Publisher: GSA
Journal: GEOL: Geology
DOI:10.1130/G36072

Spatial and temporal evolution of hyperextended rift systems: Implication for the nature, kinematics and timing of the Iberian-European plate boundary

J. Tugend[1*], G. Manatschal[1], and N.J. Kusznir[2]

[1]*IPGS, CNRS-UMR 7516, EOST, Université de Strasbourg, 1 rue Blessig, 67084 Strasbourg, France*

[2]*Department of Earth & Ocean Sciences, University of Liverpool, Liverpool L69 3BX, UK*

*Current address: Laboratoire de géologie, ENS, CNRS-UMR 8538, 24 rue Lhomond, 75005 Paris, France.

ABSTRACT

We focus on the Iberian-European plate boundary (IEPB) whose nature, age and evolution are strongly debated. In contrast to previous interpretations of the IEPB as a major lithospheric scale left-lateral strike-slip fault we propose a more complex deformation history. The mapping of rift domains at the transition between Iberia and Europe emphasized the existence of spatially disconnected rift systems. Based on their restoration, we suggest that the deformation was partitioned between a set of distinct left-lateral transtensional rift systems from Late Jurassic to Early Cretaceous. A plate kinematic reorganization at Aptian-Albian time resulted in the onset of seafloor spreading in the Western Bay of Biscay and extreme crustal and lithosphere thinning in intra-continental rift basins to the east. The formation and reactivation of the IEPB is interpreted as the result of the polyphase evolution of a diffuse transient plate boundary

that failed to localize. The results of this work may provide new insights on (1) processes preceding breakup and the initiation of segmented and strongly oblique shear margins, (2) the deformation history of nascent divergent plate boundaries, and (3) the kinematics of the southern North Atlantic and Alpine domain in Western Europe.

INTRODUCTION

Processes that control the formation of divergent or transform plate boundaries, their locking and potential reactivation during convergence are among the least understood processes in tectonics. Discoveries made at present-day rifted margins have shown a complex transition between oceans and continents, characterized by extremely thinned continental crust and/or exhumed mantle (e.g., Reston 2009), referred to as "hyperextended domains." However, at present, little is known about the spatial and temporal evolution of hyperextended rift system, especially, how extensional deformation may migrate and eventually localize to create a new stable plate boundary.

We focus on the Iberian-European plate boundary (IEPB) characterized by a complex network of Late Jurassic to Mid-Cretaceous rift systems including both oceanic and hyperextended rift domains (e.g., Vergés and García-Senz, 2001; Salas and Casas, 1993; Lagabrielle and Bodinier, 2008; Jammes et al., 2010; Roca et al., 2011; Tugend et al., 2014). The onset of the northward movement of the African plate during Santonian–Campanian time (e.g., Rosenbaum et al., 2002) initiated the reactivation of the former rift systems along the IEPB, leading to the progressive formation of a new convergent plate boundary.

The tectonic setting related to the thinning and break-up of the continental lithosphere in the western Bay of Biscay remains strongly debated, resulting in controversial interpretations of the timing, kinematic and location of the IEPB (Olivet, 1996). Based on observations on the spatial and temporal evolution of the different rift systems, we aim to provide new insights on the evolution and partitioning of the deformation at the scale of a plate boundary from its formation to its reactivation.

MAGNETIC ANOMALIES AND IMPLICATIONS FOR PLATE KINEMATICS

Debates on the evolution of the IEPB concern the amount and timing of the left lateral displacement but also the nature of the plate boundary itself (Olivet, 1996). These controversies result from contrasting interpretations and restorations of magnetic anomalies from the M-series (M3–M0, 126–118.5 Ma) identified within hyperextended domains in the Bay of Biscay and North Atlantic in general (Olivet 1996; see contrasting restorations of Sibuet et al. [2004]). They are either interpreted as related to mantle exhumation (Sibuet et al., 2007) or to an excess magmatic event during lithospheric breakup (Bronner et al., 2011). In both cases, these anomalies may not represent isochrones and may not be used as such for plate kinematic restorations.

Restorations of magnetic anomalies only consider minor pre-break up movements. Considering the widespread occurrence of hyperextended domains continentwards of first oceanic crust may lead to alternative plate kinematic models with different amounts of displacement and different ages for the formation of the proto-IEPB. In view of the evolution of the North Atlantic and/or Alpine Tethys system, some authors proposed that the left-lateral movement of Iberia relative to Europe already initiated in the Late Jurassic (e.g., Rosenbaum et al., 2002; Schettino and Scotese 2002; Canérot 2008; Jammes et al., 2010) in contrast to the Mid to Late Albian onset proposed by, e.g., Le Pichon et al. (1971), Choukroune and Mattauer (1978), Olivet (1996), and Lagabrielle and Bodinier (2008).

SPATIAL AND TEMPORAL EVOLUTION OF THE IEPB RIFT SYSTEMS

Geological and geophysical observations have been combined to map the spatial distribution of the rift systems preserved at the IEPB (Fig. 1; Tugend et al., 2014; see the GSA Data Repository[1] for details on rift domain definition). Constraints on the temporal evolution of the different rift systems come from the aggradation and subsidence histories recorded in the different sub-basins (Fig. 1B; Data Repository). The array of extensional faults and transfer zone delimiting the rift systems and their reactivation as a thrust system provide first order insights on transport direction throughout the deformation history.

The architecture of the IEPB is characterized by spatially disconnected rift systems: (1) Bay of Biscay–Parentis (BoBP), (2) Pyrenean-Basque-Cantabrian (PBC), and (3) Central-Iberian (CI) rift systems (Fig. 1A; Salas and Casas, 1993; Vergés and García-Senz, 2001; Roca et al., 2011; Tugend et al., 2014). These rift systems were separated by weakly thinned continental ribbons (Lister et al., 1986), the Landes High and Ebro Block, similar to those described in the southern North Atlantic (Fig. 1A; Tugend et al., 2014).

The Late Jurassic to Mid Cretaceous rifting is not recorded simultaneously at the scale of the IEPB as indicated by subsidence analysis results in different sub-basins (Fig. 1B; see differences between the Maestrat, Cameros, Parentis, Arzacq basins; see the Data Repository). Synrift deposits are controlled by east-west– to northwest-southeast– and northeast-southwest–trending basement faults (e.g., BoBP: Derégnaucourt and Boillot, 1982; Thinon et al., 2003; PBC: Martín–Chivelet et al., 2002; Tavani and Muñoz 2012; CI: Salas and Casas, 1993).

