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Fast dismantling of a mountain belt by mantle flow: Late-orogenic evolution of Pyrenees and Liguro-Provençal rifting

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ABSTRACT

The Pyrenean Belt ends against the Gulf of Lion passive margin. The mechanism responsible for dismantling the mountain belt during Oligocene rifting has not yet found a proper explanation. The Late Eocene and Oligocene period is characterized by a first order change in subduction dynamics in the Mediterranean and the subduction zones started to retreat with back-arc basins forming at the expense of mountain belts build earlier. The slab subducting below Provence and Sardinia-Corsica started a fast south-eastward retreat, forming the Liguro-Provençal Basin. This syn-rift period in the Gulf of Lion margin is coeval with exhumation of the eastern Pyrenean basement, while underthrusting of Iberia continued until Early Miocene. Based on interpretation of seismic lines, we propose a tentative model in which the mantle flow related with Apennine slab retreat has (1) exhumed and thinned the continental mantle below the Gulf of Lion and the eastern Pyrenees and (2) exhumed the lower crust, leading to crustal thinning and subsidence of the Gulf of Lion margin. The wide distribution of syn-rift volcanism in the transition between the Gulf of Lion and Valencia Basin is in line with the geometry observed in the margin suggesting ductile deformation of a weak continental crust, typical of volcanic margins. The direction of SKS-waves seismic anisotropy below the Pyrenees and the observed migration of exhumation toward the west fit this simple model. The concentration of syn-rift magmatism and the ductile behaviour of the crust during rifting can be explained by the high heat flow above the slab tear that separates the future Apennines and Maghreb branches of the West Mediterranean subduction zone. Finally, removal of upper mantle, inducing uplift and an increase of potential energy, may explain why thrusting continued in the Pyrenees while rifting was still active nearby along strike.

Mountain belts are not eternal features and erosion plays an important part in their destruction, but tectonics is more efficient. The Aegean Sea (Lister et al., 1984; Gautier and Brun, 1994b, 1994a) or the Basin and Range Province (Wernicke, 1981; Lister and Davis, 1989; Wernicke, 1992) are two examples of recent, still active, extensional domains set on top of former mountain belts that have been dismantled within short time periods. The Variscan Belt has recorded a similar evolution (Brun and Van Den Driessche, 1994; Faure et al., 2009; Vanderhaeghe, 2012). The processes active during the transition from a mature mountain belt to a fully active rift are however poorly understood. The case of the Pyrenees-Provence Belt can shed light on this question. At the time of a major change in subduction dynamics in the Mediterranean region (35–30 Ma) and inception of back-arc rifting (Jolivet and Faccenna, 2000), the eastern end of the belt was extended and eroded. It passed below sea level in < 10 Myrs, forming the Gulf of Lion margin (Gorini et al., 1993; Mauffret et al., 1995; Jolivet et al., 2015a). Based on onshore and offshore observations, we suggest here that the flow of asthenospheric mantle due to the retreat of the Apennine slab has first removed the lithospheric mantle from below the eastern part of the belt, leading to a regional uplift and erosion at ~30 Ma and then extracted the lower crust, leading to subsidence and hyper-extension in the Gulf of Lion. Continuous shortening in the western part of the belt during the first stages of this scenario shows that the collapse of a mountain belt can be diachronous along strike. It further shows the power of mantle flow to dissect mountain belts from below.

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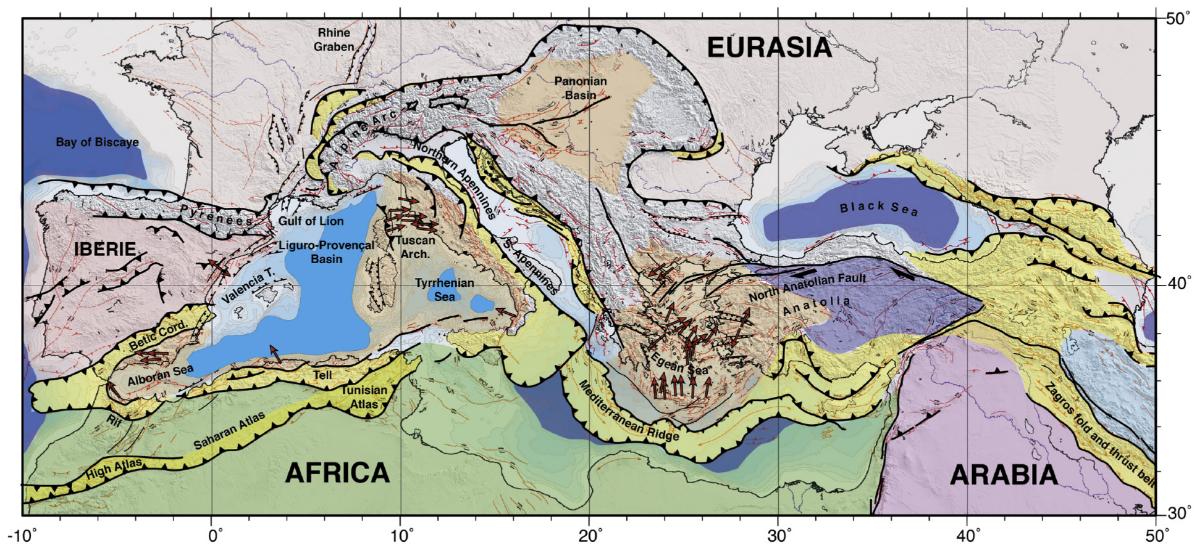

Fig. 1. Tectonic map of the Mediterranean region after Faccenna et al. (2014). Red arrows represent the strike and sense of shear of stretching lineations in the main metamorphic core complexes of the Aegean, Northern Tyrrhenian and Alboran back-arc domains (light ochre color) (Jolivet et al., 2009). Yellow domains represent domains shortened during the Neogene. Dark blue is Mesozoic oceanic crust and intense lighter blue is Miocene and Pliocene oceanic crust of the Liguro-Provençal and Tyrrhenian Sea basins. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

1. Geodynamic context of post-orogenic extension in back-arc region

It has been known since the 80s that the most efficient mechanism to erase a mountain belt is not erosion but dismantling by extension. The discovery of shallow-dipping normal faults accommodating large displacements in the Basin and Range Province led to the proposition that mountain belts can disappear because they collapse during extension (Wernicke, 1981; Davis and Lister, 1988; Dewey, 1988; Wernicke, 1992). As soon as boundary conditions change and reduce horizontal forces leading to crustal thickening, the thick crust cannot sustain its own weight and collapses. Similar behaviour was then discovered in many regions and especially in the Mediterranean (Lister et al., 1984; Platt, 1986; Jolivet et al., 1990; Morley, 1993; Gautier and Brun, 1994a; Granado et al., 2016a, 2016b) (Fig. 1). The Aegean Sea or the Alboran Sea result from the spreading by extension of older mountain belts after the Eocene (from 30 to 35 Ma onward) (Crespo Blanc et al., 1994; Azañón et al., 1997; Platt and Whitehouse, 1999; Jolivet and Faccenna, 2000; Faccenna et al., 2004; Jolivet and Brun, 2010). During extension, deep crustal rocks are exhumed below low-angle normal faults called detachments, forming metamorphic core complexes (MCC) (Davis, 1983; Davis and Lister, 1988; Lister and Davis, 1989; Buck, 1991; Van Den Driessche and Brun, 1991). Some of these MCCs show that the lower crust was partially molten, which reduces its overall resistance and thus favours collapsing and distributes deformation over wide regions (Buck, 1991; Tirel et al., 2008). Not all MCC show partial melting though. The main critical parameter of this behaviour is the contrast between the maximum and minimum resistance of the crust, which in turn depends upon its lithological stratification and the geothermal gradient (Huet et al., 2011; Labrousse et al., 2016).

The upper plate of retreating subduction zones, back-arc regions, is a favourable context for such collapsing of mountains belts. The examples of the Aegean, Tyrrhenian or Alboran Seas have been studied in detail in that respect. Extension started in these regions as soon as the subducting slab started its retreat around 30 Ma and extension migrated following this backward motion of the trench (Malinverno and Ryan, 1986; Dewey, 1988; Wortel and Spakman, 1992; Royden, 1993; Carminati et al., 1998a, 1998b; Jolivet et al., 1998; Jolivet and Faccenna, 2000; Wortel and Spakman, 2000; Spakman and Wortel, 2004; Ring et al., 2010).

Studies of the ductile and brittle deformation of the Aegean during this period shows that the whole crust of a wide domain encompassing the central and eastern Aegean region was sheared asymmetrically, a result of the underlying asthenospheric flow due to slab retreat and slab tearing (Jolivet et al., 2013, 2015b; Roche et al., 2019). This suggests that the kinematics and thermal evolution of the back-arc domain is principally controlled by the behaviour of the slab at depth, involving retreat and tearing, and the induced asthenospheric flow (Capitanio, 2014; Sternai et al., 2014; Menant et al., 2016; Roche et al., 2018). However, in the case of the Aegean, one can observe the final result of crustal collapse and describe its distribution through time and space in the overriding plate, but the role played by the mantle flowing underneath can still be debated because the spatial transition between the fully grown mountain belt, the Hellenides, and the collapsed crust is accommodated over a long distance with a large part below sea level, with little geophysical information available.

The case of the Pyrenees and the nearby Gulf of Lion passive margin (Fig. 2) offers an opportunity to observe this transition from a mountain belt to a post-orogenic rifted margin on a very short distance with recently acquired onshore and offshore seismic profiles. Moreover, an additional question posed by this region is the coeval compression in the belt in the Oligocene until the early Miocene and extension in the nearby Gulf of Lion future passive margin. The interactions in 3-D of these two apparently incompatible contexts are not explained. The internal architecture of the mountain belt and the passive margin that results from its collapse can be observed side-by-side and the respective timings described.

