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Cretaceous slab break-off in the Pyrenees: Iberian plate kinematics in paleomagnetic and mantle reference frames

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ABSTRACT

The Pyrenees at the Iberia–Europe collision zone contain sediments showing Albian–Cenomanian high-temperature metamorphism, and coeval alkaline magmatic rocks. Stemming from different views on Jurassic–Cretaceous Iberian microplate kinematics, two schools of thought exist on the trigger of this thermal pulse: one invoking hyperextension of the Iberian and Eurasian margins, the other suggesting slab break-off. Competing scenarios for Mesozoic Iberian motion compatible with Pyrenean geology, comprise (1) transtensional eastward motion of Iberia versus Eurasia, or (2) strike-slip motion followed by orthogonal extension, both favoring hyperextension-related heating, and (3) scissor-style opening of the Bay of Biscay coupled with subduction in the Pyrenean realm, favoring the slab break-off hypothesis. We test these kinematic scenarios for Iberia against a newly compiled paleomagnetic dataset and conclude that the scissor-type scenario is the only one consistent with a well-defined ~35° counterclockwise rotation of Iberia during the Early Aptian. We proceed to show that when taking absolute plate motions into account, Aptian oceanic subduction in the Pyrenees followed by Late Aptian–Early Albian slab break-off should leave a slab remnant in the present-day mid-mantle below NW Africa. Mantle tomography shows the Reggane anomaly that matches the predicted position and dimension of such a slab remnant between 1900 and 1500 km depth below southern Algeria. Mantle tomography is therefore consistent with the scissor-type opening of the Bay of Biscay coupled with subduction in the Pyrenean realm. Slab break-off may thus explain high-temperature metamorphism and alkaline magmatism during the Albian–Cenomanian in the Pyrenees, whereas hyperextension that exhumed Pyrenean mantle bodies occurred much earlier, in the Jurassic.

1. Introduction

The Pyrenees of southwestern Europe formed as a result of convergence and crustal thickening between Iberia and Eurasia since at least the Late Mesozoic (80 Ma). A conspicuous phenomenon in the Pyrenees is the occurrence in the North Pyrenean Zone adjacent to the North Pyrenean Fault (Fig. 1) of low-pressure, high-temperature metasedimentary and alkaline igneous rocks with ages of ~110–90 Ma (Ubide et al., 2014; Clerc et al., 2015). The North Pyrenean Zone is also host to numerous bodies of sub-continental mantle rocks (Bodinier et al., 1988; Lagabrielle et al., 2010; Vauchez et al., 2013). In recent years, a fierce debate has started on the interpretation and importance of these rocks for fundamental geodynamic processes. One school of thought proposed that the HT–LP metamorphism is intrinsically related to the exhumation of the sub-continental mantle bodies, and that it serves as example of the temperature evolution associated with hyperextension at continental margins (Lagabrielle et al., 2010; Clerc and Lagabrielle, 2014; Clerc et al., 2015). A second school of thought, however, propounded that the metamorphism reflects the thermal response in the crust to the detachment of a subducted slab below the proto-Pyrenees (Vissers and Meijer, 2012a) and that the exhumation of the mantle peridotites is considerably older (Late Jurassic) than the HT metamorphism and associated magmatism.

These opposing interpretations stem from a long-lasting discussion on the kinematic reconstruction of Iberia relative to Eurasia, originating from the interpretation of marine magnetic anomaly data in the Central Atlantic Ocean and the Bay of Biscay. The Bay of Biscay contains a former mid-ocean ridge that separated Iberia from Eurasia. A reconstruction for M0 times (~126 Ma) by Olivet (1996), based on the Newfoundland Gibraltar Fracture Zone (NGFZ) in combination with the broad J anomaly on each side of the Central Atlantic Ocean and on the geology-based assumption of dominant strike-slip motion in the Pyrenean domain prior to chron A33 (~79 Ma), implied a relative rotation of Iberia versus Eurasia of approximately 25°. Re-interpretation of the picks allied with the J anomaly and analysis of the magnetic lineations in the Bay of

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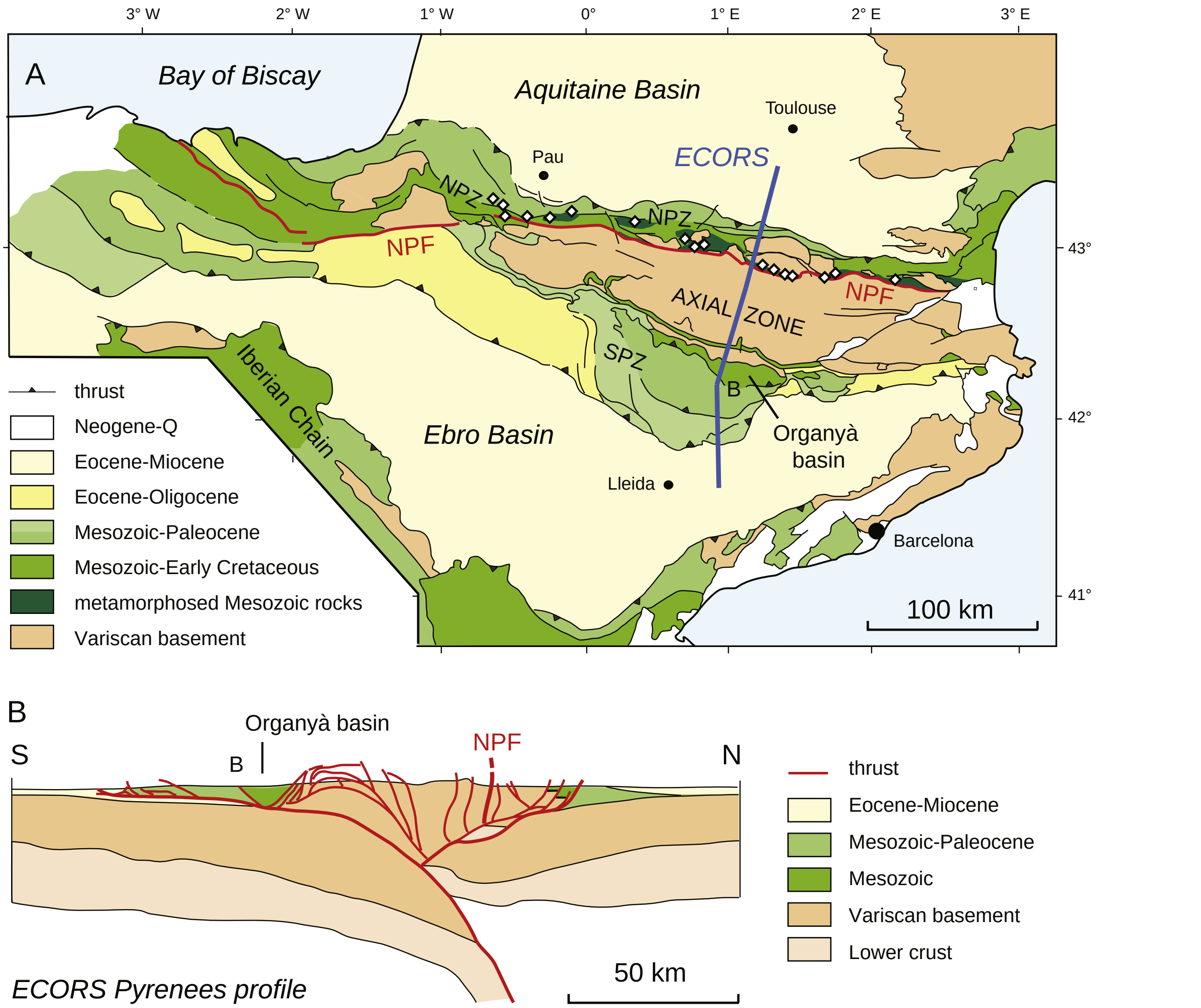