Extreme crustal thinning is evidenced in the BoBP and PBC rift systems (e.g., Thinon et al., 2003; Lagabrielle and Bodinier, 2008; Jammes et al., 2010; Roca et al., 2011; Tugend et al., 2014), whereas the CI rift system was more moderately thinned (to ~15–20 km; see Salas and Casas [1993]). Onset of hyperextension was diachronous between the BoBP and PBC rift systems (Berriasian-Barremian to Late Aptian and Aptian to Early Cenomanian respectively; see Tugend et al., 2014; Fig. 1B). Accelerated subsidence related to extreme crustal thinning in the PBC rift system is controlled by northeast-southwest transfer zones recording the north-south to northeast-southwest divergence orientation between Iberia and Europe (Jammes et al., 2010; Roca et al., 2011; Tavani and Muñoz 2012; Tugend et al., 2014).

Onset of convergence is recorded in Santonian to Campanian time in the BoBP and PCB rift systems (e.g., Thinon et al., 2001; Capote, Muñoz, Simón et al., 2002) whereas it is delayed until Middle to Late Eocene in the CI rift system (Salas and Casas, 1993; Capote, Muñoz, Simón et al., 2002). Restorations of magnetic anomalies and the east-west–trending thrust systems in the former PBC and BoBP rift systems (Fig. 1A) suggest a north-south to northeast-southwest convergence orientation (e.g., Roest and Srivastava 1991; Rosenbaum et al., 2002).

HOW IS PARTIONNED THE DEFORMATION ALONG THE IEPB?

Based on the spatial and temporal evolution of the rift systems, we propose an alternative scenario for the evolution and partitioning of the deformation at the IEPB (Figs. 2 and 3). These restorations remain qualitative because of the partial underthrusting of the rift system during convergence (e.g., Vergés and García-Senz, 2001; Roca et al., 2011; Tugend et al., 2014). The amount of left-lateral offset of the Iberian plate relative to Europe is difficult to restore and may be estimated from ~200–500 km (Olivet, 1996).

Rift Initiation: Partitioning of Transtensional Deformation (Late Jurassic to Aptian–Albian)

The Late Jurassic initiation of the left-lateral movement of Iberia relative to Europe (e.g., Rosenbaum et al., 2002; Schettino and Scotese, 2002; Canérot, 2008; Jammes et al., 2010) is recorded along the IEPB by the formation of a wide corridor of transtensional deformation progressively shaping distinct rift systems (Figs. 1A, 2A, and 3A). The segmentation pattern of rift structures (Fig. 1A) results from the complex partitioning between strike-slip and orthogonal deformation in a strongly pre-structured basement recorded as a local north-south extension in rift basins (Figs. 2A and 3A; e.g., Tavani and Muñoz, 2012).

From the Late Jurassic onward, fauna and/or sedimentary facies type indicate that the BoBP was opened toward the Atlantic (Durand-Delga, 1973), whereas the CI and PBC were connected to the Tethyian domain (Mas et al., 1993; Salas and Casas, 1993). In spite of the Landes High and Ebro block acting as crustal barriers between the rift systems (Figs. 2A and 3A), intermittent exchanges between the Atlantic and Tethysian seas occurred caused by eustatic variations (e.g., Salas and Casas, 1993; Capote, Muñoz, Simón et al., 2002). The V-shaped nature of the BoBP rift system (Fig. 1A; Jammes et al., 2010) suggests a tentative southeast propagation, while the CI rift system may have been propagating toward the northwest (Fig. 2A) as indicated by the diachronous onset of synrift subsidence (Fig. 1B; Salas and Casas 1993; Capote, Muñoz, Simón et al., 2002).

In the future PBC, discrete narrow depocenters progressively formed, only recording moderate subsidence (Figs. 2A and 3A; e.g., Martín -Chivelet et al., 2002, and references therein).

Plate Kinematic Reorganization: Tentative Localization of the Plate Boundary (Aptian–Albian to Santonian–Campanian)

The transition from left-lateral movements to north-south and northeast-southwest divergence of Iberia relative to Europe is recorded around Aptian to Mid-Albian time by northeast-southwest transfer zones controlling the formation of the PBC rift system (Fig. 2B; Jammes et al., 2010; Roca et al., 2011; Tugend et al., 2014). It is difficult to determine if this change was abrupt or if the partitioning between strike-slip and orthogonal deformation evolved progressively.

Onset of sea-floor spreading processes in the western Bay of Biscay at Aptian–Albian time (Montadert et al., 1979; fig 2B/3B) is related to a major change in the subsidence and deformation histories of the rift systems (Fig. 1B; see the Data Repository; Tugend et al., 2014). In the CI rift system, the decrease in tectonic subsidence in rift basins suggests a progressive cessation of rifting (Salas and Casas 1993) leaving a network of disconnected aborted rift basins (Figs. 2B and 3B; e.g., Cameros, Maestrat). The synchronous onset of hyperextension in the PBC rift system is therefore interpreted as the migration of deformation from the CI to PBC rift system (Figs. 1B, 2B, and 3B; see the Data Repository) consequent to the plate kinematic reorganization. Sea-floor spreading may have persisted until Late Santonian to Early Campanian time (Chron A34; Fig. 1A), resulting in north-south to northeast-southwest extension recorded in the oceanic domain of the BoBP (Figs. 2C and 3C). Eastward, this deformation seems to have been mostly transferred and partitioned between the rift basins from the PBC in a tentative development of a divergent plate boundary between Iberia and Europe (Figs. 2C and 3C).

From Subduction Initiation to Continental Collision: The Role of Rift-Inheritance (Santonian–Campanian to Eocene–Oligocene)

The north-south to northeast-southwest convergence generated by the northward movement of Africa (e.g., Rosenbaum et al., 2002) is recorded diachronously at the scale of the IEPB (Figs. 2D and 3D). First evidence of compression is documented in Late Santonian to Campanian time in the BoBP (Thinon et al., 2001) and PBC rift systems (Capote, Muñoz, Simón et al., 2002, and references therein) while sea-floor spreading processes may have just ceased. Remarkably, this deformation is not observed in the CI rift system (Figs. 2D and 3D). This contrasting reactivation may possibly be explained by the relatively moderate thinning of the continental crust in the CI rift system (Salas and Casas 1993) compared with the extreme lithosphere thinning of the BoBP and PBC rift systems (Fig. 2C). In particular, the occurrence of exhumed mantle seems to facilitate reactivation processes and subduction initiation (Lundin and Doré 2011; Tugend et al., 2014). Former rift structures such as top basement detachment faults may have been reactivated using the serpentinization front of the uppermost mantle as a decoupling layer. This interpretation compares well with numerical modeling results (e.g., Burov and Poliakov 2001; Leroy et al., 2008) suggesting that newly formed hyperextended domains are significantly weaker than moderately thinned continental crust (i.e., proximal and necking domains). The thermal state of the IEPB at the onset of convergence may therefore represent a critical factor in explaining why reactivation was initiated in the hyperextended domain.

