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Structural style of the Languedoc Pyrenean thrust belt in relation with the inherited Mesozoic structures and with the rifting of the Gulf of Lion margin, southern France

Romain Hemelsdaël[1,2], Michel Séranne[1,*], Eglantine Husson[3] and Grégory Ballas[1]

[1] Géosciences Montpellier, Université de Montpellier–CNRS, Montpellier, France
[2] GeoRessources, CNRS–Université de Lorraine, Vandœuvre-lès-Nancy, France
[3] BRGM, Orléans, France

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Abstract – The E-trending Pyrenean orogen results from the inversion of the mid-Cretaceous rift structures responding to an overall N-S extension, as suggested by the balanced and restored cross-sections oriented normal to the orogen. However, oblique convergence/divergence that involve strain partitioning and arcuate segments of the orogen prevent simple tectonic restorations. The Languedoc region (southern France) provides a case study of a complex polyphase deformation involving a range of reactivated structures and cross-cutting relationships, acquired in response to varying tectonic stresses with different orientations. We analyze and correlate the onshore-offshore structures of the Languedoc region, based on reassessment of existing and newly acquired subsurface data. New results in the poorly documented coastal area point to the existence of unrecognized major structures that improves onshore-offshore correlations. Our results show: (i) the part played by the Mesozoic (Early Jurassic, then mid-Cretaceous) extensional phases in the development and the localization of Pyrenean-related contractional structures; (ii) the control of inherited crustal structure on the later Oligocene rifting of the Gulf of Lion. This restoration of the Pyrenean shortening and Oligocene rifting, constructed along sections (approximately perpendicular to each other) indicates minimum shortening of 28 km and extension of 14 km, respectively, in the Languedoc foreland. Integration of the Pyrenean structural framework of Languedoc reveals a wide, NE-trending transfer zone linking the eastern Pyrénées to Provence.

Keywords: Languedoc / Pyrénées / oblique convergence / reactivation / structural restoration / transfer zone

Résumé – Style structural de la chaîne pyrénéenne en Languedoc, en relation avec les structures héritées du Mésozoïque et le rifting du Golfe du Lion (sud de la France). L'orogène pyrénéen, d'orientation générale E-W, résulte de l'inversion du rift crétacé « moyen », lui-même contrôlé par une extension de direction méridienne. Ceci est décrit dans les coupes structurales équilibrées et restaurées, perpendiculaires aux structures de l'orogène. Cependant, dans les cas de convergence ou divergence oblique et dans les cas de virgation, les restaurations tectoniques sont problématiques. Le Languedoc fournit un cas d'étude de déformations polyphasées, impliquant des réactivations ou des superpositions de structures, en réponse à des cinématiques distinctes et d'orientations différentes. Nous analysons et corrélons les structures à terre et en mer du Languedoc, sur la base de données anciennes réinterprétées et de données nouvellement acquises. Les résultats dans la zone littorale, jusqu'à présent très peu documentée, mettent en évidence de nouvelles structures majeures qui aident à la corrélation terre-mer. Nos résultats montrent : (i) le rôle des phases extensives mésozoïques (Jurassique inférieur et milieu du Crétacé) dans le développement et la localisation des structures compressives pyrénéennes et (ii) le contrôle de ces dernières sur le rifting Oligocène du Golfe du Lion. La restauration de coupes construites selon des directions choisies quasiment perpendiculaires entre elles donne ≥ 28 km de raccourcissement pyrénéen et ≥ 14 km d'extension Oligocène dans l'avant-pays languedocien. L'intégration au schéma structural pyrénéen dessine une large zone de transfert orientée NE-SW qui relie les Pyrénées franco-espagnoles à la Provence.

Mots clés : Languedoc / Pyrénées / convergence oblique / réactivation / restauration structurale / zone de transfert

*Corresponding author: michel.seranne@umontpellier.fr

1 Introduction

The Pyrénées provide a much-studied example of inversion of a rift into an orogen. Geological cross-sections normal to the strike of the orogen display the compressional structures and also allow to decipher the pre-orogenic extensional structures that have been inverted (Gomez-Romeu *et al.*, 2019; Jammes *et al.*, 2009; Lescoutre and Manatschal, 2020; Saspiturry *et al.*, 2020; Teixell *et al.*, 2016, 2018) Inversion of rifted margins during later convergence is controlled by the inherited lithospheric structure (Espurt *et al.*, 2019a; Jourdon *et al.*, 2019; Lacombe and Bellahsen, 2016; Lacombe and Mouthereau, 2002) and lithosphere thermal state (Dielforder *et al.*, 2019). The nature of the upper crust (crystalline basement versus layered sedimentary basins) and the distribution of sedimentary sequences are also critical (Duretz *et al.*, 2020). Syntectonic sedimentary sequences preserved in upper crustal structures and in forelands provide insights into the kinematics of rift basin formation and their subsequent inversion during later contraction (Christophoul *et al.*, 2016; Ford and Vergés, 2020; Ford *et al.*, 2016; Lagabrielle *et al.*, 2010; Lopez-Mir *et al.*, 2016). These 2D analyses based on structural sections parallel to the direction of shortening and extension assume coaxial rifting and shortening (Espurt *et al.*, 2019a; Teixell *et al.*, 2016, 2018). However, oblique convergence/divergence with related strain partitioning, evidenced by strike-slip faults and lateral ramps, are difficult to constrain (Angrand *et al.*, 2020; Olivet, 1996; Tavani *et al.*, 2018; Vissers and Meijer, 2012).

After rift inversion and mountain building, the late orogenic stages of the Pyrénées are characterized by uplift and denudation (Fillon *et al.*, 2020; Gunnell *et al.*, 2009; Tavani *et al.*, 2018). The present western and central Pyrénées experience N-S-directed extension characterized either by earthquake focal mechanisms and GPS measurements (Asensio *et al.*, 2012; Nguyen *et al.*, 2016; Rigo *et al.*, 2015). Such extension is normal to the strike of the orogen, and the previous structures inherited from the rifting are reactivated (Fillon *et al.*, 2020). However, the post-orogenic structures in the eastern Pyrénées display a different pattern, with complex interplay of reverse, strike-slip and normal faulting (Goula *et al.*, 1999; Rigo *et al.*, 2015), probably in relation with a distinct evolution of the deep lithosphere. Moreover, the deep root of the orogen is missing (Chevrot *et al.*, 2018), through lithosphere thinning (*e.g.* Gunnell *et al.*, 2009) or lateral delamination (*e.g.* Jolivet *et al.*, 2020). Most authors agree on the link between removal of the roots beneath eastern Pyrénées and the later (Oligocene-Aquitanian) rifting of the Gulf of Lion (Chevrot *et al.*, 2018; Diaz *et al.*, 2018; Wehr *et al.*, 2018). The NW-SE direction of extension is oblique to the N-S shortening in the Pyrénées, which raises questions on the possible reactivation of the E-W oriented orogenic structures during Oligocene-Aquitanian rifting. Such obliquity also requires complex step-by-step restoration in order to evaluate the direction and amount of orogenic shortening.

In addition, arcuate fold and thrust belts results from complex, non-cylindrical kinematics, involving strain partitioning, vertical axis rotation, transfer and strike-slip zones (Macedo and Marshak, 1999; Marshak, 1988; Thomas, 1990). The rather linear Cantabric-Pyrenean orogen terminates to the east, on the shores of the NW Mediterranean (Jolivet *et al.*, 2020). However, the fold and thrust belt is transferred northward and connects with Provence through a left-stepping accommodation zone, observed in the Corbières and Languedoc foreland (Arthaud and Séguret, 1981; Bestani *et al.*, 2016; Lacombe and Jolivet, 2005; Séranne *et al.*, 1995). This setting suggests a transfer zone (Frizon de Lamotte *et al.*, 1995; Mascle *et al.*, 1994; Tavani *et al.*, 2018). In such areas of oblique convergence and strain partitioning, the restoration of structural sections may be an issue. The directions of successive extension, contraction and extensional collapse may be non-coaxial. Reactivation of inherited structures will depend on their more or less favorable orientations with respect to the stress regime (*e.g.* Martín-Gonzalez *et al.*, 2021; Sibson, 1985; Soliva *et al.*, 2019), especially in foreland, where inherited fault zones weaken an overall strong crust (*e.g.* Butler *et al.*, 2006; Lescoutre and Manatschal, 2020).

In southern France, the Languedoc area recorded: (i) Early Jurassic Tethyan rifting and margin subsidence, (ii) mid-Cretaceous uplift of the Durancian ithmus, (iii) Pyrenean shortening and (iv) Oligocene Gulf of Lion rifting. These successive phases are characterized by specific and significantly different strain axes orientations. This results in a range of basement and cover structures with different orientations and cross-cutting settings. The area thus provides a case study of complex network of basement and cover faults, some of which have been reactivated once or more during a later stage. Deciphering the succession of deformation and associated kinematics are important for determining carbonate reservoir geometry and connectivity. Forelands display sedimentary sequences affected by folding and faulting, that provide reservoirs, covers and structural traps for oil and gas plays (*e.g.* Roure *et al.*, 1994). In Languedoc, such methodology is applied to water resources exploration and management (Hemelsdaël *et al.*, 2021; Ladouche *et al.*, 2019; Pétré, 2020).

The main objectives of this paper are:

- to reassess the structural evolution of the northeastern foreland of the Pyrenean orogen, in a zone of oblique convergence, linking the Pyrénées and Provence, through construction of structural sections parallel to the different directions of shortening and extension, which affected the area from Early Jurassic to Miocene;
- to document multiple reactivations of a complex structural network, in response to successive non-colinear strain axes, through (i) analyses of the different stratigraphic records in footwalls and hangingwalls, and (ii) sequential restorations of the sections.

2 Structural and stratigraphic settings of Languedoc

The Languedoc area of southern France lies between the southeastern end of the Massif Central Variscan basement and the Mediterranean (Fig. 1). A several tens of kilometres wide strip of deformed Mesozoic and Paleogene sedimentary sequences runs parallel to the shoreline, from the eastern end of the Pyrénées to Provence.

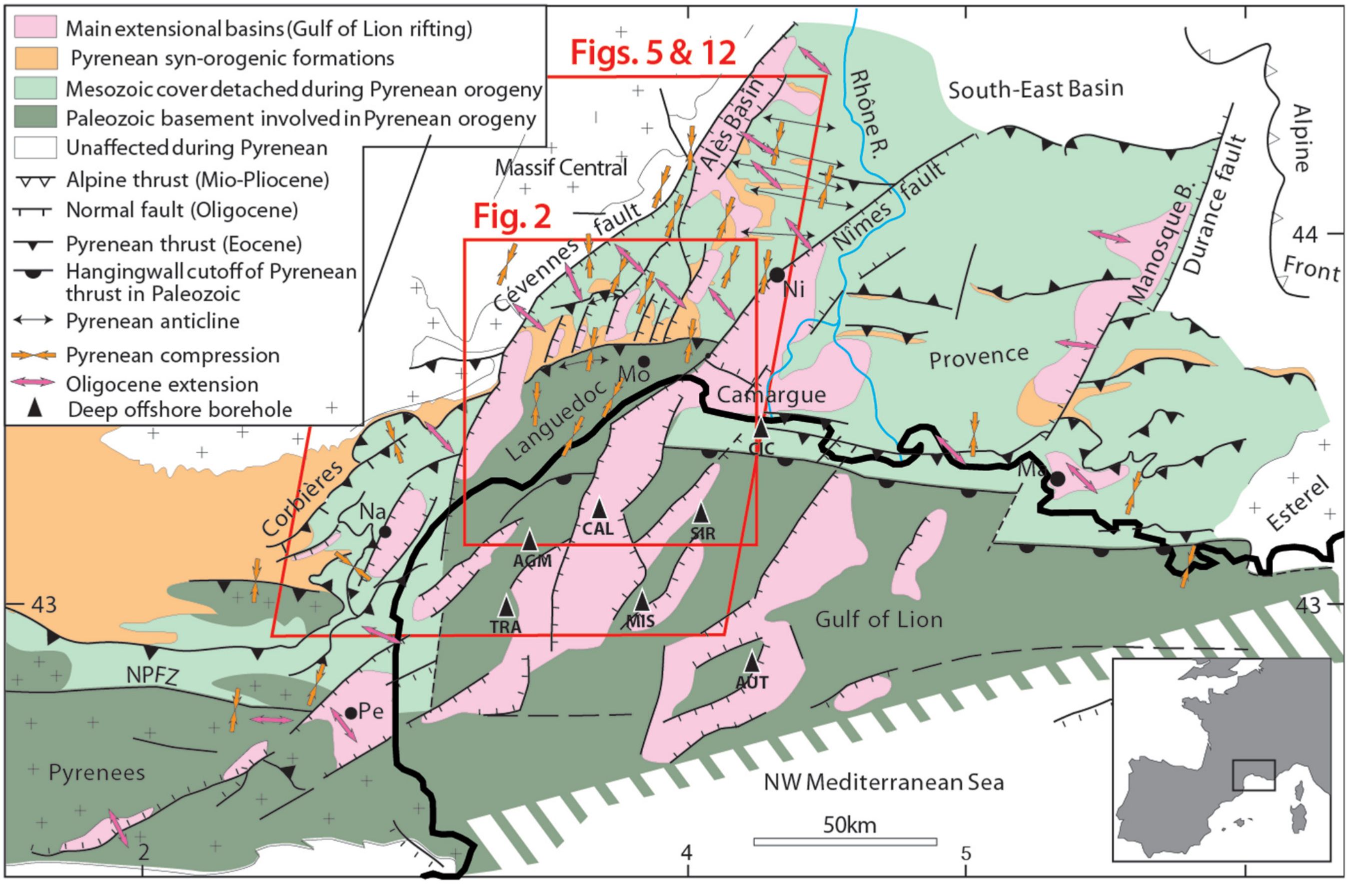

Fig. 1. Structural map of southern France showing the relation between the Pyrénées and Gulf of Lion margin; modified from Séranne *et al.* (1995). Na: Narbonne; Pe: Perpignan; Mo: Montpellier; Ma: Marseille; NPFZ: North Pyrenean Faut Zone. Offshore boreholes: AGM: Agde Maritime; AUT: Autan; CAL: Calmar; CIC: Cicindelle; MIS: Mistral; SIR: Sirocco; TRA: Tramontane. Directions of Pyrenean shortening from Gaviglio and Gonzales (1987), Lacombe *et al.* (1992), Arthaud and Laurent (1995) and Frizon de Lamotte *et al.* (2002) and Oligocene extension from Arthaud *et al.* (1977), Hippolyte *et al.* (1993) and Benedicto (1996).

