Structural style and evolution of the Gulf of Lion Oligo–Miocene rifting: role of the Pyrenean orogeny

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The Gulf of Lion margin results from the Oligo-Aquitanian rifting and Burdigalian crustal separation between continental Europe and Corsica–Sardinia. Immediately before the onset of extension, the area of the Gulf of Lion was affected by the Pyrenean orogeny which controlled the structural style of the evolving margin. During extension, the foreland of the Pyrenean orogen was affected by extensional thin-skinned tectonics. The décollement level ramped down into the basement, in areas where the latter was thickened during orogeny. In this intermediate part, the margin was extended by several crustal-scale low-angle faults, which generated small amounts of syn-rift sedimentation compared with the accumulation of post-rift sediments. However, more than 4 km of syn-rift sediments were deposited in the Camargue basin, which is located at the transition between thin- and thick-skinned extensional systems. Kinematic restorations and stratigraphy suggest a pre-rift surface elevation above sea-level of at least 1 km in the intermediate part of the margin, which is in agreement with reduced syn-rift sedimentation. The slope area extends seaward of the North Pyrenean Fault, a terrane boundary inherited from the Pyrenean collision. This part of the margin was stretched by seaward dipping low-angle block tilting of the upper crust, and antithetic lower crustal and sub-crustal detachment. The lithospheric structures inherited from the Pyrenean orogeny exerted a strong control on the kinematics of the rifting and on the distribution and history of subsidence. Such parameters need to be integrated in the definition of pre-rift initial conditions in future basin-modelling of the Gulf of Lion.

Keywords: Pyrenean orogeny; Gulf of Lion; rifting

Extension at the expense of an orogenic lithosphere has important bearings on the choice of initial conditions for subsidence models: thickness, surface elevation, thermal regime and rheology are strongly dependent on the pre-rift history. The thermal evolution of associated sedimentary basins and the maturation of organic matter are expected to reflect the effects of geotherms perturbed by the orogenic phase, whereas the inhomogeneous distribution of crustal masses inherited from the mountain-building process determines the location and the geometry of the extensional structures. The Gulf of Lion continental passive margin results from the Late Oligocene–Miocene rifting and later south-eastward drift of the Corsica–Sardinia block (Figure 1). The margin truncates the eastwards continuation of the Pyrenean range formed during the Palaeocene; extensional structures are superimposed onto the thrusts and folds of the Pyrenean foreland. Exploration for hydrocarbons triggered the first geological investi-
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**Figure 1** Location of the Gulf of Lion within the western Mediterranean, with respect to the Pyrenean fold and thrust belt. The pre-rift position of Corsica, Sardinia and the Balearics according to Réhault et al. (1984) is indicated (dotted lines) as well as the boundaries of accreted oceanic crust (grey lines). The deep seismic reflection profiles ECORS-Pyrenees and ECORS-CROP Gulf of Lion are located on this map.

...gations in the Gulf of Lion, with drilling of several exploratory wells (Cravatte et al., 1974) and syntheses of existing geological and geophysical data (Arthaud et al., 1981; Arthaud and Séguret, 1981). Different subsidence models have been tested against the borehole data in an attempt to explain the anomalously high post-rift subsidence (Steckler and Watts, 1980; Burrus and Foucher, 1986; Bessis, 1986; Kooi et al., 1992). However, these studies assumed a rather 'standard' pre-rift configuration of the lithosphere. Several papers have suggested a genetic relationship between localized Oligocene rifting and the overall convergence of the African and European plates (e.g. Tapponnier, 1977), whereas others have proposed that the Gulf of Lion was a marginal basin above the north-west subduction of the African plate (e.g. Réhault et al., 1984). The area of the Gulf of Lion was chosen for a ECORS deep seismic survey (Burrus et al., 1987; de Voogd et al., 1991), the preliminary results of which have been integrated into regional studies (Gorini et al., 1993). In this paper, we analyse variations in tectonic style across the onshore and offshore part of the continental margin and we investigate the possible role that Pyrenean orogenic structures played in the localization and kinematics of extension in the Gulf of Lion margin.

