-section A–A' between Quillan and Salvezines (see Figs 3 and 5) and (**b**) along an east–west transect north of the North Pyrenean Frontal Thrust. (For details see Supplementary material Table 1.) As well as our own mapping, primary data sources are BRGM maps and memoirs (French Geological Survey; Berger *et al.* 1982, 1993, 1997; Bessière *et al.* 1989), regional syntheses (Plaziat 1981; Debrand-Passard *et al.* 1984; Barnolas and Chiron 1996; Beziat *et al.* 2001; Christophoul *et al.* 2003) and local studies (e.g. Aragon 1988; Peybernès *et al.* 1999; Bilotte 2007).

Regional tectonics and stratigraphy

Pyrenean orogen

The N100°-trending Pyrenean orogen formed during Late Cretaceous to Early Miocene convergence of the Iberian and Eurasian plates (Fig. 1). On the north side of the orogen the North Pyrenean Zone is a narrow north-verging fold-and-thrust belt that developed on the (upper) European plate along with the adjacent Aquitaine (retro-) foreland basin and intervening Subpyrenean Zone. The Axial Zone preserves the highest relief and is characterized by mainly Paleozoic magmatic and metamorphic units organized in a series of south-verging crustal imbricates (e.g. Muñoz 1992). To the south, the south-verging South Pyrenean Thrust belt and the Ebro foreland basin developed on the Iberian plate.

The orogeny inverted a complex Mesozoic rift system with an east–west to ESE–WNW trend that linked the North Atlantic via the Bay of Biscay with the Tethys oceanic realm to the east (e.g. Stampfli *et al.* 2002; Schettino and Turco 2011; Tavani *et al.* 2018). Mesozoic rifting developed in two phases. From the Late Permian to early Jurassic distributed rifting (Vergés *et al.* 2019) affected the Iberian plate (Frizon de Lamotte *et al.* 2015; Leleu *et al.* 2016; López-Gómez *et al.* 2019). The exact duration of this early rift phase in the Pyrenees is unclear; however, in the eastern Pyrenees it is thought to have terminated in the late Lias to early Dogger (Bessière *et al.* 1989). The major rifting phase occurred from the Aptian to

Early Cenomanian (Tugend *et al.* 2014). During the Mesozoic, Iberia was translated eastward with respect to Europe some 450 km (Nirrengarten *et al.* 2018); however, the amount, timing and location of this strike-slip component and the associated rotation of Iberia are still widely debated (see Mouthereau *et al.* 2014; Barnett-Moore *et al.* 2016; Nirrengarten *et al.* 2018, for discussions). Several researchers have proposed that major sinistral motion took place in the Jurassic along NW–SE lineaments that dissect the Iberian plate and that Aptian–Albian rifting in the Pyrenees had little or no oblique component (e.g. Tugend *et al.* 2014; Nirrengarten *et al.* 2018). However, earlier workers placed the principal sinistral motion along the Iberia–Europe boundary during Aptian and Cenomanian transtensional rifting (e.g. Le Pichon and Sibuet 1971; Choukroune and Mattauer 1978; Soula and Bessière 1980; Debroas 1990).

The inverted rift system (Pyrenean Trough) is principally preserved in the North Pyrenean Zone. Remnants of mantle rocks and traces of Albian–Cenomanian synrift HT–LP metamorphism occur in the southern North Pyrenean Zone (Metamorphic Internal Zone; Fig. 3). Cretaceous exhumation of mantle rocks and associated thermal events have been attributed either to transtensional rifting (e.g. Choukroune and Mattauer 1978; Debroas 1990; Golberg and Leyreloup 1990; Choukroune 1992; Lagabrielle and Bodinier 2008) or, more recently, to pure shear hyper-extension (Jammes *et al.* 2009, 2010a; Lagabrielle *et al.* 2010, 2016, 2020; Clerc 2012, 2016; Masini *et al.* 2014; Tugend *et al.* 2014, 2015; de Saint Blanquat *et al.* 2016).
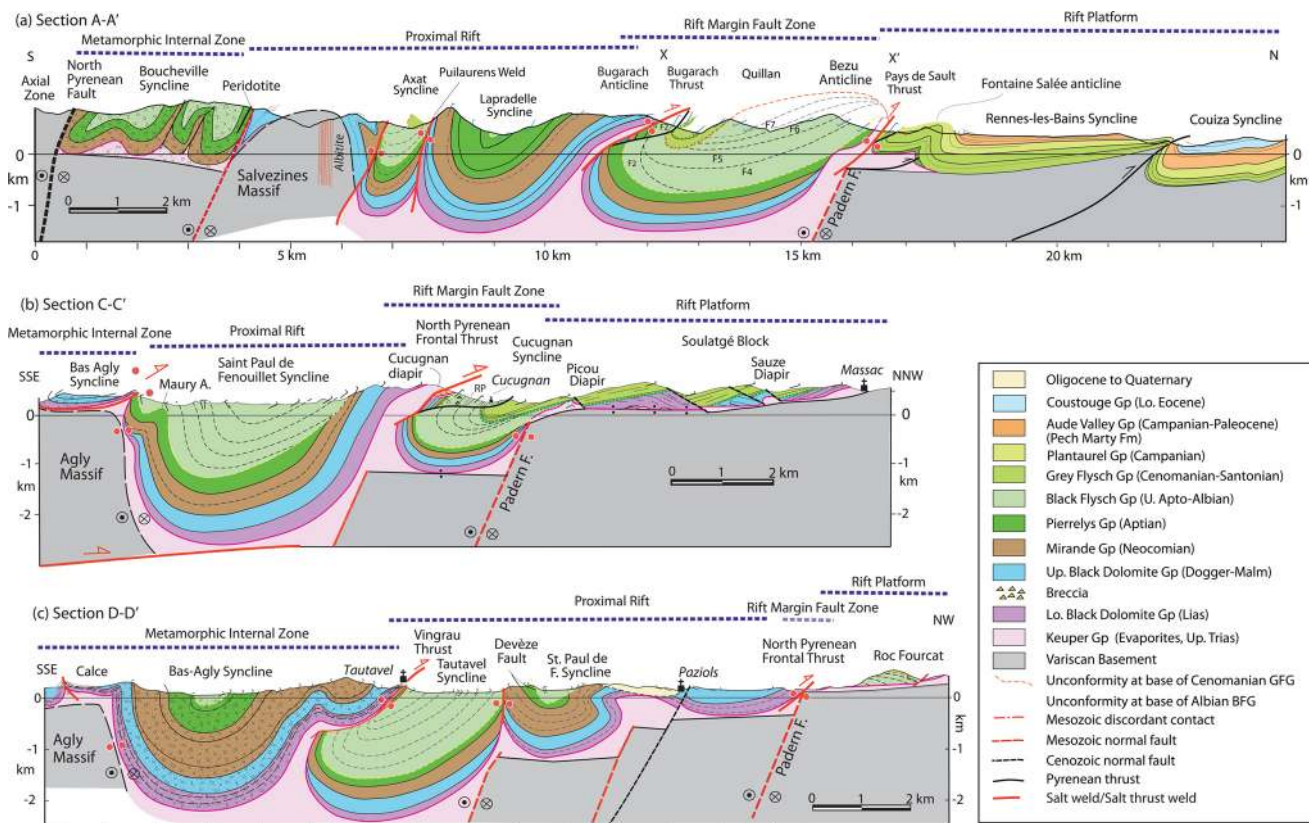
Fig. 5. Three cross-sections through the eastern North Pyrenean Zone and its foreland. Locations of sections are shown in Figure 3. Location of X–X' on section A–A' is shown in Figure 8a. Section A–A' traverses the whole North Pyrenean Zone, and sections C–C' and D–D' represent the northern North Pyrenean Zone to the Agly Massif, including part of the Metamorphic Internal Zone.

Post-rift lithospheric cooling and thermal subsidence from the mid-Cenomanian to latest Santonian (lasting 7–10 myr) was interrupted by the onset of Iberia–Europe convergence at 84 Ma (Roest and Srivastava 1991; Olivet 1996; Rosenbaum et al. 2002a, b; Schettino and Scotese 2002; Macchiavelli et al. 2017). Orogenesis records early, slow convergence from the Campanian to end-Maastrichtian followed by a quiet period before main collision from early Eocene to early Miocene time (Ford et al. 2016; Rougier et al. 2016; Grool et al. 2018). Estimates of total north–south Pyrenean shortening vary between 165 and 83 km (Muñoz 1992; Vergés et al. 1995, 2002; Beaumont et al. 2000; Mouthereau et al. 2014; Teixell et al. 2016, 2018; Grool et al. 2018). Shortening was principally accommodated

during the Eocene in the south-verging South Pyrenean Thrust belt and Axial Zone, with only an estimated 10–20% of total shortening in the northern Pyrenees (Grool et al. 2018, 2019).

Stratigraphy

The Triassic to Oligocene lithostratigraphic scheme used here follows Ford et al. (2016) and Rougier et al. (2016) (Fig. 4 and Supplementary material Table 1). Thicknesses given below are those published for surface exposures. Data were derived from BRGM maps and memoirs (French Geological Survey; Berger et al. 1982, 1993, 1997; Bessière et al. 1989), regional syntheses (Plaziat
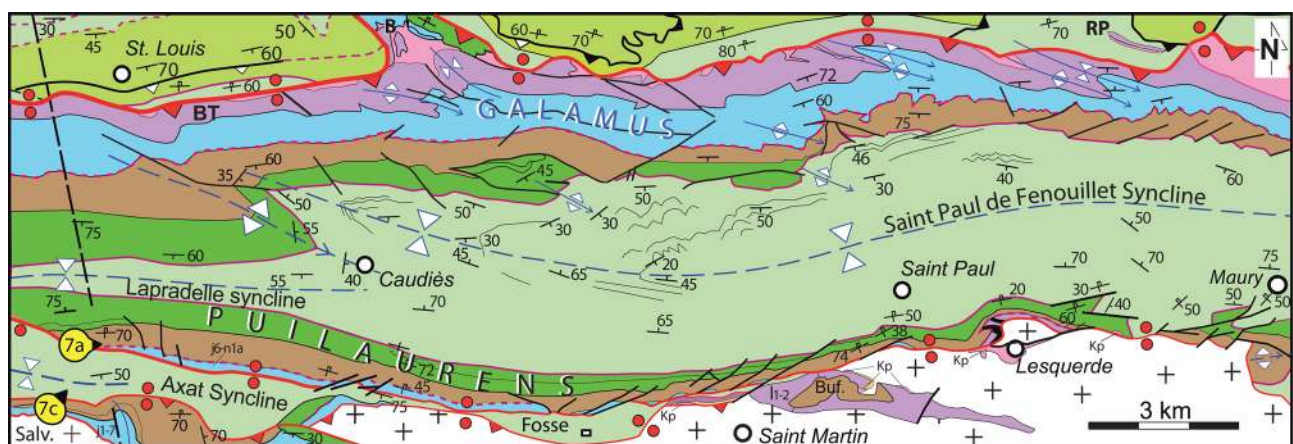
Fig. 6. Detailed geological map of the North Pyrenean Zone, the Saint Paul de Fenouillet syncline and surrounding areas. (For stratigraphy legend see the Lapradelle–St Paul syncline column in Figure 4, and for key to structures see Fig. 3.) Black unit around Lesquerde represents hematite mineralization. Yellow circles show locations from where field photographs in Figures 7a and b were taken. Kp, Keuper outcrops; BT, Bugarach thrust; B, Bugarach Mountain; Buf, Roc de la Bufferte; Salv. Salvezines basement Massif; RP, Roc Pouyrit.
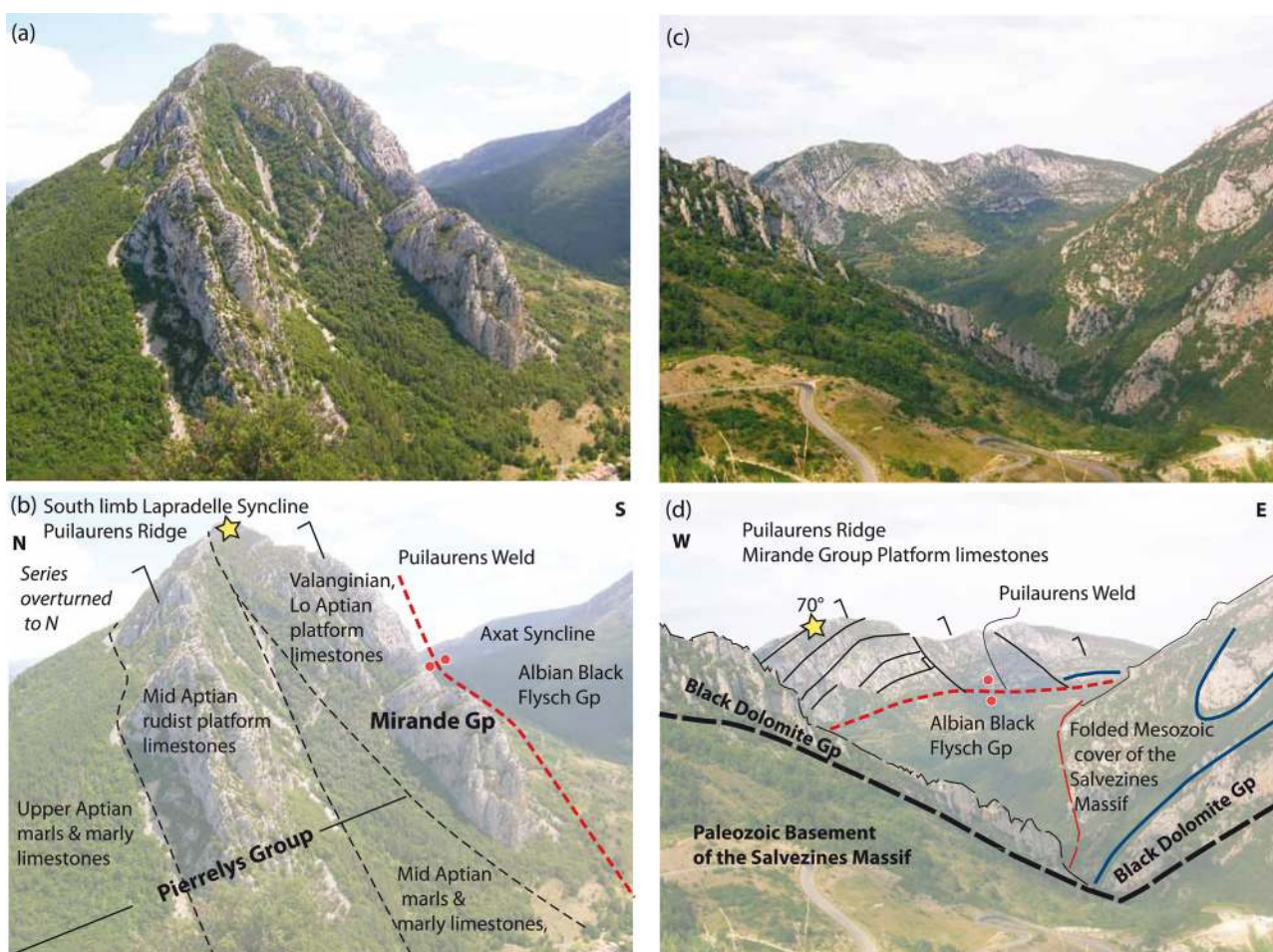
Fig. 7. (**a**) View and (**b**) interpretation of the Puilaurens Ridge looking east from Puilaurens Castle showing updip changes in facies and thickness in Lower Cretaceous carbonates. The ridge is bordered to the south by the extractive Puilaurens weld juxtaposing Albian Black Flysch of the Axat syncline. (**c**) Field photograph and (**d**) interpretation looking northward from the Salvezines basement Massif toward the Puilaurens Ridge and weld. Locations of both viewpoints are shown in Figures 3 and 6.

1981; Debrand-Passard *et al.* 1984; Barnolas and Chiron 1996; Beziat *et al.* 2001; Christophoul *et al.* 2003) and more local studies (e.g. Aragon 1988; Peybernès *et al.* 1999; Bilotte 2007) as well as our own mapping.

Thin autochthonous cover on the Paleozoic Mouthoumet massif (Fig. 3) comprises two units, which are usually included in basement in our figures. These are the Upper Permian to Lower Triassic fluvial Buntsandstein (<20 m of sandstones and conglomerates) and the Middle Triassic Muschelkalk recording earliest rifting (10–25 m dolomites, thin evaporites and marls).

The Keuper Group (Carnian to Norian) consists of thinly bedded mudstones interbedded with gypsum, anhydrite, dedolomitized dolomite (cargneules) and rare black dolomites. In rare field exposures chaotically bedded gypsum and mudstones are rich in euhedral millimetre- to centimetre-size bipyramidal quartz crystals (Charrière *et al.* 2004). No halite has been reported in the eastern Pyrenees (Azambre and Fabriès 1989). Fragments to large blocks (stringers) of Paleozoic metasediments, Muschelkalk and Liassic strata locally occur in Keuper evaporites. As pointed out by many researchers (Labaume and Teixell 2020, and references therein) the presence of stringers of Muschelkalk within salt across the northern Pyrenees suggests the presence of weak layers (evaporites or marls) within the Muschelkalk itself, similar to that described in the southern Pyrenees (Cámara and Flinch 2017). Bodies of Carnian–Norian alkaline basalts (altered to ophites) and crystalline tuffs typical of the Tethyan domain occur in easternmost Keuper evaporites of Corbières but have not been observed in the study

area (Azambre and Rossy 1981; Beziat *et al.* 2001). Owing to its mobility, Keuper thickness is extremely variable and difficult to constrain. The Keuper is absent across the Carcassonne High to the north and west of the Mouthoumet massif (Fig. 1).

Rhaetian carbonates (10–15 m) are very rarely observed in the study area and are therefore not included in lithostratigraphic columns. The Jurassic Black Dolomite Group (400–800 m) has an attenuated, often incomplete Liassic succession (<250 m) of marly limestones, altered evaporites and dolomites followed by black marls, which can behave as a secondary slip horizon (Fauré and Alméras 2006) . A local unconformity (Aalenian–Bajocian absent) is interpreted to mark the end of the first rifting phase (Bessière *et al.* 1989). Where present, Upper Dogger black dolomites and marls pass upward into shallow-water limestones and breccias (Malm; <300 m) with secondary dolomitization and brecciation (Bessière *et al.* 1989; Renard *et al.* 2019). The Neocomian platform limestone succession including algal and rudist limestones (Mirande Group; Fig. 4) can be interrupted by local unconformities (e.g. Upper Valanginian–Hauterivian). It is less than 350 m thick across the North Pyrenean Zone but reaches 600 m in the Serre de Bouchard block north of the North Pyrenean Frontal Thrust (Figs 3 and 4). Preservation of the Black Dolomite and Mirande Groups can be locally incomplete owing to a poorly defined phase of uplift and erosion from the Late Jurassic to Early Cretaceous (Neo-Cimmerian event; Canérot 2008).