2. The Eocene-Oligocene transition and back-arc rifting

30–35 Ma was a key-period in the Mediterranean realm. All back-arc basins started to form at this period in the overriding plate of retreating subduction zones, while Alpine mountain belts continuously formed above the same subduction zones before collapsing in the back-arc region (Jolivet et al., 1994, Jolivet and Faccenna, 2000, 2003). The Aegean Sea formed at the expense of the Hellenides (Le Pichon and Angelier, 1979, 1981), the Tyrrhenian Sea of the internal Apennines (Faccenna et al., 1996), the Alboran Sea results from the foundering of the internal Betics and Rif (Platt, 1986; Comas et al., 1992, 1999), or the Pannonian Basin of the Carpathians (Horvàth, 1993; Horvath and Tari, 1999). The Pyrenees end abruptly in the east leaving the place to

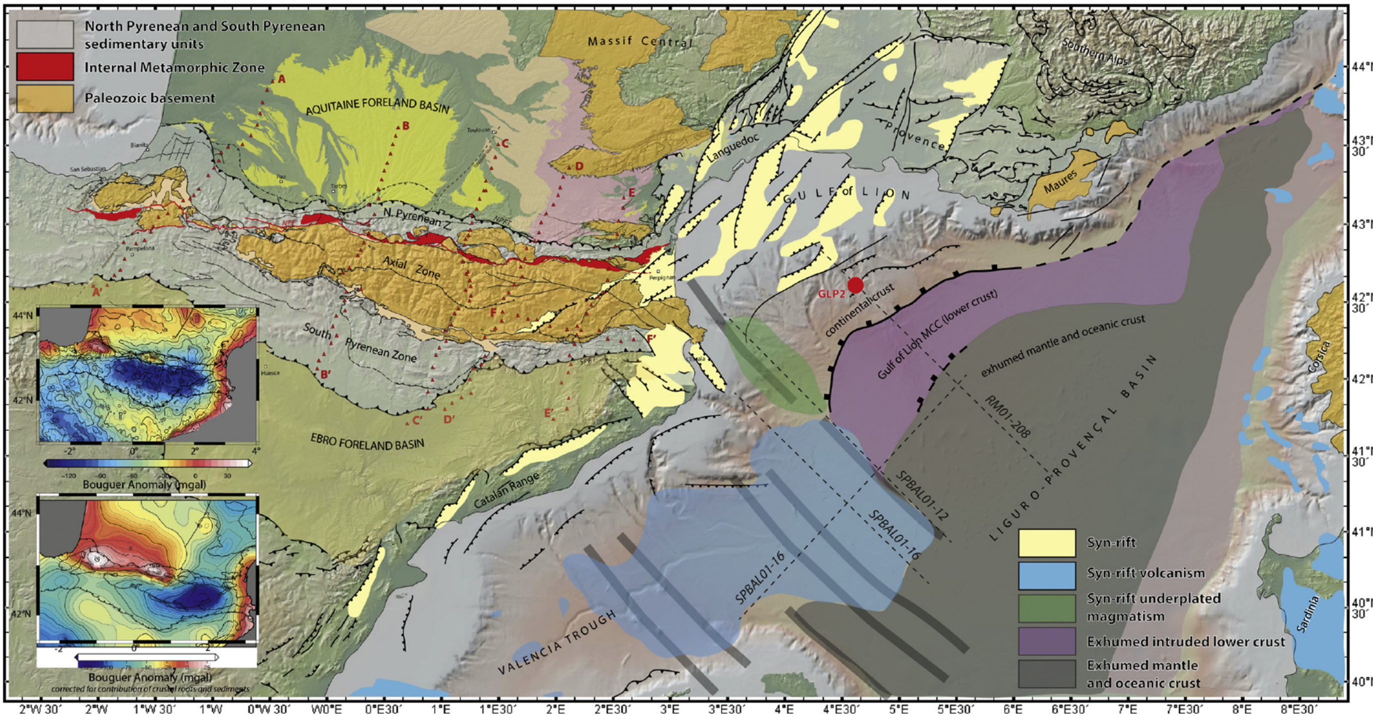

Fig. 2. Structural map of the Pyrenees and Gulf of Lion realm discussed in this paper after the interpretation of offshore seismic profiles (offshore dotted black lines). A–E are the receiver function profiles of Chevrot et al. (2018). Gravity anomaly maps are from Wehr et al. (2018). I, II and III correspond to the crustal domains discussed in Bache et al. (2010) and Jolivet et al. (2015a).

the Gulf of Lion (Réhault et al., 1984; Pascal et al., 1993; Mauffret et al., 1995), the northern margin of the Liguro-Provençal Basin (Fig. 2). The northern thrust front of the Pyrenees continues eastward in the Provence fold-and-thrust belt, the internal part of which is now integrated in the passive margin (Gorini et al., 1994; Seranne et al., 1995; Mauffret and Gorini, 1996; Vially and Tremolières, 1996; Guennoc et al., 2000; Mauffret et al., 2001; Lacombe and Jolivet, 2005; Bache et al., 2010).

The Liguro-Provençal Basin formed in the back-arc region of the retreating Apennines subduction. Since the first account of the rotation of Corsica-Sardinia as a rigid block by Argand (1924), various kinematic reconstructions have been published (Dewey et al., 1989; Mantovani et al., 1996; Rosenbaum et al., 2002; Schettino and Scotese, 2002; Jolivet et al., 2003; Lacombe and Jolivet, 2005; Carminati et al., 2012; van Hinsbergen et al., 2014; Leprêtre et al., 2018). The Valencia Basin was also partly opened during the Oligocene and Miocene. An earlier Early Cretaceous stage of rifting is however preserved, especially in the southern part (Etheve et al., 2018). While the Gulf of Lion margin is quite poorly magmatic, the Valencia Basin shows the wide development of magmatism from the Early to the Middle Miocene with an evolution through time from calc-alkaline to alkaline during the rifting and post-rift periods (Marti et al., 1992; Maillard et al., 1999; Maillard et al., 2019). The various published reconstructions (Fig. 3) show the trajectories and total displacements since the inception of back-arc extension and slab retreat up to present-day. Maximum displacement amounts to ~800 km along a WNW-SSE direction. Fig. 3 also shows the orientation of the fastest splitting velocity of SKS-waves below the Western Mediterranean (Faccenna et al., 2014; Díaz et al., 2015; Salimbeni et al., 2018) showing a good correspondence with the motion paths of back-arc extension and direction of ductile-brittle stretching in MCC (Jolivet et al., 2009).

Back-arc rifting started at about 30 Ma (32 Ma is the age of the first uplift of Provence margin and 28 Ma the age of the first onshore syn-rift sediments) and oceanic crust emplacement at 24 Ma (age of the beginning of fast paleomagnetic rotation) in the overriding plate of the retreating Apennine subduction (Auzende et al., 1973; Dewey et al., 1973; Westphal et al., 1976; Réhault et al., 1984; Dewey et al., 1989; Vigliotti and Kent, 1990; Gorini et al., 1993; Séranne et al., 1995; Gueguen et al., 1998; Chamot-Rooke et al., 1999; Séranne, 1999; Rollet et al., 2002; Speranza et al., 2002; Gattacceca et al., 2007). Drifting lasted until ~15 Ma, after which extension jumped eastward in the Tyrrhenian Sea after a short time lag (Faccenna et al., 2001). This migration of extension has continued until the present-day (Jolivet et al., 1998) and the destructive extensional earthquakes that shake the Apennines are its most recent expression (Jolivet et al., 1998; Boncio et al., 2000). The onshore Languedoc region shows the transition in time from compression to extension with grabens intersecting earlier thrust faults (Fig. 2). Field evidence shows that shortening lasted until the Bartonian (40–37 Ma). In the Priabonian (37–34 Ma) a left-lateral transtensional strike-slip event is interpreted as the formation of transfer faults of the West European Rift System and pure extension related to the Gulf of Lion rifting followed at ~30 Ma, in the Late Rupelian (Séranne, 1999).

Offshore evidence shows the details of the timing from rifting to oceanization (Fig. 4, profile RM01-208) (Gorini et al., 1994; Séranne et al., 1995; Séranne, 1999; Guennoc et al., 2000; Bache et al., 2010; Jolivet et al., 2015a). An erosional surface seen on the seismic profile separates Eocene-Oligocene (40–23 Ma) syn-rift deposits from a younger sequence of Aquitanian-Early Burdigalian age (23–18 Ma) deposits laid down during hyper-extension and lower crust/mantle exhumation, before the Late Burdigalian-to-recent post-rift sequence. The entire rifting episode, before oceanization, thus lasted from 30 to 18 Ma with a first part at shallow depth or subaerial before 23 Ma and progressive subsidence afterward. This syn-rift to post-rift evolution fits the paleomagnetic data showing a fast rotation between 24 and 15 Ma with an increase of the velocity of extension during the mantle exhumation episode. The nature of the crust in the Liguro-Provençal basin is not typically oceanic with discontinuous magnetic anomalies, exhumed mantle and localized volcanism (Rollet et al., 2002; Dannowski et al., 2019).