The structure of the onshore extensional system was assessed by compilation of the published (BRGM) and unpublished geological maps. Additional detailed mapping was carried out in specific areas (e.g. Philibert, 1992). Data from onshore industrial boreholes and the nine offshore exploratory wells (Cravatte et al., 1974; Gorini et al., 1993) were integrated. Industrial multichannel seismic reflection surveys in the Hérault, Alès and Camargue basins (Figure 2) allowed constraint of the structure at depth. The structural and deep crustal configuration of the offshore part of the margin is defined by the ECORS-CROP deep seismic survey shot in 1988 across the north-west Mediterranean from the Gulf of Lion to Sardinia (de Voogd et al., 1991), which has been reprocessed (Pascal et al., 1994; unpublished data) and by a retraction survey consisting of 11 expanded spread profiles distributed throughout the eastern part of the Gulf of Lion (Le Douaran et al., 1984, reprocessed by Pascal et al., 1993).

**Pre-rift geological setting**

The major pre-rift structures and stratigraphic features of the study area are now summarized, special attention being paid to those that exerted a strong control on the development of the Oligocene extension.

**Late Variscan tectonics**

The continental basement (Figure 2) consists of Palaeozoic rocks deformed during the Variscan orogeny (Devonian to Late Carboniferous). Late Variscan extension activated NE trending and N–S oriented strike slip faults and E–W extensional faults (Arthaud and Matte, 1975), which controlled the formation of Carboniferous and Permian continental basins (Echtler and Malavieille, 1990).

**Mesozoic extensional ‘SE Basin’**

Shales and evaporites of the Mid-Triassic period reflect a major transgression over the deeply eroded and peneplaned Palaeozoic basement. In the Gulf of Lion area, the continental to marine facies distribution shows that Triassic sediments were deposited in a triangular-shaped bay open to the east, limited to the north-west by the Massif Central and to the south by a continental elevated area extending into the present day Gulf of Lion. This palaeogeographical setting continued throughout the Jurassic, allowing deposition of a succession of marine carbonates and shale intervals, thickening towards the east in the ‘Sud-Est Basin’ (Beaudrìmont and Dubois, 1977). The Jurassic sequence deposition was controlled by the Liassic Tethys rifting, which is expressed by syn-sedimentary extensional faults along the NE trending Massif Central margin (Giot et al., 1991) and E–W trending normal faults along the southern margin, from Provence to Languedoc (Figure 2). Within this triangular-shaped basin, the top of the block-faulted Palaeozoic dips about 10° towards the axis of the synform. The Mesozoic sedimentary cover was thin and discontinuous over the southern Corsica–Sardinia continental block.

**Cretaceous wrenching and inversion**

During early Late Cretaceous opening of the Bay of Biscay and North Atlantic, the eastward drift of the Iberian block was accompanied by left-lateral shear along the North Pyrenean Fault Zone (NPFZ, Figures 1 and 2), crustal thinning along the southern European margin and development of E–W trending strike-slip basins and ridges and HT–LP metamorphism (chookroune and Mattauer, 1978; Golberg et al., 1986). This zone of shear, separating Europe and Iberia–Corsica–Sardinia extends across the Gulf of Lion. It is likely that the metamorphism of Albian age documented in the basement of the GLP2 well (Figure 2) points to the eastwards continuation of the NPFZ (Gorini, 1993). The deep and narrow basin observed north of GLP2 (Figure 2) could therefore be a Late Cretaceous strike-slip basin reactivated during Cenozoic rifting. Left-lateral motion of Iberia–
Corsica–Sardinia is also responsible for the partial inversion of the Mesozoic basin in Provence and Languedoc. Aerial erosion with westwards increasing amplitude caused the truncation and karstification of Early Cretaceous sediments across uplifted blocks and the deposition of bauxites. In the study area, Early Cretaceous series were partly preserved north of E–W trending basement faults located between Provence and Languedoc.

