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# A kinematic reconstruction of Iberia using intracontinental strike-slip corridors

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## Abstract

Despite considerable progress in restoring rifted margins, none of the current kinematic models can restore the Mesozoic motion of the Iberian block in full agreement with the circum-Iberian geology. This conflict requires a revision of the kinematic description at the onset of divergence. The circum-Iberian region has a unique geological dataset that allows calibration and testing of kinematic reconstructions and therefore it is an ideal candidate for testing intracontinental restoration approaches. Here we define intracontinental deforming regions, referred to as strike-slip corridors, based on alignments of Mesozoic rift basins and/or transfer zones bordering rigid continental blocks. We use these strike-slip corridors and data from the southern N-Atlantic and Tethys to define the motion path of the Flemish Cap, Ebro and Iberia continental blocks. The resulting Mesozoic kinematic model for the Iberian block is compatible with recently published data and interpretations describing the Mesozoic circum-Iberian geology. Large-scale intracontinental strike-slip corridors may offer a valid boundary condition for reconstructing continental block motion at the onset of divergence in intracontinental settings.

## 1 | INTRODUCTION

Great efforts have been directed recently in the plate kinematic community to consider the pre-breakup evolution in kinematic reconstructions of divergent plate boundaries (Aslanian & Moulin, 2013; Barnett-Moore et al., 2016; Nirrengarten et al., 2018; Peace et al., 2019). A robust kinematic description appears crucial to a physics-based understanding of rifting (Brune et al., 2014; Gueydan et al., 2008; Williams et al., 2019). Kinematic restoration of divergent plate boundaries relies on a common procedure, which includes: (a) tight fit of seafloor magnetic anomalies, defining the position of diverging plates through time; (b) oceanic fracture zones, interpreted as flowlines, determining the direction of the motion; (c) necking zones, defining the tightest-fit solutions of reconstructions; and (d) paleomagnetic data from continental undeformed regions, outlining rotation and latitudinal shifts (Schettino & Turco, 2011).

This four-step approach has achieved outstanding results in reconstructing global plate motions at divergent settings (Müller et al., 2019). However, problems arise when obliquely deforming continental regions are considered, as shown for the Iberian case (Angrand et al., 2020; Barnett-Moore et al., 2016; Peace & Welford, 2020; Tavani et al., 2018). During a large part of its Mesozoic history, Iberia was a continental rigid block delimited by intracontinental deforming regions, 40–200 km wide (Ady & Whittaker, 2019; Angrand et al., 2020; King et al., 2020) and hereafter referred to as strike-slip corridors. The M-series magnetic anomalies fringing Iberia on its

N-Atlantic side have been shown to not represent classical oceanic magnetic anomalies and therefore to be unreliable for reconstructions (Nirrengarten et al., 2017; Szameitat et al., 2020). Moreover, kinematic reconstructions proposed Late Cretaceous subduction east of Iberia not harmonizing with tomographic data in the Pyrenees (Chevrot et al., 2018; Gong et al., 2008; Neres et al., 2012; Nirrengarten et al., 2017; Vissers & Meijer, 2012b).

The Mesozoic left-lateral motion of Africa (AFR) relative to Europe (EU) occurred while Iberia was diverging from North America (NAM) and interleaved rigid continental blocks were moving (Müller et al., 2019). We identify strike-slip corridors limiting rigid continental blocks, which include the Newfoundland, Flemish Pass, and Bay of Biscay—Iberian Rift corridors. Continental blocks are considered rigid if their internal estimated deformation is <30 km, that is, the error value introduced in restorations (Nirrengarten et al., 2018). The motion of blocks is assumed to be perpendicular to necking lines at orthogonal intracontinental rifts or parallel to the dominant trend of strike-slip corridors. Relying on these corridors as motion paths for kinematic restorations enable to build a new kinematic model for the southern N-Atlantic and the Bay of Biscay, and to reconstruct the kinematics of Iberia from 200 to 83 Ma, that is, from Late Triassic onset of rifting in the Central Atlantic to Anomaly C34, the first unambiguous oceanic magnetic anomaly in the southern N-Atlantic.

**Statement of significance**

Evaluating intracontinental rifting remains one of the challenges of plate kinematic reconstructions. We define the motion of the Iberian block, sandwiched between Africa and Europe, to address the problem of plate motion at onset of divergence in the southern N-Atlantic. Zones of strike-slip deformation, which we call 'corridors', accommodate motion between continental rigid blocks. The use of these corridors significantly helps to reduce incompatibilities between the kinematic model and the circum-Iberia geological/geophysical record, calling for a possible widespread use of the method at the onset of deformation in divergent settings.

