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Evolution of the Alpine orogenic belts in the Western Mediterranean region as resolved by the kinematics of the Europe-Africa diffuse plate boundary

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Abstract – The West European collisional Alpine belts are the result of the inversion, initiated in the middle Cretaceous, of the complex western Neotethys and the Atlantic continental rift domains and closure of remnants of Tethys between the North Africa and European cratons. While the kinematics of Africa relative to Europe is well understood, the kinematics of microplates such as Iberia and Adria within the diffuse collisional plate boundary is still a matter of debate. We review geological and stratigraphic constraints in the peri-Iberia fold-thrust belts and basins to define the deformation history and crustal segmentation of the West European realm. These data are then implemented with other constraints from recently published kinematic and paleogeographic reconstructions to propose a new regional tectonic and kinematic model for Western Europe from the late Permian to recent times. Our model suggests that the pre-collisional extension between Europe and Africa plates was distributed and oblique, hence building discontinuous rift segments between the southern Alpine Tethys and the Central Atlantic. They were characterised by variably extended crust and narrow oceanic domains segmented across transfer structures and micro-continental blocks. The main tectonic structures inherited from the late Variscan orogeny localized deformation associated with rifting and orogenic belts. We show that continental blocks, including the Ebro-Sardinia-Corsica block, have been key in accommodating strike-slip, extension, and contraction in both Iberia and Adria. The definition of a new Ebro-Sardinia-Corsica block allows refining the tectonic relationships between Iberia, Europe and Adria in the Alps. By the Paleogene, the convergence of Africa closed the spatially distributed oceanic domains, except for the Ionian basin. From this time onwards, collision spread over the different continental blocks from Africa to Europe. The area was eventually affected by the West European Rift, in the late Eocene, which may have controlled the opening of the West Mediterranean. The low convergence associated with the collisional evolution of Western Europe permits to resolve the control of the inherited crustal architecture on the distribution of strain in the collision zone, that is otherwise lost in more mature collisional domain such as the Himalaya.

Keywords: Africa-Europe diffuse plate boundary / kinematic reconstructions / tectonic inheritance / crustal segmentation / Alpine orogenic belt / Western Mediterranean

Résumé – Reconstruction cinématique de la limite de plaque diffuse Europe-Afrique pour étudier l'évolution de la ceinture orogénique Alpine en Méditerranée occidentale. Les ceintures orogéniques alpines d'Europe occidentale sont le résultat de l'inversion, initiée au Crétacé moyen, de l'Océan Néotéthys occidental et des domaines du rift continental atlantique et de la fermeture des reliquats océaniques de la Téthys entre l'Afrique du Nord et les cratons européens. Si la cinématique de l'Afrique par rapport à l'Europe est bien comprise, celles de microplaques telles que Iberia et Adria, à l'intérieur de la limite de plaque, est encore débattue. Nous examinons les contraintes géologiques et stratigraphiques dans les ceintures orogéniques et les bassins péri-ibériques afin de définir l'histoire de la déformation et la segmentation crustale du domaine européen occidentale. Ces données sont ensuite intégrées avec d'autres contraintes issues de reconstructions cinématiques et paléogéographiques récemment publiées afin de proposer un nouveau modèle tectonique et cinématique régional de l'Europe occidentale, de la fin du Permien à l'actuel. Notre modèle montre que l'extension pré-collisionnelle entre la plaque Europe et la

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plaque Afrique était distribuée et oblique, à l'origine de segments de rift discontinus entre la partie sud de la Téthys Alpine et l'Atlantique Central. Ces rifts étaient caractérisés par une croûte variablement amincie et des domaines océaniques étroits segmentés à travers des structures de transfert et des micro-continents. Les principales structures tectoniques héritées tardi-varisques ont localisé les domaines d'amincissement et les orogènes. Nous montrons que plusieurs blocs continentaux, y compris le bloc Ebre-Sardaigne-Corse, ont joué un rôle clé dans l'accommodation des mouvements décrochants, de l'extension et de la convergence de l'Ibérie et d'Adria. De plus, nous montrons que l'existence de ce bloc permet d'affiner la relation tectonique entre l'Ibérie, l'Europe et domaine adriatique septentrional dans les Alpes. Au Paléogène, la convergence de l'Afrique referme les domaines océaniques à l'exception du bassin ionien. À partir de ce moment, la collision implique les différents blocs continentaux, permettant un transfert efficace de la déformation de l'Afrique vers l'Europe. La zone a finalement été affectée par le Rift Ouest Européen, à la fin de l'Eocène, qui a en partie contrôlé l'ouverture de la Méditerranée occidentale. La faible convergence associée à l'évolution orogénique de l'Europe occidentale permet de mieux comprendre le contrôle de l'architecture crustale héritée sur la distribution de la déformation dans la zone de collision, qui est autrement mal défini dans des domaines de collision plus matures tels que l'Himalaya.

Mots clés : limite de plaque diffuse Afrique-Europe / reconstructions cinématiques / héritage tectonique / segmentation crustale / ceinture orogénique alpine / Méditerranée occidentale

1 Introduction

The evolution of the Alpine orogenic belts in the Mediterranean region is understood to result from the accretion, subduction and back-arc extension of fragmented continents or microplates, inherited from the Tethys opening, between Africa and Europe (*e.g.*, Dewey *et al.*, 1973). Tectonic reconstructions of the Alpine collision have attempted to resolve the evolution of tectonic boundaries around two main continental microplates (*i.e.*, Adria and Iberia), assuming that the large-scale kinematics of Africa relative to Europe is reasonably understood (Handy *et al.*, 2010; van Hinsbergen *et al.*, 2020). Controversies on the exact kinematics of Adria and Iberia lead to a different number, size and position of continental blocks and oceanic domains, hence questioning the drivers of the orogenic evolution. The current issues are further challenged by the dismantlement of the initial Alpine orogenic system during the opening of the Western Mediterranean region for which slab dynamics has been well emphasized (Jolivet and Faccenna, 2000; Faccenna *et al.*, 2014).

Only recently, Iberia has been the focus of a number of studies, solving some important issues regarding the timing and amount of extension and strike-slip evolution of the plate boundary between Iberia and Europe. Specifically, the kinematics of Iberia has been subjected to a long lasting debate about the reliability of magnetic anomalies in the North Atlantic and geological evidence in the Pyrenees (Vissers and Meijer, 2012; Barnett-Moore *et al.*, 2016; Nirrengarten *et al.*, 2017). But a consensus has since emerged that the eastward movement of Iberia should be explained by strike-slip and transtension in the interior of the Iberian plate, leading to define an Ebro block. Evidence for an individual Ebro continental block has been shown for decades (Salas and Casas, 1993; Arche and López Gómez, 1996) but the intra-plate segmentation has only recently been considered in geodynamic models (Tugend *et al.*, 2015; Tavani *et al.*, 2018) and plate reconstructions (Nirrengarten *et al.*, 2018; Angrand *et al.*, 2020). These recent models have fundamental implications for the Iberia-Europe boundary, as they argue for the distribution of the left-lateral movement from the late Paleozoic to Early Cretaceous, along the Europe-Iberia plate boundary across two tectonic corridors, in the Pyrenean and Iberian rift-basins. To the south, the Iberia-Africa relative motion has been accommodated along the complex Gibraltar transform zone, which includes the Betic-Rif orogen and north African basins (Sallarès *et al.*, 2011; Schettino and Turco, 2011; Frizon De Lamotte *et al.*, 2015; Daudet *et al.*, 2020). The impact for the reconstruction of the plate boundary between Africa and Europe and farther into the Alpine Tethys and Europe/Adria plate boundary has only been recently tested for the period ranging from the Permian-Triassic to the Early Cretaceous (Angrand *et al.*, 2020).

The present-day configuration of the orogenic system between the European and African plates (Fig. 1a) is characterized by narrow mountain ranges separating small continental blocks or micro-plates that have accommodated both extension/transtension and compression/transpression since the late Paleozoic (Fig. 1b; Angrand *et al.*, 2020). For instance, the deformation between stable Europe and segmented Iberia has been distributed along several orogenic segments: the Pyrenees, which can be extended to the Provence in SE France, between Europe and Ebro (Mouthereau *et al.,* 2014; Teixell *et al.*, 2018; Espurt *et al.*, 2019a), the Basque-Cantabrian Basin between Galicia (West Iberia) and the Bay of Biscay (Cámara, 2017; García-Senz *et al.*, 2019), and the intra-Iberian basins, now inverted in the Iberian Range between South Iberia and Ebro (Aldega *et al.*, 2019; Rat *et al.*, 2019).

In this study, we aim to expand the recently published Angrand *et al.* (2020) model of the Western Tethys–North Atlantic kinematics, which focused on the late Permian-Triassic geodynamics to the middle Cretaceous. We integrate results from recently published studies of the OROGEN project, coupled with geological, geophysical, and stratigraphic data compiled from the literature in order to build a regional geodynamic and kinematic model of the Mediterranean region, accounting for the Atlantic and Alpine Tethys evolution, from the late Permian to Neogene.

Our manuscript is organized as follow. We first review geological constraints on the tectonic evolution of the complex Europe-Africa plate boundary, from SE France-Gulf of Lion to the Basque-Cantabrian-Pyrenees, Iberian Range-Central

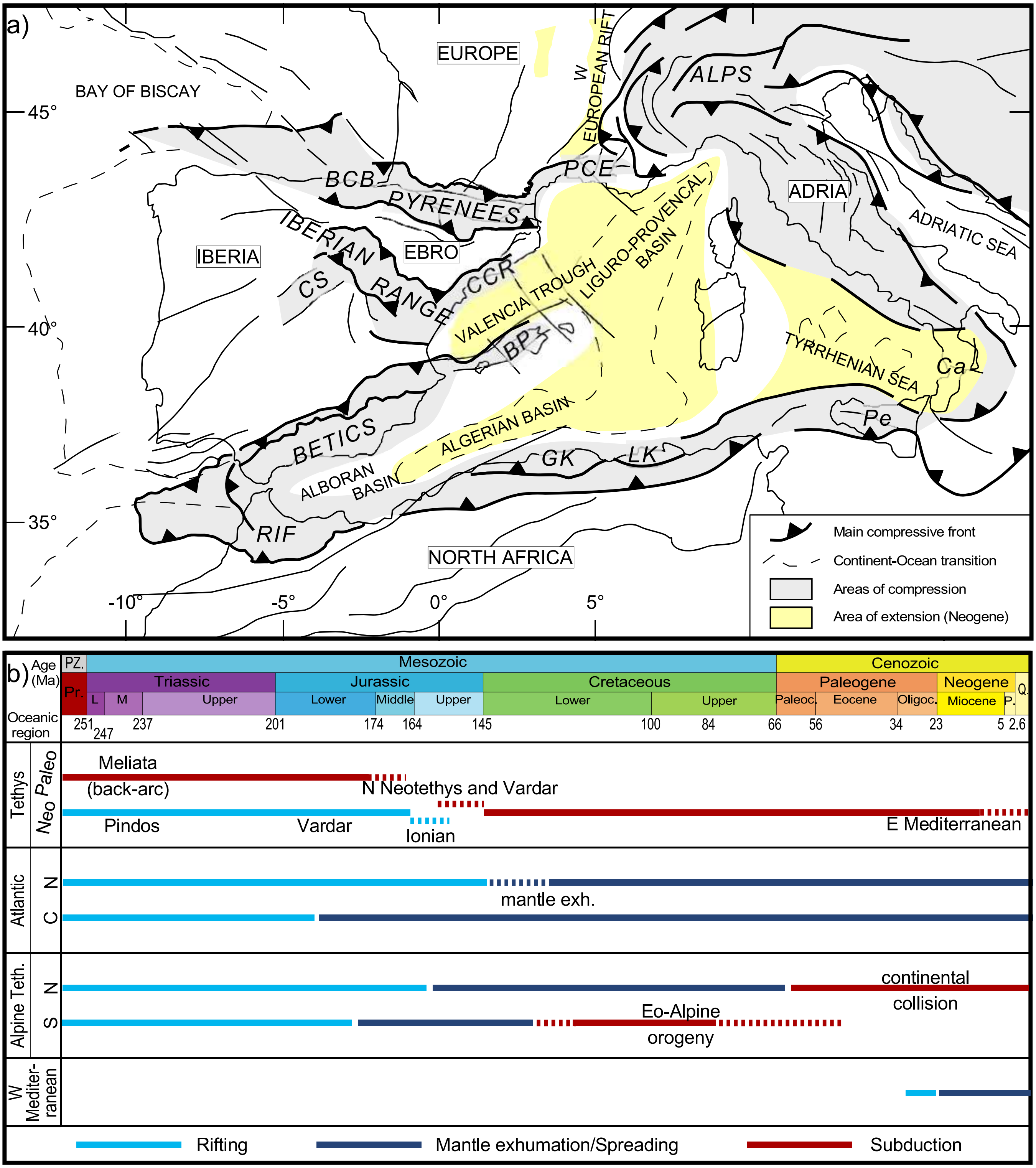

Fig. 1. (a) Structural map of the West Mediterranean showing the main tectonic plates and deformed areas. Grey: areas deformed during Alpine compression. Yellow: area deformed during Neogene extension (West European Rift and opening of the Liguro-Provençal oceanic basin). BCB: Basque-Cantabrian Basin; BP: Balearic Promontory; Ca: Calabria; CCR: Catalan Coastal Range; CS: Central System; GK: Greater Kabylies; LK: Lesser Kabylies; PCE: Provence; Pe: Peloritan. (b) Geodynamic chart of oceanic domains in the West Mediterranean (W Tethys and N Atlantic) domain since the Permian. Light blue: rifting; dark blue: mantle exhumation/spreading; red: subduction.

System, and the Betics-Alboran domain (Sects. 2 and 3). Considering the size of the area studied and the time span covered by our reconstruction, this first part is inevitably long. Using these geological constraints, we present the crustal segmentation of the West European realm, which is crucial for defining the continental plate geometry of our kinematic reconstruction (Sect. 4). Then, we present the method and the results of our kinematic reconstruction that are shown into successive key time frames (Sect. 5). The outputs of our model is then presented in terms of N-S strain distribution during the Late Mesozoic-Cenozoic (Sect. 6). Finally, we discuss several important, yet unanswered questions, regarding the kinematics of the Africa-Europe plate boundary that can be solved in Iberia (Sect. 7) such as: 1) how the late Variscan shear zones were reactivated both in extension and compression and explain first-order features of the kinematic framework; 2) what are the implications of the Ebro block kinematics on the tectonic evolution of Sardinia-Corsica, and its connection to the Provence and Briançonnais in the Alps (northern Europe/Iberia/Adria plate boundaries), and 3) how the fragmentation of Iberia controlled the tectonic evolution of AlKaPeCa terranes in the south (southern Africa/Iberia/Adria plate boundaries) and the opening of the Western Mediterranean.

2 Evolution of the Europe-Africa plate boundary since the Late Paleozoic

The post-Variscan geodynamic evolution of western Europe and northern Africa in the Carboniferous-Permian coincided, or slightly predated, the opening of the Neotethys in Permian-Triassic times (Fig. 1b) (Ziegler, 1989, 1990b; Stampfli *et al.*, 2001; Stampfli and Borel, 2002; Schettino and Turco, 2011; Angrand *et al.*, 2020). Permian crustal thinning and magmatism associated with the break-up of Pangea are recognized throughout Europe, including the Oslo Rift, North Sea and the German Permian Basin (Neumann *et al.*, 1992; Van Wees *et al.*, 2000; Glennie *et al.*, 2003; Heeremans *et al.*, 2004; Upton *et al.*, 2004), Massif Central (Bruguier *et al.*, 2003), the Alps and Corsica (Rossi *et al.*, 2009; Cassinis *et al.*, 2012; Ballèvre *et al.*, 2014), the Pyrenees (Vissers, 1992; Denèle *et al.*, 2012; Gretter *et al.*, 2015; Rodríguez-Méndez *et al.*, 2016; Espurt *et al.*, 2019b; Saspiturry *et al.*, 2019) and the peri-Iberian rift basins (Arche and López Gómez, 1996; López-Gómez *et al.*, 2019; Angrand *et al.*, 2020 and references therein) (Fig. 2). The tectonic control of the Tethyan continental rifting by the late Variscan evolution is argued by Permian-Triassic depocentres that are superposed onto older Variscan structures.

The Atlantic opening was preceded by the Late Triassic-Early Jurassic (~ 201 Ma) Central Atlantic magmatic event (CAMP, Central Atlantic Magmatic Province) (Olsen, 1997; Marzoli *et al.*, 1999; McHone, 2000; Peace *et al.*, 2019a), whose relationship with the geodynamic evolution of western Europe has been recently discussed by Peace *et al.* (2019a) and Angrand *et al.* (2020). The extension in the Central Atlantic between North America and Africa started in the Triassic (Leleu *et al.*, 2016), while the breakup and onset of oceanic spreading is commonly considered to have occurred in the Early Jurassic (190 Ma) (Figs. 1b and 2) (Schettino and Turco, 2009; Labails *et al.*, 2010).

In the Lower Jurassic, the Alpine Tethys Ocean opened between Iberia/Europe and Adria/Africa (Figs. 1b and 2) (Puga *et al.*, 2011; Schettino and Turco, 2011; Le Breton *et al.*, 2021). Recent reconstructions in the Betics considered a hyper-extended domain rather than an oceanic crust (Vergés and Fernàndez, 2012; Daudet *et al.*, 2020; Pedrera *et al.*, 2020b). The recognition of MORB-type gabbro dated at 180 Ma in the internal zones of the eastern Betics (Puga *et al.*, 2011) supports the continuation of the Alpine Tethys in the east (named Betic Tethys, Ligurian Tethys, Nevado-Filabrides Ocean, etc.) or a thinned continental crust at the Ocean-Continent transition (Gómez-Pugnaire *et al.*, 2000). However, the precise geometry of the southwestern termination of the Alpine Tethys is debated. Discussions include whether the Alpine Tethys was made of a single or a double branch (*e.g.*, Western and Eastern Ligurian Tethys) of true oceanic to hyper-extended continental crust with variable degree of rifting (see review in Guerrera *et al.*, 2019).

After a phase of stalling in the Lower Jurassic, extension resumed in the southern North Atlantic and the ridge migrated northward during the Upper Jurassic/Lower Cretaceous (see Barnett-Moore *et al.*, 2016; Nirrengarten *et al.*, 2018, for recent review and kinematic models). The E-W extension between Iberia and North America produced strike-slip movement that must be accommodated along the Iberia-Europe plate boundary. The North Atlantic ridge migration then resumed in the Aptian-late Cenomanian and opened the Bay of Biscay at high angle to the Atlantic ridge axis, resulting in the rotation of Iberia. The kinematics of Iberia has long been a matter of debate because of its implications for reconstruction of the Tethys domain. Controversies originally dealt with as to whether the "J" anomaly should be viewed or not as an M0 magnetic anomaly (~ 120 Ma). The J anomaly is indeed interpreted to reflect magmatic pulses on the Atlantic hyper-extended margin of Iberia instead of a true oceanic anomaly (Bronner *et al.*, 2011; Nirrengarten *et al.*, 2017). Two end-member models have been proposed. Reconstructions that do not consider, or only partially, the J anomaly all reproduce extension in the North Pyrenean Rift, but differ according to the timing and amount of strike-slip partitioned with N-S/NE-SW orthogonal extension along the Iberia-Europe plate boundary (Olivet, 1996; Jammes *et al.*, 2009; Tugend *et al.*, 2014a; Nirrengarten *et al.*, 2018; Angrand *et al.*, 2020). Other restorations that fit the J anomaly imply a 500 km convergence, closing a Jurassic "Tethyan" ocean or hyper-extended margin between Iberia and Europe during the Cretaceous (Srivastava *et al.*, 2000; Sibuet *et al.*, 2004; Vissers and Meijer, 2012). Geological implications of this scenario for the Pyrenees, such as the emplacement of a large basin in the Jurassic and the development of a Cretaceous accretionary prism, are not supported by geological observations. The recent reconstructions by Angrand *et al.* (2020) emphasize the key role played by the Ebro block between Iberian and Europe. Accounting for the Ebro block indeed allows transfer of deformation from the Atlantic to the Tethys domain by accommodating the required eastward translation to South Iberia. This allows minimizing strike-slip Cretaceous deformation in the Pyrenean rift, while keeping a dominant orthogonal extension during the opening of the Bay of Biscay.

The counter-clockwise rotation of Africa that resulted from the opening of the Central Atlantic in the Early Jurassic caused

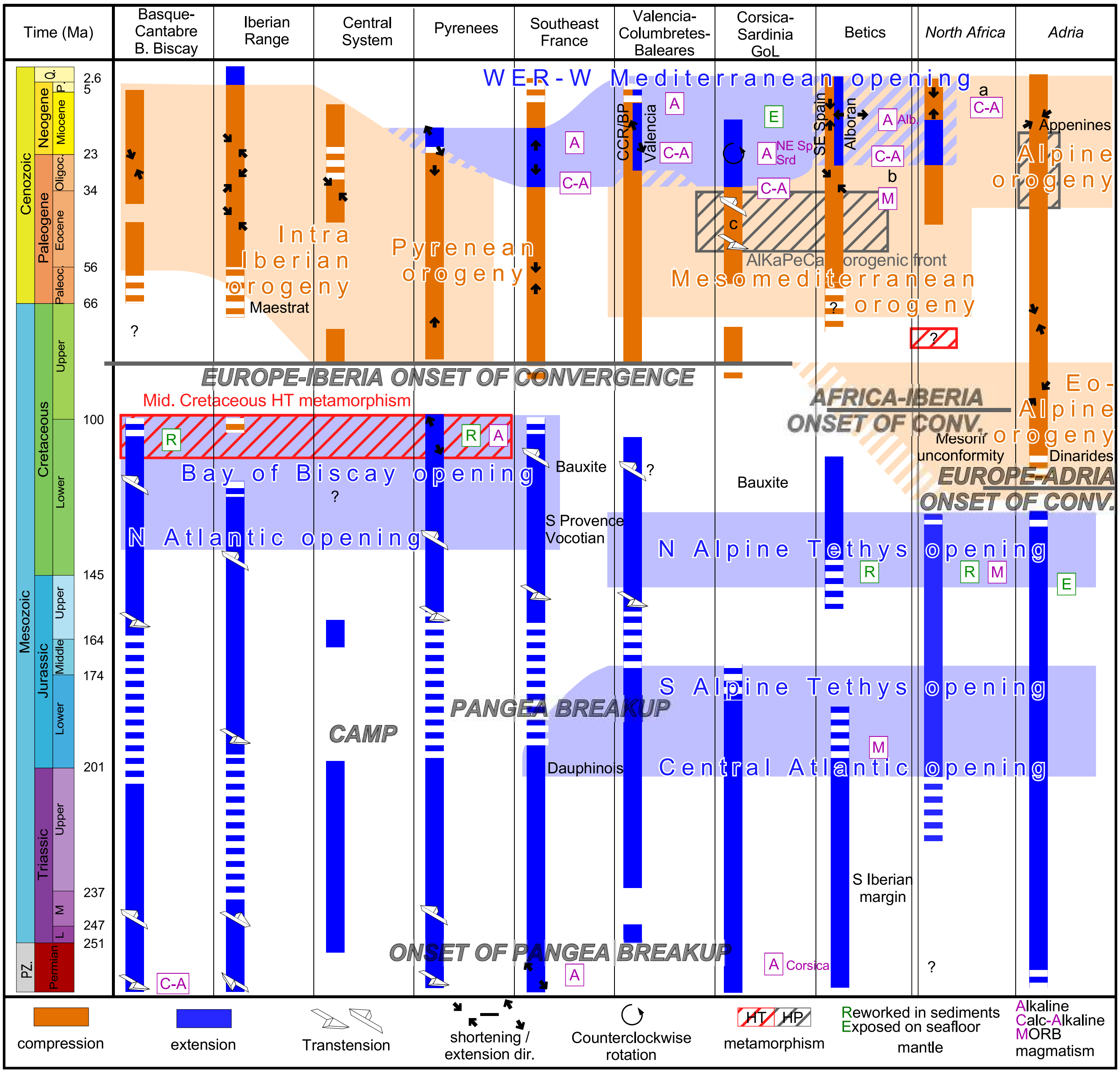

Fig. 2. Geodynamic chart of the West European rifted basins and orogens since the Permian. Blue: extension; orange: compression. Note that North Africa and Adria are simplified as they both represent larger domains than the other columns. BP: Balearic Promontory; CCR: Catalan Coastal Range; WER: West European Rift. See Sections 2 and 3 for appropriate references used in the construction of each geodynamic column.

the closure of the Neotethys and peripheral oceanic basins in eastern Europe such as the Meliata and Pindos oceans (Fig. 1b) (Schmid *et al.*, 2008; van Hinsbergen *et al.*, 2020). By Late Jurassic-Early Cretaceous times the propagation of the southern North Atlantic northwards eventually opened the Bay of Biscay in the late Aptian. The eastward movement of Iberia in turn caused the initiation of convergence in the Alpine Tethys domain (Angrand *et al.*, 2020) at the origin of Eo-Alpine deformation (Handy *et al.*, 2010, 2015). However, the exact implications on the kinematics of the continental blocks surrounding the Alpine Tethys between Europe, Iberia, Ebro and Adria are not well understood.

In Europe, the onset of Africa-Europe convergence in Late Cretaceous times is recorded from Morocco to Central Europe (*e.g.*, Kley and Voigt, 2008). This episode of early contraction is recorded by the stratigraphic record in the Pyrenees and Provence (Fig. 2) (Puigdefàbregas and Souquet, 1986; Beaumont *et al.*, 2000; Vergés *et al.*, 2002; Christophoul *et al.*, 2003; Espurt *et al.*, 2012; Bestani *et al.*, 2016; Ford *et al.*, 2016; Rougier *et al.*, 2016; Angrand *et al.*, 2018). It is followed by widespread contraction inboard Iberia from the Paleogene onward (Fig. 2), for instance, in the Betic Cordillera (Platt and Vissers, 1989; Daudet *et al.*, 2020) and the Iberian Range (*e.g.*, Rat *et al.*, 2019). In the Alps, early deformation is recorded during the Eocene, reaching its climax during the Oligocene-Miocene (Fig. 2) (Ford and Lickorish, 2004; Handy *et al.*, 2010).

The opening of N-S West European Rift in the late Eocene (~ Priabonian, 34 Ma), parallel to the direction of the regional contraction between Europe and Africa (Bois, 1993; Séranne, 1999; Dèzes *et al.*, 2004), marks a change in the internal dynamics of both the Pyrenean and the Alpine orogenic systems. As the West European Rift progresses southward it was eventually accompanied by, or even promoted opening of the Gulf of Lion (Fig. 2). However, no clear genetic affinity between the West European Rift and the West Mediterranean is yet established. At ~ 30 Ma, slab rollback-related extension in the Western Mediterranean opens the Gulf of Lion and Valencia basins, followed by extension in the Liguro-Provençal, Alboran (23–20 Ma) and Tyrrhenian basins (~ 15 Ma) (Fig. 2) (Comas *et al.*, 1992; Lonergan and White, 1997; Séranne, 1999; Jolivet *et al.*, 1999, 2020; Loreto *et al.*, 2020).

3 Geological constraints on the Europe-Africa plate boundary

3.1 France Southeast Basin and Provence

The France Southeast Basin forms a transitional domain between the Provence and the SW French Alps (Fig. 3a). Post-Variscan extension started in the Permian during the initial stages of Pangea break-up as indicated by NNE and ESE trending basins (Espurt *et al.*, 2012; Bestani *et al.*, 2016). Extension then progressively intensified during the Triassic-Jurassic period in response to the Alpine Tethys rifting leading to the formation of the Dauphinois basin in the Early Jurassic (Fig. 2) between the less subsident domains of the Provence High and the Occitan High (paleo-Massif Central) (Lemoine, 1985; Curnelle and Dubois, 1986; Baudrimont and Dubois, 1977). During the Early Cretaceous, the Provence High evolved into the Durance Isthmus, an elongated EW-directed topographic high that separated the South Provence basin from the Vocontian basin (Fig 3a).

The Early Cretaceous rift history in Provence appears to be closely linked to that of the Pyrenees and the opening of the Bay of Biscay (Curnelle and Dubois, 1986; de Graciansky and Lemoine, 1988; Tavani *et al.*, 2018). Based on age correspondence and the position in the external domain of the Western Alps (*i.e.*, west of the Briançonnais and the Penninic Front), it has also been soon suggested that the Vocontian Basin may instead be connected to the termination of the Valaisan domain (Maury and Ricou, 1983; Dercourt and Vrielynck, 1993; Dercourt *et al.*, 2000; Debelmas, 2001; Manatschal and Müntener, 2009). Other reconstructions, in contrast, assume the Valaisan domain is a large oceanic domain in continuity with the Pyrenean rift basin between the Provence and Corsica/Briançonnais, accommodating the eastward motion of Iberia (Trümpy, 1988; Stampfli, 1993; Stampfli and Borel, 2002; Turco *et al.*, 2012).

The Provence fold-thrust belt developed in response to contraction between Sardinia-Corsica and Europe associated with the Campanian-Eocene Pyrenean event. The deposition of a Late Cretaceous foreland succession is reported at this time (Espurt *et al.*, 2012; Bestani *et al.*, 2016). Shortening is thought to have resulted from 1) upper plate transpression above the oblique north-verging subduction of the Ligurian Tethys south of Sardinia-Corsica (Europe) (Lacombe and Jolivet, 2005) or 2) linked to the inversion of the Pyrenean/Valaisan rift shaped by a hyper-extended rift system (Espurt *et al.*, 2012; Bestani *et al.*, 2016). Some alternative models proposed that contraction resulted from the contact between Sardinia-Corsica (Iberia), moving along a left-lateral strike-slip fault corridor until Late Cretaceous, and Adria (Schreiber *et al.*, 2011). None of these reconstructions follow kinematic models assuming a large Pyrenean-Valaisan ocean between the Provence and Sardinia-Corsica (Trümpy, 1988; Stampfli, 1993; Stampfli and Borel, 2002; Turco *et al.*, 2012) because there is no evidence for ophiolite-like mélange or folded deep-marine sediments formed along a presumed suture zone. A total horizontal shortening of ~ 155 km is estimated between the northern edge of the Provence basins and Sardinia, including ~ 50 km in the Provence basin (Bestani *et al.*, 2016). This total shortening is in the range of the one estimated in the Pyrenean belt (see below).

The opening of the Oligocene-Miocene Gulf of Lion and Ligurian basin from 32 Ma (Fig. 2) (Gorini *et al.*, 1993; Séranne *et al.*, 1995; Séranne, 1999) resulted in N-S extension, reactivating previous Pyrenean thrusts into E-W normal faults (Bestani *et al.*, 2016). E-W extension related to the opening of West European Rift is also reported in the Forcalquier-Manosque basin (Bergerat, 1987) and the Sainte Victoire area (Lacombe *et al.*, 1992) (Fig. 3a). The Neogene to present-day Alpine contraction (Lacombe *et al.*, 1992; Espurt *et al.*, 2012; Bestani *et al.*, 2016) is superimposed on Late Cretaceous-Eocene Pyrenean compressive structures and reflects a limited amount of shortening. Among the tectonic features that our kinematic reconstruction must take into account are the NNE-SSW to NE-SW major transfer faults (Nîmes, Salon-Cavaillon, Aix, Durance, and Barjols faults, Fig. 3a). These faults intersect the Late Triassic to Early Cretaceous sedimentary cover and have recorded both the Cenozoic extension and inverse reactivation (*e.g.*, Durance Fault) during the Pyrenean and Alpine orogeny (Roure *et al.*, 1992).

3.2 Sardinia-Corsica and Gulf of Lion

The Sardinia and Corsica islands form an N-S elongated continental block in the Western Mediterranean Sea that was rifted away from Provence in southern France and rotated by 45–50° counter-clockwise during the opening of the Ligurian-Provençal oceanic basin in the early Miocene, between 20.5 and 15 Ma (Ferrandini *et al.*, 2003; Gattacceca *et al.*, 2007).

Sardinia-Corsica preserves a Variscan Paleozoic basement intruded by late Variscan upper Paleozoic calc-alkaline magmatic rocks and Permian granitoids associated with volcano-sedimentary rocks (Matte, 1991; Paquette *et al.*, 2003; Rossi *et al.*, 2009; Ballèvre *et al.*, 2014). The Alpine Corsica refers to units exposed in northeastern Corsica that comprises HP rocks in a series of Tethys-derived nappes now forming ophiolitic complexes similar to the Schistes Lustrés complex exposed in the Western Alps (Fig. 1) (Lacombe and Jolivet, 2005; Vitale Brovarone *et al.*, 2013; Malusà *et al.*, 2016). As such Alpine Corsica represents the southwestern termination of the Alpine orogenic wedge emplaced between

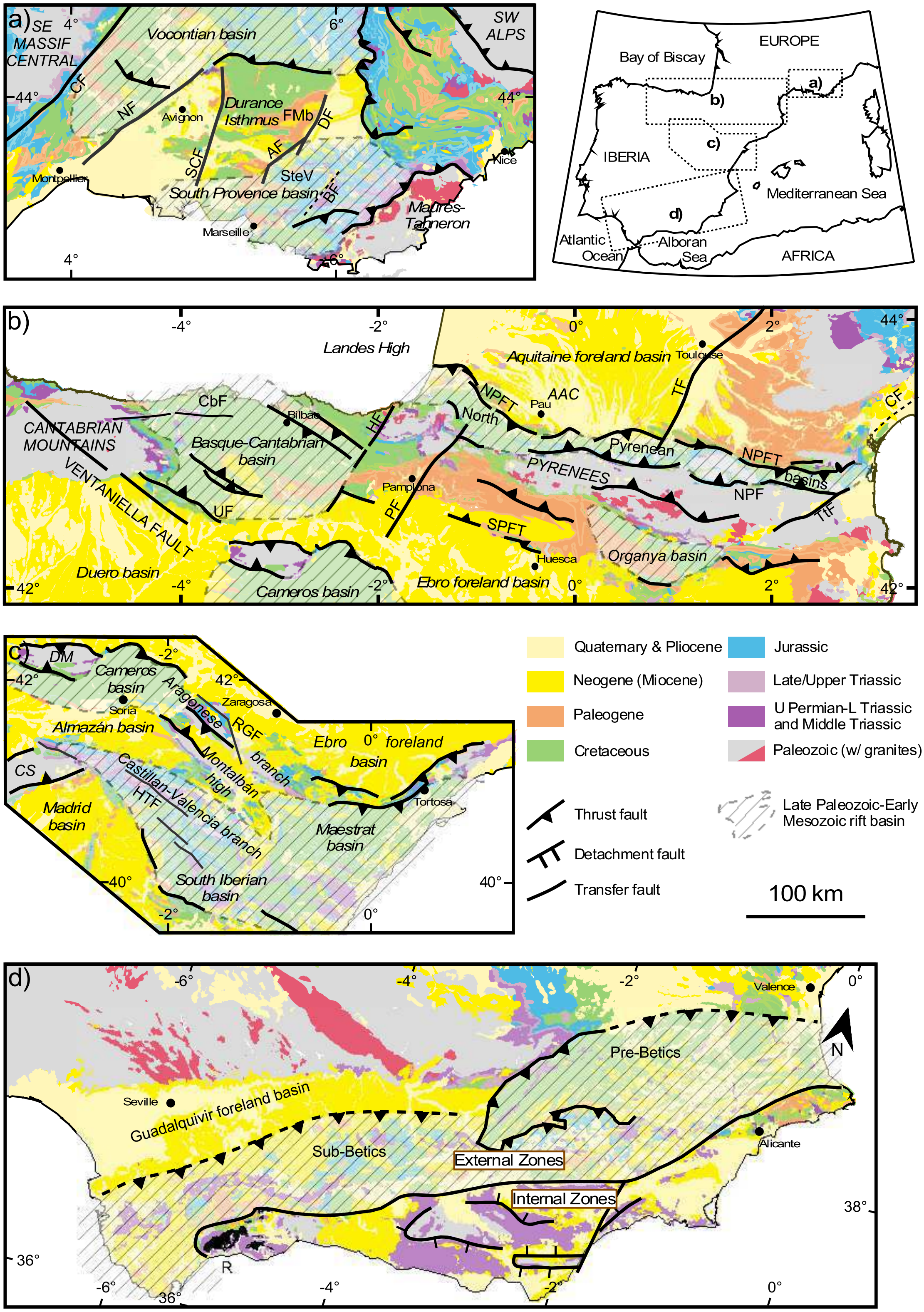

Fig. 3. Detailed geological maps of the main deformed areas used in this study, highlyting the main structures (thrust fronts, normal faults, strike-slip faults) and structural domains. (a) Provence domain. CF: Cévennes Fault; NF: Nîme Fault; SCF: Salon-Cavaillon Fault; AF: Aix Fault; BF: Barjols Fault; DF: Durance Fault; FMb: Forcalquier-Manosque basin; SteV: Sainte Victoire. Note that normal faults described in the text are to small to be shown on the map. (b) Pyrenees and Basque-Cantabrian domains. CbF: Carbuerniga Fault; UF: Ubernia Fault, HF: Hendaye Fault; PF: Pamplona Fault; NPFT: North Pyrenean Frontal Thrust; NPF: North Pyrenean Fault; TF: Toulouse Fault; TtF: Têt Fault; CF: Cévennes Fault; AAC: Adour-Arzacq-Comminges basin. (c) Iberian Range. CS: Central System; DM: Demanda Massif; HTF: High Tagus Fault, RGF: Rio Grio Fault. (d) Betic domain. R: Ronda peridotite. Note the different orientation of this map, indicated by the North arrow.

