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Kinematics of Jurassic ultra-slow spreading in the Piemonte Ligurian ocean

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ABSTRACT

The geological record of the western and northern Mediterranean region (Apennines, Alps, Carpathians) contains relics of an ocean basin of Jurassic age known as the Piemonte–Ligurian (PL), Alpine or Alpine Tethys ocean. We here reconstruct the age, direction and amount of extension in the PL basin by analyzing the differences in spreading rates based on marine magnetic anomalies and fracture zones in the Central Atlantic ocean between Africa and North America, and the North Atlantic Ocean between Iberia and North America. The difference in spreading rate must have been accommodated between Iberia and Adria, which we assume to be rigidly attached to the African plate in the late Jurassic. We compute a maximum of ∼450 km of WSW-ENE extension between Iberia and Africa, largely between ∼170 and ∼150 Ma. Relative Adria (Africa)–Europe motion predicts up to 670 km of extension at the longitude of the western Alps – distributed over the PL and Valaisan basins – decreasing to ∼315 km along the easternmost boundary of the PL basin formed by the Tornquist–Tesseyre line. We note that the Africa–Europe plate boundary in the late Jurassic was probably not discretely localized along the Tornquist–Tesseyre line, but distributed over several fault zones including the Severin oceanic basin to the west of the Moesian platform; the 315 km of PL extension in the east should hence be considered a maximum. It is unknown to what extent PL extension was accommodated by genuine ocean spreading, but full spreading rates in the western PL basin were slow, no more than 20 mm/yr. This ultraslow spreading is consistent with characteristics of western Mediterranean ophiolites, including exposure of upper mantle rocks at the sea floor, the alternation of volcanic and avolcanic segments, and the petrologic features of the pertinent magmas and peridotites.

1. Introduction

Marine geophysical studies over the last few decades and increasing accuracy of the geomagnetic polarity timescale (GPTS) have allowed improved reconstructions of plate motions with time. This invites attempts to use these data to reconstruct kinematically linked oceanic basins that have since been involved in subduction and orogeny. The Piemonte–Ligurian (PL) basin that once occupied the western and northern Mediterranean region was at least in part oceanic and is now represented by (ultra)mafic ophiolite fragments preserved in the Alpine belts of e.g. the Ligurian Apennines, Corsica, Alps, and the Carpathians. It was formed in Jurassic–Cretaceous times in response to the progressive opening of the central Atlantic and the concurrent southeastward motion of Africa relative to North America and Eurasia (e.g. Frisch, 1979, Fig. 1a and b). These motions were transferred eastward along a major transform structure now preserved as the (Newfoundland-) Azores – Gibraltar Fracture Zone (AGFZ) and differential motion of Africa with its Adriatic promontory relative to Iberia led to rifting and ocean spreading in the PL domain east of Iberia (Frisch, 1979; Frank, 1987; Stampfli, 1993; Schmid et al., 2008; Handy et al., 2010; Gaina et al., 2013; see Fig. 1a, b). Rifting and subsequent ocean spreading in the Central Atlantic gradually propagated northward into the North Atlantic between North America and Iberia, at the expense of spreading in the PL domain (Fig. 1c).

In this study we address the kinematics of extension in the PL domain. We wish to estimate the size of the PL ocean at the end of its extension, as well as the associated spreading rates through time as they resulted from differential Africa–Iberia motion. The size of the PL ocean is clearly relevant for any Late Mesozoic, early Alpine paleogeographic reconstruction, while spreading rates during oceanization are important to estimate the thermal state of the pertinent oceanic lithosphere and inherent dynamic consequences. We use our results to develop a 'simplest scenario' plate boundary evolution of the northern African plate that may serve as a baseline model for Mediterranean plate reconstructions. Our kinematic analysis assumes that since onset of the opening of the Atlantic

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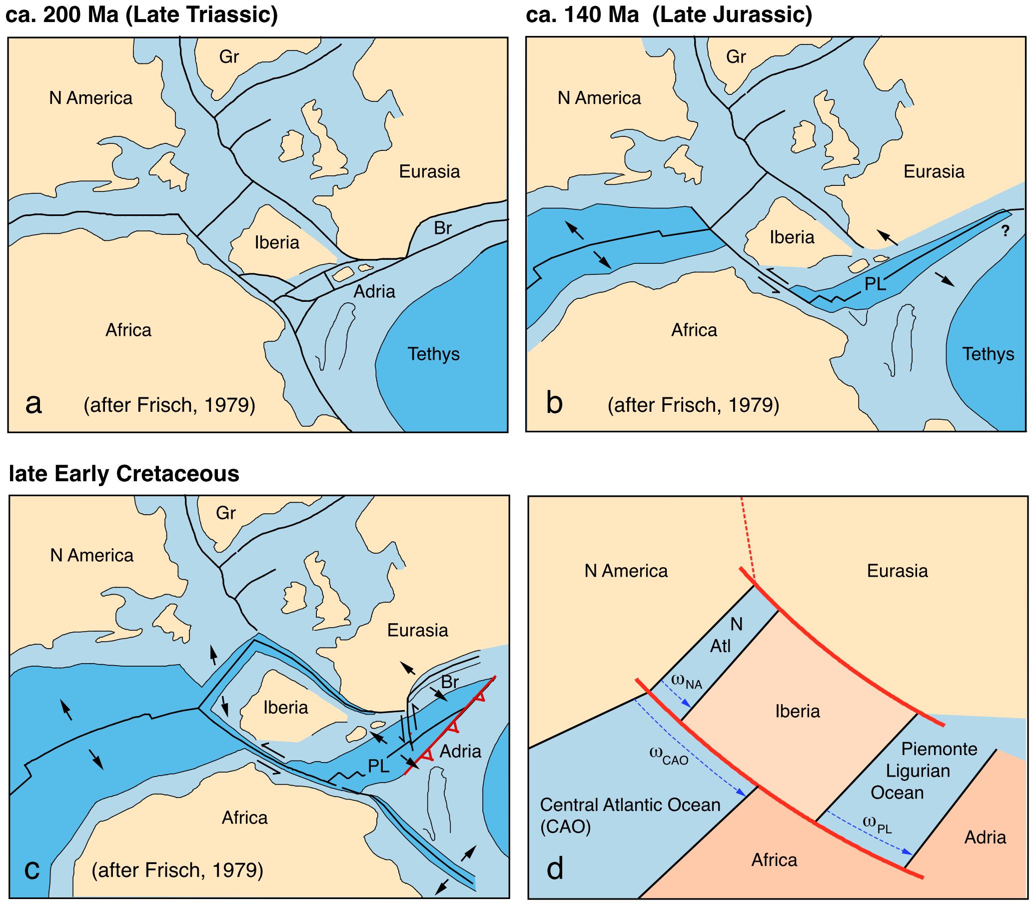