During the Late Eocene to Early Oligocene, the final stage of collision in the Pyrenees (e.g., Capote, Muñoz, Simón et al., 2002; Vergés and García-Senz, 2001) may result in a strong coupling between Iberia and Europe at the former PBC rift system. The main convergence is interpreted to progressively migrate southward leading to onset of inversion in the former CI rift system (Fig. 3E). Ultimately, the entire coupling of Iberia to Europe resulted in the complete migration of the convergent plate boundary between Iberia/Europe and Africa in Miocene in the Betics (Vergés and Fernàndez, 2012).

IMPLICATIONS FOR THE NATURE AND EVOLUTION OF PLATE BOUNDARIES

The architecture and evolution of the IEBP is more complex and polyphase than previously assumed. The interpretation proposed questions the nature of the North Pyrenean fault as being the remnant of a lithospheric-scale structure representing a former transform plate boundary (e.g., Choukroune and Mattauer, 1978) and its age. Instead, we suggest that the left-lateral displacement actually accommodated along this fault should be minimized and we favor a partitioning of transtensional deformation between distinct rift systems (BoBP, CI, and PBC rift systems). The cause of this partitioning of the deformation is not clear and may be due to the Landes High and Ebro block representing pieces of rheologically stronger crust, difficult to thin efficiently (Fig. 2; Tugend et al., 2014). These results provide insights on the partitioning of the deformation at transform to transtensional plate boundary and may represent an analogue to unravel the embryonic stages of the formation of segmented or strongly oblique shear margins observed worldwide.

The Aptian-Albian plate kinematic reorganization resulted in north-south and northeast-southwest divergence between Iberia and Europe. At the scale of the IEPB, the transition from localized sea-floor spreading to the West to a diffuse network of aborted rift systems to the east (PBC) is interpreted as the failed tentative localization of a divergent plate boundary (Figs. 2B and 2C) during the propagation of the North Atlantic Ocean. The subsequent reactivation of the IEPB, strongly controlled by rift-inherited architecture, initiated the formation of a convergent plate boundary. The progressive coupling between the Europe and Iberia resulted in the southward migration of the plate boundary. In spite of it transient nature, the IEPB may bring new insights on the complex partitioning of extensional deformation in propagating rift systems observed at nascent plate boundary and on their subsequent reactivation as observed in South East Asia (e.g., South China Sea; Franke et al., 2013; Savva et al., 2014).

Finally, it appears that pre-breakup deformation related to the formation of hyperextended domains is not negligible for plate restorations in spite of being difficult to quantify. Restorations based on magnetic anomalies alone are likely to misinterpret the amount and/or timing of movements between plates. The IEPB being at the junction between the proto-Atlantic and Tethyian rift systems, its polyphase evolution remains to be fully integrated in the understanding of both the northwards propagation of the Atlantic Ocean and evolution of the Alpine Tethys systems.

ACKNOWLEDGMENTS

We thank J.A. Muñoz, L. Gernigon, and an anonymous referee for constructive reviews, and G. Mohn, E. Masini, D. Frizon de Lamotte, and M. Pubellier for helpful discussions. The authors acknowledge financial support from the MM3 consortium.

REFERENCES CITED

Bronner, A., Sauter, D., Manatschal, G., Péron-Pinvidic, G., and Munschy, M., 2011, Magmatic breakup as an explanation for magnetic anomalies at magma-poor rifted margins: Nature Geoscience, v. 4, p. 549–553, doi:10.1038/ngeo1201.

Burov, E., and Poliakov, A., 2001, Erosion and rheology controls on synrift and postrift evolution: Verifying old and new ideas using a fully coupled numerical model: Journal of Geophysical Research. Solid Earth, v. 106, p. 16461–16481, doi:10.1029/2001JB000433.

Canérot, J., 2008, Les Pyrénées: Histoire Géologique et Itinéraires de Découvertes: Atlantica-BRGM, 643 p.

Capote, R., Muñoz, J.A., Simón, J.L., Liesa, C.L., and Arlegui, L.E., 2002, Alpine tectonics I: The Alpine system north of the Betic Cordillera, *in* Gibbons, W., and Moreno, M.T., eds., The Geology of Spain: Geological Society of London Special Publication, p.367–400.

Choukroune, P., and Mattauer, M., 1978, Tectonique des plaques et Pyrénées: Sur le fonctionnement de la faille transformante nord-pyrénéenne; comparaisons avec des modèles actuels: Bulletin de la Société Géologique de France, v. 7, p. 689–700.

Derégnaucourt, D., and Boillot, G., 1982, Structure géologique du golfe de Gascogne: Bulletin du Bureau de Recherches Géologiques et Minières, v. 2, p. 149–178.

Durand-Delga, M., 1973, Les calpionelles du golfe de Gascogne, témoin de l'ouverture de l'Atlantique nord: Bulletin de la Société Géologique de France, v. 7, p. 22–24.

Franke, D., Savva, D., Pubellier, M., Steuer, S., Mouly, B., Auxietre, J.L., Meresse, F., and Chamot-Rooke, N., 2013, The final rifting evolution in the South China Sea: Marine and Petroleum Geology, doi:10.1016/j.marpetgeo.2013.11.020.

Jammes, S., Lavier, L., and Manatschal, G., 2010, Extreme crustal thinning in the Bay of Biscay and the Western Pyrenees: From observations to modelling: Geochemistry Geophysics Geosystems, v. 11, Q10016, doi:10.1029/2010GC003218.

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

Le Pichon, X., Bonnin, J., Francheteau, J., and Sibuet, J.C., 1971, Une hypothèse d'évolution tectonique du Golfe de Gascogne, *in* Debyser, J., et al., eds, Histoire Structurale du Golfe de Gascogne: Paris, Institut Français du Pétrole, VI.11.1–VI.11.44.

Leroy, M., Gueydan, F., and Dauteuil, O., 2008, Uplift and strength evolution of passive margins inferred from 2-D conductive modelling: Geophysical Journal International, v. 172, p. 464–476, doi:10.1111/j.1365-246X.2007.03566.x.