Adria and Europe. It is worth noting the Variscan/Alpine wedge bounding fault in its pre-Neogene orientation lies parallel to the major Nîmes and Durance faults in Provence (Fig. 3a) (Lacombe and Jolivet, 2005) and must be understood as an inherited Variscan structure.

The Mesozoic sedimentary sequence in the northwest and east Sardinia shows depositional environments deepening toward the SE on the former Alpine Tethys margin (Azema, 1977; Philip and Allemann, 1982). Continental break-up associated with opening of Alpine Tethys is outlined by an unconformity dated as Bajocian (~ 170 Ma) (*e.g.*, Costamagna *et al.*, 2007; Costamagna, 2016). Details of the middle Cretaceous depositional history show similarities between Sardinia and Provence, including the regionally recognized Bauxite deposits from the Albian to the Turonian (110–90 Ma) (Philip and Allemann, 1982). This event temporally correlates with the regional opening of the Bay of Biscay, a relationship that is implicit in some previous publication (Masse and Allemann, 1982). After the deposition of marine carbonates during Coniacian-Santonian, middle Eocene (Lutetian, 48–41 Ma) conglomerates (Cixerri Formation) were deposited in southern Sardinia. They bear evidence of reworked late Albian-Cenomanian carbonate sourced from the eastern Pyrenees (Cherchi, 1976). A tectonic connection with the Pyrenees prior to rotation is therefore suggested.

A late Paleocene to middle Eocene phase of contraction is recognized for Sardinia-Corsica (Dieni *et al.*, 2008). This timing is supported by low-temperature thermochronological constraints from the Variscan basement that document diachronous exhumation events from SE Sardinia to NW Corsica beginning at 67–49 Ma (Malusà *et al.*, 2016). The emplacement of the Alpine wedge in northeast Corsica is also well constrained by remnants of Eocene (post-Lutetian, 41 Ma) foreland basin deposits that are overthrusted by HP units. Intrusions of the Cixerri Formation by andesites topped by late Oligocene-Miocene volcano-sedimentary deposits (Bellon *et al.*, 1977; Barca and Costamagna, 2010) reveal a transition, most likely during the Priabonian, from Pyrenean contraction to extension controlled by the opening of the Algero-Provençal back-arc basin (Fig. 2). The Priabonian extensional event, which marks the southern extension of the West European Rift, appears to predate the rifting in the Gulf of Lion dated as late Oligocene-early Miocene (Gorini *et al.*, 1993; Séranne *et al.*, 1995; Séranne, 1999; Réhault *et al.*, 2012). The geodynamic drivers of these two events are therefore different. The onset of rifting is confirmed in Corsica at 32 Ma by top-to-the-East shearing of metamorphic units (Lahondère and Lahondère, 1988; Fournier *et al.*, 1991; Jolivet *et al.*, 1991, 1998; Caron, 1994; Brunet *et al.*, 2000), the opening of Oligocene to earliest Miocene (Aquitanian) rift basins and exhumation in the upper crust (Zarki-Jakni *et al.*, 2004; Fellin *et al.*, 2005; Cavazza *et al.*, 2007; Danišík *et al.*, 2007; Malusà *et al.*, 2016). As rotation of Sardinia-Corsica occurred in the Aquitanian-Burdigalian (Cherchi and Montadert, 1982), volcanism spread over the whole region both onshore and offshore in the Gulf of Lion (Bellon and Brousse, 1977; Girod and Girod, 1977; Réhault *et al.*, 2012).

Controversies that need to be addressed in our reconstructions are on the pre-Miocene kinematics. Models indeed differ on whether the Sardinia-Corsica domain was part of Iberia (Trümpy, 1988; Stampfli, 1993; Stampfli and Borel, 2002; Turco *et al.*, 2012) or a separate microplate during the Jurassic-Cretaceous until contraction initiated in the Late Cretaceous (Rosenbaum *et al.*, 2002a) or until the Oligocene, after a phase of contraction with southern France in the Eocene (Advokaat *et al.*, 2014).

3.3 Pyrenees

The Pyrenees (Fig. 3b) show an exceptional preservation of the pre-collisional architecture of the rifed margin, including remnants of a sub-continental mantle exhumed during Early Cretaceous extension (Lagabrielle and Bodinier, 2008; Jammes *et al.*, 2009; Lagabrielle *et al.*, 2010), which is well imaged at depth by recent seismic tomographic images (Wang *et al.*, 2016; Chevrot *et al.*, 2018). Based on the age of the youngest sediments affected by the synrift HT metamorphism (Albarède and Michard-Vitrac, 1978; Montigny *et al.*, 1986; Vacherat, 2014; Clerc *et al.*, 2015; Saspiturry *et al.*, 2020), the crustal breakup is dated as Early Cretaceous (Fig. 2), but extension was long-lasting likely initiated as a result of Pangea break-up during the late Permian (Lucas, 1985; Saspiturry *et al.*, 2019; Angrand *et al.*, 2020).

In contrast to other peri-Tethyan domains, the stratigraphy of the northern (Europe) and southern (Iberia) margins in the Pyrenees indicate a lack of Early-Middle Jurassic tectonic subsidence (Curnelle, 1983; Brunet, 1986, 1994; Martín-Chivelet *et al.*, 2019). Rifting indeed occurred from Late Jurassic to Early Cretaceous and reached a climax in the Aptian-Albian along E-W-directed rift basins, from the Parentis and the Aquitaine basins in the West (Brunet, 1986, 1994; Bois and Ecors Scientific Party, 1990; Jammes *et al.*, 2009; Angrand *et al.*, 2018) to Organyà in the south (Berástegui *et al.*, 1990; Mencos *et al.*, 2015), including evidence for ubiquitous hyper-extension with sub-continental exhumation in the North Pyrenean basins (Masini *et al.*, 2014; Clerc *et al.*, 2015; Corre *et al.*, 2016; Teixell *et al.*, 2016; Espurt *et al.*, 2019a; Angrand *et al.*, 2021).

The onset of contraction is constrained by the late Santonian-early Campanian age of early thrusting events, exhumation and clastic influx in the northern and southern foreland basins (Puigdefàbregas and Souquet, 1986; Beaumont *et al.*, 2000; Christophoul *et al.*, 2003; Beamud *et al.*, 2011; Whitchurch *et al.*, 2011; Filleaudeau *et al.*, 2012; Mouthereau *et al.*, 2014; Ford *et al.*, 2016; Rougier *et al.*, 2016; Vacherat *et al.*, 2016, 2017; Angrand *et al.*, 2018; Ternois *et al.*, 2019) (Fig. 2). From the late Santonian/early Campanian to middle Miocene times, the Pyrenees accommodated a N-S shortening of ~ 111 km in the East (excluding the closure of the exhumed mantle domain, Grool *et al.*, 2018), ~ 100–165 km in the centre (Choukroune *et al.*, 1989, 1990: 100 km; Muñoz, 1992: 147 km; Beaumont *et al.*, 2000: 165 km; Mouthereau *et al.*, 2014: 142 km; Espurt *et al.*, 2019a: 124 km), and ~ 75–80 km in the west (Teixell, 1998).

Thermochronological ages show a southward-younging pattern, from 70 Ma to about 20 Ma, reflecting the tectonic growth of the Pyrenean mountain chain toward the lower Iberian (Ebro) plate (Fitzgerald *et al.*, 1999; Sinclair *et al.*, 2005; Gibson *et al.*, 2007; Metcalf *et al.*, 2009; Whitchurch *et al.*, 2011; Mouthereau *et al.*, 2014; Vacherat, 2014; Vacherat *et al.*, 2016, 2017; Waldner *et al.*, 2021). Orogenic growth accelerated by the middle-late Eocene (50–40 Ma) as recorded by exhumation rates, foreland flexure migration, sediment accumulation and paleoelevation estimates (Sinclair *et al.*, 2005; Huyghe *et al.*, 2012; Curry *et al.*, 2019; Garcés *et al.*, 2020). Among the possible drivers of exhumation is the increasing strain localisation in mid-crustal levels during accretion of necking and proximal domains of the Iberian margin (Mouthereau *et al.*, 2014; Jourdon *et al.*, 2019; Ternois *et al.*, 2019). More recent studies have emphasized additional post-20 Ma uplift caused by isostatic and tectonic adjustment to density contrasts inherited from the Cretaceous rifting in the West (Fillon *et al.*, 2021) and rifting of the Gulf of Lion in the eastern Pyrenees (Huyghe *et al.*, 2020).

Of particular interest to our reconstructions is the amount and timing of left-lateral strike-slip movement between Europe and Iberia from Late Jurassic to Albian that has been matter of debate for decades. A consensus has recently emerged in reconstructions accounting for strain partitioning between strike-slip and extension over a large region, encompassing the Parentis and Basque-Cantabrian basins, the Iberian basins (Cameros, Maestrat) and the Valencia and Columbretes basins (Jammes *et al.*, 2009; Tugend *et al.*, 2014b; Etheve *et al.*, 2016; Angrand *et al.*, 2020). A major change occurred in the late Aptian when the Bay of Biscay opened (Sibuet *et al.*, 2004). From this time, extension is considered to have occurred mostly orthogonal to the Pyrenean rift axis (*e.g.*, Jammes *et al.*, 2009). For instance, Angrand *et al.* (2020) estimated 19 km of left-lateral movement during the Aptian-Albian accommodated in the Pyrenees while 259 km were accommodated by transtension since the Permian.

3.4 Basque-Cantabrian Basin

The Basque-Cantabrian Basin, located west of the Pyrenean belt (Fig. 3b), represents an inverted hyper-extended Cretaceous extensional basin that developed in response to the incomplete closure of the southern margin of the Bay of Biscay, between the Alvesa Platform and the Landes High (Alonso *et al.*, 1996; Pulgar *et al.*, 1996; Gallastegui *et al.*, 2002; Roca *et al.*, 2011; Pedreira *et al.*, 2015; Quintana *et al.*, 2015; Pedrera *et al.*, 2017).

Following the collapse of the Variscan orogen and Permian Ca-K magmatism, post-orogenic extensional basins formed during the late Permian-Triassic (López-Gómez *et al.*, 2019). Subsidence resumed during the Late Jurassic (Tithonian)-Early Cretaceous after a period of tectonic quiescence associated with deposition of Hettangian-Kimmeridgian (200–160 Ma) marine carbonate platforms (Cámara, 2017; Pedrera *et al.*, 2017; Martín-Chivelet *et al.*, 2019), followed by deposition of Tithonian-Barremian (140–125 Ma) shallow marine sediments. By the late Aptian-early Albian, synrift subsidence increased as revealed by the deposition of 3 km deep-marine sediments. The total synrift sequence (145–100 Ma) is 12 km thick, locally exceeding 20 km (Quintana *et al.*, 2015; Pedrera *et al.*, 2017), and was accommodated by extreme crustal extension leading to sub-continental mantle exhumation (DeFelipe *et al.*, 2017; Pedrera *et al.*, 2017; Ducoux *et al.*, 2019). Despite the Basque-Cantabrian Basin forms a distinct rift segment from the Pyrenees to the West of the Pamplona Fault (Fig. 3b), it shows important similarities, notably the high temperature (HT) metamorphism (Cuevas and Tubía, 1999; DeFelipe *et al.*, 2017), dykes and laccoliths of an alkaline magmatism dated as late Albian (102 Ma) (Ubide *et al.*, 2014; Agirrezabala, 2015).

The Aptian-Albian synrift evolution of the Basque-Cantabrian Basin has soon been interpreted as reflecting deformation in a transtensional regime. It is debated whether strain was partitioned between N-S (or NNW-SSE) extension and NW-SE strike-slip faults (García-Mondéjar *et al.*, 1996; Cámara, 2017), or is not partitioned but rather related to NNE-SSW extension oblique to the E-W inherited Landes High and Duero-Ebro platforms (Pedrera *et al.*, 2020a). As noted by Angrand *et al.* (2020), distinguishing between the two models may be challenging as the sedimentary cover on which interpretations are based is detached in the Triassic salt layer and thus decoupled from the larger scale crustal tectonics.

In the Basque-Cantabrian Basin, the Ventaniella Fault (Fig. 3b) is part of a NW-SE fault system that acted as left-lateral shear zone during the Late Jurassic-Early Cretaceous and has been subsequently inverted with a right-lateral kinematic during the Cenozoic (De Vicente *et al.*, 2011; Tavani *et al.*, 2011; Cámara, 2017). These faults have a Triassic origin (Tavani and Granado, 2015). Tectonic activity along these faults gets younger northeastward (Ubierna fault: Late Jurassic-Early Cretaceous; Zamanza-Oña fault: Early-Middle Cretaceous; salt tectonics in the center of the basin, Cámara, 2017). Angrand *et al.* (2020) suggested that the Iberia-Ebro displacement has possibly been distributed along these structures.

Contraction in the Cantabrian belt occurred synchronously with the main continental orogenic phase of the Pyrenees (Quintana *et al.*, 2015; Macchiavelli *et al.*, 2017). Post-Santonian N-S horizontal shortening is in the same order of magnitude as the Pyrenees (97 in the upper crust and 122 km in the middle-lower crust, Quintana *et al.*, 2015).

Despite the low-temperature thermochronology analyses resolve an onset of exhumation at 50–45 Ma in the Cinco-Villas (DeFelipe *et al.*, 2019), the preservation of thick Eocene-Oligocene turbidites indicates the Basque-Cantabrian basin remained a depression during the early stages of rift inversion before a main exhumation in the late Eocene-Oligocene (Fillon *et al.*, 2016).

3.5 Iberian Range and Central System

The Iberian Range located south of the Ebro basin (Fig. 3c) is composed of the Aragonese branch (north) and the Castillan-Valencian branch (south), separated by the Teruel high, Montalbán high and the Cenozoic Almazán basin (northeastern Duero basin) (*e.g.*, De Vicente *et al.*, 2011). The Iberian Range is interpreted to result from the tectonic inversion of a series of late Paleozoic-Mesozoic rift basins that delimit the Ebro continental block from South Iberia. Three main Mesozoic rift basins are recognized: the Cameros basin on the northwestern part of the Aragonese branch, the Maestrat basin on the southeastern part of the Iberian Range (*e.g.*, Salas *et al.*, 2001) and southeastward the Columbretes basin positioned offshore in the Valencia Trough (Roca, 1992; Etheve *et al.*, 2018).

A thick series of early Permian (up to 2 km) volcano-sedimentary deposits is documented in the Central System associated with localized subsidence in post-Variscan extensional basins (Sopeña et al., 1988; Arche and López Gómez, 1996). Rapid subsidence is described in the Maestrat basin in the Early and Late Jurassic separated by a period of slow subsidence in the Sinemurian (200–190 Ma) (Van Wees et al., 1998). The latter phase is particularly obvious in the Cameros basin where it forms an asymmetric sag basin containing up to 6.5–8 km of Late Jurassic to Early Cretaceous synrift continental deposits with episodic marine incursions (Guiraud and Seguret, 1985; Alonso and Mas, 1993; Casas-Sainz and Gil-Imaz, 1998; Quijada et al., 2010; Suárez González et al., 2010; Omodeo Salè et al., 2014; García-Lasanta et al., 2017). The postrift sequence consists of 100–500 m of late Albian–Cenomanian sandstones (Utrillas Formation) and 200 m-thick Late Cretaceous marine limestone. The Cameros basin recorded greenschist facies metamorphism at 108–86 Ma (Del Río et al., 2009; Casquet et al., 1992) associated with peak temperatures of 330 °C (Rat et al., 2019) and fluid flow (Omodeo Salè et al., 2014) during the opening of the Bay of Biscay. This event was contemporaneous with metamorphic and volcanic events described in the Pyrenees and Basque-Cantabrian basins (see above). Similar synrift sequences are reported in the Maestrat and Valencia basins, although they are also recognized to be slightly older, Oxfordian-Berriasian (155–142 Ma) and Valanginian-early Albian (139–109 Ma) in age. The subsidence was also lower, characterized by the deposition of 2–4 km of marine carbonates (Van Wees et al., 1998; Salas et al., 2001; Aurell et al., 2019a). In contrast to the Cameros basin, the stratigraphic architecture and depositional environments of the Maestrat and Valencia basins show a clear affinity and polarity towards the Tethys Sea to the East.

Low-temperature thermochronology defines a 60 Ma cooling stage related to the onset of tectonic inversion (Rat et al., 2019). This timing is in agreement with Campanian deformation described in the Maestrat basin (Vergés et al., 2020). Exhumation then increased in the Cameros basin during the late Eocene-Oligocene (40–25 Ma), regionally in good agreement with the timing of exhumation in the Pyrenees. Thrusting north of Cameros basin appears to have been ongoing from 15 to 9 Ma.

The Iberian Range has received a particular attention for its role in accommodating a portion of the eastward motion of Iberia before and during the Early Cretaceous (Tugend et al., 2014b; Nirrengarten et al., 2018; Aldega et al., 2019; Angrand et al., 2020). Angrand et al. (2020) indeed propose to transfer the left-lateral strike-slip movement between Europe and Iberia (~ 245 km) in the Iberian basins during the Aptian-Albian rather than in the Pyrenean rift basin, which instead accommodates orthogonal extension (only 19 km of strike-slip motion). The High Tagus Fault (Castillan-Valencian branch), which has been active during the Middle-Late Jurassic (Aurell et al., 2019b) and the Rio Grio Fault (north Aragonese branch/ north Cameros) active since the Triassic (Aldega et al., 2019) indicate that this domain must be accounted for in tectonic models. A total shortening of ~ 75 km is estimated across the entire Iberian Range (Guimerà et al., 1996; Salas et al., 2001). During the late Eocene-Miocene, the Iberian Range accommodated ~ 40 to 50 km of N-S horizontal shortening (Salas et al., 2001; Guimerà et al., 2004; De Vicente et al., 2009; Mouthereau et al., 2014) and the Central System records 25–50 km of NW-SE horizontal shortening during the Cenozoic (Arche and López Gómez, 1996).

3.6 Catalan Coastal Range, offshore Valencia Trough and Balearic islands

The Catalan Coastal Range results from the inversion of Mesozoic rift basins that were subsequenty reactivated in extension during the Neogene opening of the Western Mediterranean Sea. The first stages of extension are reflected in Permian-Triassic rift basins and magmatic rocks exposed in the Catalan Coastal Range, Mallorca and Menorca. They were associated with opening of the Neotethys (Galán-Abellán et al., 2013; López-Gómez et al., 2019; Angrand et al., 2020, and references therein). These sediments lie above a Paleozoic basement that have affinity with the Pyrenees, Sardinia and Corsica and slight differences with the Iberian Range. Synrift subsidence started in the Middle Jurassic (Aalenian-Oxfordian; 174–160 Ma), indicating eastern Iberia formed part of the paleomargin of the Alpine (Ligurian) Tethys (Gómez and Fernández-López, 2006).

The Valencia Trough, bounded to the north by the Catalan Coastal Range (Fig. 1a), is interpreted as a NE-SW Oligocene-Miocene extensional basin formed as a result of the opening of the West Mediterranean (Liguro-Provençal basin, Fig. 2) (Bartrina et al., 1992; Roca et al., 1999; Jolivet et al., 2020). However, its connection with the Maestrat basin suggests that the Columbretes basin (southwest Valencia Trough) experienced a Late Jurassic-Early Cretaceous extension (157–105 Ma) (Etheve et al., 2018) and a middle Albian to Maastrichtian slow subsidence (Salas and Casas, 1993; Roca et al., 1994; Salas et al., 2001). The study of the pre-Neogene architecture in the Columbretes basins indeed reveals that this basin, made of 8–9 km thick Mesozoic succession initiated in the Triassic (Roca, 1992), recorded a Late Jurassic/Early Cretaceous extensional phase with hyper-extension recorded during the Albian (Etheve et al., 2018; Roma et al., 2018). The final crustal thickness is estimated at 8–10 km (Roca et al., 1999).

In the Baleares, including Ibiza and Mallorca, the Mesozoic series show the same synrift evolution as described in the Maestrat basin and the Catalan Coastal Range, including a Late Triassic-Early Jurassic rifting (Tethys event) and Late Jurassic-Early Cretaceous rifting (Cameros, Maestrat rifting) with a Middle Jurassic hiatus in between (Etheve et al., 2016; López-Gómez et al., 2019). Stratigraphic and sedimentary constraints therefore collectively indicate that the Balearic promontory lies on the paleomargin of Iberia separated from Ebro by a failed Late Jurassic-Early Cretaceous rift that connects the Valencia to the Maestrat and Cameros basins. Inversion of the Mesozoic rift that formed the Catalan Coastal Range occurred during the lower Lutetian (~ 50 Ma) (Roca and Desegaulx, 1992; Roca et al., 1999; López-Blanco, 2002; Gaspar-Escribano et al., 2004; Gómez-Paccard et al., 2012; Garcés et al., 2020). A contraction event of the same age is inferred from the upper Oligocene-Miocene unconformity in the Balearic promontory (e.g., Etheve et al., 2016), which likely corresponds to the Pyrenean collision (Fig. 2). Extension started in the early-late Oligocene (Chattian, 28 Ma) in the Catalan-Valencian domain (Roca and Desegaulx, 1992;

Roca *et al.*, 1999), preceding the opening of the Gulf of Lion (Anadón *et al.*, 1985; Bois, 1993; Jolivet and Faccenna, 2000) (Fig. 2). Extension appears to have been ongoing until the late Langhian (~ 14 Ma) in the southern Valencia Trough (Roca and Desegaulx, 1992), that is until the end of Sardinia-Corsica rotation.

The view that shortening affected the southern Valencia basin is however disputed as it requires that the Balearic promontory overthrusts the Valencia basin for which there is limited evidence (Maillard *et al.*, 1992). The late Oligocene-early Miocene extensional event is recognized locally in Ibiza (Etheve *et al.*, 2016) but not in Mallorca, where instead the interval between late Oligocene and mid-Serravallian corresponds to a shortening of about 84 km (Vergés and Sàbat, 1999; Sàbat *et al.*, 2011). This shortening is assumed to balance the extension associated with the opening of Valencia Trough (Vergés and Sàbat, 1999) but the age of the extreme crustal thinning in the Columbretes basin dated to Early Cretaceous (Etheve *et al.*, 2018) casts doubt on the hypothesis of large Neogene extension. In any case, the compression was probably short-lived as extension renewed during the late Tortonian-Serravalian (12–8 Ma).

East of the Balearic Promontary, the North-Balearic-Fracture-Zone (see Maillard *et al.*, 2020, and references therein) forms a transfer zone that accommodated the differential extension between the Valencia basin and the counterclockwise rotation of Sardinia-Corsica and extension in the Liguro-Provençal oceanic basin. The first calc-alkaline magmatic event is dated as late Oligocene-lower Miocene in the Valencia basin (24 Ma; Martí *et al.*, 1992; Fig. 2) coincident with Ca-K magmatism of Aquitanian age recognized in Sardinia. Because at this time Sardinia aligned with the Valencia basin, this Ca-K magmatism must reflect a pre- or early-synrift event (Maillard *et al.*, 2020).

Most of the current controversy are related to the pre-35 Ma reconstruction of the Baleares margin, including the Sardinia-Corsica block. They differ as to whether Baleares-Sardinia-Corsica block is positioned 1) in the lower plate (Iberia), with AlKaPeCa units in the upper plate (Handy *et al.*, 2010; Leprêtre *et al.*, 2018), which requires a polarity reversal as the W-Mediterranean slab retreated, or 2) in the lower plate, together with AlKaPeCa units, as most classically reconstructed (Jolivet and Faccenna, 2000; Rosenbaum *et al.*, 2002a; Lacombe and Jolivet, 2005; Faccenna *et al.*, 2014; van Hinsbergen *et al.*, 2014). It is worth noting, that the solution of Handy *et al.* (2010) assumes the pre-35 Ma SE-directed subduction of a Western Ligurian basin (also named Betic Ocean or Nevado-Filabrides Basin; Guerrera *et al.*, 2014).

3.7 Betic Cordillera and Alboran domain

The Betic Cordillera resulted from Cenozoic subduction along the South Iberian paleomargin and post-orogenic extension associated with opening of the Alboran domain (García-Dueñas *et al.*, 1988; Balanyá *et al.*, 1997; Crespo-Blanc and de Lamotte, 2006) (Fig. 3d). The role of slab dynamics has been emphasized to explain the arcuate shape of the Betic-Rif belt, metamorphic evolution and deep structure of the arc (Lonergan and White, 1997; Wortel and Spakman, 2000; Faccenna *et al.*, 2014). Geodynamic interpretations have varied in terms of timing, amount and vergence of subduction (Lonergan and White, 1997; Vergés and Fernàndez, 2012; van Hinsbergen *et al.*, 2014). Two end-member tectonic reconstructions currently exist. The first one proposes that the Alboran domain must be restored south of the Baleares Promontory in the Paleogene and then travelled for more than 1000 km westwards (van Hinsbergen *et al.*, 2014). Alternatively, the Alboran domain that did not exist before the Neogene (Fig. 2) was part of the Iberia paleomargin that subducted below Africa during the Paleogene; implying a limited convergence of 200–300 km (Vergés and Fernàndez, 2012). Time-temperature paths obtained from the Cretaceous and Miocene Flysch Complex (Daudet *et al.*, 2020) and recent structural balanced cross-sections (Pedrera *et al.*, 2020b) constrain a scenario in which the Alboran basement formed an hyper-extended rift segment of the Atlantic-Tethys that was inverted between Iberia and Africa in the Paleogene. Pedrera *et al.* (2020b) estimate a shortening of 100–145 km, achieved between the early Eocene and early Miocene. This value falls in the range of the total Cenozoic convergence reconstructed between Iberia and Africa (Macchiavelli *et al.*, 2017).

Above the Variscan basement of the Alboran (AlKaPeCa) domain, which underwent a high-pressure/low-temperature metamorphism during the Paleogene (García-Dueñas *et al.*, 1988; Soto and Azanon, 1994; Augier *et al.*, 2005), lies the less metamorphosed Malaguide complex that preserves continental to coastal Triassic facies (Algarra, 1987; Ortí *et al.*, 2017). In the external and Prebetic domains, the late Permian/Early Triassic series from 270 to 200 Ma (Fig. 2) record rifting on the south-Iberian margin (López-Gómez *et al.*, 2019). This first synrift sequence is intruded during the Jurassic by MORB-type gabbro dated at 180 Ma (Puga *et al.*, 2011), forming the West Ligurian basin or the Betic ocean. Whether this is related to the onset of oceanic spreading or to hyper-extended margin magmatism (Durand-Delga *et al.*, 2000) remains unclear. A second phase of rifting is recorded from Late Jurassic (Bathonian, ~170 Ma) to Early Cretaceous (Albian, 100 Ma) (Hanne *et al.*, 2003; Martín-Chivelet *et al.*, 2019).

Subsidence resumed in the early Cenozoic in the Malaguide Complex from the Danian (66–61 Ma), lower-middle Cuisian (Late Ypresian, 52–50 Ma), and middle Lutetian-Bartonian (45–38 Ma) (Hanne *et al.*, 2003) and from Thanetian (56 Ma) to late Ypresian (50 Ma) associated with the development of a turbiditic basin in the pre-Betic (Martín-Chivelet and Chacón, 2007). The Eocene calcareous turbidites witness the initiation of foreland subsidence (Serrano *et al.*, 1995; Martín-Martín *et al.*, 1997; Maaté *et al.*, 2000; Guerrera *et al.*, 2005), which coincides with the onset of cooling in the Flysch Complex (Daudet *et al.*, 2020). By the early Miocene (Aquitanian, 22 Ma) rapid subsidence occurred but this event was short-lived as indicated by a regional rapid cooling event at 20–15 Ma. This markedly synchronous phase of sediment burial and exhumation suggest a phase of rapid thinning and heating, followed by fast thermal reequilibration and denudation. Subsidence resumed in the early Tortonian (17–15 Ma), during which orogen-parallel extension occurred. From the late Messinian (5.3 Ma) onward, transition from marine to continental sedimentation was associated with regional uplift of up to 1000 m of the intramontane Neogene basins (Iribarren *et al.*, 2009;

Janowski *et al.*, 2017) triggered by westward propagation of slab tearing (or detachment) below the Betics (Spakman and Wortel, 2004; Mancilla *et al.*, 2015).

4 Crustal segmentation of the West European realm

Inverted basins and mountain chains described above form a broad zone (> 1000 km) of intra-continental contraction around Iberia that resulted from the shortening of the variably extended continental crust and closure of oceanic domains during convergence between Europe and Africa. The strong crustal segmentation of the European continent, including Iberia, appears to be inherited from the Mesozoic rifting history itself established on an older highly heterogeneous Paleozoic, mainly Variscan, crustal architecture. The different orogens and inverted basins delimit deformed crustal domains marked by less intensely deformed and undeformed continental bocks (Fig. 4). Smaller amplitude chains (Catalan Coastal Range, Central System) and crustal- to lithospheric-scale faults (Nazaré Fault, Messejana-Plasencia Fault, Fig. 4) further express the segmentation of the Iberian plate into smaller continental blocks (see below the methodology in Sect. 5.1). These different crustal elements are essential to precisely reconstruct the evolution and kinematics of the Southwest European realm.

4.1 Iberia

We divide the Iberian plate into three main domains: the Ebro block, the West Iberia block, and the South Iberian block (itself divided into two sub-domains) (Fig. 4). Hereafter, we refer to Iberia as the combination of West and South Iberia blocks. It is delimited from the Ebro continental block by the Iberian Range, a major deformation zone aligned in the NW-SE direction and stretching from the Basque Cantabrian Basin to the Valencia Basin.

The Ebro continental block is delimited by the Pyrenees to the North and the Iberian Range to the South, and by the Basque-Cantabrian Basin and the Catalan Coastal Range to the West and East, respectively (Fig. 4). Recent studies place the Ebro block within the Iberia-Europe plate boundary (Tugend *et al.*, 2015; Angrand *et al.*, 2020). Angrand *et al.* (2020) estimated a total strike-slip movement between Iberia and Europe of more than 200 km since the Triassic that has been accommodated on both the northern and southern borders of the Ebro block, in the Pyrenees and the Iberian Range, respectively.

Although we consider the Ebro block to be rigid during the Mesozoic, basin analyses (Vargas *et al.*, 2009) and geophysical data (Wehr *et al.*, 2018) beneath the Cenozoic foreland sequence argue for subsidence during the Early Mesozoic rifting. In addition to the north and south-bounding rifts, distributed deformation within the Ebro block is suggested but remains poorly constrained in terms of kinematics as no major structure can be identified within this block. At the scale of the kinematic model and for the sake of simplicity, we here adopt a rigid Ebro block hypothesis with the deformation localized at its borders.

The West Iberia block stretches westwards into the Atlantic continental margin and is delimited by the southern North Atlantic Ocean to the West and by the Basque-Cantabrian basin and Iberian Range to the East (Fig. 4). A N-S strike-slip fault system, along which ~ 50 km of Cenozoic left-lateral motion is accommodated (De Vicente *et al.*, 2011) is recognized in the West Iberia block. For this reason, we separate the West Iberia block into two sub-domains (Fig. 4). The West Iberia block is delimited to the South by the Central System-Nazaré Fault.

The Nazaré Fault is a major transfer zone across the West Iberian margin (Pereira *et al.*, 2017), that separates the West Iberia block to the north from the South Iberian block (Fig. 4). This is an important feature of the reconstruction as it minimizes the overlap of northwest Iberia (Galicia) with the Flemish Cap (North America), or the gap between southwest Iberia and Newfoundland during the late Paleozoic full-fit (Angrand *et al.*, 2020). However, no consensus currently exists on the amount of displacement along this structure, whilst its extension over 250 km (Pereira *et al.*, 2017) and its connection to the Avalon Fault during the opening of the North Atlantic (Fernández, 2019) suggest it is a major crustal boundary. In our new reconstruction, however, we remained conservative so that we have reduced the absolute strike-slip movement to ~ 100 km from 145 to 110 Ma with respect to Angrand *et al.* (2020).

The South Iberian block is delimited to the northwest by the Central System-Nazaré Fault, to the northeast by the Iberian Range, and to the south by the Betic Cordillera (Fig. 4). The Messejana-Plasencia Fault in the South Iberian block is another major strike-slip fault lineament inherited from the late Paleozoic (Pereira and Alves, 2013) and is associated with CAMP-related doleritic magmatism at the Triassic-Jurassic boundary (Cerbiá *et al.*, 2003). Kinematics across this ~ 530-km long structure is difficult to ascertain. Although it has been proposed to accommodate transtensional deformation throughout the Mesozoic (Pereira *et al.*, 2017), Paleozoic markers are barely displaced across this feature. During the Cenozoic, small-amplitude left-lateral pull-apart basins developed along the Messejana-Plasencia dyke (De Vicente *et al.*, 2011). Therefore, a limited displacement of about 30 km has been estimated in our reconstruction.

Mallorca and Menorca islands (northern Balearic Promontory, BP; Fig. 4) were attached to southeast Ebro until the opening of the Valencia Trough during the Neogene and are not much affected by the pre-Neogene deformation (see Sect. 3.6). Offshore Ibiza, in the Columbretes basin, crustal thinning during the early Cretaceous argues for the eastern propagation of the intra-Iberian rift during the opening of the Bay of Biscay (Roca, 1992; Etheve *et al.*, 2018).