Southeast of the Cévennes Fault, the area displays E-W oriented folds and thrusts, associated with latest Cretaceous to mid-Eocene synorogenic continental sedimentation, related to Pyrenean mountain-building (Arthaud and Laurent, 1995; Arthaud and Séguret, 1981). Thin-skinned, north-verging thrusting dominates deformation in the northern foreland. In the seismically poorly documented land-marine transition area, the position of the basement ramps is uncertain and still discussed (Arthaud and Séguret, 1981; Séranne *et al.*, 1995). Pyrenean deformation is also identified offshore, across the present-day Gulf of Lion (Lacombe and Jolivet, 2005; Mauffret and Gorini, 1996; Mauffret *et al.*, 2001; Séranne *et al.*, 1995). In this area, the Variscan basement has been thrusted, uplifted and eroded, prior to Neogene subsidence and sedimentation (Guennoc *et al.*, 2000). This basement is considered to have been uplifted during the early stages of mountain building (Campanian – Maastrichtian) thereby forming a major source of clastic sediments for the north Pyrenean retrowedge (Ford *et al.*, 2016; Odlum *et al.*, 2019; Vinciguerra, 2020) and the Provence foreland (Guieu and Roussel, 1990). The basement of the present-day Gulf of Lion was therefore thickened during Pyrenean orogeny and maintained at significant elevation during Campanian to Bartonian, in order to provide easterly-derived detrital sources to the retro-foreland (Ternois *et al.*, 2019). Further east, this continental block was connected with Sardinia and Corsica, the collision of which with S. Europe resulted in the Provence Pyrenean fold and thrust belt (Bestani *et al.*, 2016; Espurt *et al.*, 2019b; Lacombe and Jolivet, 2005).

In map view, Pyrenean-related structures are cross-cut by NE-trending normal faults (Fig. 1) (Andrieux *et al.*, 1971). However, in the onshore part of the margin, these extensional faults root at the basement-cover interface, thus reactivating the previous Pyrenean decollement (Séranne *et al.*, 1995). NE-trending normal faults control the formation of half-grabens in response to NW-SE extension (Fig. 1) (Benedicto *et al.*, 1999; Husson *et al.*, 2018; Maerten and Séranne, 1995; Sanchis and Séranne, 2000; Serrano and Hanot, 2005). The extensional decollement ramps down into the basement through the major Nîmes Fault (Fig. 2). Further southeast, offshore, all extension is accommodated by basement faults (Benedicto *et al.*, 1996; Guennoc *et al.*, 2000; Séranne, 1999). Offshore, extensive seismic reflection survey allowed mapping of synrift basins controlled by thick-skinned basement faults. However, synrift deposits are noticeably thin on the margin (Gorini *et al.*, 1993, 1994; Guennoc *et al.*, 2000), as a result of the post-orogenic

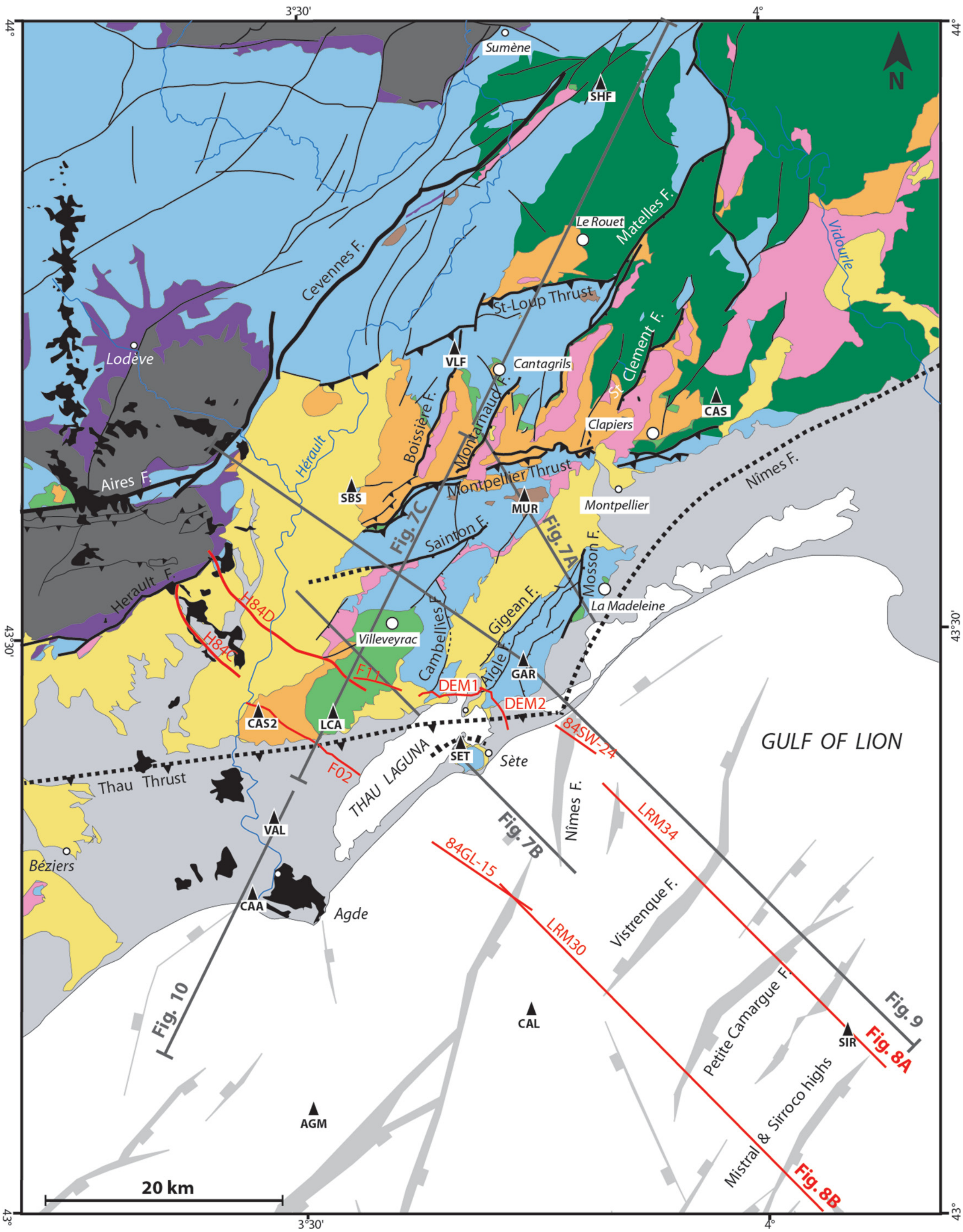

Fig. 2. Geological map of the study area, simplified from BRGM 1/250000 map of Montpellier (Alabouvette *et al.*, 2001) (location on Fig. 1). The trace of the offshore normal faults is extracted from and from Guennoc *et al.* (2000). Location of the seismic transects, of the cross-sections and the position of the deep boreholes.

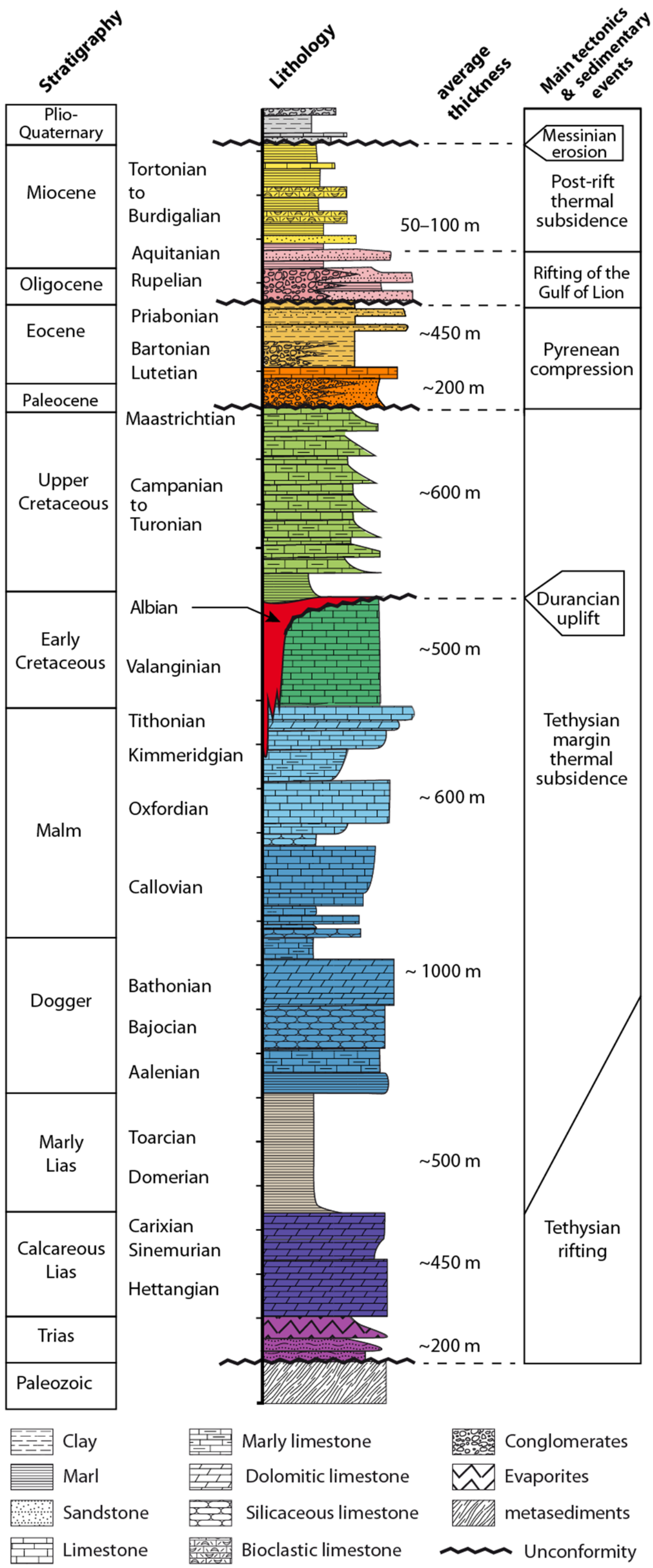

Fig. 3. Synthetic lithostratigraphic succession and main tectonic stages in the Montpellier-Sète area.

elevated topography, which did not allow preservation of synrift sedimentary formations (Séranne *et al.*, 1995). In more distal position, the rifted margin displays highly stretched and thinned continental crust and lower crust or upper mantle denudation (Jolivet *et al.*, 2015; Séranne, 1999).