Fig. 1. A: geological sketch map of the Pyrenees, compiled after Vergés et al. (1995), Vissers and Meijer (2012a) and Clerc and Lagabrielle (2014). Blue line indicates ECORS seismic section shown in B. White diamonds denote mantle peridotite bodies. Abbreviations: NPZ — North Pyrenean Zone; NPF — North Pyrenean Fault; SPZ — Southern Pyrenean Zone; B — Boixols thrust. B: ECORS crustal-scale cross-section, after Beaumont et al. (2000). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Biscay by Sibuet et al. (2004) suggested an angle of ~35° instead, whereas anomalies interpreted as A34 (~83 Ma), close to the paleo-ridge, are nearly parallel. Scenarios based on these anomalies (Srivastava et al., 1990, 2000; Sibuet et al., 2004; Vissers and Meijer, 2012a) defined an Iberia–Eurasia Euler pole in the east of the Bay, west of the present-day Pyrenees. The 35° of rotation between 125 and 83 Ma inevitably predicts up to ~500 km of oceanic lithosphere subduction in the Pyrenean realm prior to the onset of Iberia–Eurasia collision (Sibuet et al., 2004; Vissers and Meijer, 2012a). A further refinement of the timing of this rotation came from a paleomagnetic study by Gong et al. (2008), who suggested that most of the Iberian rotation occurred during the Aptian (~126–113 Ma).

The validity of the interpretation of the M0 anomaly, particularly in the Central Atlantic Ocean, is not beyond controversy, however. Bronner et al. (2011) argued that this anomaly does not reflect early sea floor spreading, but is located in mid-Cretaceous magmatic rocks that covered exhumed mantle rocks of the hyperextended Iberian and Newfoundland margins. In addition, tomographic models of the mantle under the Pyrenees (e.g.Souriau et al., 2008, Chevrot et al., 2014) show no trace of a subducted slab, which led Bronner et al. (2012) and Clerc et al. (2015) to argue that no Cretaceous subduction could have occurred in the Pyrenean realm. This brought the reconstruction of Iberian plate kinematics in an impasse.

Alternative reconstructions have attempted to estimate the kinematic history of Iberia using geological interpretation of the extension and contraction history recorded in the Pyrenees (Jammes et al., 2009; Mouthereau et al., 2014). These reconstructions also suggested a relatively small rotation of ~25° during the Early Cretaceous and involved extension across the Pyrenean realm throughout the Aptian–Albian. But because these reconstructions are based on geological interpretation of the Pyrenees, they cannot serve as an independent platform to study the origin of HT–LP metamorphism, alkaline magmatism, and mantle exhumation in the North Pyrenean zone.

In this paper, we aim to break through the current impasse on the analysis of Iberian plate kinematics and the North Pyrenean geology in two ways. First, we test the predictions of existing reconstructions for the amount and timing of rotation of Iberia against an extensive paleomagnetic database obtained from Mesozoic and Cenozoic rocks of stable Iberia. Secondly, we test whether P- and S-wave seismic tomographic images of the mantle indeed falsify the hypothesis of subduction in the Pyrenees. To this end, we first place the kinematic reconstruction of Iberia and the Pyrenean domain in its relevant absolute plate motion context and explore mantle structure at a depth range and location appropriate for a mid-Cretaceous subduction zone using global reconstructions of slab sinking rates (Van der Meer et al., 2010).

Below we first summarize geological data from the Pyrenees, describe the competing plate kinematic scenarios for Iberia in the Late Mesozoic, and show how these scenarios compare with magnetic lineations from the Central Atlantic Ocean and Bay of Biscay. We then proceed to test these scenarios against the paleomagnetic database and P- and S-wave mantle tomography.

2. Previous work

2.1. Main features of the Pyrenean geology

The Pyrenees are an ~E–W trending mountain belt, about 450 km long and 125 km wide (Fig. 1), formed in Late Cretaceous through Paleogene times in response to convergence between NE Iberia and Eurasia. Structural and deep seismic studies (ECORS Pyrenees) have shown that the orogen is an asymmetric, doubly-vergent wedge that absorbed about 165 km of shortening, with Iberian continental lithosphere underthrust at least about 80 km beneath Europe (Roure et al., 1989; Beaumont et al., 2000). At shallow crustal levels, the European continental margin preserved in the North Pyrenean Zone (NPZ) was a backthrust onto the Aquitaine foreland basin to the north, while Variscan basement units of the Axial Zone and their sedimentary cover of the Iberian margin found in the South Pyrenean Zone (SPZ) were thrust southward onto the Ebro foreland basin (Fig. 1). The NPZ and Axial Zone are separated by the North Pyrenean Fault (NPF), marked by isolated bodies of Variscan basement allied with extensional structures, mantle peridotite bodies, alkaline gabbros and volcanics and, mainly in the eastern part of the belt, metamorphosed Mesozoic rocks. The pertinent main features of the geology of the NPZ are as follows.

Mesozoic facies distributions in the NPZ and now inverted normal faults adjacent to Variscan basement blocks point to the development of 10 km scale pull-apart basins spatially associated with the NPF (e.g., Peybernès and Souquet, 1984). Middle Albian marl–turbidite sedimentation occurred in half grabens, only a few km wide, interpreted in a context of sinistral transtensile deformation, although the data do not allow discrimination between a purely tensional or a transtensional tectonic regime (Lagabrielle et al., 2010).

Upper mantle peridotites, partly serpentinized, occur amidst low-grade Triassic–Jurassic sediments in the western part of the NPZ, while in the east they are bounded by amphibolite facies Aptian–Albian carbonates (Avé Lallemant, 1967). $^{40}Ar/^{39}Ar$ dating of amphiboles from the Lherz and Caussou peridotites yield ages of 108–103 Ma, while Sm–Nd internal isochrons on garnet–amphibole pyroxenites from Lherz yield ages of 104 ± 5 Ma (Henry et al., 1998). The ages have been interpreted by these authors to indicate rapid cooling of the ultramafics during mantle exhumation to crustal levels. However, Sm–Nd linear arrays defined by whole rock, clinopyroxene and garnet analyses from layered anhydrous garnet pyroxenites yielded Jurassic Nd ages of 153 ± 3 Ma (Prades), 177 ± 3 Ma (Moncaup) and 138 ± 4 Ma (Moncaut), respectively, ascribed by Henry et al. (1998) to incomplete Nd rehomogenization during fast ascent of the mantle rocks.

Albian–Cenomanian alkaline magmatism in the NPZ occurred as submarine basaltic to trachytic flows, and as sills, dikes and gabbro bodies. Micropaleontological data from intervening sediments constrain volcanic activity to the (upper) Albian to Turonian (Dubois and Seguin, 1978). This is consistent with K–Ar age determinations by Montigny et al. (1986) who recognized three magmatic stages, a first one mainly in the central Pyrenees from 113 to 105 Ma, a second stage from 100 to 90 Ma along the entire NPZ, and a third one limited to the westernmost Pyrenees from 90 to 85 Ma. A recent re-evaluation of these ages using $^{40}Ar/^{39}Ar$ geochronology confirmed this age range (Ubide et al., 2014).