Fig. 1. Plates and plate motions involved in the opening of the PL Ocean, adapted from Frisch (1979): (a) plate geometry in Late Triassic times, (b) opening of the central Atlantic and simultaneous opening in the PL domain (PL), (c) propagation of breakup into the northern Atlantic and onset of Iberia rotation, (d) schematic representation showing how opening of the PL ocean is kinematically linked to Africa and Iberia motions. For further explanation see text.

ocean, the Adriatic promontory has been fixed relative to Africa, i.e. that the oceanic crust of the eastern Mediterranean basin that separates Adria from Africa predates the early-mid Jurassic (Rosenbaum et al., 2002, 2004; Frizon de Lamotte et al., 2008; Gallais et al., 2011; Speranza et al., 2012). GPS data show that Adria is slowly moving relative to Africa today (d'Agostino et al., 2008) and based on geological (e.g. Ustaszewski et al., 2008; Handy et al., 2010; van Hinsbergen and Schmid, 2012) and paleomagnetic data (Channell et al., 1979; Tozzi et al., 1988; Marton and Nardi, 1994; Marton et al., 2011), various and in part contrasting scenarios have been proposed for Cretaceous or Cenozoic motion of Adria relative to Africa. In particular, to accommodate kinematic interpretations of the Alps, Handy et al. (2010) proposed that Adria underwent significant extension relative to Africa in the Paleogene, followed by Neogene subduction between Africa and Adria (Apulia). We note that the resulting position of Adria versus Africa in pre-Cenozoic times inferred by Handy et al. (2010) does not differ from our proposed fixed Adria position with respect to Africa since the Middle Jurassic. Paleomagnetic data from in particular Apulia (southeastern Italy) have been used to infer no rotation of Adria versus Africa (Channell et al., 1979), ~20° clockwise late Neogene rotation (Tozzi et al., 1988) or ~20° counterclockwise rotation (Marton and Nardi, 1994). These contradicting scenarios may affect the position of Adria relative to Africa in our reconstructions somewhat, and may hence change the shape of the PL ocean in our reconstructions, but because all postulated Adria–Africa relative motions post-date the time window of interest here, these motions do not affect the amount of extension accommodated in, or the age and rate of, opening of the PL ocean.

Fig. 1d serves to illustrate our approach. The magnitude and rate of extension leading to oceanization in the PL domain should balance the differential motion of Africa and Iberia, where the motion of Africa with respect to N America exceeds that of Iberia. In a description with one single pole for the rotations of Africa and Iberia it follows that for the angular rotation rate in the PL domain:

$$\omega_{PL} = \omega_{CAO} - \omega_{NA}$$

where ω_{CAO} and ω_{NA} are the angular rotation rates in the Central and North Atlantic respectively, associated with the motion of Africa and Iberia relative to North America (Fig. 1d). During the late Early Cretaceous, opening of the Bay of Biscay and progressive rifting and breakup in the North Atlantic (Fig. 1c) induced a ~35° counterclockwise rotation of Iberia (van der Voo, 1969; Sibuet et al., 2004, in press; Gong et al., 2008; Vissers and Meijer, 2012), and the plate motions started to seriously deviate from the simple model in Fig. 1d. We therefore calculate total reconstruction poles for Africa with respect to Iberia as a basis to reconstruct the development of the PL oceanic domain. For our discussion of the eastern continuation of the PL oceanic domain, we use the rotation poles correcting for pre-drift extension between North America–Eurasia listed in Torsvik et al. (2012).

2. Plates and plate fragments involved

While the opening of the western PL oceanic domain can in essence be described via the interaction of Africa (AFR), N America (NAM) and Iberia (IB), a complete reconstruction of the plate geometry with time requires considering additional plates and plate

Table 1
Time scales and anomaly ages adopted in this study.