The sedimentary sequence in the study area (Fig. 3) consists of carbonate-dominated Mesozoic formations, thickening eastwards, toward the South-East Basin (Beaudrimont and Dubois, 1977; Debrand-Passard and Courbouleix, 1984). It was deposited during the Triassic-Liassic rifting and thermal subsidence of the Tethys margin (Bonijoly *et al.*, 1996a; Le Pichon *et al.*, 2010). The Variscan basement is unconformably overlain by 100 to 1000 m Triassic series that mainly consist of marls, sandy clays and minor amounts of gypsum. There is no evidence of salt-related structures such as those observed in the Corbières (Ford and Vergés, 2020; Menzer *et al.*, 2019) and Provence areas (Espurt *et al.*, 2019b). However, in Languedoc, the Triassic shales and gypsum acted as a major decollement level at the basement-cover interface, during the successive deformation phases (Gorini *et al.*, 1991; Maerten and Séranne, 1995; Roure *et al.*, 1992).

During mid-Cretaceous, thermal subsidence of the Tethyan margin stopped and gave way to uplift. This inversion produced uplift, limestone karstification and erosion of the sedimentary sequences in the onshore eastern Languedoc (Bardossy and Dercourt, 1990; Marchand *et al.*, 2020), known as the "Durancian uplift" (Gignoux, 1926; Guyonnet-Benaize *et al.*, 2010; Masse and Philip, 1976). Erosion and weathering occurred at distinct places of the area and at successive stages, analysed in detail elsewhere (Chanvry *et al.*, 2020; Marchand, 2019; Marchand *et al.*, 2020). Weathering of the thick sequences of the Valanginian marly limestone under wet tropical climate was followed by reworking, transport and deposition of bauxites above the karstified Late Jurassic limestones. Typically, in the study area, bauxite deposits mark an erosional hiatus, while continental sedimentation resumed in Late Cretaceous. Duration of the hiatus increases westwards and may cover the Lias-Santonian interval (Alabouvette *et al.*, 2001). The bauxite event (Combes, 1990; Lajoinie and Laville, 1979) was recently dated of early to mid-Albian age in the Villeveyrac bauxite mine (Fig. 2) (Marchand *et al.*, 2020). The driving force of the mid-Cretaceous event in Languedoc is still debated (Barbarand *et al.*, 2001; Guyonnet-Benaize *et al.*, 2010; Tavani *et al.*, 2018; Wyns *et al.*, 2003). Of interest to our purpose are the following facts:

– the regional bauxite surface constitutes a mid-Cretaceous regional reference surface (Lajoinie and Laville, 1979);
– in the study area, the bauxite deposits seals extensional faults, oriented NE-SW and E-W (Marchand *et al.*, 2020);
– this mid-Cretaceous event records both uplift onshore and subsidence offshore of the study area, respectively;
– this event is temporarily correlated with rifting in the future Pyrénées (Debroas, 1990; Ford and Vergés, 2020) and offshore Provence (Fournier *et al.*, 2016).

Continental to paralic sedimentation resumed in localized, Late Cretaceous basins, then extended across most of the study area during Maastrichtian.

Table 1. Reflection seismic surveys and profiles used in this study.

Survey	Onshore/ Offshore	Date of acquisition	Reprocessing (BRGM)	Seismic quality	Studied profiles
DEM	Onshore	2017		+	DEM01, DEM02
F	Onshore	1963	2017–2018	+	F01, F02, F05, F06, F10, F11, F12
84SW	Offshore	1984	2017	+++	84SW-10, 84SW-11, 84SW-22, 84SW23, 84SW24, 84SW25
84GL	Offshore	1984	2017	++	84GL-05, 84GL-13, 84GL-22
81GL	Offshore	1981	2017	++	81GL-02
H83	Onshore	1983	2007–2008	++	H83C, H83D, H83E, H83F, H83G, H83H, H83I, H83N, H83M, H83K
H84	Onshore	1984	2007–2008	++	H84B, H84C, H84D, H84E, H84F, H84G, H84I, H84T, H84W
LRM	Offshore	1996		+++	LRM18, LRM20, LRM22, LRM24, LRM26, LRM28, LRM30, LRM32, LRM34, LRM36, LRM05, LRM07, LRM09, LRM11, LRM13, LRM15, LRM17

The Pyrenean synorogenic series comprise Late Maastrichtian to lower Eocene continental breccia and silty marls, followed by Lutetian lacustrine deposits, and finally, Bartonian syntectonic alluvial-fan breccia that distally grade to silty marls. This sequence characterizes a two-stage compressional deformation, separated by a period of relative quiescence interval (Andrieux *et al.*, 1971; Arthaud and Séguret, 1981).

Synorogenic Pyrenean sedimentation passes upward to an intermediate fluvial succession of Priabonian age, deposited in releasing bends and oversteps of left-lateral strike-slip faults, that affect a 50 km wide wrenching zone between the Cévennes and Nîmes faults, respectively (Séranne *et al.*, 2021).

The onshore synrift late Rupelian to Aquitanian sequences consist of continental alluvial-fans, deposited along the active normal faults and grading distally to alluvial plain and/or lacustrine deposits (Benedicto *et al.*, 1999; Crochet, 1984). Postrift marine sediments dated to early Burdigalian to middle Miocene onlaps onto the synrift and prerift sequences (Maerten and Séranne, 1995; Magné, 1978; Séranne, 1999). The postrift sequence is truncated by the Messinian erosional surface and covered by prograding Plio-Pleistocene sequence (Clauzon, 1979; Lofi *et al.*, 2011 and references within).

3 Data

The study is based on the BRGM 1/50,000 geological maps, which have been locally reassessed (*e.g.* Séranne *et al.*, 2021) and detailed field mapping in the key points of the Thau-Montpellier area (*e.g.* Hemelsdaël *et al.*, 2021).

Subsurface data are provided by boreholes, deeper than 100 m, extracted from the "*Banque du Sous-Sol*" (BRGM), geothermal and water exploration boreholes (depth ranging from several 100's to 1000 m) from BRGM internal reports (Dörfliger and Le Strat, 2001) and oil and gas exploration boreholes, both onshore and offshore ("*Minergies*" database) (Figs. 1 and 2).

The seismic reflection dataset originates from different geophysical surveys of which some critical seismic profiles have been reprocessed (Tab. 1). The onshore 2D seismic data acquired in 1963, NW of the Thau lagoon and offshore 2D seismic lines acquired in 1981–1984 between Agde and Montpellier have been reprocessed (Capar and Marc, 2018a, 2018b).

Two new seismic lines (DEM1, DEM2), 11 km-long, oriented E-W and NNW-SSE, have been acquired in 2017 by CGG-Veritas. These profiles link the exploration surveys (H83–H84) in the Hérault basin to the offshore surveys in the Gulf of Lion. The details of this new seismic acquisition and processing are provided in Coppo *et al.* (2018).

In addition, we have integrated previous structural and stratigraphic interpretations of the onshore Gulf of Lion margin, based on seismic surveys acquired in the mid-80's (Benedicto *et al.*, 1996; Husson, 2013; Husson *et al.*, 2018; Maerten and Séranne, 1995; Serrano and Hanot, 2005). The upper margin has been documented by industrial and academic seismic lines (LRM, ECORS and ESP) previously interpreted (Bache *et al.*, 2010; Duvail *et al.*, 2005; Mauffret *et al.*, 2001). Despite the diversity of the seismic surveys due to different acquisition parameters and processing techniques, it is possible to interpret and correlate different seismic units (Fig. 4).

The postrift sequence is well imaged in offshore profiles. The Pliocene-Pleistocene interval progrades basinward over the Messinian erosional surface, which truncates the parallel, aggrading Miocene postrift series. The underlying synrift (Oligocene-Aquitanian) succession is imaged on both onshore and offshore profiles, characterized by divergent reflectors and evidence of growth structures. Locally, they unconformably overlie Pyrenean synorogenic sediments. The Mesozoic strata are interpreted with more uncertainties depending on the quality of the seismic surveys. The Cretaceous strata are marked by parallel to subparallel and rather continuous reflectors of moderate to high amplitude. The reflectors of the Jurassic strata are characterised by low to moderate amplitude, and they can be chaotic and semi-transparent in some places. The different units within the Jurassic succession (Malm, Dogger, marly Lias, calcareous Lias) are well identified in onshore seismic profiles (Husson, 2013; Serrano and Hanot, 2005) below the Late Cretaceous (Fig. 4A, B). In profiles DEM1 and DEM2, it was only possible to trace the high amplitude reflectors at the interface between Triassic and Jurassic units. Interpretation of the top basement surface is rather uncertain in most of the profiles.

We have thus consistently identified the following units in all available surveys, from top to bottom: (1) the Plio-Pleistocene interval, (2) the undifferentiated Miocene postrift sequence truncated by the Messinian erosional unconformity,

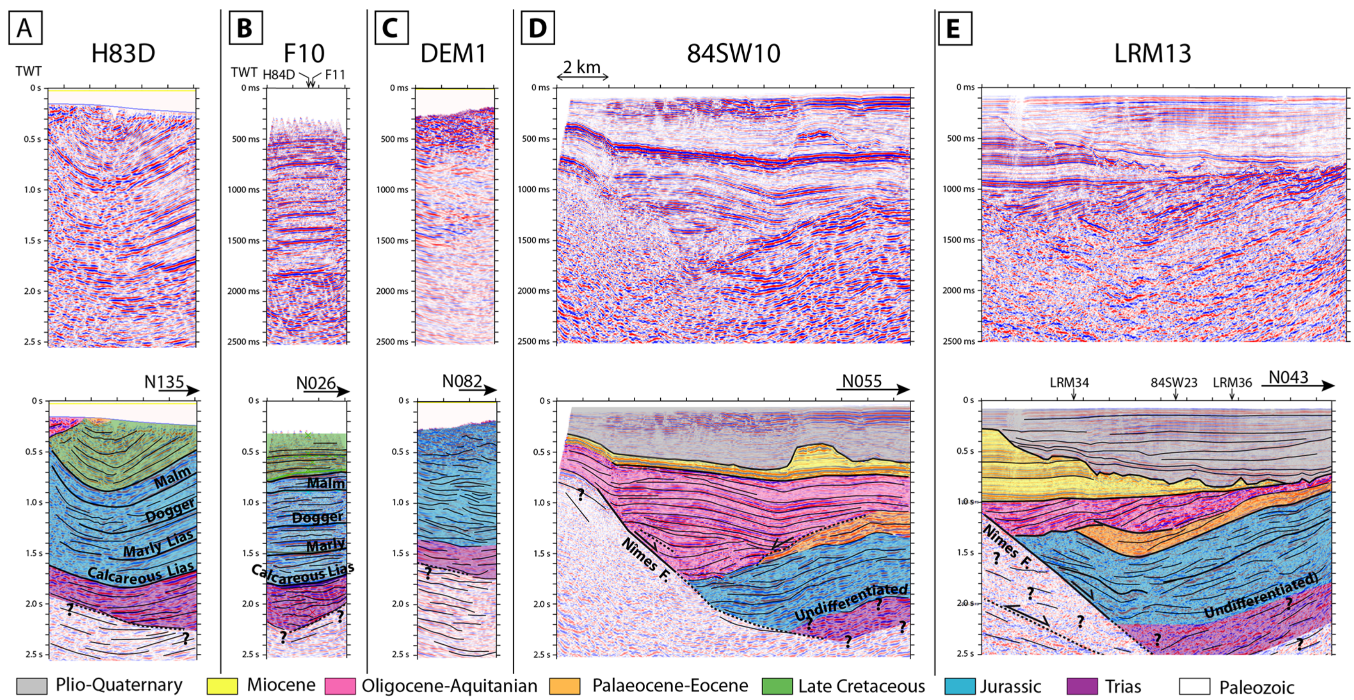

Fig. 4. Examples of seismic reflection imaging of each survey used in this study (top panels) and the interpreted stratigraphy (lower panels). The different profiles and processing are listed in Table 1.

(3) the Oligocene-Aquitanian synrift sequence, which truncates (4) the Pyrenean syntectonic sequence of Paleocene-Eocene age and (5) the undifferentiated Jurassic interval. The underlying Triassic sediments and Variscan basement remain poorly constrained.

4 Structure of the top of basement

The present-day top of the Variscan basement records deformation resulting from all tectonic phases that successively affected the Languedoc area. We compiled the map of the top of basement (Fig. 5) using different published studies. Arthaud *et al.* (1981) compiled the top of Palaeozoic basement for the onshore Languedoc, from analyses of geological map and borehole data (oil and gas exploration). Onshore seismic data allowed to image the top of the basement: N and W of Montpellier (Benedicto, 1996), in the Hérault basin (Couëffé, 2011; Maerten and Séranne, 1995; Serrano and Hanot, 2005); in Camargue (Benedicto *et al.*, 1996); and in the Gardon and Alès basin (Sanchis, 2000; Sanchis and Séranne, 2000). In the offshore Gulf of Lion, (Guennoc *et al.*, 2000) compiled a structural map of the top of prerift sequence, interpreted from extensive seismic reflection data tied to exploratory offshore wells. It has been shown that, in wide areas of the Gulf of Lion, the Palaeozoic basement appears to be unconformably covered by the Oligocene-Miocene sequences related to the rifting (Arthaud *et al.*, 1981; Cravatte *et al.*, 1974; Guennoc *et al.*, 1994). In these areas, the post-Palaeozoic interval thickness has been determined by depth conversion of the seismic data. The precise distribution and thickness of preserved Mesozoic units are still debated (Gorini, 1993), but there is evidence for preserved Mesozoic in the south of Camargue and in the downfaulted grabens of the western Gulf of Lion (Guennoc *et al.*, 2000; Mauffret and Gorini, 1996).