The Aptian Pierrelys Group (<900 m) consists principally of shallow-water carbonate platforms (often with rudists) in the study
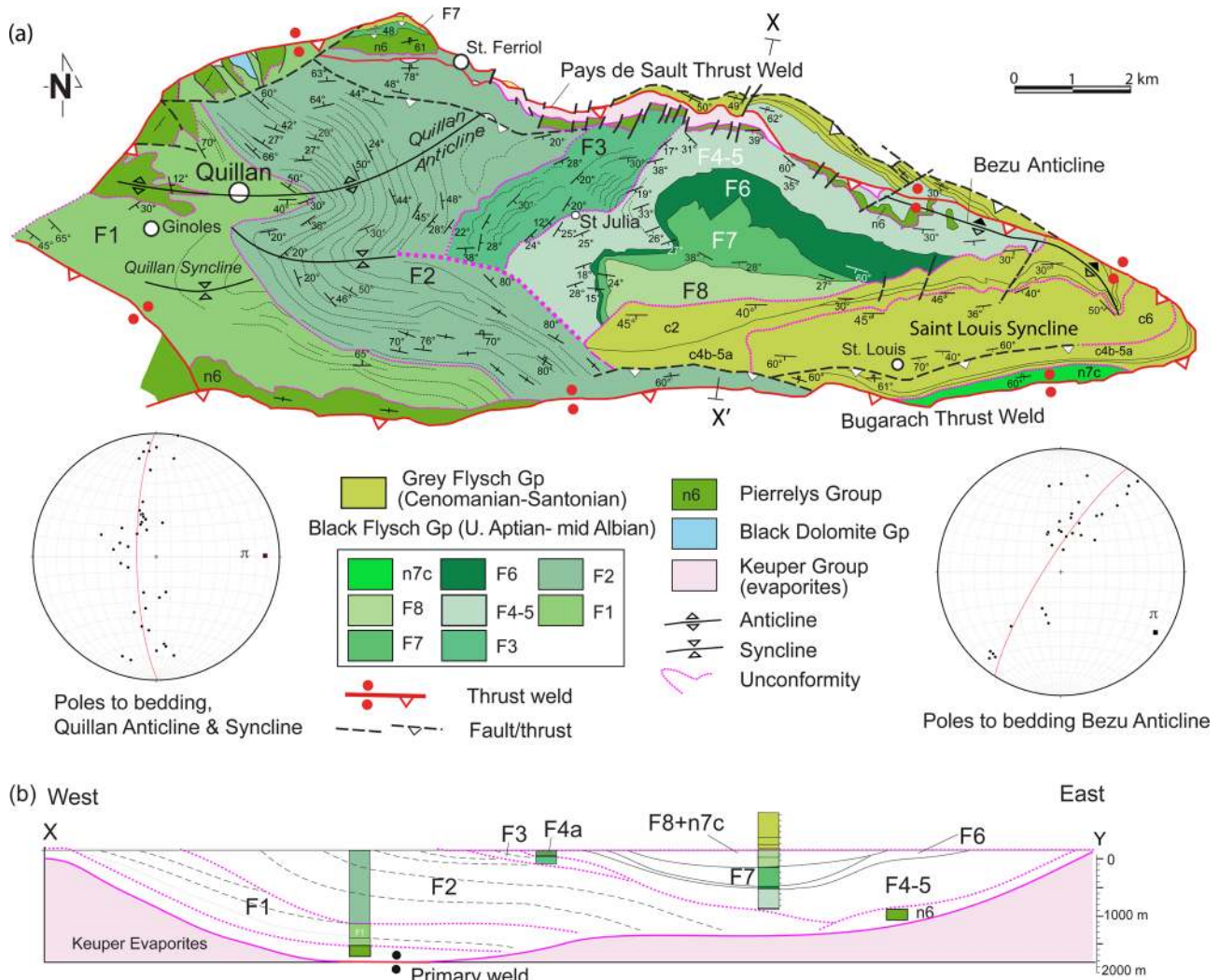
Fig. 8. (**a**) Geological map of the Quillan minibasin based mainly on new geological mapping and using the stratigraphic subdivisions (formations) of Aragon (1988) for the Aptian–Albian Black Flysch Group. The position of part of section A–A' (Fig. 5a) is shown by X–X'. Equal area sterographic plots of poles to bedding are shown for the western syncline–anticline pair (left) and for the eastern Bezu anticline (right). (**b**) Schematic longitudinal section from west to ESE along the axis of the Quillan depocentre representing the migration of the Aptian–Albian depocentres above mobile Keuper salt. An interpreted Google Earth view of this area is available in Supplementary material Figure S1.

area with shallow- to deep-water black shales defining local deep-water depocentres. The succession is characterized by complex facies and thickness changes with local unconformities (Peybernès 1976; Bessière et al. 1989). From the latest Aptian (Clanseysian) to end Albian–earliest Cenomanian rift basins were filled by deep-water and deltaic calcareous siliciclastic deposits of the Black Flysch Group (>2 km thick) sourced from the east. These depocentres can be bordered by platform carbonates (e.g. Cucugnan, Fig. 4).

A mid-Cenomanian unconformity marking the end of rifting is recognized throughout the northern Pyrenees. The post-rift Grey Flysch Group was deposited during a 7–10 myr period of post-rift subsidence in a broad marine basin that covered most of the Pyrenees, with facies recording a gradual shallowing through time (Ford et al. 2016). The >900 m succession of marine carbonates and clastic deposits onlaps and thins northward onto the Mouthoumet Massif (Berger et al. 1997; Bilotte et al. 2005; Bilotte 2007). Facies deepen southward (Bilotte 1985) and record progressive shallowing through time. Sediments continued to be supplied from the east. Youngest beds contain debris flows and breccias (Durand-Delga and Lemoine 1978). Late Cretaceous magmatism produced small volumes of alkaline microsyenite (Azambre 1966) and a nepheline syenite intrusion immediately east of the study area (Fitou, Fig. 1; Montigny et al. 1986). The onset of Pyrenean orogenesis at 84 Ma is

marked by an initial deepening of the Pyrenean Trough (Plantaurel Group, Alet Sandstone Formation, sourced from the east; Figs 3 and 4), followed by a transition to continental facies (Aude Valley Group). As the younger foreland basin succession is preserved only in the NW corner of the study area, its stratigraphy is summarized only in Supplementary material Table 1 and is represented in Figure 5a. Detailed information has been given by Christophoul et al. (2003) and Ternois et al. (2019). Oligocene–Miocene deposits in extensional NE–SW-trending depocentres related to the opening of the Gulf of Lion are preserved in the eastern part of the study area (Paziols Group; Fig. 3).

The eastern North Pyrenees

In the eastern Pyrenees the North Pyrenean Frontal Thrust separates the North Pyrenean Zone from the Subpyrenean Zone to the north (Fig. 3). The former is a 16–25 km wide fold-and-thrust belt bordered to the south by the North Pyrenean Fault, which is a major subvertical tectonic feature, generally regarded as the Iberia–Europe plate boundary (Choukroune 1989; Roure et al. 1989). At its eastern limit the North Pyrenean Zone curves anticlockwise into the 60 km wide north-trending Corbieres orocline that links northward and eastward into the east-trending Provençal fold-and-thrust belt
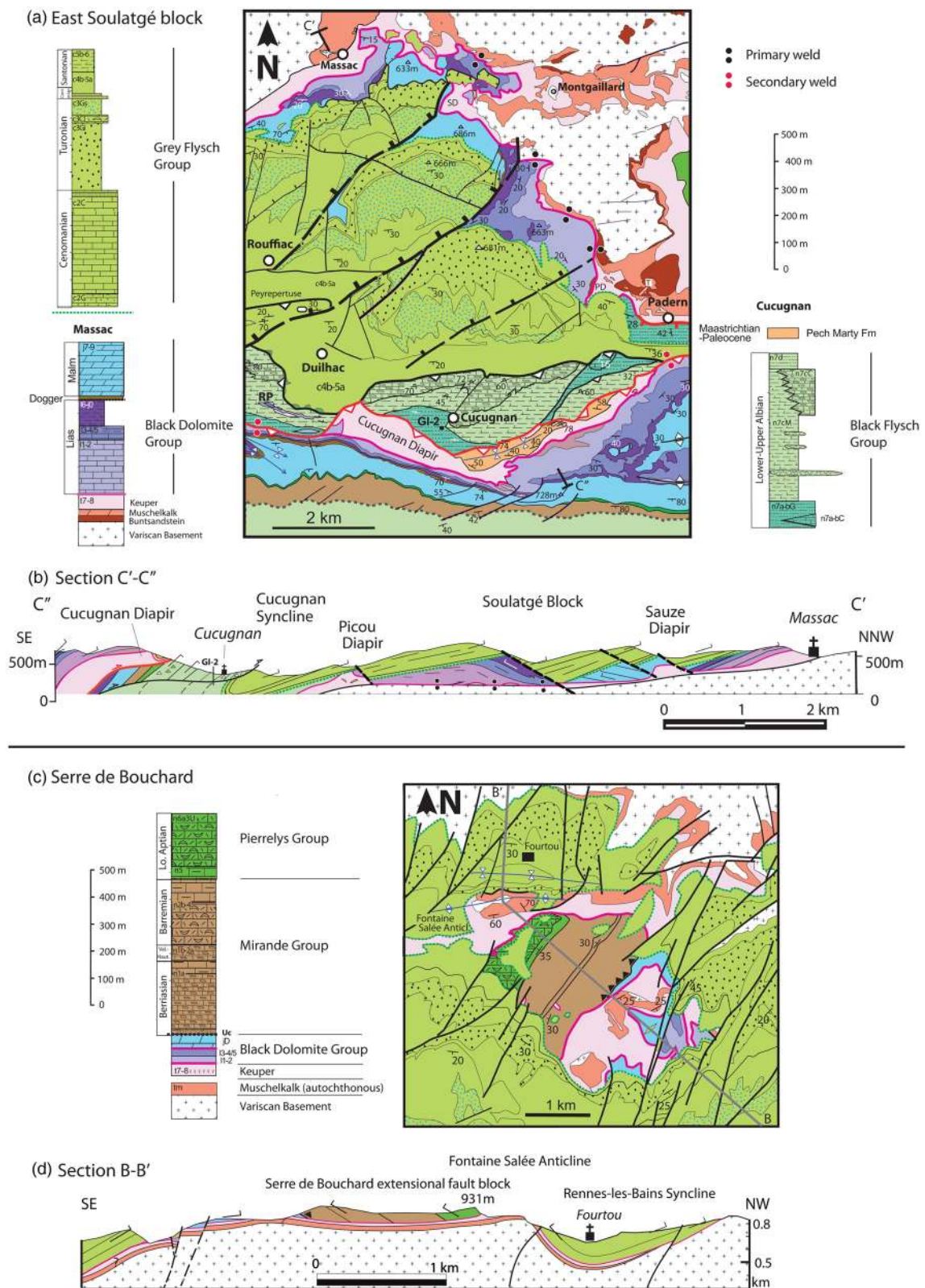
Fig. 9. (**a**) Geological map of the Cucugnan to Massac area with detailed stratigraphic columns. (**b**) NNW–SSE cross-section through the Massac to Cucugnan area (C–C'' in (a) and part of C–C', Fig. 5). (**c**) Geological map and stratigraphic column of the Serre de Bouchard inlier. (**d**) Composite NNW–SSE cross-section through the Serre de Bouchard inlier (location shown in (**c**)).

(Fig. 1). The structural evolution of the area was the subject of many studies in the 1970s and 1980s (Choukroune 1974; Choukroune and Meurisse 1970; Meurisse 1973; Leblanc and Vaudin 1984; Bessière 1987; Légier *et al.* 1987; Dauteuil 1988). To the north of the North Pyrenean Frontal Thrust, Triassic to Upper Cretaceous strata are

preserved on the SE limb of the Mouthoumet Massif, a basement-cored regional anticline (Soulatgé Block; Fig. 3). This northern area is identified as the Mesozoic rift platform.

The North Pyrenean Frontal Thrust is a complex salt-rich fault zone. It comprises multiple ESE- to east-trending segments linked

by NE–SW-striking faults. Keuper lithologies occur discontinuously along these faults, with notable masses south of Bugarach and Cucugnan villages (Fig. 3). Distinct Aptian–Albian depocentres, preserving between 1.5 and 3 km of Liassic to Albian stratigraphy (Quillan, Cucugnan; Figs 3 and 5), lie along the fault zone, each surrounded by salt welds and diapirs. On the rift platform to the north (Figs 3 and 5), a fragmented Liassic to lower Aptian succession, up to 900 m thick, lies below the strongly erosive, mid-Cenomanian unconformity. Albian strata are absent across this area. To the south in the North Pyrenean Zone a >3 km thick Keuper to Albian succession is preserved. The Mesozoic succession thickens southward across the North Pyrenean Frontal Thrust (Fig. 4a), which therefore represents the main northern boundary fault zone of the Mesozoic rift system. Despite Pyrenean inversion the top basement remains in net extension across this fault zone (Fig. 5; e.g. Choukroune et al. 1973; Peybernès and Souquet 1984).

As no subsurface data are available, the cross-sections in Figure 5 are based on surface observations. A complete stratigraphic succession is represented at depth below each syncline by laterally projecting surface data down fold plunge where possible. Highest uncertainty is associated with the presence of pre-Aptian units below the Quillan, Cucugnan, Axat and Boucheville synclines. Absence or fragmentation of pre-Aptian units below these depocentres would imply higher Cretaceous extension.

The northern sector of the North Pyrenean Zone consists of folded Mesozoic strata and represents the inverted proximal rift domain. The southern sector, consisting of the Agly–Salvezines massif and the Metamorphic Internal Zone, preserves the inverted distal rifted margin (following Vauchez et al. 2013; Clerc et al. 2016; Ducoux 2017). The Agly–Salvezines massif comprises granulite- to greenschist-grade metamorphic rocks intruded by Variscan granitic and granodioritic plutons (Vielzeuf and Kornprobst 1984; Vauchez et al. 2013). Small remnants of Jurassic and Lower Cretaceous strata are preserved in fault zones and as outliers across the massif (Figs 3 and 6). Sediments and basement carry a Cretaceous thermal overprint of c. 350°C (Clerc et al. 2016; Ternois et al. 2019). Metamorphosed Jurassic and Triassic strata recording higher temperatures are preserved in the NE sector of the Massif (Calce area; Fig. 3; Vaudin 1982; Ternois et al. 2019). The Salvezines massif further west is a tight periclinal basement-cored anticline, which refolds Jurassic and lower Cretaceous cover (Choukroune and Meurisse 1970; Demange and Pascal 1979; Figs 3 and 5a). In situ, low-temperature thermochronology data and modelling show that the Agly–Salvezines Massif was buried below at least 2 km of Mesozoic sediment at the onset of convergence (Ternois et al. 2019).

The Metamorphic Internal Zone includes the Bas Agly syncline (25 km long, up to 8 km wide) and the Boucheville syncline (30 km long and 5 km wide) that lie to the northeast and south of the Agly Massif respectively (Figs 3 and 5). Jurassic and Lower Cretaceous strata record HT metamorphism with temperatures up to 570°C (Chelalou et al. 2016; Clerc et al. 2015; Ducoux 2017), dated as late Early to early Late Cretaceous (117–92 Ma; Albarède and Michard-Vitrac 1978; Golberg et al. 1986; Clerc et al. 2015). The north-verging Bas Agly syncline has a coherent Mesozoic stratigraphy and is thrust north over the low-grade Tautavel syncline (<250°C; Chelalou et al. 2016) along the Vingrau Thrust (Figs 3 and 5d). In contrast, the Boucheville syncline records a more intense and complex polyphase structure attributed to synmetamorphic deformation and Pyrenean shortening (e.g. Choukroune 1974; Chelalou et al. 2016; Clerc et al. 2016). A 30–40 m wide block of serpentinized lherzolite lies within the Aptian–Albian succession close to the northern margin of the Boucheville syncline (P, Figs 3 and 5a; Demange and Pascal 1979). This is the most easterly of many fragments of upper mantle rocks that occur throughout the Metamorphic Internal Zone, recording exhumation of mantle rocks

during Cretaceous extension (Lagabrielle et al. 2010). Although high-temperature metamorphism and intense deformation have largely destroyed evaporitic layers, there is evidence that evaporites were present. Extensive albitization (400–450°C) affected the Agly–Salvezines basement during the early Cretaceous middle Aptian to early Turonian (117–92 Ma; Boulvais et al. 2007; Boutin et al. 2016; and references therein). Albitization and other observed forms of HT metasomatism require the presence of highly saline hydrothermal fluids, which are also necessary for the formation of minerals such as scapolite that occur throughout the Metamorphic Internal Zone (e.g. Boulvais et al. 2007).

Previous models for the area (Lagabrielle et al. 2010; Clerc et al. 2016; Odlum and Stockli 2019; Teixell et al. 2018) propose that crustal thinning was accommodated on one or more major crustal detachments. These models focused mainly on explaining the abrupt thinning of crust, the exhumation of mantle lithosphere in the centre of the rift and HT thermal events. The role of salt and the link to proximal margin tectonics were not considered and will be addressed here.

Salt-related structures in the eastern North Pyrenees

We have subdivided the study area into three distinct zones, the rift platform, rift margin fault zone and main rift (Figs 2e and 5). This section describes in detail characteristic structures from each of these zones. In each case we highlight those aspects of the structure that underpin our interpretation of these zones in terms of salt-controlled extension with reference to Figure 2 and where appropriate, evidence for a strike-slip component during extension.

Northern North Pyrenean Zone (proximal main rift)

The northern sector of the North Pyrenean Zone consists of open to tight, north facing to upright synclines involving >3 km of Triassic to Albian strata. Younger Grey Flysch strata are locally preserved in small outliers (e.g. Axat syncline; Figs 3 and 5). Regional anticlines are rare, being replaced by north-vergent thrusts or steep tectonic contacts mapped as faults, often with traces of Keuper evaporites (e.g. Puilaurens, Figs 3 and 6). The Saint Paul de Fenouillet syncline is 30 km long and 5–6 km wide and north-verging (Figs 3, 5 and 6). Its axial trace is sinuous and left-stepping, forming a sinistral, en echelon pattern with the Lapradelle and Axat synclines to the west. The axial traces of these folds are rotated clockwise with respect to the overall trend of the zone. To the east, the axial trace of the Saint Paul de Fenouillet syncline curves to NE into the Corbieres orocline, before terminating north of the Devèze block. At least 1 km of fine-grained Albian marine clastic deposits (Black Flysch Group) unconformably onlap older strata on both fold limbs (Figs 3, 5 and 6).