An	KG86	GR94	GR04	TS10	HE08–TS10*	Stage
M0	118.35	121.0	125.00	125.00	**121.20**	base Aptian
M3r**	124.19	125.7	129.00	128.94	**125.63**	Barremian
M4	125.91	127.0	130.30	130.08	**126.91**	Hauterivian
M10	130.01	130.8	134.10	133.94	**131.24**	Hauterivian
M11	132.78	133.0	136.70	135.64	**133.15**	Valanginian
M16	141.53	140.0	142.20	141.85	**140.13**	Berriasian
M17	143.02	141.7	143.40	143.43	**141.91**	Berriasian
M20	147.90	146.2	147.50	147.82	**146.85**	Tithonian
M21	149.66	147.8	148.80	148.96	**148.13**	Tithonian
M22	152.11	149.9	150.40	150.93	**150.34**	Tithonian
M25**	156.42	154.2	154.50	154.12	**153.92**	Kimmeridgean

* Ages based on linear interpolation of the Pacific M-series, calibrated with 121.2 ± 0.5 Ma age for M1n from He et al. (2008) and 155.7 Ma for M26r.
** Ages indicated for the M-series are means of reversed polarity intervals. Abbreviations: KG86: Kent and Gradstein (1986), CK95: Cande and Kent (1995), GR04: Gradstein et al. (2004), TS10: Tominaga and Sager (2010), He08: He et al. (2008).

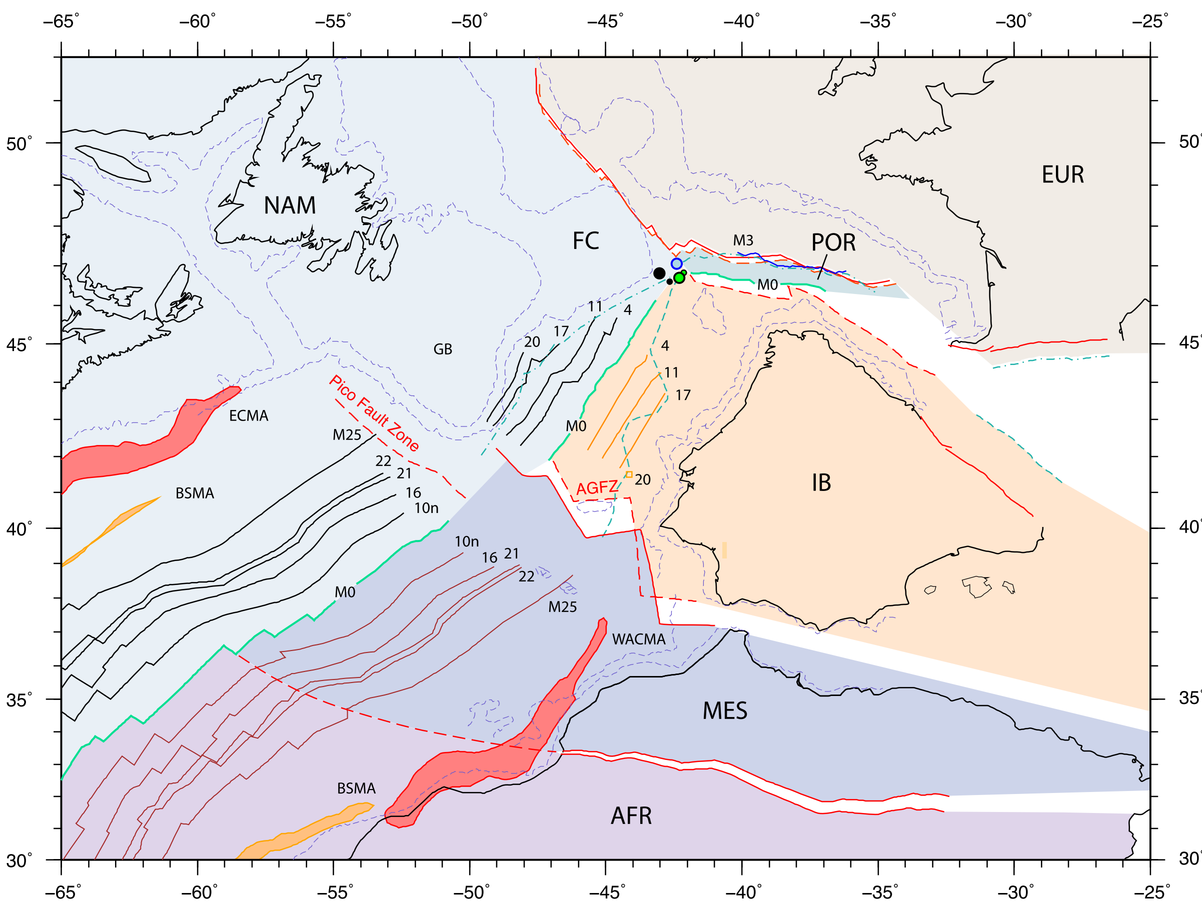

Fig. 2. Reconstruction for anomaly M0 times (base Aptian), showing plates and plate fragments involved and magnetic anomalies referred to in this study. Anomaly data in the central Atlantic following Labails (2007), anomalies in north Atlantic from Srivastava et al. (2000), anomalies north of Iberia from Sibuet et al. (2004, in press). Abbreviations: AGFZ – Azores Gibraltar Fracture Zone, BSMA – Black Spur Magnetic Anomaly, ECMA – East Coast Magnetic Anomaly, FC – Flemish Cap, GB – Grand Banks, WACMA – West African Coast Magnetic Anomaly. Abbreviations for plates and plate fragments as defined in text.

fragments. To illustrate this, a reconstruction for anomaly M0 times (121.2 Ma, Table 1) is shown in Fig. 2. This reconstruction, based on a previous study of the Cretaceous Iberia rotation (Vissers and Meijer, 2012), shows Europe (EUR) and the adjacent oceanic Porcupine (POR) platelet north and northeast of Iberia. In addition, the northwestern part of Africa comprises the Moroccan Meseta (MES) separated from the continental African mainland by the Atlas range, a Cenozoic fold-thrust belt inverting a Triassic–Jurassic rift (Beauchamp et al., 1999; Frizon de Lamotte et al., 2008). This latter plate fragment needs special attention because it separates Iberia from the main African plate, whilst the kinematic evidence for independent motion of the Meseta relative to Africa during the Jurassic seems at variance with the geological evidence from the Atlas range as discussed below.