The Mesozoic sediments are metamorphosed, notably in the eastern part of the chain, at temperatures of 550°–650 °C and pressures of 3–4 kbar (Golberg and Leyreloup, 1990). K/Ar geochronology of the metamorphism yielded ages of 95 to 85 Ma, with a climax near 95 Ma in the eastern part of the NPZ (Golberg et al., 1986; Montigny et al., 1986), while recent $^{40}Ar/^{39}Ar$ dating by Clerc et al. (2015) yielded ages of 110 to 90 Ma. In addition, reset Variscan basement rocks also yielded Ar/Ar ages in the range 110–100 Ma (Clerc et al., 2015, and references therein). High-grade Mesozoic rocks adjacent to the NPF are foliated and locally show sub-horizontal synmetamorphic stretching lineations and near-vertical fold axes of small-scale folds. Kinematic data, though limited, are consistent with transcurrent sinistral motions along the NPF (Choukroune, 1976). Montigny et al. (1986) and Golberg and Leyreloup (1990) argued that this deformation associated with the LP/HT metamorphism cannot be ascribed to the Alpine collision, and was instead related to a pre-collisional extensional stage.

2.2. Current scenarios for Mesozoic rifting in the Pyrenean realm

The Iberian Peninsula in SW Europe is currently part of the Eurasian plate and was part of Pangea in Paleozoic time (e.g., Ziegler, 1982), but has a Late Jurassic to Paleogene history as a separate microplate (e.g.Carey, 1958; Van der Voo, 1969; Le Pichon and Sibuet, 1971). During its history as an individual plate, Iberia was separated by an oceanic ridge from North America in the west, by a transform-ridge system from Africa/Adria in the south and east, and by a ridge from western Eurasia in the Bay of Biscay.

There are at least three competing scenarios describing the rifting of Iberia from Eurasia (Fig. 2). Left-lateral strike-slip opening of the Bay of Biscay (Fig. 2A) accommodated by the NPF was mainly inspired by geological observations in the Pyrenees (Le Pichon and Sibuet, 1971; Olivet, 1996) interpreted to reflect Aptian–Albian transtensional rifting in the Pyrenean domain. Scissor-type opening of the Bay of Biscay (Fig. 2B), first suggested by Carey (1958), has been documented in studies using magnetic lineations in the Atlantic and Bay of Biscay (Srivastava et al., 1990, 2000; Sibuet et al., 2004; Vissers and Meijer, 2012a). These studies indicate a N–S-directed rifting stage between anomalies M25 (Kimmeridgian, ~56 Ma) and M0 (base Aptian, 126 Ma), before rotation of Iberia between M0 and anomaly A34 (Campanian, 83 Ma). Based on recent geological studies in the NPZ and seismic studies of the eastern Bay of Biscay, a third scenario (Fig. 2C) has been proposed involving left-lateral motion of Iberia during the Jurassic–Early Cretaceous, followed by orthogonal (NE–SW) extension in Aptian–Albian times (Jammes et al., 2009). In addition, the extensional stage was inferred to have led to a hyperextended margin geometry, with mantle exhumation in a narrow rift (Tugend et al., 2014).

These scenarios vary both in nature and timing of extension, the most notorious difference being the Aptian–Albian convergence in the Pyrenean domain of more than 300 km at the location of the ECORS section (Fig. 1), and up to 500 km in the easternmost Pyrenees, predicted by the scissor-type opening of the Bay (Fig. 2B), at times that the other two models argue for either transtensional and/or orthogonal continental stretching. According to the scissor-type scenario, rifting occurred earlier, from the Late Jurassic until the Aptian, hence the hyperextended margin architecture in essence developed prior to the Aptian, while the amount of mantle exhumation and perhaps ocean spreading was significantly larger than in the purely extensional models.

2.3. Kinematic reconstructions of Iberia and the marine magnetic anomaly record

Even though magnetic lineations in the ocean floor are clearly independent from any interpretation based on geology, plate kinematic studies based on magnetic lineations have as yet not convincingly solved the kinematics of the Iberian microplate during the Mesozoic. At this stage we note that the basic assumption underlying plate kinematic reconstructions using ocean floor anomalies is that they represent genuine isochrons. This led Sibuet et al. (2004) to discard Olivet's (1996) M0 reconstruction of Fig. 2A, because the marked mismatch of the M0 anomalies in that reconstruction is inconsistent with the notion

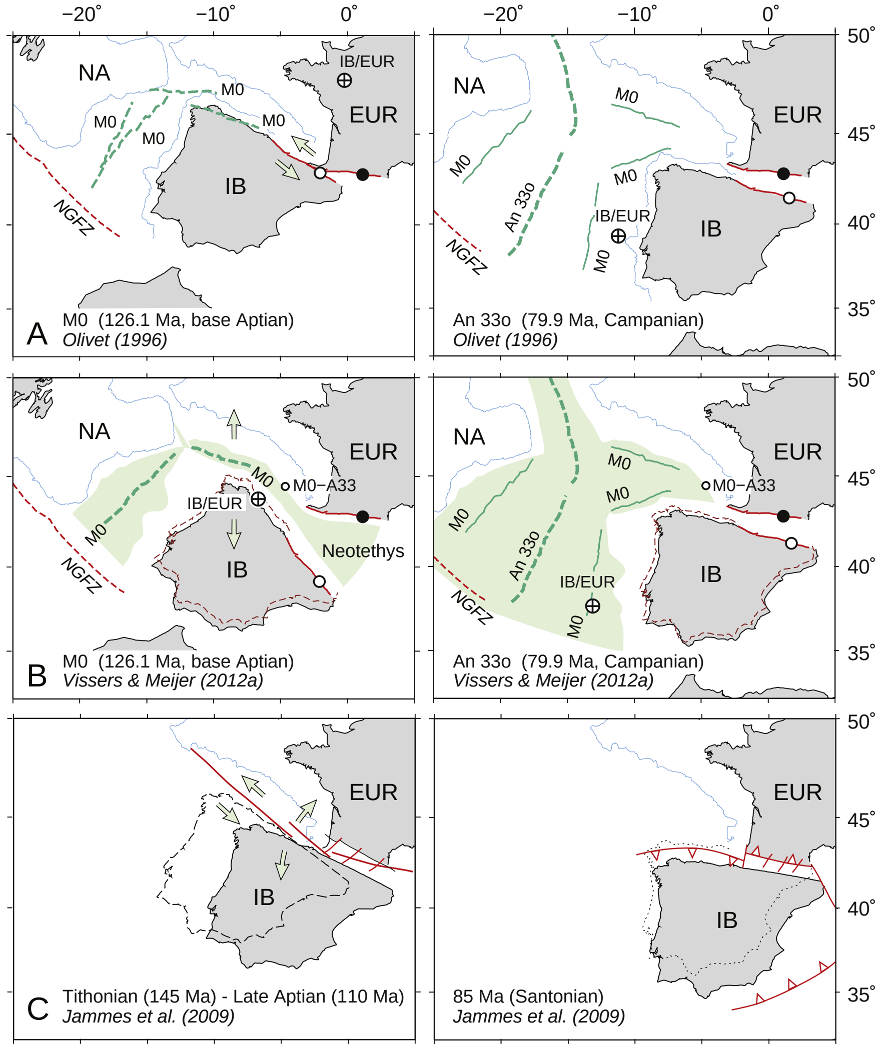

Fig. 2. Plate kinematic scenarios for the Late Mesozoic motion of Iberia with respect to Europe, with inferred position of Iberia at M0 times (left panels) and at the onset of Alpine collision (right panels). Abbreviations: NA — North America; IB — Iberia; EUR — Europe; NGFZ — Newfoundland Gibraltar Fracture Zone. North American and European 2000 m isobaths shown in blue. Circles with cross denote total reconstruction poles. A: left-lateral strike-slip model after Olivet (1996), note mismatch of M0 lineations in Atlantic and Bay of Biscay. B: scissor-type scenario after Vissers and Meijer (2012a), dashed outlines of Iberia according to Sibuet et al. (2004). Arrows in left panel indicate rifting between Kimmeridgean and Aptian. Circles labeled M0-A33 indicate stage poles describing opening of the Bay of Biscay. C: Scenario proposed by Jammes et al. (2009). Left panel shows strike-slip motion of Iberia between Tithonian (Iberia dashed) and Albian times (Iberia solid) followed by orthogonal stretching. Right panel shows Santonian position of Iberia (solid) at onset of collision, thin dashed outline of Iberia indicates present-day position. Inferred main thrust structures shown in red. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