Lister, G.S., Etheridge, M.A., and Symonds, P.A., 1986, Detachment faulting and the evolution of passive continental margins: Geology, v. 14, p. 246–250, doi:10.1130/0091-7613(1986)14<246:DFATEO>2.0.CO;2.

Lundin, E.R., and Doré, A.G., 2011, Hyperextension, serpentinisation and weakening: A new paradigm for rifted margin compressional deformation: Geology, v. 39, p. 347–350, doi:10.1130/G31499.1.

Martín-Chivelet et al., 2002, Cretaceous, *in* Gibbons, W., and Moreno, M.T., eds., The Geology of Spain: Geological Society of London Special Publication, p.255–292.

Mas, R., Alonso, A., and Guimerà, J., 1993, Evolución tectonosedimentaria de una cuenca extentional intraplaca: La cuenca finijurásica-eocretácica de Los Cameros (La Rioja-Soria): Revista de la Sociedad Geológica de España, v. 6, p. 129–144.

Montadert, L., Roberts, D.G., De Charpal, O., and Guennoc, P., 1979, Rifting and subsidence of the northern continental margin of the Bay of Biscay, *in* Montadert, L., Roberts, D.G., et al., eds., Initial Reports of the Deep Sea Drilling Project, Volume 48: Washington, D.C., US Government Printing Office, p.1025–1060.

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

Reston, T.J., 2009, The structure, evolution and symmetry of the magma-poor rifted margins of the North and Central Atlantic: A synthesis: Tectonophysics, v. 468, p. 6–27, doi:10.1016/j.tecto.2008.09.002.

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

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

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

Salas, R., and Casas, A., 1993, Mesozoic extensional tectonics, stratigraphy and crustal evolution during the Alpine cycle of the eastern Iberian basin: Tectonophysics, v. 228, p. 33–55, doi:10.1016/0040-1951(93)90213-4.

Savva, D., Pubellier, M., Franke, D., Chamot-Rooke, N., Meresse, F., Steuer, S., and Auxietre, J.L., 2014, Different expressions of rifting on the South China Sea margins: Marine and Petroleum Geology, doi:10.1016/j.marpetgeo.2014.05.023.

Schettino, A., and Scotese, C.R., 2002, Global kinematic constraints to the tectonic history of the Mediterranean region and surrounding areas during the Jurassic and Cretaceous, *in* Rosenbaum, G., and Lister, G., eds., Reconstruction of the Evolution of the Alpine-Himalayan Orogen: Journal of the Virtual Explorer 8, p.149–168.

Sibuet, J.C., Srivastava, S.P., and Spakman, W., 2004, Pyrenean orogeny and plate kinematics: Journal of Geophysical Research, v. 109, p. B08104, doi:10.1029/2003JB002514.

Sibuet, J.C., Srivastava, S., and Manatschal, G., 2007, Exhumed mantle-forming transitional crust in the Newfoundland–Iberia rift and associated magnetic anomalies: Journal of Geophysical Research, v. 112, p. B06105, doi:10.1029/2005JB003856.

Tavani, S., and Muñoz, J.A., 2012, Mesozoic rifting in the Basque–Cantabrian Basin (Spain): Inherited faults, transversal structures and stress perturbation: Terra Nova, v. 24, p. 70–76, doi:10.1111/j.1365-3121.2011.01040.x.

Thinon, I., Fidalgo-González, L., Réhault, J.P., and Olivet, J.L., 2001, Pyrenean deformations in the Bay of Biscay: Comptes Rendus de l'Académie des Sciences. Série 2. Sciences de la Terre et des Planètes, v. 332, p. 561–568.

Thinon, I., Matias, L., Réhault, J.P., Hirn, A., Fidalgo-González, L., and Avedik, F., 2003, Deep structure of the Armorican Basin (Bay of Biscay): A review of Norgasis seismic reflection and refraction data: Journal of the Geological Society, v. 160, p. 99–116, doi:10.1144/0016-764901-103.

Tugend, J., Manatschal, G., Kusznir, N.J., Masini, E., Mohn, G., and Thinon, I., 2014, Formation and deformation of hyperextended rift systems: Insights from the mapping of the Bay of Biscay–Pyrenean rift system: Tectonics, doi:10.1002/2014TC003529.

Vergés, J., and Fernàndez, M., 2012, Tethys–Atlantic interaction along the Iberia–Africa plate boundary: The Betic–Rif orogenic system: Tectonophysics, v. 579, p. 144–172, doi:10.1016/j.tecto.2012.08.032.

Vergés, J., and García-Senz, J., 2001, Mesozoic evolution and Cenozoic inversion of the Pyrenean Rift, *in* Ziegler, P.A., et al., eds., Peri-Tethys Memoir 6: Pery-Tethyan Rift/Wrench Basins and Passive Margins: Paris, Mémoires du Muséum National d’Histoire Naturelle, v. 186, p.187–212.

FIGURE CAPTIONS

Figure 1. A: Map of the structural domains forming the Bay of Biscay–Parentis (BoBP), the Pyrenean–Basque–Cantabrian (PBC), and Central–Iberian (CI) rift systems preserved at the transition between the European and Iberian plates (modified after Tugend et al., 2014). B: Deformation history of the different rift systems derived from subsidence and aggradation history (see the Data Repository [see footnote 1] for associated references).

Figure 2. Restoration of the spatial and temporal evolution of the Iberian-European plate boundary (IEPB). A: Initiation of transtensional rifting stage (Late Jurassic); B: Sea-floor spreading initiation and northeast-southwest extension (Aptian–Albian); C: Failed tentative localization of the plate boundary (before Santonian); D: Subduction initiation (Late Cretaceous). C and D modified after Tugend et al. (2014). Same legend as in Figure 1.

Figure 3. Evolution and partitioning of the deformation at the Iberian-European plate boundary (IEPB) during Late Jurassic (A); Aptian-Albian (B); before Santonian (C); Late Cretaceous (D), and Eocene-Oligocene (E).