Pyrenean orogeny

Following left-lateral wrenching, the Late Senonian–Palaeogene convergence and collision of the Iberia–Corsica–Sardinia block with the southern margin of the European plate resulted in the Pyrenean orogeny. The belt stretches E–W from the Bay of Biscay to the Gulf of Lion, and from Languedoc to Provence through the NE trending Corbières transfer zone (Mascle et al., 1994). The structure of the western segment, i.e. the present day Pyrenees, is now well constrained by ECORS deep seismic reflection (Choukroune and ECORS-Team, 1989; Roure et al., 1989). This profile displays a wide, thickened, south-verging thrust belt on the Iberian part, which is separated by the NPFZ from the narrower, north-verging European counterpart lying above a subcrustal lithospheric wedge. Shortening of about 100 km is associated with crustal thickening and the development of roots about 50 km below the Iberian plate. In contrast, the eastern segment of the Pyrenees is less well constrained, as most of this thrust belt is now lying under the Gulf of Lion, with only the northern foreland being exposed. The asymmetrical structure of the Pyrenees seems to have flipped across the NE trending transfer zone: wide north-verging, deformed areas extend north of the NPFZ, whereas palinspastic reconstruction of Sardinia (poorly deformed during the Pyrenean orogeny) in its pre-rift position does not allow for a wide southern domain.

The similarity of the Languedoc–Provence belt to the present day southern Pyrenean foreland has already been noted by Arthaud and Séguret (1981). Thin-skinned tectonics above the décollement level of the Triassic evaporites involves thrusting or folding, depending on the thickness of the Mesozoic series. The direction of thin-skinned thrusting (Figure 2) varies from north-westward in the NE trending transfer zone.

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**Figure 2** Structural map of the Gulf of Lion area, showing the superimposition of the Oligo–Aquitanian extensional structures over the Pyrenean (Eocene) compressional structures. Note the nearly perpendicular directions of compressional and extensional deformations. NPFZ, North Pyrenean Fault Zone; Av, Avignon; Ma, Marseille; Mo, Montpellier; Na, Narbonne; Ni, Nîmes; Pe, Perpignan; To, Toulon; A, Aix basin; Ag, Agde marine; Au, Autan 1; Be, Beauduc; Ca, Calmar; Ci, Cicindelle; GLP2, Golfe du Lion Profond 2; Mi, Mistral; Na, Narbonne; Ra, Rascasse; Sl, Sirocco; and Tr, Tramontane. Regional sections shown in this paper are located on this map. ESPs 201 to 205 are indicated along the ECORS 'NW' profile. Geometry of the offshore syn-rift structures modified from Gorini (1993). Directions of compression and extension from Arthaud and Séguret (1981), Arthaud et al. (1981), Arthaud and Piste (1993), Tempier (1987) and Hippolite et al. (1993)
which can also be traced in the Gulf of Lion (Gorini, fault across the basin (Maerten and Sèranne, in press), basin provides evidence for a NNW-trending transfer from the Triassic décollement level, which passed during rifting. Faulting propagated north-westwardsments unconformably overlie the previous deposits and migration of depocentres. Burdigalian marine sediments fill gives evidence for an overall north-westward small fault-bounded basins now deeply buried below The landwardmost part of the margin extends south-east of the Cévennes fault which controlled the formation of the Oligocene Hérault and Alèse half-graben basins (Figure 2). They are the larger basins active during the post-Pyrenean rifting phase, the other extensional structures being very small half-graben. The Hérault basin (Maerten, 1994; Maerten and Sèranne, in press) (Figures 2 and 3) displays a NW dipping monoclinal series unconformably overlying the north-verging Eocene Montpellier thrust. The onset of syn-rift sedimentation occurred during the Stampian in small fault-bounded basins now deeply buried below later syn-rift Aquitanian alluvial plain deposits. Syn-rift basin-fill gives evidence for an overall north-westward migration of depocentres. Burgiddalnaian marine sediments unconformably overlie the previous deposits and onlap pre-rift basement to the SE. Extensional faulting affects the pre-rift Mesozoic cover detached above the Palaeozoic basement, which remained undeformed during rifting. Faulting propagated north-westwards from the Triassic décollement level, which passed downdip into — and reactivated in an extensional regime — the basement ramp of the Montpellier thrust (Figure 3). Depocentres distribution in the Hérault basin provides evidence for a NNW-trending transfer fault across the basin (Maerten and Sèranne, in press), which can also be traced in the Gulf of Lion (Gorini, 1993) and that we informally name the sétoise transferzone (Figure 2).