of these anomalies being isochrons. It is also this assumption that was questioned first by Jammes et al. (2009), and addressed in more detail by Bronner et al. (2011). The latter authors argued that in rifted settings with low magma supply, the transition between continental and oceanic crust is wide, with a gradual change from continental crust via exhumed blocks of continental mantle to oceanic crust. While the timing and location of continental breakup is commonly defined by the first magnetic anomaly generated by magma erupted from the newly formed mid-ocean ridge, they suggest that the J anomaly north of the Newfoundland–Gibraltar Fracture Zone, conventionally thought to have formed at chron M0 (Tucholke and Sibuet, 2007), instead represents a pulse of later magmatism – about 112 Ma ago – that may have triggered continental breakup before seafloor spreading, hence that the M0 anomaly cannot be interpreted as a genuine isochron. The scenario proposed by Jammes et al. (2009) thus explicitly disregards the M0 anomalies in the Atlantic Ocean and Bay of Biscay.

As noted in a comment by Tucholke and Sibuet (2012) to Bronner et al. (2011), the magnetic model central to the Bronner et al. (2011) study is plausible but leads to marked problems in terms of plate reconstructions. They also note that while that magnetic model is plausible, it is “no more so than models based on M-series geomagnetic reversal data” such as proposed by Srivastava et al. (2000), Sibuet et al. (2004) and Vissers and Meijer (2012a). In contrast, the scenarios of Olivet (1996) and Jammes et al. (2009) are clearly inconsistent with the ocean floor magnetic anomalies.

As matters stand, the current debate on the significance of the magnetic lineations in the Central Atlantic Ocean and the Bay of Biscay precludes a consensus on the kinematics of Iberia motion during the Mesozoic, because the ocean floor anomalies are not accepted as a valid independent criterion to either confirm or discard the different kinematic scenarios. These scenarios, therefore, need to be tested against other criteria, equally independent of geological interpretation of the Pyrenees, such as onshore paleomagnetism and mantle structure.

3. Paleomagnetic constraints on Iberian rotation

3.1. Paleomagnetic database of Iberia since 200 Ma

Since the pioneering work of Van der Voo (1969) who concluded ~35° counterclockwise (ccw) rotation of Iberia sometime between the

Late Triassic and Late Cretaceous, onshore paleomagnetic studies have accumulated into a large dataset. To test whether the onshore paleomagnetic data are consistent with the amount of Iberia–Eurasia rotation predicted by the different kinematic models, we have compiled a database of all paleomagnetic data collected from stable Iberia from rocks of 200 Ma and younger (Fig. 3). This database, provided as Supplementary information, was built in and can be uploaded in the online tool www.paleomagnetism.org (Koymans et al., accepted pending revision). Each entry in the database contains a reference to the published source, and references are included in this paper.

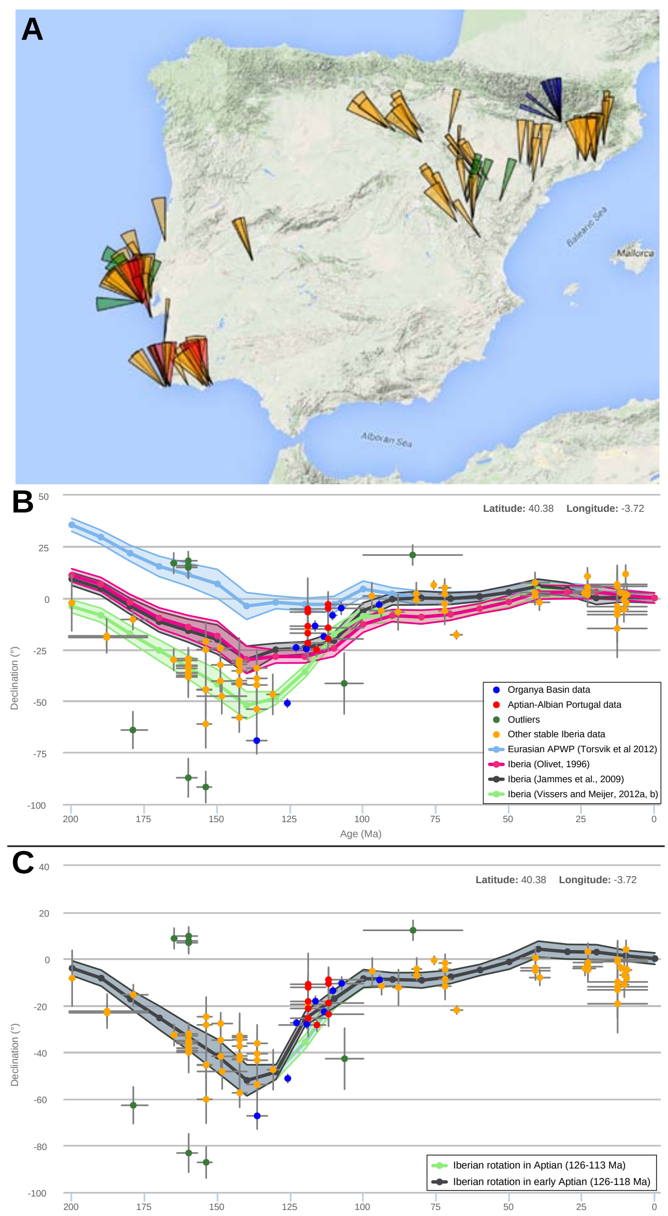

Fig. 3. Iberian plate kinematics in a paleomagnetic reference frame. A) Map with locations and declinations of the paleomagnetic sites of stable Iberia. Color coding same as in legend of panel B. B) Declinations are shown for the three kinematic scenarios discussed in this paper, compared to measured paleomagnetic data from stable Iberia. C) A better fit with the data is obtained for the scissor-type scenario when the Iberian rotation is assumed to occur entirely in Early Aptian time, 126–118 Ma, instead of throughout the Aptian (126–113 Ma) as suggested before by Gong et al. (2008). For explanation, see text. Figure drafted using the www.paleomagnetism.org toolkit (Koymans et al., accepted pending revision), database provided in the supplementary information. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

The database contains ~100 sites and was built according to the following selection criteria. Paleomagnetic data from rocks older than Jurassic, as well as archeomagnetic data, were not included. Because we aim to test the rotation of the Iberian continent, we have not included paleomagnetic results from the Betic Cordillera or the Pyrenees where rotations may stem from regional tectonics. One exception to this concerns the paleomagnetic results of the Cretaceous of the Organyà basin in the Southern Pyrenees of Gong et al. (2008), which were collected from a coherent stratigraphy. Although this basin as a whole may have undergone rotation during Cenozoic thrusting, the relative rotations recorded within this stratigraphy can be used to obtain age constraints on the rotation history, as proposed by Gong et al. (2008). All directions are given in tectonic coordinates, i.e., corrected for bedding tilt, and were converted to normal polarity. In addition, we applied and expand on quality criteria as detailed in Lippert et al. (2014): data were excluded from sites that 1) are not used by the original authors if a reason for exclusion is provided; (2) are characterized by fewer than four samples; (3) were not analyzed using principle component analysis (Kirschvink, 1980); (4) have site k-values (Fisher (1953) precision parameter) below 7; we have not a priori excluded data that fall outside the A95 min/max reliability envelope of Deenen et al. (2011); and (5) do not contain magnetizations of primary origin according to the original authors. Lava sites were discarded if these (6) contained directions of mixed polarity, as lava sites should be spot readings that cannot record a reversal; (7) have k-values <50. Where lava sites were reported, we combined these into one pole and discard sites that (8) are beyond a 45° angular threshold, following Johnson et al. (2008).