[1] GSA Data Repository item 2014xxx, xxxxxxxx, is available online at www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

Figure 1

Click here to download high resolution image

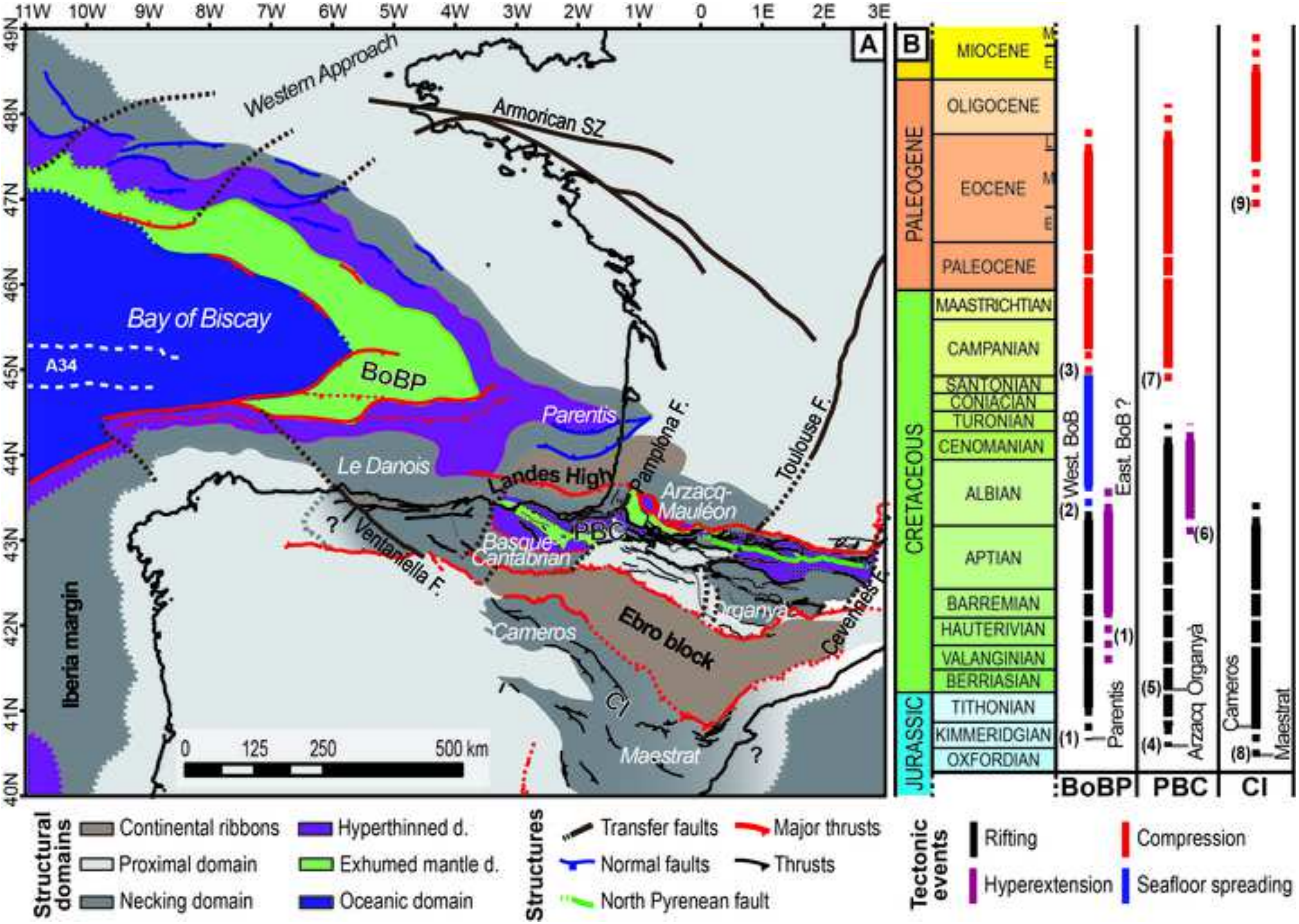


Figure 2

Click here to download high resolution image

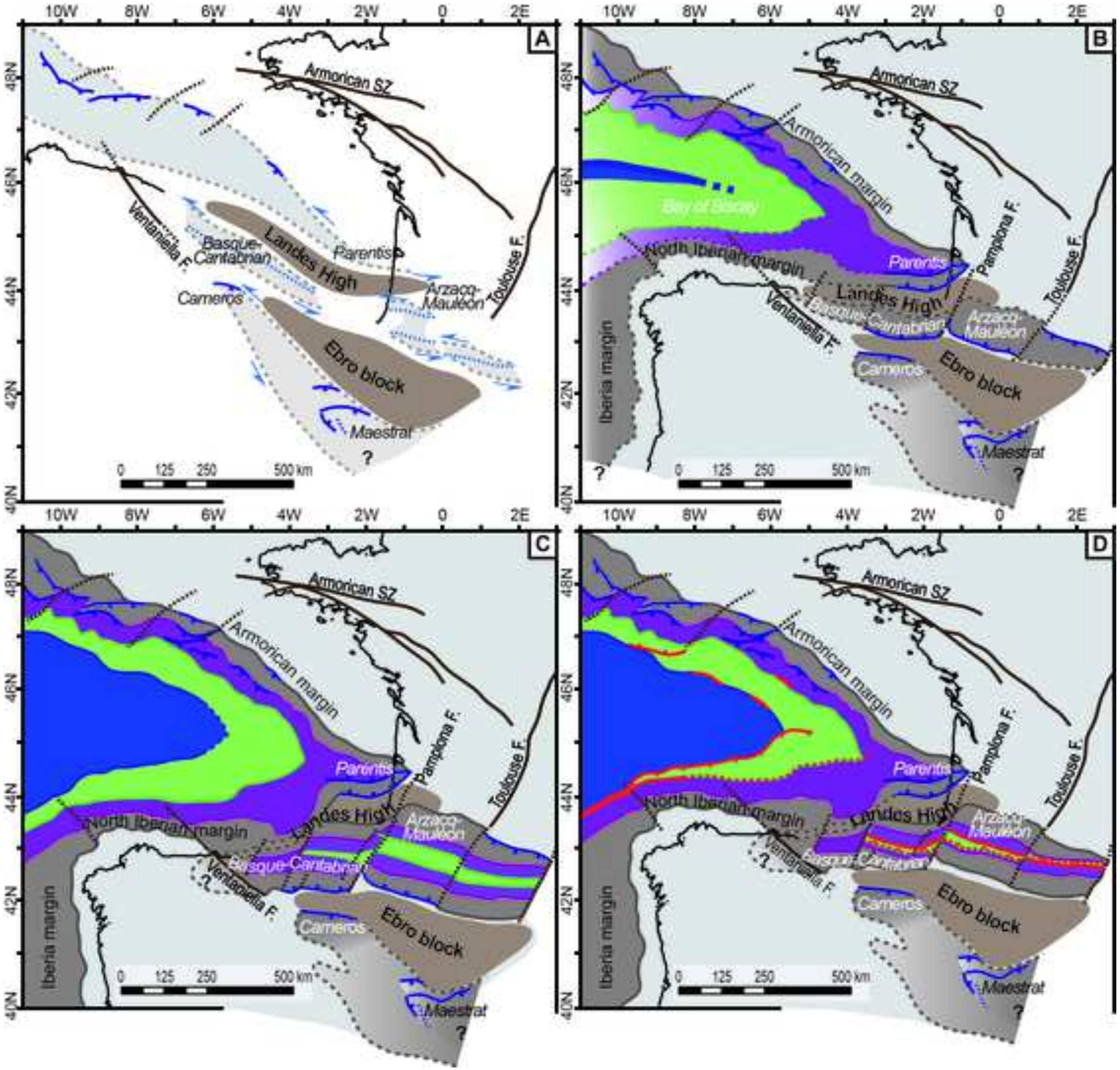
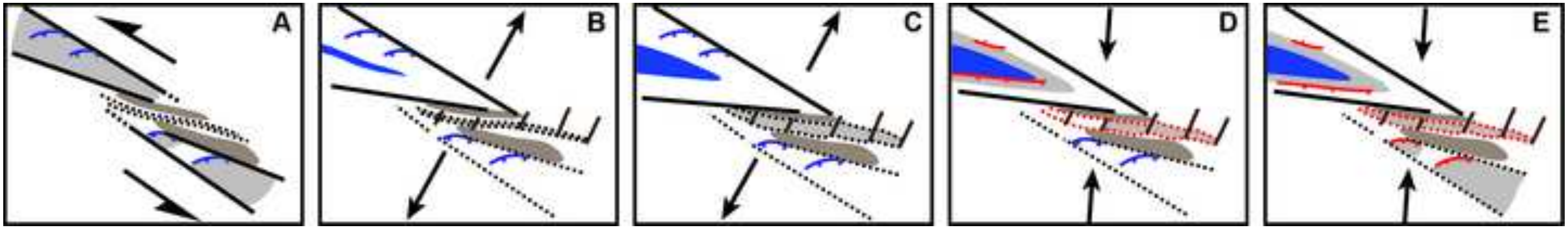