4.2 South-East France and Sardinia-Corsica

The France Southeast Basin recorded a succession of tectonic events since the late Paleozoic, including Early Jurassic and Early Cretaceous crustal thinning, Cenozoic contraction and extension (Baudrimont and Dubois, 1977; Lacombe *et al.*, 1992; Lacombe and Mouthereau, 2002; Espurt *et al.*, 2012; Bestani *et al.*, 2015, 2016; see Sect. 3.1). On this basis, we included the rift basins of South-East France, the

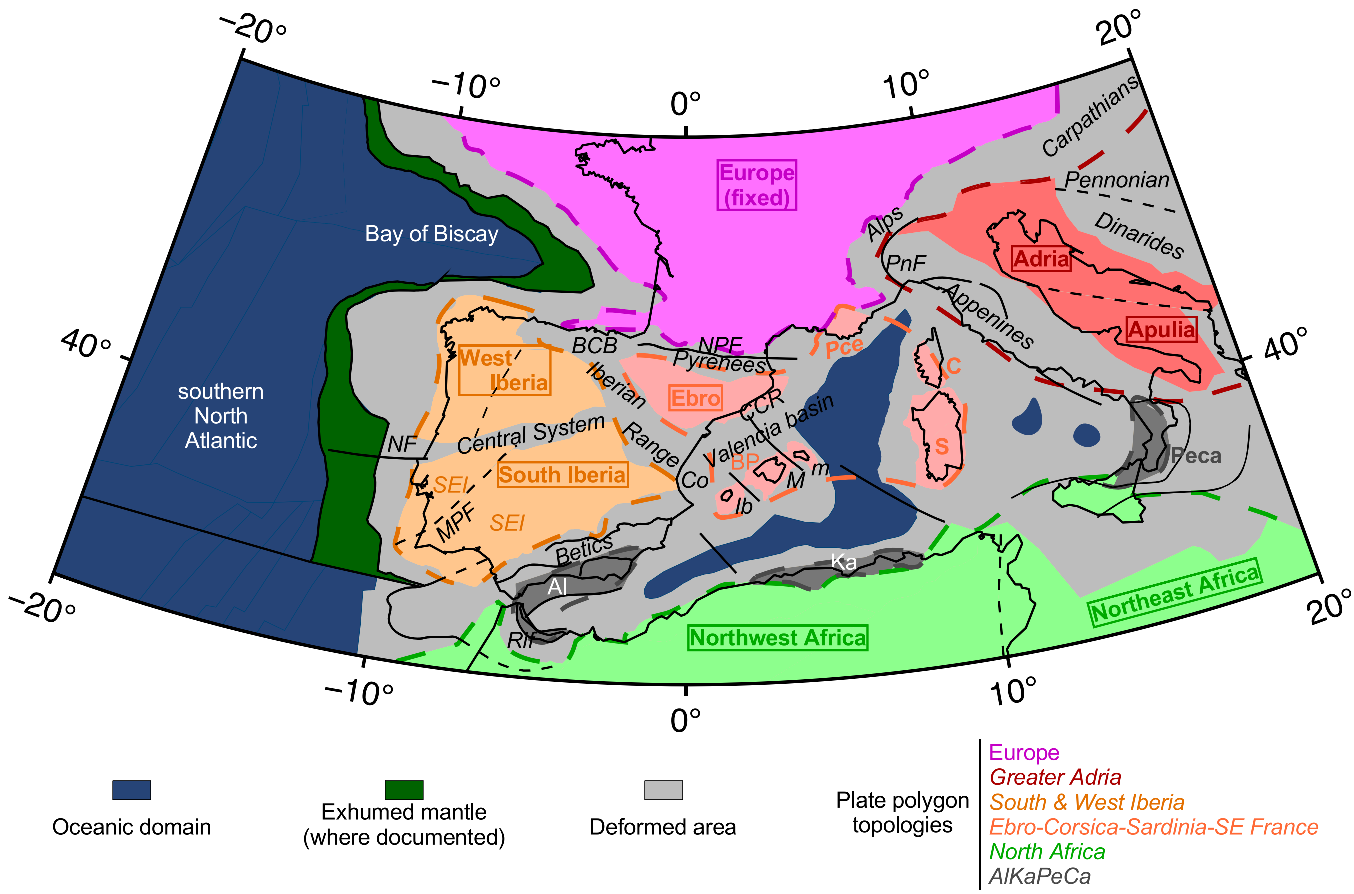

Fig. 4. Crustal segmentation of the West European domain. Variscan basement, which is assumed rigid (light colored), is transected by chains of alpine deformation (grey). Al: Alboran; BCB: Basque-Cantabrian basin; BP: Balearic Promontory; C: Corsica; CCR: Catalan Coastal Range; Ka: Kabylides; Pce: Provence; PeCa: Pelorita-Calabria; S: Sardinia.

Provence and the Vocontian basins, into a separated Provence continental domain, which is bounded to the west by inherited NE-SW crustal-scale faults (*e.g.*, Nîmes and Durance faults) and to the north and east by the Alpine orogen.

The similarities between the timing of collision, metamorphic and post-collisional events in the Variscan basement (Rossi *et al.*, 2009), including the late Carboniferous-Permian deformation and volcanism (Maures-Estérel Massif and Corsican Monte Cinto) and paleomagnetic directions between the Provence and the Sardinia-Corsica block (Maures-Estérel-Corsica-Sardinia –MECS– of Edel *et al.*, 2014, 2015), indicate they formed a single block prior the Early Cretaceous rifting. The question of whether Sardinia-Corsica belongs to the European plate or to the Iberian plate is debated. Reconstructions that consider Sardinia-Corsica as part of Europe (*e.g.*, van Hinsbergen *et al.*, 2020) are based on paleomagnetic data in Sardinia that indeed indicate a different rotation history for Iberia at 121 Ma (Advokaat *et al.*, 2014). It further implies a shortening of 400–500 km between Iberia and southern Sardinia of which there is no geological evidence.

Together with sedimentary affinities between Paleozoic sedimentary rocks documented in the eastern Pyrenees, the southern Sardinia, the Montagne Noire, and the SW France (*e.g.*, Padel *et al.*, 2018; see Sect. 3.6), paleomagnetic constraints during the late Paleozoic (Edel *et al.*, 2014) indicate that Ebro, Catalan Coastal Range, Sardinia and Corsica formed a coherent continental block until at least the Triassic (Edel *et al.*, 2014, 2015). We therefore adopt a solution in which Sardinia-Corsica belongs to the Ebro block. Hence, the Maures-Estérel-Sardinia-Corsica domain was part of the same Ebro continental block rather than Europe or Iberia. As such Maures-Estérel-Sardinia-Corsica domain moved eastward in left-lateral strike-slip movement relative to Europe from the late Permian to Early Cretaceous.

4.3 Greater Adria

Although focusing on the Iberian realm, our reconstruction aims to be integrated into a large-scale kinematic model that includes Iberia and Greater Adria. Greater Adria as defined by van Hinsbergen *et al.* (2020) comprises Adria *sensu-stricto*, Apulia (*i.e.*, southern Adria), and the future Alpine terranes, including AlCaPa, *i.e.*, the Alps, the Carpathian, and the Pannonian regions (Schmid *et al.*, 2008; Handy *et al.*, 2010).

According to paleomagnetic studies in NE Africa and Greater Adria, Muttoni *et al.* (2001) proposed that Greater Adria has been linked to Africa since the late Permian. These two plates drifted eastwards during the Early Jurassic as the Ionian basin opened (Tugend *et al.*, 2019). During the

Cenozoic, parts of the northern Alpine Tethys are accreted into the Apennines (Handy *et al.*, 2015; Marroni *et al.*, 2017) while the northern edge of Adria collided with Europe into the Alpine orogen (Rosenbaum *et al.*, 2002b; Handy *et al.*, 2010, 2015).

Some recent kinematic reconstructions accounted for internal deformation between Adria to the north and Apulia to the south to avoid overlap between Adria and Sardinia-Corsica prior to the opening of the Alpine Tethys (Le Breton *et al.*, 2017, 2021; Müller *et al.*, 2019). But the lack of geological evidence precludes precise quantitative estimates of the internal strain and segmentation within Greater Adria. In order to avoid overlap between Adria and the Balearic Promontory, over 200 km of intraplate shortening along the precursor of the Mid-Adriatic Ridge has been proposed (Müller *et al.*, 2019), which is much larger than in other reconstructions (*e.g.*, ~ 30 km for van Hinsbergen *et al.*, 2020). In this study, we choose another approach. The kinematics of Adria is reconstructed based on the kinematics of Apulia, which has NE Africa as a reference plate (Muttoni *et al.*, 2001). As a consequence in our reconstruction we assume a left-lateral strike-slip movement of ~ 100 km between Adria and Apulia.

In the Western Alps, crustal domains have been restored relative to the Penninic Front (Ramsay, 1981; Butler, 1985), which represents the neckline of the European margin (Mohn *et al.*, 2014). In the footwall of the Penninic Front, the crustal domain is deformed only during the orogeny (Ultrahelvetic nappes; Butler, 1985), while in the hanging wall, the Penninic units were deformed during the Tethyan extension and inverted during the Alpine orogeny.

4.4 AlKaPeCa

The Neogene evolution of the Western Mediterranean orogenic arcs (Gibraltar and Tyrrhenian) has been related to the tectonics of the AlKaPeCa microcontinent or terrane that originated from the southern European margin (Bouillin *et al.*, 1986) or alternatively from a Mesomediterranean microplate stretching between Africa/Adria and Europe during the Mesozoic. The existence and origin of these two models (see Guerrera *et al.*, 2019, for a recent review of the different published models) are basically related to two different Mesozoic reconstructions of the Alpine Tethys, including its connection to the Central Atlantic. The main difference between those end-member models is linked to the existence or not of an oceanic domain north of AlKaPeCa. Reconstructions that restore AlKaPeCa on the southern margin of Iberia consider a single oceanic domain to the south between Europe and Africa that represents the Alpine Tethys (Bouillin *et al.*, 1986; Lonergan and White, 1997; Lacombe and Jolivet, 2005; Billi *et al.*, 2011; Schettino and Turco, 2011; van Hinsbergen *et al.*, 2014). In a recent reconstruction, Angrand *et al.* (2020) accounted for the presence of a hyper-extended domain in the Betics, instead of an oceanic spreading center, that actually separates a "Briançonnais-like" rifted block representing Alboran and the Kabylides terranes. The second category of models adopts a solution with two oceanic branches, the Maghrebian Tethys (or East Ligurian Tethys) connected to the Lucanian basin in the east and the Nevado-Filabrides ocean (or Betic ocean) in the north, that is assumed to represent the Alpine Tethys through the connection with a West Ligurian ocean (Guerrera *et al.*, 2005; Michard *et al.*, 2006; Handy *et al.*, 2010; Guerrera and Martín-Martín, 2014; Leprêtre *et al.*, 2018).

Here, we adopt a different approach by suggesting that Alboran and Kabylides terranes are disconnected from the Peloritan and Calabrian blocks. This is supported by the following arguments. Alboran, including the internal parts of the Betics-Rif orogen, and Kabylides shared the same extensional history on the western termination of the Alpine Tethys (see Sect. 3.7), which is also very similar to the tectonic evolution of North Africa (Chalouan and Michard, 1990; Michard *et al.*, 2006). In contrast, the Peloritan-Calabrian domain to the east, once formed the distal margin of Sardinia-Corsica on the northern Alpine Tethys margin (Vitale *et al.*, 2013, 2019; Vitale and Ciarcia, 2013) later rifted from Sardinia during the Neogene due to back-arc extension in the Tyrrhenian Sea (Rossetti *et al.*, 2001; Faccenna *et al.*, 2014). HP metamorphism is reported to have occurred during the Paleogene in Alboran, Kabylides and in Peloritania (see above Sects. 3.2 and 3.7). This indicates these originally dispersed Mesozoic rift units all underwent subduction during Africa-Europe convergence, indicating a similar tectonic evolution during the main Cenozoic compressional event.

5 Kinematic reconstruction of the Africa-Europe plate boundary: from Tethys and Atlantic rifting to opening of the West-Mediterranean Sea

5.1 Implementation of recent kinematic models and reconstruction workflow

In addition to conform with geological constraints regarding the direction and amount of shortening/extension, and timing of deformation all over Iberia and in the South France, our kinematic model presented in Figures 5–12 also builds on the revision and updates of recent reconstructions of Africa, Adria, and Eastern Europe.

From 270 to 100 Ma, our reconstructions update the former kinematic model of Angrand *et al.* (2020). We remind that this study itself is based on the implementation of previous regional kinematic models of the North Atlantic (Barnett-Moore *et al.*, 2016; Nirrengarten *et al.*, 2018; Peace *et al.*, 2019b), Tethyan domains (Schmid *et al.*, 2008; Handy *et al.*, 2010; van Hinsbergen *et al.*, 2020) and global kinematic reconstructions (Müller *et al.*, 2019). We have applied minor modifications to the initial model by improving the full-fit adjustment between Iberia and North America during the late Permian-Triassic stage to correct the overestimated (and unsupported) strike-slip movement along the Nazaré Fault. In addition, we modified the geometry of the southern termination of the Alpine Tethys as well as the Ionian ocean to better represent the variable degree of crustal stretching and the tectonic evolution of oceanic domains (now consummed or preserved) in the Western Mediterranean domain.

After 100 Ma, the reconstruction of Eastern Europe follows that of van Hinsbergen *et al.* (2020). Kinematics of Africa and Apulia follows Müller *et al.* (2019) and Le Breton *et al.* (2021),

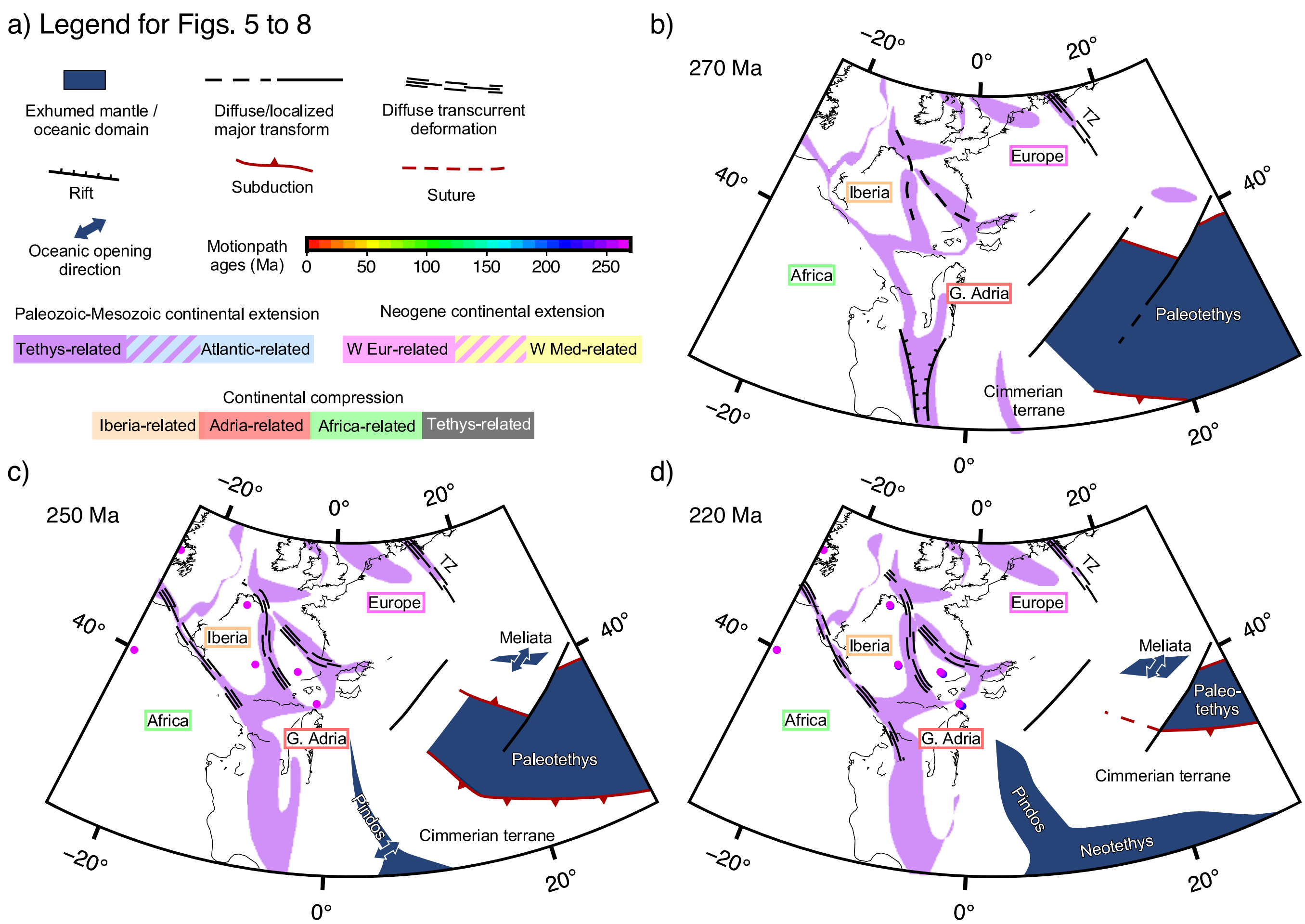

Fig. 5. Legend for Figures 5b–5d, 6, 7 and 8 (a) and large-scale geodynamic reconstruction of the Tethys–Atlantic area shown in orthographic projection for (b) 270 Ma, (c) 250 Ma, and (d) 220 Ma.

but we adopt a solution involving much smaller displacements between Apulia and Adria. The reconstruction of Alboran (Internal Betics) back to 60 Ma is based on the original position of the Cretaceous and Tertiary Flysch units of the Alboran domain which are restored 150 km to the south of present-day subduction front. This solution is supported by tectonic reconstruction of the Betic thrust wedge by Pedrera *et al.* (2020b). They are both consistent with the amount of convergence estimated between South Iberia and Africa (Macchiavelli *et al.*, 2017). The kinematic evolution of Sardinia-Corsica from 50 Ma onward follows Frasca *et al.* (2017). From 35 Ma onward, the kinematics of the West Mediterranean is based on Romagny *et al.* (2020) with the noticeable exception for Alboran that we have placed farther west at 35 Ma (Daudet *et al.*, 2020).

These input models were then updated according to the geological constraints presented in Section 3. These constraints include: (1) age of rifting, mantle exhumation, onset of oceanic spreading in the Atlantic; (2) the present-day position of ophiolite bodies and the timing of rifting, oceanic spreading and subduction in the Tethyan domains (Paleotethys, Neotethys, Pindos, Meliata, Vardar); (3) from 84 to 66 Ma, the closure exhumed mantle domain in the Pyrenean basins; (4) from 66 to ~25 Ma, continental deformation throughout Iberia and most of Western Europe (5) from ~35 Ma onward, continental deformation occurs in the Alps, coeval with the opening of the Gulf of Lion and the West Mediterranean domain.

Our reconstruction workflow relies on the use of GPlates version 2.2 (Müller *et al.*, 2018), an open-source plate tectonic geographic information system software that allows to visualize reconstructed data through time and to build evolving plate tectonic models. Stable continental domains are represented as rigid polygons.

Because of the inherent complexity associated with the reconstruction of highly segmented domains, defining the relationships between moving plate and their reference plate is not straightforward. In practice, we have defined new rigid polygons for Iberia (Galicia, Ebro, SW and SE Iberia), representing the three main continental domains presented in Section 4.1 (SW and SE Iberia being two sub-domains of South Iberia) separated by deformable domains. The plate circuit of Iberian continental blocks has been built as follows.

(1) West Iberia (Galicia) kinematics is based on the reconstruction of the southern North Atlantic, whose evolution

Table 1. Rotation poles of the main plates or continental blocks. Poles without references are from this study. See the complete list in the GPlates rotation file in Supplementary Material 2.

Plate	Age (Ma)	Latitude	Longitude	Angle	Ref plate	References
North America						
	0.0	90.0	0.0	0.0	NWA	Müller *et al.* (1999)
	10.9	81.0	22.90	2.84	NWA	Müller *et al.* (1999)
	20.1	80.6	24.50	5.53	NWA	Müller *et al.* (1999)
	33.1	75.99	5.98	9.77	NWA	Müller *et al.* (1999)
	40.1	74.50	−1.20	12.60	NWA	Müller *et al.* (1999)
	47.9	74.90	−4.60	15.61	NWA	Müller *et al.* (1999)
	55.9	80.64	6.57	17.90	NWA	Müller *et al.* (1999)
	67.7	82.30	−1.70	21.51	NWA	Müller *et al.* (1999)
	83.0	76.81	−20.59	29.51	NWA	Nirrengarten *et al.* (2018)
	120.4	66.28	−19.82	54.44	NWA	Nirrengarten *et al.* (2018)
	126.7	66.11	−18.95	56.48	NWA	Nirrengarten *et al.* (2018)
	131.9	65.95	−18.50	57.45	NWA	Nirrengarten *et al.* (2018)
	139.6	66.12	−18.38	59.90	NWA	Nirrengarten *et al.* (2018)
	147.7	66.54	−17.98	62.08	NWA	Nirrengarten *et al.* (2018)
	154.3	67.15	−15.98	64.75	NWA	Nirrengarten *et al.* (2018)
	170.0	67.09	−13.86	70.55	NWA	Nirrengarten *et al.* (2018)
	190.0	64.31	−15.19	77.09	NWA	Nirrengarten *et al.* (2018)
	203.0	64.28	−14.74	78.05	NWA	Nirrengarten *et al.* (2018)
	600.0	64.28	−14.74	78.05	NWA	Nirrengarten *et al.* (2018)
Europe						
	0.0	90.0	0.0	0.0	NAM	Gaina *et al.* (2002)
	10.90	66.44	132.98	−2.57	NAM	Gaina *et al.* (2002)
	20.10	68.91	132.51	−5.09	NAM	Gaina *et al.* (2002)
	33.10	68.22	131.53	−7.65	NAM	Gaina *et al.* (2002)
	47.90	65.38	138.44	−10.96	NAM	Gaina *et al.* (2002)
	55.90	56.17	145.06	−13.24	NAM	Gaina *et al.* (2002)
	68.70	60.38	146.96	−16.33	NAM	Barnett-Moore *et al.* (2018)
	79.10	63.40	147.75	−18.48	NAM	Gaina *et al.* (2002)
	79.10	48.1723	121.6263	−12.709	GRN	Barnett-Moore *et al.* (2018)
	120.0	48.1723	121.6263	−12.709	GRN	Barnett-Moore *et al.* (2018)
	120.0	68.0131	153.6058	−21.0127	NAM	Barnett-Moore *et al.* (2018)
	200.0	71.41	152.6	−23.68	NAM	Barnett-Moore *et al.* (2018)
	270.0	71.41	152.6	−23.68	NAM	Barnett-Moore *et al.* (2018)
West Iberia (Galicia)						
	0.0	90.0	0.0	0.0	EUR	Macchiavelli *et al.* (2017)
	20.0	34.6758	−22.684	0.7335	EUR	Macchiavelli *et al.* (2017)
	33.0	36.9056	−25.185	−0.6474	EUR	Macchiavelli *et al.* (2017)
	46.0	−42.8207	158.4065	1.5161	EUR	Macchiavelli *et al.* (2017)
Southwest Iberia						
	0.0	90.0	0.0	0.0	GAL	
	1.0	90.0	0.0	0.0	GAL	
	7.0	35.3354	−1.1946	1.3522	GAL	
	60.0	36.5119	−31.7606	−1.5482	GAL	
	118.0	38.7885	−12.696	−4.2946	GAL	
	145.0	47.461	−13.1361	−5.6787	GAL	
	270.0	48.7405	−14.5492	−5.2511	GAL	
Ebro						
	0.0	90.0	0.0	0.0	EUR	
	20.0	90.0	0.0	0.0	EUR	
	59.0	−17.2411	130.203	1.1119	EUR	
	66.0	−17.2411	130.203	1.1119	EUR	
	66.0	37.8382	−6.8077	4.9793	SEI	
	84.0	40.5405	−5.2984	6.2884	SEI	
	94.0	42.9344	−2.20179	14.8977	SEI	
	118.0	46.5014	−0.781799	22.4665	SEI	
	118.0	−48.3395	−177.11	−17.9568	GAL	
	145.0	−48.7407	−173.541	−18.9312	GAL	
	145.0	−62.6742	−175.549	9.1506	EUR	
	230.0	−62.6742	−175.549	9.1606	EUR	
	270.0	−60.7558	−174.8312	11.1754	EUR	
Adria						
	0.0	90.0	0.0	0.0	APU	Müller *et al.* (2019)
	40.0	90.0	0.0	0.0	APU	Müller *et al.* (2019)
	60.0	35.6104	168.3145	0.9504	APU	Müller *et al.* (2019)
	120.0	35.6104	168.3145	0.9504	APU	
	250.0	35.6104	168.3145	0.9504	APU	
	270.0	35.6104	168.3145	0.9504	APU	
Apulia						
	0.0	90.0	0.0	0.0	EUR	Le Breton *et al.* (2017)
	20.0	38.2028	−3.1628	−5.3474	EUR	Le Breton *et al.* (2017)
	20.0	50.6886	16.3661	−3.4177	NEA	Müller *et al.* (2019)
	100.0	50.6886	16.3661	−3.4177	NEA	Müller *et al.* (2019)
	120.0	50.6886	16.3661	−3.4177	NEA	Müller *et al.* (2019)
	170.0	10.0343	18.9526	−3.9175	NEA	Müller *et al.* (2019)
	175.0	39.7055	4.3502	−3.4621	NEA	Müller *et al.* (2019)
	230.0	68.6343	−39.6767	−3.6207	NEA	Müller *et al.* (2019)
	270.0	68.6343	−39.6767	−3.6207	NEA	

Table 1. (continued).

Plate	Age (Ma)	Latitude	Longitude	Angle	Ref plate	References
	55.0	−17.8873	158.2049	1.7971	EUR	Macchiavelli *et al.* (2017)
	66.0	−34.5095	166.578	3.16	EUR	Macchiavelli *et al.* (2017)
	71.0	−36.2468	167.9516	3.7895	EUR	Macchiavelli *et al.* (2017)
	84.0	−43.3004	165.5395	5.5275	EUR	Macchiavelli *et al.* (2017)
	86.0	−40.18	170.57	10.07	EUR	
	120.0	−47.9216	179.85	22.8717	EUR	
	135.0	−49.5226	−177.8405	27.0209	EUR	
	145.0	−53.1902	−175.2977	27.8977	EUR	
	200.0	−51.2012	−174.7002	28.0853	EUR	
	270.0	51.42.15	5.6495	−28.4531	EUR	
Southeast Iberia						
	0.0	90.0	0.0	0.0	SWI	
	60.0	31.1736	−0.6048	−0.9804	SWI	
	270.0	47.5228	−15.9198	1.3018	SWI	
Northwest Africa						
	0.0	90.0	0.0	0.0	NEA	Heine *et al.* (2013)
	110.0	90.0	0.0	0.0	NEA	Heine *et al.* (2013)
	145.0	25.21	5.47	2.87	NEA	Heine *et al.* (2013)
	190.0	28.6241	7.0804	2.8771	NEA	Heine *et al.* (2013)
	250.0	25.21	5.47	2.87	NEA	Heine *et al.* (2013)
	270.0	25.21	5.47	2.87	NEA	
Northeast Africa						
	0.0	90.0	0.0	0.0	AFR	Heine *et al.* (2013)
	110.0	90.0	0.0	0.0	AFR	Heine *et al.* (2013)
	145.0	4.0	34.0	1.61	AFR	Heine *et al.* (2013)
	250.0	4.0	34.0	1.61	AFR	Heine *et al.* (2013)
	270.0	4.0	34.0	1.61	AFR	

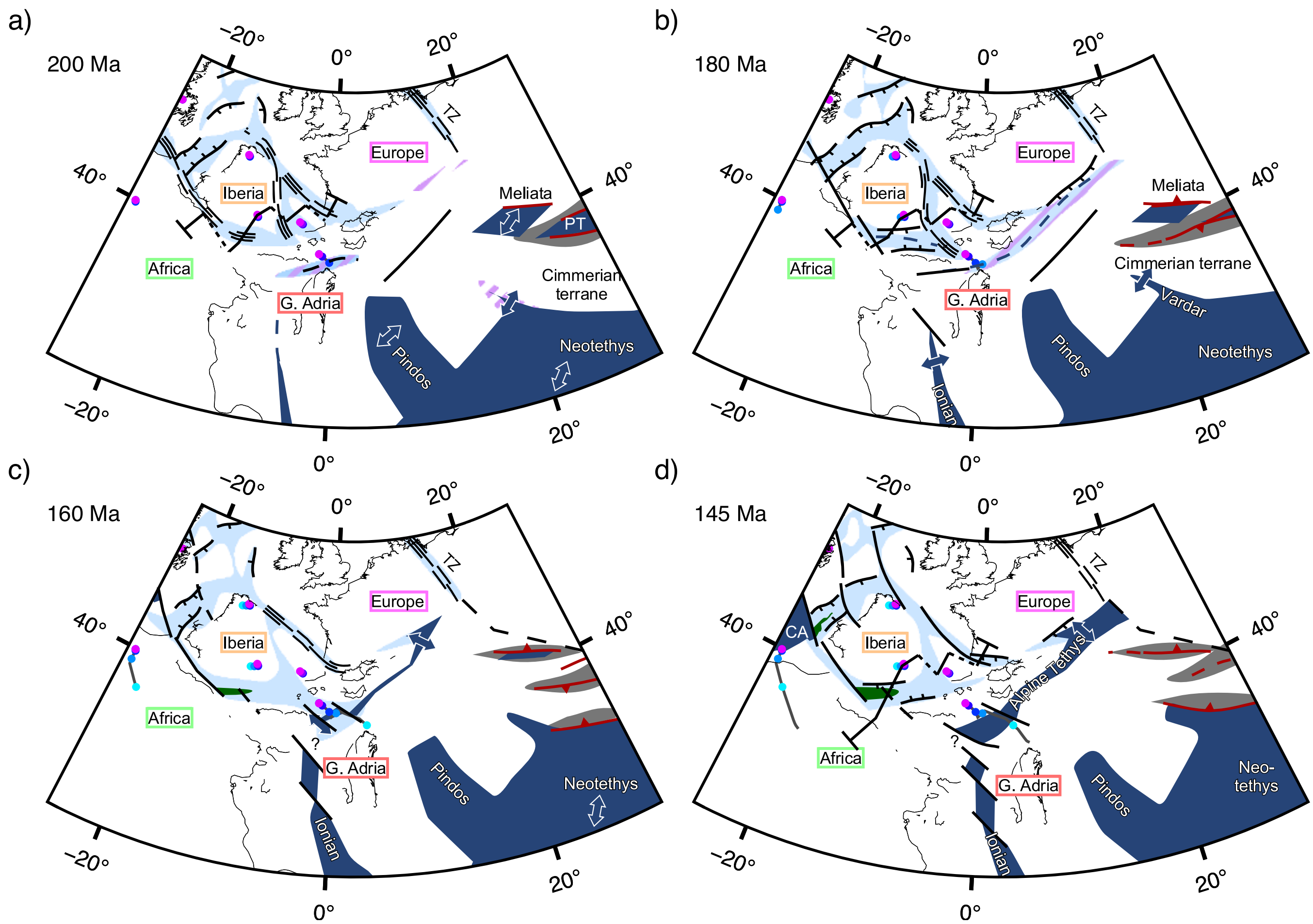

Fig. 6. Large scale reconstructions of the Tethys-Atlantic area shown in orthographic projection for (a) 200 Ma, (b) 180 Ma, (c) 160 Ma, and (d) 145 Ma. For legend see Figure 5a.

is constrained by study of oceanic magnetic anomalies (Nirrengarten *et al.*, 2018).

(2) The Ebro block has a much complex kinematic history. From 270 to 145 Ma, Ebro is attached to Europe, whereas from 145 to 118 Ma, Ebro is moving along with Galicia which movement is driven by the opening of the southern North Atlantic. From 118 to 84 Ma, Ebro motion follows that of Southeasth Iberia to take into account the N-S extension associated with the opening of the Bay of Biscay. Finally, the Ebro block is reconstructed relative to Europe from 66 Ma, once the Pyrenean rift domain is closed.

(3) The southwest and southeast Iberia are two sub-domains of southern Iberia that reflect minor displacement along the Messejana-Plasencia Fault. Southeast Iberia is attached to southwest Iberia, the latter being attached to Galicia.

We present our reconstructions into successive time frames at different spatial scales so as to emphasize 1) the large scale plate configuration between whole Europe and northern Africa highlighting the connection between Atlantic, Alpine Tethys and Neotethys (Figs. 5–8), and 2) a more regional scale reconstruction of the Mediterranean region putting more emphases on the main structures, microplates, strain distribution, and paleogeography (*i.e.*, continental domain *versus* main rift/orogenic basins) (Figs. 9–12). Results of the kinematic model are synthesized as rotation poles for the main plates in Table 1 (see also Supplementary Material 2 for GPlates files).

5.2 Plate reconstruction

5.2.1 Late Permian-Lower Triassic (270–200 Ma)

The breakup of Pangea during the late Paleozoic was accompanied by the closure of the Paleotethys and the opening of the Neotethys to the south (Figs. 5 and 6) (Stampfli *et al.*, 2001; Stampfli and Borel, 2002). The northward drift of the Cimmerian terrane associated with the subduction of the Paleozoic Paleotethys Ocean (*e.g.*, van Hinsbergen *et al.*, 2020), resulted in the opening of back-arc Pindos and Meliata oceanic basins during the Early (∼250 Ma) and Late Triassic (Carnian, 220 Ma), respectively (Fig. 5) (Channell and Kozur, 1997; Stampfli *et al.*, 2001).