## 2 | TECTONIC SETTING

Following Nirrengarten et al. (2018), the current Iberia consisted, before 83 Ma, of two continental rigid blocks, Iberia (IB) and Ebro (EBR), that were surrounded, at different periods, by other smaller blocks such as Flemish Cap (FL), Porcupine (PR) and Morocco (MO) (Figure 1). Figure 1 summarizes the stage Euler poles reported for the different blocks. Flemish Cap and Porcupine blocks separate North America from Europe. Morocco is the northwestern promontory of Africa, while Ebro is the promontory of Europe (Angrand et al., 2020; Favre & Stampfli, 1992). Significant ~N–S directed extension is invoked after 126 Ma between Ebro and Europe (Jammes et al., 2009; Lescoutre and Manatschal, 2020; Tavani et al., 2018). Motion is recorded in the Atlas separating Morocco from Africa during Early to Middle Jurassic (El Kochri & Chorowicz, 1996; Favre et al., 1991; Laville et al., 2004; Stampfli & Hochard, 2009).

Three large-scale strike-slip corridors have been identified around IB: (a) the Newfoundland corridor, (b) the Flemish Pass corridor, and (c) the Bay of Biscay-Iberian Rift corridor, B-IR (Angrand et al., 2020; Reid, 1988; Sandoval et al., 2019) (Figure 1). These strike-slip corridors are up to 200 km wide and can contain local structures with variable trends and kinematics. The corridors connect aligned Upper Jurassic–Lower Cretaceous, laterally confined and narrow depocenters, sometimes reactivated during later events (Cadenas et al., 2020). Offshore, subvertical structures belonging to the corridors are often difficult to interpret on seismic reflection data.

The Newfoundland corridor extends into the Newfoundland Fracture Zone separating the Central and N-Atlantic and fringing the North America and Morocco blocks. The corridor evolved to a transform margin bounded by oceanic crust, allowing to use magnetic anomalies to define its timing. The Flemish Pass corridor is proposed to run south of the E and W Orphan basins and is perpendicular to the necking zones bounding Flemish Cap. Restoration of the Late Jurassic to Lower Cretaceous E and W Orphan basins result in a dextral motion along this corridor (Lundin & Doré, 2019; Sandoval et al., 2019; Sibuet et al., 2007). As suggested by Lundin and Doré (2019) an associated zone of strike-slip may extend north of the Orphan basins into the proto-Labrador Sea (Figure 1). This strike-slip corridor may continue in the Biscay-Iberian Rift (B-IR) corridor, which defines the boundary between Iberia and Europe—Ebro. The B-IR is here interpreted by the alignment of Late Jurassic–Lower Cretaceous basins from north of the Balearic Islands to the Asturian basin and the northern Bay of Biscay margin (Cadenas et al., 2020; Omodeo Salè et al., 2014; Sandoval et al., 2019; Thinon et al., 2002; Tugend et al., 2014).

## 3 | METHOD

The kinematic model proposed here is designed to respect boundary conditions defined by the global motion of the larger plates around IB in Mesozoic time, as described by Müller et al. (2019) (Figure 2, Table 1, first column, Data Repository S1–S3). Position and timing of present-day Edges of Continental Crust (ECC) and Restored Edge of Continental Crust (RECC) define the shape of the deforming regions (as defined in Nirrengarten et al., 2018, Figures 2a–c and 3a). The previously described strike-slip corridors are part of the deforming regions built on GPlates 2.1 software. In contrast to previous restorations (e.g. Nirrengarten et al., 2018), we do not use the best-fit criteria as a base for the model (Figure 2d). Our method thus appears suitable for regions where strong oblique motions preclude RECC tight-fit restorations or where significant magmatic additions prevent robust quantification of the original volumes of continental crust.

The initial condition of the model is the position of the four main continental blocks (NAM, IB, EU; AFR) at 83 Ma along anomaly C34,