Figure 3

Click here to download high resolution image



Spatial and temporal evolution of hyperextended rift systems: implication for the nature, kinematics and timing of the Iberian–European plate boundary

J. Tugend, G. Manatschal & N. J. Kusznir

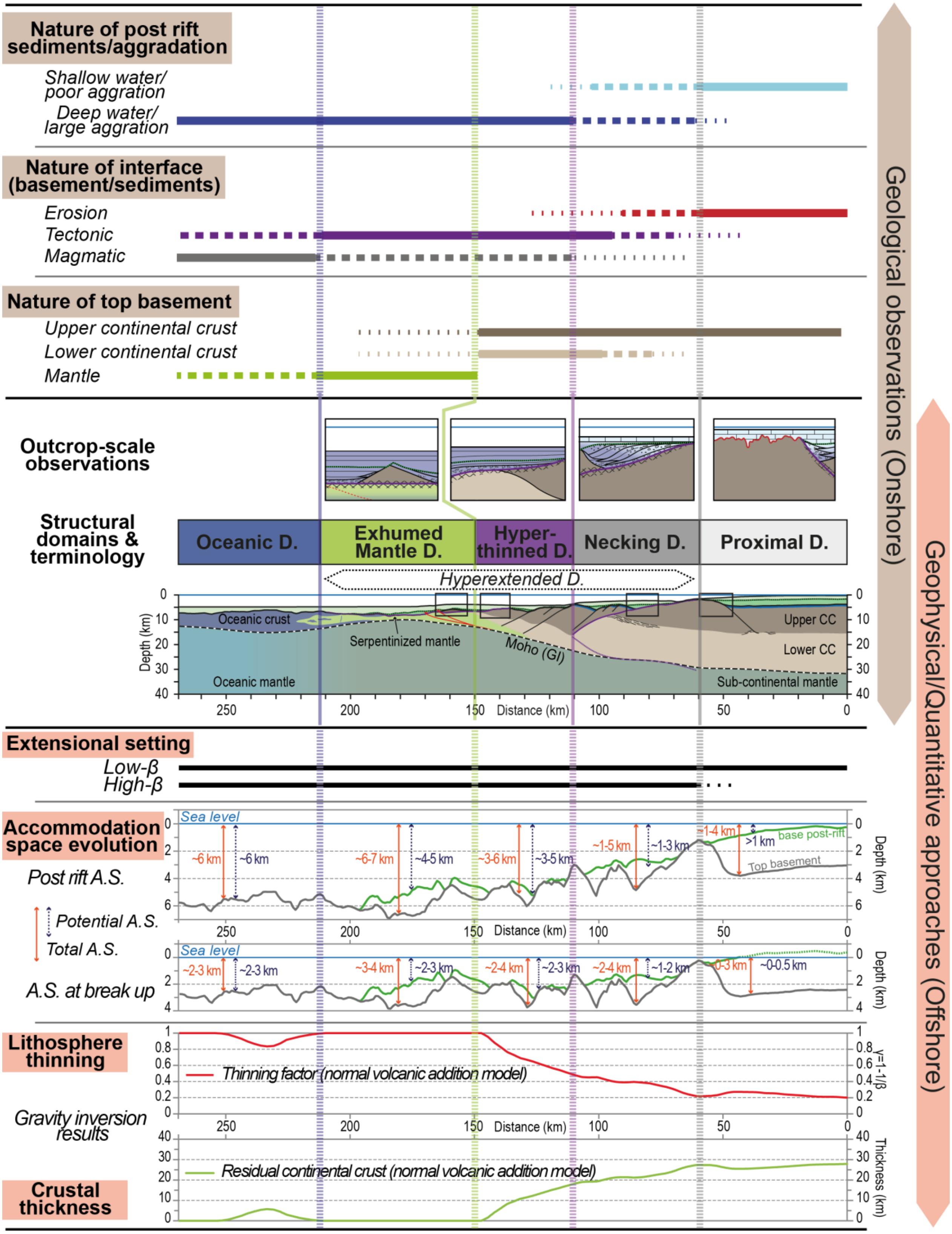
SUPPLEMENTARY METHODS

Mapping rift domains using onshore and offshore observations

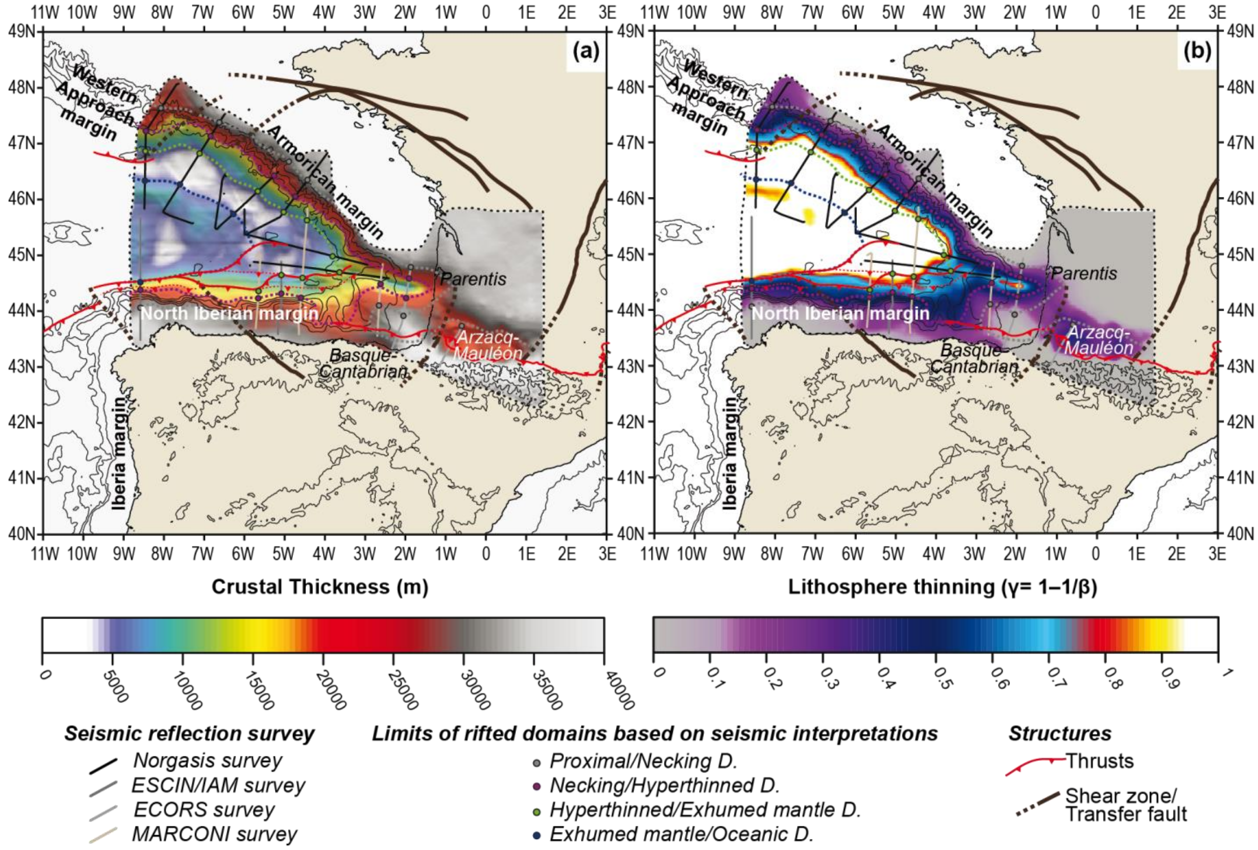
We use the approach developed by Tugend et al., in press enabling the characterization identification and mapping of comparable structural rift domains in present-day magma-poor rifted margins and their fossil analogues preserved in collisional orogens (Supplementary Figure DR1).

Offshore, we use flexural backstripping techniques (Kusznir et al., 1995; Roberts et al., 1998) and gravity inversion (Greenhalgh and Kusznir, 2007; Chappell and Kusznir, 2008; Alvey et al., 2008) to estimate *accommodation space*, *crustal thickness* and *lithosphere thinning* (Supplementary Figure DR2) while seismic interpretation enables the recognition of *extensional settings* (low- and high-β settings; Wilson et al., 2001). Onshore mapping relies on observations from remnants of the rift system preserved within well-defined compressive tectonic units on the *aggradation history*, on the *nature of basement rocks* and *sediments*, and of *their interface*. Based on this qualitative and quantitative characterisation, we distinguish geophysical and geological diagnostic elements to identify five structural rift domains at magma-poor rifted margins and their fossil analogues: the proximal, necking, hyperthinned, exhumed mantle and oceanic domains (Supplementary Figure DR1, comparison with other terminologies in Tugend et al., in press, Fig.1).