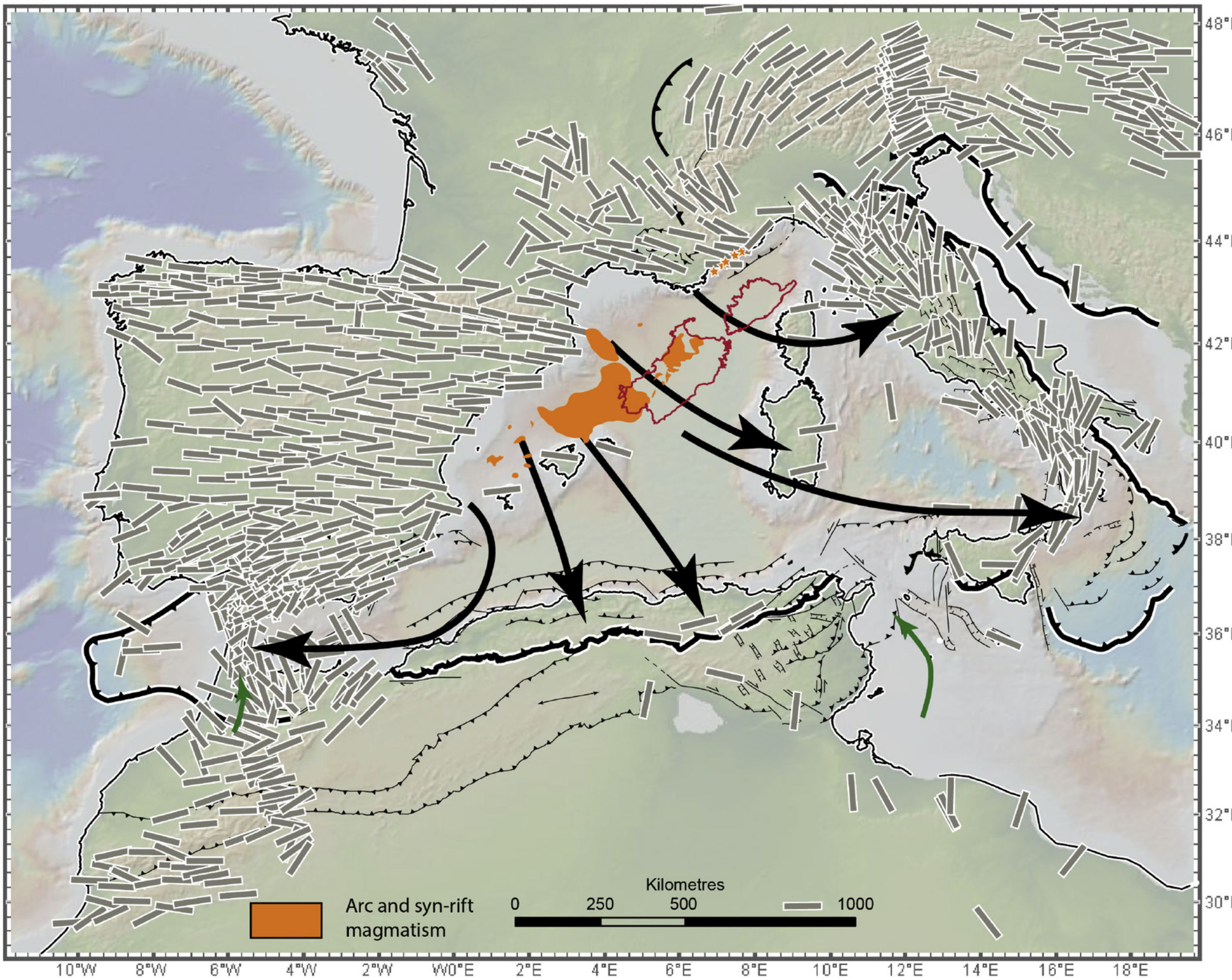

Fig. 3. Displacements during the formation of the Western Mediterranean back-arc basins since 35 Ma. Thick black arrows show the estimates of finite displacements of arcs and slab retreat schematized from various reconstructions (Rosenbaum et al., 2002; Lacombe and Jolivet, 2005) compared with the pattern of SKS-wave anisotropy (Díaz et al., 2006; Faccenna et al., 2014; Salimbeni et al., 2018). The orange domains are the main patches of syn-rift volcanism after Lustrino et al. (2009), Maillard and Mauffret (1999) and this work.

3. The Pyrenees at the Eocene-Oligocene transition

The Pyrenees form an E-W bi-vergent range between the Mediterranean Sea and the Atlantic Ocean (Figs. 2 and 5). Topography along strike (Fig. 5) shows a widening of the belt from west to east and a positive topographic gradient until a maximum with an average altitude around 2000 m and then a negative gradient from the first significant strike-slip and normal fault, the ENE-WSW striking Têt Fault that crosses most of the belt and dips northward (Cabrera et al., 1988). From there on, topography decreases rapidly to reach sea level along the Languedoc coastline and the Gulf of Lion margin.

The Pyrenean orogen results from the Late Cretaceous to Oligocene closure of a series of early Cretaceous rift basins with syn-rift high-temperature and low-pressure (HT-LP) metamorphism and mantle exhumation (Choukroune, 1989; Roure et al., 1989; Choukroune et al., 1990; Vergés et al., 2002; Lagabrielle and Bodinier, 2008; Jammes et al., 2010; Mouthereau et al., 2014; Clerc et al., 2015; Canérot, 2016; Clerc et al., 2016; Canérot, 2017; Chevrot et al., 2018; Teixell et al., 2018; Bellahsen et al., 2019; Ducoux et al., 2019; Tavani et al., 2018). Shortening results from the convergence of the small Iberian Plate with Europe after 84 Ma (Late Santonian) and it lasted until the Oligocene and early Miocene (Verges et al., 1995; Mouthereau et al., 2014; Teixell et al., 2018). The Early Miocene shortening along the southern thrust front of the belt is documented by the deformation of the Upper Oligocene and Early Miocene molasse of the Ebro basin (Labaume et al., 2016; Teixell et al., 2018) and by low-temperature thermochronology data (Jolivet et al., 2007). Convergence was accommodated by underthrusting of the Iberian lithosphere underneath Europe as shown by seismic profiles (Choukroune, 1989; Roure et al., 1989; Chevrot et al., 2018; Teixell et al., 2018). The belt is made of a core of Paleozoic basement rocks and their Paleozoic to Mesozoic-Cenozoic cover (the so-called Axial Zone). The main Mesozoic deposits date back to the Triassic until the Late Cretaceous-Eocene. The Axial Zone is a stack of several crustal nappes emplaced with the southward vergence above the north-dipping Iberian underthrusting Iberian crust (Choukroune, 1989; Mouthereau et al., 2014; Teixell et al., 2018; Bellahsen et al., 2019). Thrusts have propagated southward within the southern Ebro foreland basin forming the stack of the South Pyrenean Zone (Muñoz et al., 2013; Labaume et al., 2016; Teixell et al., 2018). On the opposite northern side of the belt, back-thrusts propagate in the Aquitaine flexural basin (Angrand et al., 2018), forming the North Pyrenean Zone that also involves crustal units known as the North Pyrenean Massifs and the syn-rift Albian flysch deposits (Déramond et al., 1985; Roure et al., 1989; Debroas, 1990; Ford et al., 2016; Teixell et al., 2018; Ternois et al., 2019). The northern thrust front (North Pyrenean Front) extends eastward within the Corbières thrust in an acute bend that makes the junction with the Provence fold-an-thrust belt, which developed at the same period of the Late Cretaceous and Eocene (Arthaud and Séguret, 1981; Tempier and Durand, 1981; Tempier, 1987; Lacombe et al., 1992; Mascle et al., 1994; Oudet et al., 2010; Fournier