In order to avoid ambiguities we use abbreviations for the various plates in denoting total reconstruction poles as well as forward motion stage poles. As an example, the rotation needed to bring Iberia (IB) in its original position with respect to North America (NAM) at anomaly M0 times, hence to match the rotated Iberian anomaly M0 with its North American counterpart, is denoted:

$$R\,(IB/NAM)\ 0 \rightarrow M0,\ \text{or (briefly)}\ R\,(IB/NAM)\ \text{for M0.}$$

3. Data used in this study

The early opening of the Central Atlantic is well documented (Klitgord and Schouten, 1986; Sahabi et al., 2004; Labails, 2007; Labails et al., 2010) and the presently available data seem to form an adequate basis to describe the motion of Africa with respect to North America. In a detailed study of the central Atlantic, Labails (2007) documented reconstruction poles (R AFR/NAM) for the early stages of continental rifting at 203 and 190 Ma, followed by poles for the Black Spur Magnetic Anomaly (BSMA) at 170 Ma, as well as the following – in part resampled – magnetic anomalies M25, M22, M21, M16, M10n and M0 (Table 1, Fig. 2). In addition, Labails (2007) and Labails et al. (2010) have calculated total reconstruction poles for the Moroccan Meseta Block (MES) with respect to N America.

There are only few published total reconstruction poles for the Mesozoic opening of the N Atlantic between N America and Iberia. Srivastava and Verhoef (1992) have proposed reconstruction poles for M0 and, on the basis of a unstretching technique of continental overlaps, for the earlier M25 at the onset of oceanization and the initial fit (estimated at ∼175 Ma but with a large age uncertainty). Srivastava et al. (2000) propose the same M0 reconstruction pole for Iberia relative to North America, but also report magnetic anomalies for M20, M17, M15, M11, M4 and M3 which in the western part of the system are generally well defined, but rather poorly defined or even absent to the east (Fig. 2). They use these anomalies to estimate spreading rates at different stages, but no reconstruction poles have been calculated.

A recent paper by Bronner et al. (2011) proposes a much younger age of seafloor spreading in the Northern Atlantic. These new data, however, seem at variance with onland paleomagnetic results as outlined in the Discussion below.

Inherent to the different anomaly data for the Central and North Atlantic, total reconstruction poles based on anomalies between AFR/NAM that are not documented for IB/NAM (and vice versa) need to be estimated via interpolation assuming constant rotation/spreading rates between picked anomalies. To calculate such interpolated poles, but also to estimate spreading rates, the African and Iberian motions with respect to North America need to be related to one common time scale. The anomalies in the central Atlantic and associated AFR/NAM reconstruction poles of Labails (2007) and Labails et al. (2010) have been referred to the Gradstein et al. (2004) time scale, whilst the anomalies in the northern Atlantic were used by Srivastava et al. (2000) to calculate spreading rates based on the Geomagnetic Polarity Time Scale (GPTS) of Kent and Gradstein (1986). In this study we follow Vissers and Meijer (2012) in using the GPTS of Tominaga and Sager (2010) for the Late Jurassic and Early Cretaceous, but calibrated via linear interpolation of the Pacific M-series with a 121.2 ± 0.5 Ma age for M0r from He et al. (2008) and 155.7 Ma for the base of M26r (Table 2). This time scale differs only slightly from that of Gradstein et al. (1994) often used in plate kinematic analyses (Table 1). In addition, we follow Cande and Kent (1995) for the anomaly A34 reconstruction shown in Fig. 2. Ages of the pertinent anomalies according to these different time scales are listed in Table 1.

4. Plate-kinematic analysis

4.1. Analysis of the data

Fig. 3 illustrates the Jurassic – Early Cretaceous motion of Africa (AFR) and the Moroccan Meseta (MES) with respect to NAM using total reconstruction poles of Labails (2007) and Labails et al. (2010) listed in Table 2. Two aspects of the motion paths seem noteworthy. First, there is a marked change in the direction of motion from almost southward (i.e., relative to North America in its present-day position) during the initial rifting stages to southeastward since about 170 Ma. Secondly, albeit small, there is a clear component of convergence between MES and AFR. This is puzzling because the Atlas ranges do not show any evidence for such convergence but instead represent a Triassic to Mid-Jurassic rift with Jurassic–Cretaceous post-rift sedimentation (Beauchamp et al., 1999; Frizon de Lamotte et al., 2008). This is clearly inconsistent with a Jurassic–Cretaceous convergent relative motion between MES and AFR. Using the Labails (2007) pole data for Africa and the Meseta block, we have calculated total reconstruction poles for this relative motion. The resulting MES/AFR poles are all close to each other, with a tendency for the earliest poles to have somewhat larger rotation angles. In view of the lack of evidence for Late Jurassic to Early Cretaceous deformation in the Atlas and the very small motions involved in the early Mesozoic extension and Cenozoic shortening in the Atlas region (of the order of a few tens of km, e.g. Frizon de Lamotte et al., 2008), we hypothesize that the associated changes of the MES/AFR poles are within the errors involved in the MES/NAM and AFR/NAM poles, hence within errors in the MES/AFR poles (see also Ruiz-Martinez et al., 2012). For practical purposes we therefore assume that the Cenozoic (mainly Eocene) displacement of the Meseta block relative to Africa can be described by one single R (MES/AFR) correction pole (latitude 27.3° N, longitude 13.73° W, rotation angle 1.91 in van Hinsbergen et al., submitted for publication based on restoring shortening estimates for the Atlas mountains). The main corollary is that during the Jurassic and Early Cretaceous the Meseta can be assumed to be fixed to Africa and that, irrespective of the precise Euler location and rotation angle of the correction pole, any forward motion stage pole for the Meseta with respect to N America should equal the corresponding stage pole for Africa, or:

$$\mathrm{R}\,(\mathrm{MES/NAM})\ \mathrm{t2} \rightarrow \mathrm{t1} = \mathrm{R}\,(\mathrm{AFR/NAM})\ \mathrm{t2} \rightarrow \mathrm{t1}$$

We now turn to explore the reconstructed positions and inherent motion of Iberia (Fig. 3) based on the Srivastava and Verhoef (1992) IB/NAM poles for M0, M25 and the initial fit estimated at 175 Ma. There are two main problems with this reconstruction. First, the implied motion path makes a distinct angle with those of Africa and the Meseta, which should lead to considerable contraction on the Iberia–Africa/Meseta boundary. Secondly, and irrespective of the time scale used, interpolated M4, M11, M17 and M20 positions for Iberia based on the Srivastava and Verhoef (1992) poles for M0 and M25 consistently yield gross mismatches of the associated anomalies. As the M0 fit using the R (IB/NAM) $0 \rightarrow$ M0 pole is excellent, there seems no other option than to discard the Srivastava and Verhoef (1992) pole for M25.

4.2. New reconstruction poles for Iberia

Rather than accepting a quite large angle between the motion paths of Iberia and Meseta/Africa we assume that these motions must, at the height of the Azores–Gibraltar Fracture Zone, have been parallel. The simplest way to have this guaranteed is to assume that for any stage t2 to t1, the location of the forward motion stage poles R IB/NAM t2 $\rightarrow$ t1 and R (MES/NAM) t2 $\rightarrow$ t1 coincided, albeit that the angles of rotation may have been different (i.e. there can have been motion along the Azores–Gibraltar Fracture Zone). Based on this assumption we now calculate total reconstruction poles for each of the anomalies t = M20, M17, M11 and M4 using

$$\begin{aligned}
&\mathrm{R}\,(\mathrm{IB/NAM})\ 0 \rightarrow \mathrm{t}\\
&\quad = -\mathrm{R}\,(\mathrm{IB/NAM})\ \mathrm{t} \rightarrow 0\\
&\quad = -\big(\mathrm{R}\,(\mathrm{IB/NAM})\ \mathrm{t} \rightarrow \mathrm{M0} + \mathrm{R}\,(\mathrm{IB/NAM})\ \mathrm{M0} \rightarrow 0\big)
\end{aligned}$$