The Alès basin (Figure 2) shows a rollover and a syn-tectonic diverging basin-fill, indicating the control by an extensional listric fault that is superimposed onto, and partly reactivates, the Cévennes Fault. Reconstruction of the Oligocene fault shows that it detaches in the Triassic level, whereas earlier studies suggest the existence of a structurally lower detachment in the Carboniferous (Roure et al., 1992). Syn-rift sedimentation unconformably overlies the syn-tectonic compressional Middle Eocene sediments. Extension started earlier (latest Eocene) than in the rest of Languedoc and extended into the Late Oligocene (Alabouvette and Cavelier, 1984). The exclusively continental basin-fill consists of alluvial fans along the NW margin that pass to silty and lacustrine limestones in the axis of the basin. The maturity of organic matter within pre-rift late Cretaceous shales located in the hanging wall suggests a late uplift of several hundred metres (A. Masce, pers. comm.) that is related to Alpine inversion, and which is not detailed here (see Roure et al., 1992). To the SW, the basin is associated with a NNW trending transfer fault zone, which is identified in the Palaeozoic footwall and whose structural and stratigraphic effects can be recognized across the whole margin (Figure 2). It corresponds to the Arlésienne transfer fault zone (Gorini, 1993). North-east of this transform zone, the only significant syn-rift basins are located along the Cévennes fault (Alès basin) and close to the Durance fault (Manosque and Aix basins, Figure 2). Seismic reflection data clearly indicate that these basins have been formed on listric faults that detach above the Hercynian basement (Biondi et al., 1992; Roure et al., 1992) and there is no Oligocene basin overlying the thick and tabular Mesozoic cover which could indicate basement ramps located between the Cévennes and Durance faults. The mechanism by which the continental crust is extended north-east of the Arlésienne transfer fault zone remains an open question.

Les Matelles basin example

Les Matelles basin (Figure 4, location on Figure 3) is an asymmetrical NE-trending syncline. The SE limb displays the complete regional stratigraphic series from Mesozoic marine carbonate up to the latest Eocene alluvial deposits ("Ludian", previously dated Early Oligocene (Alabouvette and Cavelier, 1984)). The NW steep limb corresponds to a hanging wall flat resting against the footwall ramp of the Les Matelles fault. The NW limb displays a thin interval of lower Cretaceous marly limestones and lower Eocene marls, and the complete middle Eocene limestone. The uppermost Eocene interval onlaps toward the NW and is not exposed in the NW limb. This gives evidence for pre-Oligocene downthrow of the SE block of Les Matelles fault (Figure 4), due to previous Pyrenean left-lateral strike-slip (Arthaud and Sèguret, 1981). The syncline is cored by coarse breccia, which locally unconformably overlie the NW steep limb in a typical syn-tectonic progressive unconformity pattern. These coarse and angular breccia were generated along the NW active margin of the basin at the expense of Lower Cretaceous or Middle Eocene limestones; there is no significant input from the presently exposed Upper Jurassic lime-
Figure 3 Cross-section of the upper structures in the onshore Gulf of Lion. The landward part of the margin is characterized by thin-skinned tectonics, whereas SE of the Nimes Fault, the margin was extended by thick-skinned low angle faulting. Note the discontinuity between sections A and B. Location in Figure 2.
stone of the footwall. The small (500 m radius) alluvial fans interfinger with marly shales and conglomerate channel-fill belonging to an axial south-westward flowing braided fluvial system, or with lacustrine carbonate deposits in the NE part of the basin (Crochet, 1984). These sediments are biostratigraphically well dated as latest Stampian and span a time interval less than one million years (Grambast, 1962; Rey, 1962; Crochet, 1984) The structure of the basin is complicated by the occurrence of slivers of Lutecian limestone — some tens of metres thick and several kilometres along-strike — within the syn-rift sediments (Figure 4a). The Lutecian imbricate thrusts overlie and deform the lower part of the Oligocene breccia and they are sealed by the same formation. Clast composition and distribution within the breccia suggests that a significant part of the clasts are derived from the Lutecian thrusts. The deformation pattern at the front of the thrusts indicates a SE vergence and shows that they have been emplaced in the basin during sedimentation of the syn-rift Oligocene (Philibert, 1992). The structure of the basin can be accounted for by thin-skinned extensional tectonics, characterized by a ramp in the massive Upper Jurassic limestones, a flat in the Lower Cretaceous marly limestones and an emerging ramp in the Middle Eocene limestones (Figure 4b). Seismic reflection and rollover geometry indicate that the ramp across the Upper Jurassic (Les Matelles Fault) is a listric fault that detaches in the Triassic series at a depth of 4000 m. During extension along the Les Matelles Fault, the Lutecian hanging wall flat was transported towards the ramp and formed the hanging wall syncline, where detritus was trapped. Part of the hanging wall flat became detached from the ramp/flat system and was gravitationally emplaced into the basin as an olistolith, and subsequently eroded and overlain by syn-tectonic syn-rift sedimentation. The imbricate thrusts represent successive reactivations of the surface of gravitational slide, following successive increases of accommodation in the basin due to the activity of the Les Matelles Fault. The structural and stratigraphic model of the Les Matelles hanging wall syncline basin applies to most small-scale Oligocene basins of Languedoc.