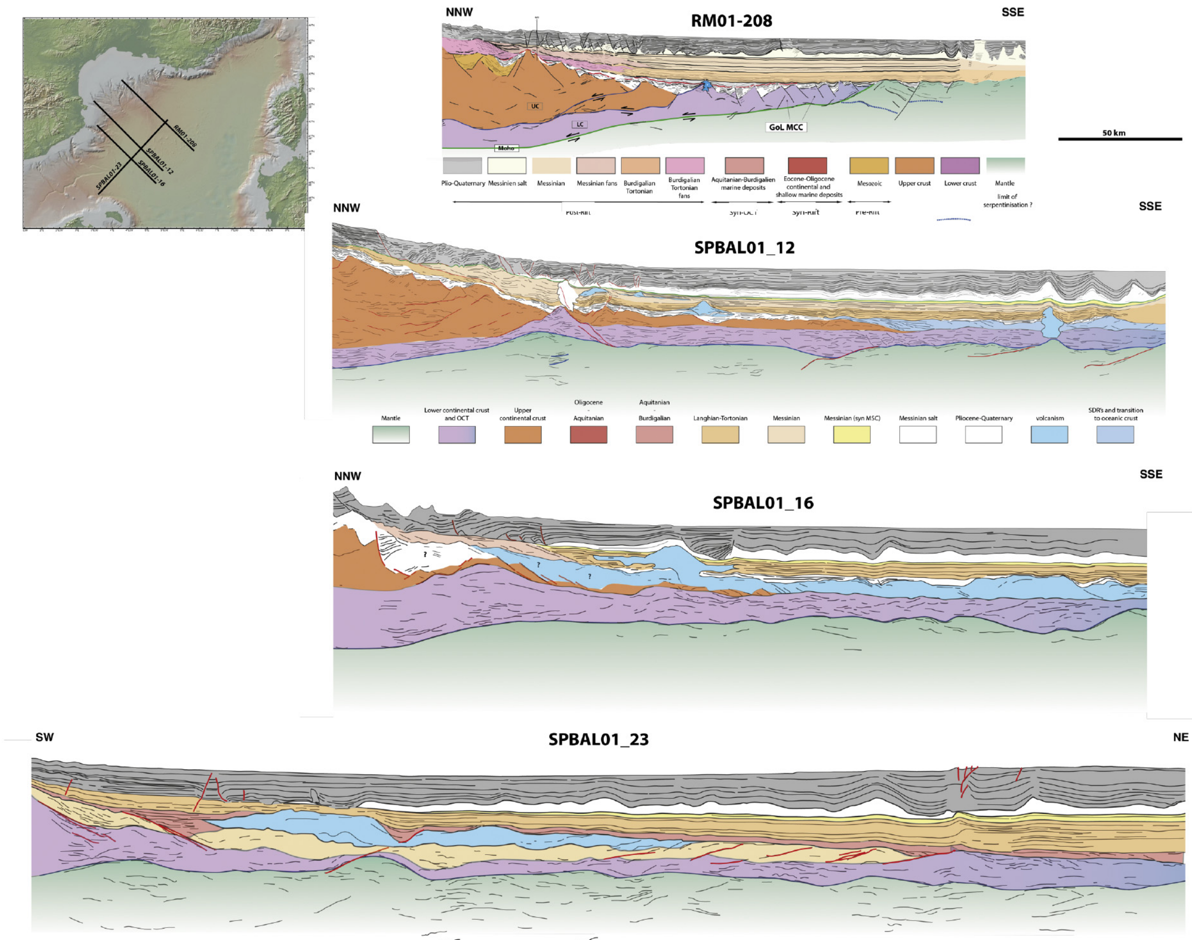

Fig. 4. Interpretation of 4 offshore seismic profiles (location on inset and Fig. 2). The interpretation of RM01-208 is after Jolivet et al. (2015a).

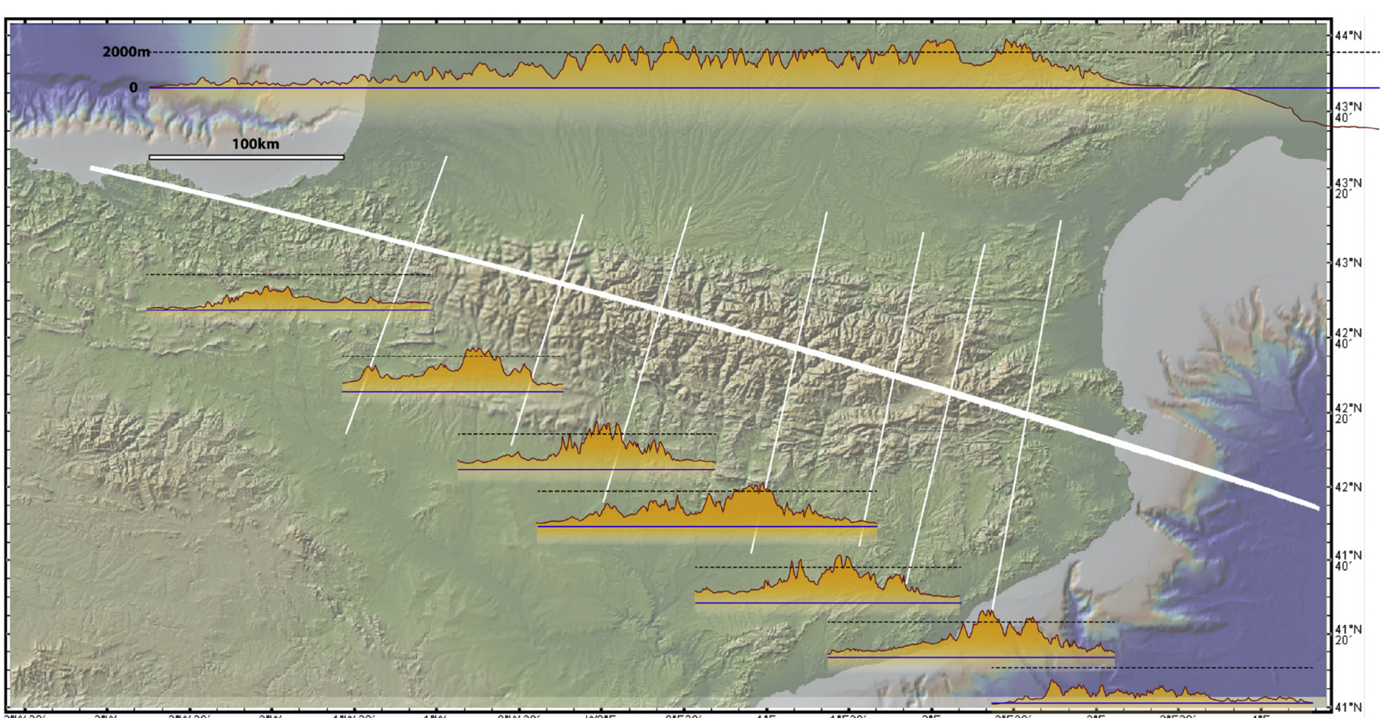

Fig. 5. Topography of the Pyrenees (base-map and cross-sections made with GeoMapApp, Ryan et al., 2009).

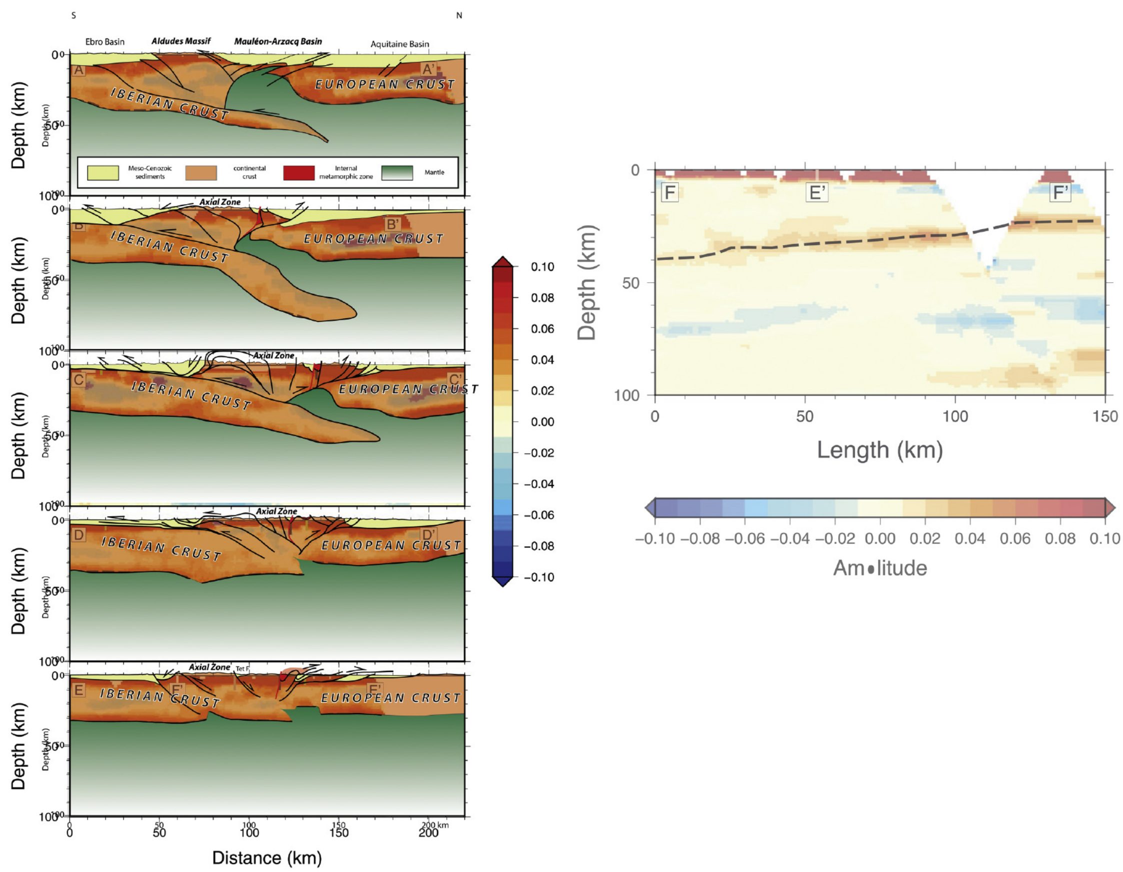

Fig. 6. Schematic cross-sections of the Pyrenees built from the receiver-functions profiles of Chevrot et al. (2018).

et al., 2016). A major dislocation, the North Pyrenean Fault, separates the Axial Zone from the North Pyrenean Zone (Choukroune and Mattauer, 1978). It is associated with narrow Mesozoic Basins, severely shortened during the Pyrenean compression (Debroas, 1990; Clerc et al., 2012; Masini et al., 2014; Clerc et al., 2016; Canérot, 2017). These basins are mostly filled with Jurassic and early Cretaceous limestones followed by an Early Cretaceous thick pile of black shales deposited during rifting, and followed by post-rift Late Cretaceous to Eocene syn-orogenic deposits (Debroas, 1990; Ford et al., 2016). These basins show evidence for high-temperature and low-pressure metamorphism dated at 90–100 Ma, coeval with hyper-extension and subcontinental mantle exhumation (Ravier, 1959; Goldberg and Leyreloup, 1990; Lagabrielle and Bodinier, 2008; Clerc et al., 2015; Ducoux et al., 2019). The Pyrenean HT-LP metamorphism was more precisely dated from the Early Cretaceous in syn-rift sediments and their Paleozoic basement defining the Internal Metamorphic Zone (IMZ) (Fig. 2) within the North Pyrenean Zone (NPZ), between 112 and 84 Ma with a clustering of ages between 100 and 90 Ma (see a compilation of ages in Clerc et al., 2015). Borehole GLP2, drilled on the Gulf of Lion margin, encountered Paleozoic metamorphic rocks yielding ages between 103 and 116 Ma showing that the IMZ extends below the thick passive margin post-rift sediments (Rapport interne Elf-Aquitaine, 1984, reported in Gorini, 1993 and Guennoc et al., 2000) (Fig. 2).