Gravity maps acquired by the GOCE project provide a regional, low resolution image at the scale of the western Mediterranean (Dufréchou *et al.*, 2019). In this study, we used published Bouger and gravity residual maps (Canva, 2018; Canva *et al.*, 2020; Guennoc *et al.*, 2004), to localize the main density contrasts, interpreted as Variscan basement highs and lows.

The top of basement map (Fig. 5A) displays a complex structure with a range of elevations varying from more than 1.5 km (altitude of the Aigoual summit) down to depth exceeding 9 km (N. of Nîmes). Such basement depth corresponds to the western end of the South-East Basin (Beaudrimont and Dubois, 1977; Le Pichon *et al.*, 2010). Highs and lows are generally oriented along a NE-SW trend, with higher gradients normal to this trend. Superposition of the simplified structural sketch (Fig. 5B) suggests that the present-day top of basement elevation is controlled by the Pyrenean orogeny and later rifting of the Gulf of Lion. However, several structures are unaccounted for, especially in coastal areas, where geological structures are masked by Plio-Pleistocene cover, and unexplored by seismic reflection (SE of Béziers, SW of Montpellier, W of the CIC coastal borehole). This suggests that: (i) some structures are not correctly documented, (ii) some other structures may result from earlier tectonic events, and (iii) interactions of the successive stages of deformation are not fully understood.

5 Pre-Pyrenean structures

The study area, located in the westernmost South-East Basin of France (Fig. 1) (Beaudrimont and Dubois, 1977;

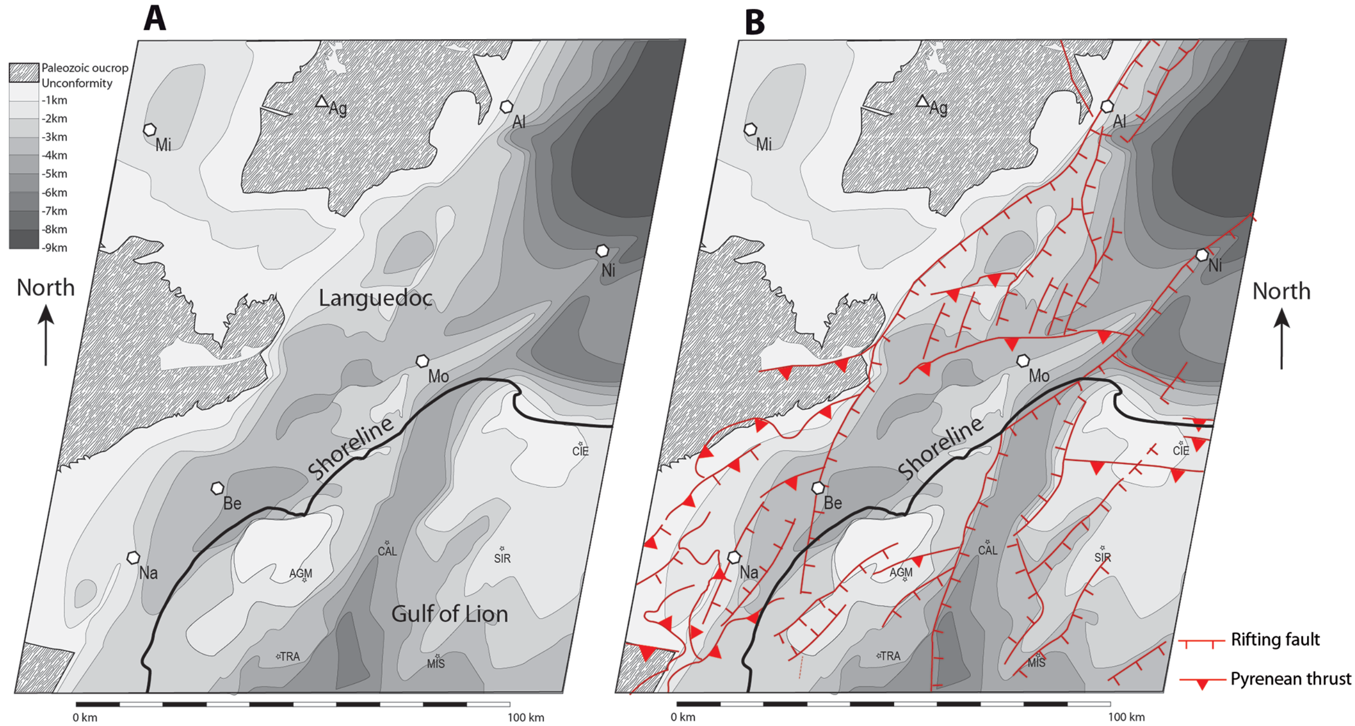

Fig. 5. A. Isobath map of the top of the Paleozoic basement, compiled from various sources (see text for references). **B.** Same map with superimposed structural framework of Séranne *et al.* (1995). Main cities: Al: Alès; Be: Béziers; Mi: Millau; Mo: Montpellier; Na: Narbonne; Ni: Nîmes; Ag: Aigoual summit (1567 m). Offsore boreholes: AGM: Agde Maritime; CAL: Calmar; CIC: Cicindelle; SIR: Sirocco. Location of this map on Figure 1.

Dubois and Delfaud, 1989) is characterised by large thickness variations within the Mesozoic successions, documented by seismic and borehole data (Alabouvette *et al.*, 2001; Benedicto *et al.*, 1996; Bonijoly *et al.*, 1996a; Maerten and Séranne, 1995; Sanchis and Séranne, 2000). The thickening of the Jurassic series towards the SE, across NE-trending normal margin faults has also been described (Beaudrimont and Dubois, 1977; Bonijoly *et al.*, 1996a, 1996b; Dubois and Delfaud, 1989; Merzeraud and Colombie, 1999). In the study area (Fig. 2), boreholes and field sections show large thickness variations over short distances, which are interpreted as evidence for differential block faulting during margin development (Fig. 6A). The marly Lias unit is 100 to 500 m thick, but reaches 1000 m in the northern area (VLF well, Fig. 2). The Dogger unit gradually thickens towards the south (about 1300 m of Dogger in GAR well) but then drastically thins in the Sète area where the Jurassic series are significantly reduced. The presence of reduced Tethyan series in the Sète area is here explained by a N-dipping normal fault (Sète F., Fig. 6A) to the north of the Sète peninsula, although we have poor control on its strike. This normal fault correlates with the horst of the Gardiole structural high (Fig. 2), also identified along-strike in the Montpellier area beneath the Neogene cover (Husson, 2013). This fault accommodated differential subsidence during the Dogger and possibly also during the Liassic times. Another feature of the Sète area is the presence of the Palaeozoic basement at shallow depth (<1500 mbsl). Deep oil and gas exploration boreholes show that the Palaeozoic basement top lies at 1583 mbsl in GAR well and abruptly plunges toward the west below the Hérault Basin (about 4500 mbsl).

The Gardiole Massif is bordered by normal faults, oriented NE-SW, dipping between 45° and 60°. Other minor faults are characterised by low dips toward the SE (15–30°), and they pre-date the mid-Cretaceous bauxitic event (Combes, 1965; Gottis *et al.*, 1967). The lack of calcareous Liassic unit in the GAR well (Fig. 6A) is explained by the presence of a low-angle south-dipping normal fault (Arthaud and Durand, 1989; Combes, 1965). Reduced Mesozoic interval in Sète also implies a horst structure during Tethyan margin formation. The differential thickening of the Jurassic series and the presence of basement structural highs beneath Gardiole and Sète areas strongly suggest the presence of inherited horsts and sub-basins limited by NE-trending faults. These newly described features are used for the construction of the regional cross-sections.

The pre-Pyrenean structures also include mid-Cretaceous Durancian faults, which are sealed by the bauxite erosional surface (Combes, 1990; Lajoinie and Laville, 1979). Northeast of the study area, Valanginian to Hauterivian series are preserved in downfaulted blocks, whereas the uplifted blocks (bounded by EW-oriented and NE-trending faults) are eroded and karstified down to Late Jurassic limestone (Husson, 2013). Later deformation inverted or masked these faults so they are now only evidenced by the distinct stratigraphic record in the footwall and hangingwall, respectively (Fig. 6B). The area was therefore subjected to mid-Cretaceous faulting coeval with the bauxitic event, which developed in relation to the opening of the Pyrénées-South Provence mid-Cretaceous rift and the uplift of the southern Massif Central (Chanvry *et al.*, 2020; Marchand, 2019; Marchand *et al.*, 2020).

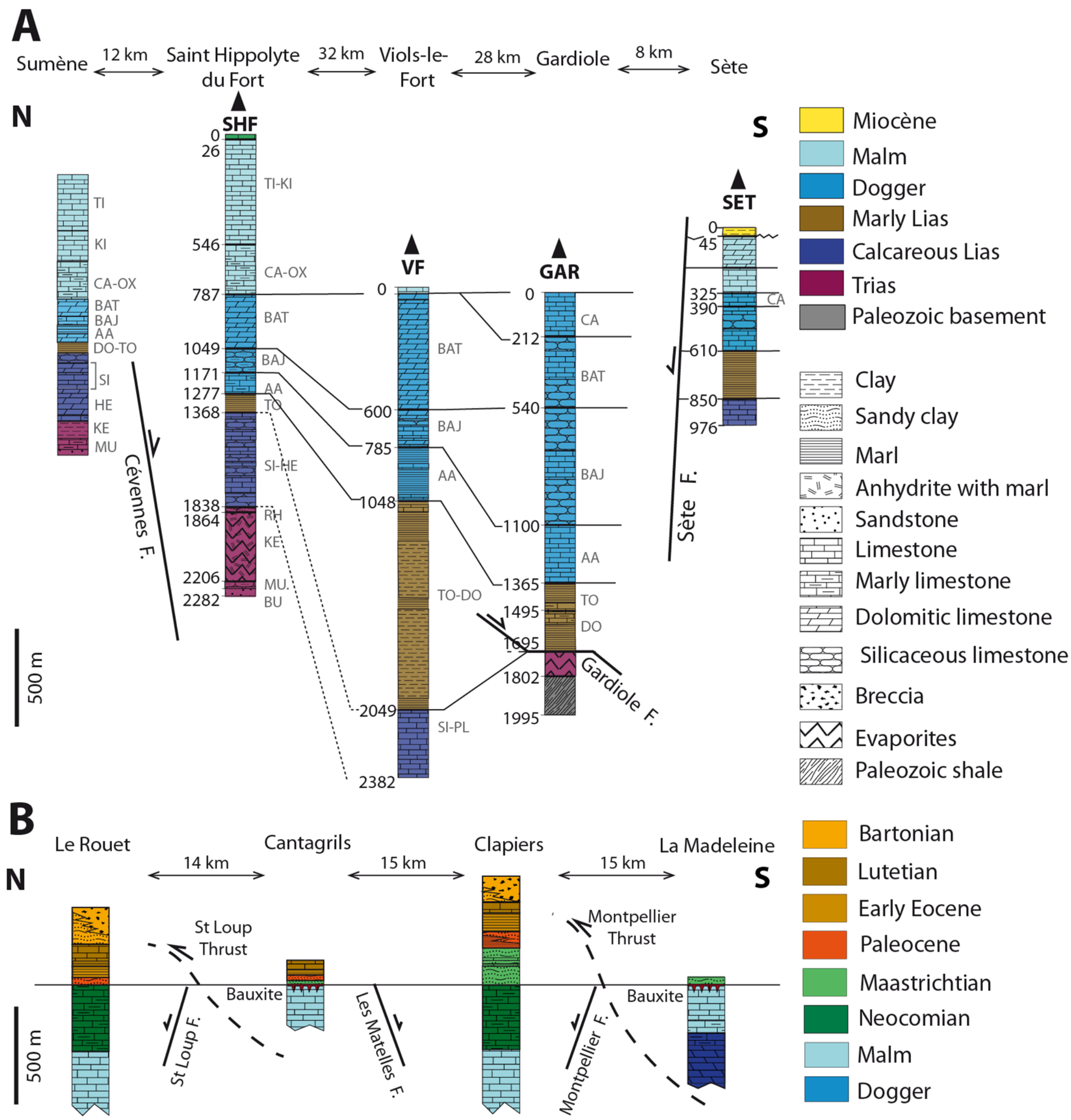

Fig. 6. A. Correlation diagram of selected boreholes along a N–S transect (location on Fig. 2) and providing evidence for Jurassic ("Tethyan") fault-controlled subsidence. Note that the northernmost section (Sumène) is measured in the field. **B.** Correlation diagram of stratigraphic sections measured in the field (location on Fig. 2) and showing evidence of mid-Cretaceous ("Durancian") faulting. BU: Buntsandstein; MU: Muschelkalk; KE: Keuper; RH: Rhetian; HE: Hettangian; SI: Sinemurian; PL: Pleinsbachien; DO: Domerian; TO: Toarcian; BAJ: Bajocian; BAT: Bathonian; CA: Callovian; OX: Oxfordian; KI: Kimmeridgian; TI: Tithonian; BE: Berriasian; VA: Valanginian; MA: Maastrichtian.