The westward propagation of the Neotethys into the European lithosphere resulted in distributed extension in Western Europe and North Africa, extending further north in the future North Atlantic domain (Angrand *et al.*, 2020, and references therein; Ziegler, 1990a; Leleu *et al.*, 2016; Tavani *et al.*, 2018; Soto *et al.*, 2019). From early Permian to Middle

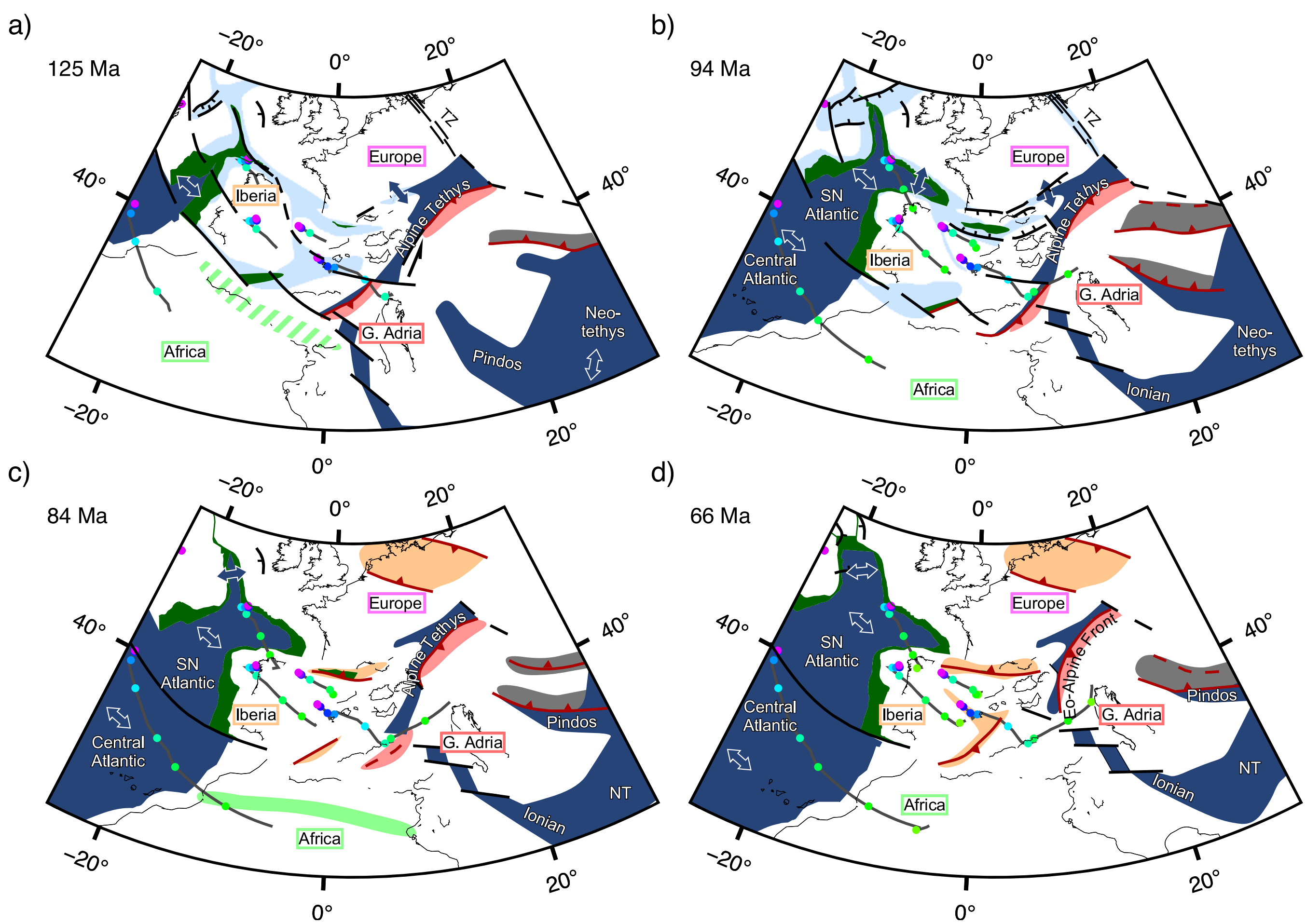

Fig. 7. Large scale reconstructions of the Tethys-Atlantic area shown in orthographic projection for (a) 125 Ma, (b) 94 Ma, (c) 84 Ma, and (d) 66 Ma. For legend see Figure 5a.

Triassic, the Arctic rift propagated southwards into a North Atlantic rift, making links in the North Sea basins with the Neotethys ocean (Goldsmith *et al.*, 2003). This is indicated by the development of numerous Permian-Triassic salt-rich basins (Van Wees *et al.*, 2000), and by the acceleration of subsidence in the Betic, Catalonia, and Provence areas (Espurt *et al.*, 2012; Tavani *et al.*, 2018; Angrand *et al.*, 2020) synchronous with the onset of crustal thinning in the Alpine Tethys (Figs. 5 and 9) (Stampfli and Borel, 2002; Schmid *et al.*, 2008).

The exact position of the Alboran and Kabylide terranes is speculative. However, there are several lines of evidence suggesting that Alboran, and by extension the Kabylides, were located south of Iberia, between Adria and Africa, in the center of a rift zone precursor to the Alpine Tethys (Fig. 9). This is corroberated by 1) the occurrence of a Permian-Triassic rift positioned on the south Iberian margin (López-Gómez *et al.*, 2019), north Alboran and Kabylides, including the thick evaporites in the Late Triassic in the external Betic and Pre-Betic (Flinch and Soto, 2017), 2) the facies of Triassic carbonates of the Alpujarride Complex that places the Internal Zone of the Alboran domain in the Alpine Tethys rift (Martin-Rojas *et al.*, 2009), and 3) upper Paleozoic reconstructions that consider the Alboran Paleozoic basement close to the south Iberian paleomargin (Jabaloy-Sánchez *et al.*, 2021). The position of the Peloritani-Calabria terrane is also difficult to precisely assess. According to the two-oceans hypothesis, the Peloritani and Calabria terranes are restored east of the Mesomediterrean microplate on the margin of the Ionian and East Ligurian rift (*e.g.*, Perrone *et al.*, 2006). Here we follow reconstructions that restore Peloritani and Calabria terranes east of Sardinia (present-day coordinates) prior the opening of the Tyrrhenian Sea in the Neogene (Rossetti *et al.*, 2001; Shimabukuro *et al.*, 2012; Vitale and Ciarcia, 2013; Milia and Torrente, 2014). We acknowledge that Calabria may have been slightly rifted from Sardinia later during the Jurassic (Malusà *et al.*, 2016) but this is ill-defined and has not been explicitly taken into account in our reconstruction.

5.2.2 Jurassic (200–145 Ma)

The opening of the Central Atlantic during the Early Jurassic tiggered the northward propagation of the rift in the southern North Atlantic, on the south-western margin of Iberia (Figs. 6 and 10) (Murillas *et al.*, 1990; Leleu *et al.*, 2016). This stage was preceded by the Central Atlantic Magmatic Province (CAMP, Olsen, 1997; Marzoli *et al.*, 1999; McHone, 2000), associated with magmatic intrusions in Iberia (Messejana-

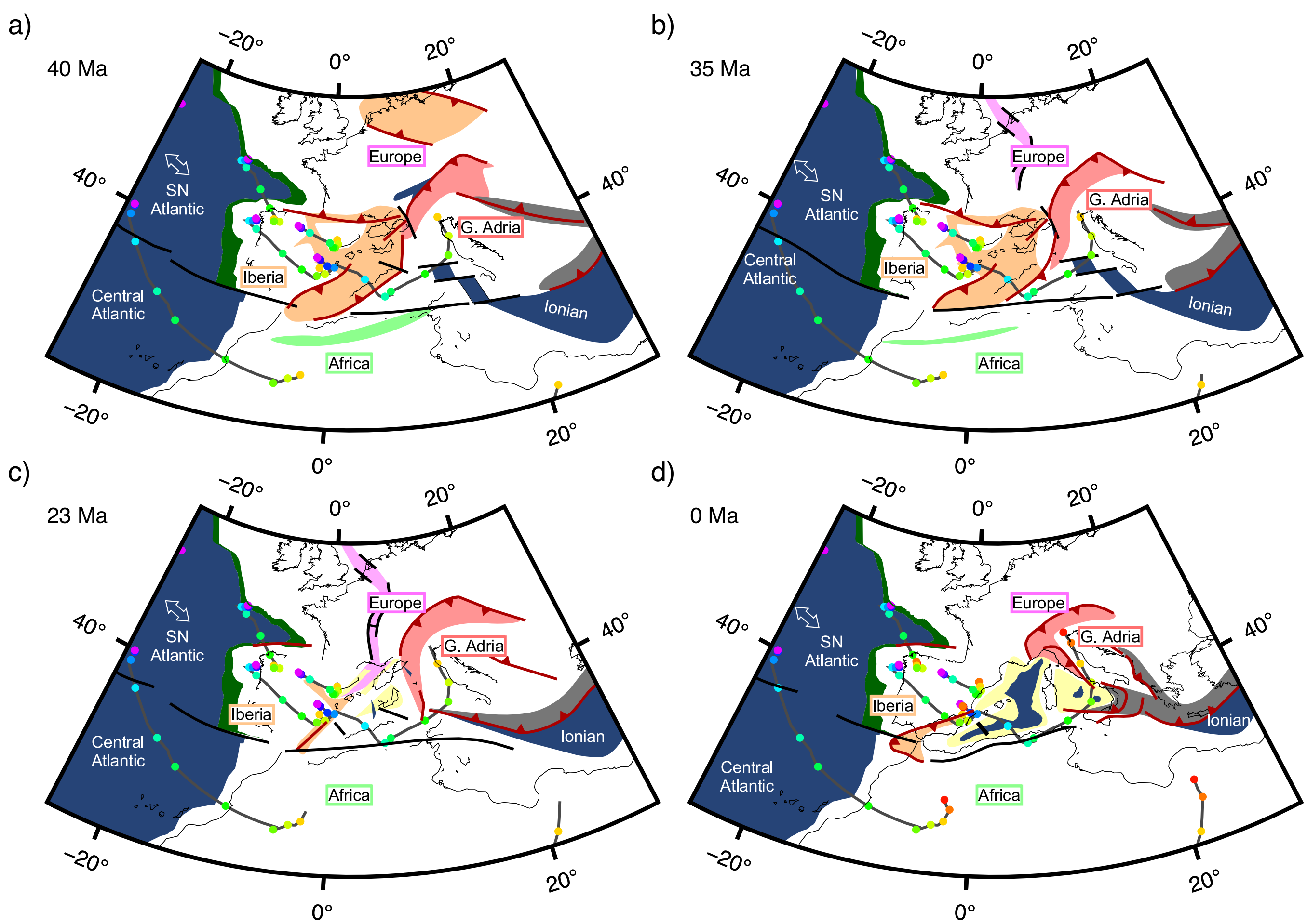

Fig. 8. Large scale reconstructions of the Tethys-Atlantic area shown in orthographic projection for (a) 40 Ma, (b) 35 Ma, (c) 23 Ma, and (d) 0 Ma. For legend see Figure 5a.

Plasencia dyke; Cerbiá *et al.*, 2003), in the Pyrenees (ophitic magmatism; *e.g.*, Azambre *et al.*, 1987), and possibly in the Rif (Gimeno-Vives *et al.*, 2019) predating the opening of the southern Alpine Tethys (also named the Maghrebian Tethys). Although the exact age for the onset of oceanic extension may be debated (Schettino and Turco, 2009; Labails *et al.*, 2010; Kneller *et al.*, 2012), the opening of the Central Atlantic in the Early Jurassic (~ 190 Ma) (Schettino and Turco, 2009; Labails *et al.*, 2010) is in agreement with the regional geodynamics and magmatic events (CAMP). Changes in the opening directions and rates of the Central Atlantic ocean then controlled the Africa kinematics from the Late Jurassic to Early Cretaceous (Labails *et al.*, 2010).

Rifting and opening of Alpine Tethys initiates rifting between Iberia and Adria (Schmid *et al.*, 2008; Marroni *et al.*, 2017; Le Breton *et al.*, 2021), which occurred by the reactivation of Triassic Neotethyan rift structures (Angrand *et al.*, 2020). The exact timing of continental breakup is determined by the MORB-type gabbro at the Atlantic-Tethys junction dated as Lower to early Middle Jurassic (~ 190 Ma) (Fernández, 2019) consistent with the age of eclogitized gabbros of ~ 185 Ma from the Betic ophiolites interpreted as being formed at a slow-spreading ridge or ocean-continent transition at the southwestern termination of the Alpine Tethys (Puga *et al.*, 2011) (Figs. 6d and 10d). In our reconstruction, the Betic rift between Alboran and Iberia is suggested to propagate to the north, but appears interrupted along transfer zones (possibly connected with basins of the Iberian Range) thus forming rift segments in the Alpine Tethys south of the Sardinia-Corsica-Peloritani-Calabrian domain, but not directly connected to it.

The timing of MORB-type magmatism in the Betics and North Africa is consistent, despite slightly older, with the Middle Jurassic (170–161 Ma, Fig. 6) ages for the onset of oceanic spreading in the northern Alpine Tethys as constrained in the Alps (Schaltegger *et al.*, 2002), and in agreement with the first postrift sediments (Bill *et al.*, 2001). This is also indicated by the subsidence associated with the southern Alpine Tethys on the paleo-Calabria margin (Bouillin *et al.*, 1988).

The age of opening of the Ionian basin between Adria and Africa is debated. Continental extension and spreading has been suggested to have started in the late Permian-Triassic (*e.g.*, Stampfli *et al.*, 2001). Despite rifting did occur in the Tethyan realm since the late Permian, there are no firm constraints on oceanic spreading before the Lower Jurassic (~ 180 Ma, Tugend *et al.*, 2019). The opening of the Ionian basin causes Adria to rotate and move northeastward relative to

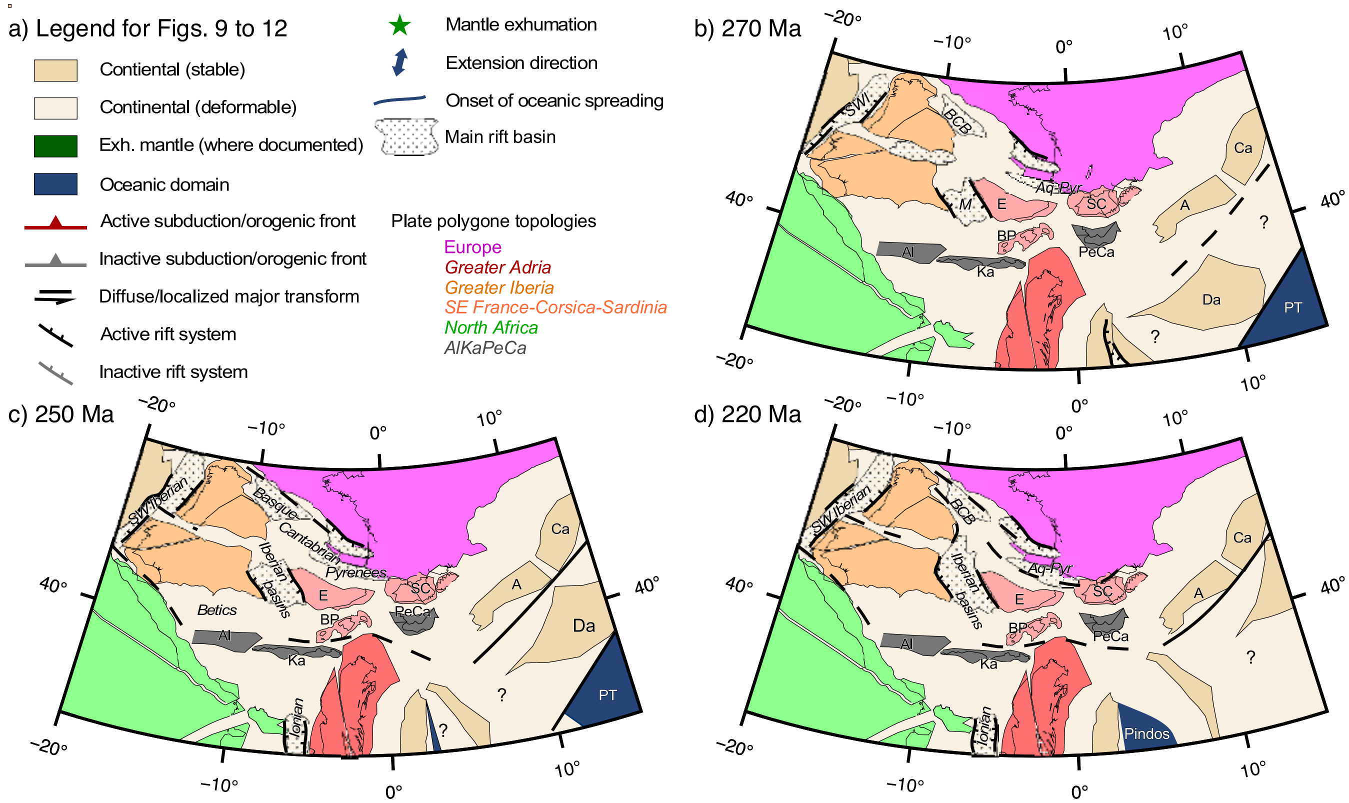

Fig. 9. Legend for Figures 9b–9d, 10, 11 and 12 (a) and kinematic reconstruction maps showing the main structural events of the Africa-Europe plate boundary with the main rift basins shown in orthographic projection for (b) 270 Ma, (c) 250 Ma, and (d) 220 Ma. A: Austro-Alpine; Al: Alboran; Aq-Pyr: Aquitaine–Pyrenean Basin; BCB: Basque–Cantabrian Basin; BP: Balearic Promontory; Ca: Carpathian; Da: Dacia; E: Ebro; Ka: Kabylides; M: Maestrat; PeCa: Pelorita-Calabria; PT: Paleo-Tethys; SC: Sardinia-Corsica; SWI: southwest Iberia.

Africa. Rifting triggered extension in the southern Alpine Tethys and segmentation along continental transfer faults from 180 Ma onward (Figs. 6b and 10b). The eastward drift of Adria relative to Africa at ~160 Ma induced the opening of the Alpine Tethys. The resulted strain accommodated by the differential extension between the Atlantic and the Alpine Tethys along a transform plate boundary between Iberia and Africa. This transform fault temporally coincides with a pause in the north-directed ridge propagation of the Atlantic, as argued by 3D numerical modelling of ridge migration (Jourdon *et al.*, 2020). Coeval with the counterclockwise rotation of Africa and its eastwards displacement, subduction occurs along the northern Neotethys margin and closes the Vardar ocean (Figs. 7c and 7d) (Schmid *et al.*, 2008).

Because the tectonic reorganization during the Early to Middle Jurassic focused east of Iberia, in the Alpine Tethys, this stage defines an apparent tectonic quiescence along the Iberia-Europe boundary in the Pyrenees-Provence. This is also true for Central Iberia that recorded slow subsidence or even uplift between 200 and 160 Ma, contrasting with the previous Permian-Triassic rifting stage between Ebro and Western Iberia (Figs. 6 and 10).

During the Late Jurassic-Early Cretaceous continental rifting occurred between North Africa and the Iberian Range rift. It resulted in transtensional deformation between Ebro and Iberia, which extended farther eastward into the Alpine Tethys (Figs. 6d, 7a, 10d and 11a). This is in agreement with the segmented nature of the East Iberian margin between the ENE-WSW oriented Betics and NE-SW trending Catalan Coastal Ranges at that time (Handy *et al.*, 2010; Frizon De Lamotte *et al.*, 2011; Sallarès *et al.*, 2011; Schettino and Turco, 2011; Vergés and Fernàndez, 2012; Vergés *et al.*, 2020).

5.2.3 Lower to middle Cretaceous (145–94 Ma)

Rift propagation in the southern North Altantic was associated with the spread of extension over Iberia, in the Iberian Range, the Betics, the Basque-Cantabrian and the Valencia (Columbretes) basins, while the Provence and Sardinia-Corsica formed a topographic high and the Pyrenees recorded moderate extension (Figs. 7 and 11).

The opening of the southern North Atlantic induced the eastward displacement of South Iberia relative to the Ebro-Sardinia-Corsica block, which in turn moved eastwards relative to Europe. Extension reactivated earlier rift basins of Permian-Triassic (*e.g.*, Pyrenees, Iberian Range) or Jurassic ages (southern Tethys). The obliquity of extension relative to the direction of Parentis and Pyrenees-Provence rifts caused transtensional opening in the Basque-Cantabrian and Iberia Ranges (Tugend *et al.*, 2015; Aurell *et al.*, 2019a; Rat *et al.*, 2019) (Fig. 7a). Rifting in the Valencia basin (Columbretes) further reveals that extension reached the east of the Ebro block and the eastern Pyrenean rift (Corbières). We suggest

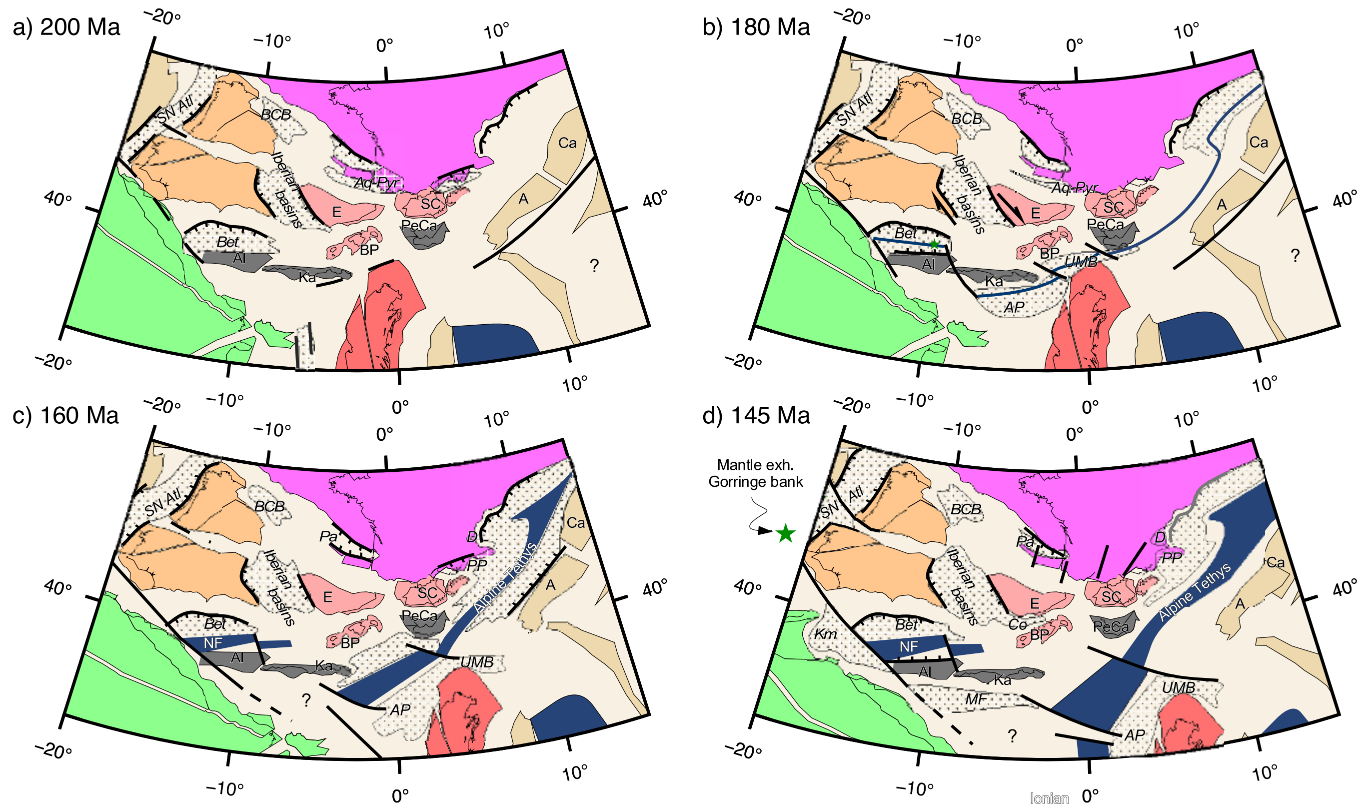

Fig. 10. Kinematic reconstruction maps for the main structural events of the Africa-Europe plate boundary with the main rift basins shown in orthographic projection for (a) 200 Ma, (b) 180 Ma, (c) 160 Ma, and (d) 145 Ma. For legend see Figure 9a. A: Austro-Alpine; AP: Appennine Platform; Aq-Pyr: Aquitaine-Pyrenees; Al: Alboran; BP: Balearic Promontory; BCB: Basque-Cantabrian basin; Bet: Betic basin; Ca: Carpathian; Co: Columbretes basin; D: Dauphinois; E: Ebro; Ka: Kabylides; Km: Ketama basin; MF: Maghrebian Flysch basin; PeCa: Pelorita-Calabria; PP: Provence Platform; SC: Sardinia-Corsica; SN Atl: Southern North Atlantic; UMB: Umbria-Marche basin.

extension was associated with the reactivation of ENE-SW trending faults (*e.g.*, Nîmes Fault) inherited from the late Variscan evolution.

After a phase of stalling, the northward propagation of the Atlantic resumed at 147–133 Ma (Fig. 6d) in SW Iberia (Sallarès *et al.*, 2013) and at 139 Ma offshore southwest Galicia margin (Mohn *et al.*, 2015) as shown by mantle exhumation. Oceanic spreading then occurred at 135–133 Ma in SW Iberia (Figs. 7a and 11a) and at 121–112 Ma on the Galicia margin (Bronner *et al.*, 2011; Vissers and Meijer, 2012). Migration of extension to the north (Figs. 17a and 17b) (*e.g.*, Rat *et al.*, 2019) ultimately led to oceanic spreading in the Bay of Biscay and hyper-extension in the Parentis and Pyrenean rift basins at ~120 Ma (Jammes *et al.*, 2009; Lagabrielle *et al.*, 2010; Mouthereau *et al.*, 2014; Tugend *et al.*, 2014a; Tugend *et al.*, 2015). From the late Aptian to Cenomanian, the direction of extension in the Pyrenean basins changed to approximately N-S (Sibuet *et al.*, 2004; Barnett-Moore *et al.*, 2016; Angrand *et al.*, 2020).

The eastward movement of Iberia relative to Adria is suggested to have resulted in the closure of the southern Alpine Tethys during the Early Cretaceous between 125–90 Ma (Angrand *et al.*, 2020; Le Breton *et al.*, 2021) (Fig. 11b). The movement of Iberia is modest at this time but sufficient to start closing the narrow southern Alpine Tethys domain. Such Early Cretaceous contractional event implied by the model seems supported by data from the Kabylides, as there are some evidence of ductile shearing in the gneissic rocks of the paleozoic Kabylides basement dated at 128 Ma (Hauterivian-Barremenian) (Cheilletz *et al.*, 1999). In addition, intra-oceanic subduction associated with emplacement of mantle materials from the Edough Massif of the Kabylides has been suggested (Fernandez *et al.*, 2020). Moreover, geological constraints from the Ligurian units of the North Apennines (Marroni *et al.*, 2017) indicate a limited sedimentary thickness (estimated at 500 m) on the Adria margin from Late Jurassic to Santonian that can hardly be accounted for by postrift subsidence. Although these data are sparse, they argue that Early Cretaceous obduction/subduction is likely to have occurred in the southern Alpine Tethys.

From the late Aptian to the Cenomanian, the southward movement of Ebro due to N-S extension in the Bay of Biscay-Pyrenean basins was responsible for transpression between SW Ebro and the eastern West Iberian block. A modest shortening of ~20 km is estimated on the western Iberian basins (Fig. 11a). Such a contraction is suggested to have been recorded in the Cameros basin between the early Albian and Cenomanian, before the HT metamorphism peak at ca. 100 Ma (Casas-Sainz and Gil-Imaz, 1998) and coeval with a halt of tectonic subsidence (Omodeo-Salé *et al.*, 2017). The axial-plane cleavages documented in the Cameros basin may indeed reflect a contraction phase, much earlier that the collision-

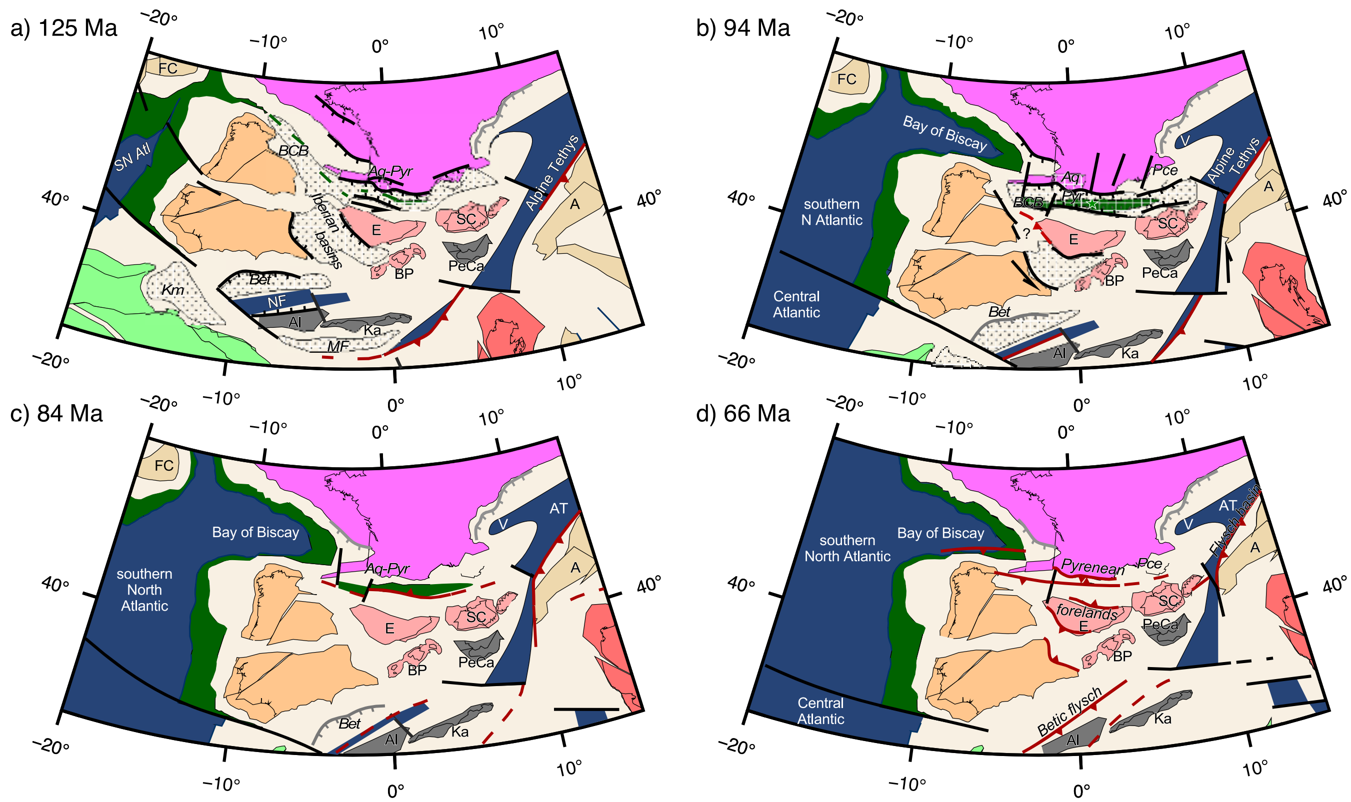

Fig. 11. Kinematic reconstruction maps for the main structural events of the Africa-Europe plate boundary with the main rift basins shown in orthographic projection for (a) 125 Ma, (b) 94 Ma, (c) 84 Ma, and (d) 66 Ma. For legend see Figure 9a. A: Austro-Alpine; Al: Alboran; AP: Apennine Platform; Aq-Pyr: Aquitaine-Pyrenees; BCB: Basque-Cantabrian basin; Bet: Betic basin; BP: Balearic Promontory; E: Ebro; FC: Flemish Cap; Ka: Kabylides; Km: Ketama basin; MF: Maghrebian Flysch basin; Pce: Provence basin; PeCa: Pelorita-Calabria; SC: Sardinia-Corsica; SN Atl: Southern North Atlantic; UMB: Umbria-Marche basin.

related cooling stage at 60 Ma (Rat *et al.*, 2019). To our knowledge there is no evidence for contraction elsewhere in the Iberian Range. At 94 Ma (late Cenomanian; Figs. 7b and 11b), extension reached its maximum in the Pyrenean arm and in the Betics, but appears limited in the Iberian Range despite the high thermal gradients and metamorphism of this age reported in the Cameros Basin. The regional HT anomaly found close to the Bay of Biscay and Pyrenees suggests control by channelized low-viscosity asthenospheric mantle rising below the Bay of Biscay spreading ridge and directed towards the east.

In the Late Jurassic-Early Cretaceous, a new episode of rifting occurred on the European margin associated with the development of the Valais basin (Schettino and Turco, 2011). While it was previously regarded as a western oceanic branch of the northern Alpine ocean between Adria (or Alcapia of Handy *et al.*, 2010) and Europe, its timing preferably suggests a relationship with the eastward drift of the Iberian plate (Beltrando *et al.*, 2007; Schettino and Turco, 2011) or, more exactly, with the Ebro-Sardinia-Corsica block in our reconstruction (Figs. 7a, 7b, 11a and 11b). The opening of the Valais ocean lasted until the middle Cretaceous (93 Ma) as nappe stacking in the Austro-Alpine domain started (Eo-Alpine orogeny, *e.g.*, Handy *et al.*, 2010) due to the northward movement of Greater Adria (Figs. 7a and 7b) (Müller *et al.*, 2019). It is worth noting that the Pyrenees-Provence rift is not extended further east into the Alpine Tethys but rather jumps into the Vocontian basin, which arguably defined the termination of the Valais ocean. In this case, the Briançonnais block is inferred to be the continuation of the Provence High to the east.

The onset of subduction of the northern Alpine Tethys that responds to the NE-directed movement of Adria (Fig. 7a) is dated at 125 Ma in our model, which is slightly older than in other reconstructions (Schettino and Scotese, 2002: 110 Ma; Handy *et al.*, 2010: 94–84 Ma; van Hinsbergen *et al.*, 2020: 94 Ma). This movement implies transcurrent left-lateral movement along the western margin of Adria, which also limits the amount of subduction below the Adria margin, along the Sardinia-Corsica-Peloritani-Calabria segment, in accord with geological constraints.

5.2.4 Late Cretaceous to Paleogene (84–35 Ma)

The late Santonian-Campanian marks the onset of N-S convergence between Africa, Iberia and Europe, postdating the onset of N-directed drift of Adria. This kinematic change induced the acceleration of closure of Alpine Tethys in the Western Alps and the inversion of most Mesozoic rifted domains in Iberia and Ebro-Sardinia-Corsica (Figs. 7c and 11c). In the west, convergence is accommodated by underthrusting and closure of the exhumed mantle domain

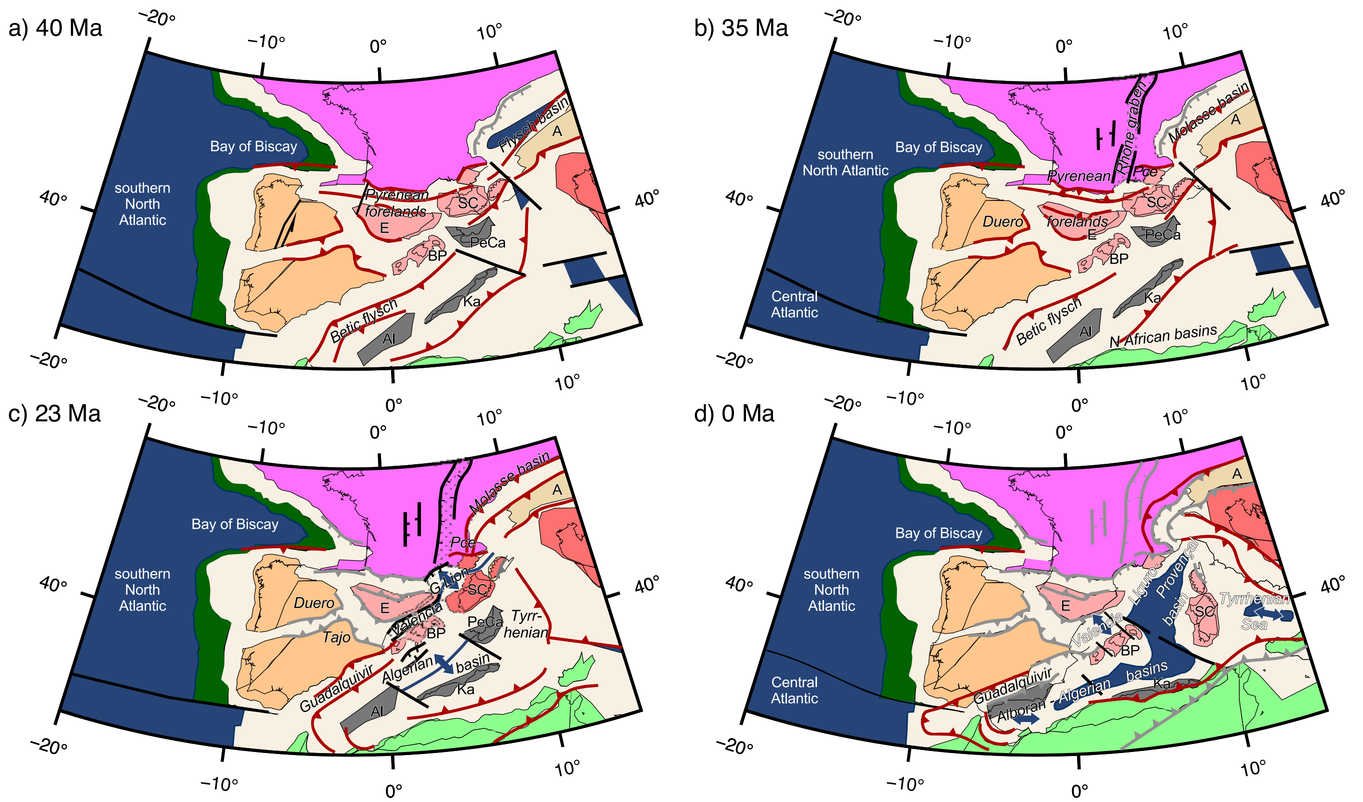

Fig. 12. Kinematic reconstruction maps for the main structural events of the Africa-Europe plate boundary shown in orthographic projection for (a) 40 Ma, (b) 35 Ma, (c) 23 Ma, and (d) 0 Ma. For legend see Figure 9a. A: Austro-Alpine; Al: Alboran; BP: Balearic Promontory; E: Ebro; Ka: Kabylides; Pce: Provence; PeCa: Pelorita-Calabria; SC: Sardinia-Corsica.

in the Pyrenean (Mouthereau *et al.*, 2014; Ford *et al.*, 2016; Teixell *et al.*, 2016) and Basque-Cantabrian basin (DeFelipe *et al.*, 2017; Pedrera *et al.*, 2017). Early syn-orogenic exhumation is suggested by an early cooling episode at 75–70 Ma (Mouthereau *et al.*, 2014; Ternois *et al.*, 2019; Waldner *et al.*, 2021) and a first influx of sediments accumulated in the Pyrenees in pro- and retro-foreland basins (Vergés *et al.*, 1995; Sinclair *et al.*, 2005; Grool *et al.*, 2018).