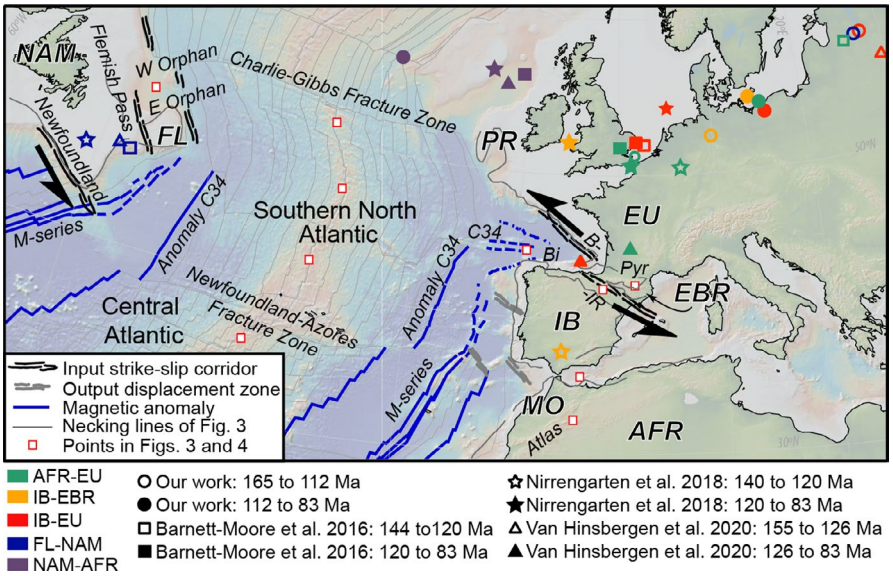


**FIGURE 1** Present-day postulated location of strike-slip corridors and magnetic anomalies. Euler stage poles represent relative motions for plates and microplates (different colors) (Angrand et al., 2020; Lundin & Doré, 2019; Reid, 1988; Sandoval et al., 2019; Sibuet et al., 2007). Necking lines outline the boundaries of the rigid continental blocks (Figure 3; Angrand et al., 2020; Gómez et al., 2019; King et al., 2020; Nirrengarten et al., 2018; Peace & Welford, 2020). Symbols refer to our and previous global kinematic models that do not separate Iberia in numerous continental blocks (Barnett Moore et al., 2016; Nirrengarten et al., 2018; Van Hinsbergen et al., 2020). Full or empty symbols indicate the time span. AFR = NW Africa; Bi = Biscay; EBR = Ebro; EU = Europe; FL = Flemish Cap; MO = Morocco; NAM = North America; PR = Porcupine; Pyr = Pyrenees; B-IR = Biscay (B)—Iberian Rift System (IR). White squares refer to the location of data in columns of Figure 2 and onset of arrows in Figure 3 [Colour figure can be viewed at wileyonlinelibrary.com]

the first unambiguous oceanic magnetic anomaly (Figures 1 and 3a) (Vissers & Meijer, 2012a). The strike-slip corridors have broadly the same trend at 83 Ma (Figures 3a and 4a). We translate Iberia backward from this first step (83 Ma) using: (a) estimates of crustal extension in the Atlantic, and (b) a direction of motion parallel to the trend of the strike-slip corridors (Figure 3). Since the strike-slip corridors do not represent in reality simple linear plate boundaries, the motion is hypothetically assumed orthogonal to rift necking lines in orthogonal settings and parallel to the corridors borders where strike slip dominates (Figure 2). For the Atlantic, between 112 and 83 Ma, we use the extensional template of Gómez-Romeu et al. (2020), which provides extension values for FL and NAM relative to IB, in strong agreement with independently obtained values proposed by Sutra et al. (2013). Concerning the strike-slip corridors, synchronous movements between 165 and 112 Ma (Late Jurassic to Aptian) allow the definition of coherent motion of AFR relative to NAM (Newfoundland), NAM relative to FL (Flemish Pass) and IB relative to EU (Biscay) as input (Figures 3a and 4). The motion of NAM relative to Iberia (Tagus Plain), and IB relative to Africa (Gorringe Bank) are considered as output (Figure 2d).

## 4 | RESULTS AND DISCUSSION

### 4.1 | The Iberia-Europe-Ebro region

In our kinematic model, the lateral motion of IB relative to EBR is: (a) 370 km from 155 to 112 Ma, resulting in the development of Late Jurassic to Aptian depocenters along the Iberian Rift System (Salas et al., 2001), and (b) 320 km from 112 to 83 Ma, suggesting that strike-slip component of the motion continued inside the Iberian Rift System after the Aptian. According to Angrand et al. (2020) strike-slip motion stopped at 100 Ma. Our model suggests (a) a migration of orthogonal extensional deformation from the B-IR corridor to the Pyrenean segment at 126 Ma (see Lescoutre and Manatschal, 2020; Figure 4b–d), and (b) defines 80 km as a maximum N–S extension within the Pyrenean rift between EBR and EU from 126 to 83 Ma, consistent with values inferred from hyperextended basins in the Pyrenees (e.g., Quintana et al., 2015; Teixell, 1998) and with post-83 Ma inferred N–S Alpine shortening in north Iberia (Macchiavelli et al., 2017; Wang et al., 2016).