Paleomagnetic data from sedimentary sites were included on a per site level as reported by the original authors. If GPS coordinates of sites were not provided, these were determined with the location information provided in the original paper using Google Earth. Reported stratigraphic ages were converted to the latest timescale of Gradstein et al. (2012). The paleomagnetic community does not normally publish their original data, but provide only statistical descriptions of the data set. This is not problematic for lava sites, whereby acquisition of the natural remanent magnetization occurs geologically instantaneous upon lava cooling and the recorded direction can be regarded as a spot reading of the paleomagnetic field. For sediments or plutons, however, each sample can at first order be considered as a spot reading (although for sediments, particularly those with low sedimentation rates, some averaging of paleosecular variation may occur within one sample). As pointed out by Deenen et al. (2011), a better approach is then to always perform statistics on paleomagnetic directions instead of site averages, also to weigh larger over smaller datasets. Except for the few sites where we had the original directions at our disposal, we have therefore created parametrically sampled data sets for each site. The average directions in the database are based on these parametrically sampled data sets and may slightly, but insignificantly, differ from the published average directions. The predicted declinations of each site are shown in Fig. 3A.

3.2. Testing Iberian reconstructions against paleomagnetic data

We now test whether the reconstructions of Vissers and Meijer (2012a), Olivet (1996), and Jammes et al. (2009) successfully predict paleomagnetic data from Iberia. The amount of rotation of Iberia in these kinematic models was not based on paleomagnetic data, which can therefore serve as an independent test. We note that the *timing* of Iberian rotation in the model of Vissers and Meijer (2012a) was inspired by paleomagnetic data of Gong et al. (2008), but the amount of rotation was based on fitting the M0 anomalies on either side of the Bay of Biscay.

To test the kinematic reconstructions against the declinations measured in Iberia through time, we computed the declinations for Iberia predicted by the Global Apparent Polar Wander Path (GAPWaP) of Torsvik et al. (2012) for each of the kinematic models for Iberia. The GAPWaP is based on a compilation of paleomagnetic data from all continents that were rotated into a South African frame of reference using a global plate reconstruction. The GAPWaP then constrains the position of the South African reference plate by applying a 20 Ma moving average to the dataset, in 10 Myr intervals. To arrive at paleomagnetic directions for Iberia, the GAPWaP has to be rotated from South African to Iberian coordinates using a SAF-Iberia Euler pole, in 10 Myr time steps. Vissers and Meijer (2012a, 2012b) and Vissers et al. (2013), as well as Olivet (1996) provided a set of Iberia–Eurasia Euler poles. The scenario proposed by Jammes et al. (2009) did not provide Euler rotations for their reconstruction of Iberia, but we estimated poles from their cartoons, using GPlates plate reconstruction software (Boyden et al., 2011).We integrated each of these reconstructions with the global plate reconstruction using Euler poles for Eurasia–North America, North America–Northwest Africa, and Northwest Africa–South Africa as detailed in Torsvik et al. (2012). From this, we computed South Africa–Iberia Euler poles in 10 Myr time intervals, interpolating between poles given by, or suggested by, the Iberian kinematic reconstructions, and used these to rotate the GAPWaP in Iberian coordinates for each scenario. The predicted paleomagnetic directions for Iberia in Fig. 3A were then calculated for a coordinate coinciding with Madrid (40.38°N, 3.72°W). The predicted declinations for the kinematic models of Vissers and Meijer (2012a, 2012b), Olivet (1996) and Jammes et al. (2009) are shown in Fig. 3B, together with the paleomagnetic data measured for Iberia.

The three models do not show major differences in the last 100 Myr, and all predict the measured paleomagnetic data well. Apart from a few outliers, indicated in green in Fig. 3A–C, deviating by >45° from the mean, Jurassic–Lower Cretaceous (200–135 Ma) declinations cluster well around the Iberian declination predicted by Vissers and Meijer (2012a, 2012b), but display a consistently higher counterclockwise rotation than predicted by the models of Jammes et al. (2009) and Olivet (1996). Upper Jurassic–Lower Cretaceous declinations (~155–135 Ma) contain a ~30° variation, likely reflecting a component of local rotations due to local tectonics along the southwest Iberian margin in the Central Iberian ranges where most of these data were collected. The paths predicted by Jammes et al. (2009) and Olivet (1996) coincide with a few of these data, but 200–160 Ma declinations all display a ~15° higher counterclockwise rotation, as previously also pointed out by Ruiz-Martinez et al. (2012).

All three kinematic models are unsuccessful in predicting the rate at which the rotation of Iberia occurred. Paleomagnetic data, not only from the South Pyrenean Organyà basin indicated in blue in Fig. 3, but also from various localities in Portugal indicated in red (Fig. 3), suggest that the rotation of Iberia occurred in the Early Aptian, even faster than concluded by Gong et al. (2008). The timing of the Iberian rotation in the model of Vissers and Meijer (2012a) during the Cretaceous Normal Superchron (between M0 and A34o, ~126–83 Ma) was based on the suggestion by Gong et al. (2008) that this occurred until the Albian–Aptian boundary (113 Ma). We can obtain a much better fit with the presently compiled data if we assume an end of rotation around 118 Ma instead (Fig. 3C). The models of Olivet (1996) and Jammes et al. (2009) predict a rotation rate that is significantly slower than shown by the data.

Based on this analysis, we conclude that (i) the paleomagnetic declinations from Iberia require an amount of rotation that fits well with the angle between the M0 anomalies on either side of the Bay of Biscay, and that is considerably higher than that predicted by the fits of Jammes et al. (2009) and Olivet (1996) and (ii) the rotation of Iberia occurred almost entirely in the Early Aptian (126–~118 Ma, Fig. 3C) and certainly well before the onset of North Pyrenean high temperature metamorphism and alkaline magmatism.

4. Past subduction and present-day mantle structure

4.1. Approach: geological records, mantle structure, and absolute plate motion

Jammes et al. (2009) and Olivet (1996) assumed that the rotation of Iberia resulted from a (transtensional) strike-slip motion of Iberia along the Armorican–South Pyrenean margin. This, however, cannot generate more than ~25° of rotation. More than 25° of rotation inevitably requires that during Iberian rotation, there was convergence across the Pyrenean plate boundary between Iberia and Eurasia. Sibuet et al. (2004) were the first to realize the need for a subduction zone with such high rotations and suggested that subduction occurred below the present Ebro basin, placing the Pyrenean domain in an Aptian–Albian back-arc setting to explain the Aptian–Albian extension inferred from the Pyrenean geology. Later evidence that the Organyà basin, located in the presumed back-arc of Sibuet et al. (2004), also experienced the Iberian rotation led Vissers and Meijer (2012a) to suggest that subduction must have occurred below the Eurasian margin instead, and that the North Pyrenean fault zone represents the suture. As emphasized by Bronner et al. (2012) and later Clerc et al. (2015), two recent tomographic studies have shown that there is no evidence for the existence of a subducted slab below the Pyrenean domain. According to Souriau et al. (2008) no signature of an oceanic subducted slab could be detected anywhere along the Pyrenean range, a result which in their view ruled out the opening of a large oceanic basin before the Late Cretaceous compression recorded in the geology of the Pyrenean fold–thrust belt. Chevrot et al. (2014) arrived at the same conclusion, and noted that the absence of a deep pronounced high-velocity anomaly in the upper mantle and transition zone also rules out the presence of a detached oceanic lithospheric slab beneath the Pyrenees and SW Eurasia.