On the syncline's north limb, c. 900 m of Black Dolomite and Mirande carbonates form the prominent Galamus Ridge, in the immediate hanging wall of the salt-rich North Pyrenean Frontal Thrust (Figs 3 and 5). Bedding dips steepen eastward along the ridge (Fig. 6) becoming overturned to the SE of Cucugnan where the strata are overlain in marked angular unconformity by Albian strata (Fig. 5d) recording syn-extension tilting and erosion along the synclinal north limb. Along the central Galamus Ridge in the immediate hanging wall of the North Pyrenean Frontal Thrust, instead of a single hanging-wall anticline, a series of small-scale (wavelength <2 km) sinistral en echelon fold pairs plunge some 30° toward N100° (Fig. 6). These folds are again rotated clockwise with respect to the regional east–west trend. All have Keuper in their hinges (Leblanc and Vaudin 1984). These folds can involve either Jurassic units only or upper Jurassic to Albian strata dying out rapidly down plunge to the ESE into Albian Black Flysch. The Galamus Ridge is cut by N60–N70° sinistral faults that are difficult to trace into the Black Flysch (Fig. 6). The orientation and

distribution of these second-order folds and faults are compatible with a component of sinistral strike-slip deformation along the Galamus Ridge that predates Pyrenean inversion. Similar en echelon folds are reported in Jurassic strata along the NE margin of the Agly Massif, where they have also been interpreted as recording pre-Pyrenean sinistral strike-slip (Calce region, Figs 3 and 5c; Vaudin 1982; Leblanc and Vaudin 1984).

The 15 km long Puilaurens Ridge forms the southern limb of the Saint Paul de Fenouillet and Lapradelle synclines (Figs 5a and 6). Steep to overturned Neocomian to Albian limestones (Mirande and Pierrelys Groups) show up-dip and along-strike thickness variations (Figs 3, 5a and 6; Leblanc and Vaudin 1984). Uppermost Jurassic limestones (j6-n1a, Fig. 6) occur as a thin, incomplete and fragmented level along the faulted southern boundary of the ridge. The overturned western ridge is juxtaposed against subvertical to south-dipping and south-younging Black Flysch of the Axat syncline (Figs 5a, 6 and 7). When traced eastward, this steep boundary juxtaposes the Puilaurens Ridge against Paleozoic granite of the Agly Massif (Figs 3 and 6). Keuper evaporites occur sporadically along this contact, notably at Fosse and Lesquerde (Kp, Fig. 6). At Lesquerde the Puilaurens Ridge becomes strongly overturned to the north to form a flap-like structure involving highly attenuated Jurassic strata with a scapolite-grade thermal metamorphic overprint, and a strongly mineralized contact with basement (hematite; Berger et al. 1993). The easternmost ridge is cut by numerous NE–SW sinistral faults dying out into the Maury anticline, where Albian Black Flysch unconformably overlies steeply north-dipping and north-younging Mirande Group strata (Figs 3, 5 and 6).

At the eastern end of the Saint Paul de Fenouillet syncline Black Flysch strata unconformably overlie the NE–SW-trending Devèze block (Fig. 3) comprising Lower Cretaceous units. Albian Black Flysch strata of the Tautavel syncline are juxtaposed against the southern boundary of the Devèze block along a steep strike-slip fault zone. We interpret this boundary as a sheared salt weld, as traces of gypsum are found along its length (Fig. 5d). The highly asymmetric Tautavel syncline is overthrust by the metamorphosed Base Agly syncline along the Vingrau Thrust (Figs 3 and 5) with Keuper evaporites preserved at its western termination (Fig. 3; cross-section C–C', Fig. 5).

The North Pyrenean Frontal Thrust is interpreted as the inverted northern rift boundary marked by a network of major salt diapirs that developed above basement-cutting faults at depth. To the south of these major diapirs large en echelon extensional minibasins including Saint Paul de Feouillet and Lapradel developed. The main growth of these minibasins was during the Albian. A zone of major diapirs controlled their southern margins, as evidenced by the Puilaurens weld. The Axat syncline may also have developed as a minibasin between the Puilaurens diapir and a salt wall along its southern margin. The Tautavel syncline is also interpreted as an extensional minibasin with the Devèze diapir along its northern margin (Fig. 5c). Pyrenean shortening was accommodated principally by squeezing of salt walls to create secondary welds and thrust welds as described in Figure 2 and by tightening of synclinal depocentres.

The Quillan Minibasin (rift margin fault zone)

The Quillan minibasin is located between two salt-rich segments of the North Pyrenean Frontal Thrust (Figs 3, 5a and 8, and Supplementary material Fig. S1) and represents a distinct depocentre that developed along the rift margin fault zone. It is is a c. 20 km long and c. 8 km wide, east–west-trending broadly synclinal feature and preserves a cumulative thickness of at least 3 km of Upper Aptian–Middle Albian Black Flysch Group. The eight formations of the Black Flysch group (F1–F8; Aragon 1988) are characterized by rapid changes in thickness, facies and

orientation, and are often separated by angular unconformities with onlap surfaces (Figs 4 and 8 and Fig. S1). The succession consists of fine- to medium-grained, marine deltaic to deep-water prodelta calcareous siliciclastic deposits sourced from the east (Peybernès 1976; Aragon 1988). Overall, formations young towards the east and then to the SE (Fig. 8 and Fig. S1). The youngest Upper Albian formation of marls and limestones, rich in olistostromes (up to 300 m), is found only in an overturned, north-vergent imbricate immediately below the Bugarach Thrust (n7c, Figs 4 and 8; Peybernès 1976; Bessière et al. 1989). The Grey Flysch Group unconformably overlies older units. The youngest Upper Santonian marine Labastide Formation is preserved in the east–west-trending north-verging Saint Louis syncline (Figs 4a and 8; Bessière et al. 1989; Bilotte et al. 2005; Bilotte 2007).

The lozenge-shaped Quillan minibasin is bordered by two north-vergent thrusts (Pays de Sault and Bugarach thrusts; Fig. 3 and 5a). Keuper evaporites crop out abundantly along both faults (Fig. 8a). Discontinuous Urgonian limestones (Pierrelys Group) lie directly above Keuper evaporites in the WNW-trending Bezu anticline along the eastern boundary, and along the eastern and northern borders of the basin. These are unconformably and transgressively overlain by eastward younging Black Flysch formations. In the western sector the east-plunging Quillan syncline and anticline fold the F1 and F2 formations. Their curving axial traces are discontinuous across the base F2 angular unconformity, indicating synsedimentary fold growth. The Quillan anticline disappears rapidly eastward as bedding trends swing clockwise across several unconformities (Fig. 8 and Fig. S1). The north-verging tight Quillan syncline has a subvertical to overturned south flank in F1 and F2. Younger formations (F3–F7 and possibly F8) onlap onto the steep upper boundary of F2. For most of its length the syncline shows an east to SE plunge that decreases eastward (from 40° to 15°; Fig. 8). This upward shallowing fold plunge strongly suggests a syndeposi-tional eastward tilting of the depocentre. We interpret this tilting together with the other features described above to record a salt-related basin evolution as detailed below.

With the exception of rare fragments of Jurassic carbonates along the basin's northern boundary, Aptian Urgonian limestones are the oldest outcropping deposits above the evaporites. Although no subsurface data are available, we represent the presence of all stratigraphic units at depth in our cross-sections (Fig. 5a) to minimize the estimated amount of extension. The Black Flysch Formations constitute halokinetic sequences deposited during salt movement. F1 and F2 (1300 m) record an abrupt increase in water depth and sediment delivery from the east into the minibasin (Aragon 1988). This deepening event is also recorded elsewhere along the Pyrenean rift system (e.g. Debroas 1987). The lozenge shape of the Quillan depocentre, even when Alpine shortening has been restored, suggests that the basin was created by sinistral transtension similar to that invoked for the opening of other Aptian–Albian basins along the North Pyrenean Zone further west (e.g. Debroas 1987, 1990; Canérot 2017). Both tectonics and sediment supply could have triggered or accelerated salt movement. The steep southern limb of the minibasin in F1 and F2 is interpreted as a flap structure that developed to the north of the Bugarach diapir and onto which younger halokinetic sequences onlap. The contact between the subvertical F2 beds on the southern flank and the gently SE-dipping F3–F7 beds is difficult to explain otherwise (Figs 8 and 9). Given the considerable level of erosion, we cannot derive more information on the detailed character of this flap structure or its evolution. Overall, the Quillan Aptian–Albian depocentre appears to have migrated eastward between salt walls that limited the basin to the north and south (Figs 8 and Fig. S1 in Supplementary Data), and that were later inverted and squeezed to form the Pays de Sault Thrust Weld and the Bugarach Thrust Weld respectively. The salt walls converge eastward to merge at the eastern limit of the basin

marked by the salt-rich and highly complex thrust zone around Bugarach Mountain (B, Fig. 6). In the late Aptian F1 and F2 units were deposited in a western depocentre until all salt was evacuated from below (grounding; Fig. 8b). Subsidence then migrated east during the latest Aptian to Middle Albian to gradually deposit the deepening facies of F3–F8. This model offers a new tectonostratigraphic interpretation of the Quillan depocentre, which is compatible with the northeastward delta regression facies model of Aragon (1988). Similar depocentre migration has been described in subsurface studies of minibasins (e.g. Jackson et al. 2019; Ge et al. 2020). The post-rift Grey Flysch Group unconformably overlies eroded Albian strata and may record the end of salt-controlled tilting of the Quillan minibasin until inversion during the Pyrenean orogeny.

During Pyrenean convergence the Quillan minibasin was shortened by a combination of new folding (Bezu anticline, Saint Louis syncline; Fig. 8a), tightening of synsedimentary folds (Quillan anticline and syncline) and by squeezing and shear of surrounding salt walls to form the Bugarach and Pays de Sault thrust welds. In this type of deeply eroded synclinal depocentre it difficult to quantify the relative importance of purely halokinetic signatures and later contractional strain.

The Cucugnan Minibasin (rift margin fault zone)

To the east of the Quillan syncline along the North Pyrenean Frontal Thrust lies the Cucugnan syncline, an inverted Albian minibasin, preserving >700 m of Black Flysch (Figs 4 and 9a, b; Berger et al. 1997; Bessière et al. 1989). The north-facing syncline is unconformably overlain by Grey Flysch, also folded, and is overthrust and largely hidden by north-vergent imbricates of its overturned south limb (Figs 5b and 9). Along the northern margin of the basin, Albian strata terminate against the basement-cutting Padern Fault and its associated diapir (Picou diapir; Fig. 9a and b). This normal fault was not reactivated during Pyrenean orogenesis and remains sealed below the mid-Cenomanian unconformity. South of Cucugnan the syncline is bordered by a 500 m wide band of Keuper evaporites (Cucugnan diapir; Figs 3 and 9a) whose northern boundary is mapped as the North Pyrenean Frontal Thrust. The Cucugnan depocentre terminates to the east against the extensive Keuper outcrops surrounding Tauch Mountain (Bouillin and Magné 1973; Berger et al. 1997).

The Black Flysch succession of the Cucugnan Basin comprises platform carbonates in the north that thicken and pass southward into deeper water glauconitic sandstones and marls, rich in olistostromes and olistoliths (Fig. 4b; Bouillin 1967; Bouillin and Magné 1973; Berger et al. 1997). The olistostromes contain abundant clasts of Muschelkalk, Keuper marls and gypsum, with lesser quantities of Upper Jurassic, Neocomian and Aptian lithologies and rare Paleozoic units. Bipyramidal quartz crystals (from Keuper) are ubiquitous. At Roc Pouyrit, a large olistolith (1.3 km long, 50–100 m thick) conformably lies within the vertical north-younging Black Flysch succession (RP in Figs 6 and 9a). It consists of a north-younging succession of Keuper evaporites to Liassic dolomites and marls terminating in a poorly cemented breccia of Liassic to Aptian clasts.

An outlier of the Maastrichtian to Paleocene Aude Valley Group (Pech Marty Formation) directly overlies the Cucugnan diapir, preserved in a synclinal closure locally overturned to the north (Fig. 9a and b; Charrière and Durand Delga 2004; Bilotte and Canerot 2006). The 100–150 m succession of continental clastic deposits and lacustrine limestones is rich in fragments of older lithologies from Triassic gypsum to green Albian sandstones as well as containing bi-pyramidal quartz crystals (Mattauer and Proust 1967).

These features suggest that the Cucugnan depocentre developed as a minibasin between the Picou salt diapir to the north and the larger Cucugnan diapir to the south. Emergent diapir(s), principally the Cucugnan diapir, fed debris and olistoliths into the depocentre. Post-rift Grey Flysch strata later covered the minibasin before it was folded and overthrust along the Cucugnan salt wall during Pyrenean convergence. The Maastrichtian-Paleocene Pech Marty formation is a remnant of an early syn-orogenic depocentre that developed on or close to the emergent Cucugnan diapir (Bilotte and Canerot 2006).

The Soulatgé Block (rift platform)

The Soulatgé block (Fig. 3) preserves a stratigraphy and structure typical of a rift platform. The term rift platform is used here to describe a less subsiding area with a thinner evaporite layer lying landward of the main rift and in the footwall of the main boundary fault(s) (e.g. Nalpas and Brun 1993; Stewart and Clark 1999). Lying today on the southeastern flank of the Mouthoumet Massif, the Soulatgé block is predominantly covered by gently south-dipping Grey Flysch Group strata (Fig. 3). Jurassic to Lower Aptian strata can be observed below the erosive mid-Cenomanian unconformity in the Serre de Bouchard inlier and along the eastern edge of the Grey Flysch outcrop between Massac and Padern (Figs 3 and 9). Gentle Pyrenean north- to NW-directed shortening (folds and faults) affects both basement and Mesozoic cover (Figs 3 and 9d; Berger et al. 1997). The area is cut by later NE–SW-trending rotational extensional faults downthrowing to the NW and often rooting into Keuper evaporites (Figs 3 and 9a).

The Serre de Bouchard inlier reveals a deeply eroded block of Jurassic to lower Aptian limestones and dolomites up to 600 m thick, dipping 30–50° NW, striking NE–SW and truncating downward onto Keuper evaporites and unconformably overlain by gently dipping Grey Flysch strata (Figs 3 and 9c, d; Kuhfuss 1981; Bessière et al. 1989; Clerc 2012). The preserved tilted block is only 100–200 m high, which prevents further investigation of stratal geometries. This is the only outcrop of the Neocomian Mirande Group north of the North Pyrenean Frontal Thrust and it is at its thickest (>600 m) and most complete here.

Along the eastern edge of the Grey Flysch outcrop (Massac to Padern, Figs 3 and 9a, b) tilted Jurassic strata truncate downward onto a discontinuous primary weld or partial weld (Figs 9a and b). When post-Cenomanian faults and tilting are restored, these strata lie in extensional fault blocks striking east to NE with southward vergence and separated by small salt rollers (Sauze, Massac, Fig. 9b). These fault blocks have also been deeply eroded below the mid-Cenomanian unconformity so that we can only say that they underwent pre-Cenomanian extension detached along Keuper evaporites.

The Serre de Bouchard fault block (Fig. 9c and d) is interpreted as an extensional raft that records Early Cretaceous basement-decoupled extension and subsidence. The Massac–Cucugnan section (Fig. 9a and b) appears to record considerably less extension but in the same style. Preserved stratal geometries at Serre de Bouchard are consistent with a landward-dipping rollover above a SE-dipping listric normal fault (e.g. Fig. 2b; Brun and Mauduit 2008; Jackson and Hudec 2017). The NE–SW trend of the Serre de Bouchard fault block is compatible with the orientation of Massac–Cucugnan fault blocks and with Tauch Mountain structures. These observations indicate that the rift platform underwent significant NW–SE extension and subsidence from the Jurassic to at least the mid-Aptian. However, owing to deep erosion we cannot constrain the precise style, timing and amount of extension. The rift platform then records major uplift and erosion over a period of c. 15 myr (from mid-Aptian to mid-Cenomanian) during which time deformation focused into the main rift further south (Cucugnan, Quillan, North Pyrenean Zone depocentres). The northern limit of rifting therefore migrated south in the mid- to late Aptian in this region. From mid-Cenomanian onward the whole rift records post-
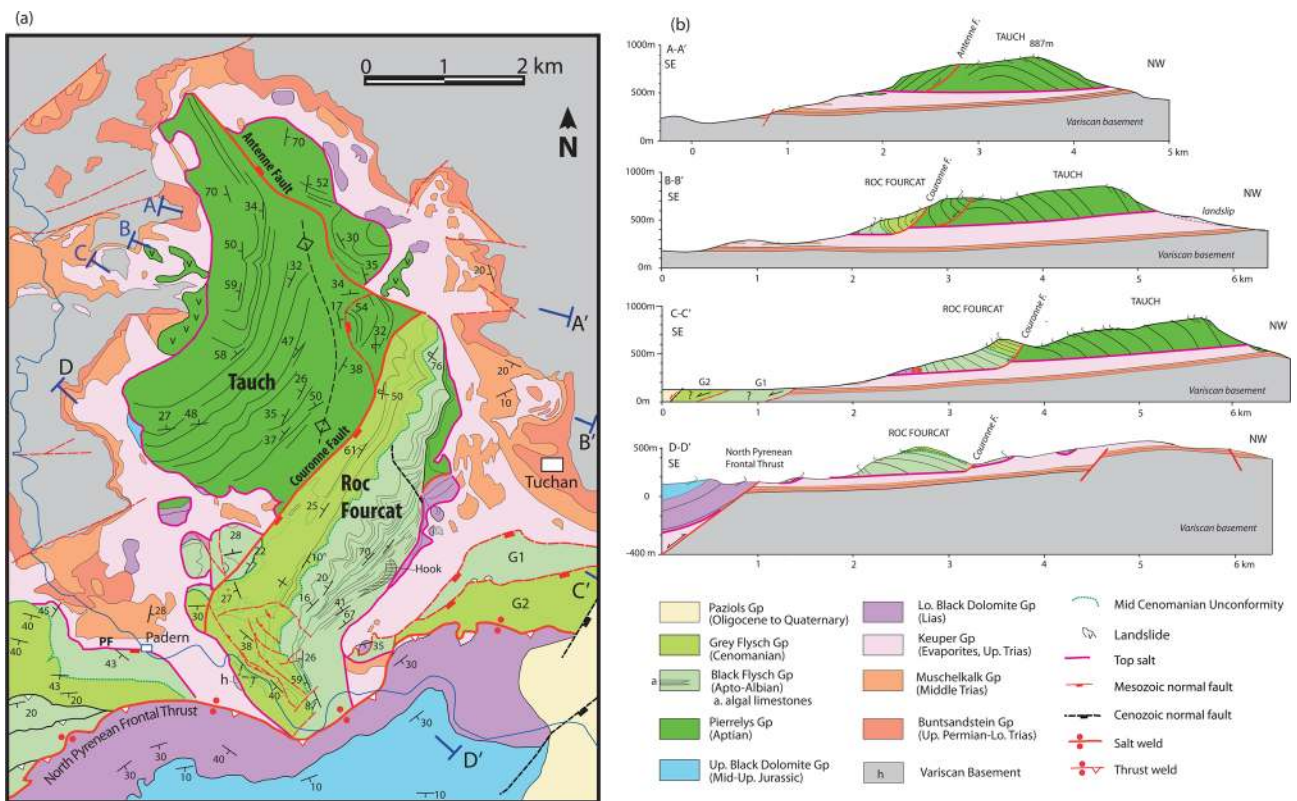
Fig. 10. (**a**) Detailed geological map of Tauch Mountain, with Tauch and Roc Fourcat units, based on new mapping and the Tuchan BRGM map (Berger et al. 1997). (**b**) Four cross-sections across the Tauch and Roc Fourcat units (location shown in (**a**)).

rift subsidence with marine strata progressively onlapping northward across the deeply eroded platform (Bilotte 1985).