### 4.2 | The southern N-Atlantic

Although the southern N-Atlantic provides some first-order input in our model, due to the existence of a complete data set, including reflection, refraction seismic data and ODP boreholes, our model also has some outputs that can be tested in this region. The validity of the reconstruction is supported by the parallelism between the computed FL-IB motion path and the trend of the displacement zone shown by Mohn et al. (2015) and interpreted as Lower Cretaceous (Figure 1). Similarly, the reconstructed Jurassic IB-AFR motion path is parallel to displacement zones inferred by Fernández et al. (2019). Both structural trends fit with the motion path and confirm the validity of our approach (Figure 1).

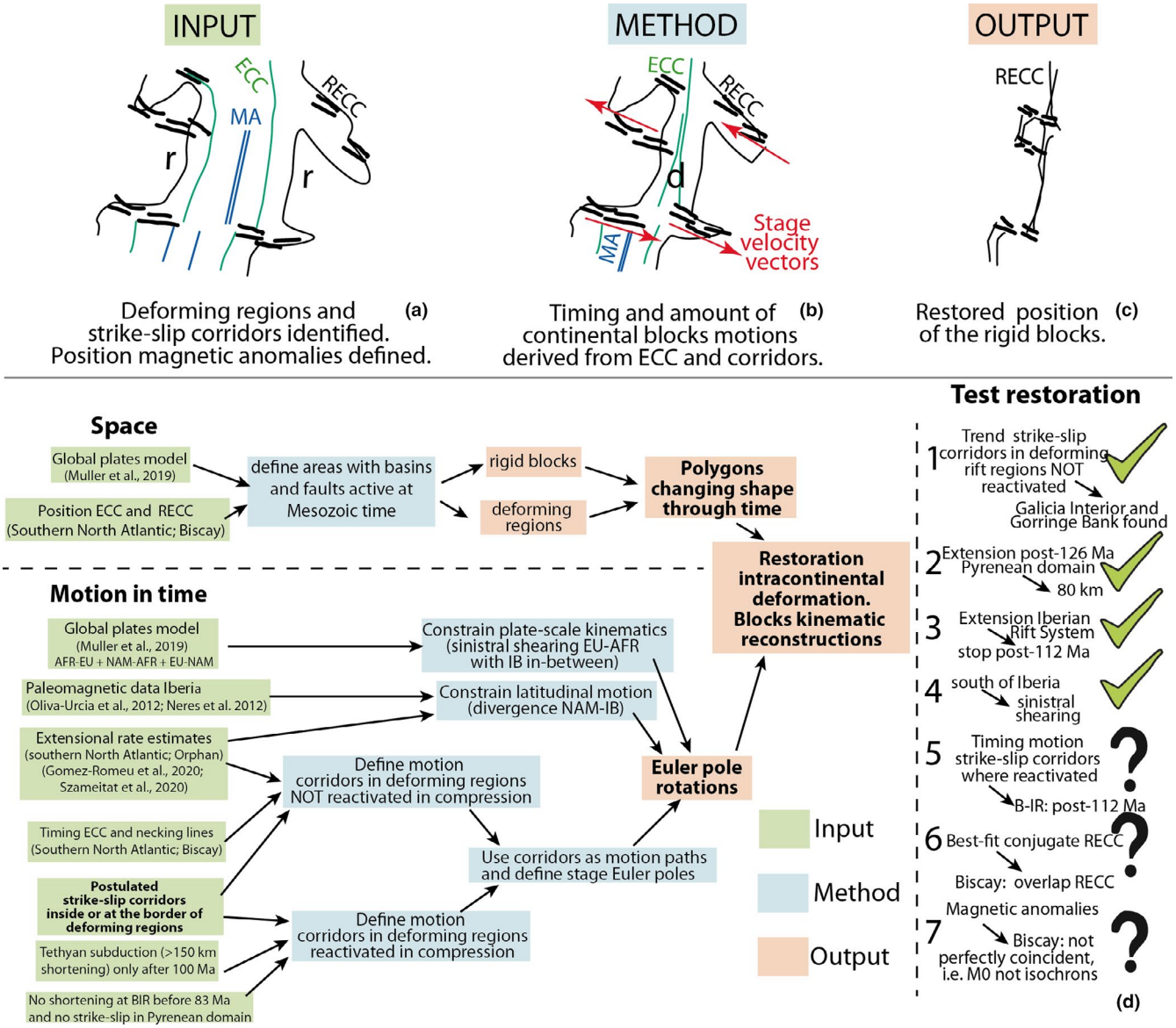


**FIGURE 2** Simplified sketch of the restoration method with input situation (a), method representation (b), and expected results (c). Diagram showing the decision-making process applied to the kinematic reconstruction built on GPlates 2.1 software (d) [Colour figure can be viewed at wileyonlinelibrary.com]