6 Pyrenean thrusts in the Montpellier-Thau area

The Montpellier thrust constitutes the major onshore compressional structure related to the Pyrenean orogeny in the study area (Arthaud and Séguret, 1981). Thrust geometry is constrained by the Murviels borehole data (MUR, Fig. 2), which documents lower Liassic limestone above syntectonic Paleocene-Maastrichtian sediments, indicating a minimal offset of 4 km (Andrieux *et al.*, 1971). According to fold geometry in the hangingwall and regional paleostress reconstruction, the structure responds to a NNE-SSW shortening (Arthaud and Laurent, 1995). It is associated with NNE-trending lateral ramps, involving a left-lateral strike-slip component of movement (Arthaud and Durand, 1989; Benedicto *et al.*, 1996). This indicates shortening oblique to the surface trace of the thrust, with a component of left-lateral strike-slip movement. Seismic reflection interpretation across the whole area allowed 3D structural modelling of the Montpellier Thrust (Husson, 2013; Husson *et al.*, 2018).

The sections in Figure 7 show the geometry at depth of the Montpellier Thrust. Section C is close to the NNE direction of transport, and it corresponds to the transect of a previous regional cross-section displaying Pyrenean shortening (Arthaud and Laurent, 1995). The NW-SE sections (A and B) are close to normal to transport direction and display the fault as lateral or oblique ramp. The Montpellier Thrust

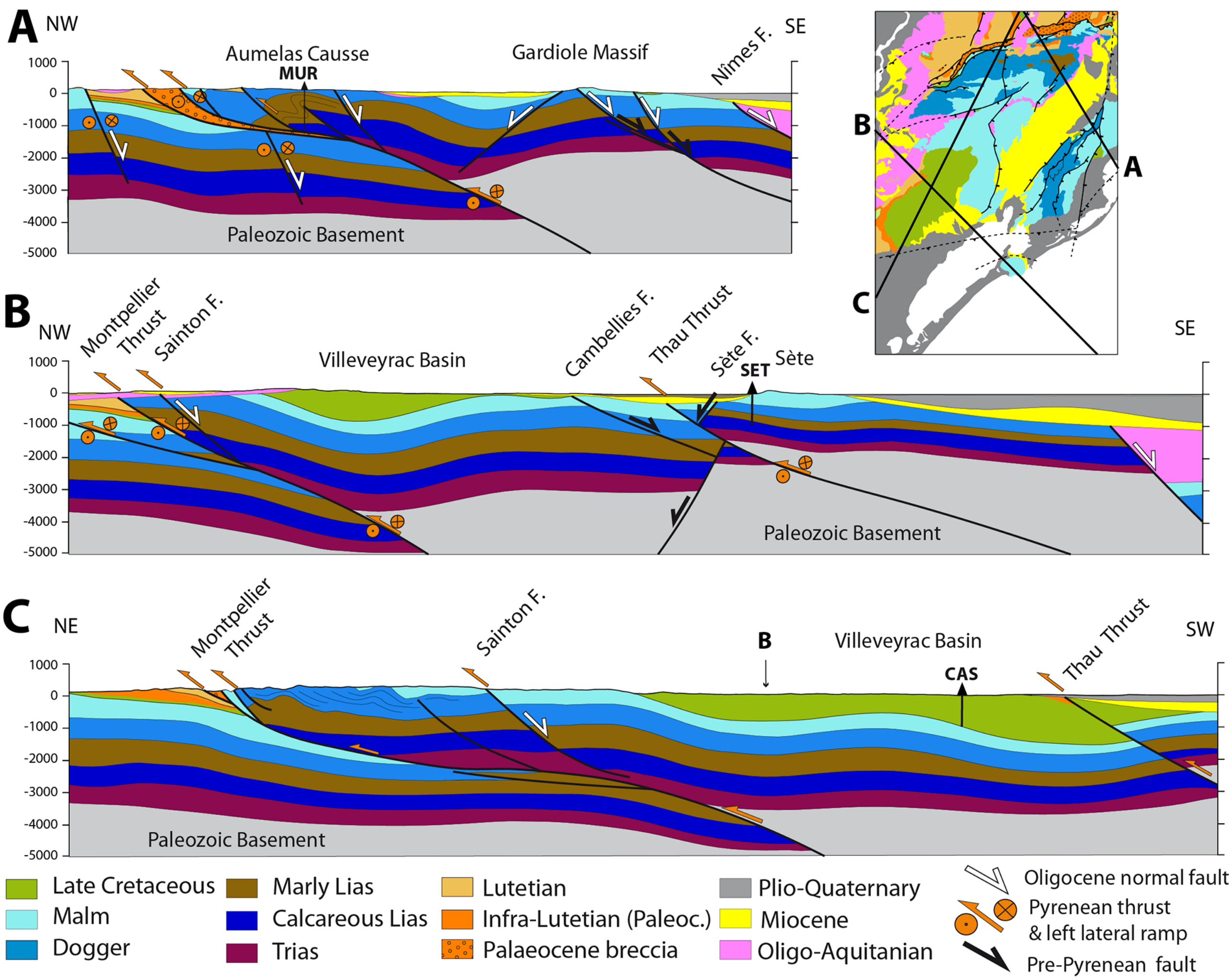

Fig. 7. Structural sections in the Montpellier–Thau area. Position given in the upper right corner and in Figure 2. See text for method and comments. Note that the fault activities related to the main tectonic stages are indicated (color-coded).

hangingwall consists of a Jurassic to Late Cretaceous monocline and the main thrust ramps down into the basement further south.

Tectonic-sedimentation relationships at the thrust front allow the analysis of the chronology of Montpellier Thrust (Arthaud and Séguret, 1981). Initial folding of the hangingwall and deposition of syntectonic formations at the thrust front occurred between the latest Cretaceous and Early Eocene. Alluvial-fan breccia made of carbonate clasts in a distinctive matrix of red silty marls commonly display *microcodium*: the "Vitrolian" facies (Freytet and Plaziat, 1982). These continental formations interfinger northwards with fan-deltas with a marine calcareous matrix that yielded early Palaeocene foraminifera (Combes *et al.*, 2007). A second phase of shortening occurred after deposition of the mid-Eocene lacustrine limestones (classically of Lutetian age). The latter is observed to unconformably seal the folded thrust front, and it is also folded and thrusted within alluvial fans that rapidly pass distally (*i.e.* northward) to silty marls with pedogenesis that characterize an alluvial plain environment (Andrieux *et al.*, 1971). This second syntectonic formation is dated to the Bartonian (Arthaud and Séguret, 1981). Across the Montpellier Thrust, the amplitude of this shortening is moderate compared to the previous shortening phase, whereas Bartonian shortening corresponds to the major tectonic phase in the Saint-Loup thrust, located some 20 km northward (Philip *et al.*, 1978; Séranne *et al.*, 2021).

The Thau Thrust is a newly described major structure of the study area, which is entirely covered by Neogene sediments and the Thau lagoon (Fig. 7B, C). Several lines of evidence converge to confirm its existence:

- the upper Jurassic carbonates on both sides of the Thau lagoon dip 25°–30° to the SSW, which allows to interpolate a vertical offset in the range of 400 m. Such structural setting could result from either a north-verging thrust or a north-facing normal fault;
- beneath the Neogene cover, several shallow water wells along the northern shore of the Thau lagoon ("*Banque du Sous-Sol*" BRGM database) have encountered reddish continental sandy marls, containing breccia of Jurassic limestones, which can be correlated with either outcrops of synrift Oligocene or syntectonic Paleocene-Eocene. Since Oligocene is not documented in this area (Gottis *et al.*, 1967), we interpret this interval as synorogenic Pyrenean

sediments deposited north of an emerging Pyrenean thrust. Correlative continental detritals of early Eocene age are exposed 15 km west of Sète (Berger *et al.*, 1981);
- the thrust documented in Valensac borehole (VAL, Fig. 2) (Arthaud and Laurent, 1995), east of the Thau lagoon, extends along-strike northeast-ward and correlates with the newly described structure. Further east, past the shoreline, this thrust connects with the Nîmes Fault (Husson *et al.*, 2018). Symmetrically, the Thau Thrust can also be considered as a compressive splay of the major Nîmes Fault;
- beneath the Neogene cover, the Thau Thrust trace is constrained by the results of a passive seismic acquisition (Bourgeois, 2019) providing a detailed map of the top Jurassic surface in the Sète-Balaruc area. The Thau Thrust subcrop is marked by topographic anomalies of the top Jurassic at shallow depth (<200 m), consistent with the E-W orientation of the Pyrenean thrusts.

Therefore, the Sète peninsula is an isolated and uplifted block corresponding to the hangingwall of the E-W oriented Pyrenean Thau Thrust, in a complex structural zone interacting with NNE-trending left-lateral wrenching (Nîmes Fault). In addition, the Thau Thrust is superimposed onto a previous north-facing, extensional fault of Tethyan age. The lack of exposure prevents any direct dating of the Thau thrust activity. It is however likely that the Thau thrust records the same tectonic history as the Montpellier Thrust.

7 Rifting structures of the Gulf of Lion margin

The study area underwent NW-SE extension during the Oligocene to Aquitanian times. Detailed analyses in the onshore part of the rifted margin have documented an extensional system, consisting of NE-striking extensional faults that detached in the Variscan basement-Mesozoic cover interface, and that controlled half-graben formation (Benedicto, 1996; Husson, 2013; Maerten and Séranne, 1995; Serrano and Hanot, 2005; Séranne *et al.*, 1995). In the offshore part, the extensional faults affect the basement and control the deposition of thin synrift sequence (Gorini *et al.*, 1994; Guennoc *et al.*, 2000).

The established seismic stratigraphy (Fig. 4) enables us to construct two 80 km long seismic regional cross-sections linking the onshore and offshore domains (Fig. 8). These sections are parallel to the extension direction, so that the imaged extensional structures are significant for the rifting history.

In the offshore part of the profiles, the Miocene to Plio-Quaternary succession forms a thick wedge as a result of postrift subsidence, compared with the onshore thin and discontinuous sequence (Hérault basin). The Hérault Fault corresponds to the Oligocene top-of-basement extensional decollement. It propagates landwards and emerges along the inherited, basement-involved, Cévennes Fault, of which, it reactivates the shallowest part (Maerten and Séranne, 1995). Similar structural setting is also observed along-strike in the synrift Alès basin: the Alès Fault activates the top-of-basement decollement during Oligocene rifting. Accordingly, the Alès Fault propagates upward and reactivates the Cévennes Fault, close to the surface (Sanchis and Séranne, 2000). Therefore, the Hérault Fault bounding the synrift Hérault basin does not affect the Palaeozoic basement. On the opposite, the Nîmes Fault affects the basement and bounds the major synrift basins, which are characterised by diverging reflectors. Its vertical synrift offset decreases toward the SW, from more than 2sTWTT offset in the onshore Camargue graben (Benedicto *et al.*, 1996) to less than 1 s TWTT and 0.2 s TWTT (Fig. 8A and B, respectively). The offset is transferred to the antithetic, NW-facing, Vistrenque Fault, thus forming a relay zone.

One of the most striking features is a structural high in the coastal zone, with basement top at about 1.5 s TWT (Fig. 8). This basement high is located between the Nîmes Fault and the Thau Thrust, thus forming a complex zone of interaction between Pyrenean thrusts and Oligocene extensional faults. The reactivated Nîmes Fault connects with the Thau Thrust system below 2.0 s TWT. As argued above, the basement offset is explained by the combined effects of the north-dipping Sète Fault, which forms a Tethyan horst, and later Pyrenean thrusting across the Thau Thrust system. Unfortunately, the poor quality of the reprocessed line F02 in the Hérault Basin (Figs. 2 and 8B) does not allow satisfactory seismic imaging of the geometry of the Thau Thrust system and associated deformed units.