Structure of the intermediate part of the margin

The intermediate part of the margin extends over 100 km from the Nimes Fault to the trace of the NPZ in the Gulf of Lion (Figure 2). The thin-skinned extensional system of the NW end of the margin, ramps down into the Nimes Fault. This NE trending fault strikes normal to the extensional direction and acts as a frontal ramp. On this transect, three major normal faults involve the Palaeozoic basement and formed several syn-rift graben. The pre-rift surface corresponds to the Pyrenean erosional unconformity that exhumes allochthonous Mesozoic cover beneath Camargue and Palaeozoic basement beneath the gulf. This intermediate zone is characterized by a large thickness of post-rift series that is not proportional to the thin and discontinuous syn-rift series nor to the amount of crustal thinning. However, due to its structural position on the margin, the 4000 m deep Carmargue basin (Figure 2) stands out as an exception in the group of syn-rift basins.

Camargue basin

The Camargue basin is subdivided into the NE trending Vistrenque graben and the associated Petit Rhône graben (or Petite Camargue in the offshore along strike continuation) (Figures 2 and 3). The over 4000 m thick Stampian to Aquitanian syn-rift series unconformably overlies Mesozoic carbonates. Stampian sequences comprise thick continental to lagoonal shales and silts overlain by evaporitic sediments characterizing playa environments. The structural repetition of evaporites results from basinward gravity thrusting above the rollover during syn-rift sedimentation (Valette, 1991; Valette and Benedicto, 1995). Overlying Aquitanian shales and silts were deposited in littoral to very shallow marine environments. The entire syn-rift series was thus deposited close to sea level, indicating that sedimentation always balanced accommodation. It further indicates that surface elevation in the Vistrenque basin was close to sea level from Early Oligocene times onwards. A Burdigalian marine sequence onlaps an erosional unconformity developed under subaerial conditions (Valette, 1991), which is interpreted as the break-up unconformity. The upper part of the basin-fill is truncated by the erosional surface corresponding to the Messinian lowstand of the Mediterranean; this unconformity is onlapped by the transgressive Pliocene to Present series.

The structure of the Vistrenque graben is controlled by the NE trending, SE dipping Nimes Fault. Sections across the south-western part of the graben display a typical rollover due to the concave-upward profile of the bounding fault in the upper 3 km of the crust (Figure 3), whereas sections across the north-easter part of the graben display compensation graben due to a planar attitude of the fault (Valette and Benedicto, 1995). Syn-rift series of the Vistrenque basin extend over the entire down-faulted block, beyond the hanging wall crest. This indicates subsidence due to the low angle (25°) Nimes Fault, which is planar from 3 km
Present-day situation

NW  SE

Messinian erosion

Syn-rift filling

Nîmes Fault

Pyrenean Thrust

Ramp-flat fault

No pre-rift relief

Ramp fault

Pre-rift relief = 1250 m

Figure 5 Sketch of a simplified present day section in the Camargue basin, showing the geometrical relationships between extensional fault, previous thrust and partially preserved syn-rift infill (sediments deposited close to sea level). The two possible fault profiles imply two pre-rift hanging wall topographies.

downwards and that penetrates the basement to at least 10-km depth (Figure 3). In contrast, the Petit-Rhône basin that developed in the hanging wall of the Nîmes Fault is characterized by a lack of syn-rift sedimentation beyond the rollover crest. The bounding fault is a listric ramp which flattens in the Triassic décollement and it is associated further to the SE with a ramp in the basement.