The computed total ~185 km of extension for the Orphan Basin during the Mesozoic (Figures 2 and 4f,g) is compatible with reported observations (MacMahon et al., 2020; Peace & Welford, 2020). Our orthogonal setting has a NAM-FL pole of rotation far from Flemish Cap, in contrast to previous estimations (Sibuet et al., 2007; see Figure 1). In the southern N-Atlantic, the progressive northward oceanization is compatible with the model of Szameitat et al. (2020) involving a V-shape propagator.

The Newfoundland intracontinental strike-slip corridor motion (MO-NAM) combined with the motion AFR-NAM, as defined independently by Müller et al. (2019), implies ~80 km of dextral displacement in the Atlas (MO-AFR deforming region) during the Early Jurassic (Favre & Stampfli, 1992; Stampfli & Hochard, 2009). A left-lateral movement of the Morocco micro-block relative to the Iberia continental block during the whole Cretaceous after the docking of Morocco and NW Africa (Figure 4g) is also in agreement with geological data (Gimeno-Vives et al., 2019).

### 4.3 | Strike-slip corridors: A new approach to restore pre-breakup rigid blocks

The kinematic reconstruction of Iberia prior to magnetic anomaly C34 is problematic due to the absence of large-scale, restorable marker features such as oceanic fracture zones or well defined oceanic magnetic anomalies, and because plate separation occurred during the magnetic quiet period (e.g. Cretaceous Normal Superchron) (Nirrengarten et al., 2017). Here we use intra-continental strike-slip corridors to assess the kinematic framework during continental

**TABLE 1** Main tectonic events in the NAM-AFR-EUR area around IB as defined by Müller et al. 2019 in the first column. Computed values of displacement in kilometres for the points shown in Figure 1 and time steps represented in maps of Figures 3 and 4. Input data are in black, while outputs are grey. Computed values and 2σ method explained in Data Repository. Colours in the background show the evolution from rifting to drifting [Colour table can be viewed at wileyonlinelibrary.com]

| Steps Figs. 3 & 4 (Ma) | | Events around Iberia | INPUT (km) NAM-Morocco/AFR | INPUT (km) IB-NAM | INPUT (km) IB-FL | INPUT (km) FL-NAM | OUTPUT (km) PR/EU-FL | OUTPUT (km) EU-IB | OUTPUT (km) EBR-IB | OUTPUT (km) EBR-EU | OUTPUT (km) IB-AFR | OUTPUT (km) Morocco-AFR |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 83 | Cretaceous | NAM-EU Rifting | 343±27 | 256±2 | 220±19 | | 18±9 | 166±4 | 142±13 | | 73±30 | |
| 97 | | NAM-AFR Drifting | 391±11 | 292±1 | 240±1 | | 26±18 | 65±28 | 146±10 | 21±7 | 183±1 | |
| 112 | | | 200±5 | 146±3 | 89±2 | 41±1 | 43±1 | 97±2 | 80±4 | 22±5 | 33±12 | |
| 120 | | | 226±1 | 143±12 | 64±7 | 68±3 | 50±4 | 100±2 | 71±2 | 27±2 | 44±1 | |
| 133 | | | 209±1 | 102±7 | 37±6 | 64±1 | 53±4 | 66±3 | 35±6 | | 110±4 | |
| 145 | Jurassic | AFR-EU Strike-Slip | 518±18 | 173±12 | 57±17 | 111±17 | 98±14 | 109±4 | 69±1 | | 276±5 | |
| 165 | | AFR-NAM Rifting | 404±3 | 76±13 | 68±12 | | 35±31 | | | | 238±23 | 86±25 |
| 200 | Triassic | | | | | | | | | | | |