Tauch Mountain (eastern end of rift platform to rift margin)

Tauch Mountain is a *c.* 6 km by *c.* 4 km Cretaceous klippe directly overlying Keuper evaporites on the southeastern side of the Mouthoumet massif. It lies to the north of the eastern termination of the North Pyrenean Frontal Thrust. The NE–SW-trending Couronne Fault separates the inlier into two fault blocks with distinct Cretaceous stratigraphy and different bedding disposition (Tauch unit to north, Roc Fourcat unit to south; Figs 10 and 11). The underlying Keuper evaporites display average thicknesses of 100–150 m and incorporate a chaotic distribution of blocks of Upper Carboniferous metasediments, Muschelkalk and various Jurassic limestones and dolomites. Below the Keuper a thin (20 m) autochthonous succession of Buntsandstein and Muschelkalk unconformably overlies Paleozoic basement. Although its unusual stratal geometries have long been recognized, Tauch Mountain was previously interpreted as an isolated klippe of a northward-verging thrust sheet originating in the North Pyrenean Zone (de Graciansky 1963).

The Tauch unit consists uniquely of Aptian platform limestones (Pierrelys Group; Fig. 4) with an estimated cumulative thickness up to 1500 m. The karstified and fractured limestones mainly dip steeply west to NW with some shallow to moderate east to SE dips in the faulted NE sector, suggesting the presence of a north–south-trending, north-plunging anticline (Fig. 10). Strata truncate downwards onto top Keuper, a roughly planar surface that dips gently SE (Figs 10 and 11a). Small blocks of Middle Jurassic limestones lie along this contact and are here interpreted as welded stringers (Fig. 2). Beds are locally overturned close to the Couronne Fault. The NW–SE normal Antenne Fault bounds

the NE block where Aptian limestones dip steeply to moderately E to ENE.

The Couronne Fault is a listric normal fault downthrowing to the SE with a salt roller in its footwall (Keuper >300 m; Figs 10a, b and 11a). In its hanging wall, the NE–SW-trending Roc Fourcat unit incorporates Aptian Pierrelys limestones, the full Albian Black Flysch Group and lower units of the Grey Flysch Group (Cenomanian) (Figs 4b, 10 and 11b). Stratal units are separated by unconformities and have a total thickness <1000 m. Geometries vary along-strike from a rollover anticline with NW-dipping and fanning strata in the SW and centre (Figs 10b, D–D', and 11b) to strongly overturned, SE-dipping strata in the NE (Fig. 10b, B–B'). The Black Flysch shows a maximum thickness in the centre of the block and records rapid thickness and dip variations with internal unconformities (Figs 10b and 11b). All strata terminate downward onto top salt or against the Couronne Fault. Lower strata also onlap along-strike toward the NE onto an unconformity above docked Aptian and Liassic stringers that line the top salt boundary (Figs 10 and 11b). In the oldest Black Flysch, where strata are vertical, a distinctive halokinetic hook geometry closing toward the NE is preserved (Fig. 12b). Algal carbonates (n7a-bC) lie in the hook's core and pass to the SW into marine glauconitic turbidites (Berger et al. 1997).

Omission of stratigraphy across the basal contact of both the Tauch and Roc Fourcat Units indicates a net extensional origin. The overall geometry of the Tauch unit is here interpreted as an extensional turtle structure (Fig. 2b; Hudec and Jackson 2011). Stratal geometries suggest that this Aptian depocentre was surrounded by rising diapirs that progressively lost salt along their flanks during extension to create the anticlinal structure. Extension then migrated basinward to the Roc Fourcat depocentre. Given its younger age, its seaward position with respect to Tauch and its stratal geometries we interpret this depocentre as a younger trough with a landward-dipping rollover above the SE-dipping listric Couronne Fault. It was generated by
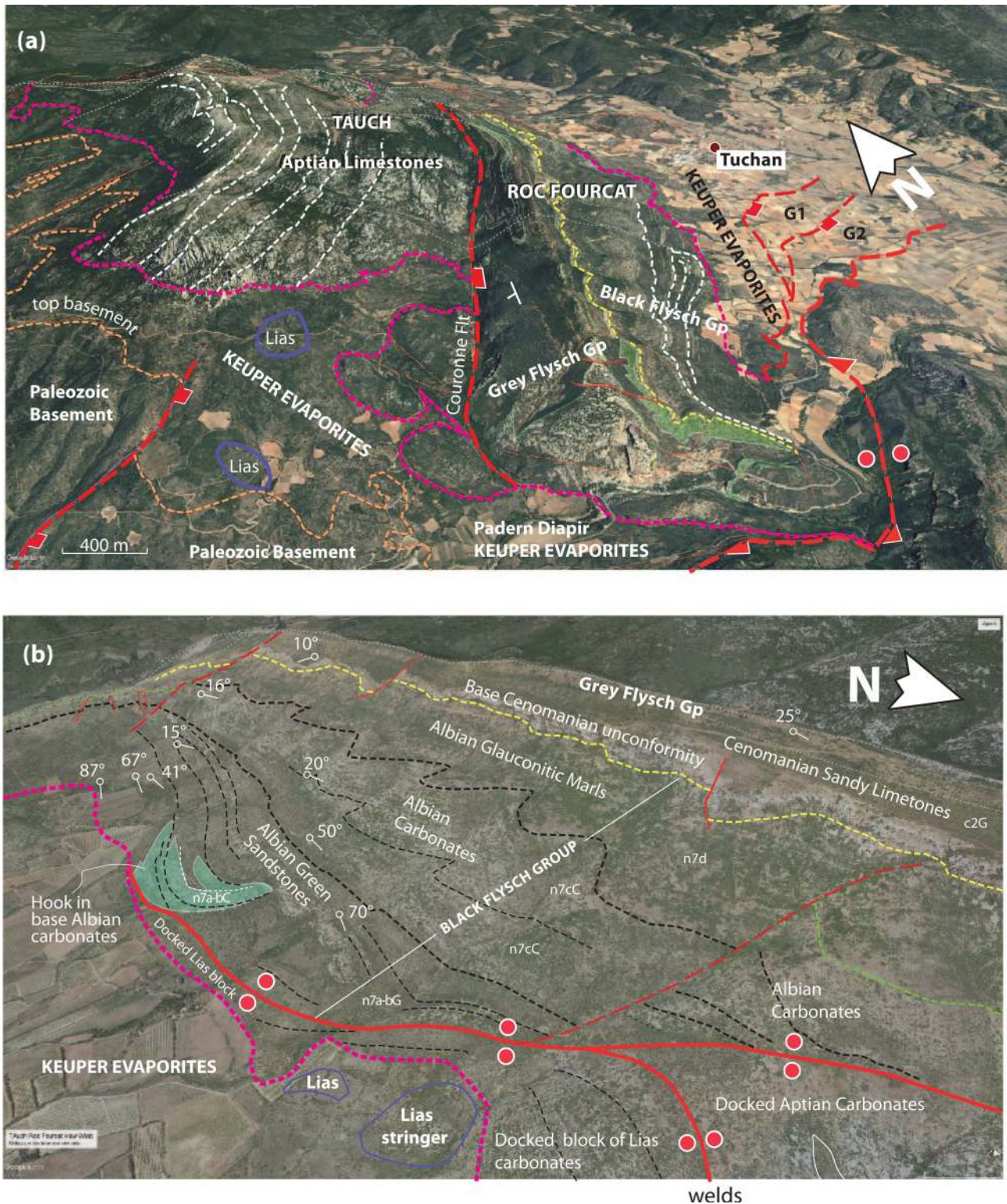
Fig. 11. (**a**) Google Earth view toward the NE of the southwestern side of Tauch Mountain showing main tectonic and stratigraphic units and contacts. (**b**) Google Earth view toward the west of the SE slopes of the Roc Fourcat unit showing principal stratigraphic boundaries, and dips. Pink dashed lines are top Keuper; red dashed lines are faults; yellow dashed lines are unconformities; white or black fine dashed lines are bedding traces; orange dashed lines represent top of Variscan basement. In (**b**) the following features should be noted: (1) the hook structure in basal Albian carbonates (n7a-bC), which pass basinward (to SW) into glauconitic turbidites, and (2) the dip fan displayed by Black Flysch strata.

rafting during the Albian that continued into the Cenomanian. The small hook on the SE flank of Roc Fourcat combined with the thinning, onlapping and overturning of strata toward the NE all indicate the presence of rising diapirs to the NE and east of the Roc Fourcat depocentre. In the idealized model shown in Figure 2b the fault blocks to the left of the section represent the main characteristics of the Tauch and Roc Fourcat depocentres that migrated basinward

above a seaward-dipping detachment. We correlate the Roc Foucat block with the Quillan and Cucugnan depocentres as they align along the boundary between rift platform and main rift, although the main rift fault zone appears to have nearly died out.

Because all tectonic contacts are either extractive or in stratigraphic continuity, it is difficult to detect Pyrenean compression. However, some inversion of the Tauch and Roc
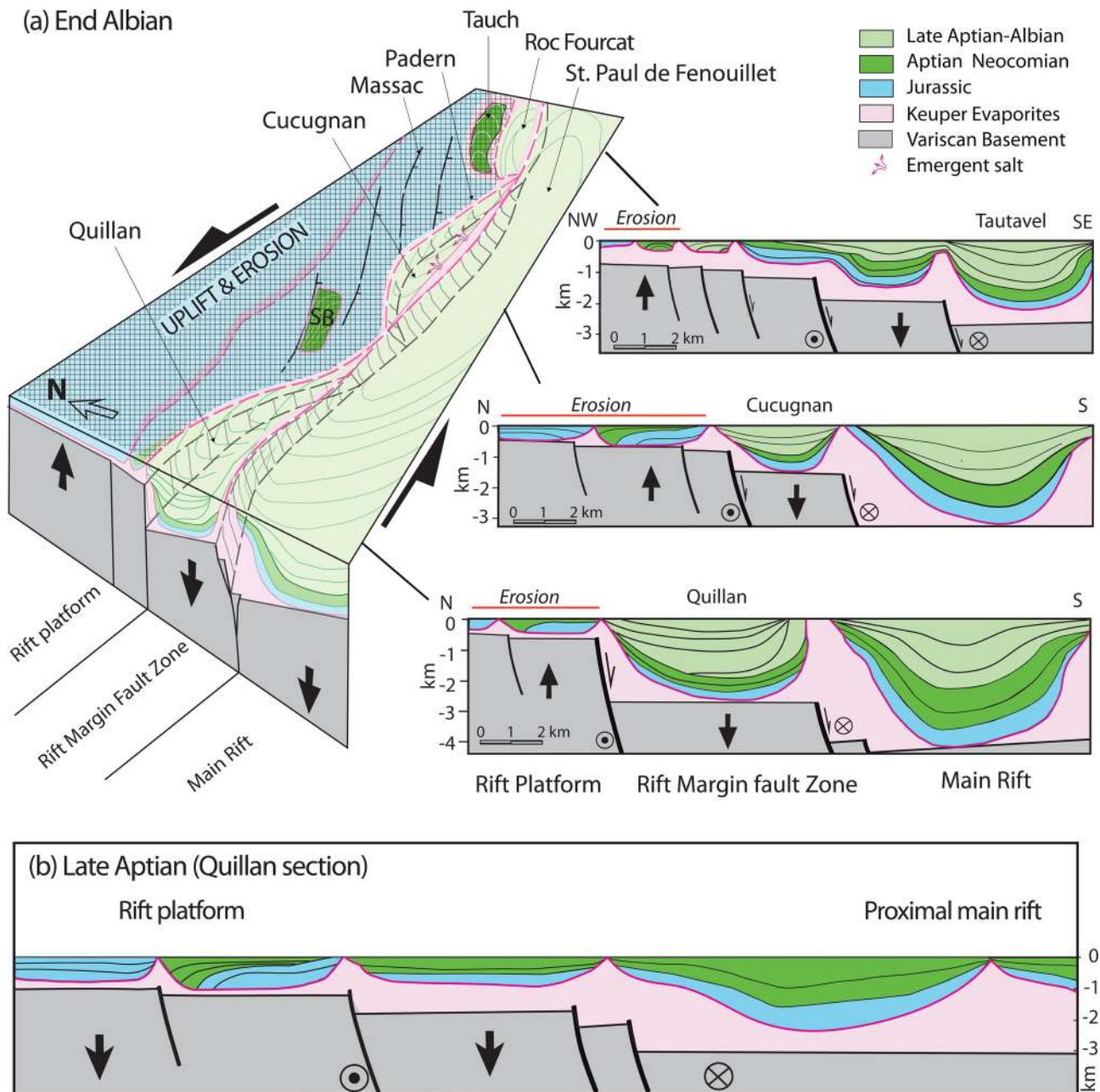
Fig. 12. Three-dimensional schematic illustration of the northern salt-rich rifted margin of the eastern Pyrenees viewed toward the east. The distribution and geometry of Aptian and Albian depocentres and of salt structures change along and across the rift platform, the rift margin fault zone and the main rift. To the right, three schematic cross-sections represent depocentre styles along the margin at the end of rifting (end Albian–Cenomanian). The rift margin fault zone loses definition toward the east. (**b**) Schematic illustration of Late Aptian cross-section (Quillan) representing the geometries and distribution of Jurassic and early Cretaceous depocentres controlled by early salt mobilization.

Fourcat depocentres is suggested by (1) the periclinal closure at the SW end of the Roc Fourcat Unit (Figs 10a and 12a) showing geometries typical of an inverted basin sidewall and (2) the higher elevation of the mid-Cenomanian unconformity of Tauch Mountain compared with its regional in the adjacent Soulatgé block (Fig. 3). The amount of Pyrenean shortening and any possible post-depositional rotation of Tauch Mountain cannot, as yet, be constrained.

Role of salt in the evolution of the northern Pyrenean rifted margin

To reconstruct the Mesozoic rift history along the east European margin of the Pyrenean Trough we divide the area into the rift platform to the north (Soulatgé block, Tauch) and the proximal main rift to the south (northern North Pyrenean Zone), separated by the main fault zone with associated minibasins (Quillan, Cucugnan, Roc Fourcat, Fig. 12). The main fault zone becomes less well-defined eastward. These three settings show contrasting synrift halokinetic depositional sequences discussed below.

On the rift platform only isolated fragments of Mesozoic strata are preserved and exposed below the highly erosive mid-Cenomanian unconformity. We therefore cannot constrain the true dimensions of the original platform. The Triassic to Aptian succession is organized in basement detached rotational fault blocks above a salt detachment (Serre de Bouchard, Massac–Padern, Tauch; Fig. 12a). Albian strata are conspicuously absent. Stratigraphic thicknesses indicate that significant accommodation was created on the platform during the Neocomian to Aptian. The NE–SW-trending fault blocks are markedly oblique with respect to the east–west rift margin.

Displacement vergence was consistently seaward, suggesting a south to SE slope on the Keuper detachment.

Development of extensional fault blocks requires weak to moderate decoupling between basement and cover across a salt layer (Withjack and Calloway 2000; Jackson and Hudec 2017). Around the Serre de Bouchard inlier the outcropping Keuper detachment layer is thin (tens of metres), appears to be stratigraphically autochthonous and contains no visible stringers, consistent with low mobility of a relatively thin evaporite layer. In the Massac to Padern sector small salt rollers containing stringers suggest a thicker original salt layer with limited diapirism. The salt layer thickens again significantly to the east, where raft tectonics is recorded by the Tauch and Roc Fourcat units. Numerous floating and docked stringers along the base of these units also record high salt mobility.

Up to the mid-Aptian, we can envisage gentle and slow extension in the basement on the rift platform (Fig. 12b) that became increasingly decoupled from the suprasalt cover toward the east owing to thickening of evaporites (Vendeville et al. 1995; Duffy et al. 2013; Jackson and Hudec 2017). Decoupled extensional blocks on a rift platform can be created either (1) by transfer of extension from the main rift boundary fault into its footwall along the detachment layer to accommodate the development of hanging-wall synclinal basins in the main rift (Vendeville et al. 1995; Withjack and Calloway 2000; Dooley et al. 2005; Ferrer et al. 2017) or (2) as a response of the cover to regional widening of the basin regardless of the position of basement faults (Vendeville et al.

1995). Oblique NW–SE extension in the platform cover is consistent with regional east–west sinistral transtension. A similar regime has been described in suprasalt cover adjacent to a salt wall affected by strike-slip deformation in the Dead Sea rift (Alsop et al. 2015). Halokinetic raft structures as seen in Tauch and Roc Fourcat are generally observed on salt-rich passive margins and generated by gravity forces (Brun and Fort 2012; Rowan and Ratliff 2012; Rowan 2014). They can also develop above extending basement with full decoupling on thick salt (Hudec and Jackson 2007; Jackson and Hudec 2017). During the Albian and early Cenomanian the rift platform was uplifted and deeply eroded (Fig. 13a) as rifting intensified and migrated south into the main rift zone (North Pyrenean Zone). From the mid-Cenomanian onward, post-rift strata progressively onlapped from the south across the rift platform.