A key point to address is the offshore continuity of the Mesozoic units. Only two offshore boreholes, close to the coastline, encountered the Mesozoic substratum (CAL, CIC; Fig. 2). The other deep boreholes drilled the Variscan basement directly underlying the synrift or postrift sediments, displaying Palaeozoic metasediments in AUT, MIS and TRA wells, or granitic pluton in SIR well. Based on our seismic interpretations and the offshore borehole data, we propose that Mesozoic sequences are present north and northwest of the Mistral-Sirocco high (MIS, SIR, Fig. 1). Seismic data display parallel reflectors, interpreted as Mesozoic stratified sequences, below the synrift Vistrenque graben (Fig. 8). These seismic transects also provide clues to interpret the geometry and kinematics of the Pyrenean structures affecting the prerift basement. Despite the strong obliquity of the profiles with respect to the direction of compression, some south-dipping reflectors in the offshore seismic profiles are attributed to basement thrusts, such as between the Vistrenque and Petite Camargue faults (Fig. 8A), as well as below the coastal structural high (Fig. 8A, B). It thus appears that this coastal basement high results from the Pyrenean Thau Thrust. Similarly, although not clearly imaged by seismics, we suggest that a major NNE-verging thrust system controls the uplift and erosion of the Sirocco basement high. Likewise, the Mesozoic strata would have been preserved in the thrust footwall, but there is neither borehole or seismic evidence for Mesozoic strata SE of the Petite Camargue Fault (eroded or never deposited?). Later extensional faults, well imaged on the seismic data, developed horsts atop the thrust hangingwall culmination. This structural setting is used to build the structural cross sections presented below.

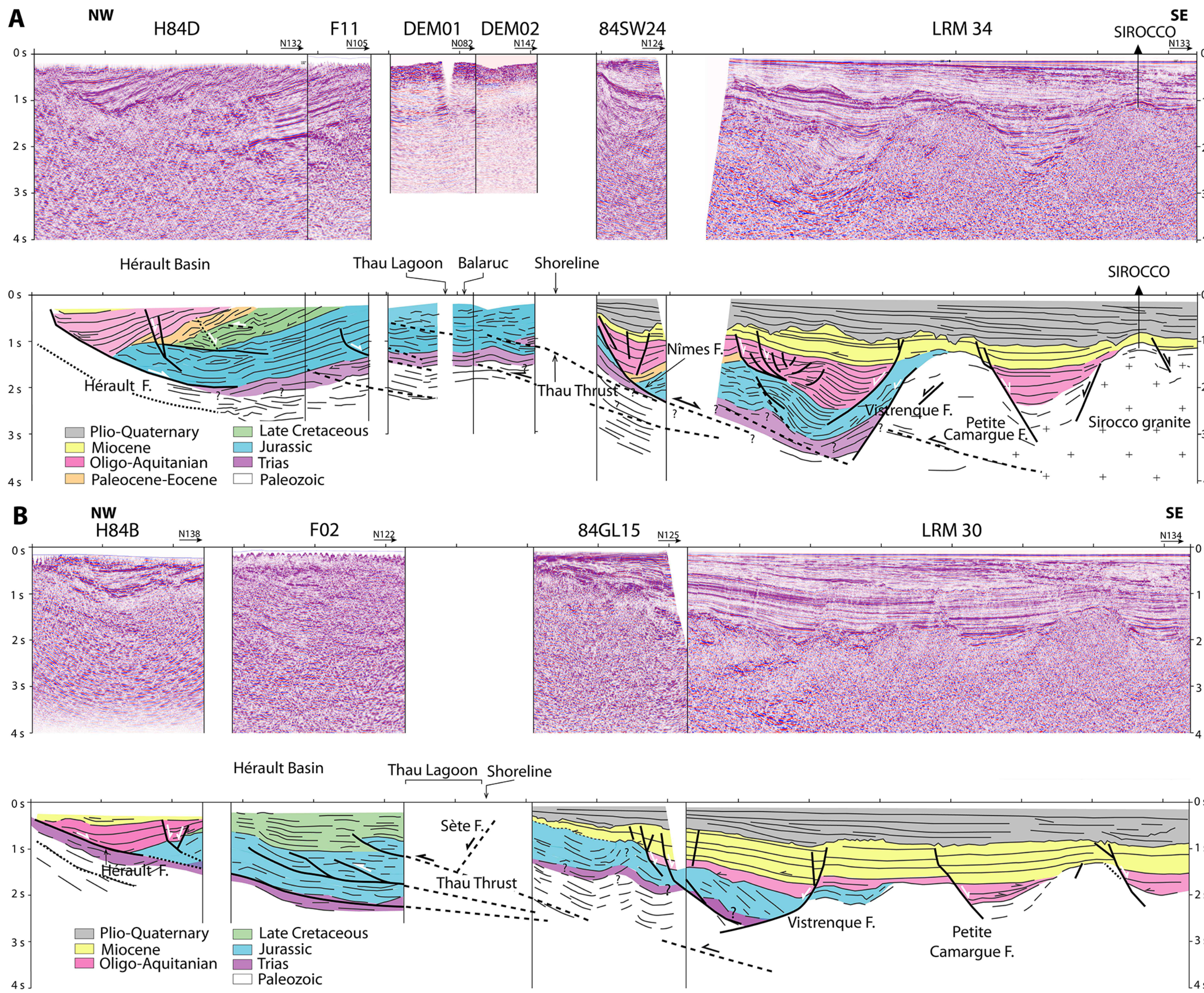

Fig. 8. Two composite seismic reflection transects across the study area (upper panels) and interpreted sections (lower panels). The NW–SE orientation of the sections, *i.e.* parallel to the direction of extension, displays the rifting structures in the upper crust, and their onshore-offshore correlation. Note that vertical scales are in seconds two-way-travel-time. Position of the two transects given in Figure 2.

8 Restorations of sections

8.1 NW-SE cross-section: The extensional structures

A first section, oriented NW-SE, runs from the Cévennes Fault to the offshore Sirocco basement horst (64 km long; Fig. 9) and is used to restore the extensional structures of the proximal Gulf of Lion rifted margin. This cross section is parallel to both onshore-offshore seismic cross-sections (Fig. 8A), parallel to the direction of extension (Séranne, 1999) and crosses the main extensional structures, thus allowing restoration of the Oligocene rifting structures. When possible, interpreted offshore seismic sections were converted to depth, using velocity stacks provided by the seismic profiles, and controlled by the few available boreholes on the line (GAR and SIR). In addition, interval velocities were determined on the neighbouring profiles that are tied to the other offshore wells. Onshore, the Jurassic stratigraphic intervals display fairly well constrained thickness variation across faults. Offshore, between the Nîmes and Vistrenque faults, seismic reflection shows layered seismic units above the Variscan basement, interpreted as undifferentiated Jurassic succession. Dogger carbonates were also found in CAL well (Fig. 2). The prerift structure between the antithetic Nîmes and Vistrenque faults, that form a relay zone, remains poorly constrained.

On the section (Fig. 9), we distinguish the Oligocene rifting faults, the Pyrenean compressional structures and the Tethyan normal faults. The balanced cross sections were built and restored on the basis of surface conservation, and deformation of normal fault hangingwall by antithetic shearing along a 60° angle (Benedicto, 1996; Withjack and Peterson, 1993). Restoration of the Oligocene rifting structures was performed assuming a progressive increase of topography toward the south, up to 1000 m representing a Pyrenean orogenic topography (Benedicto, 1996; Séranne *et al.*, 1995, 2021). Restoration to pre-Oligocene rifting shows about 14 km of total extension, of which, the Nîmes and the Vistrenque Faults

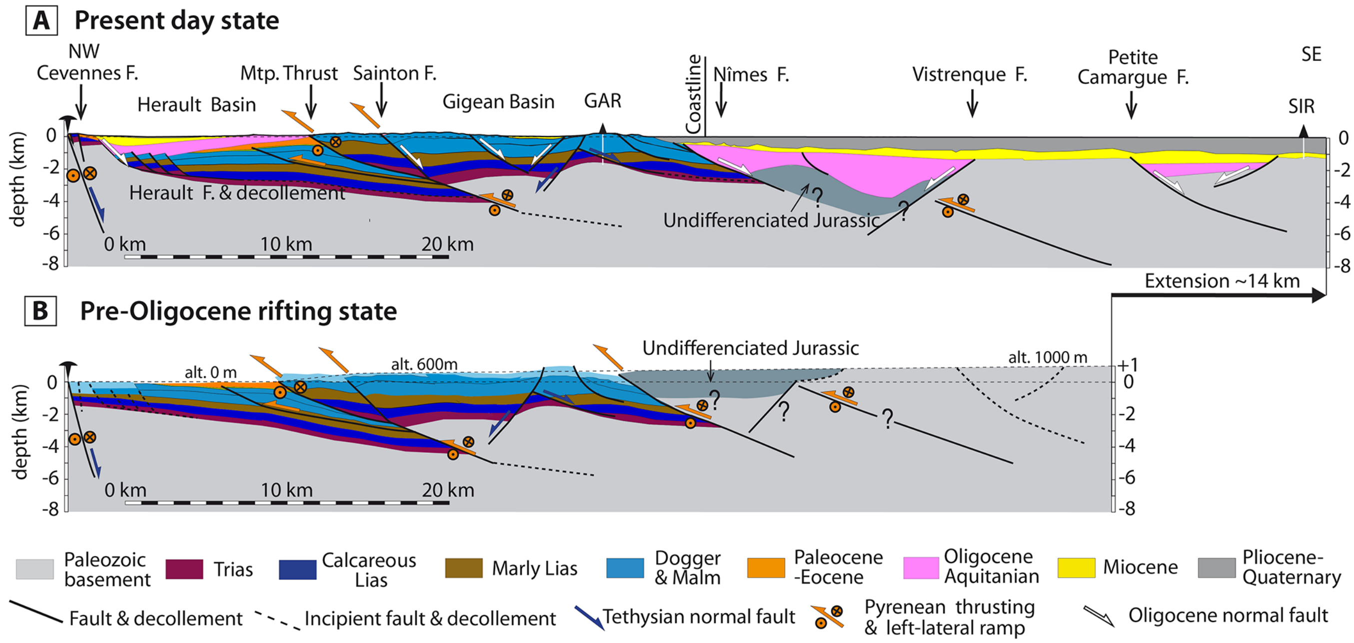

Fig. 9. Geological cross-section oriented parallel to the extension direction, in order to show the rifting structures (note identical vertical and horizontal scales). See location on Figure 2. This section is primarily derived from the seismic transect and then restored section in a post-Pyrenean state. See text for justification of topography.

accommodates 5 km and 3 km, respectively. The prerift Nîmes Fault reveals a reverse offset of the basement-cover interface, with similar amplitude to that of the Montpellier Thrust. Considering the strong obliquity (circa 80°) of the section with respect to the direction of Pyrenean shortening, the 3 to 5 km offset measured across these structures reflects the reverse component of movement, which was associated with a significant off-section, left-lateral, strike-slip component. The Nîmes Fault therefore accommodated oblique (combined reverse and left-lateral) offset during the Pyrenean shortening.

Restoration to the prerift, post-Pyrenean state also highlights the presence of an inherited structural high between the Montpellier Thrust and the Nîmes Fault, in the Gardiole Massif. There is no evidence of Pyrenean shortening within the Gardiole Massif, which is affected by low angle normal faults of Tethyan age. We thus interpret the structural high as passively uplifted in the hangingwall of the Montpellier Thrust, during Pyrenean compression. Indeed, the Nîmes Fault, which bounds the Gardiole massif to the SE is known to be active during Tethyan margin formation, NE of the study area (Le Pichon *et al.*, 2010; Séguret *et al.*, 1997). The Gardiole high persisted during the Oligocene rifting, as flexural uplift in the footwall of the Nîmes Fault, which prevented preservation of Oligocene synrift deposits. Consequently, only the postrift Miocene transgressive deposits are recorded in the Gigean Basin (Figs. 2 and 9).