Using the mantle structure below the Pyrenees to evaluate a Cretaceous subduction history assumes that southwestern Europe, Iberia, and the Pyrenees have not moved relative to the mantle since the Early Cretaceous. Motion of Iberia/Eurasia relative to the mantle, however, could have laterally displaced the Pyrenean realm from any sinking slab remnant after slab break-off. A clear example of such a process was recently provided by Schellart and Spakman (2015). They demonstrated that due to post-Eocene northward absolute plate motion of Australia, a slab that detached in Eocene time along the northern margin of Australia in Papua New Guinea is now found at the top of the lower mantle below southern Australia. Similar examples have been documented in the Caribbean region (Van Benthem et al., 2013), in the Neotethyan realm between Arabia, India, and Eurasia (Van der Voo et al., 1999; Hafkenscheid et al., 2006; Replumaz et al., 2010; van Hinsbergen et al., 2012; Gaina et al., 2015), and in the eastern Paleo-Pacific and western United States (Van der Meer et al., 2010, 2012; Sigloch and Mihalynuk, 2013). Likewise, one should take the absolute plate motions of Iberia and Eurasia into account when assessing whether or not the mantle structure falsifies Pyrenean subduction.

The hypothesis of an Aptian–Albian subduction–detachment process, therefore, requires a more extensive test against mantle tomography results. For this, two factors need to be taken into account, namely, absolute plate motions, i.e., motions of the plates relative to the mantle, and sinking rates of detached slab fragments. These allow for predicting the paleogeographic position of slab detachment and the approximate mantle depth of the slab remnant in the present-day mantle, respectively (Van der Meer et al., 2010).

Absolute plate motion models based on different approaches have been put forward. The farther back in time, the less consistent these become in their predictions (e.g., Williams et al., 2015). Moving hotspot reference frames (O'Neill et al., 2005; Doubrovine et al., 2012) use hotspot tracks, corrected for relative motions between the hotspot sources, to infer absolute plate motions. These frames are less well constrained in Cretaceous time, because fewer hotspot tracks are available. To go deeper into geologic time, paleomagnetic data have been used, corrected for true polar wander, to infer past positions since post-Middle Paleozoic time. These are cast in a mantle reference frame by invoking the strong correlations of two large regions of anomalously low seismic velocity atop the core–mantle boundary with the reconstructed positions of past occurrences of large igneous provinces and kimberlites (Torsvik et al., 2008).

Alternatively, van der Meer et al. (2010) demonstrated a strong correlation of paleosubduction zone configurations in plate reconstructions with positive seismic anomalies in the lower mantle, which they assumed to represent remnants of subduction. Their correlation is based on identifying 28 lower mantle slab remnants and linking these to the orogenic systems (not including the Pyrenees orogeny) from which they likely detached at a given time interpreted from geological records. Assuming on average vertical sinking of detached slabs, the study by van der Meer et al. (2010) has resulted in a provisional set of longitude corrections of the true polar wander-corrected reference frame of Steinberger and Torsvik (2008), which can be translated to Euler poles describing the motion of Africa in a 'slab-fitted' mantle reference frame, or slab reference frame (Van der Meer et al., 2010). Furthermore, as a spin-off result, van der Meer et al. (2010) obtained the first empirical estimate of the average sinking rate of lower mantle slab fragments of 12 ± 3 mm yr^{-1}, i.e. 12 ± 3 km/Myr.

Williams et al. (2015) noted that hotspot reference frames prior to 70 Ma predict rapid, major motions of subduction zones relative to the mantle. For the Aegean subduction zone, which was already active in this period (van Hinsbergen et al., 2005), this would culminate in >1000 km of westward motion of the trench relative to the Aegean slab between 100 and 70 Ma, which we regard as unlikely. In the slab reference frame, however, the Aegean slab is an anchor point to the mantle. In our analysis of testing the Pyrenean subduction history against mantle structure, we therefore use the slab reference frame of van der Meer et al. (2010) as a basis for predicting the present-day location of any Pyrenean slab remnant.

4.2. Mantle tomography as test for a detached Pyrenean slab: the Reggane anomaly

We illustrate the absolute plate motion history of Africa in Fig. 4A as a sequence, at 10 Myr intervals, of restored marker points representing Ceuta on the Moroccan coast, bearing in mind an uncertainty in latitude equal to the error in true polar wander-corrected paleomagnetic reference frames, and in longitude in slab-fitting, both on the order of 5–10° (Steinberger and Torsvik, 2008; Van der Meer et al., 2010). Total reconstruction poles for Iberia and Europe with respect to Africa, and Africa restored to the slab reference frame, allow the placement of the scenario of Fig. 2B in this mantle reference frame; details are given as Supplementary information. Fig. 4A shows the calculated positions of Africa, Iberia and Europe for M0 (126.1 Ma) and Late Aptian (118 Ma), i.e., the time by which the main 35° rotation was completed according to the onland paleomagnetic data as outlined above, hence that subduction effectively came to a halt. The implication is that, assuming near-vertical sinking, any gravitationally unstable slab fragment detached during the Late Aptian from the Pyrenean domain should reside in the mantle underneath the locus of detachment, indicated in Fig. 4A as a red star. For detachment at say 115 Ma of a subducted slab of some 500 km length, hence with a midpoint at about 250 km depth at the onset of detachment, and a sinking rate of 12 ± 3 mm yr^{-1}, one may expect the corresponding anomaly in a depth range of 1285–1975 km. Note that the depth of the midpoint differs from the depth of detachment. To calculate average sinking rate, the distance between the midpoint of the longest portion of the slab at the moment of detachment is subtracted with the midpoint of the imaged (detached) slab, and divided by the time elapsed since detachment. For a later, Early Albian detachment (~110 Ma) we expect the corresponding anomaly at a depth between 1240 and 1900 km. The predicted locus of detachment (white star in Fig. 4A) is shifted, however, due to ongoing motion of the system in the slab reference frame between 115 and 110 Ma.

The tomography shown in Fig. 4A (P-wave model UU-P07 of Amaru, 2007) shows a horizontal section at 1700 km depth, where it reveals a marked anomaly ~5° south of the point where detachment with respect to the slab reference frame would predict a Pyrenees slab, below south-western Algeria. The N–S cross-section of Fig. 4B shows the anomaly