In the Alpine realm, the Late Cretaceous period, from Turonian to Santonian, corresponds to the Eo-Alpine metamorphic event in the eastern Alps (Villa *et al.*, 2000) associated with the accretion of the Austro-Alpine units to Adria and south-verging subduction of the Alpine Tethys (Schettino and Scotese, 2002; Schmid *et al.*, 2004; Handy *et al.*, 2010; van Hinsbergen *et al.*, 2020). In the Western Alps, the Late Cretaceous Helminthoid Flysch sequence recorded the early Alpine deformation during the latest Cretaceous (Kerckhove, 1969; Decarlis *et al.*, 2014) synchronous with the accretion of the Sesia-Dent Blanche Nappe to Adria (Rubatto *et al.*, 1999; Manzotti *et al.*, 2014; Regis *et al.*, 2014).

During the early Paleogene (~66 Ma) contraction and related exhumation spread over the whole domain from Africa to Europe (Figs. 7d and 11d), as argued in the Pyrenees (Choukroune *et al.*, 1990; Muñoz, 1992; Vergés *et al.*, 1995; Mouthereau *et al.*, 2014; Ford *et al.*, 2016), the Iberian Range (Rat *et al.*, 2019), the Basque-Cantabrian Basin (Pedreira *et al.*, 2007; Cámara, 2017), the Betics (Vergés and Fernàndez, 2012; Daudet *et al.*, 2020), and in the Provence (Espurt *et al.*, 2012; Bestani *et al.*, 2016). In the Betics, early-stage exhumation of high-pressure rocks at 49–28 Ma is reported (Monié *et al.*, 1991; Augier *et al.*, 2005). There is also evidence for pre-Late Oligocene deformation in the Balearic promontory and Valencia basin (Etheve *et al.*, 2016, 2018), and for Eocene exhumation in Sardinia and Corsica (Malusà *et al.*, 2016). We infer that all domains comprising Iberia, the Betics, the Balearic promontory and the Ebro-Sardina-Corsica experienced contraction, uplift and moderate exhumation. The corollary is that a proto-Betic orogenic domain stretching between Europe and Africa, now dismantled by backarc extension should have existed at the emplacement of the Western Mediterranean Sea during the Paleogene (at least Eocene) (Figs. 8a and 12a).

This Paleogene orogenic system dismantled by the opening of the West Mediterranean Sea, was segmented and deformation was likely heterogenous, hence reflecting the geometrically complex margins of the Southern Alpine Tethys domain. It included a rapidly exhuming segment (Pyrenees), an uplifted but slightly deforming domain (Sardinia-Corsica), and zones of localized strain characterized by high-pressure metamorphism like the Betic-Rif domain. Closure of the Betic rift in the west and of the eastern Maghrebian basin between Kabylides and Africa/Sicilia produced the formation of the Mesomediterranean orogen (Fig. 13) that once existed as a coherent orogenic ensemble before the end of Eocene. It is worth mentioning that because deformation occurred on the margins of the AlKaPeCa continental terranes, the basement in the core of these domains were not necessarily affected by significant orogenic exhumation.

The closure of the Alpine Tethys between Corsica-Briançonnais and Adria resulted in the formation of the Western Alps (Figs. 8 and 12). Blueschist-to-greenschist facies units, including Jurassic-Cretaceous metaophiolites/metasediments (Briançonnais) and European basement (Tenda in Corsica), exhumed in the Paleocene-Eocene (58–47 Ma). This first orogenic system was followed by exhumation of eclogitic units of the distal European margin (Monte Rosa, Gran Paradiso, and Dora-Maira), and metaophiolites (Viso) in the late Eocene (44–34 Ma) (Malusà *et al.*, 2011). Further east, deformation along the Dinarides occurred during the latest Cretaceous in association with subduction of remnants of the Vardar ocean (van Hinsbergen *et al.*, 2020). The onset of convergence in the Dinarides system may have started in the middle Cretaceous, as attested by calc-alkaline magmatism (Handy *et al.*, 2015).

5.2.5 Latest Paleogene to recent (35–0 Ma)

From the late Oligocene until the early Miocene, a major geodynamic change occurred in the geodynamics of the Western Europe. As the Alpine orogenic front advances towards the northwest, the West European Rift opened and propagated southward (Bois, 1993; Séranne, 1999; Dèzes *et al.*, 2004; Ziegler and Dèzes, 2006). The first extensional phase (35–23 Ma) is well documented in the Provence, in the eastern Pyrenees, and in the Valencia Trough, coeval with the late activities of the West European Rift (Merle and Michon, 2001; Ziegler and Dèzes, 2006). A change from compression to back-arc extension is recorded in Alpine Corsica at 32 Ma (see Sect. 3), leading to opening of the Tyrrhenian Sea by Apenninic slab retreat eastwards. On the opposite side of the Alpine arc, late tectonic collision of the Western Alps occurred at 35 Ma as indicated by the deposition of Alpine Flysch at the west-migrating deformation front (Ford *et al.*, 2006) (Fig. 12) and exhumation of the Paleozoic basement in the External Massifs (Bellahsen *et al.*, 2014).

The late Eocene extensional event of the West European Rift predates back-arc opening of the Gulf of Lion and Liguro-Provençal basins that occurred during a second rift phase from 23 Ma onward (Figs. 8a, 8b, 12a and 12b). The onset of spreading in the Liguro-Provençal basin between 20.5 and 15 Ma was associated with the rotation of the Sardinia-Corsica block triggered by the eastward retreat of the subduction front toward the Ionian Tethys. This event caused a radical reorganisation of the westernmost Mediterranean Sea as indicated by the distribution of volcanism (*e.g.*, Maillard *et al.*, 2020). Extension and spreading migrated southwestward in the Algerian Mediterranean domain but the driver was different due to the absence of a large slab. The limited convergence between Alboran and the Iberia paleomargin highlighted by recent data (Daudet *et al.*, 2020; Pedrera *et al.*, 2020b) argue that the Alboran Sea opened by the westward retreat of delaminated slab Alboran mantle, leading to dismantlement of the former proto-Betic orogen. From the Tortonian (~ 11 Ma), slab detachement and slab tearing in the margins of the Alboran Sea, in the Betics and Rif, triggered a regional uplift associated with extension and anorogenic alkaline volcanism. This late stage controlled

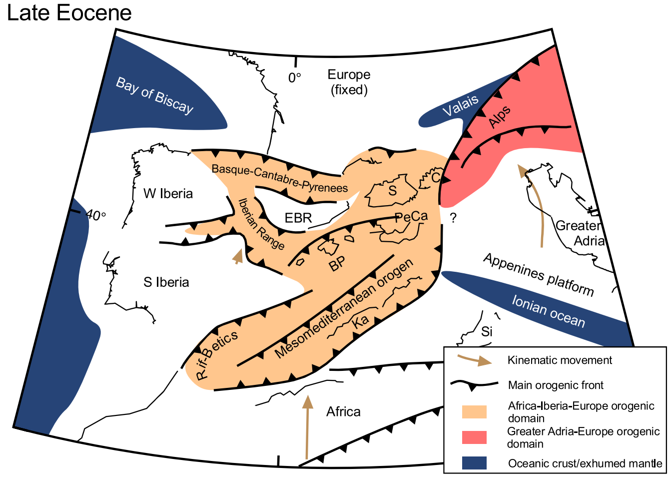

Fig. 13. Schematic reconstruction of the Alpines orogen in the late Eocene.

by asthenospheric flow and magmatism is suggested to account for uplift on the western margin of the Gulf of Lion in eastern Pyrenees (Huyghe *et al.*, 2020) as well as over the whole of Iberia (Conway-Jones *et al.*, 2019).

6 N-S evolution of the Africa-Iberia-Europe plate boundary

6.1 Crustal strain distribution across the African, Iberian and European domains

To gain a better understanding of the role of crustal architecture and segmentation across the Africa-Europe plate boundary, we present a reconstruction of the spatial evolution of crustal strain along a N-S composite transect (Figs. 14 and 15).

During the late Permian-Triassic (270–240 Ma), Tethyan extension is broadly distributed between Africa and Europe and crustal thinning is limited (Figs. 14b and 14c). From the Lower Jurassic to the Early Cretaceous (180–125 Ma), the opening of the Central Atlantic and Alpine Tethys, between the Iberia paleomargin and the Internal Betics (Alboran), is reflected in the Betic rift floored by an attenuated crust or an incipient oceanic basin (Figs. 14d and 14e) (Durand-Delga *et al.*, 2000; Puga *et al.*, 2011; Vergés and Fernàndez, 2012). Extension is also partly accommodated by right-lateral strike-slip movement to the north of Africa, reactivating late Variscan shear zones. During the Late Jurassic-lowermost Cretaceous (125 Ma), oblique extension occurred between Ebro and South Iberia in the Iberian Range rift and in the Betics. From this stage onwards extension focused along the Ebro-Europe plate boundary.

The opening of the Bay of Biscay during the Lower to middle Cretaceous (125–94 Ma) is accompanied by hyper-extension and exhumation of the sub-continental mantle in the Pyrenean basins (Figs. 14e and 15a). This large extension north of Ebro block implies a small amount of shortening (~ 20 km) in the other side of Ebro, in the northern Iberian Range.

The convergence between Africa and Europe started in the uppermost Cretaceous (Santonian, 84 Ma) and rapidly spread all over Europe in the Paleogene (Kley and Voigt, 2008;

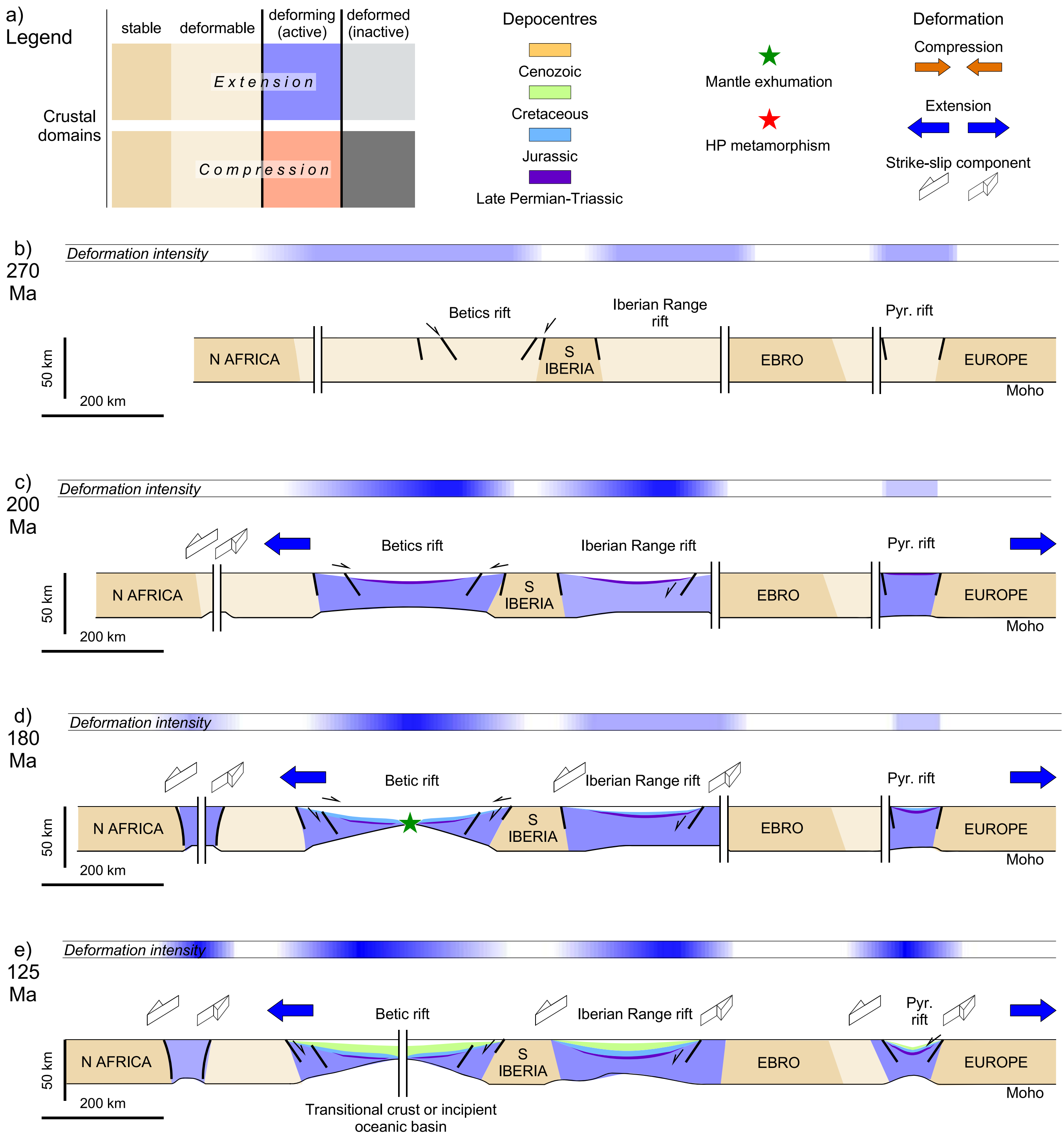

Fig. 14. Legend for Figures 14b–14e and 15 (a) and schematic crustal-scale cross-sections from North Africa to Southern Europe for (b) 270 Ma, (c) 200 Ma, (d) 180 Ma, and (e) 125 Ma. See location in Figures 6 and 7.

Mouthereau *et al.*, 2021). Across Iberia, thrust-related exhumation is reported in the Betics and is indicated by the closure of the exhumed mantle domain in the Pyrenean basins (Fig. 15b). Between 66 Ma and 40 Ma, the advancing contraction led to progressive closure of rift basins in the Pyrenees, the Betics and the Iberian Range (Fig. 15c), characterized by the growth of orogenic topography in these regions.

From the Neogene to present (Figs. 15d and 15e) the internal reorganization of the Africa-Europe convergence, contemporaneous with the opening of the Western Mediterranean, points to a period of increasing control by

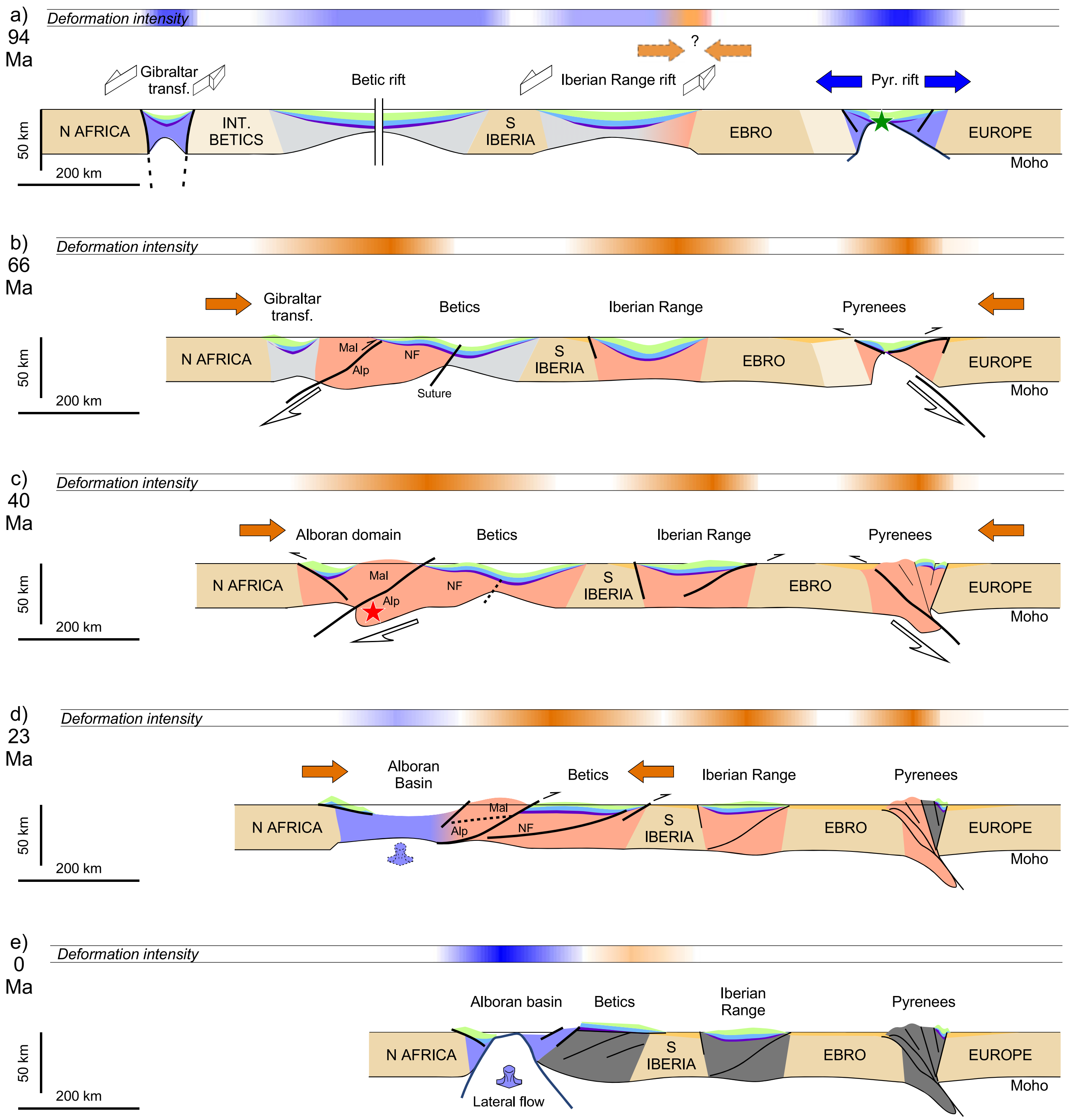

Fig. 15. Schematic crustal-scale cross-sections from North Africa to Southern Europe for (a) 94 Ma, (b) 66 Ma (c) 40 Ma, (d) 23 Ma and (e) 0 Ma. For legend see Figure 14. See location in Figure 7.

sub-lithosphere processes through slab retreat and delamination. This led, along our section, to the shift of contraction from the Pyrenees to the Betics, and extension in the Alboran basin as the slab retreated westward. Following recent models that proposed a limited displacement of the Alboran basin, we interpret the back-arc extension in Abloran as the result of delamination and retreat of lithospheric mantle from below the thickened crust of the proto-Betics.

6.2 Kinematics of the Africa-Europe convergence along a N-S transect since the Late Mesozoic

In this section, we analyze the implication of our kinematic reconstruction along a N-S transect positioned to explore the relative motions of Africa, Ebro and South Iberia since the late Mesozoic. For each time step, we have projected the motion paths derived from our model onto the N10°E direction

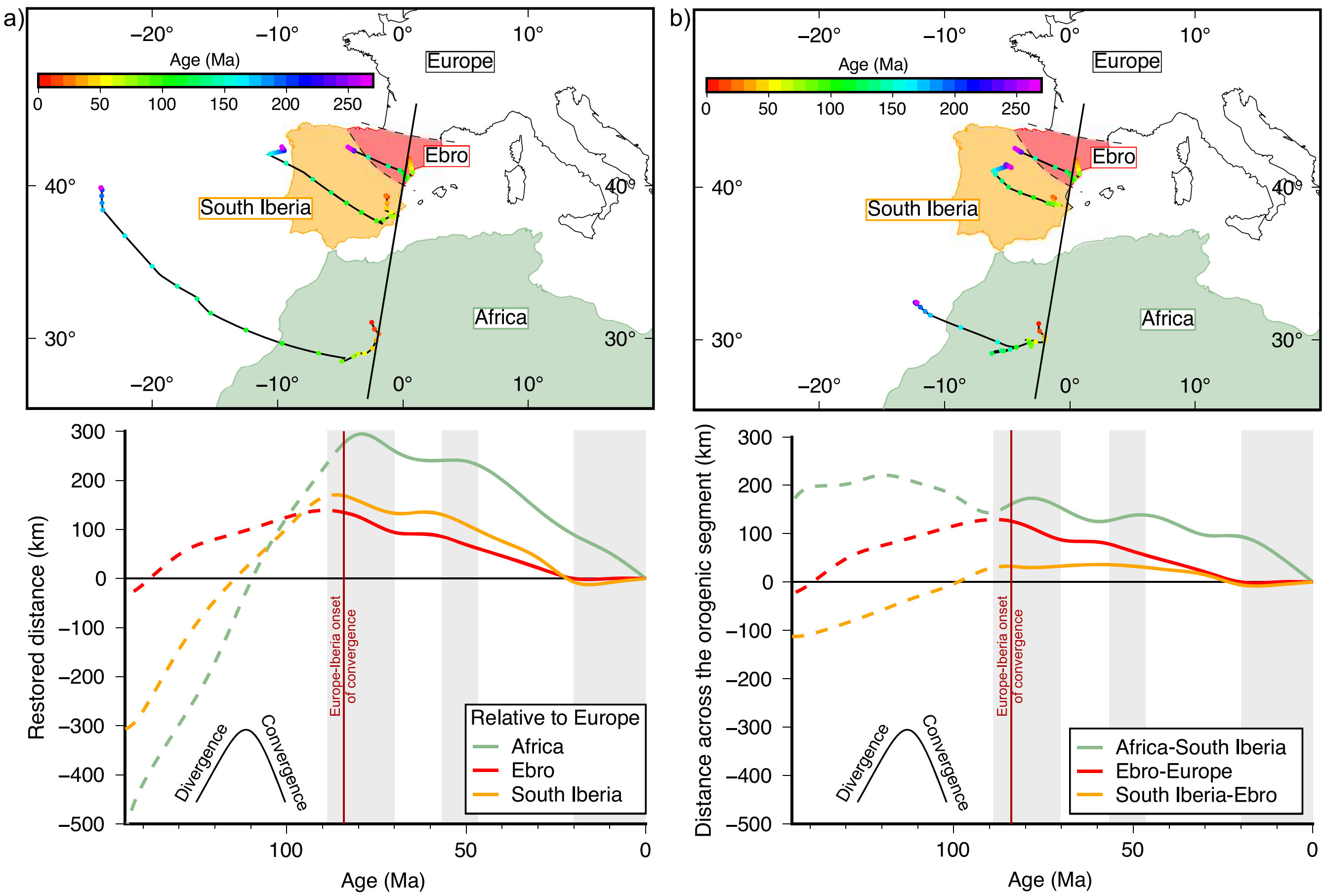

Fig. 16. (a) Top: Motion paths of Ebro, South Iberia, and Africa relative to Europe. Bottom: Calculated restored distance (northward migration) between Africa (green), Ebro (red), and South Iberia (orange) relative to Europe since 145 Ma. Motion paths are plotted along a N10°E axis, which is parallel to the main transport direction during the converging phase. Note that before 84 Ma, the curve cannot be used for quantitative analyses because of the high amount of strike-slip movement. (b) Top: Motion paths of Ebro relative to Europe, South Iberia relative to Ebro, and Africa relative to South Iberia. Bottom: Calculated distance between Africa and South Iberia (green), Ebro and Europe (red), and South Iberia and Ebro (orange) since 145 Ma. Motion paths are plotted along a N10°E axis, parallel to the main transport direction during convergence. Note again that, before 84 Ma, the curve cannot be used for quantitative analyses because of the high amount of strike-slip.

between coordinates 2.3°W/28.3°N to the south and 1.2°E/44.9°N to the north, which is taken as the mean direction of contraction since the Late Cretaceous of all blocks relative to Europe (Fig. 16a). Motion paths have been computed in each block by selecting 4 sites in northwest Africa (2.48°W/31.10°N), eastern Iberia (1.24°E/39.31°N), Ebro (0.49°E/41.66°N) and southwest France (2.02°E/47.72°N). We have also calculated shortening and extension between continental blocks by substracting their respective displacement across each orogenic segment: Africa relative to South Iberia (Betic-Rif), South Iberia relative to Ebro (Iberian Range) and Ebro relative to Europe (Pyrenees) (Fig. 16b). Because relative movements are calculated between adjacent continental blocks, the effects of rotation and obliquity with respect to direction N10°E are minimized in Figure 16b.

From 145 to ~90–84 Ma, Africa, South Iberia and Ebro altogether have a left-lateral movement with respect to Europe that is decreasing northward (Figs. 10 and 11). As continental blocks move away from Europe they show cumulated extension on our N-S transect, which is the largest for Africa, decreasing northwards for Iberia and Ebro (dashed curves in Fig. 16). Figure 16b shows a contraction instead of extension across the North Africa-South Iberian orogenic segment. In our reconstruction (Fig. 11) shortening is mainly accommodated between North Africa and Alboran and Kabylies and does not seem to affect South Iberia. Although no clear evidence exists for this event in the field, the Mesorif unconformity (Gimeno-Vives *et al.*, 2020) may in part be due to this transient shortening event.

Since 84 Ma, the total convergence between Africa and Europe is about 300 km of the same order as estimated by Macchiavelli *et al.* (2017). In details, the convergence of Africa, South Iberia and Ebro relative to Europe appears to be punctuated by periods of contraction at 80–70 Ma, ~50 Ma and after 20 Ma, and stages of tectonic quiescence. Note that instead of quiescence, short intervals of very minor extension are also apparent at ~80 and 50 Ma across Africa-South Iberia boundary (Fig. 16b). They reflect spurious wandering of motion paths. From 84 Ma to 70 Ma, both Ebro and South Iberia converge toward Europe (Fig. 16a) but shortening of

50 km is mostly accommodated at the Ebro-Europe boundary (Fig. 16b) and no convergence is recorded across the South Iberia-Ebro boundary. From 66 to ~35 Ma, the amount of shortening between South Iberia and Ebro remains small because of left-lateral motion at the plate boundary (Figs. 10 and 11) (Anadón *et al.*, 1989). This is coherent with a right-lateral convergent deformation regime in the Iberian Range during the early Cenozoic (Fig. 11) (Parés *et al.*, 1988). From 60–50 Ma and until 20 Ma, the main part of the shortening is accommodated across the Betic-Rif (~50 km across Africa-South Iberia boundary) and the Pyrenees (~80 km across the Ebro-Europe boundary). After 20 Ma, both Ebro and South Iberia kinematically belong to Europe. The remaining N-S convergence (~90–100 km) between Africa and Europe is therefore accommodated between Africa and South Iberia in the Betic-Rif region.

7 Discussion

7.1 Variscan inheritance and late Variscan position of Ebro-Sardinia-Corsica

The fragmentation of Western Europe into several micro-continents partly reflects Pangea breakup in the late Permian as the Neotethys Ocean opened and progressed westward (Ziegler, 1990b; Angrand *et al.*, 2020). Major shear zones are accounted for in our kinematic restoration. They are major fault zones reactived during the Mesozoic rifting inherited for a large part from late Variscan dextral shear zones emplaced during the late Paleozoic (Fig. 17) (Edel *et al.*, 2015; Ballèvre *et al.*, 2018; Molli *et al.*, 2020; Simonetti *et al.*, 2020).

Paleomagnetic constraints (Edel *et al.*, 2015) further suggest that during the late Carboniferous-early Permian (300–290 Ma), Catalonia (Ebro block including the Catalan Coastal Ranges) together with Sardinia-Corsica and Maures-Esterel (Sardinia-Corsica and Provence in our model), were disconnected from Iberia (South Iberia in our model). At this time, the westward migration and clockwise rotation of the Ebro-Sardinia-Corsica block relative to Europe is suggested to have been accommodated along the East Variscan Shear Zone. This is a major tectonic boundary that currently lies in the External Massif disconnecting the Massif Central from allochtonous terranes of Sardinia-Corsica (Ballèvre *et al.*, 2018). In the Western Alps, the anisotropic lithosphere structure inherited from the East Variscan Shear Zone may also have triggered Early Jurassic rifting in the Alpine Tethys and later oceanic spreading south of the Penninic fault.

To the south, this displacement is suggested to be synchronous with the deformation of the Iberian orocline, in West and South Iberia block, along the North Pyrenean Shear Zone (Ballèvre *et al.*, 2018) during the late Carboniferous-early Permian (Edel *et al.*, 2018; Pastor-Galán *et al.*, 2020). These results suggest that both Ebro and Sardinia-Corsica were tectonically distinct from Iberia. The Ebro block should therefore not be restored together with Iberia during the Permian, as commonly assumed in kinematic models that keep Ebro attached to West Iberia (Galicia) (Olivet, 1996; Vissers and Meijer, 2012; Le Breton *et al.*, 2021). This further emphasizes the key role played by the shear zone positioned south of Ebro in the late Carboniferous, here named the Iberian

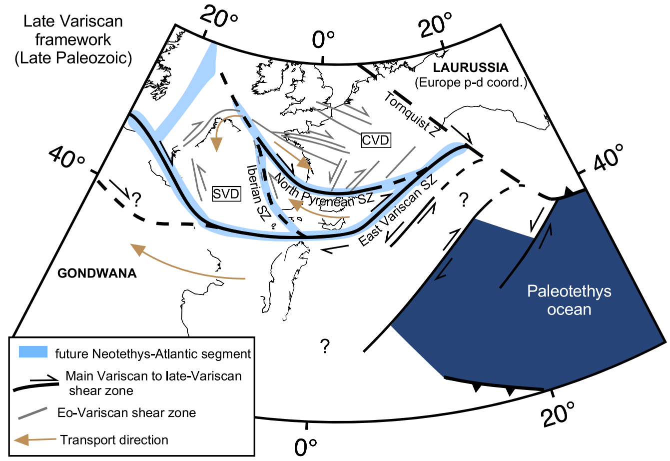

Fig. 17. Schematic reconstruction of the Late Variscan tectonic framework (late Paleozoic), showing the superposition of the Tethys and Atlantic oceanic domains over inherited Variscan tectonic boundaries. CVD: Central Variscan Domain; SVD: South Variscan Domain; SZ: Shear Zone.

Shear Zone (Fig. 17), that has been reactivated after the late Permian-Triassic and is currently shaping the Iberian Range. The late Variscan segmentation described above can further be extended between Iberia and North Africa and between Iberia and North America (Fig. 17) (Fernández, 2019).

7.2 Early Cretaceous reactivation of Tethyan rifted margins: en-échelon opening and contraction in the Alpine domain

A major kinematic change occurred between Europe and Africa during the Late Jurassic-Early Cretaceous (145–125 Ma) as a result of the northward propagation of southern North Atlantic west of Iberia and the Mediterranean region (Fig. 18). This resulted in the eastward drift of Iberia, Ebro-Sardinia-Corsica, and AlKaPeCa that in turn impacted the evolution of the Alpine Tethys, including Adria and European margins (Figs. 10 and 11). The east-directed movement of these blocks had two main consequences for the Alpine Tethys. First, our model predicts that the southern segments of the Alpine Tethys began to close due to comparatively much slower eastward displacement of Adria. We found indeed tectonic arguments in support of an Early Cretaceous closure based on shear zone geochronology and geochemistry from the Kabylides (Cheilletz *et al.*, 1999; Fernandez *et al.*, 2020), and this is indirectly supported on the Adria margin. Northward along the segment of Sardinia-Corsica and Peloritani-Calabria (Fig. 10a) there is no direct evidence for such a contractional event, *e.g.*, Calabria preserves only a few meter of early Cretaceous sediments (Bouillin *et al.*, 1988). As Adria moved in the NE direction, the northwest margin of Adria became highly oblique, thus accommodating transcurrent deformation and preventing large subduction of the Alpine Tethys in this region. The northern margin of Adria however recorded subduction of the Alpine Tethys responsible for Eo-Alpine deformation (*e.g.*, Handy *et al.*, 2010).

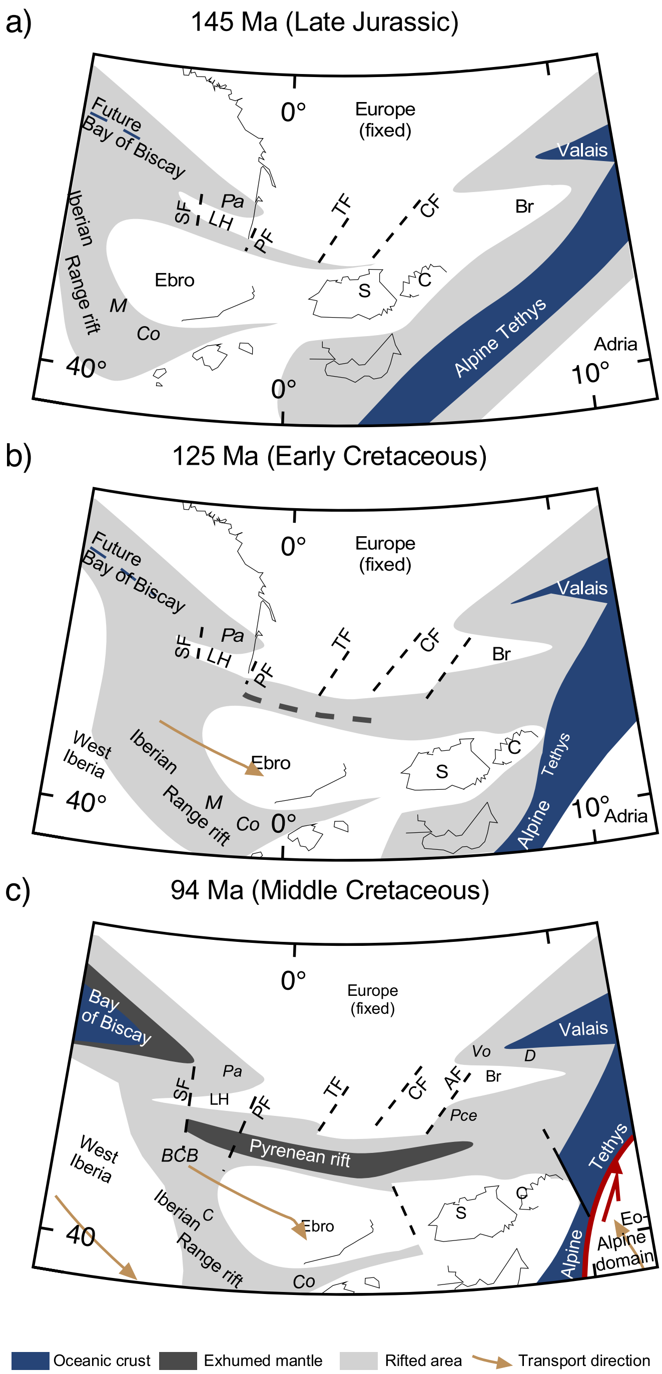

Fig. 18. Schematic reconstruction of the Late Jurassic-Early Cretaceous rift system between Iberia, Adria, and Europe for 145 Ma (a), 125 Ma (b) and 94 Ma (c). AF: Aix Fault; BCB: Basque-Cantabrian basin; Br: Briançonnais; C: Corsica; Co: Columbretes basin; CF: Cévennes Fault; D: Dauphinois; LH: Landes High; M: Maestrat basin; Pa: Parentis basin; Pce: Provence basin; PF: Pamplona Fault; S: Sardinia; SF: Santander Fault; TF: Toulouse Fault; Vo: Vocontian.