While the onset of shortening was coeval along strike, its end appears diachronous on the southern and northern sides of the belt and along strike, with a westward migration. In the North Pyrenean Zone, compression is recorded until the early Rupelian (~30 Ma) in the east and the Aquitanian (~23 Ma) in the west (Vergés et al., 2002; Jolivet et al., 2007; Mouthereau et al., 2014; Bosch et al., 2016; Labaume et al., 2016; Teixell et al., 2018). On the southern side, it lasted until the Chattian (28–23 Ma in the east) and the Aquitanian (~20 Ma) in the west (Gibson et al., 2007; Jolivet et al., 2007; Bosch et al., 2016; Labaume et al., 2016). Low-temperature thermochronology shows the succession of several episodes of exhumation (Morris et al., 1998; Gibson et al., 2007; Whitchurch et al., 2011; Fillon and van der Beek, 2012; Fillon et al., 2016; Waldner et al., 2019). The first episode, between ~70 and ~35 Ma, corresponds to the main syn-orogenic period with the construction of the belt and it is mainly recorded in the centre with a southward migration (Waldner et al., 2019). A second episode is observed at about 25–35 Ma in the eastern part of the belt (Morris et al., 1998; Fitzgerald et al., 1999; Beamud et al., 2011; Rushlow et al., 2013; Bosch et al., 2016). This episode is coeval with the inception of rifting in the Gulf of Lion. It is also coeval with the uplift of the NE part of Iberia during the rifting of Valencia Basin (Lewis et al., 2000; Vergés et al., 2002). The third one, mostly recorded in the west, is coeval with the last thrusts in the south thrust front at about 20 Ma (Jolivet et al., 2007; Bosch et al., 2016; Labaume et al., 2016). A last episode, after 12 Ma, is recorded all over the belt (Gunnell et al., 2009).

4. The Eocene-Oligocene event in the Western Mediterranean

30 Ma is thus a transitional period from compression to extension coeval with rifting in the Gulf of Lion and exhumation focussed on the eastern Pyrenees. At the same period, a major change is also recorded in the Alps with the transition from continental subduction to collision (Ford et al., 2006; Vignaroli et al., 2008). At about 32–34 Ma, the proximal part of the European passive margin entered the subduction zone and the basement was progressively uplifted above east-dipping thrust faults (Ford et al., 2006; Bellahsen et al., 2014; Bellanger et al., 2014). This episode induces (i) creation of relief and (ii) shallowing of the foreland basin with a change of sedimentary facies from flysch to molasse deposits (Kuhlemann et al., 2002; Kuhlemann and Kempf, 2002; Ford et al., 2006). This westward propagation of thrusts in the Alps at the time of inception of extension in the Liguro-Provençal Basin

and in other Mediterranean back-arc basins has been interpreted as a lateral effect of slab retreat under the Apennines (Ford et al., 2006; Vignaroli et al., 2008). The toroidal mantle flow at the northern end of the Apennine slab pushes the east-dipping European slab westward, inducing the westward migration of thrusts and the fast exhumation of the metamorphic part of the belt. At the same period, the end of UHP metamorphism is recorded in the internal zones of the Alps (Duchêne et al., 2006; Malusà et al., 2011). A similar age (~34 Ma) recorded in several metamorphic belts where (U)HP-LT metamorphism is present, from the Alps to Alpine Corsica and the Edough Massif on the North African coast (Vitale Brovarone and Herwartz, 2013; Bruguier et al., 2017), dating the end of continental crust deep subduction recording in exhumed units, suggesting again that this period corresponds to a unique event of changing conditions in the subduction zone.

5. Crustal-scale structure of the Pyrenees, the teaching of seismic profiles

A recent series of receiver-functions profiles across the Pyrenees (Chevrot et al., 2015, 2018) shows a clear along-strike evolution (Fig. 6). Profiles perpendicular to the belt show the underthrusting of the Iberian crust below the belt and the uplift of mantle up to shallow levels beneath the North Pyrenean Zone and former Early Cretaceous rift basins. Alternative sections can be proposed as in Teixell et al. (2018) with less mantle wedge above the underthrusting Iberian crust but they do not challenge the underthrusting. As recalled above, this zone is also characterized by syn-rift mantle exhumation and HT-LP metamorphism in the Internal Metamorphic Zone bounded to the south by the North Pyrenean Fault (Masini et al., 2014; Clerc et al., 2015, 2016). It is commonly interpreted as the boundary between the Iberian and European crust in the pre-orogenic geometry of the Pyrenees (Choukroune and Mattauer, 1978; Choukroune, 1989; Vergés et al., 2002; Mouthereau et al., 2014; Teixell et al., 2018; Espurt et al., 2019). This orogenic geometry is preserved all along the belt until the two easternmost profiles where it is totally lost (Fig. 6). There, the Moho is shallower and flat at about 30 km for the easternmost profile. Field evidence however does not show less shortening in the east than in the centre and west, and the belt is known to extend eastward below the Gulf of Lion where the equivalent of the Axial Zone is probably hidden (Gorini et al., 1993; Gorini et al., 1994; Mauffret et al., 1995; Séranne et al., 1995; Séranne, 1999; Mauffret et al., 2001). The Provence fold-and-thrust belt shows basement units overthrusting the Mesozoic thrust packages at Cape Sicié that could be lateral equivalent of the North Pyrenean Massifs (Vially and Tremolières, 1996; Lacombe and Jolivet, 2005; Fournier et al., 2016).

The present-day image at depth below the eastern Pyrenees then rather results from post-orogenic dynamics. This is confirmed by a profile along strike in the eastern part of the belt (Chevrot et al., 2018) where progressive shallowing of the Moho is obvious (Fig. 6). The progressively more subdued topography thus corresponds to a rising Moho, a geometry compatible with the transition to the passive margin. This part of the eastern Pyrenees is also supported by a thinner lithosphere (Gunnell et al., 2009; Palomeras et al., 2017). Moreover, a recent 3-D geological model of the entire belt accounting for gravimetric data explains the Bouguer anomaly with a good precision and shows an anomalous crust below the Eastern Pyrenees where the dense lower crust is missing (Wehr et al., 2018).

Crustal and lithospheric thinning in the transition zone from the Pyrenees to the Gulf of Lion passive margin starts way before the coastline and is not associated with major extensional features onshore, only two main steep normal faults with a significant strike-slip component, the Têt and Tech Faults that were mostly active later than the main rifting event (Cabrera et al., 1988). It could be argued that the crust was initially thinned during the Cretaceous and that Eocene finite shortening was less intense here than further west (Mauffret et al., 2001), but balanced cross-sections do not show drastic differences of finite shortening between the central and eastern parts of the belt (Mouthereau et al., 2014) and plate kinematic constraints do not predict less shortening in the east (Nirrengarten, 2016; Macchiavelli et al., 2018). Furthermore, the presence of a significant pre-rift relief at the emplacement of the Gulf of Lion margin is attested by directions of north-westward paleo-currents in the Eocene-Early Oligocene deposits of Languedoc (Egerton, 1996; Ford et al., 2016; Séranne et al., 2019). A thick crust was then present there before back-arc extension started. If not in the upper crust, crustal thinning must be found in the lower crust, fitting gravimetric data as summarized above (Wehr et al., 2018). The eastward extension of the Axial Zone is confirmed by the presence of metamorphic rocks of the IMZ in the lowermost section of hole GLP2, as reported above. This shows that the lower section of the passive margin was developed at the expense of the Axial Zone.

6. Offshore crustal structure, the teaching of seismic profiles

As said above, the onshore profile shows a clear Moho rise below the eastern part of the belt and the syn-orogenic lithospheric structure seen below the central and western Pyrenees is totally lost in the east. This difference was interpreted as reflecting a difference of the pre-orogenic template (Chevrot et al., 2018) but, given the similar finite amounts of shortening in the centre and east, there is no reason to believe that the eastern section did not behave as the central one during the building of the Pyrenees. The geometry seen today in the east would thus result from a late evolution of the lithosphere, hence from the Oligocene rifting episode. The Gulf of Lion margin has been studied with deep penetration seismics, multichannel reflection and refraction that can shed light on this question (De Voogd et al., 1991; Pascal et al., 1993; Mauffret et al., 1995; Gailler et al., 2009; Bache et al., 2010; Aslanian et al., 2012; Jolivet et al., 2015a; Moulin et al., 2015; Granado et al., 2016a, 2016b).

Fig. 4 shows the interpretation of 4 seismic reflection profiles across the margin from the Gulf of Lion to the transition with Valencia Basin (Jolivet et al., 2015a; Maillard et al., 2019). The seismic profiles SPBAL01 used in this study were provided by the “Archivo Técnico de Hidrocarburos of the Spanish Ministerio de Industria Comercio”. Data were acquired by Spectrum Energy and InSeis AS in November and December 2001 onboard the Polar Princess seismic survey vessel. The datasets consist of 2700 km of 2D acquired with a 4240 $in.^3$ Bolt LL air gun towed at 6 m depth and a 640-channel, 8000 m long, digital seal streamer lying at 10 m (12.5 m group interval; 50 m shot point interval per shot). Recording was performed with a Seal-Sercel system (12 s record length; 2 ms sampling rate; 200 Hz high-cut). Data processing was performed by the client and not described in the report provided with the digital data. The three SPBAL profiles studied in this paper are shown without interpretation in Supplementary material. For a detailed interpretation of the whole set of profiles the reader is referred to Maillard et al. (2019).