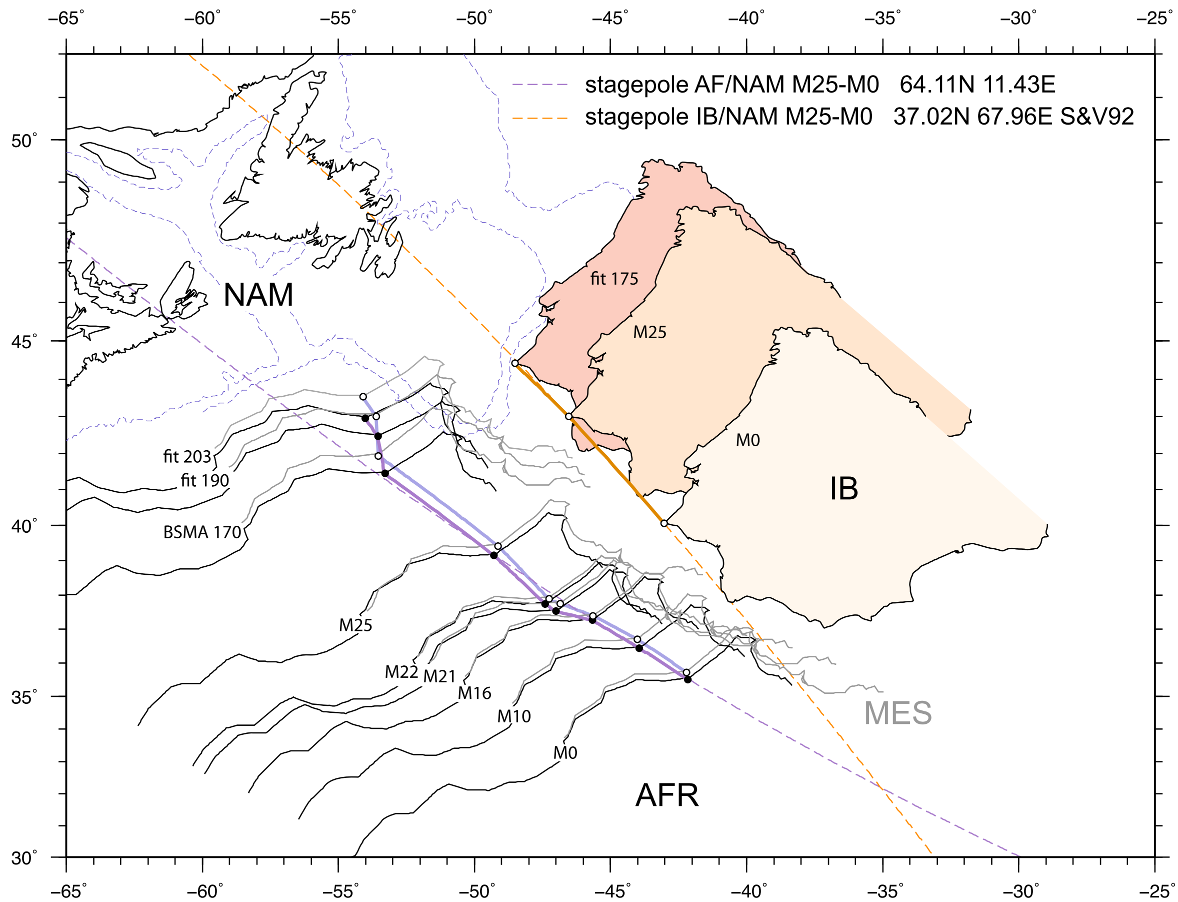

Fig. 3. Motion paths of Africa, Moroccan Meseta and Iberia relative to N America fixed. Marker point on NW African coast at Rabat, marker on Iberian west coast at Cabo de San Vicente. Stages with African and Meseta coastlines based on reconstruction poles by Labails (2007) and Labails et al. (2010), stages for Iberia based on Srivastava and Verhoef (1992). Note marked angle between small circles around the respective stage poles for M25 → M0 implying compression between Iberia and Africa. Non-dashed red and purple lines accentuate the motion paths of Iberia, Moroccan Meseta and Africa, respectively. Note that these motion paths are close to the IB/NAM and AF/NAM small circles defined by the respective M25–M0 stage poles. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

Table 2
Total reconstruction poles for Africa and Moroccan Meseta w.r.t. North America.

An	Age	AFR/NAM			MES/NAM		
		lat	lon	angle	lat	lon	angle
M0	121.2	65.95	−20.46	−54.560	67.17	−19.51	−53.010
M4	126.91	*−65.93*	*160.25*	*56.260*	*−67.18*	*161.35*	*54.630*
M10n	131.24	65.92	−19.24	−57.550	67.18	−18.02	−55.860
M11	133.15	*−66.06*	*161.01*	*57.934*	*−67.07*	*162.07*	*56.552*
M16	140.13	66.57	−18.08	−59.340	66.71	−17.62	−59.080
M17	141.91	*−66.44*	*161.77*	*59.996*	*−66.69*	*162.37*	*59.525*
M20	146.85	*−66.09*	*161.39*	*61.818*	*−66.65*	*162.35*	*60.760*
M21	148.13	66.00	−18.70	−62.290	66.64	−17.65	−61.080
M22	150.34	66.08	−18.44	−62.800	66.61	−17.66	−61.830
M25	153.92	67.10	−15.86	−64.230	68.52	−13.69	−61.750
BSMA	170	67.09	−13.86	−70.550	69.47	−9.56	−66.590
Fit 190	190	64.31	−15.19	−77.090	66.31	−11.78	−72.950
Fit 203	203	64.28	−14.74	−78.050	66.23	−11.28	−73.910

Poles for anomalies in boldface from Labails (2007) and Labails et al. (2010).
Poles in *italic* are interpolated.

with R (IB/NAM) t → M0 a forward motion stage pole, and R (IB/NAM) M0 → 0 the forward motion pole for M0, i.e., *minus* the total reconstruction pole R (IB/NAM) 0 → M0.

The R (IB/NAM) t → M0 stage poles needed are calculated as follows. As noted above, we require parallel motion of Iberia and Meseta/Africa along the AGFZ, meaning that for each of the anomalies the unknown forward motion stage pole R (IB/NAM) t → M0 coincides with R (MES/NAM) t → M0, although the rotation angle may be different. Note again that based on our assumption of one single correction pole for the motion of the Meseta with respect to Africa, MES/NAM forward motion stage poles are equal to AFR/NAM stage poles. For each stage investigated we therefore use the AFR/NAM stage pole calculated from the pertinent total reconstruction poles. Note also that the anomalies M20 to M4 north of the AGFZ have not been sampled in the Central Atlantic such that we use interpolated AFR/NAM poles listed in Table 2. The rotation