The proximal main rift comprises long en echelon minibasins (e.g. Saint Paul de Fenouillet, Axat, Lapradelle, Tautavel; Fig. 3a). These show halokinetic depositional sequences and typical diapiric structures such as flaps, wedges and internal unconformities recording gradual subsidence between passive salt walls, which were most active during the late Aptian and Albian. Although Mesozoic stratigraphy can change in thickness between depocentres, similarities in facies suggest that they were not isolated. Sediment was principally supplied axially from the east. Basement-cutting faults at depth are required to create accommodation. Synsedimentary faults in suprasalt cover from this period have not yet been clearly identified. Major salt walls were generally oriented east–west and formed complex networks. Similar extensional
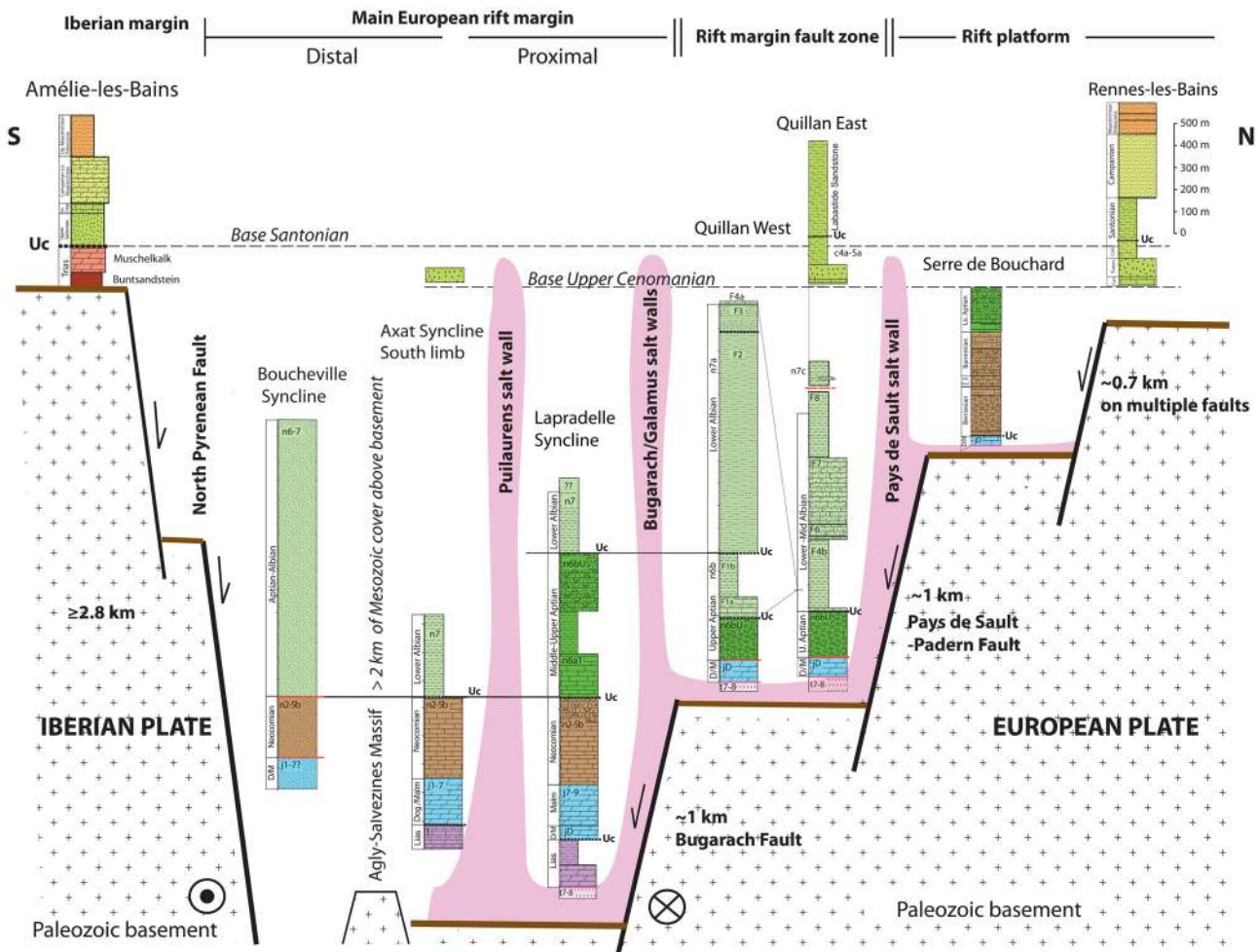
Fig. 13. Reconstruction of the Pyrenean Trough along the cross-section A–A' based on lateral correlations between stratigraphic columns presented in Figure 4a. The northern rift platform is represented by projection of the Serre de Bouchard unit. The southern rift margin is represented by Mesozoic stratigraphy at Amélie-les-Bains (location shown in Fig. 1; Bilotte et al. 1979; Casas and Torrades 1986).

minibasins above thick pre-rift salt have been described in the Danish Central graben of the North Sea (Duffy *et al.* 2013; Dooley and Hudec 2020) and in the High Atlas of Morocco (Saura *et al.* 2014; Martín-Martín *et al.* 2017; Moragas *et al.* 2017). Although our area provides limited data on Jurassic stratal geometries, we propose that diapirs began to grow gently from the Early Jurassic onward. This hypothesis is consistent with recent studies in adjacent Pyrenean, Iberian and Alpine domains that document gentle Jurassic growth synclines developing between passive salt pillows with little evidence of initial reactive diapirism (Graham *et al.* 2012; Espurt *et al.* 2019; Labaume and Teixell 2020; Vergés *et al.* 2020).

The northern boundary of the main rift is now inverted along the North Pyrenean Frontal Thrust Weld, a fault zone particularly rich in salt. During the Late Aptian to Albian minibasins developed between coalescing and diverging salt walls and were aligned above a deep basement fault zone that loses definition toward the east (Quillan, Cucugnan, Roc Fourcat; Fig. 12a). Stringers of basement and sub-Keuper lithologies (Muschelkalk) as well as super-Keuper lithologies are found scattered throughout evaporites exposed along this fault zone, recording high evaporite mobility during rifting. The debris flows in the Cucugnan basin indicate that salt diapirs were emergent during Albian and late Cretaceous. The lozenge shapes of Quillan and Cucugnan minibasins and the orientation and organization of pre-Pyrenean second-order oblique folds and faults along the Galamus Ridge all suggest a component of sinistral strike-slip along the rift margin.

In summary, a two-phase evolution of the eastern Pyrenean proximal rift margin was strongly influenced by Keuper salt, which increased southward and eastward in thickness and mobility. From the Jurassic to mid-Aptian widespread differential subsidence was controlled by sinistral transtension (Fig. 12b). During this period, the rift platform underwent oblique decoupled extension while synclinal depocentres developed in the main rift zone between rising salt walls. The rift platform was then uplifted and deeply eroded as late Aptian and Albian transtension focused into the main rift zone to the south where minibasin growth accelerated (Fig. 13a). Similar behaviour including migration of deformation toward the rift axis has been simulated in numerical modelling (e.g. Cowie *et al.* 2005; Brune *et al.* 2014) and widely documented in the North Sea (e.g. Bell *et al.* 2014; Phillips *et al.* 2019) and in other rifts and passive margins (e.g. Brune *et al.* 2017; Espurt *et al.* 2012).

Discussion

In this study, in the eastern segment of the northern Pyrenees, six Mesozoic sedimentary depocentres have been analysed (Quillan, Cucugnan, Saint Paul de Fenouillet, Serre de Bouchard, Tauch, Roc Fourcat). Whereas all share a Jurassic to lower Upper Cretaceous succession above Upper Triassic evaporites, thicknesses and stratigraphic geometries are variable from one basin to the next. Evaporite outcrops surrounding the sedimentary basins represent original salt walls sourced from the Keuper layer, which also acted as a decoupling horizon. Salt walls have been squeezed during Alpine compression, to form secondary salt welds or thrust welds. Although Alpine shortening is significant, its contribution is difficult to quantify as syn-orogenic deposits are poorly preserved in the region. We can say that it has done little to significantly alter the original salt-related rift margin geometries north of the Agly–Salvezines Massif. The tectono-sedimentary relations obtained in the eastern North Pyrenean sedimentary basins have been used to constrain the more regional evolution of the proximal rifted European margin. Here, we will explore the significance of the area as part of the Mesozoic plate boundary between Iberia and Europe by discussing the following: (1) the full geometry of the eastern Pyrenean Trough along a north–south transect; (2) integration into a regional tectonic, thermal and plate-tectonic framework; (3) plate kinematic models of the Iberia–Europe plate boundary.

Geometry of the Pyrenean Trough along a north–south transect

To investigate the structure of the European margin at the end of rifting, we construct a model along the north–south cross-section A–A' (Fig. 13) using stratigraphic columns in Figure 4. This model integrates the depocentres of Boucheville, Axat, Lapradelle and Quillan. We projected Serre de Bouchard stratigraphy onto the section to represent the rift platform to the north. The vertical scale represents non-decompacted sedimentary thicknesses, and the horizontal scale provides the approximate position of depocentres on the rifted margin. Sections are correlated along the base of the Cenomanian level in northern depocentres and the foreland, along the Aptian–Albian boundary level between Quillan and Lapradelle and along top Neocomian level between Lapradelle, Axat and Boucheville depocentres. The link between the European and Iberian Upper Cretaceous successions is made along the base Santonian, which is well recognized at Rennes-les-Bains and at Amélie-les-Bains (Els Banys d'Amèlia), respectively (Bilotte *et al.* 1979; Casas and Torrades 1986) . These subhorizontal correlations do not take into account palaeobathymetry. Adding palaeo-water depths would increase estimated throw on basement faults.

The total cumulative thickness of these stratigraphic logs can sometimes be greater than the height of the vertical succession at the time of deposition; for example, owing to progressive block rotation. This is especially true in basins showing significant halokinetic activity during their development such as Quillan and Serre de Bouchard. In the Quillan minibasin, the depocentre migrated from west to east above the salt layer (Fig. 8b). We therefore place the eastern and western stratigraphic columns side by side correlated on top salt. The Albian uplift and erosion of the rift platform is not represented here. If integrated, it would increase displacement on the rift margin faults. As the thickness of the upper Triassic evaporites is unknown we use a uniform arbitrary value.

The Boucheville syncline (Metamorphic Internal Zone) and the hydrothermally altered Salvezines–Agly basement (Figs 3 and 13) represent the distal European rift margin, an area of extreme crustal thinning where mantle was exhumed, providing the heat source and hydrothermal fluids responsible for metamorphism and metasomatism (Vauchez *et al.* 2013; Clerc and Lagabrielle 2014; Clerc *et al.* 2015, 2016). In some rift reconstructions, the Salvezines–Agly massif is represented as an exhumed palaeohigh separating the HT metamorphosed Boucheville and Bas Agly depocentres (Vauchez *et al.* 2013; Clerc and Lagabrielle 2014; Clerc *et al.* 2016). However, new thermochronology data combined with published *P–T* conditions for the HT events indicate that the Agly–Salvezines massifs were buried to at least 2 km at the end of rifting as shown here (mid-Cenomanian; Ternois *et al.* (2019).

Despite uncertainties, this reconstruction provides insight into the full structure of the Pyrenean Trough. Top basement and top Keuper descend southward across a series of faults with a cumulative throw of at least 2.8 km matched by the throw for the North Pyrenean Fault to the south. On our cross-sections (Fig. 5) we integrate a more complete Neocomian and Jurassic succession below the Quillan depocentre. If this scenario were integrated into the rifted margin model on Figure 13, it would simply increase throw on the Pays de Sault–Padern Fault and decrease throw on the Bugarach Fault.

Integration into a regional tectonic, thermal and plate-tectonic framework

The chronology of diapiric activity in the eastern North Pyrenees defined above is here compared and integrated with North

M. Ford and J. Vergés
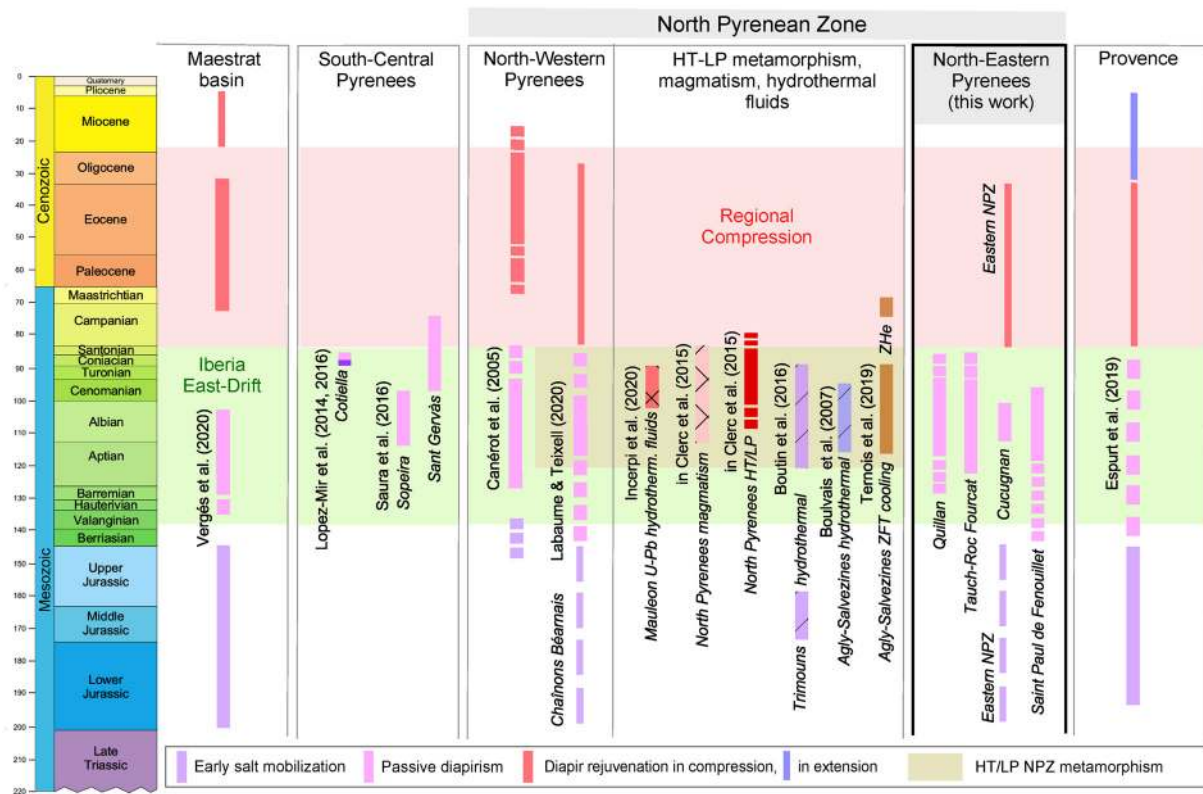
Fig. 14. Chronostratigraphic correlation of major diapiric and tectonic activity, metamorphic, magmatic and hydrothermal events across the northern Pyrenees and adjacent areas on Iberian and European plates.

Pyrenean thermal events and also with halokinetic and tectonic histories of adjacent Pyrenean, Iberian and Alpine domains (Fig. 14). We have shown that our North Pyrenean depocentres all record main halokinetic activity from the middle Early Cretaceous to the end of the Albian although some diapiric structures are still active to at least Cenomanian times and possibly later. Because Jurassic strata crop out more discontinuously, earlier salt mobilization is more than likely across the eastern North Pyrenean zone. Pyrenean convergence led to the narrowing and closing of diapiric walls and their reactivation in places as thrust welds. This three-step history of halokinetic activity is very similar to that established further west in the North Pyrenean Zone by Canérot et al. (2005) and Labaume and Teixell (2020). In the Pyrenean–Provençal belt of SE France, Espurt et al. (2019) document diapiric activity throughout the Jurassic and during the Albian and Late Cretaceous, with reactivation during the latest Cretaceous–Paleogene compression phase and then during back-arc opening of the Gulf of Lion (Fig. 14).

On the southern side of the Pyrenees, the Cotiella and Sopeira–Sant Gervàs structures (Fig. 1) have also been redefined as salt-related extensional depocentres. Both localities share good continuity of 3D outcrops. They record very short-lived diapiric activity but of different ages. The Cotiella locality shows a very short episode of roll-over development on north-verging listric normal faults tied to diapirism during the Turonian–Coniacian (McClay et al. 2004; Lopez-Mir et al. 2014, 2015). The Sopeira–Sant Gervàs minibasins are related to a large diapiric province along the Iberian margin (Saura et al. 2016). Despite being side by side and only separated by the north–south-trending Llastarri salt weld, the two minibasins show subsidence ages that follow one another in time: the Sopeira minibasin evolved from the latest Aptian to early Cenomanian whereas the Sant Gervàs minibasin subsided through the Turonian to Campanian, coinciding with the onset of compression in the southern Pyrenees. In a recent paper a part of

the Maestrat basin at the SE end of the Iberian Range (Fig. 1, Iberian rift system) has also been identified as a diapiric province (Vergés et al. 2020). Here, the structures around the north–south-trending Miravete anticline record mild Jurassic and strong Valanginian to middle Albian salt tectonics (Fig. 14).

Figure 14 shows that late Early Cretaceous maximum diapiric activity can be correlated across all these regions north and south of the Pyrenean Trough. In addition, as indicated in the paper by Vergés et al., this period coincides broadly with maximum eastward drift velocities of the Iberian microplate, itself a result of the opening of the southern segment of the North Atlantic according to the plate-tectonic model of Nirrengarten et al. (2018). Nirrengarten and coworkers evoke transtensional corridors in both the Pyrenean and Iberian rift systems. Although acknowledging high uncertainty in the true distribution of displacement, they propose maximum lateral displacement of Iberia on the latter lineament during the Aptian, with transtensional rifting in the Pyrenean system during the Albian.

The existence of regional hydrothermal events and their coincidence in time in the NW region of the Iberian rift system (Cameros Basin) and in the Pyrenean Trough has been documented by Vergés and Garcia-Senz (2001) and more recently by Rat et al. (2019). In the case of the Pyrenean Trough, where hydrothermal activity is widespread along the length of the North Pyrenean Zone (e.g. Incerpi et al. 2020) and is of higher temperature than in the Cameros Basin, there is a first episode during the Jurassic (174–160 Ma) possibly related to a Europe-wide event (Cathelineau et al. 2012) and a second and more intense episode between the early Aptian and the Turonian–Campanian (Fig. 14; 122–80 Ma; Clerc et al. 2015). During this second episode, temperatures reached 500–600°C and local magmatism is recorded throughout the northern Pyrenees (Boutin et al. 2016; Clerc et al. 2016). Although there may have been transtensional rifting along the two major tectonically weak zones, these observations suggest that the Pyrenean rift system

was the more active of the two in accommodating the lateral displacement of Iberia.

In summary, along the North Pyrenean Zone, the principal phase of passive diapirism (Late Aptian to early Cenomanian) is synchronous with significant thermal, hydrothermal and magmatic events that are related to crustal and upper mantle thinning. The distribution of thermal, hydrothermal and volcanic events throughout the North Pyrenean Zone, during the Cretaceous, and its continuity over Cretaceous time make this narrow transtensional rift domain the best candidate for being the principal plate boundary between Iberia and Europe to accommodate lateral displacements of the Iberian microplate.

Plate kinematic models for the Iberia–Europe plate boundary

The accepted evolutionary model for the Pyrenean Trough during the 1970s and 1980s required left-lateral strike-slip along the North Pyrenean Zone and North Pyrenean Fault (e.g. Choukroune and Mattauer 1978; Olivet 1996; among others). The numerous slivers of lherzolite cropping out along the North Pyrenean Zone were explained as locally exhumed in pull-apart basins that opened along the strike-slip system. Synrift high-temperature metamorphism was interpreted as generated by circulation of high-temperature fluids above exhumed mantle and along deep-rooted faults in pull-apart basins in a manner similar to that observed today in the Salton Sea

basin located along the San Andreas Fault (e.g. Golberg and Leyreloup 1990). Beginning in the 1990s the worldwide analysis of hyperextended continental margins (e.g. Pérez-Gussinyé 2013) with wide bands of exhumed mantle along the most distal domains sparked renewed interest in the lherzolite blocks of the North Pyrenees. This led to reinterpretations of their significance within a pure shear extensional history followed by pure shear inversion during Pyrenean convergence (e.g. Jammes et al. 2009; Lagabrielle et al. 2010; Clerc and Lagabrielle 2014; Tugend et al. 2014 among others). Most of these studies interpreted the lherzolites as remnants of a continuous domain, some 50 km wide, in which the extreme thinning of the crust put lithospheric mantle in contact with the base of the Mesozoic sediments.