These offshore profiles confirm that the amount of extension deduced from the upper crustal normal faults is lower than the total amount of extension, an apparent paradox noticed very early in this region (Burrus, 1984). A NW-SE profile across the Gulf of Lion margin offshore Montpellier (profile RM01-208 in Fig. 4) and reaching the ocean-continent transition (OCT) zone suggests that the hyper-extended part of the margin is made of lower crustal material extracted from below the margin by low-angle normal faults dipping toward the continent, interpreted as a metamorphic core complex (Jolivet et al., 2015a). An alternative interpretation could be that the OCT is made of serpentinized exhumed mantle (see a discussion in Gailler et al. (2009) and Moulin et al. (2015)) but Moulin et al. concluded that lower crust partly intruded with magmatic material better fits the refraction data. In a late stage, the Gulf of Lion MCC is reworked by steep normal faults delimitating crustal blocks and half-grabens filled with syn-rift material. Fig. 7 shows a comparison of the Gulf of Lion MCC with the large complex of the Rhodope Massif in northern Greece (Brun and Sokoutis,

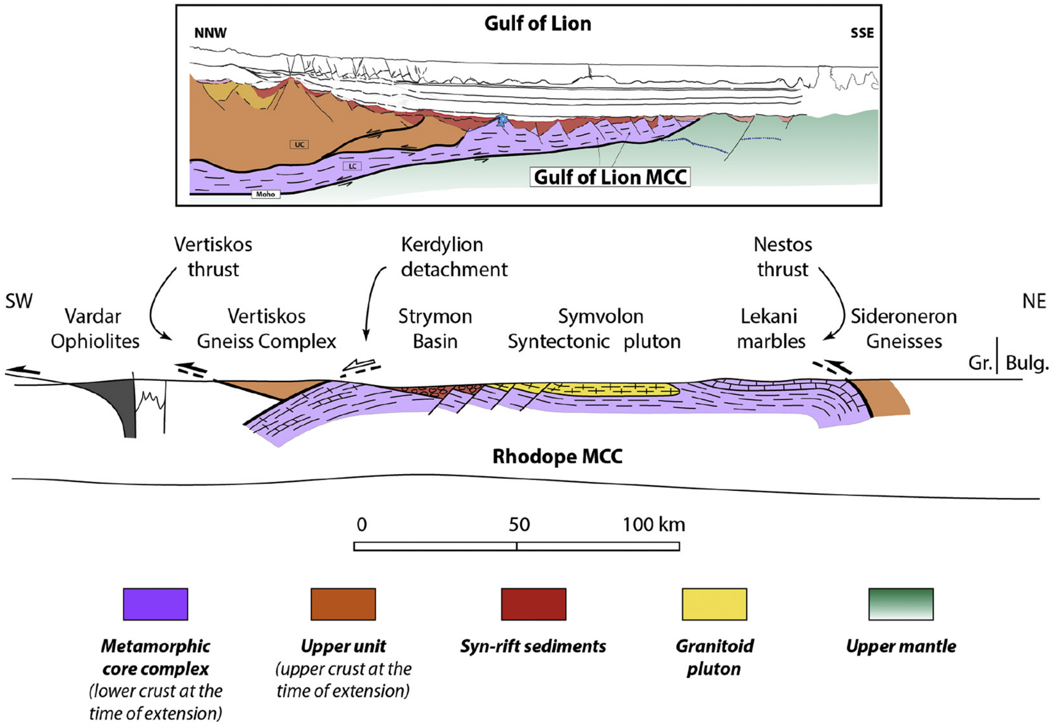

Fig. 7. Comparison of the Gulf of Lion metamorphic core complex (MCC) (Jolivet et al., 2015a) and the Rhodope MCC (Brun and Sokoutis, 2007).

2007). These two examples show comparable sizes and a similar transition through time from ductile exhumation to brittle reworking by steeper normal faults. South of this lower crustal metamorphic core complex and before the true oceanic crust, a portion of sub-continental mantle is exhumed. The larger amount of extension at crustal scale is thus achieved by the extraction of lower crust from below the margin, an observation not explained by the exhumed mantle hypothesis. An unconformity seen on the whole margin (Bache et al., 2010; Jolivet et al., 2015a) shows that the first syn-rift episode was achieved in subaerial conditions. A similar geometry is reported from seismic profiles shot further west, closer to the eastern end of the Pyrenees. Granado et al. (2016a, 2016b) interpret these profiles also with extraction of lower crust from below the margin thanks to continent-ward dipping normal faults and they propose a schematic diagram of the structure of the NW Mediterranean margins where the toe of the margin is also made of exhumed lower crust and the transition with oceanic crust made of exhumed mantle.

The nature of the exhumed body at the toe of the Gulf of Lion margin is however still debated, whether lower continental crust or exhumed serpentinized mantle. There is a general consensus on the anomalous seismic velocities from 6 to 7.5 km/s (Pascal et al., 1993; Gailler et al., 2009; Bache et al., 2010; Moulin et al., 2015) but being anomalous, these velocities are not readily diagnostic of either mantle or lower crustal material. Moulin et al. (2015) have compared 1-D seismic velocity profiles of the Gulf of Lion OCT with exhumed serpentinized mantle situations in different examples. They conclude to significant differences, especially a higher velocity in the upper layers and lower velocities in the lower layers and they propose that it could be exhumed lower continental crustal material, probably intruded by magmatic products. The presence of magmatic intrusions in this portion of the exhumed crust is indeed very likely. Although evidence for syn-rift volcanism is rare along this transect, one small volcano has been recognized in Jolivet et al. (2015a) on a parallel profile and significant magmatic underplating and contamination of the lower crust was recently proposed by Canva et al. (2019). We will thus consider in the following that the OCT at the toe of the Gulf of Lion margin is made of exhumed lower crustal material, probably intruded by magmatic products, with a low-magnetic susceptibility compared to volcanic edifices.

We have in addition interpreted three profiles of the same acquisition campaign (SPBAL01_12, 16 and 23, Fig. 4) as Granado et al. (2016a, 2016b). For more detailed interpretations of these profiles the reader is referred to Maillard et al. (2019). Profiles SPBAL01_12 and SPBAL01_16 were shot perpendicular to the Gulf of Lion margin, parallel to profile RM01-208. All these profiles show a thin crust made of reflective material covered with a reflection-free layer connected to known volcanic edifices. This layer is thus interpreted as made of volcanic material. Maillard et al., (1999) already proposed the existence of such a large amount of volcanism during and after rifting in the Valencia Basin, but the new seismic profiles show it with enhanced resolution and confirm this finding. In a first approach, these two profiles confirm the hyper-extension and exhumation of the lower crust with north-dipping reflectors that can be interpreted as extensional shear zones and possibly also magmatic intrusions. This thin crust with low-angle shear zones controlling domes thus shows the ductile behaviour of the continental crust during rifting. The main difference with RM01-208 is the presence of large amounts of volcanic products. This magmatism is also observed on the third profile, which strikes perpendicular to the first two, profile SPBAL01_23. The volcanism appears mostly active during the Aquitanian-Burdigalian rifting stage, but it is still observed within the later post-rift deposits, until the Messinian salt. The strongest magnetic anomalies in the Valencia Basin correspond to volcanic edifices while the distribution of magmatism appears much wider. The exact nature of the magmatic rocks in the reflection-free layer should thus be investigated to see which part of it could be gabbro (less magnetic) instead of basalts. Although it keeps some similarities with non-volcanic margins (mantle exhumation), the western part of the Gulf of Lion margin thus also has several characteristics of a hot magmatic margin: (i) the ductility of the crust and the exhumation with landward-dipping shear zones and exhumation of the lower crust, and (2) the presence of large amounts of volcanism in the Ocean-Continent transition zone, especially along transfer faults. This volcanism is not a new finding *per se* although it is much better imaged on these new profiles. Maillard and Mauffret (1999) had indeed already observed and mapped it further west in the Valencia Basin where it is also associated with volcanic edifices at the sea bottom (Fig. 3).

7. Discussion

7.1. Summary of observations

The structure of the Pyrenees and Gulf of Lion at crustal scale implies that a significant part of crustal thinning must have been accommodated by lower crust removal from below to explain the apparent inconsistency between overall thinning of the crust and the small number of normal faults in the upper crust (Jolivet et al., 2015a). The analysis of gravimetric data indeed confirms this hypothesis (Wehr et al., 2018). Offshore profiles furthermore show that the hyper-extended margin of the Gulf of Lion is made of exhumed lower crust and mantle and that extension was achieved in a hot environment reminiscent of volcanic passive margins. Stratigraphic constraints further show that the first stage of crustal thinning was achieved above sea level or in a very shallow sea during the Oligocene, until the 23 Ma old erosional surface in the Gulf of Lion, after which the whole system got under water and subsided (Bache et al., 2010; Jolivet et al., 2015a). The distal part of the margin results from the hyper-extension of the Axial Zone of the Pyrenees, south of the IMZ encountered at drill hole GLP2.