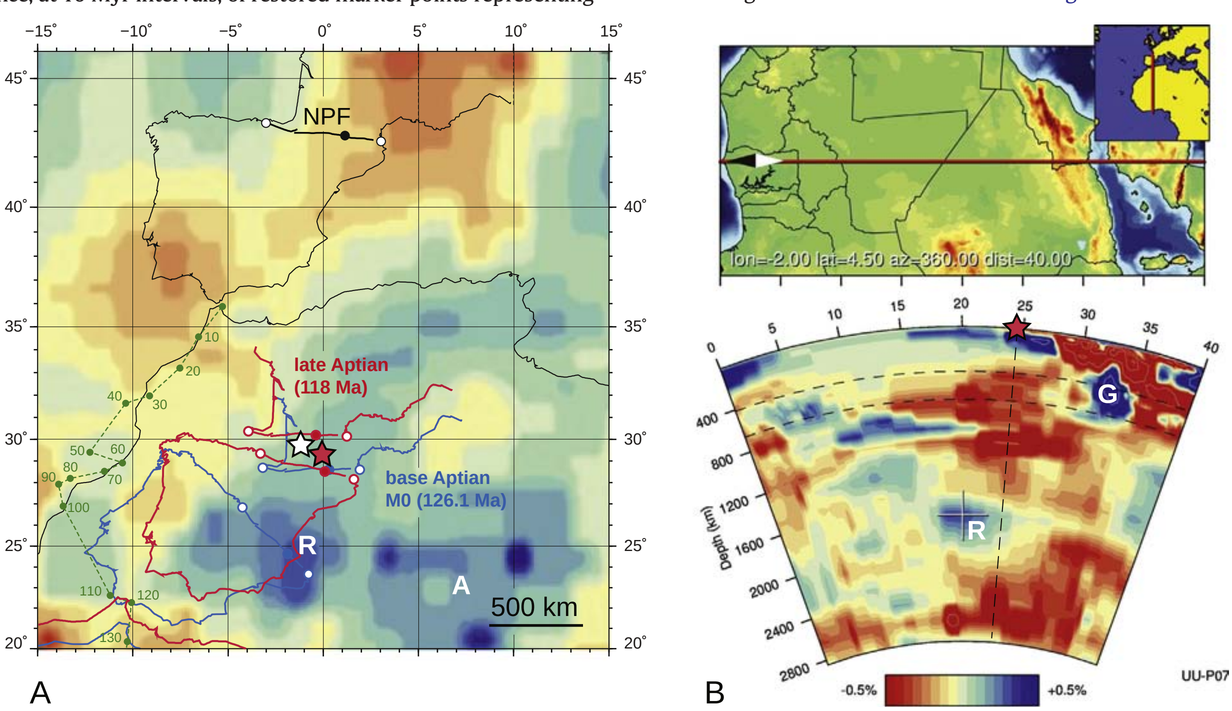

Fig. 4. Iberian plate kinematics viewed in a slab reference frame, and pertinent upper mantle tomography (model UU-P07). Abbreviations: NPF — North Pyrenean Fault, white markers at ends and black marker at intersection with ECORS profile; R — Reggane anomaly, A — Algeria anomaly, G — Gibraltar slab. Color scale represents velocity anomalies (shown in B). A: restored positions of Africa, Iberia and Europe for base Aptian (M0, 126.1 Ma) in blue, and Late Aptian (118 Ma) in red. Green track with markers at 10 Ma intervals illustrates motion of marker point at Ceuta in mantle reference frame. Red star marks estimated location of slab midpoint upon Late Aptian detachment around 115 Ma, white star for Early Albian detachment around 110 Ma. Note that the latter location is shifted due to ongoing absolute plate motion. Depth of horizontal tomographic section 1700 km. B: NS cross-section across the Reggane anomaly, with midpoint at 1700 km depth. Radius through estimated locus of detachment (red star) accentuates vertical. Note that latitudes are shown with respect to southern end of section at latitude 4.5° N. Euler poles for the slab reference frame of van der Meer et al. (2010) can be downloaded from www.geologist.nl/reconstructions.html. For further explanation see text. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

with its midpoint at 1700 km depth. We note that this anomaly, here named the Reggane anomaly after a village in southwestern Algeria, is also imaged in S-wave tomography model S40RTS (Ritsema et al., 2011), which independently attributes to its existence (see Supplementary information). The Reggane anomaly lies within the depth range predicted by the global average sinking rate, and lies within the area predicted by the slab reference frame of van der Meer et al. (2010).

A further test of whether the Reggane anomaly may represent a Pyrenean slab detached in the Late Aptian–Early Albian is the regional consistency with other anomalies, in particular the large N–S trending "Algeria slab" identified by van der Meer et al. (2010). This slab is observed between ~2300 and 1500 km depth, and is itself located southwest of the Aegean slab which reaches a depth of ~1500 km (van Hinsbergen et al., 2005), suggesting in first approximation that the age of break-off of the Algerian slab and the age of initiation of the Aegean subduction zone (~130–100 Ma) can be similar. Van der Meer et al. (2010) therefore correlated the Algerian slab with subduction that emplaced the Jurassic Balkanide ophiolite belt, now found from Greece to the eastern Alps and Carpathians, over Adria in Early Cretaceous time (~130–120 Ma; e.g., Schmid et al., 2008). All subduction events associated with post-Albian tectonics in the western Mediterranean region are accounted for by shallower slabs such as the Gibraltar slab (Spakman and Wortel, 2004; Bezada et al., 2013; Van Hinsbergen et al., 2014) (Fig. 4). From this correlation, it follows that the Reggane slab must have formed due to subduction west of Adria, consistent with the prediction of Pyrenean subduction. We conclude that the presence, in a slab reference frame, of a clear velocity anomaly near the predicted depth and location, is consistent with Aptian Pyrenean subduction and Late Aptian–Early Albian detachment of a slab subducted in the Pyrenean realm. We also conclude that the structure of the upper mantle below the present-day Pyrenees cannot confirm nor falsify an Aptian–Albian subduction history of the Pyrenees, hence that it provides no basis to discard kinematic scenarios based on marine magnetic and paleomagnetic data that demonstrate Iberia's ~35° rotation in this time period.

5. Discussion

We have tested three different kinematic scenarios for Iberian motion against onland paleomagnetic data from Iberia. We conclude that the paleomagnetic declinations require an amount of Iberia rotation that fits well with the angle between the M0 anomalies on either side of the Bay of Biscay, hence with scissor-type scenarios proposed by Sibuet et al. (2004) and Vissers and Meijer (2012a), but that the rotation is considerably higher than that predicted by the scenarios of Jammes et al. (2009) and Olivet (1996). Conversely, we argue on geometrical grounds that strike-slip motion along the Armorican margin precludes rotations in excess of ~25° unless, during the rotation, convergence was accommodated in the Pyrenean realm. In addition, the paleomagnetic database strongly suggests that the rotation of Iberia occurred almost entirely in the Early Aptian (126–~118 Ma) and certainly well before the onset of North Pyrenean high-temperature metamorphism and alkaline magmatism.

While the scissor-type scenario of Sibuet et al. (2004) and Vissers and Meijer (2012a) successfully predicts the ~35° rotation of Iberia during the Aptian, we show that the consequent subduction and detachment during Aptian times of an oceanic domain in the Pyrenean realm is not falsified by mantle tomography. Viewed in a mantle reference frame, P- and S-wave tomography show a marked anomaly within the area where detachment would predict a Pyrenees slab, with its midpoint at 1700 km depth. i.e., within the depth range predicted by the global average sinking rate. This strongly suggests that scissor-type opening of the Bay of Biscay and allied subduction and detachment in the Pyrenean domain is a viable hypothesis. We propose that Pyrenean subduction and detachment were likely accommodated to the east by a transform fault that must have separated Iberia from Sardinia, which in Aptian–Albian time did not undergo any significant vertical axis rotation (Advokaat et al., 2014). This transform fault may have become reactivated during the Late Oligocene–Early Miocene as the North Balearic Transform Zone (Van Hinsbergen et al., 2014).

Jammes et al. (2009) and Bronner et al. (2012) argued that there is no evidence in the Pyrenean geology of subduction. There are, indeed, no high-pressure, low-temperature metamorphic rocks at the surface, nor is there evidence in the form of e.g. a distinct volcanic arc. In our view, a main reason for this lack of geological evidence may be the nature of the subducting lithosphere, formed during Late Jurassic–Early Cretaceous stretching at a time-averaged rate of less than 1 mm/year, i.e., under conditions of ultraslow spreading (Vissers and Meijer, 2012a; Vissers et al., 2013). This would result in a partly serpentinized exhumed mantle type of ocean floor lacking any appreciable magmatic crust, such that a typical ophiolite-type of oceanic crust and associated depleted uppermost mantle did not develop. We suggest that only few mantle peridotite bodies of this exhumed mantle lithosphere became scraped off during subduction and are now found in the NPZ. This subduction, however, occurred fast, led to a short slab that subducted for only a short amount of time that may not have been sufficient to generate a stable volcanic arc. In this case, absence of evidence is not evidence of absence.