This geological/geophysical approach can be used as an interface between onshore and offshore observations. For the interpretation of offshore seismic sections, geological insights on rift structures and on the nature of sediment and basement can be suggested based on onshore analogies. The large scale geometry and stratigraphic architecture imaged offshore may be used to restore onshore fossil remnants back into a rifted margin context. This combined approach has been applied to map the spatial distribution of the rift systems preserved at the Iberian-European plate boundary (Tugend et al., 2014).



***Supplementary Figure DR1**: Terminology and geological/geophysical diagnostic elements enabling the characterization of rift domains (modified after Tugend et al., in press).*



Supplementary Figure DR2: (a) *Crustal thickness and (b) Lithosphere thinning maps determined from gravity inversion (same parameters as Tugend et al., 2014). The limit of rift domains is indicated (after Tugend et al., 2014). Seismic surveys used for offshore mapping are also indicated.*

DATA & REFERENCES FOR RIFT BASIN SUBSIDENCE AND DEFORMATION HISTORY:

***Supplementary Table DR1*:** Subsidence and deformation history of rift basins. BoBP: Bay of Biscay-Parentis; PBC: Pyrenean-Basque-Cantabrian; CI: Central Iberian

Label in Fig.1	Rift system	References
1	BoBP (*Parentis*)	Brunet, (1994)
2	BoBP	Montadert et al., (1979)
	BoBP	Boillot, 1984
3	BoBP	Thinon et al., (2001)
4	PBC (*Arzacq*)	Désegaulx and Brunet, (1990)
5	PBC (*Organyà*)	Martin-Chivelet et al., (2002)
6	PBC (*Basque-Cantabrian*)	Garcia-Mondejar et al., (1996; 2005)
	PBC (*Pyrenean basins*)	Debroas et al., (1987; 1990)
7	PBC	Garrido-Megias and Rios, (1972)
	PBC	McClay et al., (2004)
8	CI (*Maestrat/Cameros*)	Salas et al., (2001)
	CI (*Maestrat/Cameros*)	Salas and Casas, (1993)
	CI (*Maestrat/Cameros*)	Capote, Muñoz, Simon et al., (2002)
9	CI	Salas et al., (2001)
	CI	Capote, Muñoz, Simon et al., (2002)

REFERENCES

Alvey, A., Gaina, C., Kusznir, N. J., and Torsvik, T. H., 2008, Integrated crustal thickness mapping and plate reconstructions for the high Arctic: Earth and Planetary Science Letters, v.274, p.310–321.