Crustal thinning | Mantle exhumation | Oceanic drifting | Oblique motion

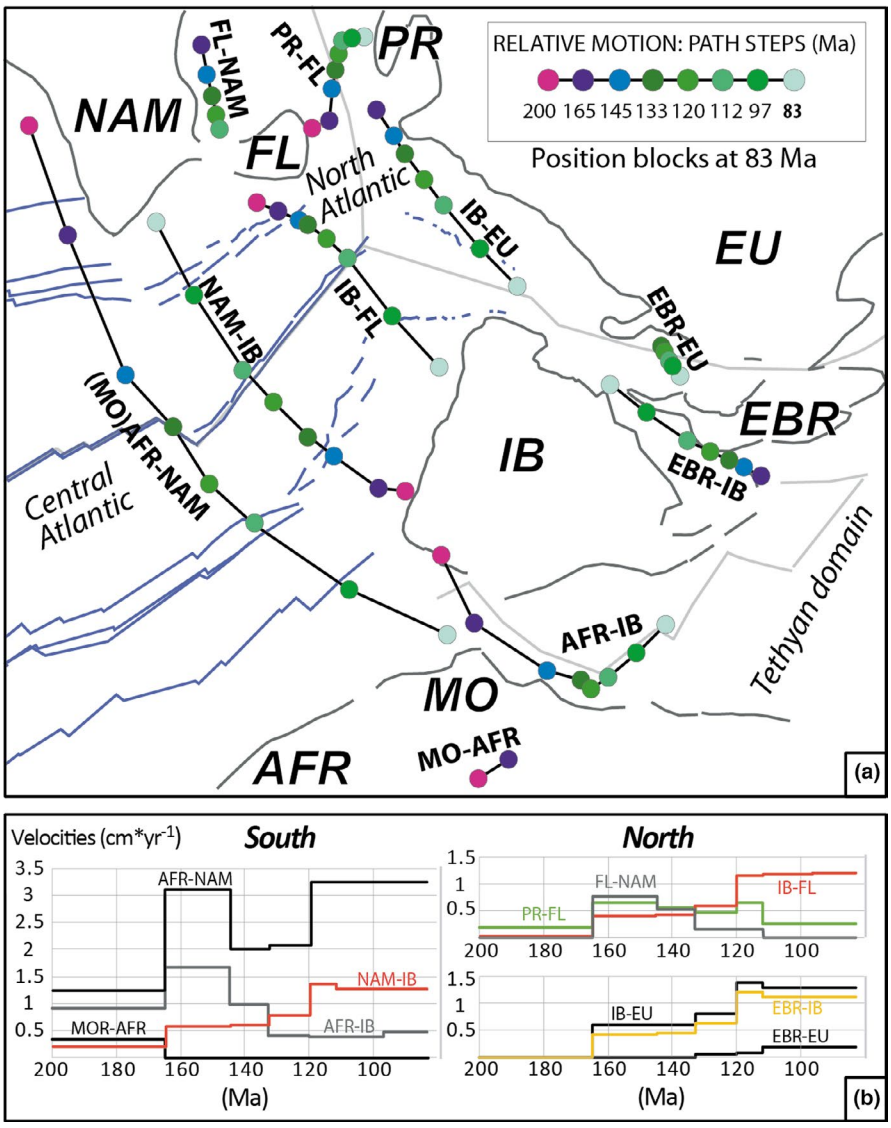


**FIGURE 3** (a) Motion paths for points reported in Figure 1. Note the similar trend between paths and corridor border trends in Figure 1. (b) Stage relative velocities between blocks during the time steps of Figure 4 [Colour figure can be viewed at wileyonlinelibrary.com]