Although the main objective of our study is not to make a reliable interpretation of the Iberia–Europe plate boundary we have, nevertheless, obtained results that help to better constrain its scale, geometry and evolution for the Cretaceous period. The reconstruction in Figure 13 shows a highly asymmetrical rift with major faults distributed across a wider northern margin whereas the abrupt and narrow southern margin is controlled principally by the North Pyrenean Fault. Published width estimates for the Albian rift system vary widely from 50–60 km (Clerc et al. 2016; Ternois et al. 2019) to 150–200 km (Tugend et al. 2014; Teixell et al. 2018). We estimate that the proximal European rift margin (north of Agly–Salvezines) was some 22–30 km wide (Fig. 13), consistent with Grool et al. (2018) and Ternois et al. (2019). We can obtain an
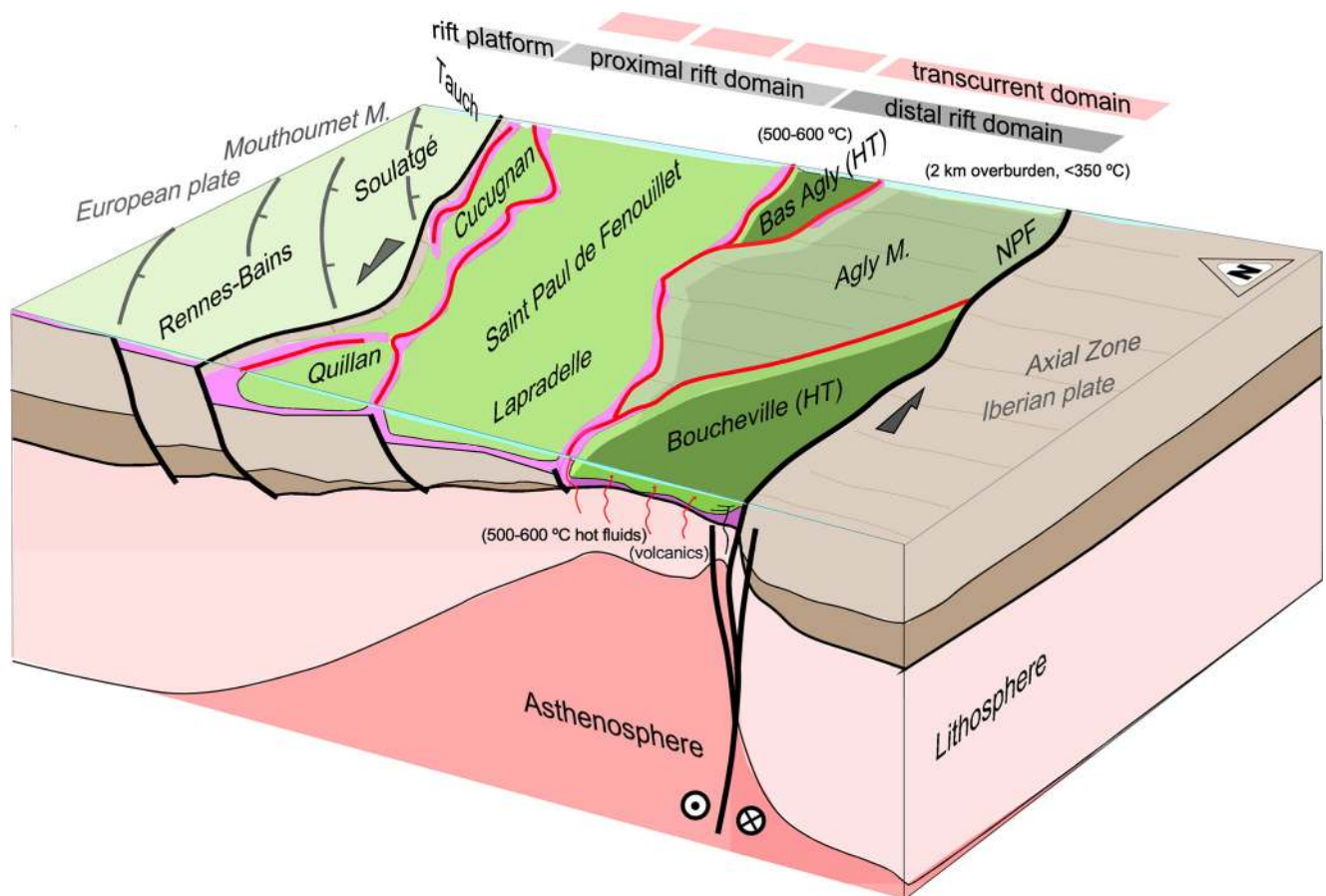
Fig. 15. Block diagram of the eastern Pyrenees showing a scale-free reconstruction during the late Early Cretaceous (inspired by the interpetation of Cochelin et al. (2018) of an area about 80 km west of this study). The rift platform, proximal rift and distal rift domains of the Pyrenean Trough are bounded by steep basement normal faults, and the North Pyrenean Fault system is the southern limit of the Pyrenean Trough. The Upper Triassic salt forms a thick and efficient level of detachment and a total structural decoupling of cover and basement. Crustal and upper mantle thinning beneath Boucheville and Bas Agly minibasins, and to a lesser degree below the Agly Massif, led to the direct tectonic contact of upper mantle and Upper Triassic evaporites and younger strata and the protracted HT metamorphic events recorded in those basins (Fig. 14). We interpret all these processes as the consequence of a regional left-lateral strike-slip to transtensional movement along the Iberia–Europe plate boundary during the late Early Cretaceous.

estimate of 30 km for the width of the central rift (including the zone of exhumed mantle) by subtracting the estimated convergence of Macchiavelli et al. (2017) for the eastern Pyrenees (140 km) and the estimated restored width of the rifted margin (111 km) obtained from the well constrained restoration of an adjacent cross-section by Grool et al. (2018), which excludes the zone of mantle exhumation. The total width of the Pyrenean Trough including exhumed mantle before the onset of compression would therefore be around 52–60 km. The narrow width and asymmetrical faulted geometry of the eastern Pyrenean Trough proposed here (Fig. 15) contrasts strongly with recent models showing symmetrical, smooth conjugate slopes on both Iberian and European margins, separated by a continuous domain of exhumed upper mantle (e.g. Teixell et al. 2018; Labaume and Teixell 2020; Lagabrielle et al. 2020, and references therein). In these pure shear models, the extending plate boundary is configured as a region of progressive and ductile crustal thinning involving minor normal faults in the upper crust. Lagabrielle et al. (2020) argue that Upper Triassic evaporites play a crucial role in 'smooth-slope' basin evolution by facilitating the gliding of suprasalt sediments downward into the basin centre where they pile up on exhumed mantle. Our detailed observations in the eastern Pyrenees, in contrast, seem to indicate a different history, recording a two-phase transtensional rifting evolution on asymmetrical margins. Initial distributed faulting across a broad area is followed by a seaward migration of faulting into the rift axis. The European margin records strong decoupling on salt and the growth of salt diapirs above major basement faults responsible for thinning the upper crust but we have found no evidence for gravitational gliding of cover into the rift axis.

Although asymmetry is characteristic of hyperextended conjugate passive margins (e.g. Lavier and Manatschal 2006; Pérez-Gussinyé 2013; Brune et al. 2014; Doré and Lundin 2015; Dielforder et al. 2019), the broader of the two margins is typically 100–200 km wide. Pure shear thermomechanical simulations demonstrate that margin width is mainly controlled by extension rate and by initial lithospheric strength; however, to date, no numerical model has simulated a hyperextended rift of the dimensions proposed here for the eastern Pyrenean Trough. We suggest that the narrowness and internal complex structure along with geological features described above are due to its development in a transtensional regime.

The lateral movement of Iberia over hundreds of kilometres was triggered by the opening of the southern North Atlantic during the Cretaceous (Nirrengarten et al. 2018). As was already widely accepted in the 1970s to 1980s, we argue that the Pyrenean Trough was created by this left-lateral transtensional movement (Fig. 15) that was fully synchronous with halokinetic activity and also with most well-calibrated thermal events (Fig. 14). High-temperature low-pressure metamorphism of Mesozoic rocks, alkaline volcanism and metasomatic alterations of basement by HT hydrothermal fluids occur along the southern margin of the North Pyrenean Zone and more locally in the Axial Zone (Poujol et al. 2010; Clerc et al. 2015), often related to specific structures such as, for example, the HT metamorphic minibasin of Boucheville and Bas Agly separated by the LT metamorphic Agly Massif. This could indicate that HT events were restricted to laterally discontinuous regions associated with faults at depth and/or pull-apart basins along the oblique margin in accordance with the transtensional model of Golberg and Leyreloup (1990). We have integrated these key observations into a 3D model of the eastern Pyrenean rift in Figure 15. The narrowness of the North Pyrenean Zone coupled with the highly irregular distribution and intensity of HT metamorphism in the Boucheville and Base Agly minibasins (500–600°C) separated by the less metamorphosed Agly–Salvezines Massif (<350°C) suggest a transtensional regime for the Iberia–Europe plate boundary during the late Early and early

Late Cretaceous. In this model, the distal European margin accommodates most of the transcurrent motion and is characterized by deep faults limiting laterally discontinuous crustal domains and hyperextended 'hot' pull-apart domains with upper mantle rocks directly beneath the sedimentary cover. We suggest that the proximal rift and platform domains (our study area) accommodated a significant but weaker component of strike-slip.

Conclusions

In this paper we have shown that Mesozoic depocentres in the eastern North Pyrenees (1) were controlled by active salt tectonics displaying a wide range of clear halokinetic features, (2) developed in a sinistral transtensional regime, (3) record changing characteristics and evolution from rift platform across the main rift margin fault zone, to proximal and distal parts of the main rift, and, finally, (4) record moderate to minor Pyrenean shortening that was mainly accommodated by squeezing of salt walls. We have dated main halokinetic activity from the late Early Cretaceous to early Late Cretaceous, corresponding to the principal transcurrent rifting event in the Pyrenees. In placing these detailed observations in a regional context, we propose that both detailed and regional characteristics of the salt-rich Aptian–Albian rift system can be best understood within a sinistral transtensional regime.

The area that we have analysed has been the site of several major controversies in the past regarding the regional significance of observed deformation and unconformities, which we can now attribute to halokinetic events. On a more regional scale the northern Pyrenees has been the focus in the last 20 years of numerous publications arguing that Aptian–Albian rifts record pure shear hyperextension. These highly influential models have tended to attach little importance to evidence for strike-slip during rifting. We hope our data and discussion will convince the community to reconsider the importance of strike-slip in the evolution of this rift system.

These spectacular field examples illustrate the variety and complexity of stratigraphic architectures that can develop in salt-controlled depocentres and also what can happen when they are inverted. They can serve as excellent analogues of salt-rich basins on inaccessible passive margins. Many more salt-related structures and depocentres remain to be investigated and described in the eastern North Pyrenees.

Salt-rich transtensional rift margin, Pyrenees

Scientific editing by Stephen Daly

References

Albarède, F. and Michard-Vitrac, A. 1978. Age and significance of the North Pyrenean metamorphism. *Earth and Planetary Science Letters*, **40**, 327–332, https://doi.org/10.1016/0012-821X(78)90157-7

Alsop, G.I., Weinberger, R., Levi, T. and Marco, S. 2015. Deformation within an exposed salt wall: Recumbent folding and extrusion of evaporites in the Dead Sea Basin. *Journal of Structural Geology*, **70**, 95–118, https://doi.org/10.1016/j.jsg.2014.11.006

Angrand, P., Ford, M. and Watts, A.B. 2018. Lateral Variations in Foreland Flexure of a Rifted Continental Margin: The Aquitaine Basin (SW France). *Tectonics*, **37**, 430–439, https://doi.org/10.1002/2017TC004670

Aragon, J.-C. 1988. *Sédimentologie et Stratigraphie Sequentielle de l'Ablien dans le Bassin de Quillan et de Synclinorium d'Axat (Zone Nord-Pyrénéene, Aude)*. PhD thesis, Université Paul Sabatier, Toulouse.

Azambre, B. 1966. Sur le caractère agpaitique de quelques syénites néphélinitiques des Pyrénées. *Compte Rendues de l'Académie des Sciences de Paris*, **263**, 16–19.

Azambre, B. and Fabriès, J. 1989. Mezosoic Evolution of Upper Mantle beneath the Eastern Pyrenaean Range. *Tectonophysics*, **170**, 213–230, https://doi.org/10.1016/0040-1951(89)90272-2

Azambre, B. and Rossy, M. 1981. Caractère alcalin du magmatisme triasique des Corbières orientales. *Bulletin de la Société Géologique de France*, **S7-XXIII**, 253–262, https://doi.org/10.2113/gssgfbull.S7-XXIII.3.253

Barnett-Moore, N., Hosseinpour, M. and Maus, S. 2016. Assessing discrepancies between previous plate kinematic models of Mesozoic Iberia and their constraints. *Tectonics*, **35**, 1843–1862, https://doi.org/10.1002/2015TC004019

Barnolas, A. and Chiron, J.C. (eds) 1996. *Synthèse Géologique et Géophysique des Pyrénées: Cycle Hercynien*. BRGM–ITGE, Orléans.

Beaumont, C., Muñoz, J.A., Hamilton, J. and Fullsack, P. 2000. Factors controlling the Alpine evolution of the central Pyrenees inferred from a comparison of observations and geodynamical models. *Journal of Geophysical Research*, **105**, 8121–8145, https://doi.org/10.1029/1999JB900390

Bell, R.E., Jackson, C.A.L., Whipp, P.S. and Clements, B. 2014. Strain migration during multiphase extension: Observations from the northern North Sea. *Tectonics*, **33**, 1936–1963, https://doi.org/10.1002/2014TC003551

Berger, G., Alabouvette, B. *et al.* 1997. *Memoir for Tuchan (1078) Geological Map (1/50000)*. Bureau de Recherches Géologiques et Minières, Orléans.

Berger, G.-M., Aloïsi, J.-C., Got, H., Marchal, J.-P., Martin, R., Michaux, J. and Monaco, A. 1982. *Memoir of Leucate Geological Map (1079) (1/50000)*. Bureau de Recherches Géologiques et Minières, Orléans.

Berger, G.M., Fonteilles, M., Leblanc, D., Clauzon, G., Marchal, J.P. and Vautrelle, C. 1993. *Memoir of Rivesaltes (1090) Geological Map (1/50000)*. Bureau de Recherches Géologiques et Minières, Orléans.

Bessière, G. 1987. *Modèle d'Evolution Polyorogénique d'un Massif Hercynien: Le Massif de Mouthoumet (Pyrénées Audoises)*. PhD thesis, Toulouse University.

Bessière, G., Bilotte, M., Crochet, B., Peybernès, B., Tambareau, Y. and Villatte, J. 1989. *Memoir for Quillan Geological Map (1077), France (1/50 000)*. Bureau de Recherches Géologiques et Minières, Orléans.

Beziat, D., Cabanis, B., Curnelle, R., Lago, M. and Fur-Balouet, S.L. 2001. Magmatisme alpin. Vue de l'ensemble et interpretation géodynamique. *In*: Barnolas, A. and Courbouleix, S. (eds) *Synthèse Géologique et Géophysique des Pyrénées. Volume 3. Cycle Alpin: Phénomènes Alpins*. BRGM–ITGE, Orléans.

Bilotte, M. 1985. Le Crétacé Supérieur des Plates-Formes Est-Pyrénéennes. *Strata*, **5**, 1–438.

Bilotte, M. 2007. Permanence, au Crétacé supérieur, de la position de la limite plate-forme/bassin dans la zone sous-pyrénéenne orientale. *Géologie de France*, **1**, 33–53.

Bilotte, M. and Canerot, J. 2006. Rôles respectifs des tectoniques fini-crétacée et éocène dans la partie orientale de la chaîne des Pyrénées. Le «Garumnien» de Cucugnan et ses relations avec le Chevauchement Frontal Nord-Pyrénéen (Corbières méridionales, France). *Eclogae Geologicae Helvetiae*, **99**, 17–27, https://doi.org/10.1007/s00015-006-1179-8

Bilotte, M., Peybernès, B. and Souquet, P. 1979. Les Pyrénées catalanes dans la région de l'Empordà. Relations entre zones isopiques crétacées et unités structurales. *Acta geológica hispánica*, **14**, 280–288.

Bilotte, M., Koess, L. and Debroas, E. 2005. Rélations tectonique–sedimentation sur la marge nord-orientale du sillon sous-pyrénéen au cours du Santonien supérieur. *Bulletin de la Societe Géologiqe de France*, **176**, 443–455, https://doi.org/10.2113/176.5.443

Biteau, J.-J., Le Marrec, A., Le Vot, M. and Masset, J.-M. 2006. The Aquitaine Basin. *Petroleum Geoscience*, **12**, 247–273, https://doi.org/10.1144/1354-079305-674

Bouillin, J.-P. 1967. Les klippes sédimentaires du Crétacé du sillon sous-pyrénéen entre Cubières et Cucugnan (Aude). *Comptes Rendus de l'Académie des Sciences*, **265**, 1668–1671.

Bouillin, J.P. and Magné, J. 1973. L'Albien et le Cénomanien de la zone sous-pyrénéenne entre Cubières et Cucugnan (Aude). *Bulletin du BRGM (2ème série)*, **1**, 119–132.

Boulvais, P., Ruffet, G., Cornichet, J. and Mermet, M. 2007. Cretaceous albitization and dequartzification of Hercynian peraluminous granite in the Salvezines Massif (French Pyrénées). *Lithos*, **93**, 89–106, https://doi.org/10.1016/j.lithos.2006.05.001

Boutin, A., de Saint Blanquat, M., Poujol, M., Boulvais, P., de Parseval, P., Rouleau, C. and Robert, J.-F. 2016. Succession of Permian and Mesozoic metasomatic events in the eastern Pyrenees with emphasis on the Trimouns talc–chlorite deposit. *International Journal of Earth Sciences*, **105**, 747–770, https://doi.org/10.1007/s00531-015-1223-x

Brun, J.P. and Fort, X. 2012. Salt tectonics at passive margins: Geology versus models – Reply. *Marine and Petroleum Geology*, **37**, 195–208, https://doi.org/10.1016/j.marpetgeo.2012.04.008

Brun, J.P. and Mauduit, T.P.O. 2008. Rollovers in salt tectonics: The inadequacy of the listric fault model. *Tectonophysics*, **457**, 1–11, https://doi.org/10.1016/j.tecto.2007.11.038

Brune, S., Heine, C., Pérez-Gussinyé, M. and Sobolev, S.V. 2014. Rift migration explains continental margin asymmetry and crustal hyper-extension. *Nature Communications*, **5**, 1–9, https://doi.org/10.1038/ncomms5014

Brune, S., Heine, C., Clift, P.D. and Pérez-Gussinyé, M. 2017. Rifted margin architecture and crustal rheology: Reviewing Iberia–Newfoundland, Central South Atlantic, and South China Sea. *Marine and Petroleum Geology*, **79**, 257–281, https://doi.org/10.1016/j.marpetgeo.2016.10.018

Cámara, P. and Flinch, J.F. 2017. The Southern Pyrenees: A Salt-Based Fold-and-Thrust Belt. *In*: Soto, J.I., Flinch, J.I. and Tari, G. (eds) *Permo-Triassic Salt Provinces of Europe. North Africa and the Atlantic Margins*, 395–415, Elsevier, Amsterdam.