Boillot, G., 1984, Le Golfe de Gascogne et les Pyrénées, *in*, Boillot, G., Montadert, M., Lemoine, M., and Biju-Duval, B., eds, Les marges continentales actuelles et fossiles autour de la France, Masson, Paris, p.5–81.

Brunet, M. F., 1994, Subsidence in the Parentis Basin (Aquitaine, France): Implications of the Thermal Evolution, ed, *in* Mascle, A., Hydrocarbon and Petroleum Geology of France: Special Publication of the European Association of Petroleum Geoscientists, Volume 4, p.187–198.

Capote, R., Muñoz, J. A., Simón, J. L., Liesa, C. L., and Arlegui, L. E., 2002, Alpine tectonics I: the Alpine system north of the Betic Cordillera, *in* Gibbons, W., and Moreno, M. T., eds, The geology of Spain: Geological Society, London, Special Publication, p.367–400.

Chappell, A.R., and Kusznir, N.J., 2008, Three-dimensional gravity inversion for Moho depth at rifted continental margins incorporating a lithosphere thermal gravity anomaly correction: Geophysical Journal International, v.174, p.1–13, doi: 10.1111/j.1365-246X.2008.03803.x.

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

Debroas, E. J., 1990, Le flysch noir albo-cénomanien témoin de la structuration albienne à sénonienne de la Zone nord-pyrénéenne en Bigorre (Hautes-Pyrénées, France): Bulletin de la société Géologique de France, v.8, p.273–285.

Désegaulx, P., and Brunet, M-F., 1990, Tectonic subsidence of the Aquitaine basin since Cretaceous times: Bulletin de la Société géologique de France, v.6, p.295–305.

García-Mondéjar, J., Agirrezabala, L. M., Aranburu, A., Fernández-Mendiola, P. A., Gómez-Pérez, I., López-Horgue, M., and, Rosales, I., 1996, Aptian–Albian tectonic pattern of the Basque–Cantabrian Basin (Northern Spain): Geological Journal, v.31, p.13–45.

García-Mondéjar, J., López-Horgue, M. A., Aranburu, A., and Fernández-Mendiola, P. A., 2005, Pulsating subsidence during a rift episode: stratigraphic and tectonic consequences (Aptian–Albian, northern Spain): Terra Nova, v.17, p.517–525.

Garrido- Megías, A., and Ríos, L. M., 1972, Síntesis geologica del Secundario y Terciario entre los ríos Cinca y Segre (Pirineo Central de la vertiente surpirenaica, provincias de Huesca y Lerida): Boletín Geológico y Minero, v.83, p.1–47.

Greenhalgh, E. E., and Kusznir, N. J., 2007, Evidence for thin oceanic crust on the extinct Aegir Ridge, Norwegian Basin, NE atlantic derived from satellite gravity inversion: Geophysical Research Letters, v.34, L06305, doi:10.1029/2007GL029440.

Kusznir, N. J., Roberts, A. M., and Morley, C. K., 1995, Forward and reverse modelling of rift basin formation, *in*, Lambiase, J., ed., Hydrocarbon Habitat in Rift Basins, Geological Society, London, Special Publications, v.80, p.33–56.

Martín-Chivelet, J., Berástegui, X., Rosales, I., et al., 2002, Cretaceous, *in*: Gibbons, W. & Moreno, M. T., eds, The geology of Spain: Geological Society, London, Special Publication, p.255–292.

McClay, K., Munoz, J. A., and García-Senz J., 2004, Extensional salt tectonics in a contractional orogen: A newly identified tectonic event in the Spanish Pyrenees: Geology, v.32, p.737–740.

Montadert, L., Roberts, D.G., De Charpal, O., and Guennoc, P., 1979, Rifting and subsidence of the northern continental margin of the Bay of Biscay, *in*: Montadert, L., Roberts, D.G., et al., eds, Initial Reports of the Deep Sea Drilling Project, Volume 48: Washington, DC, US Government Printing Office, p.1025–1060.

Roberts, A. M., Kusznir, N. J., Yielding, G., and Styles, P., 1998, 2D flexural backstripping of extensional basins; the need for a sideways glance: Petroleum Geoscience, v.4, p.327–338.

Salas, R., and Casas, A., 1993, Mesozoic extensional tectonics, stratigraphy and crustal evolution during the Alpine cycle of the eastern Iberian basin: Tectonophysics, v.228, p.33–35.

Salas, R., Guimerá, J., Mas, R., Martín-Closas, C., Meléndez, A., and Alonso, A., 2001, Evolution of the Mesozoic Central Iberian Rift System and its Cenozoic inversion (Iberian chain), in: Ziegler, P. A., Cavazza, W., Robertson, A. H. F., and Crasquin-Soleau, S., eds, Peri-Tethys Memoir 6: Pery-Tethyan Rift/Wrench Basins and Passive Margins: Mémoires du Muséum National d'Histoire Naturelle, Paris, Volume 186, p.145–185.

Thinon, I., Fidalgo-González, L., Réhault, J. P. and Olivet, J. L., 2001, Pyrenean deformations in the Bay of Biscay: Comptes Rendus de l'Académie des Sciences, Série IIa, v.332, p.561–568.

Tugend, J., G. Manatschal, N. J. Kusznir, and E. Masini, 2015, Characterizing and identifying structural domains at rifted continental margins and its western pyrenean fossil remnants, in Sedimentary Basins and Crustal Processes at Continental Margins: From Modern Hyper-extended Margins to Deformed Ancient Analogues, Gibson, G., Roure F., and Manatschal G., Geological Society of London, Special Publications, v. 413, http://dx.doi.org/10.1144/SP413.3.

Tugend, J. Manatschal, G., Kusznir, N. J., Masini, E., Mohn, G., and Thinon, I., 2014 Formation and deformation of hyperextended rift systems: Insights from the mapping of the Bay of Biscay–Pyrenean rift system: Tectonics, v. 33, p.239–1276, doi: 10.1002/2014TC003529

Wilson, R. C. L, Manatschal, G., and Wise S., 2001, Rifting along non-volcanic passive margins: Stratigraphic and seismic evidence from the Mesozoic successions of the Alps and Western Iberia, Geological Society Special Publications, London, v.187, p.429–452.