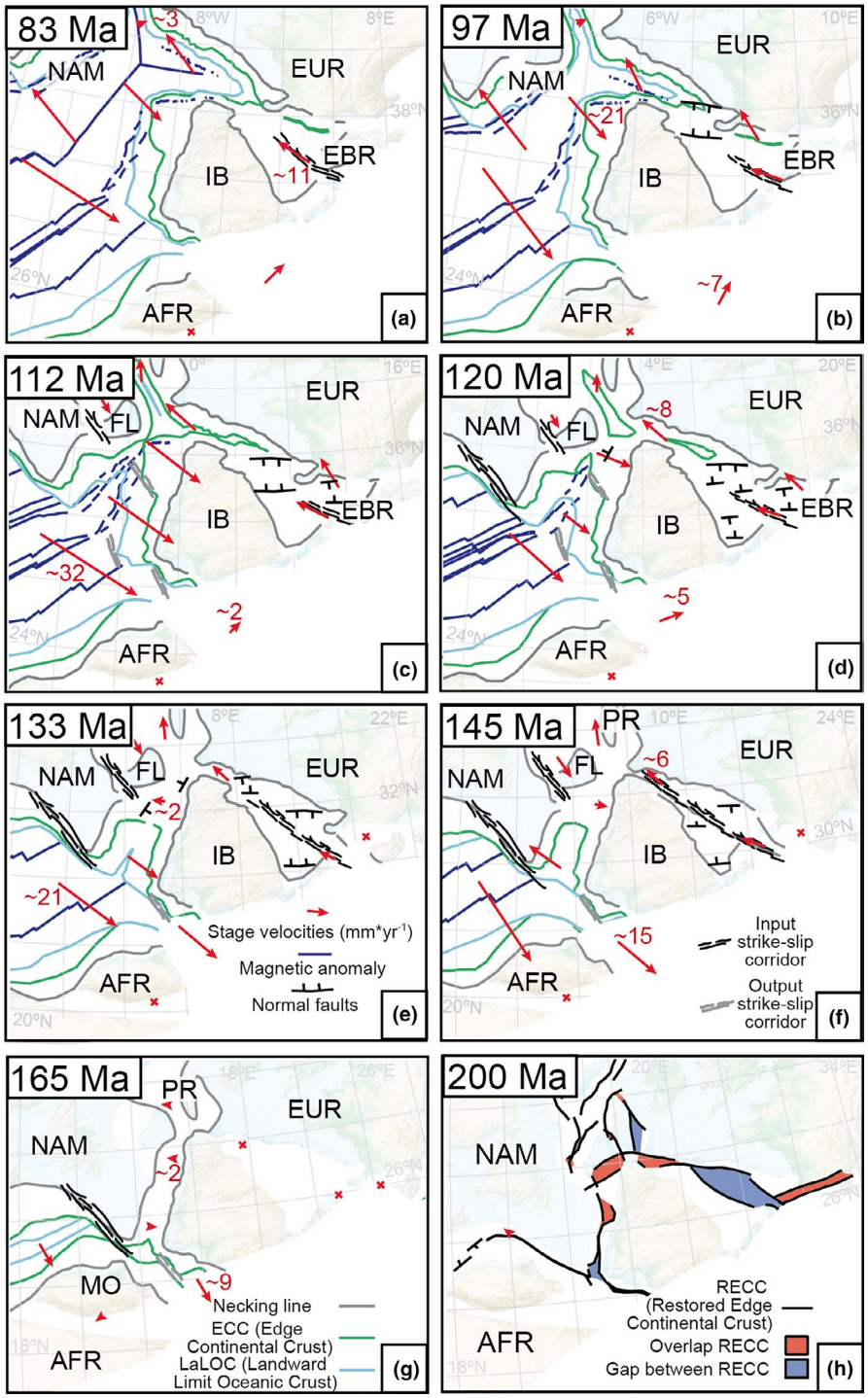


**FIGURE 4** Tectonic restoration of Iberia and surrounding plates. Present-day geographic configuration is shown for the stable parts of the plates; deforming continental regions are white. Each map represents the incremental deformation in the time span between the same and the previous map, reported in Figure 3. (a) ~83 Ma: magnetic anomaly C34 and onset of AFR-IB-EU convergence. (b) ~97 Ma: mantle exhumation in the Pyrenees and post-rift in Iberian Range basins. (c) ~112 Ma: mantle exhumation in northern Southern North Atlantic and syn-rift in Iberian Range. (d) ~120 Ma: magnetic anomalies appear in southernmost North Atlantic. (e) ~133 Ma: Break-up in southernmost North Atlantic. (f) ~145 Ma: Onset thinning continental crust in northernmost Southern North Atlantic. (g) ~165 Ma: Break-up in the Central Atlantic and onset IB-EUR relative motion. (h) ~200 Ma: Tight fit IB-NAM for southernmost North Atlantic. Necking lines in grey and edge of the continental crust region in green, first oceanic crust and magnetic anomalies in light and dark blue. Size of arrows is proportional to the stage velocities (mm/year)[Colour figure can be viewed at wileyonlinelibrary.com]

rifting. Considering the complex strain partitioning in the strike slip corridors, local kinematic indicators do not necessarily provide information on the plate kinematic scale. Furthermore, strike slip and decoupling levels, such as the Triassic salt, can trigger local rotations, hampering the analysis of regional kinematics. Therefore, upscaling of field observations and of paleomagnetic data (Neres et al., 2012; López-Gómez et al., 2019; Oliva-Urcia et al., 2012; Osete et al., 2011) to a plate kinematic scale requires a careful study and good, large-scale outcrops.