Pre-rift restoration

An E–W structural high extending along the shoreline corresponds to a Pyrenean thrust in the Mesozoic cover. Such a high in the hanging wall of the Nîmes Fault may (i) be the result of the flattening of the fault profile at depth or (ii) pre-date the extensional structure (Figure 5). The Messinian erosion prevents observing the geometry of the syn-rift sequences against this high. Restoration of the extensional fault in the case of a planar low angle fault (as suggested by seismic reflection) indicates a pre-rift relief south-east of the Vistrenque basin, in excess of 1000 m, that would be inherited from northwards Pyrenean thrusting. Thrusting and erosional denudation of the Palaeozoic basement becomes prominent south of the Camargue basin. Pre-rift sedimentary cover is extremely reduced in the nearshore boreholes and Palaeozoic rocks subcrop beneath syn- or post-rift sequences in the offshore wells. Restoration of the extensional motion on the three major basement faults in Camargue (Figure 6) points to a pre-rift topography having an elevation of about 2000 m. These estimates possibly include errors due to (i) the lack of isotropic compensation and (ii) the lack of a precise pre-rift topographic reference datum as the area has been later truncated by the Messinian erosion; however, they provide a valuable indication of the location and order of magnitude of the pre-rift relief.

Crustal sections

From the shoreline to an area between ESP201 and ESP202, the ECORS profile (Figure 7A) displays a flat Moho reflection, at about 20 km depth, and a 5 km thick reflective lower crust. The reflections corresponding to the major faults that affect the upper crust either disappear above or merge with the reflective crust (Figure 7A). Major faults dip basinward, with the exception of the steep fault bounding the Vistrenque basin, at the NW end of ECORS. This landward dip-
Figure 7 Crustal-scale sections of the Gulf of Lion area (location on Figure 2) showing the variation of structural style across the margin. (A) Section constrained by ECORS NW profile (pre-stack depth migrated in the lower part of the margin). (B) Camargue section constrained by seismic reflection and by data from Gorini (1993) in the lower margin.
Foldout 1 Slope section of the ECORS NW profile (see Figure 7A) showing the tilted blocks reflector. Me, Messinian erosion; t-B, top-Burdigalian; prU, post-rift unconformity; and sr, seismically defined Moho, at ESP 203. Vertical = horizontal scale. Pre-stack depth migration.
and low-angle faults linked to the group of reflections (R reflector), and the landward-dipping T in-rift. Velocities analyses (Pascal et al., 1993) indicate that the T reflector is located above the performed using Migpack software (Pascal et al., 1994; unpublished data).
ping fault could be interpreted as an antithetic fault of the Nimes Fault (Guennoc et al., 1994). However, the available data do not suggest the existence of a major SE dipping normal fault between the NW end of ECORS and onshore outcrops. The Nimes Fault seems to die out south-eastwards before it reaches the Sèteoise transfer zone and deformation is taken up by the landward-dipping normal fault. According to the ECORS section, the fault bounding the Petite Camargue basin has a listric profile rooted in a mid-crustal level, which is in agreement with the rollover of the pre-rift. This Petite Camargue Fault correlates north-eastwards with the fault bounding the Petit Rhône basin (Figure 7B).

Transition from a listric basement ramp profile in the SW (Figure 7A) to a listric–flat–basement ramp in the NE (Figure 7B) is achieved through the reactivation of the Pyrenean thrust as lateral ramp, north of Cincinelle well. In addition, a major NE trending, low-angle (25°), intra-crustal planar reflector has been mapped offshore (Gorini et al., 1993) bounding the Grand Faraman basin (Figure 7A), and which correlates with the major extensional fault beneath Beauduc well (Figure 7B).