An issue related to the nature of the subducted and detached oceanic lithosphere previously formed under ultraslow spreading conditions concerns its age at the time of subduction, because this principally affects its thermally controlled density and thereby its tomographic detectability. The plate kinematic reconstructions of Sibuet et al. (2004) and Vissers and Meijer (2012a) involve a rifting stage in the Bay of Biscay since the Kimmeridgian (157.3–152.1 Ma) proceeding till M0 times (126.1 Ma), i.e., the onset of Iberia rotation. In the Pyrenean realm, Eurasia was bounded to the south by Alpine Tethyan ocean floor developed during the rifting of Adria from Eurasia (Wortmann et al., 2001; Rosenbaum et al., 2002; Vissers et al., 2013), which during the ultraslow rifting and spreading process must have grown to the inferred 300–500 km of oceanic lithosphere that subsequently subducted during Iberia rotation and allied convergence during the Aptian. It follows that, upon subduction, at least part of that oceanic lithosphere was young, not older than ~40 Myr, but in view of its previous ultraslow spreading history it must have been much colder than expected for the case of a ridge-dominated oceanic lithosphere formed at moderate to fast spreading rates.

The Cretaceous extension documented in the Pyrenees as small basins, possibly with a transtensile component, is one of the key arguments for the extensional model of Jammes et al. (2009). In the light of an Aptian subduction history, these extensional basins may instead be explained as a result of a post slab break-off rebound, coevally with HT–LP metamorphism and alkaline volcanism. This metamorphism affected an accretionary mélange that contained the peridotite massifs and probably led to the resetting of the ^{40}Ar/^{39}Ar and Sm–Nd clocks of amphiboles from the Lherz and Caussou peridotites at 108–103 Ma (Henry et al., 1998). Instead of an incomplete rehomogenization during fast ascent of these mantle rocks, we note that the Jurassic–Early Cretaceous Nd ages of 153 $\pm$ 3 Ma (Prades), 177 $\pm$ 3 Ma (Moncaup), and 138 $\pm$ 4 Ma (Moncaut) (Henry et al., 1998) coincide with the extension related to the breakup of Iberia from Eurasia and Adria from Iberia, and that these ages may represent the timing of hyperextension at the southwestern Eurasian margin. The geological record of Albian extension, metamorphism and magmatism is thus likely unrelated to hyperextension and mantle exhumation, which occurred 40–70 Myr earlier. In other words, the high-temperature metamorphism documented in the NPZ around 100 Ma does not result from hyperextension during Pangea breakup, but must post-date a phase of subduction (Fig. 5). A straightforward alternative to explain the high-temperature pulse, magmatism and possibly part of the extensional structures in the Pyrenees is Late Aptian–Early Albian slab detachment following the arrest of Iberian rotation and associated rapid convergence, and

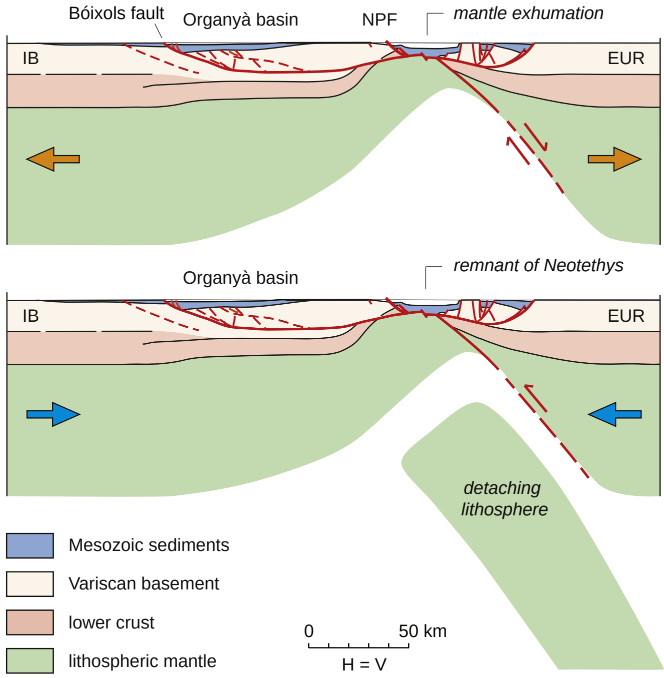

Fig. 5. Cartoons illustrating opposing views on the Albian geometry of the Pyrenean realm at the longitude of the ECORS section. Upper panel shows hyperextended margins bordering a narrow rift zone in which mantle rocks are exhumed in response to continental stretching. Lower panel shows same crustal geometry, underlain by a north-dipping slab of mantle lithosphere previously exhumed during a pre-Aptian extensional phase, and followed by Aptian convergence. Note that in both cases asthenospheric mantle occurs up to lower-crustal levels which accounts for Albian magmatism and high-temperature metamorphism in the Pyrenees. Note also that the detachment of a slab and concurrent ascent of hot asthenosphere enhances the gravitational potential energy of the Pyrenean domain, such that local extension may occur despite the overall convergent boundary conditions.

the consequent ascent of hot asthenosphere to shallow levels (e.g., Platt and England, 1994, see also van de Zedde and Wortel, 2001; Vissers and Meijer, 2012a) (Fig. 5) leading to alkaline magmatism and inducing a marked heat pulse. We suggest that the thermal effects of hyperextension on sedimentary successions in the hanging wall should not be studied in the Pyrenees, but may be better explored at e.g. exhumed oceanic core complexes in ophiolites (e.g., Maffione et al., 2015).

Finally, we suggest that the subducting oceanic lithosphere and associated slab-pull in the Pyrenean realm may have contributed to the dynamics driving rapid rotation of the Iberian microplate during Aptian opening of the Bay of Biscay, and that slab-pull may have driven the N–S extension documented during rotation in the north Iberian sedimentary basins (e.g., Gong et al., 2009a, 2009b) but also in the central Iberian chains (e.g., Simón et al., 1998).

6. Conclusions

We test prevailing plate kinematic scenarios for the Late Mesozoic motion of Iberia against an extensive database of onshore paleomagnetic data from Iberia. While each of these scenarios can be reconciled with the geological data, magnetic anomaly-based reconstructions involving Late Jurassic till Barremian rifting, Aptian rotation of Iberia and concurrent convergence in the Pyrenean realm, followed by Late Aptian–Early Albian slab detachment is the only one consistent with the Iberian paleomagnetic data. We test previous arguments claiming that the absence of evidence for slab remnants in the mantle below the Pyrenees falsifies Pyrenean subduction by studying the Pyrenean evolution in a mantle reference frame. Absolute plate motion reconstructions of the Pyrenees predict that a subducted slab remnant that detached in Late Aptian–Albian time below the Pyrenees should reside in the mid-mantle below Algeria. Seismic tomography is consistent with this prediction and shows an anomaly below the town of Reggane in Algeria between 1500 and 1900 km depth. We conclude that the structure of the upper mantle below the Pyrenees is irrelevant in falsifying or confirming a Cretaceous subduction history in the Pyrenees, and that it provides no basis to discard kinematic scenarios involving scissor-type opening of the Bay of Biscay coupled with subduction in the Pyrenean realm. This suggests that the geological evidence in the Pyrenees for Albian high-temperature metamorphism and alkaline magmatism may well reflect Late Aptian–Early Albian detachment of a subducting slab and the consequent ascent of hot asthenospheric mantle, rather than the currently widely perceived hyperextension of the adjacent margins.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.gr.2016.03.006.

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