### 4.4 | Open questions

Three intriguing issues arise from the kinematic reconstruction (Data Repository S4, S5). The first issue regards gaps and overlaps in the restored edges of continental crust (RECC), respectively in the Bay of Biscay and east of Flemish Cap (Figure 4h). Discrepancies are nevertheless expected in such an oblique setting, as underlined by Peace et al. (2019). Gaps at the 200 Ma reconstruction might be justified by poorly-constrained Triassic and older extension (López-Gómez, et al., 2019;

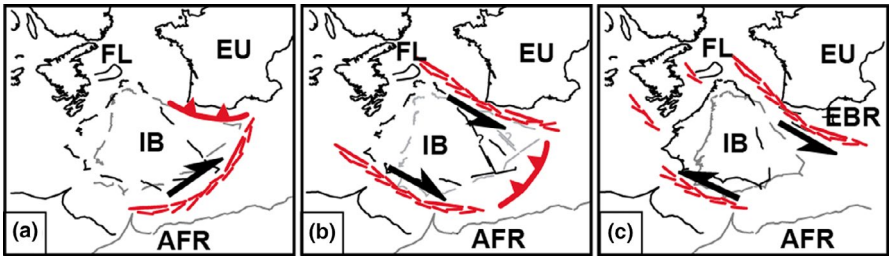


**FIGURE 5** Sketch view of three end-member solutions for the motion of Iberia: (a) based on the J magnetic anomaly (e.g., Van Hinsbergen et al., 2020); (b) based on tight fit of restored continental crust (e.g., Nirrengarten et al., 2018); (c) based on strike-slip corridors, our solution. Note that the solution by Nirrengarten et al. (2018) is influenced east of Iberia by the use of the global plate kinematic framework of Seton et al. (2012). Note that Europe is fix in the sketch but the arrows south of Iberia represent the relative motion between Iberia and Africa. Thick red lines represent subduction zones [Colour figure can be viewed at wileyonlinelibrary.com]

van Hinsbergen et al., 2020). The second issue is the post-112 Ma large strike-slip motion between Ebro and Iberia. Post-112 Ma overprint due to N–S extension and shortening in the Iberian Rift System could hamper its recognition. However, our kinematic model is able to reproduce for the first time strike-slip and subsequent orthogonal N–S extension reported by field-based studies (Cadenas et al., 2020; Lescoutre and Manatschal, 2020; Figure 4b–d). As a third issue, M-series magnetic anomalies in the Bay of Biscay do not correspond to isochrons in our model (Figure 4b–e). The V-shaped propagation of these magnetic anomalies could result from lateral contrast of magnetization between different types of crust, as described by Szameitat et al. (2020) for the M-series in the southern N-Atlantic (Figure 4b,c).

### 4.5 | Differences with previous kinematic reconstructions

The reconstruction of the southern N-Atlantic was traditionally based on two end-member approaches. A first group used the M-series magnetic anomalies as isochrons (Rowley & Lottes, 1988; Sibuet et al., 2004; Vissers & Meijer, 2012b; Figure 5a) while a second group used Triassic tight-fit restorations of rigid continental blocks (Barnett-Moore, Müller, et al., 2016; Nirrengarten et al., 2018; Figure 5b). Resulting models imply: (a) an acceleration of Iberia relative to Africa between 126 and 112 Ma and thus a dextral shearing in the deforming region east (Figure 5a) or south (Figure 5b) of Iberia; and (b) significant shortening in either the Pyrenean or Tethys domains, triggering subduction between 126 and 112 Ma (Figure 5a,b) Van Hinsbergen et al. (2020) and Angrand et al. (2020). Our model does not produce subduction north and east of Iberia in Aptian-Albian time, compatible with the lack of thrust faults, volcanic arc, terrigenous "flysch" deposits and high-pressure metamorphism older than 100 Ma (Chevrot et al., 2018; Faccenna et al., 2001; Fernández, 2019; Fichtner & Villaseñor, 2015; Le Breton et al., 2021; Molli & Malavieille, 2011). Our workflow gives priority to first-order, large-scale onshore and offshore seismic observations and robust regional interpretations (Figure 2d). Our model represents a new solution involving left-lateral motion between Iberia and Africa, south of Iberia (Figure 5c), contrarily to the latest models of Nirrengarten et al. (2018) and Angrand et al. (2020). As such, the left-lateral motion of Africa relative to Europe appears crucial to control the Mesozoic kinematics of Iberia.

## 5 | CONCLUSIONS

The key point of the present reconstruction of Iberia is the definition of motion paths using strike-slip corridors, mainly marked by alignments of laterally confined and narrow rift basins or transfer zones. The resulting reconstruction of Iberia conforms at a first order with the circum-Iberian regional geology, suggesting that intracontinental strike-slip corridors may be used as a robust boundary condition to restore large rigid blocks back to the onset of rifting.

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### CONFLICT OF INTEREST

The authors declare no conflict of interest.

### DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available in the supplementary material of this article.

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## SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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