This timing can be compared with the timing of shortening and extension onshore and the timing of exhumation. The second episode of exhumation of the Axial Zone of the Pyrenees around 30 Ma is partly coeval with the first stage of rifting observed offshore with some short time-lag that may correspond to the time needed by an elevated topography to reach sea level. The unconformity at the Oligocene-Miocene transition (Bache et al., 2010; Jolivet et al., 2015a) can be the result of this Oligocene stage of exhumation if it were associated with the creation of relief. This episode of exhumation is more intense in the eastern part of the belt and it is followed by a third episode at ~20 Ma in the west (Bosch et al., 2016). Fig. 8 shows a tentative strike cross-section across the Pyrenees and the Gulf of Lion margin. It was constructed using information provided by the onshore and offshore seismic profiles described above (Chevrot et al., 2018). As for the lower crust, we used the conclusion of Wehr et al. (2018) showing that it is missing below the eastern Pyrenees.

7.2. A new model

A tentative scenario can be proposed to reconcile these observations (Figs. 8 and 9). Extracting the lithospheric mantle and the lower crust from below the continental margin would involve a strong component of shearing. Simple convective removal by Rayleigh-Taylor instabilities (Platt and Vissers, 1989; Burov and Molnar, 2008) may remove some part of the mantle or even some dense lower crust (if eclogitized) but it would not extract it laterally. A candidate for this shearing is a flow of the asthenospheric mantle toward the back-arc domain (Jolivet et al., 2009). Seismic anisotropy data indeed suggest that the mantle in this region is sheared parallel to the Pyrenees toward the retreating subduction zone (Barruol and Granet, 2002; Barruol et al., 2004; Lucente et al., 2006; Buontempo et al., 2008; Jolivet et al., 2009; Barruol et al., 2011; Díaz et al., 2015; Bonnin et al., 2017). Some of the anisotropic signal may reside in the asthenosphere and the remaining part within the lithosphere below the Pyrenees (Bonnin et al., 2017). Fig. 3 shows that the flow suggested by SKS anisotropy is roughly E-W way beyond the Pyrenean Belt and results from a process active on a larger scale than the Pyrenees. Perturbations of the this E-W flow can be seen around the Gibraltar Arc and the Apennines, as well as around the Alps. The Pyrenees thus sit above a large-scale flow in the asthenosphere that does not result from Pyrenean deformation. In this region, such a flow can be induced by the retreat of the subducting Apennines and Alboran slabs that has accelerated some 30–35 Myrs ago (Barruol et al., 2004; Lucente et al., 2006; Jolivet et al., 2009, 2015a). As proposed for the Gulf of Lion margin (Jolivet et al., 2015a) this flow would extract first the mantle and then the lower crust from below the Pyrenees. The consequences would then be (1) an uplift of the belt when part of the lithospheric mantle is removed and the lithosphere thus made lighter and (2) subsidence of the eastern part of the belt when the lower crust is removed. Stage one should happen during the Oligocene and before the erosional surface, and the second stage during the earliest Miocene. With this scenario it is expected that the lithosphere be eroded from below in the east and then in the west, which could fit the faster exhumation in the east at 30 Ma and the westward migration of exhumation afterward. The uplift of the belt due to removal of the lithospheric mantle would lead to an increase of gravitational potential energy stored in the lithosphere and thus enhance lateral spreading, thus potentially providing an explanation for continuing thrusting in the southwest Pyrenees until the base of the early Miocene.

This scenario offers an alternative to models favouring a pre-orogenic discontinuity at about 1° of east longitude, approximately between profiles C and D (Figs. 2 and 6). According to Chevrot et al. (2018), this transition corresponds to a shift in the pre-orogenic structure of the Early Cretaceous rift systems and a possible change of its polarity. The absence of evidence of large-scale structures related to the underthrusting of Iberia would however suggest a much smaller amount of shortening in the east, which is not documented. We thus prefer to interpret this change in the large-scale structure of the belt as resulting from post-orogenic extension during the rifting of the Gulf of Lion. This question however remains open and further studies should find ways of testing the two interpretations.

A recent 3-D joint inversion of geoelectrical data in the Central and Eastern Pyrenees also reveals a contrast between the two regions (Campanyà et al., 2018). In the Central Pyrenees the subducted Iberian lower crust is associated with a geoelectrical anomaly due to partial melting while in the eastern Pyrenees this anomaly is absent. The higher electrical resistivity of the lithospheric mantle below the eastern Pyrenees suggests a heterogeneity of the Iberian lithosphere with a missing lithospheric root in the east. Moreover, the flat geometry of the lithosphere-asthenosphere boundary deduced from this same study fits

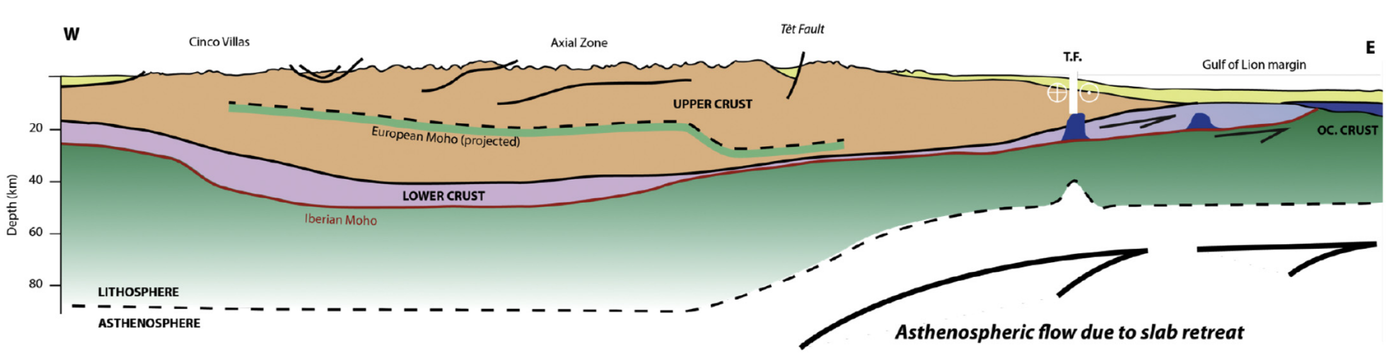

Fig. 8. Longitudinal section of the Pyrenees and Gulf of Lion margin using the transverse sections of Fig. 7 and the 3-D model of Wehr et al. (2018).

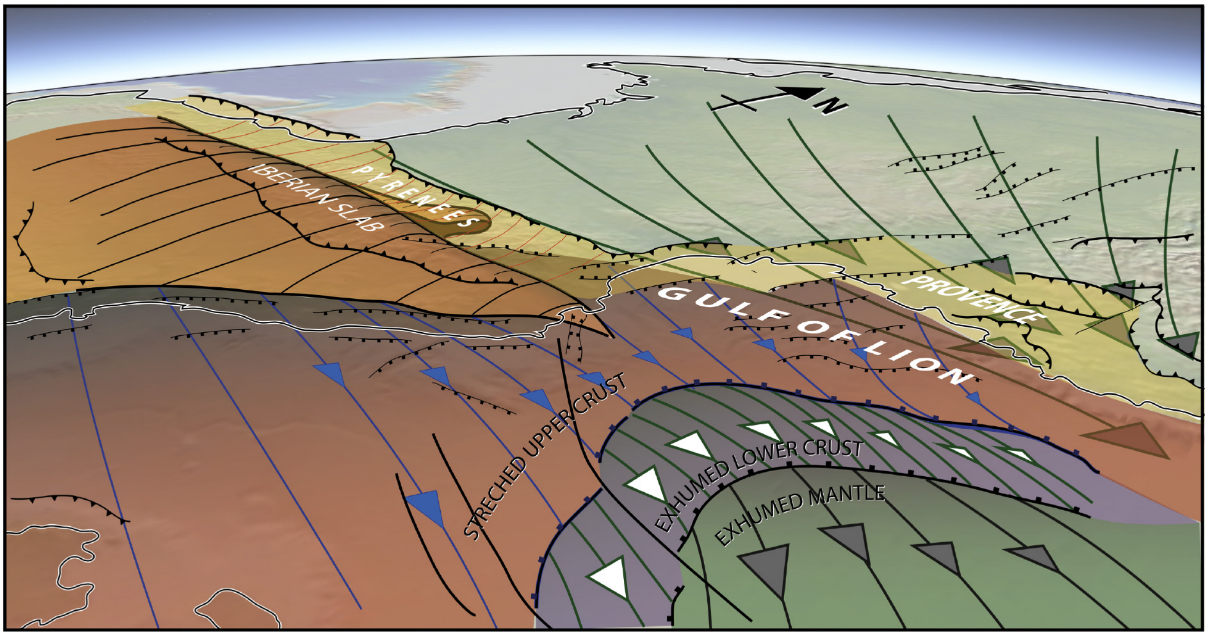

Fig. 9. Interpretative 3-D view of the Pyrenees-Gulf of Lion transition and the exhumation of upper mantle and lower crust is response to shearing by asthenospheric flow due to slab retreat.

our scenario of a missing lithospheric root and orogenic collapse.

7.3. Transfer faults, localization of exhumation and crustal thickness

If this new model holds, the oblique orientation of transfer faults east of the Pyrenees implies a significant transtensional component. Seismic profiles crossing these faults indeed show low-angle normal faults, syn-rift basins and lower crust and mantle domes (Fig. 4) (Maillard et al., 2019). The stretching direction in the exhumed domain, either lower crust or mantle, is unknown. One can only see the component parallel to the profiles, shot perpendicular to the Gulf of Lion margin (Jolivet et al., 2015a) but a significant perpendicular component is also seen on strike profiles. In the crust, the direction of extension and the direction of transfer faults are controlled by both the rigid motion and the mantle flow underneath. The origin of the exhumed lower crust, whether Iberia or Europe, is difficult to ascertain. Considering the clear underthrusting of Iberia below Europe and the presence of a root of Iberian crust, the best guess is that the exhumed lower crust at the toe of the Gulf of Lion is the Iberian crust, but the situation at depth before the Oligocene is not known.