Looking closer to the movement of the Ebro-Sardinia-Corsica block relative to Europe, we infer that from Late Jurassic to Early Cretaceous, the progressive rifting from west to east opened en-échelon basins, represented by the Parentis basin, the Pyrenees-Provence basin and further eastward the France Southeast basin. In this context, the relationship between the Pyrenees-Provence rift and the France Southeast basin is of particular interest. The Dauphinois basin that formed during the Early Jurassic stage of Alpine Tethys rifting on the European margin was in part reactivated in the Late Jurassic-Early Cretaceous, hence forming the Vocontian basin. This event was synchronous with the rifting in the Bay of Biscay. All these basins are disconnected en-échelon basins aligned in the EW-direction along the plate boundary between Ebro-Sardinia-Corsica and Europe. They are separated by structural highs, including the Landes High in the western termination of the Pyrenean rift and Durancian uplift between the Provence and the Vocontian basins (Fig. 18). The Vocontian and the Dauphinois basins are suggested to emplaced on the proximal European margin (*e.g.*, Decarlis *et al.*, 2017), now inverted in the Ultra-Helvetic nappes (Ramsay, 1981; Butler, 1985). In this configuration, the Vocontian basin therefore represents the western termination of the Valais Ocean. In our view, the Valais Ocean although tectonically related to the Bay of Biscay is not directly connected to the Pyrenean rift, as commonly suggested (Schmid *et al.*, 2008; Handy *et al.*, 2010; Advokaat *et al.*, 2014; van Hinsbergen *et al.*, 2020). Another important implication is that the Briançonnais forms the eastern promontory (necking domain) of the Provence domain rather that the northeastern promontory of Ebro-Sardinia-Corsica as also commonly suggested (Trümpy, 1988; Stampfli, 1993; Stampfli and Hochard, 2009; Handy *et al.*, 2010; Advokaat *et al.*, 2014; van Hinsbergen *et al.*, 2020). This would be consistent with the slightly deeper sedimentary facies documented in the Briançonnais than in Provence (Laubscher, 1971; Ricou, 1980; Trümpy, 1988). When the Bay of Biscay opened in the late Aptian-Albian (125 and 94 Ma stages; Figs. 18b and 18c), orthogonal extension reactivated the late Variscan North Pyrenean Shear Zone at the origin of the Pyrenean rift, crustal break-up and mantle exhumation. The Albian HT metamorphism affected the Pyrenean rift and the domains close to the spreading centre (Basque-Cantabrian basin, Cameros basin). During this second stage N-S or NE-SW extension was accompanied by the reactivation of NE-SW directed late Variscan inherited faults (*e.g.*, Nîmes Fault, Toulouse Fault). Note that this is a slightly different model than shown in Tavani *et al.* (2018).

Although our model is a viable solution that explains several different types of constraints, it is still to be refined north of Africa and west of Adria (Maghrebian basin, east Ligurian Tethys and Ionian basin). A careful synthesis of basin architecture and geochronological constraints on Mesozoic mafic rocks in these regions may allow testing implications of our model.

7.3 Alpine Tethys and Cenozoic evolution of the West Tethys-Mediterranean region

Because Mesozoic extension was highly oblique to the plate boundary between Africa and Europe, the plate-scale left-lateral shearing induced the opening of narrow basins and distributed extension between the Iberia, Ebro and Adria microplates along pre-existing Permian-Triassic structures (*e.g.*, Angrand *et al.*, 2020). The opening of Alpine Tethys during the Lower Jurassic between the Atlantic and the Neotethys oceans in this oblique kinematic setting did not produce a large oceanic basin. The Alpine Tethys is understood to have been noticeably segmented and floored partially by oceanic crust. Two segments are identified. The western rift segment (Betic ocean/West Ligurian ocean) was positioned to the east of the Iberia paleomargin and arguably extended northward in the eastern Pyrenees during the Late Jurassic-Early Cretaceous reactivation. The ultra-mafic bodies dated at 180 Ma in the eastern Betics originated from a very attenuated crust and/or slow spreading ridge. The eastern branch (Alpine Tethys/East Ligurian basin/eastern Maghrebian basin) was the largest oceanized domain between Adria/Africa (Sicilia) and AlKaPeCa terranes. This is in agreement with an established oceanic subduction which existence is corroborated by fore-arc peridodites associated with the emplacement of the Kabylides (Fernandez *et al.*, 2020). In this framework, the western Maghrebian basin was underlain by a very thin crust, laterally evolving eastward into the eastern Maghrebian basin.

At the beginning of the Africa/Europe convergence (84 Ma), remnants of oceanic crusts of Alpine Tethys and of the Ionian basins origin are positioned in the Betics and west of Adria. In the course of convergence, mountain belts formed by inversion of Mesozoic rifts such as the Pyrenees-Provence/Basque Cantabrians, Betics, Iberian Range, Catalan Coastal Range. The formation of the Mesomediterranean orogen resulted from the inversion of the Betic rift in the west and closure of the eastern Maghrebian basin between Kabylides and Africa/Sicilia in the east (Fig. 13). We infer that most oceanic domains were closed by the late Eocene, with the noticeable exception of the Ionian Sea. The North Africa/Adria slab retreated toward the Ionian basin triggering the opening of the Western Mediterranean Sea. The formation of the Alboran sea is suggested to have occurred by a different mechanism related to the westward migration of a delaminated mantle (*e.g.*, Daudet *et al.*, 2020). This is suggested by the opposite direction of subduction and slab retreat between the Alboran and Algerian basins (westward and southeastward, respectively) imaged by seismic tomography (Spakman and Wortel, 2004; Amaru, 2007).

The different evolution of the Western Mediterranean Sea with respect to the Eastern Mediterranean is likley related to strong segmentation of the southwestern Alpine Tethys, which was variably floored by hyperextended continental crust and oceanic crust between Iberia and Africa. The absence of a well-defined slab beneath both Greater and Lesser Kabylia supports our reconstruction of the southern Alpine Tethys. Indeed, only Lesser (eastern) Kabylia preserves evidence of subducted material, as attested by a small positive seismic velocity anomaly south of Sardinia (see a compilation of seismic tomography depth-slices from Amaru (2007) in Supplementary Material 1). As the Kabylides moved southward relative to the Alpine Tethys subduction (Figs. 7, 8, 11 and 12), the subducted material would now be preserved south of present-day Sardinia. This favors our "hybride-type" model of the southern Alpine Tethys that includes variably extended crust and oceanic crust in both the Betic rift and Maghrebian Tethys, but excludes a continuous AlKaPeCa domain prior to the Cenozoic.

Finally, Oligocene calc-alkaline magmatism in Sardinia (Bellon *et al.*, 1977) may not be simply related to the subduction of the Alpine Tethys below Sardinia. Indeed, our reconstructions do not account for significant subduction of the Alpine Tethys at this time below Sardinia (Figs. 7, 8, 11 and 12). Other mechanisms such as extension or mantle delamination associated with re-melting of continental lithosphere marked by previous subduction may produce similar calc-alkaline magmas (*e.g.*, Richards, 2009).

8 Conclusions

In this paper we aimed to produce a kinematic reconstruction of the West Mediterranean since the late Paleozoic between Africa and Europe, accounting for the fragmentation of Iberia and its implication for strain distribution during plate convergence. Our main conclusions are:

(1) Iberia appears segmented into three main micro-continents, the West Iberia, the South Iberia and the Ebro-Sardinia-Corsica blocks inherited from late Variscan evolution. The Iberia-Europe plate boundary is therefore represented by two main NW-SE (present-day coordinates) strike-slip systems, in the Pyrenean and Iberian Range basins. These main tectonic features allow partitioning the left-lateral strike-slip kinematics between stable Iberia and Europe along two tectonic corridors, the Pyrenean and the Iberian rifts. These tectonic boundaries have been active throughout the Mesozoic. They accommodated transtensional deformation relative to Europe and therefore are critical to explain how Iberia translated to the east in the Alpine Tethys and during the opening of the southern North Atlantic and Bay of Biscay.

(2) We define a new plate configuration between Europe, Iberia, and Adria. It includes a newly defined Ebro-Sardinia-Corsica block and places the Briançonnais unit in continuity of the Provence promontory. The Vocontian basin is therefore suggested to connect with the Valaisan basin. These basins are both part of a larger en-échelon Early Cretaceous rift system between the south Provence and the Pyrenean regions.

(3) The opening of the Alpine Tethys resulted in the development of hyperextended rift domains and narrow oceanic basins forming discontinuous distal terranes between South Iberia, Ebro-Sardinia-Corsica, AlKaPeCa and Africa. The closure of these rift basins formed an elongated orogen during the Paleogene, dismantled during the opening of the West Mediterranean Sea.

This study shows that in such complex intra-continental geodynamic settings, plate boundaries should not be considered as a continuous and/or unique structural feature. Instead, we have distinguished a number of small stable crustal domains between lithosphere-scale shear zones that shape the Africa-Europe plate boundary. Most of these shear zones show complex architecture characterized by orientation inherited from the late Variscan orogeny. Despite the obvious relationships between tectonics and Mesozoic plate kinematics, firm constraints connecting the late Variscan and Alpine evolution are however lacking. More geochronological data and field-based studies supplemented by novel tectonic constraints from Permian and Triassic rocks, or from Variscan basement with a Permian record are needed to fill this gap.

Supplementary Materials

Supplementary Material 1. Depth-slices tomographic model (Amaru, 2007) at 100 km, 200 km, 300 km, 400 km, 500 km, and 600 km depth. Depth-slices have been compiled from the SubMachine website (Hosseini *et al.*, 2018). The thick white dashed contour corresponds to the Alboran (*i.e.*, Betics) slab. The thick black dashed line corresponds to the Kabylian slab. Hosseini, K., Matthews, K.J., Sigloch, K., Shephard, G.E., Domeier, M., Tsekhmistrenko, M. (2018). SubMachine: Web-Based tools for exploring seismic tomography and other models of Earth's deep interior. *Geochemistry, Geophysics, Geosystems* 19. https://doi.org/10.1029/2018GC007431.
Supplementary Material 2. GPlates data presented in this study.

The Supplementary Material is available at http://www.bsgf.fr/10.1051/bsgf/2021031/olm.

Data availability

This study is based on data compilation. Data used in this study can be found in the appropriate references. Kinematic model files are available online in the Supplementary Material.

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Author contribution

This article was written by Paul Angrand and Frédéric Mouthereau. Paul Angrand carried out the compilation of data, interpretation, and kinematic model and figures, in tight collaboration with Frédéric Mouthereau.

References

Advokaat EL, van Hinsbergen DJJ, Maffione M, Langereis CG, Vissers RLM, Cherchi A, *et al.* 2014. Eocene rotation of Sardinia, and the paleogeography of the western Mediterranean region. *Earth and Planetary Science Letters* 401: 183–195. https://doi.org/10.1016/j.epsl.2014.06.012.

Agirrezabala LM. 2015. Syndepositional forced folding and related fluid plumbing above a magmatic laccolith: Insights from outcrop (Lower Cretaceous, Basque-Cantabrian Basin, western Pyrenees. *GSA Bulletin* 127(7-8): 982–1000.

Albarède F, Michard-Vitrac A. 1978. Age and significance of the North Pyrenean metamorphism. *Earth and Planetary Science Letters* 40(3): 327–332. https://doi.org/10.1016/0012-821X(78)90157-7.

Aldega L, Viola G, Casas-Sainz A, Marcén M, Román-Berdiel T, van der Lelij R. 2019. Unraveling multiple thermotectonic events accommodated by crustal-scale faults in northern Iberia, Spain: Insights from K-Ar dating of clay gouges. *Tectonics* 38(10): 3629–3651. https://doi.org/10.1029/2019TC005585.

Algarra AM. 1987. Evolucion geologica alpina del contacto entre las zonas internas y las zonas externas de la cordillera Bética (sector centro-occidental). Universidad de Granada.

Alonso A, Mas JR. 1993. Control tectónico e influencia del eustatismo en la sedimentación del Cretácico inferior de la cuenca de Los Cameros.

Alonso J, Pulgar J, García-Ramos J, Barba P. 1996. In: Friend PF, Dabrio CJ, eds. *W5 Tertiary basins and Alpine tectonics in the Cantabrian Mountains (NW Spain. Tertiary Basins of Spain): The stratigraphic record of crustal kinematics*, pp. 214–227.

Amaru ML. 2007. Global travel time tomography with 3-D reference models (Vol. 274). Utrecht University.

Anadón P, Rera LCAB, Guimera J. 1985. The southeastern margin of the Ebro Basin.

Anadón P, Cabrera L, Julià R, Roca E, Rosell L. 1989. Lacustrine oil-shale basins in Tertiary grabens from NE Spain (Western European rift system). *Palaeogeography, Palaeoclimatology, Palaeoecology* 70(1-3):7–28.

Angrand P, Ford M, Watts AB. 2018. Lateral variations in foreland flexure of a rifted continental margin: The Aquitaine Basin (SW France). *Tectonics* 37(2): 430–449. https://doi.org/10.1002/2017TC004670.

Angrand P, Mouthereau F, Masini E, Asti R. 2020. A reconstruction of Iberia accounting for Western Tethys-North Atlantic kinematics since the late-Permian-Triassic. *Solid Earth* 11(4): 1313–1332. https://doi.org/10.5194/se-11-1313-2020.

Angrand P, Ford M, Ducoux M, De Saint Blanquat M. 2021. Extension and early orogenic inversion along the basal detachment of a hyper-extended rifted margin: An example from the Central Pyrenees (France). *Journal of the Geological Society*. https://doi.org/10.1144/jgs2020-003.

Arche A, López Gómez J. 1996. Origin of the Permian-Triassic Iberian Basin, central-eastern Spain. *Tectonophysics* 266(1-4): 443–464.

Augier R, Agard P, Monié P, Jolivet L, Robin C, Booth-Rea G. 2005. Exhumation, doming and slab retreat in the Betic Cordillera (SE Spain): in situ $^{40}Ar/^{39}Ar$ ages and P-T-d-t paths for the Nevado-Filabride complex. *Journal of Metamorphic Geology* 23(5): 357–381.

Aurell M, Fregenal-Martínez M, Bádenas B, Muñoz-García MB, Élez J, Meléndez N, *et al.* 2019a. Middle Jurassic–Early Cretaceous tectono-sedimentary evolution of the southwestern Iberian Basin (central Spain): Major palaeogeographical changes in the geotectonic framework of the Western Tethys. *Earth-Science Reviews* 199(July): 102983. https://doi.org/10.1016/j.earscirev.2019.102983.

Aurell M, Fregenal-Martínez M, Bádenas B, Muñoz-García MB, Élez J, Meléndez N, *et al.* 2019b. Middle Jurassic-Early Cretaceous tectono-sedimentary evolution of the southwestern Iberian Basin (central Spain): Major palaeogeographical changes in the geotectonic framework of the Western Tethys. *Earth-Science Reviews* 199(October): 102983. https://doi.org/10.1016/j.earscirev.2019.102983.

Azambre B, Rossy M, Lago M. 1987. Caractéristiques pétrologiques des dolérites tholéiitiques d'âge triasique (ophites) du domaine pyrénéen. *Bulletin de Minéralogie* 110(4), 379–396.

Azema J. 1977. Nouvelles donnees micropaleontologiques, stratigraphiques et paleogeographiques sur le portlandien et le neocomien de sardaigne.

Balanyá JC, García-Dueñas V, Azañón JM, Sánchez-Gómez M. 1997. Alternating contractional and extensional events in the Alpujarride nappes of the Alboran Domain (Betics). *Gibraltar Arc. Tectonics* 16(2): 226–238.

Ballèvre M, Martínez Catalan JR, López-Carmona A, Pitra P, Abati J, Fernández RD, *et al.* 2014. Correlation of the nappe stack in the Ibero-Armorican arc across the Bay of Biscay: A joint French-Spanish project. *Geological Society Special Publication* 405(1): 77–113. https://doi.org/10.1144/SP405.13.

Ballèvre M, Manzotti P, Dal Piaz GV. 2018. Pre-alpine (Variscan) inheritance: A key for the location of the future Valaisan Basin (Western Alps). *Tectonics* 37(3): 786–817. https://doi.org/10.1002/2017TC004633.

Barca S, Costamagna LG. 2010. New stratigraphic and sedimentological investigations on the Middle Eocene-Early Miocene continental successions in southwestern Sardinia (Italy): Paleogeographic and geodynamic implications. *Comptes Rendus Geoscience* 342(2): 116–125.

Barnett-Moore N, Hosseinpour M, Maus S. 2016. Assessing discrepancies between previous plate kinematic models of Mesozoic Iberia and their constraints. *Tectonics* 35(8): 1843–1862. https://doi.org/10.1002/2015TC004019.

Barnett-Moore N, Müller DR, Williams S, Skogseid J, Seton M. 2018. A reconstruction of the North Atlantic since the earliest Jurassic. *Basin Research* 30: 160–185. https://doi.org/10.1111/bre.12214.

Bartrina MT, Cabrera L, Jurado MJ, Guimerà J, Roca E. 1992. Evolution of the central Catalan margin of the Valencia trough (western Mediterranean). *Tectonophysics* 203(1-4): 219–247.

Baudrimont A, Dubois P. 1977. Un bassin Mésogéen du domaine Peri-Alpin : le Sud-Est de la France. *Bulletin des Centres de Recherche Exploration-Production Elf-Aquitaine* 1: 261–308. https://pascal-francis.inist.fr/vibad/index.php?action=getRecordDetail&idt=PASCALGEODEBRGM7720381078.

Beamud E, Muñoz JA, Fitzgerald PG, Baldwin SL, Garcés M, Cabrera L, *et al.* 2011. Magnetostratigraphy and detrital apatite fission track thermochronology in syntectonic conglomerates: constraints on the exhumation of the South-Central Pyrenees. *Basin Research* 23(3): 309–331. https://doi.org/10.1111/j.1365-2117.2010.00492.x.

Beaumont C, Muñoz JA, Hamilton J, Fullsack P. 2000. Factors controlling the Alpine evolution of the central Pyrenees inferred from a comparison of observations and geodynamical models. *Journal of Geophysical Research: Solid Earth* 105(B4): 8121–8145. https://doi.org/10.1029/1999jb900390.

Bellahsen N, Mouthereau F, Boutoux A, Bellanger M, Lacombe O, Jolivet L, *et al.* 2014. Collision kinematics in the western external Alps. *Tectonics* 33(6): 1055–1088.

Bellon H, Brousse R. 1977. Le magmatisme periméditerraneen occidental ; essai de synthèse. *Bulletin de La Société Géologique de France* 7(3): 469–480.

Bellon H, Coulon C, Edel J-B. 1977. Le déplacement de la Sardaigne ; synthèse des données géochronologiques, magmatiques et paléomagnetiques. *Bulletin de La Société Géologique de France* 7(4): 825–831.

Beltrando M, Rubatto D, Compagnoni R, Lister G. 2007. Was the Valaisan basin floored by oceanic crust? Evidence of Permian magmatism in the Versoyen Unit (Valaisan domain, NW Alps). *Ofioliti* 32(2): 85–99.

Berástegui XA, García-Senz JM, Losantos M. 1990. Tecto-sedimentary evolution of the Organyà extensional basin (central south Pyrenean unit, Spain) during the Lower Cretaceous. *Bulletin de La Société Géologique de France* 6(2): 251–264.

Bergerat F. 1987. Stress fields in the European platform at the time of Africa-Eurasia collision. *Tectonics* 6(2): 99–132.

Bestani L, Espurt N, Lamarche J, Floquet M, Philip J, Bellier O, *et al.* 2015. Structural style and evolution of the Pyrenean-Provence thrust belt, SE France. *Bulletin de La Société Géologique de France* 186(4-5): 223–241. https://doi.org/10.2113/gssgfbull.186.4-5.223.

Bestani L, Espurt N, Lamarche J, Bellier O, Hollender F. 2016. Reconstruction of the Provence chain evolution, southeastern France. *Tectonics* 35(6): 1506–1525. https://doi.org/10.1002/2016TC004115.

Bill M, O'Dogherty L, Guex J, Baumgartner PO, Masson H. 2001. Radiolarite ages in Alpine-Mediterranean ophiolites: Constraints on the oceanic spreading and the Tethys-Atlantic connection. *Bulletin of the Geological Society of America* 113(1): 129–143. https://doi.org/10.1130/0016-7606(2001)113<0129:RAIAMO>2.0.CO;2.

Billi A, Faccenna C, Bellier O, Minelli L, Neri G, Piromallo C, *et al.* 2011. Recent tectonic reorganization of the Nubia-Eurasia convergent boundary heading for the closure of the western Mediterranean. *Bulletin de La Societe Geologique de France* 182 (4): 279–303. https://doi.org/10.2113/gssgfbull.182.4.279.

Bois C. 1993. Initiation and evolution of the Oligo-Miocene rift basins of southwestern Europe: Contribution of deep seismic reflection profiling. *Tectonophysics* 226(1-4): 227–252.

Bois C, Ecors Scientific Party. 1990. Major geodynamic processes studied from the ECORS deep Seismic profiles in France and adjacent areas. *Tectonophysics* 173(1-4): 397–410. https://doi.org/10.1016/0040-1951(90)90233-X.

Bouillin J-P, Durand-Delga M, Olivier P. 1986. Betic-Rifian and Tyrrhenian Arcs: Distinctive features, genesis and development stages. *Developments in Geotectonics* 21: 281–304. https://doi.org/10.1016/B978-0-444-42688-8.50017-5.

Bouillin J-P, Mouterde R, Olivier P, Majesté-Menjoulas C. 1988. Le Jurassique de Longobucco (Calabre, Italie), a la jonction de la Tethys ligure et de la Tethys maghrebine. *Bulletin de La Société Géologique de France* 4(1): 93–103.

Bronner A, Sauter D, Manatschal G, Péron-Pinvidic G, Munschy M. 2011. Magmatic breakup as an explanation for magnetic anomalies at magma-poor rifted margins. *Nature Geoscience* 4(8), 549–553. https://doi.org/10.1038/nphys1201.

Bruguier O, Becq-Giraudon JF, Clauer N, Maluski H. 2003. From late Visean to Stephanian: Pinpointing a two-stage basinal evolution in the Variscan belt. A case study from the Bosmoreau basin (French Massif Central) and its geodynamic implications. *International Journal of Earth Sciences* 92(3): 338–347.

Brunet C, Monié P, Jolivet L, Cadet J-P. 2000. Migration of compression and extension in the Tyrrhenian Sea: Insights from $^{40}Ar/^{39}Ar$ ages on micas along a transect from Corsica to Tuscany. *Tectonophysics* 321(1): 127–155. https://doi.org/10.1016/S0040-1951(00)00067-6.

Brunet M-F. 1986. The influence of the evolution of the Pyrenees on adjacent basins. *Tectonophysics* 129(1-4): 343–354. https://doi.org/10.1016/0040-1951(86)90260-X.

Brunet M-F. 1994. Subsidence in the Parentis Basin (Aquitaine, France): Implications of the thermal evolution. In: *Hydrocarbon and Petroleum Geology of France*. Heidelberg, Berlin: Springer

Berlin Heidelberg, pp. 187–198. https://doi.org/10.1007/978-3-642-78849-9_14.
Butler RWH. 1985. The restoration of thrust systems and displacement continuity around the Mont Blanc massif, NW external Alpine thrust belt. *Journal of Structural Geology* 7(5): 569–582. https://doi.org/10.1016/0191-8141(85)90029-X.
Cámara P. 2017. Salt and strike-slip tectonics as main drivers in the structural evolution of the Basque-Cantabrian Basin, Spain. In: *Permo-Triassic Salt Provinces of Europe, North Africa and the Atlantic Margins*. Elsevier, pp. 371–393.
Caron J.-M. 1994. Metamorphism and deformation in Alpine Corsica. *Schweizerische Mineralogische Und Petrographische Mitteilungen* 74(1): 105–114.
Casas-Sainz AM, Gil-Imaz A. 1998. Extensional subsidence, contractional folding and thrust inversion of the eastern Cameros basin, northern Spain. *International Journal of Earth Sciences* 86 (4): 802–818.
Casquet C, Galindo Francisco M, González Casado JM, Alonso Millán Á. 1992. El metamorfismo en la cuenca de los Cameros. Geocronología e implicaciones tectónicas. *Geogaceta* 11: 22–25.
Cassinis G, Perotti CR, Ronchi A. 2012. Permian continental basins in the southern Alps (Italy) and peri-mediterranean correlations. *International Journal of Earth Sciences* 101(1): 129–157.
Cavazza W, DeCelles PG, Fellin MG, Paganelli L. 2007. The Miocene Saint-Florent Basin in northern Corsica: stratigraphy, sedimentology, and tectonic implications. *Basin Research* 19(4): 507–527.
Cerbiá JM, López-Ruiz J, Doblas M, Martins LT, Munha J. 2003. Geochemistry of the Early Jurassic Messejana-Plasencia dyke (Portugal-Spain): Implications on the origin of the Central Atlantic Magmatic Province. *Journal of Petrology* 44(3): 547–568. https://doi.org/10.1093/petrology/44.3.547.
Chalouan A, Michard A. 1990. The Ghomarides nappes, Rif coastal range, Morocco: A variscan chip in the Alpine belt. *Tectonics* 9(6): 1565–1583.
Channell JET, Kozur HW. 1997. How many oceans? Meliata, Vardar, Pindos oceans in Mesozoic Alpine paleogeography. *Geology* 25(2): 183–186. https://doi.org/10.1130/0091-7613(1997)025<0183:HMOMVA>2.3.CO;2.
Cheilletz A, Ruffet G, Marignac C, Kolli O, Gasquet D, Féraud G, *et al.* 1999. ^{40}Ar/^{39}Ar dating of shear zones in the Variscan basement of Greater Kabylia (Algeria). Evidence of an Eo-Alpine event at 128 Ma (Hauterivian-Barremian boundary): Geodynamic consequences. *Tectonophysics* 306(1): 97–116.
Cherchi A. 1976. Présence de galets du Vraconien supérieur-Cénomanien basal de provenance ibérique dans le Paléogène continental du sud-ouest de la Sardaigne. *Bulletin de La Société Géologique de France* 18(5): 1217–1219.
Cherchi A, Montadert L. 1982. Oligo-Miocene rift of Sardinia and the early history of the western Mediterranean basin. *Nature* 298 (5876): 736–739.
Chevrot S, Sylvander M, Diaz J, Martin R, Mouthereau F, Manatschal G, *et al.* 2018. The non-cylindrical crustal architecture of the Pyrenees. *Scientific Reports* 8(1): 1–8. https://doi.org/10.1038/s41598-018-27889-x.
Choukroune P, Mediavila F, Vauthier A, Munoz JA, Servei CP. 1989. The ECORS Pyrenean deep seismic profile reflection data and the overall structure of and orogenic belt. *Tectonics* 8(1): 23–39.
Choukroune P, Roure F, Pinet B, Ecors Pyrenees Team. 1990. Main results of the ECORS Pyrenees profile. *Tectonophysics* 173(1-4). https://doi.org/10.1016/0040-1951(90)90234-Y.
Christophoul F, Soula JC, Brusset S, Elibana B, Roddaz M, Bessiere G, *et al.* 2003. Time, place and mode of propagation of foreland basin systems as recorded by the sedimentary fill: Examples of the Late Cretaceous and Eocene retro-foreland basins of the north-eastern Pyrenees. *Geological Society Special Publication* 208 (1995): 229–252. https://doi.org/10.1144/GSL.SP.2003.208.01.11.
Clerc C, Lahfid A, Monié P, Lagabrielle Y, Chopin C, Poujol M, *et al.* 2015. High-temperature metamorphism during extreme thinning of the continental crust: A reappraisal of the North Pyrenean passive paleomargin. *Solid Earth* 6(2): 643–668. https://doi.org/10.5194/se-6-643-2015.
Comas MC, García-Dueñas V, Jurado MJ. 1992. Neogene tectonic evolution of the Alboran Sea from MCS data. *Geo-Marine Letters* 12(2-3): 157–164.
Conway-Jones BW, Roberts GG, Fichtner A, Hoggard M. 2019. Neogene Epeirogeny of Iberia. *Geochemistry, Geophysics, Geosystems* 20(2): 1138–1163. https://doi.org/10.1029/2018GC007899.
Corre B, Lagabrielle Y, Labaume P, Fourcade S, Clerc C, Ballèvre M. 2016. Deformation associated with mantle exhumation in a distal, hot passive margin environment: New constraints from the Saraillé Massif (Chaînons Béarnais, North Pyrenean Zone). *Comptes Rendus – Geoscience* 348(3-4): 279–289. https://doi.org/10.1016/j.crte.2015.11.007.
Costamagna LG. 2016. The Middle Jurassic Alpine Tethyan unconformity and the eastern Sardinia-Corsica Jurassic high: A sedimentary and regional analysis.
Costamagna LG, Barca S, Lecca L. 2007. The Bajocian–Kimmeridgian Jurassic sedimentary cycle of eastern Sardinia: Stratigraphic, depositional and sequence interpretation of the new "Baunei Group". *Comptes Rendus Geoscience* 339(9): 601–612.
Crespo-Blanc A, de Lamotte DF. 2006. Structural evolution of the external zones derived from the Flysch trough and the South Iberian and Maghrebian paleomargins around the Gibraltar arc: A comparative study. *Bulletin de La Société Géologique de France* 177(5): 267–282.
Cuevas J, Tubía JM. 1999. The discovery of scapolite marbles in the Biscay Synclinorium (Basque-Cantabrian basin, Western Pyrenees): Geodynamic implications. *Terra Nova* 11(6): 259–265.
Curnelle R. 1983. Evolution structuro-sedimentaire du Trias et de l'Infra-Lias d'Aquitaine. *Bulletin des Centres de Recherches Exploration-Production Elf- Aquitaine* 7(1): 69–99.
Curnelle R, Dubois P. 1986. Évolution mésozoique des grands bassins sédimentaires Français ; bassins de Paris, d'Aquitaine et du Sud-Est. *Bulletin de La Société Géologique de France* 2(4): 529–546.
Curry ME, van der Beek P, Huismans RS, Wolf SG, Muñoz JA. 2019. Evolving paleotopography and lithospheric flexure of the Pyrenean Orogen from 3D flexural modeling and basin analysis. *Earth and Planetary Science Letters* 515: 26–37. https://doi.org/10.1016/j.epsl.2019.03.009.
Danišík M, Kuhlemann J, Dunkl I, Székely B, Frisch W. 2007. Burial and exhumation of Corsica (France) in the light of fission track data. *Tectonics* 26(1).
Daudet M, Mouthereau F, Brichau S, Crespo-Blanc A, Gautheron C, Angrand P. 2020. Tectono-stratigraphic and thermal evolution of the Western Betic Flysch: Implications for the geodynamics of South Iberian Margin and Alboran Domain. *Tectonics* 39(7): 1–29. https://doi.org/10.1029/2020TC006093.
de Graciansky PC, Lemoine M. 1988. Early Cretaceous extensional tectonics in the southwestern French Alps; A consequence of North Atlantic rifting during Tethyan spreading. *Bulletin de La Société Géologique de France* 4(5): 733–737.

De Vicente G, Vegas R, Muñoz-Martín A, Van Wees JD, Casas-Sáinz A, Sopeña A, *et al.* 2009. Oblique strain partitioning and transpression on an inverted rift: The Castilian Branch of the Iberian Chain. *Tectonophysics* 470(3-4): 224–242. https://doi.org/10.1016/j.tecto.2008.11.003.

De Vicente G, Cloetingh S, Van Wees JD, Cunha PP. 2011. Tectonic classification of Cenozoic Iberian foreland basins. *Tectonophysics* 502(1-2): 38–61. https://doi.org/10.1016/j.tecto.2011.02.007.

Debelmas J. 2001. La zone subbriançonnaise et la zone valaisanne savoyarde dans le cadre de la tectonique des plaques. *Géologie Alpine* 77: 3–8.

Decarlis A, Maino M, Dallagiovanna G, Lualdi A, Masini E, Seno S, *et al.* 2014. Salt tectonics in the SW Alps (Italy-France): From rifting to the inversion of the European continental margin in a context of oblique convergence. *Tectonophysics* 636: 293–314. https://doi.org/10.1016/j.tecto.2014.09.003.

Decarlis A, Beltrando M, Manatschal G, Ferrando S, Carosi R. 2017. Architecture of the distal Piedmont-Ligurian rifted margin in NW Italy: Hints for a flip of the Rift System Polarity. *Tectonics* 36(11): 2388–2406. https://doi.org/10.1002/2017TC004561.

DeFelipe I, Pedreira D, Pulgar JA, Iriarte E, Mendia M. 2017. Mantle exhumation and metamorphism in the Basque-Cantabrian Basin (NSpain): Stable and clumped isotope analysis in carbonates and comparison with ophicalcites in the North Pyrenean Zone (Urdach and Lherz). *Geochemistry, Geophysics, Geosystems* 18(2): 631–652. https://doi.org/10.1002/2016GC006690.

DeFelipe I, Pedreira D, Pulgar JA, Van der Beek PA, Bernet M, Pik R. 2019. Unraveling the Mesozoic and Cenozoic tectonothermal evolution of the eastern Basque-Cantabrian zone–western Pyrenees by low-temperature thermochronology. *Tectonics* 38(9): 3436–3461.

Del Río P, Barbero L, Stuart FM. 2009. Exhumation of the Sierra de Cameros (Iberian Range, Spain): Constraints from low-temperature thermochronology. *Geological Society, London, Special Publications* 324(1): 153–166.

Denèle Y, Paquette JL, Olivier P, Barbey P. 2012. Permian granites in the Pyrenees: The Aya pluton (Basque Country). *Terra Nova* 24(2): 105–113. https://doi.org/10.1111/j.1365-3121.2011.01043.x.

Dercourt J, Vrielynck B. 1993. Atlas Tethys paleoenvironmental maps. Gauthier-Villars.

Dercourt J, Gaetani M, Vrielynck B. 2000. Atlas Peri-Tethys palaeogeographical maps. CCGM.

Dewey JF, Pitman WC, Ryan WBF, Bonnin J. 1973. Plate tectonics and the evolution of the Alpine system. *Geological Society of America Bulletin* 84(10): 3137–3180.

Dèzes P, Schmid SM, Ziegler PA. 2004. Evolution of the European Cenozoic Rift System: Interaction of the Alpine and Pyrenean orogens with their foreland lithosphere. *Tectonophysics* 389(1-2): 1–33. https://doi.org/10.1016/j.tecto.2004.06.011.