8.2 NNE-SSW cross-section — The inherited Pyrenean structures

Large scale Pyrenean structures are associated with horizontal stress σ1, oriented NNE-SSW, as derived from microtectonics markers (Arthaud and Laurent, 1995). Following these authors, we assume a generalized NNE-SSW shortening in the study area, and consequently, chose to analyse the Pyrenean deformation along a NNE-SSE regional cross-section (77 km long, Fig. 10). This cross-section includes the Cévennes Fault to the north and the Saint-Loup, Montpellier, Thau and Agde thrusts, respectively from north to south. Since this cross-section does not intercept significant Oligocene extensional fault, the pre-Pyrenean state can be restored without interference with rifting deformation. The Pyrenean thrusts, mid-Cretaceous Durancian faults, and Tethyan faults are distinguished on the section. The geometry of the Montpellier Thrust is consistent with the deformation style observed at surface level. The Jurassic series of the hangingwall is affected by folding, including subvertical axial planes running parallel to the thrust trace, over a 5 km wide area. Such folding is associated with subordinate thrusts (not represented on this section, but in Fig. 7 – section A) locally bringing the marly Liassic unit at surface, close to MUR borehole (Fig. 2). South of the Sainton Fault, the amount of deformation in the hangingwall decreases significantly, with monocline structures and long-wavelength folding involving late Cretaceous sequences. This abrupt decrease of deformation of the hangingwall is interpreted as the expression of the footwall ramp gently dipping to the south and then into the Palaeozoic basement, while the wide Late Cretaceous, syncline results from varying dip of the basement ramp.

The depth of the hangingwall flat is constrained by borehole data (MUR borehole, Fig. 2). The Sainton Fault connects with the main thrust at depth, at the transition from flat-ramp geometry (Fig. 7). While the flat-ramp geometry of the Montpellier Thrust is consistent with both surface and borehole data, there is no topographic culmination to explain such basement structure. Evidence for limited hangingwall erosion comes from bauxite remnants preserved on the present

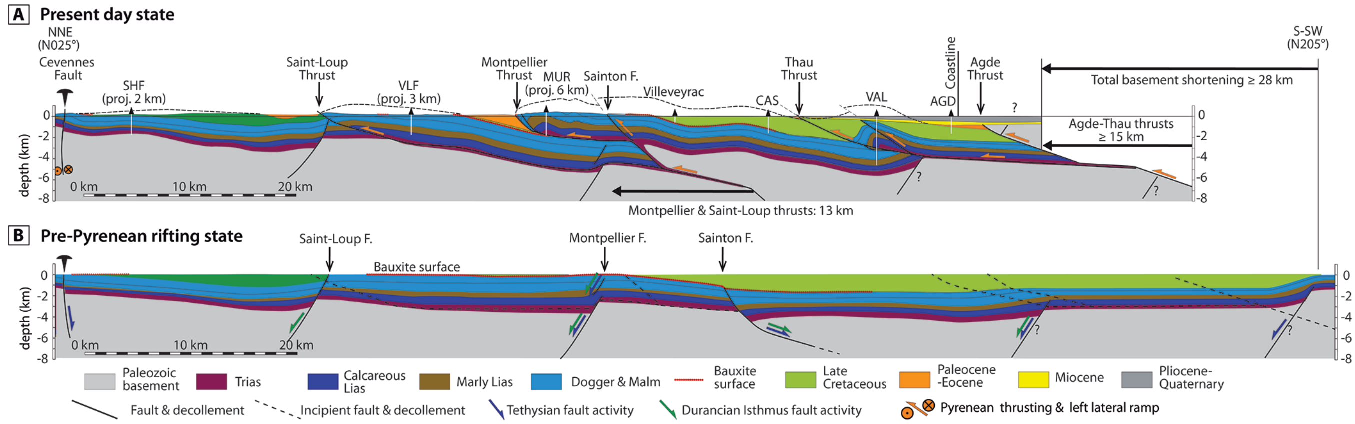

Fig. 10. A. Geological cross-section oriented parallel to the Pyrenean shortening direction, in order to show the Pyrenean thrusting and folding in the upper crust. See location on Figure 2. **B:** Restored section in a late Cretaceous/pre-Pyrenean state, showing the localization of the EW oriented thrusts above structures inherited from the Durancian uplift event and/or Late Cretaceous differential subsidence.

topography. This thus requires a significant footwall flexure of the autochthonous Palaeozoic basement, driven by the thrust load, in order to accommodate the thickness of the formations in the hangingwall.

The Montpellier foreland mostly comprises Palaeocene to Early Eocene syntectonic sediments while the Saint-Loup foreland consists of younger Middle Eocene syntectonic series. The thin-skinned Saint-Loup Thrust merges at depth with the Montpellier Thrust and propagates northward at the basement-cover interface. Its emergence is controlled by an inherited, north-facing normal fault of Durancian age, sealed by the bauxite surface.

To the south, the Jurassic series is buried below the Late Cretaceous series. The Thau Thrust, presently entirely covered by Neogene sediments, is identified by a deep borehole (VAL well), which documents several fault segments, folded strata and variable thickness within the Jurassic series. We interpret this structure as a detachment fold and imbricate thrusts rooted in the Triassic decollement level. Further to the south, the Adge Thrust represents the most important thrust in the region, although it is neither imaged on seismic or sampled by borehole. Its location beneath the Neogene cover is shown by a sharp gravimetric gradient (Guennoc *et al.*, 2004) and it is evidenced by correlating the deep boreholes CAA and AGM, onshore and offshore, respectively (Fig. 2). Palaeocene syntectonic series overlies a thick (>1000 m) Late Cretaceous sequences in the onshore footwall of the Agde Thrust, while offshore, the Miocene postrift unconformably overlies the Variscan basement at 1100 m depth (Guennoc *et al.*, 2000). Such hiatus suggests that the basement was exhumed by thrusting during the Pyrenean compression, and possibly formed a significant topography in the hinterland. The thin-skinned Thau Thrust branches on the basement ramp of the Agde Thrust, located close to the southern basin border.

Borehole data suggests thickening of the Mesozoic basin towards the centre of the basin, north of the VAL well. Both Tethyan and Durancian, north-facing, normal faults are likely to have accommodated such thickening (Fig. 10B).

The results of our restoration show that the Montpellier and Thau-Agde thrusts accommodated 13 and ≥15 km of shortening, respectively (Fig. 10). The displacement accommodated by the Agde Thrust is only a minimal value, as the amount of created hangingwall topography cannot be estimated, since it was later eroded prior to Miocene postrift sedimentation. Therefore, the total shortening along this transect is at least 28 km.

The restoration to the pre-Pyrenean state exhibits a Jurassic high between two distinct Cretaceous basins. To the north, an Early Cretaceous (Neocomian) basin is bounded by the Saint-Loup Fault, which is sealed by the bauxite surface (Fig. 6B). To the south, a Late Cretaceous basin developed above the bauxite surface, prior to the main Pyrenean phase. The driving force behind the formation of this southern basin is questionable. It could reflect the flexural response to an early phase of the Pyrenean orogeny (*e.g.* Ternois *et al.*, 2019). Alternatively, and more likely, it may represent the thermal recovery of the lithosphere, thinned during the Aptian-Albian rifting (Grool *et al.*, 2018; Rougier *et al.*, 2016). Better resolution of the chrono-stratigraphy of this Late Cretaceous basin is required in order to fuel this discussion. Future paleothermal analyses of Late Cretaceous cores from the boreholes would also help to understand the origin of the Late Cretaceous basin.

The restored cross-section depicts a repeated pattern of localisation of the Pyrenean thrusts above inherited horsts and normal faults corresponding to mid-Cretaceous Durancian and/or Jurassic Tethyan extensional faults. The Saint-Loup Thrust emerged above a N-facing Durancian fault, informally named the Saint-Loup Fault. Similarly, the Montpellier thrust emerges above the Durancian Montpellier Fault (Fig. 6B). The Thau Thrust is localized above the N-facing extensional Sète Fault of Tethyan age (Figs. 7B and 8B). Thus, the Montpellier-Sète structural high has been formed since at least the mid-Cretaceous Durancian uplift. This structural high controls the transition from thin-skinned to thick-skinned thrusting.

9 Discussion

Restoration of 2D structural sections involves several simplifications. The estimated shortening must be computed along a section, which is parallel to the shortening direction. In this study, we determine the Pyrenean shortening direction by using the compressional stress trajectories derived from

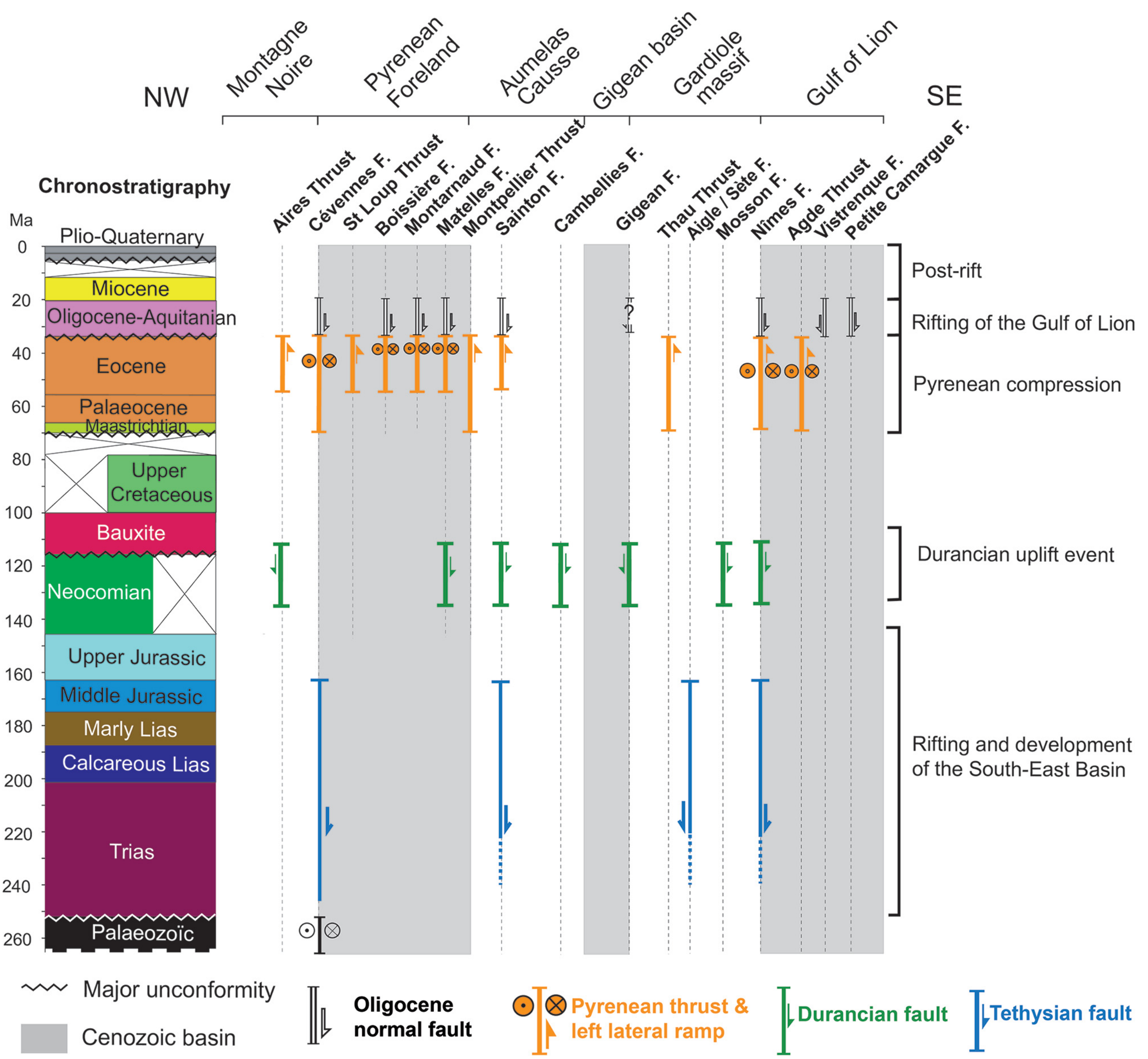

Fig. 11. Fault activity chronological diagram, highlighting multiple reactivations according to (i) their orientation and (ii) the successive tectonic stages recorded in the area. Faults are identified on Figure 2.

microtectonic structures (Arthaud and Laurent, 1995). This does not account for possible decoupling of the sedimentary cover from the basement, including possible rotations such as those, documented south of the study area in the Corbières (Frizon de Lamotte *et al.*, 1995; Rouvier *et al.*, 2012). Decoupling of the Mesozoic cover from the Variscan basement, within the Keuper shales and evaporite (Late Triassic) has been evidenced in Corbières (Ford and Vergés, 2020) and in Provence (Espurt *et al.*, 2019b). In the study area, possible salt tectonics may have affected the Mesozoic sequences especially in areas where the Keuper interval is thick (≥800 m in the lower Hérault valley or towards the South-East Basin, Fig. 2). However, in the central part of the study area, the Keuper sequence is much thinner (about 100 m) and there are no field or seismic evidence of intense salt tectonics involving diapirs. It appears that the Keuper interval just behaved as a low friction interface, that allowed decoupling of the cover.