Canérot, J. 2008. Le Passage Jurassique–Crétacé. *In*: *Les Pyrénées. Histoire Géologique et Itinéraires de Découverte. Volume 1, Histoire Géologique*. Atlantica–BRGM, Biarritz, 155–170.

Canérot, J. 2017. Origine de la chaîne des Pyrénées: collision entre les plaques ibérique et européenne ou inversion d'un ancien rift intracontinental avorté? *Bulletin de la Société d'Histoire naturelle de Toulouse*, **153**, 95–110.

Canérot, J., Hudec, M.R. and Rockenbauch, K. 2005. Mesozoic diapirism in the Pyrenean orogen: Salt tectonics on a transform plate boundary. *AAPG Bulletin*, **89**, 211–229, https://doi.org/10.1306/09170404007

Casas, J.M. and Torrades, P. 1986. Estructura de la cuenca mesozoica de Els Banys d'Arles. *Geo-Temas*, **10**, 214.

Cathelineau, M., Boiron, M.C. *et al.* 2012. A major Late Jurassic fluid event at the basin/basement unconformity in western France: $^{40}Ar/^{39}Ar$ and K–Ar dating, fluid chemistry, and related geodynamic context. *Chemical Geology*, **322–323**, 99–120, https://doi.org/10.1016/j.chemgeo.2012.06.008

Charrière, A. and Durand Delga, M. 2004. Le jeu fin-Crétacé du front nord-pyrénéen aux environs de Cucugnan (Corbières méridionales, Aude, France). *Comptes Rendus Géoscience*, **336**, 1199–1208, https://doi.org/10.1016/j.crte.2004.07.001

Charrière, A., Delga, M.D. and Fauconnier, D. 2004. Succession stratigraphique et datation palynologique du Trias autochtone au Nord-Est du massif de Mouthoumet. *Géologie de France*, **1**, 25–34.

Chelalou, R., Nalpas, T. *et al.* 2016. New sedimentological, structural and paleo-thermicity data in the Boucheville Basin (eastern North Pyrenean Zone, France). *Comptes Rendus Géoscience*, **348**, 312–321 https://doi/doi:10.1016/j.crte.2015.11.008

Choukroune, P. 1974. *Structure et Évolution Tectonique de La Zone Nord-Pyrénéenne: Analyse de la Déformation dans une Portion de Chaîne à Schistosité Sub-Verticale*. PhD Thesis, Université des Sciences et Techniques de Montpellier 2.

Choukroune, P. 1989. The ECORS Pyrenean deep seismic profile reflection data and the overall structure of an orogenic belt. *Tectonics*, **8**, 23–39, https://doi.org/10.1029/TC008i001p00023

Choukroune, P. 1992. Tectonic evolution of the Pyrenees. *Annual Review of Earth and Planetary Sciences*, **20**, 143–158, https://doi.org/10.1146/annurev.ea.20.050192.001043

Choukroune, P. and Mattauer, M. 1978. Tectonique des plaques et Pyrénées; sur le fonctionnement de la faille transformante nord-pyrénéenne; comparisons avec des modeles actuels. *Bulletin de la Société Géologique de France*, **7**, 689–700, https://doi.org/10.2113/gssgfbull.S7-XX.5.689

Choukroune, P. and Meurisse, M. 1970. Phases de déformation superposées dans le Mésozoique de la zone nord-pyrénéenne sur la transversale du massif de Salvezines (Aude). *Comptes Rendus de l'Académie des Sciences*, **270**, 14–17.

Choukroune, P., Seguret, M. and Galdeano, A. 1973. Caractéristiques et évolution structurale des Pyrénées; un modèle de rélations entre zone orogénique et mouvement des plaques. *Bulletin de la Société Géologique de France*, **S7–XV**, 600–611, https://doi.org/10.2113/gssgfbull.S7-XV.5-6.600

Christophoul, F., Soula, J.-C., Brusset, S., Elibana, B., Roddaz, M., Bessiere, G. and Deramond, J. 2003. Time, place and mode of propagation of foreland basin systems as recorded by the sedimentary fill: examples of the Late Cretaceous and Eocene retro-foreland basins of the north-eastern Pyrenees. *Geological Society, London, Special Publications*, **208**, 229–252, https://doi.org/10.1144/GSL.SP.2003.208.01.11

Clerc, C. 2012. *Evolution du Domaine Nord-Pyrénéen au Crétacé. Amincissement Crustal Extreme et Thermicité Elévée: Un Analogue Pour Les Marges Passives*. PhD thesis, Université Pierre et Marie Curie – Paris VI.

Clerc, C. and Lagabrielle, Y. 2014. Thermal control on the modes of crustal thinning leading to mantle exhumation: Insights from the Cretaceous Pyrenean

M. Ford and J. Vergés

hot paleomargins. *Tectonics*, **33**, 1340–1359, https://doi.org/10.1002/2013TC003471

Clerc, C., Lahfid, A. *et al.* 2015. High-temperature metamorphism during extreme thinning of the continental crust: A reappraisal of the North Pyrenean passive paleomargin. *Solid Earth*, **6**, 643–668, https://doi.org/10.5194/se-6-643-2015

Clerc, C., Lagabrielle, Y. *et al.* 2016. Basement–cover decoupling and progressive exhumation of metamorphic sediments at hot rifted margin. Insights from the Northeastern Pyrenean analog. *Tectonophysics*, **686**, 82–97, https://doi.org/10.1016/j.tecto.2016.07.022

Cochelin, B., Lemirre, B., Denèle, Y., de Saint Blanquat, M., Lahfid, A. and Duchêne, S. 2018. Structural inheritance in the Central Pyrenees: the Variscan to Alpine tectonometamorphic evolution of the Axial Zone. *Journal of the Geological Society, London*, **175**, 336–351, https://doi.org/10.1144/jgs2017-066

Cowie, P.A., Underhiill, J.R., Behn, J., Lin, J. and Gill, C. 2005. Spatio-temporal evolution of strain accumulation derived from multi-scale observations of Late Jurassic rifting in the northern North Sea: A critical evaluation of models for lithospheric extension. *Earth and Planetary Science Letters*, **234**, 401–419, https://doi.org/10.1016/j.epsl.2005.01.039

Dauteuil, O. 1988. Le comportement de noyaux de socle dans un couloir décrochant: les massifs de Besséde et de Salvezines (Pyrénées orientales, France). *Comptes Rendus de l'Académie des Sciences, Série II*, **307**, 423–428.

Debrand-Passard, S., Courbouleix, S. and Lienhardt, M.J. 1984. Synthèse géologique du sud-est de la France. *Mémoires du Bureau de Recherches Géologiques et Minières*, **125–126**, 615.

Debroas, E.-J. 1987. Modèle de bassin triangulaire à l'intersection de décrochements divergents pour le fossé albo-cénomanien de la Ballongue (zone nord-pyrénéenne, France). *Bulletin de la Société Géologique de France*, **III**, 887–898, https://doi.org/10.2113/gssgfbull.III.5.887

Debroas, E. 1990. Le Flysch noir albo-cénomanien témoin de la structuration albienne à sénonienne de la Zone nord-pyrénéenne en Bigorre (Hautes-Pyrénées, France). *Bulletin de la Société Géologique de France*, **VI**, 273–285, https://doi.org/10.2113/gssgfbull.VI.2.273

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

de Graciansky, P.C. 1963. Données stratigraphiques et tectoniques nouvelles sur la Montagne de Tauch. *Bulletin de la Société Géologique de France (Série 7)*, **IV**, 509–527.

Demange, M. and Pascal, M.-L. 1979. Structure du massif hercynien nord-pyrénéen de Salvezines (Aude). *Comptes Rendus de l'Académie des Sciences*, **289**, 711–714.

de Saint Blanquat, M., Bajolet, F. *et al.* 2016. Cretaceous mantle exhumation in the central Pyrenees: New constraints from the peridotites in eastern Ariège (North Pyrenean zone, France). *Comptes Rendus Géoscience*, **348**, 268–278 https://doi.org/10.1016/j.crte.2015.12.003

Dielforder, A., Frasca, G., Brune, S. and Ford, M. 2019. Formation of the Iberian-European Convergent Plate Boundary Fault and Its Effect on Intraplate Deformation in Central Europe. *Geochemistry, Geophysics, Geosystems*, **20**, 2395–2417, https://doi.org/10.1029/2018GC007840

Dooley, T.P. and Hudec, M.R. 2020. Extension and inversion of salt-bearing rift systems. *Solid Earth*, **11**, 1187–1204, https://doi.org/10.5194/se-11-1187-2020

Dooley, T. and R. Hudec, M. 2020. Extension and inversion of salt-bearing rift systems. *Solid Earth*, **11**, 1187–1204, https://doir.org/10.5194/se-11-1187-2020

Dooley, T., McClay, K.R., Hempton, M. and Smit, D. 2005. Salt tectonics above complex basement extensional fault systems: Results from analogue modelling. In: Doré, A. G. & Vining, B. A. (eds) *Petroleum Geology Conference Proceedings*. Geological Society, London, 1631–1648, https://doi.org/10.1144/0061631

Doré, T. and Lundin, E. 2015. Hyperextended continental margins – Knowns and unknowns. *Nature*, **43**, 95–96, https://doi.org/10.1016/0040

Ducoux, M. 2017. *Structure, Thermicité et Évolution Géodynamique de la Zone Interne Métamorphique des Pyrénées*. Université d'Orléans.

Duffy, O.B., Gawthorpe, R.L., Docherty, M. and Brocklehurst, S.H. 2013. Mobile evaporite controls on the structural style and evolution of rift basins: Danish Central Graben, North Sea. *Basin Research*, **25**, 310–330, https://doi.org/10.1111/bre.12000

Durand-Delga, M. and Lemoine, M. 1978. The Pyrenees and Lower Provence. *In*: Lemoine, M. (ed.) *Geological Atlas of Europe and Adjoining Alpine Areas*. Elsevier, Amsterdam, 113–162.

Espurt, N., Callot, J.-P., Roure, F., Totterdell, J.M., Struckmeyer, H.I.M. and Vially, R. 2012. Transition from symmetry to asymmetry during continental rifting: an example from the Bight Basin–Terre Adélie (Australian and Antarctic conjugate margins). *Terra Nova*, **24**, 167–180, https://doi.org/10.1111/j.1365-3121.2011.01055.x

Espurt, N., Wattellier, F., Philip, J., Hippolyte, J.C., Bellier, O. and Bestani, L. 2019. Mesozoic halokinesis and basement inheritance in the eastern Provence fold–thrust belt, SE France. *Tectonophysics*, **766**, 60–80, https://doi.org/10.1016/j.tecto.2019.04.027

Fauré, P. and Alméras, Y. 2006. Le Dogger de la partie orientale des Pyrénées franco-espagnoles (Aude, France et Haute-Catalogne, Espagne). Précisions

biostratigraphiques, corrélations et évolution paléogéographique. *Revue de Paléobiologie*, **25**, 643–670.

Ferrer, O., Roca, E., Benjumea, B., Muñoz, J.A., Ellouz, N. and MARCONI Team 2008. The deep seismic reflection MARCONI-3 profile: Role of extensional Mesozoic structure during the Pyrenean contractional deformation at the eastern part of the Bay of Biscay. *Marine and Petroleum Geology*, **25**, 714–730, https://doi.org/10.1016/j.marpetgeo.2008.06.002

Ferrer, O., Jackson, M.P.A., Roca, E. and Rubinat, M. 2012. Evolution of salt structures during extension and inversion of the Offshore Parentis Basin (Eastern Bay of Biscay). *Geological Society, London, Special Publications*, **363**, 361–379, https://doi.org/10.1144/SP363.16

Ferrer, O., McClay, K. and Sellier, N.C. 2017. *Influence of fault geometries and mechanical anisotropies on the growth and inversion of hanging-wall synclinal basins: Insights from sandbox models and natural examples*. Geological Society, London, Special Publications, **439**, 487–509, https://doi.org/10.1144/SP439.8

Ford, M., Hemmer, L., Vacherat, A., Gallagher, K. and Christophoul, F. 2016. Retro-wedge foreland basin evolution along the ECORS line, eastern Pyrenees, France. *Journal of the Geological Society, London*, **173**, 419–437, https://doi.org/10.1144/jgs2015-129

Frizon de Lamotte, D.F., Fourdan, B., Leleu, S., Leparmentier, F. and de Clarens, P. 2015. Style of rifting and the stages of Pangea breakup. *Tectonics*, **34**, 1009–1029, https://doi.org/10.1002/2014TC003760

Ge, Z., Gawthorpe, R.L., Zijerveld, L. and Oluboyo, A. P. 2020. Spatial and temporal variations in minibasin geometry and evolution in salt tectonic provinces: Lower Congo Basin, offshore Angola, Basin Research, first published online, June 20, 2020, https://doi.org/10.1111/bre.12486

Golberg, J.M. and Leyreloup, A.F. 1990. High temperature–low pressure Cretaceous metamorphism related to crustal thinning (Eastern North Pyrenean Zone, France). *Contributions to Mineralogy and Petrology*, **104**, 194–207, https://doi.org/10.1007/BF00306443

Golberg, J.M., Maluski, H. and Leyreloup, A.F. 1986. Petrological and age relationship between emplacement of magmatic breccia, alkaline magmatism, and static metamorphism in the North Pyrenean Zone. *Tectonophysics*, **129**, 275–290, https://doi.org/10.1016/0040-1951(86)90256-8

Graham, R., Jackson, M., Pilcher, R. and Kilsdonk, B. 2012. Allochthonous salt in the sub-Alpine fold–thrust belt of Haute Provence, France. *Geological Society, London, Special Publications*, **363**, 595–615, https://doi.org/10.1144/SP363.30

Grool, A.R., Ford, M., Vergés, J., Huismans, R.S., Christophoul, F. and Dielforder, A. 2018. Insights Into the Crustal-Scale Dynamics of a Doubly Vergent Orogen From a Quantitative Analysis of Its Forelands: A Case Study of the Eastern Pyrenees. *Tectonics*, **37**, 450–476, https://doi.org/10.1002/2017TC004731

Grool, A.R., Huismans, R.S. and Ford, M. 2019. Salt décollement and rift inheritance controls on crustal deformation in orogens. *Terra Nova*, **31**, 562–568, https://doi.org/10.1111/ter.12428

Harrison, J.C. and Jackson, M.P.A. 2014. Exposed evaporite diapirs and minibasins above a canopy in central Sverdrup Basin, Axel Heiberg Island, Arctic Canada. *Basin Research*, **26**, 567–596, https://doi.org/10.1111/bre.12037

Henry, J. and Zolnai, G. 1971. Sur le Trias resédimenté dans le sud-ouest du bassin aquitain. *Centre de Recherches de Pau, Bulletin*, **5**, 389–398.

Hudec, M.R. and Jackson, M.P.A. 2007. Terra infirma: Understanding salt tectonics. *Earth-Science Reviews*, **82**, 1–28, https://doi.org/10.1016/j.earscirev.2007.01.001

Hudec, M.R. and Jackson, M.P.A. 2011. *The Salt Mine. A Digital Atlas of Salt Tectonics*. University of Texas at Austin, Bureau of Economic Geology, Udden Book Series 5 and AAPG Memoir **99**.

Incerpi, N., Manatschal, G., Martire, L., Bernasconi, M., Gerdes, A. and Bertok, C. 2020. Characteristics and timing of hydrothermal fluid circulation in the fossil Pyrenean hyperextended rift system: new constraints from the Chaînons Béarnais (W Pyrenees). *International Journal of Earth Sciences*, **109**, 1071–1093, https://doi.org/10.1007/s00531-020-01852-6

Jackson, M.P.A. and Hudec, M.R. 2017. *Salt Tectonics. Principles and Practice*. Cambridge University Press, Cambridge.

Jackson, C.A.L., Duffy, O.B., Fernandez, N., Dooley, T.P., Hudec, M.R., Jackson, M.P.A. and Burg, G. 2019. The stratigraphic record of minibasin subsidence, Precaspian Basin, Kazakhstan. *Basin Research*, 1–25, https://doi.org/10.1111/bre.12393

James, V. and Canérot, J. 1999. Diapirisme et structuration post-triasique des Pyrénées occidentales et de l'Aquitaine méridionale (France). *Eclogae Geologicae Helvetiae*, **92**, 63–72, https://doi.org/10.5169/seals-168647

Jammes, S., Manatschal, G., Lavier, L. and Masini, E. 2009. Tectonosedimentary evolution related to extreme crustal thinning ahead of a propagating ocean: Example of the western Pyrenees. *Tectonics*, **28**, TC4012, 1–24, https://doi.org/10.1029/2008TC002406

Jammes, S., Lavier, L. and Manatschal, G. 2010*a*. Extreme crustal thinning in the Bay of Biscay and the Western Pyrenees: From observations to modeling. *Geochemistry, Geophysics, Geosystems*, **11**, Q10016, 1–26, https://doi.org/10.1029/2010GC003218

Jammes, S., Lavier, L. and Manatschal, G. 2010*b*. Interaction between prerift salt and detachment faulting in hyperextended rift systems: The example of the Parentis and Mauléon basins (Bay of Biscay and western Pyrenees). *AAPG Bulletin*, **94**, 957–975, https://doi.org/10.1306/12090909116

Kuhfuss, A. 1981. *Géologie et Hydrogéologie des Corbières Méridionales. Région de Bugarach–Rouffiac des Corbières*. PhD thesis, Université de Toulouse.

Labaume, P. and Teixell, A. 2020. Evolution of salt structures of the Pyrenean rift (Chaînons Béarnais, France): From hyper-extension to tectonic inversion. *Tectonophysics*, **785**, 228451, https://doi.org/10.1016/j.tecto.2020.228451

Lagabrielle, Y. and Bodinier, J.L. 2008. Submarine reworking of exhumed subcontinental mantle rocks: Field evidence from the Lherz peridotites, French Pyrenees. *Terra Nova*, **20**, 11–21, https://doi.org/10.1111/j.1365-3121.2007.00781.x

Lagabrielle, Y., Labaume, P. and de Saint Blanquat, M. 2010. Mantle exhumation, crustal denudation, and gravity tectonics during Cretaceous rifting in the Pyrenean realm (SW Europe): insights from the geological setting of the lherzolite bodies. *Tectonics*, **29**, TC4012, https://doi.org/10.1029/2009TC002588

Lagabrielle, Y., Clerc, C. *et al.* 2016. Very high geothermal gradient during mantle exhumation recorded in mylonitic marbles and carbonate breccias from a Mesozoic Pyrenean palaeomargin (Lherz area, North Pyrenean Zone, France). *Comptes Rendus Géoscience*, **348**, 290–300, https://doi.org/10.1016/j.crte.2015.11.004

Lagabrielle, Y., Asti, R. *et al.* 2020. A review of Cretaceous smooth-slopes extensional basins along the Iberia–Eurasia plate boundary: How pre-rift salt controls the models of continental rifting and mantle exhumation. *Earth-Science Reviews*, **201**, 103071, https://doi.org/10.1016/j.earscirev.2019.103071

Lavier, L.L. and Manatschal, G. 2006. A mechanism to thin the continental lithosphere at magma-poor margins. *Nature*, **440**, 324–328, https://doi.org/10.1038/nature04608

Leblanc, D. and Vaudin, J.-L. 1984. Les déformations du Mesozoïque de la zone nord-pyrénéenne à l'est de l'Aude. *Géologie de France*, **4**, 57–68.