Dieni I, Massari F, Médus J. 2008. Age, depositional environment and stratigraphic value of the Cuccuru'e Flores Conglomerate: insight into the Palaeogene to Early Miocene geodynamic evolution of Sardinia. *Bulletin de La Société Géologique de France* 179(1): 51–72.

Ducoux M, Jolivet L, Callot JP, Aubourg C, Masini E, Lahfid A, *et al.* 2019. The Nappe des Marbres Unit of the Basque-Cantabrian Basin: The Tectono-thermal evolution of a fossil hyperextended Rift Basin. *Tectonics* 38(11): 3881–3915. https://doi.org/10.1029/2018TC005348.

Durand-Delga M, Rossi P, Olivier P, Puglisi D. 2000. Situation structurale et nature ophiolitique de roches basiques jurassiques associees aux flyschs maghrebins du Rif (Maroc) et de Sicile (Italie). *Comptes Rendus de l'Academie de Sciences – Serie IIa: Sciences de la Terre et des Planetes* 331(1): 29–38. https://doi.org/10.1016/S1251-8050(00)01378-1.

Edel J-B, Casini L, Oggiano G, Rossi P, Schulmann K. 2014. Early Permian 90° clockwise rotation of the Maures-Estérel-Corsica-Sardinia block confirmed by new palaeomagnetic data and followed by a Triassic 60° clockwise rotation. *Geological Society Special Publication* 405(1): 1–29. https://doi.org/10.1144/SP405.10.

Edel J-B, Schulmann K, Lexa O, Diraison M, Géraud Y. 2015. Permian clockwise rotations of the Ebro and Corso-Sardinian blocks during Iberian-Armorican oroclinal bending: Preliminary paleomagnetic data from the Catalan Coastal Range (NE Spain). *Tectonophysics* 657: 172–186. https://doi.org/10.1016/j.tecto.2015.07.002.

Edel JB, Schulmann K, Lexa O, Lardeaux JM. 2018. Late Palaeozoic palaeomagnetic and tectonic constraints for amalgamation of Pangea supercontinent in the European Variscan belt. *Earth-Science Reviews* 177(November 2017): 589–612. https://doi.org/10.1016/j.earscirev.2017.12.007.

Espurt N, Hippolyte J-C, Saillard M, Bellier O. 2012. Geometry and kinematic evolution of a long-living foreland structure inferred from field data and cross-section balancing, the Sainte-Victoire System, Provence, France. *Tectonics* 31(4): n/a–n/a. https://doi.org/10.1029/2011TC002988.

Espurt N, Angrand P, Teixell A, Labaume P, Ford M, de Saint Blanquat M, *et al.* 2019a. Crustal-scale balanced cross-section and restorations of the Central Pyrenean belt (Nestes-Cinca transect): Highlighting the structural control of Variscan belt and Permian-Mesozoic rift systems on mountain building. *Tectonophysics* 764 (December 2018), 25–45. https://doi.org/10.1016/j.tecto.2019.04.026.

Espurt N, Wattellier F, Philip J, Hippolyte J-C, Bellier O, Bestani L. 2019b. Mesozoic halokinesis and basement inheritance in the eastern Provence fold-thrust belt, SE France. *Tectonophysics* 766: 60–80.

Etheve N, de Lamotte DF, Mohn G, Martos R, Roca E, Blanpied C. 2016. Extensional vs contractional Cenozoic deformation in Ibiza (Balearic Promontory, Spain): Integration in the West Mediterranean back-arc setting. *Tectonophysics* 682: 35–55.

Etheve N, Mohn G, Frizon De Lamotte D, Roca E, Tugend J, Gómez-Romeu J. 2018. Extreme mesozoic crustal thinning in the Eastern Iberia Margin: The example of the Columbrets Basin (Valencia Trough). *Tectonics* 37(2): 636–662. https://doi.org/10.1002/2017TC004613.

Faccenna C, Becker TW, Auer L, Billi A, Boschi L, Brun JP, *et al.* 2014. Mantle dynamics in the Mediterranean. *Reviews of Geophysics* 52(3): 283–332.

Fellin MG, Zattin M, Picotti V, Reiners PW, Nicolescu S. 2005. Relief evolution in northern Corsica (western Mediterranean): Constraints on uplift and erosion on long-term and short-term timescales. *Journal of Geophysical Research: Earth Surface* 110(F1).

Fernandez L, Bosch D, Bruguier O, Hammor D, Caby R, Arnaud N, *et al.* 2020. Vestiges of a fore-arc oceanic crust in the Western Mediterranean: Geochemical constraints from North-East Algeria. *Lithos* 370: 105649.

Fernández O. 2019. The Jurassic evolution of the Africa-Iberia conjugate margin and its implications on the evolution of the Atlantic-Tethys triple junction. *Tectonophysics* 750(December 2018): 379–393. https://doi.org/10.1016/j.tecto.2018.12.006.

Ferrandini J, Gattacceca J, Ferrandini M, Deino A, Janin M-C. 2003. Chronostratigraphie et paléomagnétisme des dépôts oligo-miocènes de Corse: implications géodynamiques pour l'ouverture du bassin liguro-provençal. *Bulletin de La Société Géologique de France*.

Filleaudeau P-Y, Mouthereau F, Pik R. 2012. Thermo-tectonic evolution of the south-central Pyrenees from rifting to orogeny: Insights from detrital zircon U/Pb and (U-Th)/He thermochronometry. *Basin Research* 24(4): 401–417. https://doi.org/10.1111/j.1365-2117.2011.00535.x.

Fillon C, Pedreira D, van der Beek P, Huismans RS, Barbero L, Pulgar JA. 2016. Alpine exhumation of the central Cantabrian mountains, northwest Spain. *Tectonics* 35(2): 339–356.

Fillon C, Mouthereau F, Calassou S, Pik R, Bellahsen N, Gautheron C, *et al.* 2021. Post-orogenic exhumation in the western Pyrenees: evidence for extension driven by pre-orogenic inheritance. *Journal of the Geological Society* 178(2): jgs2020-079. https://doi.org/10.1144/jgs2020-079.

Fitzgerald PG, Muñoz JA, Coney PJ, Baldwin SL. 1999. Asymmetric exhumation across the Pyrenean orogen: Implications for the tectonic evolution of a collisional orogen. *Earth and Planetary Science Letters* 173(3): 157–170. https://doi.org/10.1016/S0012-821X(99)00225-3.

Flinch JF, Soto JI. 2017. Allochthonous Triassic and Salt Tectonic Processes in the Betic-Rif Orogenic Arc. In: *Permo-Triassic Salt Provinces of Europe, North Africa and the Atlantic Margins*. Elsevier, pp. 417–446. https://doi.org/10.1016/B978-0-12-809417-4.00020-3.

Ford M, Lickorish WH. 2004. Foreland basin evolution around the western Alpine arc. *Geological Society Special Publication* 221: 39–63. https://doi.org/10.1144/GSL.SP2004.221.01.04.

Ford M, Duchêne S, Gasquet D, Vanderhaeghe O. 2006. Two-phase orogenic convergence in the external and internal SW Alps. *Journal of the Geological Society* 163(5): 815–826. https://doi.org/10.1144/0016-76492005-034.

Ford M, Hemmer L, Vacherat A, Gallagher K, Christophoul F. 2016. Retro-wedge foreland basin evolution along the ECORS line, eastern Pyrenees, France. *Journal of the Geological Society* 173(3): 419–437. https://doi.org/10.1144/jgs2015-129.

Fournier M, Jolivet L, Goffé B, Dubois R. 1991. Alpine Corsica metamorphic core complex. *Tectonics* 10(6): 1173–1186.

Frasca G, Dielforder A, Ford M, Vergés J. 2017. Cretaceous to Tertiary paleogeographic reconstructions of the Alps-Pyrenees linking zone. In: *EGU General Assembly Conference Abstracts, 7021*. https://ui.adsabs.harvard.edu/abs/2017EGUGA.19.7021F.

Frizon De Lamotte D, Raulin C, Mouchot N, Wrobel-Daveau J-C, Blanpied C, Ringenbach J-C. 2011. The southernmost margin of the Tethys realm during the Mesozoic and Cenozoic: Initial geometry and timing of the inversion processes. *Tectonics* 30(3): n/a–n/a. https://doi.org/10.1029/2010TC002691.

Frizon De Lamotte D, Fourdan B, Leleu S, Leparmentier F, De Clarens P. 2015. Style of rifting and the stages of Pangea breakup. *Tectonics* 34(5): 1009–1029. https://doi.org/10.1002/2014TC003760.

Gaina C, Roest WR, Müller RD. 2002. Late Cretaceous Cenozoic deformation of northeast Asia. *Earth and Planetary Science Letters* 197: 273–286.

Galán-Abellán B, López-Gómez J, Barrenechea JF, Marzo M, De la Horra R, Arche A. 2013. The beginning of the Buntsandstein cycle (Early–Middle Triassic) in the Catalan Ranges, NE Spain: Sedimentary and palaeogeographic implications. *Sedimentary Geology* 296: 86–102. https://doi.org/10.1016/j.sedgeo.2013.08.006.

Gallastegui J, Pulgar JA, Gallart J. 2002. Initiation of an active margin at the North Iberian continent-ocean transition. *Tectonics* 21(4): 15-1-15-14. https://doi.org/10.1029/2001TC901046.

Garcés M, López-Blanco M, Valero L, Beamud E, Muñoz JA, Oliva-Urcia B, *et al.* 2020. Paleogeographic and sedimentary evolution of the South Pyrenean foreland basin. *Marine and Petroleum Geology* 113: 104105. https://doi.org/10.1016/j.marpetgeo.2019.104105.

García-Dueñas V, Martinez Martinez JM, Orozco M, Soto JI. 1988. Plis-nappes, cisaillements syn-à post-métamorphiques et cisaillement ductiles-fragiles en distension dans les Nevado-Filábrides (Cordillères Bétiques, Espagne). *Comptes Rendus de l'Académie Des Sciences. Série 2, Mécanique, Physique, Chimie, Sciences de l'univers, Sciences de La Terre* 307(11): 1389–1395.

García-Lasanta C, Casas-Sainz A, Villalaín JJ, Oliva-Urcia B, Mochales T, Speranza F. 2017. Remagnetizations used to unravel large-scale fold kinematics: A case study in the Cameros Basin (Northern Spain). *Tectonics* 36(4): 714–729. https://doi.org/10.1002/2016TC004459.

García-Mondéjar J, Agirrezabala LM, Aranburu A, Fernández-Mendiola PA, Gómez-Pérez I, López-Horgue M, *et al.* 1996. Aptian-Albian tectonic pattern of the Basque-Cantabrian Basin (northern Spain). *Geological Journal* 31(1): 13–45. https://doi.org/10.1002/(SICI)1099-1034(199603)31:1<13::AID-GJ689>3.0.CO;2-Y.

García-Senz J, Ja RA, Pedrera A. 2019. 5.2 The North Iberian Continental Margin. In: *The Geology of Iberia: A Geodynamic Approach: Volume 3: The Alpine Cycle*. Springer, p. 171.

Gaspar-Escribano JM, Garcia-Castellanos D, Roca E, Cloetingh SAPL. 2004. Cenozoic vertical motions of the Catalan Coastal Ranges (NE Spain): The role of tectonics, isostasy, and surface transport. *Tectonics* 23(1): n/a–n/a. https://doi.org/10.1029/2003TC001511.

Gattacceca J, Deino A, Rizzo R, Jones DS, Henry B, Beaudoin B, *et al.* 2007. Miocene rotation of Sardinia: New paleomagnetic and geochronological constraints and geodynamic implications. *Earth and Planetary Science Letters* 258(3-4): 359–377. https://doi.org/10.1016/j.epsl.2007.02.003.

Gibson M, Sinclair HD, Lynn GJ, Stuart FM. 2007. Late- to post-orogenic exhumation of the Central Pyrenees revealed through combined thermochronological data and modelling. *Basin Research* 19(3): 323–334. https://doi.org/10.1111/j.1365-2117.2007.00333.x.

Gimeno-Vives O, Mohn G, Bosse V, Haissen F, Zaghloul MN, Atouabat A, *et al.* 2019. The Mesozoic margin of the Maghrebian Tethys in the Rif belt (Morocco): Evidence for polyphase rifting and related magmatic activity. *Tectonics* 38(8): 2894–2918.

Gimeno-Vives O, Frizon De Lamotte D, Leprêtre R, Haissen F, Atouabat A, Mohn G. 2020. The structure of the Central-Eastern External Rif (Morocco); Poly-phased deformation and role of the under-thrusting of the North-West African paleo-margin. *Earth-Science Reviews* 205(May): 103198. https://doi.org/10.1016/j.earscirev.2020.103198.

Girod M, Girod N. 1977. Contribution de la pétrologie à la connaissance de l'évolution de la Méditerranée occidentale depuis l'Oligocène. *Bulletin de La Société Géologique de France* 7(3): 481–488.

Glennie KW, Higham J, Stemmerik L. 2003. Permian. In Evans D, Graham C, Armour A, Bathurst P, eds. *The Millennium Atlas; Petroleum Geology of the Central and Northern North Sea*. Geological Society of London, pp. 91–103.

Goldsmith PJ, Hudson G, Van Veen P. 2003. Triassic. In: Evans D, Graham C, Armour A, Bathurst P, eds. *The Millennium Atlas; Petroleum Geology of the Central and northern North Sea*. Geological Society of London, pp. 105–127.

Gómez JJ, Fernández-López SR. 2006. The Iberian Middle Jurassic carbonate-platform system: Synthesis of the palaeogeographic elements of its eastern margin (Spain). *Palaeogeography, Palae-*

oclimatology, Palaeoecology 236(3-4): 190–205. https://doi.org/10.1016/j.palaeo.2005.11.008.

Gómez-Paccard M, López-Blanco M, Costa E, Garcés M, Beamud E, Larrasoaña JC. 2012. Tectonic and climatic controls on the sequential arrangement of an alluvial fan/fan-delta complex (Montserrat, Eocene, Ebro Basin, NE Spain. *Basin Research* 24 (4): 437–455.

Gómez-Pugnaire MT, Ulmer P, López-Sánchez-Vizcaíno V. 2000. Petrogenesis of the mafic igneous rocks of the Betic Cordilleras: A field, petrological and geochemical study. *Contributions to Mineralogy and Petrology* 139(4): 436–457. https://doi.org/10.1007/s004100000148.

Gorini C, Le Marrec A, Mauffret A. 1993. Contribution to the structural and sedimentary history of the Gulf of Lions (western Mediterranean) from the ECORS profiles, industrial seismic profiles and well data. *Bulletin de La Société Géologique de France* 164(3): 353–363.

Gretter N, Ronchi A, López-Gómez J, Arche A, De la Horra R, Barrenechea J, *et al.* 2015. The Late Palaeozoic-Early Mesozoic from the Catalan Pyrenees (Spain): 60 Myr of environmental evolution in the frame of the western peri-Tethyan palaeogeography. *Earth-Science Reviews* 150: 679–708. https://doi.org/10.1016/j.earscirev.2015.09.001.

Grool AR, Ford M, Vergés J, Huismans RS, Christophoul F, Dielforder A. 2018. Insights into the crustal-scale dynamics of a doubly vergent orogen from a quantitative analysis of its forelands: A case study of the eastern Pyrenees. *Tectonics* 37(2): 450–476. https://doi.org/10.1002/2017TC004731.

Guerrera F, Martín-Martín M. 2014. Geodynamic events reconstructed in the Betic, Maghrebian, and Apennine chains (central-western Tethys). *Bulletin de La Société Géologique de France* 185 (5): 329–341. https://doi.org/10.2113/gssgfbull.185.5.329.

Guerrera F, Martín-Martín M, Perrone V, Tramontana M. 2005. Tectono-sedimentary evolution of the southern branch of the Western Tethys (Maghrebian Flysch Basin and Lucanian Ocean): Consequences for Western Mediterranean geodynamics. *Terra Nova* 17(4): 358–367. https://doi.org/10.1111/j.1365-3121.2005.00621.x.

Guerrera F, Mancheño MA, Martín-Martín M, Raffaelli G, Rodríguez-Estrella T, Serrano F. 2014. Paleogene evolution of the External Betic Zone and geodynamic implications. *Geologica Acta* 12(3): 171–192.

Guerrera F, Martín-Martín M, Tramontana M. 2019. Evolutionary geological models of the central-western peri-Mediterranean chains: A review. *International Geology Review* 00(00): 1–22. https://doi.org/10.1080/00206814.2019.1706056.

Guimerà J, Salas R, Vergés J, Casas A. 1996. Mesozoic extension and Tertiary compressive inversion in the Iberian Chain: results from the analysis of a gravity profile. *Geogaceta* 20(7): 1691–1694.

Guimerà J, Mas R, Alonso Á. 2004. Intraplate deformation in the NW Iberian Chain: Mesozoic extension and Tertiary contractional inversion. *Journal of the Geological Society* 161(2): 291–303. https://doi.org/10.1144/0016-764903-055.

Guiraud M, Seguret M. 1985. A releasing solitary overstep model for the late Jurassic-Early Cretaceous (Wealdian) Soria strike-slip basin (Northern Spain).

Handy MR, Schmid S, Bousquet R, Kissling E, Bernoulli D. 2010. Reconciling plate-tectonic reconstructions of Alpine Tethys with the geological-geophysical record of spreading and subduction in the Alps. *Earth-Science Reviews* 102(3-4): 121–158. https://doi.org/10.1016/j.earscirev.2010.06.002.

Handy MR, Ustaszewski K, Kissling E. 2015. Reconstructing the Alps-Carpathians-Dinarides as a key to understanding switches in subduction polarity, slab gaps and surface motion. *International Journal of Earth Sciences* 104(1): 1–26. https://doi.org/10.1007/s00531-014-1060-3.

Hanne D, White N, Lonergan L. 2003. Subsidence analyses from the Betic Cordillera, southeast Spain. *Basin Research* 15(1): 1–21. https://doi.org/10.1046/j.1365-2117.2003.00192.x.

Heeremans M, Timmerman MJ, Kirstein LA, Faleide JI. 2004. New constraints on the timing of Late Carboniferous-Early Permian volcanism in the central North Sea. *Geological Society Special Publication* 223(1): 177–194. https://doi.org/10.1144/GSL.SP2004.223.01.08.

Heine C, Zoethout J, Müller RD. 2013. Kinematics of the South Atlantic rift. *Solid Earth* 4(2): 215–253. https://doi.org/10.5194/se-4-215-2013.

Huyghe D, Mouthereau F, Emmanuel L. 2012. Oxygen isotopes of marine mollusc shells record Eocene elevation change in the Pyrenees. *Earth and Planetary Science Letters* 345-348: 131–141. https://doi.org/10.1016/j.epsl.2012.06.035.

Huyghe D, Mouthereau F, Segalen L, Furió M. 2020. Long-term dynamic topographic support during post-orogenic crustal thinning revealed by stable isotope (δ18O) paleo-altimetry in eastern Pyrenees. *Scientific Reports* 10(1): 1–8.

Iribarren L, Vergés J, Fernàndez M. 2009. Sediment supply from the Betic-Rif orogen to basins through Neogene. *Tectonophysics* 475 (1): 68–84. https://doi.org/10.1016/j.tecto.2008.11.029.

Jabaloy-Sánchez A, Talavera C, Rodríguez-Peces MJ, Vázquez-Vílchez M, Evans NJ. 2021. U-Pb geochronology of detrital and igneous zircon grains from the Águilas Arc in the Internal Betics (SE Spain): Implications for Carboniferous-Permian paleogeography of Pangea. *Gondwana Research* 90: 135–158. https://doi.org/10.1016/j.gr.2020.10.013.

Jammes S, Manatschal G, Lavier L, Masini E. 2009. Tectonosedimentary evolution related to extreme crustal thinning ahead of a propagating ocean: Example of the western Pyrenees. *Tectonics* 28 (4): 1–24. https://doi.org/10.1029/2008TC002406.

Janowski M, Loget N, Gautheron C, Barbarand J, Bellahsen N, Van Den Driessche J, *et al.* 2017. Neogene exhumation and relief evolution in the eastern Betics (SE Spain): Insights from the Sierra de Gador. *Terra Nova* 29(2): 91–97. https://doi.org/10.1111/ter.12252.

Jolivet L, Faccenna C. 2000. Mediterranean extension and the Africa-Eurasia collision. *Tectonics* 19(6): 1095–1106.

Jolivet L, Daniel J-M, Fournier M. 1991. Geometry and kinematics of extension in Alpine Corsica. *Earth and Planetary Science Letters* 104(2-4): 278–291. https://doi.org/10.1016/0012-821X(91)90209-Z.

Jolivet L, Faccenna C, Goffé B, Mattei M, Rossetti F, Brunet C, *et al.* 1998. Midcrustal shear zones in postorogenic extension: Example from the northern Tyrrhenian Sea. *Journal of Geophysical Research: Solid Earth* 103(B6): 12123–12160. https://doi.org/10.1029/97JB03616.

Jolivet L, Faccenna C, D'Agostino N, Fournier M, Worrall D. 1999. The kinematics of back-arc basins: Examples from the Tyrrhenian, Aegean and Japan Seas. *Geological Society, London, Special Publications* 164(1): 21–53. https://doi.org/10.1144/GSL.SP1999.164.01.04.

Jolivet L, Romagny A, Gorini C, Maillard A, Thinon I, Couëffé R, *et al.* 2020. Fast dismantling of a mountain belt by mantle flow: Late-orogenic evolution of Pyrenees and Liguro-Provençal rifting. *Tectonophysics* 776(December 2019): 228312. https://doi.org/10.1016/j.tecto.2019.228312.

Jourdon A, Le Pourhiet L, Mouthereau F, Masini E. 2019. Role of rift maturity on the architecture and shortening distribution in mountain belts. *Earth and Planetary Science Letters* 512: 89–99. https://doi.org/10.1016/j.epsl.2019.01.057.

Jourdon A, Le Pourhiet L, Mouthereau F, May D. 2020. Modes of propagation of continental break-up and associated oblique rift structures. *Journal of Geophysical Research: Solid Earth* 125(9): 1–27. https://doi.org/10.1029/2020JB019906.

Kerckhove C. 1969. La « zone du Flysch » dans les nappes de l'Embrunais-Ubaye (Alpes occidentales. *Géologie Alpine* 45: 5–204.

Kley J, Voigt T. 2008. Late Cretaceous intraplate thrusting in central Europe: Effect of Africa-Iberia-Europe convergence, not Alpine collision. *Geology* 36(11): 839–842. https://doi.org/10.1130/G24930A.1.

Kneller EA, Johnson CA, Karner GD, Einhorn J, Queffelec TA. 2012. Inverse methods for modeling non-rigid plate kinematics: Application to mesozoic plate reconstructions of the Central Atlantic. *Computers and Geosciences* 49: 217–230. https://doi.org/10.1016/j.cageo.2012.06.019.

Labails C, Olivet JL, Aslanian D, Roest WR. 2010. An alternative early opening scenario for the Central Atlantic Ocean. *Earth and Planetary Science Letters* 297(3-4): 355–368. https://doi.org/10.1016/j.epsl.2010.06.024.

Lacombe O, Jolivet L. 2005. Structural and kinematic relationships between Corsica and the Pyrenees-Provence domain at the time of the Pyrenean orogeny. *Tectonics* 24(1): n/a–n/a. https://doi.org/10.1029/2004TC001673.

Lacombe O, Mouthereau F. 2002. Basement-involved shortening and deep detachment tectonics in forelands of orogens: Insights from recent collision belts (Taiwan, Western Alps, Pyrenees). *Tectonics* 21(4): 12-1-12–22. https://doi.org/10.1029/2001TC901018.

Lacombe O, Angelier J, Laurent P. 1992. Determining paleostress orientations from faults and calcite twins: a case study near the Sainte-Victoire Range (southern France). *Tectonophysics* 201(1-2): 141–156. https://doi.org/10.1016/0040-1951(92)90180-E.

Lagabrielle Y, Bodinier JL. 2008. Submarine reworking of exhumed subcontinental mantle rocks: Field evidence from the Lherz peridotites, French Pyrenees. *Terra Nova* 20(1): 11–21. https://doi.org/10.1111/j.1365-3121.2007.00781.x.

Lagabrielle Y, Labaume P, De Saint Blanquat M. 2010. Mantle exhumation, crustal denudation, and gravity tectonics during Cretaceous rifting in the Pyrenean realm (SW Europe): Insights from the geological setting of the lherzolite bodies. *Tectonics* 29(4): 1–26. https://doi.org/10.1029/2009TC002588.

Lahondère J-C, Lahondère D. 1988. Organisation structurale des « schistes lustrés » du Cap Corse (Haute Corse). *Comptes Rendus de l'Académie Des Sciences. Série 2, Mécanique, Physique, Chimie, Sciences de l'univers, Sciences de La Terre* 307(9): 1081–1086.

Laubscher HP. 1971. Das Alpen-Dinariden-Problem und die Palinspastik der südlichen tethys. *Geologische Rundschau* 60(3): 813–833.

Le Breton E, Handy MR, Molli G, Ustaszewski K. 2017. Post-20 Ma motion of the Adriatic Plate: New constraints from surrounding orogens and implications for crust-mantle decoupling. *Tectonics* 36 (12): 3135–3154. https://doi.org/10.1002/2016TC004443.

Le Breton E, Brune S, Ustaszewski K, Zahirovic S, Seton M, Müller RD. 2021. Kinematics and extent of the Piemont-Liguria Basin – Implications for subduction processes in the Alps. *Solid Earth* 12(4): 885–913. https://doi.org/10.5194/se-12-885-2021.

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

Lemoine M. 1985. Structuration jurassique des Alpes occidentales et palinspastique de la Tethys ligure. *Bulletin de La Société Géologique de France* I(1): 127–137. https://doi.org/10.2113/gssgfbull.I.1.127.

Leprêtre R, Frizon De Lamotte D, Combier V, Gimeno-Vives O, Mohn G, Eschard R. 2018. The Tell-Rif orogenic system (Morocco, Algeria, Tunisia) and the structural heritage of the southern Tethys margin. *BSGF – Earth Sciences Bulletin* 189(2). https://doi.org/10.1051/bsgf/2018009.

Lonergan L, White N. 1997. Origin of the Betic-Rif mountain belt. *Tectonics* 16(3): 504–522.

López-Blanco M. 2002. Sedimentary response to thrusting and fold growing on the SE margin of the Ebro basin (Paleogene, NE Spain). *Sedimentary Geology* 146(1-2): 133–154. https://doi.org/10.1016/S0037-0738(01)00170-1.

López-Gómez J, Alonso-Azcárate J, Arche A, Arribas J, Barrenechea JF, Borruel-Abadía V, *et al.* 2019. Permian-Triassic rifting stage. In: *The Geology of Iberia: A Geodynamic Approach*. Springer, pp. 29–112.

Loreto MF, Zitellini N, Ranero CR, Palmiotto C, Prada M. 2020. Extensional tectonics during the Tyrrhenian back-arc basin formation and a new morpho-tectonic map. *Basin Research* August 2019, 1–21. https://doi.org/10.1111/bre.12458.

Lucas C. 1985. Le grès rouge du versant nord des Pyrénées : essai sur la géodynamique de dépôts continentaux du Permien et du Trias. Université de Toulouse.

Maaté A, Martín-Algarra A, Martín-Martín M, Serra-Kiel J. 2000. Nouvelles donnéessur le Paléocène-Éocène des zones internes bético-rifaines. *Geobios* 33(4): 409–418. https://doi.org/10.1016/S0016-6995(00)80074-1.

Macchiavelli C, Vergés J, Schettino A, Fernàndez M, Turco E, Casciello E, *et al.* 2017. A new southern North Atlantic Isochron map: Insights into the drift of the Iberian Plate since the Late Cretaceous. *Journal of Geophysical Research: Solid Earth* 122 (12): 9603–9626. https://doi.org/10.1002/2017JB014769.

Maillard A, Mauffret A, Watts AB, Torné M, Pascal G, Buhl P, *et al.* 1992. Tertiary sedimentary history and structure of the Valencia trough (western Mediterranean). *Tectonophysics* 203(1-4): 57–75.

Maillard A, Jolivet L, Lofi J, Thinon I, Couëffé R, Canva A, *et al.* 2020. Transfer zones and associated volcanic province in the eastern Valencia Basin: Evidence for a hot rifted margin? *Marine and Petroleum Geology* 119(May): 104419. https://doi.org/10.1016/j.marpetgeo.2020.104419.

Malusà MG, Faccenna C, Garzanti E, Polino R. 2011. Divergence in subduction zones and exhumation of high pressure rocks (Eocene Western Alps). *Earth and Planetary Science Letters* 310(1-2): 21–32. https://doi.org/10.1016/j.epsl.2011.08.002.

Malusà MG, Danišík M, Kuhlemann J. 2016. Tracking the Adriatic-slab travel beneath the Tethyan margin of Corsica-Sardinia by low-temperature thermochronometry. *Gondwana Research* 31: 135–149.

Manatschal G, Müntener O. 2009. A type sequence across an ancient magma-poor ocean-continent transition: the example of the western Alpine Tethys ophiolites. *Tectonophysics* 473(1-2): 4–19.

Mancilla F de L, Booth-Rea G, Stich D, Pérez-Peña JV, Morales J, Azañón JM, *et al.* 2015. Slab rupture and delamination under the Betics and Rif constrained from receiver functions. *Tectonophysics* 663: 225–237. https://doi.org/10.1016/j.tecto.2015.06.028.

Manzotti P, Ballèvre M, Zucali M, Robyr M, Engi M. 2014. The tectonometamorphic evolution of the Sesia-Dent Blanche nappes (internal Western Alps): Review and synthesis. *Swiss Journal of Geosciences* 107(2-3): 309–336.

Marroni M, Meneghini F, Pandolfi L. 2017. A revised subduction inception model to explain the Late Cretaceous, double-vergent orogen in the precollisional Western Tethys: Evidence from the Northern Apennines. *Tectonics* 36(10): 2227–2249. https://doi.org/10.1002/2017TC004627.

Martí J, Mitjavila J, Roca E, Aparicio A. 1992. Cenozoic magmatism of the valencia trough (western mediterranean): Relationship between structural evolution and volcanism. *Tectonophysics* 203 (1-4): 145–165.

Martín-Chivelet J, Chacón B. 2007. Event stratigraphy of the upper Cretaceous to lower Eocene hemipelagic sequences of the Prebetic Zone (SE Spain): Record of the onset of tectonic convergence in a passive continental margin. *Sedimentary Geology* 197(1-2): 141–163. https://doi.org/10.1016/j.sedgeo.2006.09.007.

Martín-Chivelet J, López-Gómez J, Aguado R, Arias C, Arribas J, Arribas ME, *et al.* 2019. The Late Jurassic–Early Cretaceous rifting. In: *The Geology of Iberia: A Geodynamic Approach*. Springer, pp. 169–249.

Martín-Martín M, Mamoune B El, Martín-Algarra A, Serra-Kiel J. 1997. La formation As, datée de l'Oligocène, est impliquée dans les charriages des unités malaguides supérieures de la Sierra Espuña (zones internes bétiques, province de Murcie, Espagne. *Comptes Rendus de l'Académie Des Sciences – Series IIA – Earth and Planetary Science* 325(11): 861–868. https://doi.org/10.1016/S1251-8050(99)80186-4.

Martin-Rojas I, Somma R, Delgado F, Estévez A, Iannace A, Perrone V, *et al.* 2009. Triassic continental rifting of Pangaea: direct evidence from the Alpujarride carbonates, Betic Cordillera, SE Spain. *Journal of the Geological Society* 166(3): 447–458.

Marzoli A, Renne PR, Piccirillo EM, Ernesto M, Bellieni G, De Min A. 1999. Extensive 200-million-year-old continental flood basalts of the Central Atlantic Magmatic Province. *Science* 284(5414): 616–618. https://doi.org/10.1126/science.284.5414.616.

Masini E, Manatschal G, Tugend J, Mohn G, Flament JM. 2014. The tectono-sedimentary evolution of a hyper-extended rift basin: The example of the Arzacq-Mauléon rift system (Western Pyrenees, SW France). *International Journal of Earth Sciences* 103(6): 1569–1596. https://doi.org/10.1007/s00531-014-1023-8.

Masse J-P, Allemann J. 1982. Relations entre les séries carbonatées de plate-forme provençale et sarde au Crétacé inférieur. *Cretaceous Research* 3(1-2): 19–33.

Matte P. 1991. Accretionary history and crustal evolution of the Variscan belt in Western Europe. *Tectonophysics* 196(3-4): 309–337.

Maury P, Ricou LE. 1983. Le décrochement subbriançonnais: une nouvelle interprétation de la limite interne-externe des Alpes franco-italiennes. *Revue de Géologie Dynamique et de Géographie Physique Paris* 24 (1): 3–22.

McHone JG. 2000. Non-plume magmatism and rifting during the opening of the central Atlantic Ocean. *Tectonophysics* 316(3-4): 287–296. https://doi.org/10.1016/S0040-1951(99)00260-7.

Mencos J, Carrera N, Muñoz JA. 2015. Influence of rift basin geometry on the subsequent postrift sedimentation and basin inversion: The Organyà Basin and the Bóixols thrust sheet (south central Pyrenees. *Tectonics* 34(7): 1452–1474.

Merle O, Michon L. 2001. The formation of the West European Rift; a new model as exemplified by the Massif Central area. *Bulletin de La Societe Geologique de France* 172(2): 213–221. https://doi.org/10.2113/172.2.213.

Metcalf JR, Fitzgerald PG, Baldwin SL, Muñoz J-A. 2009. Thermochronology of a convergent orogen: Constraints on the timing of thrust faulting and subsequent exhumation of the Maladeta Pluton in the Central Pyrenean Axial Zone. *Earth and Planetary Science Letters* 287(3-4): 488–503. https://doi.org/10.1016/j.epsl.2009.08.036.

Michard A, Negro F, Saddiqi O, Bouybaouene ML, Chalouan A, Montigny R, *et al.* 2006. Pressure-temperature-time constraints on the Maghrebide mountain building: Evidence from the Rif-Betic transect (Morocco, Spain), Algerian correlations, and geodynamic implications. *Comptes Rendus Geoscience* 338(1-2): 92–114. https://doi.org/10.1016/j.crte.2005.11.011.

Milia A, Torrente MM. 2014. Early-stage rifting of the Southern Tyrrhenian region: The Calabria-Sardinia breakup. *Journal of Geodynamics* 81: 17–29. https://doi.org/10.1016/j.jog.2014.06.001.

Mohn G, Manatschal G, Beltrando M, Haupert I. 2014. The role of rift-inherited hyper-extension in Alpine-type orogens. *Terra Nova* 26(5): 347–353. https://doi.org/10.1111/ter.12104.

Mohn G, Karner GD, Manatschal G, Johnson CA. 2015. Structural and stratigraphic evolution of the Iberia-Newfoundland hyper-extended rifted margin: A quantitative modelling approach. *Geological Society Special Publication* 413(1): 53–89. https://doi.org/10.1144/SP413.9.

Molli G, Brogi A, Caggianelli A, Capezzuoli E, Liotta D, Spina A, *et al.* 2020. Late Palaeozoic tectonics in Central Mediterranean: A reappraisal. *Swiss Journal of Geosciences* 113(1): 1–32. https://doi.org/10.1186/s00015-020-00375-1.

Monié P, Galindo-Zaldivar J, Lodeiro FG, Goffe B, Jabaloy A. 1991. 40Ar/39Ar geochronology of Alpine tectonism in the Betic Cordilleras (southern Spain). *Journal of the Geological Society* 148 (2): 289–297.