A number of reflectors which are apparently unrelated to Cenozoic graben (below ESP201) and are observed at middle crustal levels (SE of Sirocco) are interpreted as Pyrenean north-verging thrusts. In addition, the tectonic contact which accommodates the thin-skinned extension in the Hérault basin corresponds to the basement ramp of the previous Pyrenean Montpellier thrust (motion oblique to the section in Figure 7A). Major low-angle extensional faults bound half-graben, the sedimentary fill of which displays divergent and partly onlapping reflectors interpreted as syn-tectonic sediments. They are truncated by a break-up unconformity attributed to the earliest Burdigalian (Valette and Benedicto, 1995) or the latest Aquitanian (Gorini et al., 1993). Depth conversion of the profile using the velocity stacks indicates syn-rift sediments with a maximum thickness of 1000 m in the offshore Vistrenque and Petite Camargue basins, and less in the more seaward syn-rift depocentres. This is far less than what is measured in the onshore Camargue basin. On the parallel section (Figure 7B) the thin-skinned tectonic zone displays only one large syn-rift basin in the Camargue. This section is characterized by the three major SE dipping basement faults described earlier, in the hanging wall of which a structurally high Palaeozoic basement is directly overlain by post-rift sediments. In spite of SE dipping extensional faults, the top of the basement is located at a higher structural level in the hanging wall than in the footwall. This is in agreement with pre-extension basement culmina
tion and erosion of the Mesozoic cover in the offshore domain of the Gulf of Lion. The pre-rift surface elevation can easily account for the lack of very small amount of syn-rift sediments in this part of the margin. If continental basins were formed on the collapsing mountain belt, they were rapidly cannibalized. There is thus no stratigraphic record of the early stages of rifting (Oligocene) in the areas of surface pre-rift elevation. In contrast, where surface elevation was close to sea level from the onset of extension as in Camargue, the complete syn-rift sequence has been preserved. The presence of the deepest syn-rift depocentre localized in the Camargue basin can be accounted for by the combined effects of (i) preservation of syn-rift sedimentation north of the elevated area of the Pyrenean range and (ii) control by a crustal-scale low-angle extensional fault which allowed a large amount of accommodation. The Central Graben (Figure 2), the large syn-rift depocentre in the SW of the Gulf of Lion (Gorini et al., 1993; Guennoc et al., 1994) lies in a similar structural position.

Structure of the basinward part of the margin

The basinward part of the continental margin, imaged on the ECORS profile (Figure 7A), is limited by a deep and narrow basin probably controlled by a SE dipping steep fault. This narrow basin is located in the eastward, along-strike continuation of the North Pyrenean Fault (see Figure 2). Newly reprocessed pre-stack migration of the ECORS profile (Pascal et al., 1994; unpublished data) displays the structures of this part of the margin (Foldout 1). It is characterized by tilted blocks bounded by low-angle normal faults. Half-graben contain tilted and diverging reflectors, interpreted as syn-rift sediments. The basal unconformity is unclear. Depending on the interpretations, there is at least 1000 m and a maximum of 2000 m of syn-rift in the deepest depocentre. Syn-rift series are truncated by a prominent post-rift unconformity. Syn-rift sedimentation did not keep up with faulting as the crest of the tilted blocks stand above the post-rift unconformity, resulting in elevation of the tilted block crests above the syn-rift basins. The post-rift unconformity is overlain by a post-rift sequence onlapping to the NW onto the basement highs. The GLP2 borehole located on the side of a structural high drilled the upper part of this transgressive sequence. It indicates that the first sediments onlapping the basement at this point (late Burdigalian) are continental and that they very rapidly pass upwards into open marine series (Gorini, 1993). This implies that: (i) the diachronous lower boundary of the transgressive post-rift sequence corresponds to a coastal onlap on the flank of an emergent land presenting high topographies; (ii) the syn-rift Oligo–Aquitanian sediments were deposited in continental environment; and (iii) the rate of post-rift subsidence was very fast.

This 60 km wide zone coincides with a sharp rise of the Moho discontinuity from 20 km (beneath GLP2) to 15 km (at ESP 203) and a decrease in crustal thickness from 15 to 5 km. In this area, the lower crust does not display the typical laminated seismic facies as in the intermediate zone. The upper crust is affected by tilted blocks controlled by low-angle normal faults dipping 30°–35° towards the basin (Foldout 1). These faults seem to detach in a group of very shallow dipping reflectors located about 2–3 km beneath the top of the fault blocks, which could correlate landwards with the R reflector that cuts the top of the basement near GLP2 well (de Voogd et al., 1991). At variance with the S reflector which is imaged on the northern Bay of Biscay Margin (Le Pichon and Barbier, 1987), the R reflector cuts down-section towards the basin, synthetically to the normal faults bounding the tilted blocks. It lies within a domain of typical crustal velocities (6.2 km/s), differing in this respect from the S reflector observed on
the Galicia margin, where it is interpreted as the tectonic boundary between crustal material in the hanging wall and serpentinized peridotites in the footwall (Boillot et al., 1988). We interpret the R reflector as an extensional intra-crustal shear zone into which the low angle normal faults are rooted, and which allows stretching of the upper crustal level. Estimates of the extension across the low-angle faults indicate horizontal extension of about 60% above the R reflector, which cannot account alone for the whole crustal thinning observed on this part of the ECORS profile.