Légier, C., Tempier, C. and Vauchez, A. 1987. Tectonique tangentielle ductile syn-métamorphe d'âge Crétacé supérieur dans la couverture du massif de l'Agly (zone nord-Pyrénéenne orientale). *Comptes Rendus de l'Académie des Sciences*, **305**, 907–911.

Leleu, S., Hartley, A.J., van Oosterhout, C., Kennan, L., Ruckwied, K. and Gerdes, K. 2016. Structural, stratigraphic and sedimentological characterisation of a wide rift system: The Triassic rift system of the Central Atlantic Domain. *Earth-Science Reviews*, **158**, 89–124, https://doi.org/10.1016/j.earscirev.2016.03.008

Le Pichon, X. and Sibuet, J.-C. 1971. Western extension of boundary between European and Iberian plates during the Pyrenean orogeny. *Earth and Planetary Science Letters*, **12**, 83–88, https://doi.org/10.1016/0012-821X(71)90058-6

López-Gómez, J., Alonso-Azcárate, J. *et al.* 2019. Permian–Triassic Rifting Stage. *In*: Quesada, C. and Oliveira, J.T. (eds) *The Geology of Iberia: A Geodynamic Approach*. Springer, Cham, 29–112, https://doi.org/10.1007/978-3-030-11295-0_3

Lopez-Mir, B., Muñoz, J.A. and García Senz, J. 2014. Restoration of basins driven by extension and salt tectonics: Example from the Cotiella Basin in the central Pyrenees. *Journal of Structural Geology*, **69**, 147–162, https://doi.org/10.1016/j.jsg.2014.09.022

López-Mir, B., Muñoz, J.A. and García-Senz, J. 2015. Extensional salt tectonics in the partially inverted Cotiella post-rift basin (south–central Pyrenees): structure and evolution. *International Journal of Earth Sciences*, **104**, 419–434, https://doi.org/10.1007/s00531-014-1091-9

Macchiavelli, C., Vergés, J. *et al.* 2017. A New Southern North Atlantic Isochron Map: Insights Into the Drift of the Iberian Plate Since the Late Cretaceous. *Journal of Geophysical Research: Solid Earth*, **122**, 9603–9626, https://doi.org/10.1002/2017JB014769

Martín-Martín, J.D., Vergés, J. *et al.* 2017. Diapiric growth within an Early Jurassic rift basin: The Tazoult salt wall (central High Atlas, Morocco). *Tectonics*, **36**, 2–32, https://doi.org/10.1002/2016TC004300

Masini, E., Manatschal, G., Tugend, J., Mohn, G. and Flament, J.-M. 2014. The tectono-sedimentary evolution of a hyper-extended rift basin: the example of the Arzacq–Mauléon rift system (Western Pyrenees, SW France). *International Journal of Earth Sciences*, **103**, 1569–1596, https://doi.org/10.1007/s00531-014-1023-8

Mattauer, M. and Proust, F. 1967. L'évolution structurale de la partie Est du domaine pyrénéo-provençal au Crétacé et au Paléogène. *Extrait des Comptes rendus du colloque sur la Biogéographie du Crétacé–éocène de la France Méridionale, Travaux de Laboratoire de Géochimie de la Biosphère, Ecole Pratique des Hautes Études*, **310**, 9–20.

McClay, K., Muñoz, J.A. and García-Senz, J. 2004. Extensional salt tectonics in a contractional orogen: A newly identified tectonic event in the Spanish Pyrenees. *Geology*, **32**, 737–740, https://doi.org/10.1130/G20565.1

Meurisse, M. 1973. *Etude Structurale de La Zone Nord-Pyrénéenne Orientale*. PhD thesis, Université Pierre et Marie Curie, Paris.

Montigny, R., Azambre, B. and Thuizat, R. 1986. K–Ar study of Cretaceous magmatism and metamorphism from the Pyrenees. *Tectonophysics*, **129**, 257–213, https://doi.org/10.1016/0040-1951(86)90255-6

Moragas, M., Vergés, J., Nalpas, T., Saura, E., Martín-Martín, J.D., Messager, G. and Hunt, D.W. 2017. The impact of syn- and post-extension prograding sedimentation on the development of salt-related rift basins and their inversion: Clues from analogue modelling. *Marine and Petroleum Geology*, **88**, 985–1003, https://doi.org/10.1016/j.marpetgeo.2017.10.001

Mouthereau, F., Filleaudeau, P. *et al.* 2014. Placing limits to shortening evolution in the Pyrenees: Role of margin architecture and implications for the Iberia/Europe convergence. *Tectonics*, **33**, 1–32, https://doi.org/10.1002/2014TC003663

Muñoz, J.A. 1992. Evolution of a continental collision belt: ECORS-Pyrenees crustal balanced cross-section. *In*: McClay, K. (ed.) *Thrust Tectonics*. Chapman & Hall, London, 235–246.

Nalpas, T. and Brun, J.P. 1993. Salt flow and diapirism related to extension at crustal scale. *Tectonophysics*, **228**, 349–362, https://doi.org/10.1016/0040-1951(93)90348-N

Nirrengarten, M., Manatschal, G., Tugend, J., Kusznir, N. and Sauter, D. 2018. Kinematic Evolution of the Southern North Atlantic: Implications for the Formation of Hyperextended Rift Systems. *Tectonics*, **37**, 89–118, https://doi.org/10.1002/2017TC004495

Odlum, M.L. and Stockli, D.F. 2019. Thermotectonic Evolution of the North Pyrenean Agly Massif During Early Cretaceous Hyperextension Using Multi-mineral U–Pb Thermochronometry. *Tectonics*, **38**, 1509–1531, https://doi.org/10.1029/2018TC005298

Olivet, J.L. 1996. La cinématique de la plaque Ibérique. *Bulletin des Centres de Recherches Exploration–Production Elf Aquitaine*, **20**, 131–195.

Pérez-Gussinyé, M. 2013. A tectonic model for hyperextension at magma-poor rifted margins: an example from the West Iberia–Newfoundland conjugate margins. *Geological Society, London, Special Publications*, **369**, 403–427, https://doi.org/10.1144/SP369.19

Peybernès, B. 1976. *Le Jurassique et Le Crétacé Inférieur des Pyrénées franco-espagnoles, Entre La Garonne et La Méditerranée*. PhD thesis, University of Toulouse.

Peybernès, B. and Souquet, P. 1984. Basement blocks and tecto-sedimentary evolution in the Pyrenees during Mesozoic times. *Geological Magazine*, **121**, 397–405, https://doi.org/10.1017/S0016756800029927

Peybernès, B., Fauré, P. and Alméras, Y. 1999. Datations et corrélations nouvelles dans les séquences de dépôt du Lias terminal et du Dogger des Corbières (Aude, France) grâce aux ammonites et aux brachiopodes. *Comptes Rendus de l'Académie des Sciences*, **329**, 211–217.

Phillips, T.B., Fazlikhani, H. *et al.* 2019. The Influence of Structural Inheritance and Multiphase Extension on Rift Development, the Northern North Sea. *Tectonics*, **38**, 4099–4126, https://doi.org/10.1029/2019TC005756

Plaziat, J.-C. 1981. Late Cretaceous to Late Eocene palaeogeographic evolution of southwest Europe. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **36**, 263–320, https://doi.org/10.1016/0031-0182(81)90110-3

Poujol, M., Boulvais, P. and Kosler, J. 2010. Regional-scale Cretaceous albitization in the Pyrenees: evidence from *in situ* U–Th–Pb dating of monazite, titanite and zircon. *Journal of the Geological Society, London*, **167**, 751–767, https://doi.org/10.1144/0016-76492009-144

Rat, J., Mouthereau, F., *et al.* 2019. Tectonothermal Evolution of the Cameros Basin: Implications for Tectonics of North Iberia. *Tectonics*, **38**, 440–469, https://doi.org/10.1029/2018TC005294

Renard, S., Pironon, J., Sterpenich, J., Carpentier, C., Lescanne, M. and Gaucher, E.C. 2019. Diagenesis in Mesozoic carbonate rocks in the North Pyrénées (France) from mineralogy and fluid inclusion analysis: Example of Rousse reservoir and caprock. *Chemical Geology*, **508**, 30–46, https://doi.org/10.1016/j.chemgeo.2018.06.017

Ríos, J.M., Almela, A. and Garrido, J. 1943. Contribución al conocimiento de la zona subpirenaica catalana. 1a parte: Observaciones geológicas sobre el borde sur de los Pirineos Orientales. *Boletin del Instituto Geológico y Minero de España*, **56**, 337–389.

Roca, E., Muñoz, J.A., Ferrer, O. and Ellouz, N. 2011. The role of the Bay of Biscay Mesozoic extensional structure in the configuration of the Pyrenean orogen: constraints from the MARCONI deep seismic reflection survey. *Tectonics*, **30**, TC2001, https://doi.org/10.1029/2010TC002735

Roest, W.R. and Srivastava, P.S. 1991. Kinematics of the plate boundaries between Eurasia, Iberia, and Africa in the North Atlantic from the Late Cretaceous to the present. *Geology*, **19**, 613–616, https://doi.org/10.1130/0091-7613(1991)019<0613:KOTPBB>2.3.CO;2

Rosenbaum, G., Lister, G.S. and Duboz, C. 2002*a*. Reconstruction of the tectonic evolution of the western Mediterranean since the Oligocene. *Journal of the Virtual Explorer*, **8**, 107–126, https://doi.org/10.3809/jvirtex.2002.00053

Rosenbaum, G., Lister, G.S. and Duboz, C. 2002*b*. Relative motions of Africa, Iberia and Europe during Alpine orogeny. *Teconophysics*, **359**, 117–129, https://doi.org/10.1016/S0040-1951(02)00442-0

Rougier, G., Ford, M., Christophoul, F. and Bader, A.-G. 2016. Stratigraphic and tectonic studies in the central Aquitaine Basin, northern Pyrenees: Constraints on the subsidence and deformation history of a retro-foreland basin. *Comptes Rendus de l'Académie des Sciences*, **348**, 224–235. https://doi.org/10.1016/j.crte.2015.12.005

Roure, F., Choukroune, P. *et al.* 1989. ECORS deep seismic data and balanced cross sections: Geometric constraints on the evolution of the Pyrenees. *Tectonics*, **8**, 41–50, https://doi.org/10.1029/TC008i001p00041

Rowan, M.G. 2014. Passive-margin salt basins: hyperextension, evaporite deposition, and salt tectonics. *Basin Research*, **26**, 154–182, https://doi.org/10.1111/bre.12043

Rowan, M.G. and Ratliff, R.A. 2012. Cross-section restoration of salt-related deformation: Best practices and potential pitfalls. *Journal of Structural Geology*, **41**, 24–37, https://doi.org/10.1016/j.jsg.2011.12.012

Rowan, M.G. and Vendeville, B.C. 2006. Foldbelts with early salt withdrawal and diapirism: Physical model and examples from the northern Gulf of Mexico and the Flinders. **23**, 871–891, https://doi.org/10.1016/j.marpetgeo.2006.08.003

Saura, E., Vergés, J. *et al.* 2014. Syn- to post-rift diapirism and minibasins of the Central High Atlas (Morocco): The changing face of a mountain belt. *Journal of the Geological Society, London*, **171**, 97–105, https://doi.org/10.1144/jgs2013-079

M. Ford and J. Vergés

Saura, E., Ardèvol, L., Teixell, A. and Vergés, J. 2016. Rising and falling diapirs, shifting depocenters and flap overturning in the Cretaceous Sopeira and Sant Gervàs subbasins (Ribagorça basin, Southern Pyrenees). *Tectonics*, **35**, 638–662, https://doi.org/10.1002/2015TC004001

Schettino, A. and Scotese, C. 2002. Global kinematic constraints to the tectonic history of the Mediterranean region and surrounding areas during the Jurassic and Cretaceous. *Journal of the Virtual Explorer*, **8**, 149–168, https://doi.org/10.3809/jvirtex.2002.00056

Schettino, A. and Turco, E. 2011. Tectonic history of the Western Tethys since the Late Triassic. *Bulletin of the Geological Society of America*, **123**, 89–105, https://doi.org/10.1130/B30064.1

Serrano, A. and Martínez del Olmo, W. 1990. Tectónica salina en el Dominio Cántabro-Navarro: Evolución, edad y origen de las estructuras salinas. *In*: Ortí, F. and Salvany, J.M. (eds) *Formaciones Evaporíticas de La Cuenca Del Ebro y Cadenas Periféricas, y de La Zona de Levante*. Enresa, Madrid, 39–53.

Serrano, O., Delmas, J., Hanot, F., Vially, R., Herbin, J.-P., Houel, P. and Tourlière, B. 2006. *Le Bassin d'Aquitaine: Valorisation des Données Sismiques, Cartographique Structurale et Potentiel Pétrolier*, Edition BRGM.

Soula, J.C. and Bessière, G. 1980. Sinistral horizontal shearing as a dominant process of deformation in the alpine Pyrenees. *Journal of Structual Geology*, **2**, 69–74, https://doi.org/10.1016/0191-8141(80)90036-X

Stampfli, G.M., Borel, G.D., Marchant, R. and Mosar, J. 2002. Western Alps geological constraints on western Tethyan reconstructions. *Journal of the Virtual Explorer*, **8**, 77–106, https://doi.org/10.3809/jvirtex.2002.00057

Stewart, S.A. and Clark, J.A. 1999. Impact of salt on the structure of the Central North Sea hydrocarbon fairways. *In*: Fleet, A.J. and Boldy, S.A. (eds) *Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference*. Geological Society, London, 179–200, https://doi.org/10.1144/0050179

Tavani, S., Bertok, C., Granado, P., Piana, F., Salas, R., Vigna, B. and Muñoz, J.A. 2018. The Iberia–Eurasia plate boundary east of the Pyrenees. *Earth-Science Reviews*, **187**, 314–337, https://doi.org/10.1016/j.earscirev.2018.10.008

Teixell, A., Labaume, P. and Lagabrielle, Y. 2016. The crustal evolution of the west–central Pyrenees revisited: Inferences from a new kinematic scenario. *Comptes Rendus Géoscience*, **348**, 257–267, https://doi.org/10.1016/j.crte.2015.10.010

Teixell, A., Labaume, P., Ayarza, P., Espurt, N., de Saint Blanquat, M. and Lagabrielle, Y. 2018. Crustal structure and evolution of the Pyrenean–Cantabrian belt: A review and new interpretations from recent concepts and data. *Tectonophysics*, **724–725**, 146–170, https://doi.org/10.1016/j.tecto.2018.01.009

Ternois, S., Odlum, M. *et al.* 2019. Thermochronological Evidence of Early Orogenesis, Eastern Pyrenees, France. *Tectonics*, **38**, 1308–1336, https://doi.org/10.1029/2018TC005254

Tugend, J., Manatschal, G., Kusznir, N.J. and Masini, E. 2014. Characterizing and identifying structural domains at rifted continental margins: application to the Bay of Biscay margins and its Western Pyrenean fossil remnants. *Geological Society, London, Special Publications*, **413**, 171–203, https://doi.org/10.1144/SP413.3

Tugend, J. Manatschal, G. and Kusznir, N. J. 2015. Spatial and temporal evolution of hyperextended rift systems: Implication for the nature, kinematics, and timing of the Iberian-European plate boundar, *Geology*, **43**, 15–18. https://doi.org/10.1130/G36072.1

Vauchez, A., Clerc, C., Bestani, L., Lagabrielle, Y., Chauvet, A., Lahfid, A. and Mainprice, D. 2013. Preorogenic exhumation of the North Pyrenean Agly massif (Eastern Pyrenees-France). *Tectonics*, **32**, 95–106, https://doi.org/10.1002/tect.20015

Vaudin, J.L. 1982. *Étude Géologique de La Couverture de Mesozoique de l'Agly*. PhD thesis, Université Paul Sabatier, Toulouse.

Vendeville, B.C., Ge, H. and Jackson, M.P.A. 1995. Scale models of salt tectonics during basement-involved extension. *Petroleum Geoscience*, **1**, 179–183, https://doi.org/10.1144/petgeo.1.2.179

Vergés, J. and Garcia-Senz, J. 2001. Mesozoic evolution and Cainozoic inversion of the Pyrenean Rift. *In*: Ziegler, P.A., Cavazza, W., Robertson, A.H.F. and Crasquin Soleau, S. (eds) *Peri-Tethys Memoir 6: Peri-Tethyan Rift/Wrench Basins and Passive Margins*. Mémoires du Muséum National d'Histoire Naturelle, **186**, 187–212.

Vergés, J., Millán, H. *et al.* 1995. Eastern Pyrenees and related foreland basins: pre-, syn- and post-collisional crustal-scale cross-sections. *Marine and Petroleum Geology*, **12**, 893–915, https://doi.org/10.1016/0264-8172(95)98854-X

Vergés, J., Fernàndez, M. and Martínez, A. 2002. The Pyrenean orogen: pre-, syn-, and post-collisional evolution. *Journal of the Virtual Explorer*, **8**, 55–74, https://doi.org/10.3809/jvirtex.2002.00058

Vergés, J., Moragas, M. *et al.* 2017. Salt Tectonics in the Atlas Mountains of Morocco. *In*: Soto, J.I., Flinch, J.I. and Tari, G. (eds) *Permo-Triassic Salt Provinces of Europe, North Africa and the Atlantic Margins*, 563–579, Elsevier, Amsterdam, https://doi.org/10.1016/B978-0-12-809417-4.00027-6

Vergés, J., Kullberg, J.C. *et al.* 2019. An Introduction to the Alpine Cycle in Iberia. *In*: Quesada, C. and Oliveira, J.T. (eds) *The Geology of Iberia: A Geodynamic Approach*. Springer, Cham, 1–14, https://doi.org/10.1007/978-3-030-11295-0_1

Vergés, J., Poprawski, Y. *et al.* 2020. Tectono-sedimentary evolution of Jurassic–Cretaceous diapiric structures: Miravete anticline, Maestrat Basin, Spain. *Basin Research*, First published online April 2, 2020, https://doi.org/10.1111/bre.12447

Vielzeuf, D. and Kornprobst, J. 1984. Crustal splitting and the emplacement of Pyrenean lherzolites and granulites. *Earth and Planetary Science Letters*, **67**, 87–96, https://doi.org/10.1016/0012-821X(84)90041-4

Withjack, M. and Calloway, S. 2000. Active Normal Faulting Beneath a Salt Layer: An Experimental Study of Deformation Patterns in the Cover Sequence. *AAPG Bulletin*, **84**, 627–651, https://doi.org/10.1306/C9EBCE73-1735-11D7-8645000102C1865D