Montigny R, Azambre B, Rossy M, Thuizat R. 1986. K-Ar study of cretaceous magmatism and metamorphism in the pyrenees: Age and length of rotation of the Iberian Peninsula. *Tectonophysics* 129 (1-4): 257–273. https://doi.org/10.1016/0040-1951(86)90255-6.

Mouthereau F, Filleaudeau P-Y, Vacherat A, Pik R, Lacombe O, Fellin MG, *et al.* 2014. Placing limits to shortening evolution in the Pyrenees: Role of margin architecture and implications for the Iberia/Europe convergence. *Tectonics* 33(12): 2283–2314. https://doi.org/10.1002/2014TC003663.

Mouthereau F, Angrand P, Jourdon A, Ternois S, Fillon C, Calassou S, *et al.* 2021. Cenozoic mountain building and topographic evolution in Western Europe: Impact of billion years of lithosphere evolution and plate kinematics. *BSGF – Earth Sciences Bulletin*, this volume.

Müller RD, Royer JY, Cande SC, Roest WR, Maschenkov S. 1999. New constraints on the Late Cretaceous/Tertiary plate tectonic evolution of the Caribbean. In: *Sedimentary Basins of the World* (Vol. 4, pp. 33–59). Elsevier.

Müller DR, Cannon J, Qin X, Watson RJ, Gurnis M, Williams S, *et al.* 2018. GPlates: building a virtual earth through deep time. *Geochemistry, Geophysics, Geosystems* 19(7): 2243–2261. https://doi.org/10.1029/2018GC007584.

Müller DR, Zahirovic S, Williams SE, Cannon J, Seton M, Bower DJ, *et al.* 2019. A global plate model including lithospheric deformation along major rifts and orogens since the Triassic. *Tectonics* 38(6): 1884–1907. https://doi.org/10.1029/2018TC005462.

Muñoz JA. 1992. Evolution of a continental collision belt: ECORS-Pyrenees crustal balanced cross-section. In: McClay KR, ed. *Thrust Tectonics*. Springer Netherlands, pp. 235–246. https://doi.org/10.1007/978-94-011-3066-0_21.

Murillas J, Mougenot D, Boillot G, Comas MC, Banda E, Mauffret A. 1990. Structure and evolution of the Galicia Interior Basin (Atlantic western Iberian continental margin. *Tectonophysics* 184: 297–319.

Muttoni G, Garzanti E, Alfonsi L, Cirilli S, Germani D, Lowrie W. 2001. Motion of Africa and Adria since the Permian: Paleomagnetic and paleoclimatic constraints from northern Libya. *Earth* *and Planetary Science Letters* 192(2): 159–174. https://doi.org/10.1016/S0012-821X(01)00439-3.

Neumann E-R, Olsen KH, Baldridge WS, Sundvoll B. 1992. The Oslo rift: A review. *Tectonophysics* 208(1-3): 1–18.

Nirrengarten M, Manatschal G, Tugend J, Kusznir NJ, Sauter D. 2017. Nature and origin of the J-magnetic anomaly offshore Iberia-Newfoundland: implications for plate reconstructions. *Terra Nova* 29(1): 20–28.

Nirrengarten M, Manatschal G, Tugend J, Kusznir NJ, Sauter D. 2018. Kinematic evolution of the Southern North Atlantic: Implications for the formation of hyperextended rift systems. *Tectonics* 37(1): 89–118. https://doi.org/10.1002/2017TC004495.

Olivet JL. 1996. La cinématique de la plaque ibérique. *Bulletin des Centres de Recherches Exploration-Production Elf-Aquitaine* 20 (1): 131–195.

Olsen PE. 1997. Stratigraphic record of the Early Mesozoic breakup of Pangea in the Laurasia-Gondwana rift system. *Annual Review of Earth and Planetary Sciences* 25(1): 337–401. https://doi.org/10.1146/annurev.earth.25.1.337.

Omodeo Salè S, Guimerà J, Mas R, Arribas J. 2014. Tectono-stratigraphic evolution of an inverted extensional basin: the Cameros Basin (north of Spain). *International Journal of Earth Sciences* 103 (6): 1597–1620. https://doi.org/10.1007/s00531-014-1026-5.

Omodeo-Salé S, Salas R, Guimerà J, Ondrak R, Mas R, Arribas J, *et al.* 2017. Subsidence and thermal history of an inverted Late Jurassic-Early Cretaceous extensional basin (Cameros, North-Central Spain) affected by very low- to low-grade metamorphism. *Basin Research* 29: 156–174. https://doi.org/10.1111/bre.12142.

Ortí F, Pérez-López A, Salvany JM. 2017. Triassic evaporites of Iberia: Sedimentological and palaeogeographical implications for the western Neotethys evolution during the Middle Triassic-Earliest Jurassic. *Palaeogeography, Palaeoclimatology, Palaeoecology* 471: 157–180. https://doi.org/10.1016/j.palaeo.2017.01.025.

Padel M, Clausen S, Álvaro JJ, Casas JM. 2018. Review of the ediacaran-lower ordovician (Pre-sardic) stratigraphic framework of the eastern pyrenees, southwestern Europe. *Geologica Acta* 16(4): 339–355. https://doi.org/10.1344/GeologicaActa2018.16.4.1.

Paquette J-L, Ménot R-P, Pin C, Orsini J-B. 2003. Episodic and short-lived granitic pulses in a post-collisional setting: Evidence from precise U-Pb zircon dating through a crustal cross-section in Corsica. *Chemical Geology* 198(1-2): 1–20.

Parés JM, Banda E, Santanach P. 1988. Paleomagnetic results from the southeastern margin of the Ebro Basin (northeastern Spain): Evidence for a tertiary clockwise rotation. *Physics of the Earth and Planetary Interiors* 52(3-4): 267–282. https://doi.org/10.1016/0031-9201(88)90120-3.

Pastor-Galán D, Gutiérrez-Alonso G, Weil AB. 2020. The enigmatic curvature of Central Iberia and its puzzling kinematics. *Solid Earth* 11(4): 1247–1273. https://doi.org/10.5194/se-11-1247-2020.

Peace AL, Phethean J, Franke D, Foulger GR, Schiffer C, Welford JK, *et al.* 2019a. A review of Pangaea dispersal and large igneous provinces-in search of a causative mechanism. *Earth-Science Reviews*, November 2018: 102902. https://doi.org/10.1016/j.earscirev.2019.102902.

Peace AL, Welford JK, Ball PJ, Nirrengarten M. 2019b. Deformable plate tectonic models of the southern North Atlantic. *Journal of Geodynamics* 128(May): 11–37. https://doi.org/10.1016/j.jog.2019.05.005.

Pedreira D, Pulgar JA, Gallart J, Torné M. 2007. Three-dimensional gravity and magnetic modeling of crustal indentation and wedging in the western Pyrenees-Cantabrian Mountains. *Journal of Geophysical Research: Solid Earth* 112(12): 1–19. https://doi.org/10.1029/2007JB005021.

Pedreira D, Afonso JC, Pulgar JA, Gallastegui J, Carballo A, Fernàndez M, *et al.* 2015. Geophysical-petrological modeling of the lithosphere beneath the Cantabrian Mountains and the North-Iberian margin: geodynamic implications. *Lithos* 230: 46–68. https://doi.org/10.1016/j.lithos.2015.04.018.

Pedrera A, García-Senz J, Ayala C, Ruiz-Constán A, Rodríguez-Fernández LR, Robador A, *et al.* 2017. Reconstruction of the exhumed mantle across the North Iberian Margin by crustal-scale 3-D gravity inversion and geological cross-section. *Tectonics* 36 (12): 3155–3177. https://doi.org/10.1002/2017TC004716.

Pedrera A, García-Senz J, Peropadre C, Robador A, López-Mir B, Díaz-Alvarado J, *et al.* 2020. The Getxo crustal-scale cross-section: Testing tectonic models in the Bay of Biscay-Pyrenean rift system. *Earth-Science Reviews*, 103429.

Pedrera A, Ruiz-Constán A, García-Senz J, Azor A, Marín-Lechado C, Ayala C, *et al.* 2020. Evolution of the South-Iberian paleomargin: From hyperextension to continental subduction. *Journal of Structural Geology* 138: 104122.

Pereira R, Alves TM. 2013. Crustal deformation and submarine canyon incision in a Meso-Cenozoic first-order transfer zone (SW Iberia, North Atlantic Ocean). *Tectonophysics* 601: 148–162. https://doi.org/10.1016/j.tecto.2013.05.007.

Pereira R, Alves TM, Mata J. 2017. Alternating crustal architecture in West Iberia: A review of its significance in the context of NE atlantic rifting. *Journal of the Geological Society* 174(3): 522–540. https://doi.org/10.1144/jgs2016-050.

Perrone V, Martín-Algarra A, Critelli S, Decandia FA, D'errico M, Estevez A, *et al.* 2006. "Verrucano" and "Pseudoverrucano" in the Central-Western Mediterranean Alpine Chains: palaeogeographical evolution and geodynamic significance. *Geological Society, London, Special Publications* 262(1): 1–43.

Philip J, Allemann J. 1982. Comparaison entre les plates-formes du Crétacé supérieur de Provence et de Sardaigne. *Cretaceous Research* 3(1-2), 35–45.

Platt JP, Vissers RLM. 1989. Extensional collapse of thickened continental lithosphere: A working hypothesis for the Alboran Sea and Gibraltar arc. *Geology* 17(6), 540–543.

Puga E, Fanning M, Díaz de Federico A, Nieto JM, Beccaluva L, Bianchini G, *et al.* 2011. Petrology, geochemistry and U-Pb geochronology of the Betic Ophiolites: Inferences for Pangaea break-up and birth of the westernmost Tethys Ocean. *Lithos* 124 (3-4): 255–272. https://doi.org/10.1016/j.lithos.2011.01.002.

Puigdefàbregas C, Souquet P. 1986. Tecto-sedimentary cycles and depositional sequences of the Mesozoic and Tertiary from the Pyrenees. *Tectonophysics* 129(1-4): 173–203. https://doi.org/10.1016/0040-1951(86)90251-9.

Pulgar JA, Gallart J, Fernández-Viejo G, Pérez-Estaún A, Álvarez-Marrón J, Group E. 1996. Seismic image of the Cantabrian Mountains in the western extension of the Pyrenees from integrated ESCIN reflection and refraction data. *Tectonophysics* 264(1-4): 1–19.

Quijada IE, Suárez González P, Benito Moreno MI, Mas Mayoral JR, Alonso Millán Á. 2010. Un ejemplo de llanura fluvio-deltaica influenciada por las mareas: el yacimiento de icnitas de Serrantes (Grupo Oncala, Berriasiense, Cuenca de Cameros N. de España). *Geogaceta* 49: 15–18.

Quintana L, Pulgar JA, Alonso JL. 2015. Displacement transfer from borders to interior of a plate: A crustal transect of Iberia. *Tectonophysics* 663: 378–398. https://doi.org/10.1016/j.tecto.2015.08.046.

Ramsay JG. 1981. Tectonics of the Helvetic Nappes. *Geological Society Special Publication* 9: 293–309. https://doi.org/10.1144/GSL.SP1981.009.01.26.

Rat J, Mouthereau F, Brichau S, Crémades A, Bernet M, Balvay M, *et al.* 2019. Tectonothermal evolution of the Cameros Basin: Implications for tectonics of North Iberia. *Tectonics* 38(2): 440–469. https://doi.org/10.1029/2018TC005294.

Regis D, Rubatto D, Darling J, Cenki-Tok B, Zucali M, Engi M. 2014. Multiple metamorphic stages within an Eclogite-facies terrane (Sesia Zone, Western Alps) revealed by Th-U-Pb petrochronology. *Journal of Petrology* 55(7): 1429–1456. https://doi.org/10.1093/petrology/egu029.

Réhault JP, Honthaas C, Guennoc P, Bellon H, Ruffet G, Cotten J, *et al.* 2012. Offshore Oligo-Miocene volcanic fields within the Corsica-Liguria Basin: Magmatic diversity and slab evolution in the western Mediterranean Sea. *Journal of Geodynamics* 58: 73–95.

Richards JP. 2009. Postsubduction porphyry Cu-Au and epithermal Au deposits: Products of remelting of subduction-modified lithosphere. *Geology* 37(3): 247–250. https://doi.org/10.1130/G25451A.1.

Ricou L-E. 1980. La zone sub-briançonnaise des Alpes occidentales interprétée comme la trace d'un ample décrochement senestre sub-méridien.

Roca E. 1992. L'estructura de la conca Catalano-Balear: Paper de la compressió i de la distensió en la seva gènesi. PhD Thesis, Universitat de Barcelona.

Roca E, Desegaulx P. 1992. Analysis of the geological evolution and vertical movements in the Valencia Trough area, western Mediterranean. *Marine and Petroleum Geology* 9(2): 167–185.

Roca E, Guimerà J, Salas R. 1994. Mesozoic extensional tectonics in the southeast Iberian Chain. *Geological Magazine* 131(2): 155–168. https://doi.org/10.1017/S0016756800010694.

Roca E, Sans M, Cabrera L, Marzo M. 1999. Oligocene to Middle Miocene evolution of the central Catalan margin (northwestern Mediterranean). *Tectonophysics* 315(1-4): 209–229. https://doi.org/10.1016/S0040-1951(99)00289-9.

Roca E, Muñoz JA, Ferrer O, Ellouz N. 2011. The role of the Bay of Biscay Mesozoic extensional structure in the configuration of the Pyrenean orogen: Constraints from the MARCONI deep seismic reflection survey. *Tectonics* 30(2): 1–33. https://doi.org/10.1029/2010TC002735.

Rodríguez-Méndez L, Cuevas J, Tubía JM. 2016. Post-Variscan basin evolution in the central Pyrenees: Insights from the Stephanian-Permian Anayet Basin. *Comptes Rendus Geoscience* 348(3-4): 333–341. https://doi.org/10.1016/j.crte.2015.11.006.

Roma M, Ferrer O, Roca E, Pla O, Escosa FO, Butillé M. 2018. Formation and inversion of salt-detached ramp-syncline basins. Results from analog modeling and application to the Columbrets Basin (Western Mediterranean). *Tectonophysics* 745: 214–228. https://doi.org/10.1016/j.tecto.2018.08.012.

Romagny A, Jolivet L, Menant A, Bessière E, Maillard A, Canva A, *et al.* 2020. Detailed tectonic reconstructions of the Western Mediterranean region for the last 35 Ma, insights on driving mechanisms. *BSGF – Earth Sciences Bulletin* 191: 37. https://doi.org/10.1051/bsgf/2020040.

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

Rosenbaum G, Lister GS, Duboz C. 2002b. Relative motions of Africa, Iberia and Europe during Alpine orogeny. *Tectonophysics* 359(1-2): 117–129.

Rossetti F, Faccenna C, Goffé B, Monié P, Argentieri A, Funiciello R, *et al.* 2001. Alpine structural and metamorphic signature of the Sila Piccola Massif nappe stack (Calabria, Italy): Insights for the tectonic evolution of the Calabrian Arc. *Tectonics* 20(1): 112–133.

Rossi P, Oggiano G, Cocherie A. 2009. A restored section of the "southern Variscan realm" across the Corsica-Sardinia microcontinent. *Comptes Rendus Geoscience* 341(2-3): 224–238.

Rougier G, Ford M, Christophoul F, Bader AG. 2016. Stratigraphic and tectonic studies in the central Aquitaine Basin, northern Pyrenees: Constraints on the subsidence and deformation history of a retro-foreland basin. *Comptes Rendus – Geoscience* 348(3-4): 224–235. https://doi.org/10.1016/j.crte.2015.12.005.

Roure F, Brun J-P, Colletta B, Van Den Driessche J. 1992. Geometry and kinematics of extensional structures in the Alpine foreland basin of southeastern France. *Journal of Structural Geology* 14(5): 503–519.

Rubatto D, Gebauer D, Compagnoni R. 1999. Dating of eclogite-facies zircons: the age of Alpine metamorphism in the Sesia-Lanzo Zone (Western Alps). *Earth and Planetary Science Letters* 167 (3-4): 141–158.

Sàbat F, Gelabert B, Rodríguez-Perea A, Giménez J. 2011. Geological structure and evolution of Majorca: Implications for the origin of the Western Mediterranean. *Tectonophysics* 510(1-2): 217–238. https://doi.org/10.1016/j.tecto.2011.07.005.

Salas R, Casas A. 1993. Mesozoic extensional tectonics, stratigraphy and crustal evolution during the Alpine cycle of the eastern Iberian basin. *Tectonophysics* 228(1-2): 33–55. https://doi.org/10.1016/0040-1951(93)90213-4.

Salas R, Guimerà J, Mas R, Martín-Closas C, Melendez A, Alonso A. 2001. Evolution of the Mesozoic Central Iberian Rift System and its Cainozoic inversion (Iberian chain). In: Ziegler PA, Cavazza W, Robertson AHF, Crasquin-Soleau S, eds. *Peri-Tethys Memoir 6: Peri-Tethyan Rift/Wrench Basins and Passive Margins* (Mémoir, Vol. 186, Issue 2, pp. 145–186).

Sallarès V, Gailler A, Gutscher M-A, Graindorge D, Bartolomé R, Gràcia E, *et al.* 2011. Seismic evidence for the presence of Jurassic oceanic crust in the central Gulf of Cadiz (SW Iberian margin). *Earth and Planetary Science Letters* 311(1-2): 112–123. https://doi.org/10.1016/j.epsl.2011.09.003.

Sallarès V, Martínez-Loriente S, Prada M, Gràcia E, Ranero C, Gutscher MA, *et al.* 2013. Seismic evidence of exhumed mantle rock basement at the Gorringe Bank and the adjacent Horseshoe and Tagus abyssal plains (SW Iberia). *Earth and Planetary Science Letters* 365: 120–131. https://doi.org/10.1016/j.epsl.2013.01.021.

Saspiturry N, Cochelin B, Razin P, Leleu S, Lemirre B, Bouscary C, *et al.* 2019. Tectono-sedimentary evolution of a rift system controlled by Permian post-orogenic extension and metamorphic core complex formation (Bidarray Basin and Ursuya dome, Western Pyrenees). *Tectonophysics* 768: 228180. https://doi.org/10.1016/j.tecto.2019.228180.

Saspiturry N, Lahfid A, Baudin T, Guillou-Frottier L, Razin P, Issautier B, *et al.* 2020. Paleogeothermal gradients across an inverted hyperextended rift system: Example of the Mauléon Fossil Rift (Western Pyrenees). *Tectonics* 39(10): 1–36. https://doi.org/10.1029/2020TC006206.

Schaltegger U, Desmurs L, Manatschal G, Müntener O, Meier M, Frank M, *et al.* 2002. The transition from rifting to sea-floor spreading within a magma-poor rifted margin: Field and isotopic constraints. *Terra Nova* 14(3): 156–162.

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

Schettino A, Turco E. 2009. Breakup of Pangaea and plate kinematics of the central Atlantic and Atlas regions. *Geophysical Journal International* 178(2): 1078–1097. https://doi.org/10.1111/j.1365-246X.2009.04186.x.

Schettino A, Turco E. 2011. Tectonic history of the Western Tethys since the Late Triassic. *Bulletin of the Geological Society of America* 123(1-2): 89–105. https://doi.org/10.1130/B30064.1.

Schmid SM, Fügenschuh B, Kissling E, Schuster R. 2004. Tectonic map and overall architecture of the Alpine orogen. *Eclogae Geologicae Helvetiae* 97(1): 93–117.

Schmid SM, Bernoulli D, Fügenschuh B, Matenco L, Schefer S, Schuster R, *et al.* 2008. The Alpine-Carpathian-Dinaridic orogenic system: Correlation and evolution of tectonic units. *Swiss Journal of Geosciences* 101(1): 139–183. https://doi.org/10.1007/s00015-008-1247-3.

Schreiber D, Giannerini G, Lardeaux JM. 2011. The Southeast France Basin during Late Cretaceous times: The spatiotemporal link between Pyrenean collision and Alpine subduction. *Geodinamica Acta* 24(1): 21–35. https://doi.org/10.3166/ga.24.21-35.

Séranne M. 1999. The Gulf of Lion continental margin (NW Mediterranean) revisited by IBS: an overview. *Geological Society, London, Special Publications* 156(1): 15–36. https://doi.org/10.1144/GSL.SP1999.156.01.03.

Séranne M, Benedicto A, Labaum P, Truffert C, Pascal G. 1995. Structural style and evolution of the Gulf of Lion Oligo-Miocene rifting: Role of the Pyrenean orogeny. *Marine and Petroleum Geology* 12(8): 809–820.

Serrano F, Sanz de Galdeano C, Delgado F, López-Garrido AC, Martín-Algarra A. 1995. The Mesozoic and Cenozoic of the Malaguide Complex in the Málaga area: A Paleogene olistostrome-type chaotic complex (Betic Cordillera, Spain). *Geologie En Mijnbouw* 74: 105.

Shimabukuro DH, Wakabayashi J, Alvarez W, Chang S. 2012. Cold and old: The rock record of subduction initiation beneath a continental margin, Calabria, southern Italy. *Lithosphere* 4(6): 524–532. https://doi.org/10.1130/L222.1.

Sibuet J-C, Srivastava SP, Spakman W. 2004. Pyrenean orogeny and plate kinematics. *Journal of Geophysical Research: Solid Earth* 109(B8): 1–18. https://doi.org/10.1029/2003JB002514.

Simonetti M, Carosi R, Montomoli C, Cottle JM, Law RD. 2020. Transpressive deformation in the Southern European Variscan belt: New insights from the Aiguilles Rouges Massif (Western Alps). *Tectonics* 39(6): 1–24. https://doi.org/10.1029/2020tc006153.

Sinclair HD, Gibson M, Naylor M, Morris RG. 2005. Asymmetric growth of the Pyrenees revealed through measurement and modeling of orogenic fluxes. *American Journal of Science* 305 (5): 369–406. https://doi.org/10.2475/ajs.305.5.369.

Sopeña A, López J, Arche A, Pérez-Arlucea M, Ramos A, Virgili C, *et al.* 1988. Permian and Triassic rift basins of the Iberian Peninsula. In: Developments in Geotectonics (Vol. 22, Issue C, pp. 757–786). https://doi.org/10.1016/B978-0-444-42903-2.50036-1.

Soto JI, Azanon JM. 1994. Zincian staurolite in metabasites and metapelites from the Betic-Cordillera (SE Spain). *Neues Jahrbuch Fur Mineralogie-Abhandlungen* 168(2): 109–126.

Soto R, Casas-Sainz AM, Oliva-Urcia B, García-Lasanta C, Izquierdo-Llavall E, Moussaid B, *et al.* 2019. Triassic stretching directions in Iberia and North Africa inferred from magnetic fabrics. *Terra Nova* 31(5): 465–478. https://doi.org/10.1111/ter.12416.

Spakman W, Wortel R. 2004. A tomographic view on western Mediterranean geodynamics. In: The TRANSMED atlas. The Mediterranean region from crust to mantle (Issue January 2004, pp. 31–52. Springer. https://doi.org/10.1007/978-3-642-18919-7.

Srivastava SP, Sibuet J-C, Cande S, Roest WR, Reid ID. 2000. Magnetic evidence for slow seafloor spreading during the formation of the Newfoundland and Iberian margins. *Earth and Planetary Science Letters* 182(1): 61–76. https://doi.org/10.1016/S0012-821X(00)00231-4.

Stampfli G.M. 1993. Le Briançonnais, terrain exotique dans les Alpes ? *Eclogae Geologicae Helvetiae* 86(1): 1–45.

Stampfli GM, Borel GD. 2002. A plate tectonic model for the Paleozoic and Mesozoic constrained by dynamic plate boundaries and restored synthetic oceanic isochrons. *Earth and Planetary Science Letters* 196(1-2): 17–33. https://doi.org/10.1016/S0012-821X(01)00588-X.

Stampfli GM, Hochard C. 2009. Plate tectonics of the Alpine realm. *Geological Society, London, Special Publications* 327(1): 89–111. https://doi.org/10.1144/SP327.6.

Stampfli GM, Mosar J, Favre P, Pillevuit A, Vannay J-C. 2001. Permo-Mesozoic evolution of the western Tethyan realm: the Neotethys/East- Mediterranean connection. In: Ziegler PA, Cavazza W, Robertson AHF, Crasquin-Soleau S, eds. *Peri-Tethys Memoir 6: Peri-Tethyan Rift/Wrench Basins and Passive Margins* (Vol. 186, pp. 51–108). Mémoirs du Muséum d'Histoire Naturelle.

Suárez González P, Quijada IE, Mas JR, Benito MI. 2010. Nuevas aportaciones sobre la influencia marina y la edad de los carbonatos de la Fm Leza en el sector de Préjano (SE de LaRioja. Cretácico Inferior, Cuenca de Cameros. *Geogaceta* 49: 7–10.

Tavani S, Granado P. 2015. Along-strike evolution of folding, stretching and breaching of supra-salt strata in the Plataforma Burgalesa extensional forced fold system (northern Spain). *Basin Research* 27(4): 573–585. https://doi.org/10.1111/bre.12089.

Tavani S, Quintà A, Granado P. 2011. Cenozoic right-lateral wrench tectonics in the Western Pyrenees (Spain): The Ubierna Fault System. *Tectonophysics* 509(3-4): 238–253. https://doi.org/10.1016/j.tecto.2011.06.013.

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

Teixell A. 1998. Crustal structure and orogenic material budget in the west central Pyrenees. *Tectonics* 17(3): 395–406.

Teixell A, Labaume P, Lagabrielle Y. 2016. The crustal evolution of the west-central Pyrenees revisited: Inferences from a new kinematic scenario. *Comptes Rendus – Geoscience* 348(3-4): 257–267. https://doi.org/10.1016/j.crte.2015.10.010.

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

Ternois S, Odlum M, Ford M, Pik R, Stockli D, Tibari B, *et al.* 2019. Thermochronological Evidence of Early Orogenesis, Eastern Pyrenees, France. *Tectonics* 38(4): 1308–1336. https://doi.org/10.1029/2018TC005254.

Trümpy R. 1988. A possible Jurassic-Cretaceous transform system in the Alps and the Carpathians, pp. 93–110. https://doi.org/10.1130/SPE218-p93.

Tugend J, Manatschal G, Kusznir NJ, Masini E. 2014a. Characterizing and identifying structural domains at rifted continental margins: Application to the Bay of Biscay margins and its Western Pyrenean fossil remnants. *Geological Society Special Publication* 413(1): 171–203. https://doi.org/10.1144/SP413.3.

Tugend J, Manatschal G, Kusznir NJ, Masini E, Mohn G, Thinon I. 2014b. Formation and deformation of hyperextended rift systems: Insights from rift domain mapping in the Bay of Biscay-Pyrenees. *Tectonics* 33(7): 1239–1276. https://doi.org/10.1002/2014TC003529.

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

Tugend J, Chamot-Rooke N, Arsenikos S, Blanpied C, Frizon de Lamotte D. 2019. Geology of the Ionian Basin and Margins: A key to the East Mediterranean geodynamics. *Tectonics* 38(8): 2668–2702. https://doi.org/10.1029/2018TC005472.

Turco E, Macchiavelli C, Mazzoli S, Schettino A, Pierantoni PP. 2012. Kinematic evolution of Alpine Corsica in the framework of Mediterranean mountain belts. *Tectonophysics* 579: 193–206.

Ubide T, Wijbrans JR, Galé C, Arranz E, Lago M, Larrea P. 2014. Age of the Cretaceous alkaline magmatism in northeast Iberia: Implications for the Alpine cycle in the Pyrenees. *Tectonics* 33 (7): 1444–1460.

Upton BGJ, Stephenson D, Smedley PM, Wallis SM, Fitton JG. 2004. Carboniferous and Permian magmatism in Scotland. *Geological Society, London, Special Publications* 223(1): 195–218.

Vacherat A. 2014. Inversion d'une marge hyper-amincie : contexte thermo-cinématique et interactions tectonique-érosion au Nord des Pyréńes. Université Pierre et Marie Curie.

Vacherat A, Mouthereau F, Pik R, Bellahsen N, Gautheron C, Bernet M, *et al.* 2016. Rift-to-collision transition recorded by tectono-thermal evolution of the northern Pyrenees. *Tectonics* 35(4): 907–933. https://doi.org/10.1002/2015TC004016.

Vacherat A, Mouthereau F, Pik R, Huyghe D, Paquette JL, Christophoul F, *et al.* 2017. Rift-to-collision sediment routing in the Pyrenees: A synthesis from sedimentological, geochronological and kinematic constraints. *Earth-Science Reviews* 172(January): 43–74. https://doi.org/10.1016/j.earscirev.2017.07.004.

van Hinsbergen DJJ, Vissers RLM, Spakman W. 2014. Origin and consequences of western Mediterranean subduction, rollback, and slab segmentation. *Tectonics* 33(4): 393–419. https://doi.org/10.1002/2013TC003349.

van Hinsbergen DJJ, Torsvik TH, Schmid SM, Maţenco LC, Maffione M, Vissers RLM, *et al.* 2020. Orogenic architecture of the Mediterranean region and kinematic reconstruction of its tectonic evolution since the Triassic. *Gondwana Research* 81: 79–229. https://doi.org/10.1016/j.gr.2019.07.009.

Van Wees JD, Arche A, Beijdorff CG, López-Gómez J, Cloetingh SAPL. 1998. Temporal and spatial variations in tectonic subsidence in the Iberian Basin (eastern Spain): Inferences from automated forward modelling of high-resolution stratigraphy (Permian-Mesozoic). *Tectonophysics* 300(1-4): 285–310. https://doi.org/10.1016/S0040-1951(98)00244-3.

Van Wees J-D, Stephenson RA, Ziegler PA, Bayer U, McCann T, Dadlez R, *et al.* 2000. On the origin of the southern Permian Basin, Central Europe. *Marine and Petroleum Geology* 17(1): 43–59.

Vargas H, Gaspar-Escribano JM, López-Gómez J, Van Wees JD, Cloetingh S, de La Horra R, *et al.* 2009. A comparison of the Iberian and Ebro Basins during the Permian and Triassic, eastern Spain: A quantitative subsidence modelling approach. *Tectonophysics* 474(1-2): 160–183. https://doi.org/10.1016/j.tecto.2008.06.005.

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

Vergés J, Sàbat F. 1999. Constraints on the Neogene Mediterranean kinematic along a 1000 km transect from Iberia to Africa. In: Durand B, Jolivet L, Horváth F, Séranne M, eds. The *The Mediterranean Basins: Tertiary extension within the Alpine Orogen*. Geological Society of London, pp. 63–80.

Vergés J, Millán H, Roca E, Muñoz J-A, Marzo M, Cirés J, *et al.* 1995. Eastern Pyrenees and related foreland basins: pre-, syn- and post-collisional crustal-scale cross-sections. *Marine and Petroleum Geology* 12(8): 903–915. https://doi.org/10.1016/0264-8172(95)98854-X.

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

Vergés J, Poprawski Y, Almar Y, Drzewiecki PA, Moragas M, Bover-Arnal T, *et al.* 2020. Tectono-sedimentary evolution of Jurassic-Cretaceous diapiric structures: Miravete anticline, Maestrat Basin, Spain. *Basin Research* 00, 000–000. https://doi.org/10.1111/bre.12447.

Villa IM, Hermann J, Müntener O, Trommsdorff V. 2000. ^{39}Ar-^{40}Ar dating of multiply zoned amphibole generations (Malenco, Italian Alps). *Contributions to Mineralogy and Petrology* 140(3): 363–381.

Vissers RLM. 1992. Variscan extension in the Pyrenees. *Tectonics* 11 (6): 1369–1384.

Vissers RLM, Meijer PT. 2012. Iberian plate kinematics and Alpine collision in the Pyrenees. *Earth-Science Reviews* 114(1-2): 61–83. https://doi.org/10.1016/j.earscirev.2012.05.001.

Vitale S, Ciarcia S. 2013. Tectono-stratigraphic and kinematic evolution of the southern Apennines/Calabria-Peloritani Terrane system (Italy). *Tectonophysics* 583: 164–182. https://doi.org/10.1016/j.tecto.2012.11.004.

Vitale S, Fedele L, Tramparulo FD, Ciarcia S, Mazzoli S, Novellino A. 2013. Structural and petrological analyses of the Frido Unit (southern Italy): New insights into the early tectonic evolution of the southern Apennines-Calabrian Arc system. *Lithos* 168-169: 219–235. https://doi.org/10.1016/j.lithos.2013.02.006.

Vitale S, Ciarcia S, Fedele L, Tramparulo FDA. 2019. The Ligurian oceanic successions in southern Italy: The key to decrypting the first orogenic stages of the southern Apennines-Calabria chain system. *Tectonophysics* 750(November 2018): 243–261. https://doi.org/10.1016/j.tecto.2018.11.010.

Vitale Brovarone A, Beyssac O, Malavieille J, Molli G, Beltrando M, Compagnoni R. 2013. Stacking and metamorphism of continuous segments of subducted lithosphere in a high-pressure wedge: The example of Alpine Corsica (France). *Earth-Science Reviews* 116 (1): 35–56. https://doi.org/10.1016/j.earscirev.2012.10.003.

Waldner M, Bellahsen N, Mouthereau F, Bernet M, Pik R, Rosenberg CL, *et al.* 2021. Central Pyrenees mountain building: Constraints from new LT thermochronological data from the Axial Zone. *Tectonics* 40(3): e2020TC006614.

Wang Y, Chevrot S, Monteiller V, Komatitsch D, Mouthereau F, Manatschal G, *et al.* 2016. The deep roots of the western Pyrenees revealed by full waveform inversion of teleseismic P waves. *Geology* 44(6): 475–478. https://doi.org/10.1130/G37812.1.

Wehr H, Chevrot S, Courrioux G, Guillen A. 2018. A three-dimensional model of the Pyrenees and their foreland basins from geological and gravimetric data. *Tectonophysics* 734-735(April), 16–32. https://doi.org/10.1016/j.tecto.2018.03.017.

Whitchurch AL, Carter A, Sinclair HD, Duller RA, Whittaker AC, Allen PA. 2011. Sediment routing system evolution within a diachronously uplifting orogen: Insights from detrital zircon thermochronological analyses from the South-Central Pyrenees.

American Journal of Science 311(5): 442–482. https://doi.org/10.2475/05.2011.03.

Wortel MJR, Spakman W. 2000. Subduction and Slab Detachment in the Mediterranean-Carpathian Region. *Science* 290(5498): 1910–1917. https://doi.org/10.1126/science.290.5498.1910.

Zarki-Jakni B, van der Beek P, Poupeau G, Sosson M, Labrin E, Rossi P, *et al.* 2004. Cenozoic denudation of Corsica in response to Ligurian and Tyrrhenian extension: Results from apatite fission track thermochronology. *Tectonics* 23(1).

Ziegler PA. 1989. Geodynamic model for Alpine intra-plate compressional deformation in Western and Central Europe. In: Cooper MA, Williams GD, eds. *Inversion Tectonics* (Vol. 3, Issue 44, pp. 63–85. Geological Society Special Publication.

Ziegler PA. 1990a. Collision related intra-plate compression deformations in Western and Central Europe. *Journal of Geodynamics* 11(4): 357–388.

Ziegler PA. 1990b. Geological atlas of western and central Europe.

Ziegler PA, Dèzes P. 2006. Crustal evolution of Western and Central Europe. *Geological Society, London, Memoirs* 32(1): 43–56. https://doi.org/10.1144/GSL.MEM2006.032.01.03.

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