The shortening estimate derived from restoration of sections gives only a minimal value, as it does not take into account possible lateral movements along strike-slip faults parallel to the contraction direction (*e.g.* Krézsek *et al.*, 2013). The post-Late Jurassic left-lateral displacement of the Cévennes Fault has been estimated up to 17 km (Bodeur, 1980). The post-Pyrenean and pre-rifting (Priabonian) left-lateral displacement between Cévennes and Nîmes faults has recently been estimated to 5 km (Séranne *et al.*, 2021). Unfortunately, the strike-slip offset across the Nîmes fault during Pyrenean shortening is not constrained. The amount of shortening across thrusts provides a reasonable estimate of the

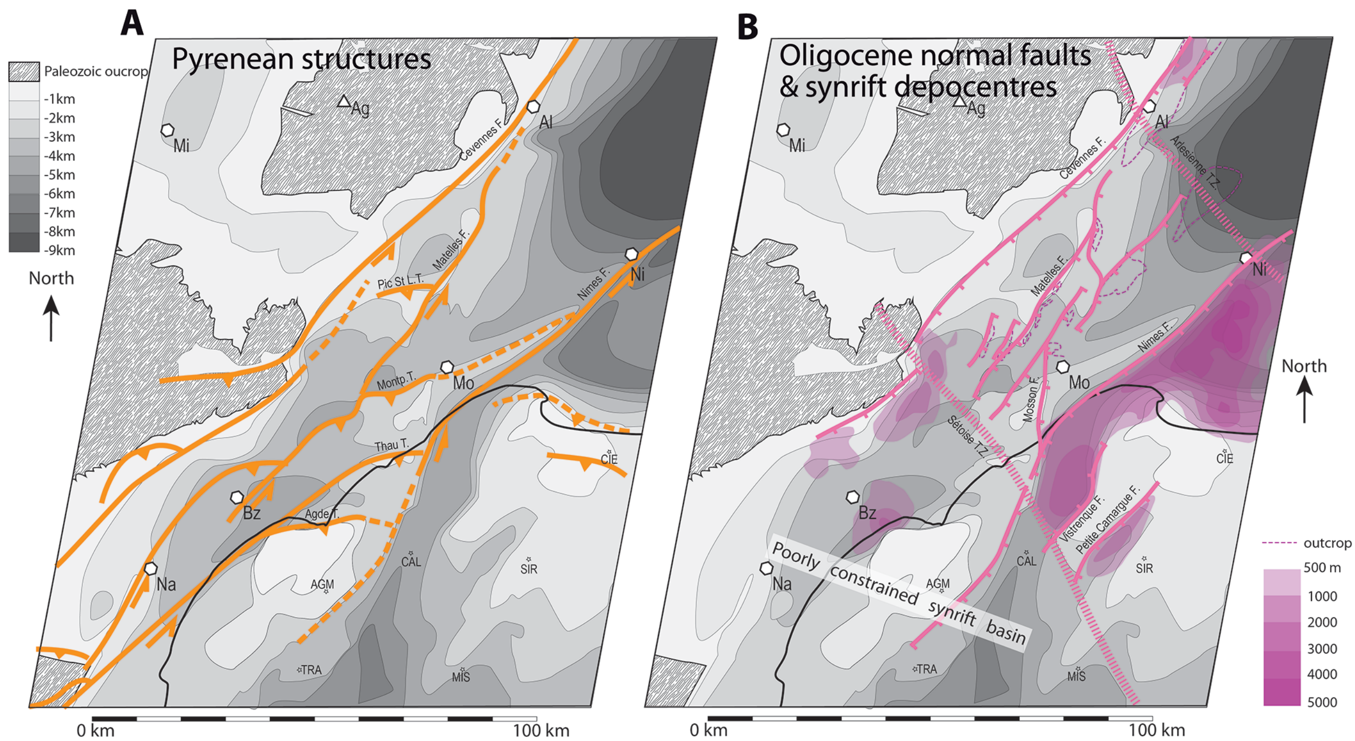

Fig. 12. **A.** Simplified Pyrenean structural sketch of the study area, superimposed onto the top-of-basement map (shades of grey). The overall structure corresponds to a left-lateral wrenching accommodating oblique convergence; the thrusts appear as restraining bends or splays of major, NE-striking basement strike-slip faults. **B.** Simplified rifting structural sketch of the study area. The synrift isopach map (shades of pink overlay) highlights the major extensional fault. The NW-trending transfer zones did not appear in the previous stage: they are thus newly formed during rifting. Note that synrift structures in the SW corner of the area are poorly documented in the present study.

offset across their lateral or oblique ramps; accordingly, the 28 km shortening measured along the section sub-parallel to the major Cévennes and Nîmes faults (Fig. 10) suggests a Pyrenean left-lateral displacement of similar amplitude, distributed between the two faults.

Similarly, computing synrift amount of extension provides only minimal values. The exact amount of extensional displacement along inverted Pyrenean thrusts cannot be determined because the offset of the initial thrust is unknown. For example, the Sainton Thrust has been completely inverted during Oligocene extension and presently displays a normal fault setting. In contrast, the basement ramp of the Montpellier Thrust kept its thrust geometry, even though it may have been reactivated as an extensional fault during rifting (Fig. 9).

Within the northern foreland of the Pyrénées-Provence thrust belt, the Agde Thrust is located in a similar structural setting as the North Pyrenean Frontal Thrust (Grool *et al.*, 2018) and the Cap Sicié thrust in Provence (Bestani *et al.*, 2016). We find discrepancies in the amount of shortening in the northern foreland of the orogen. The late Cretaceous to Eocene 28 km of shortening across the Languedoc section (Fig. 10) is higher than the 13.3 km of shortening across the northern foreland of eastern Pyrénées (Grool *et al.*, 2018), and lower than the 40 km of shortening across central Provence (Bestani *et al.*, 2015). Such discrepancies could be accounted for by the different width of the restored orogenic wedge. More likely, the deformed Pyrénées-Provence foreland is segmented by oblique strike-slip faults, such as Cévennes, Nîmes, Durance Faults, which separates blocks accommodating varying amounts of shortening (*e.g.* Lacombe and Jolivet, 2005). Unlike the Eastern Pyrénées and Provence characterized by east-west oriented thrusts, Pyrenean deformation style in Languedoc is characterized by a complex association of NNE-trending strike-slip faults associated with N-verging thrusts located between the major Cévennes and Nîmes Faults. The Pyrenean northern thrust front is therefore displaced some 60 km northward across the Corbières-Cévennes transfer zone (Mascle *et al.*, 1994; Rouvier *et al.*, 2012). In Languedoc, the decollement of the Mesozoic cover is not associated with significant salt tectonics, in contrast to what has been described in the neighboring areas of Corbières and Provence (Bestani *et al.*, 2015; Espurt *et al.*, 2019b; Ford and Vergés, 2020). This is probably due to a thinner Triassic sequence and dominance of siliciclastic sediments over the Keuper evaporites (Lopez, 1992).

The faults identified in this study reveal different histories of tectonic activity (Fig. 11). The NNE trending regional faults (Cévennes and Nîmes Faults) were initiated as strike-slip faults during the late Variscan plate reorganization (Arthaud and Matte, 1975), and they have later been reactivated during each of the successive tectonic phase, as extensional or strike-slip faults. Secondary faults of similar orientation have only been reactivated once or twice, as normal faults or left-lateral strike-slip faults. Other secondary faults (see names on Fig. 2) of either EW (*i.e.* Cambellies Fault) or N-S orientation (*i.e.* Mosson Fault) have been active only during the Durancian uplift. Finally, north-verging thrusts of E-W orientation are not reactivated structures, they were formed during Pyrenean deformation. The tectonic chronology chart of Figure 11 shows that the Pyrenean shortening phase stands out, with the association of newly formed, E-W thrusts and reactivated NNE-trending structures as strike-slip faults. The general structural pattern of the Pyrenean deformation in onshore Languedoc is that of a sinistral wrench zone along inherited NNE-trending crustal faults, with newly formed E-W thrusts in restraining bends and right-stepping relays zones (Christie-Blick and Biddle, 1985) (Fig. 12A). The Languedoc area therefore corresponds to a transpressional transfer zone between Pyrénées (SW of the study area) and Provence (to the E) segments of the orogen (Lacombe and Jolivet, 2005). The study area is a northeastward extension of the Corbières transfer (Frizon de Lamotte *et al.*, 1995; Mascle *et al.*, 1994; Rouvier *et al.*, 2012), in line with the Cévennes Fault (Arthaud and Matte, 1975), which corresponds to the SE margin of the Massif Central Variscan basement. During Pyrenean shortening, this oblique transpressional zone corresponded to a weak lithosphere, which had been thinned during Tethyan and mid-Cretaceous rifting phases. It separated the thicker and more rigid Massif Central lithosphere from a continental block, extending from the present-day Gulf of Lion to Sardinia (Advokaat *et al.*, 2014; Bestani *et al.*, 2016; Vinciguerra, 2020).

Oligocene extensional faults mostly reactivated Pyrenean left-lateral strike-slip faults, which detach above the Triassic decollement in the onshore domain (Séranne *et al.*, 1995). Offshore, SE of the Nîmes Fault, extensional faults affect the basement and seem to have initiated during this event. Another specific feature of the structural framework developed during rifting of the Gulf of Lion, is the formation of transfer zones (Sétoise and Arlésienne transfer zones; Fig. 12B) parallel to the extension direction that affected the whole Gulf of Lion margin (Gorini *et al.*, 1994; Maillard *et al.*, 2020; Séranne *et al.*, 1995). The Sétoise transfer zone separates two distinct synrift depocenters in the onshore Hérault Basin; it also bounds to the SW the basement high offshore Camargue, and acts as lateral ramp for the main synrift depocenters (Vistrenque and Petite Camargue grabens). Such transfer zones correspond to an area of distributed deformation in the upper crust and sedimentary cover that accommodates mid- or lower crustal strike-slip faulting. The major Catalan transfer zone, south of the study area (Jolivet *et al.*, 2021; Maillard *et al.*, 2020), is interpreted as the response of the overriding plate above slab tears, in a retreating subduction (Romagny *et al.*, 2020). However, it is unlikely that the minor transfer zones documented here depict multiple slab tears, instead, they probably represents partitioning of the extensional deformation in the proximal part of the overriding plate, driven by shearing at the base of the lithosphere, and leading to lower continental crust exhumation in the distal part of the margin (Jolivet *et al.*, 2020).

10 Conclusion

1. This structural analysis of the Languedoc area demonstrates complex 3D interaction of inherited upper-crustal structures, expressed by multiple fault reactivations through time, under different successive stress orientations. Pyrenean structures and polyphase tectonics are deciphered by linking both onshore and offshore domains across the Gulf of Lion proximal margin. Integration of new acquisitions and reappraisal of published data give rise to newly described Pyrenean and pre-Pyrenean structures in the coastal Montpellier-Sète area.
2. In Languedoc, two Mesozoic extensional phases: Tethyan (Triassic-Liassic rifting and subsequent thermal subsidence) followed by Durancian (mid-Cretaceous Pyrenean rifting and northern rift-shoulder uplift) reactivated NE-SW and E-W oriented structures, respectively, as extensional faults. Both Tethyan and Durancian Mesozoic basins were bounded southward by a non-subsiding continental block extending in the present-day Gulf of Lion.
3. During oblique convergence of the Gulf of Lion-Sardinia continental block with the NE-trending margin of the Variscan Massif Central, the NE-SW faults were reactivated as left-lateral strike-slip faults, and E-W oriented thrusts were generated. The latter acted as contractional splays of the formers, and they emerged above the previous E-W Durancian faults. The Languedoc and Corbières areas therefore correspond to a NE-trending transfer zone that accommodates oblique convergence, and link the Iberian Pyrénées with Provence.
4. The Montpellier Thrust is interpreted as a basement-involved structure with a double flat-ramp geometry. Further to the south, in the coastal area, the Thau Thrust is a newly described major structure that links eastwards with the Nîmes Fault. Southwestwards, the thin-skinned Thau Thrust branches on the basement ramp of the Agde Thrust.
5. The ≥28 km amount of shortening, estimated in the Languedoc foreland, is a minimal value of the Pyrenean shortening, and must be used with caution as it does not include the complete left-lateral offset across the Corbières-Languedoc transfer zone. Our section parallel to the NNE directed oblique convergence does not show significant reactivation during later NW-SE rifting; consequently, this single step restoration enables us to reconstruct the pre-orogenic setting, which is now buried below the Gulf of Lion syn- and postrift sequences.
6. Oligocene rifting structures formed in response to a NW-SE extension, which reactivates the previous NE-trending strike-slip faults. Onshore thin-skinned extensional tectonics ramps down into the basement, through the reactivation of the Nîmes Fault and of the inherited Montpellier and Agde basement thrusts, respectively. Finally, the distinctive NW-trending transfer zones responsible for the segmentation of the Gulf of Lion margin represent newly-formed rifting structures, which accommodate differential extension rates.

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