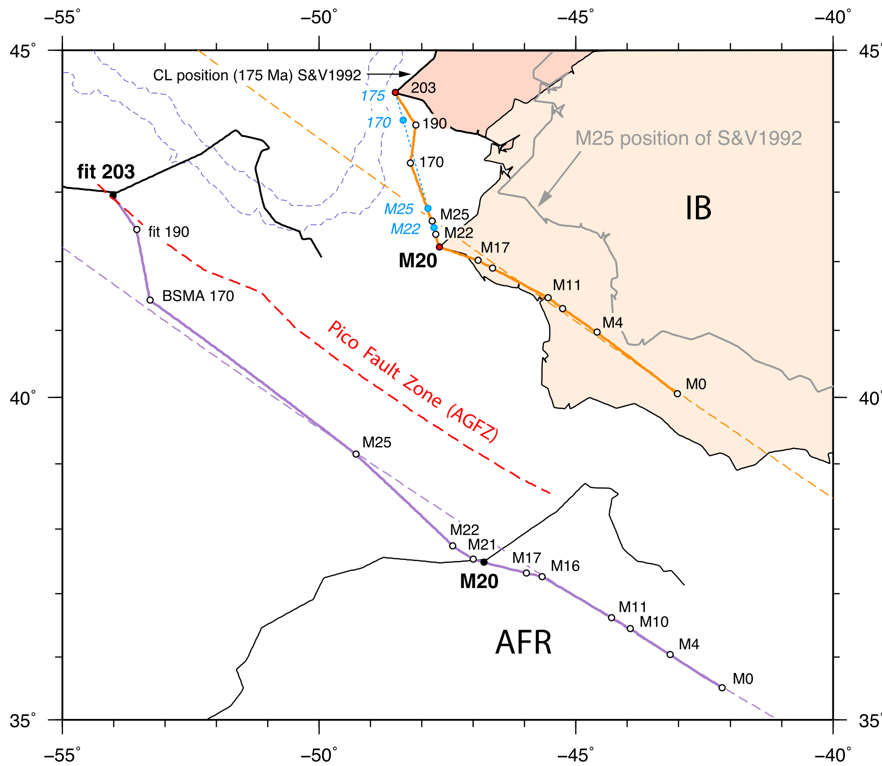

Fig. 4. Analysis of the Iberian motion path with respect to North America. Positions of Iberian marker at M20, M17, M11 and M4 according to reconstruction poles calculated in this study assuming coherent motion with Africa along the AGFZ and using pertinent anomaly picks reported by Srivastava et al. (2000). Stages in bold italic show interpolated positions between continental closure (CL) according to Srivastava and Verhoef (1992, abbreviated S&V1992) and our calculated M20 position. Note considerable component of shortening between 170 Ma and M20 times. Under the assumption that the continental fit of Iberia with North America is in fact older, and that Iberia started to rift away from North America together with Africa since 203 Ma, a much more southerly position of Iberia at 170 Ma is obtained leading to a considerable reduction of shortening across the AGFZ. Dashed lines denote approximately parallel small circles around the forward motion stage poles R (AFR/NAM) M25 → M0 (violet) and R (IB/NAM) M25 → M0 (orange). Non-dashed violet and orange lines delineate motion paths of Africa and Iberia relative to NAM. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

angle of the R (IB/NAM) t → M0 stage pole is found as the angle between the two great-circles through the R (AFR/NAM) t → M0 stage pole and the corresponding western and eastern anomalies in their positions at M0.

There is no magnetic anomaly constraint on the IB/NAM reconstruction pole for M25 nor for any earlier stage, because the earliest anomaly recorded in the northern Atlantic is M20 (Fig. 2). Note that the IB/NAM total reconstruction pole for M25 of Srivastava and Verhoef (1992) would imply an unlikely shortening component of more than 100 km between M25 and M20 (Fig. 4) perpendicular to the AGFZ transform orientation, and a similarly large component of shortening seems implied in the IB/NAM reconstruction pole proposed by these authors for the early continental fit. As already noted, we discard their M25 IB/NAM pole, but their pole for the continental fit deserves some additional analysis, as follows.

In the absence of any reasonable alternative for the initial fit of Iberia and North America ('CL', Fig. 4) assigned to 175 Ma, we assume that this fit is essentially correct. Using the associated total reconstruction pole for that fit and our IB/NAM pole calculated for M20, we calculate interpolated poles for 170 Ma, M25, M22 and M21. The resulting positions of an Iberian markerpoint are shown in Fig. 4. The consequence of the motion path implied by the interpolated poles is a still considerable component of shortening between 170 Ma and M25 times (∼154 Ma), while Africa moves coherent with the general transform orientation in the Central Atlantic and the presumably parallel trending AGFZ. While accepting the CL fit of Srivastava and Verhoef (1992), we hypothesize that this problem arises because of the age assigned by these authors to the onset of Iberia–North America break-up. As noted by Tucholke and Sibuet (2007) and Tucholke et al. (2007), rifting between Newfoundland and Iberia started during the Late Triassic–Earliest Jurassic. This rifting affected a broad region within the Grand Banks leading to the development of e.g. the Jeanne d'Arc, Whale and Horseshoe basins, whilst the Lusitanian, Porto, and possibly Galicia Interior basins opened on the Iberia margin (Murillas et al., 1990; Rasmussen et al., 1998). It follows that this rifting phase was synchronous with rifting between Africa and North America in the central Atlantic domain farther south. In line with these marine geological data, we suggest that the IB/NAM continental closure (CL) is in fact older, and tentatively assign an age of 203 Ma, i.e. a Late Triassic age, to the onset of rifting between Iberia and North America, which coincides with the age of continental closure between Africa and North America adopted by Labails et al. (2010).

There are no further geometrical or kinematic constraints on the rifting process between Iberia and North America, and we therefore assume a scenario involving coherency between the motions of Iberia and Africa, which for the simplest case implies that Iberia and Africa move together such that their motions can be described by one single forward motion stage pole. Based on this assumption we calculate R (IB/NAM) poles for t = 190 Ma and 170 Ma via

$$\mathrm{R\,(IB/NAM)}\,0 \to t = \mathrm{R\,(IB/NAM)}\,0 \to 203 + \mathrm{R\,(IB/NAM)}\,203 \to t$$

where R (IB/NAM) 203 → t equals R (AFR/NAM) 203 → t as implied by the AFR/NAM poles of Labails (2007) and Labails et al. (2010). The resulting positions of Iberia for those two stages are illustrated in Fig. 4. The earlier rifting leads to a more southerly position of Iberia at 170 Ma such that the component of shortening normal to the motion path of Africa, hence normal to the AGFZ, is considerably reduced. We then calculate poles for M25,

Table 3
Total reconstruction poles for Iberia w.r.t. N America and Africa w.r.t. Iberia (PL ocean).