The only thing we know is that the lower crust is missing below the eastern part of the Pyrenees and that some lower crust could now be observed below the distal Gulf of Lion margin. This lower crust was then distributed below the margin and partly exhumed with a kinematics probably intermediate between that of the mantle flow and that of extension of the Gulf of Lion, implying a decoupling between mantle flow and crustal deformation.

The restored position of the Corsica-Sardinia block is based upon paleomagnetic data giving the sense, amount and timing of rotation (Gattacceca et al., 2007), as well as a simple surface balancing of the crust during rifting following Jolivet et al. (2015a) restoring the thickness of the crust to ~35 km. This means that the Eocene shortening has not really been taken into account because we have no precise idea of the initial crustal thickness prior to rifting (see a discussion in Lacombe and Jolivet, 2005). It is on the one hand difficult to escape from an extension of the Pyrenees below the Gulf of Lion margin during the Eocene, as the continuous thrust front from the North Pyrenean Front to the Corbières and Provence fold-and-thrust belts implies the existence of a buttress to the south that could be the extension of the Axial Zone of the Pyrenees, a conclusion strengthened by the presence of the IMZ below the margin at GLP2. This is also reinforced by the observation of a northward thrust of basement rocks on top of the cover along the southern coast of Provence (Sicié imbricate) suggesting that the Western Corsica Paleozoic basement was involved in the shortening south of Provence (Ducrot, 1967; Vially and Tremolières, 1996; Lacombe and Jolivet, 2005; Fournier et al., 2016). Paleocurrent analyses also suggest the existence of a basement relief east of the Pyrenees during the Eocene (Ford et al., 2016). But, on the other hand, the presence of a preserved thick Mesozoic depot-centre in the Columbrets basin in the southwestern corner of the Valencia Basin (Etheve et al., 2018) suggests that similar basins may have existed also below the Gulf of Lion, although the main part of extension further to the NE in the Valencia Basin is Oligo-Miocene. This would then imply that the pre-rift crust was not as thick as it is below the present-day Pyrenees. Gorini (1993), Mauffret et al. (1995) and Guennoc et al. (2000) however interpreted some south-dipping reflectors seen on the Ecors line as former Pyrenean thrusts. The presence of the IMZ at GLP2 also shows that the metamorphic parts of the Early Cretaceous syn-rift basins had been exhumed before the rifting started in the Gulf of Lion, like in the rest of the Pyrenees due to Eocene compression. It is thus likely that the crust had been thickened during the Eocene before rifting. It then results from this short discussion that although the status of the pre-rift crust below the Gulf of Lion is not precisely known but was likely thick. The solution we used for reconstructing the initial position of Corsica is rather conservative and should be taken as a minimum value, and a tighter fit could be envisaged.

One further question arising with this scenario is the focalisation of lithospheric mantle and lower crustal removal below the belt and less laterally. One reason is that the crust/lithosphere was thicker below the mountain belt and thus hotter and weaker, more easily sheared off by the flow of asthenospheric mantle. Follow-up questions then are the lateral distribution of extension and the significance of the abrupt end of the belt to the east. Two reasons may be discussed. (i) The first reason is that the end of the Pyrenees corresponds more or less to the abrupt bend of the northern thrust front from the Pyrenees to Provence through the Corbières Massif (Mascle et al., 1994; Séranne et al., 2019). One may then assume the existence of a transfer zone within the belt that could have been reactivated during extension, limiting the propagation of rifting toward the west. This transfer zone would be parallel to the North Balearic/Catalan Transfer Zone that accommodated the differential movement of Sardinia during rifting and later spreading (Guennoc et al., 2000; Mauffret et al., 2001; Canva et al., 2019; Dufréchou et al., 2019; Maillard et al., 2019). The relative displacement accommodated by this transfer zone during rifting must increase southward from no displacement in Languedoc to maximum displacement in the oceanic domain. The effects of this strike-slip shearing on the continental lithosphere below the eastern Pyrenees and the continental margin are thus probably quite limited. Then, as shown by Maillard et al. (2019) and Canva et al. (2019), the geometry of these transfer faults implies a component of extension across them (see above). (ii) Another reason can be looked for in the kinematic boundary conditions and the thermal maturity of the lithosphere below the belt when rifting started. East of the present-day Pyrenees, the belt was built above the slab that would retreat fast from 35 to 30 Ma onward and this is also where the volcanic arc now cropping out in west Sardinia developed (Fig. 3). This arc was the onshore continuation of the calco-alkaline volcanism observed offshore in the western Gulf of Lion and Valencia Basin (Lustrino et al., 2007; Lustrino and Wilson, 2007; Lustrino et al., 2009; Maillard et al., 2019). The formation of the volcanic arc implies a high heat flow and thus a hot, thin and weak lithosphere that would then be prone to collapsing, an hypothesis confirmed by the hot margin-like behaviour of the crust during rifting.

The Gulf of Lion embayment would then represent the emplacement of this weaker lithosphere during the construction of the eastern part of the belt, subjected to extensional boundary conditions and ductile collapse when slab retreat started. The present-day Pyrenees would be, on the opposite, the coldest part of the belt, always with compressional boundary forces after 84 Ma. Further east, the continental margin is narrower on either side on the paleorift (Maures-Esterel *vs* Corsica), suggesting a colder and less ductile behaviour during rifting. Some Miocene volcanic products are known offshore there, but not to the extent observed at the transition between the Gulf of Lion and the Valencia Basin and most of these volcanic products were erupted after the end of rifting, except for the limited outcrops of the French coast of Esterel and Maures massifs (Réhault et al., 2012). Whether this is real or due to less powerful seismic acquisition can be debated. Acquiring new data there would be a good way to test this simple model.

The domain concentrating most magmatic activity, associated with a ductile behaviour of the crust, is found in the vicinity of the Catalan transfer zone which separates the future Apennines and Maghreb branches of the Western Mediterranean subduction zones. It is thus above a slab tear or a step-fault in the sense of Govers and Wortel (2005). It moreover corresponds to the hinge zone of the retreating arc where the fastest retreat is expected. The high retreat velocity and the presence of a slab tear are two reasons favouring a high heat flow. (i) The fast asthenospheric inflow erodes thermally and mechanically the lithosphere that is replaced by hot asthenosphere and (ii) fast mantle flow in the vicinity of the slab tear favours heat production in the mantle by shear heating, as shown in 3-D numerical models of retreating subduction (Roche et al., 2018). The volcanic arc, the inflow of hot asthenosphere and shear heating around the slab tear thus favour the high heat flow explaining the ductile behaviour of the continental crust during rifting.

One final important question to address is the relative timing of underthrusting of Iberia and this erosion from below of the eastern Pyrenees and, thus, the complex 3-D geometry at depth at the junction of the Pyrenees and the Gulf of Lion. Evidence for compressional deformation along the southern thrust front is mainly observed in the central part and western parts of the belt. Whether it corresponds to continuing underthrusting of Iberia under Europe or results from a form of gravitational spreading of the belt is debatable. But recently published cross-sections (Mouthereau et al., 2014; Labaume et al., 2016; Teixell et al., 2018; Muñoz et al., 2018) all show the thrust front connecting with crustal scale thrust planes, suggesting active underthrusting of Iberia. Was it still active in the eastern Pyrenees while the Gulf of Lion was already in a rifting stage? In that case the Iberian lithosphere would have been eroded by the south-eastward asthenospheric flow during its northward subduction. This complex question remains open and would require high resolution 3-D numerical modelling to better understand the geometry of the flow at lithospheric and crustal scale.

8. Conclusion

Based on a comparison of on-land and offshore crustal-scale structures of the Pyrenees and the Gulf of Lion, we propose that the abrupt eastern end of the Pyrenees and the transition with the Gulf of Lion passive margin is the consequence of eastward mantle and lower crust extraction by the asthenospheric flow caused by slab rollback in Oligocene and Early Miocene. In this scenario, the lower crust missing beneath the eastern Pyrenees now makes the toe of the margin in the Gulf of Lion. The Gulf of Lion embayment results from the ductile collapse of the Pyrenees-Provence orogen in the overriding plate in the back-arc region of the young Apennine retreating subduction zone. The large amount of volcanic syn-rift products in the westernmost Gulf of Lion and eastern Valencia Basin and the associated high heat flow during rifting has favoured a ductile behaviour of the crust and the development of a wide margin with some characteristics of the South Atlantic volcanic passive margins. This intense volcanic activity is focussed in the vicinity of the transfer zones (Catalan/North Balearic fracture zone, Central FZ) that accommodate the differential movements of the future Apennines and Maghreb subductions, and is thus likely to have been favoured by a slab tear underneath. This slab tear might have also contributed to the high heat flow and ductile behaviour of the crust as suggested by 3-D numerical models of retreating subduction involving shear heating.

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Credit author statement

Laurent Jolivet had the original idea and wrote the paper. Adrien Romagny and Christian Gorini brought their expertise in the geology of the Western Mediterranean. Agnès Maillard and Isabelle Thinon provided their knowledge of the offshore geology and interpretation of seismic profiles. Renaud Couëffé, Maxime Ducoux and Michel Séranne helped with their knowledge of onshore geology. All authors contributed to the design and content of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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