Near the base of the crustal section a 5–20° landward dipping reflector T is visible on the prestack migration as well as on the initial processing (e.g. Gorini et al., 1993). It links the 20 km deep Moho beneath ESP202 to a 12 km deep level below ESP203, where, according to the ESP203 velocity determinations, it lies within crustal material (Foldout 1). The T reflector therefore offsets the Moho discontinuity by 5 km between the GLP2 and ESP203 locations. Mapping of this reflector shows that it is parallel to the margin and that it is consistently located above the seismic Moho (Pascal et al., 1993). We interpret T as a shallow dipping extensional fault that truncates the upper lithospheric mantle and the lower crust. Blockfaulting and seaward dipping shear zones in the upper crust, together with antithetic extensional detachment in the lower crust, may account for the extreme thinning of this zone. Consequently, this interpretation requires that the crust located seawards of the T reflector is composed of lower crust and upper lithospheric mantle, exhumed in a fashion similar to that proposed for the Galicia margin (Boillot et al., 1988). Alternatively, the T reflector may be compared with the lower crustal and subcrustal reflectors observed on BIRPS profiles which are interpreted as shear zones transferring the bulk strain from upper crustal faults to mantle faults (Reston, 1990).

Basinwards of the emergence of the T reflector, the crust is characterized by a constant thickness (4 km). According to Pascal et al. (1993), velocities from expanded spread profiles suggest the existence of a crust with intermediate characters. It could be either a lower continental crust, stretched and intruded by mafic volcanics, or serpentinized peridotites at the top of the mantle, denuded by a landward dipping extensional detachment (T reflector). Typical oceanic crust is found in the basin beyond ESP207.

Discussion and conclusion

The extensional structural style of the Gulf of Lion passive continental margin changes considerably from the landward end to the continent–ocean transition (Figure 8). The zoning of the Oligo–Miocene extensional province reflects the zoning of the Pyrenean structures: the extensional thin-skinned system overprints the external thin-skinned thrust system which characterizes the northern foreland of the Pyrenees. South-west of the Arlesienne transfer fault the thin-skinned extensional system ramps down into the basement at the Nimes fault. Figure 8 also shows that the Pyrenean inherited frontal ramps were reactivated as oblique extensional ramps along a restricted E–W segment near the Sétoise transform and linking shallow to deep extensional ramps. The intermediate zone, corresponding to thick-skinned faulting, developed in the area of previous Pyrenean crustal thickening, where the Mesozoic cover was removed by erosion. The evidence for surface elevation in that area accounts for the rather thin syn-rift series. Stretching resulted firstly in the collapse of the elevated relief without syn-rift sediment preservation. At the periphery of the topographic high where surface elevation was close to sea level (e.g. Camargue), stretching was associated with sedimentation from the onset of rifting, allowing for the formation of the thickest syn-rift series. Note that the extensional faults in this area are trending NE, therefore they are not reactivated Pyrenean thrusts. They are either neoformed faults or inherited lateral ramps of the contractional system. The zone of low-angle block faulting characterized by extreme continental stretching and very thick post-rift series is located south of the NPFZ, e.g. the Iberia–Sardinia–Corsica plate. The structural style and the subsidence pattern change across the terrane boundary between the European (north of the NPFZ) and the Iberia–Sardinia–Corsica plate. The present day structure of the Pyrenees.
Figure 9 Cartoon representing the possible crustal pre-rift and present day configuration across the Gulf of Lion. The upper panel is inspired from the ECORS-Pyrenees section (Roure et al., 1989, location in Figure 1), which has been inverted to account for the flip of the asymmetrical structures across the NE trending transfer fault zone in the Cobières: in this instance, the foreland and the wide area of thickened crust extends in the European plate. The lower panel is based on the present interpretation of the ECORS-Gulf of Lion profile. Thin-skinned extensional tectonics developed in the foreland zone of the orogen. The intermediate zone of the margin corresponds to the thickened and elevated part of the orogen, almost devoid of syn-rift deposits and which was extended by thick-skinned tectonics. The seaward part of the margin correlates with a narrow deformed zone which was moderately thickened during orogeny, located south of the NPFZ (Corsica–Sardinia).

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