An	Age	IB/NAM			AFR/IB (PL ocean)		
		lat	lon	angle	lat	lon	angle
M0	†	64.71	−18.94	−58.110	50.31	6.85	3.785
M4	126.91*	64.72	−18.01	−60.973	54.46	5.98	4.911
M10	131.24	*−64.85*	*162.35*	*61.931*	55.04	6.54	4.557
M11	133.15*	64.90	−17.49	−62.353	54.03	6.24	4.611
M16	140.13	*−65.21*	*162.85*	*63.611*	50.75	3.85	4.508
M17	141.91*	65.29	−17.06	−63.932	52.41	6.47	4.139
M20	146.85*	64.96	−17.49	−65.902	52.63	5.73	4.283
M21	148.13	*−65.18*	*162.81*	*65.5075*	54.62	13.28	3.397
M22	150.34	*−65.56*	*163.34*	*64.8289*	54.67	29.32	2.239
M25	153.92*	*−66.18*	*164.26*	*63.7361***	−44.79	30.27	1.094
BSMA	*170*	−69.14	169.49	58.94	−55.65	168.07	11.889
Fit 190	*190*	−65.81	166.64	65.363	−55.63	168.09	11.889
Fit 203	*203*	65.72	−12.82	−66.32	−55.63	168.08	11.890

† Adapted from Srivastava and Verhoef, 1992.
* IB/NAM poles calculated in this study.
** IB/NAM pole for M25 from Srivastava and Verhoef (1992) is 66.90 −12.93 −60.45. IB/NAM poles in *italic* are interpolated.

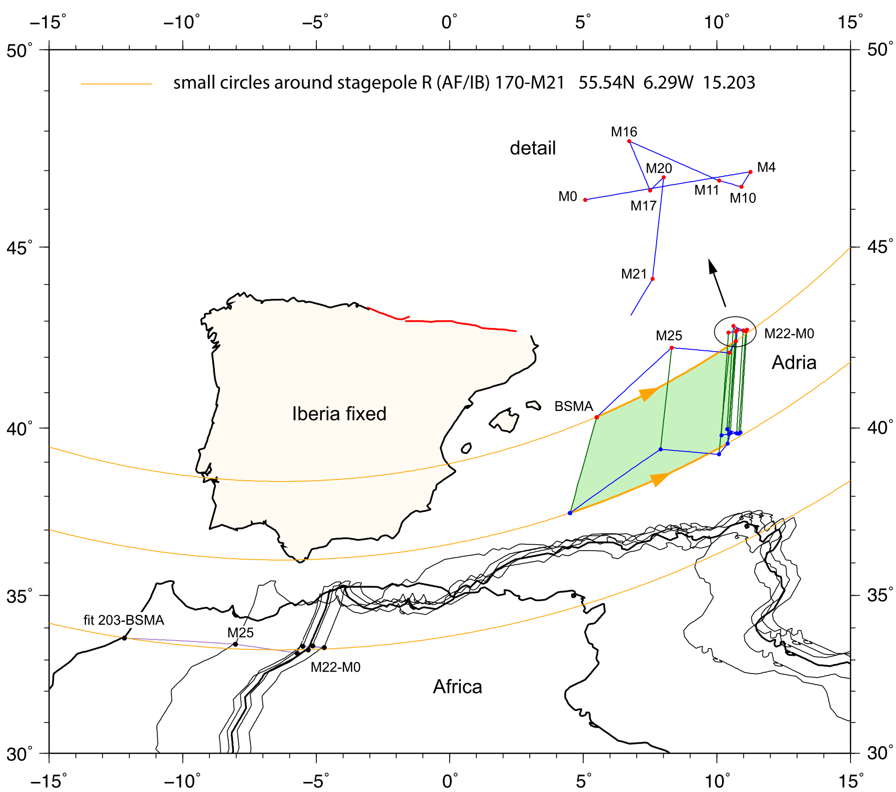

Fig. 5. Modeled opening of the PL ocean between Adria (Africa) and Iberia. Markerpoints move with Adria (Africa), and indicate that the main opening must have occurred in between BSMA and M21 times. The overall trend of the spreading is accentuated by small circles around the R AFR/IB 170 → M21 forward motion stage pole, presumably parallel to the trend of possible transform structures. Detail for the period M21–M0 reveals variably oriented small and ultraslow motions. For further explanation see text.

M22 and M21 by interpolation between the reconstruction poles for 170 Ma and M20, and also obtain an M25 pole that better confirms the overall southeast trend of AGFZ motion, i.e., with a small component of shortening across the AGFZ of a few tens of km only.

4.3. Spreading in the Piemonte–Ligurian domain between Adria and Iberia

The Jurassic–Early Cretaceous motions of Africa/Meseta and Iberia with respect to North America allow to estimate the kinematics of extension and spreading in the PL domain east of Iberia.

Note again that, except for M25 and M0, the total reconstruction poles for Africa/Meseta and Iberia relative to N America have been based on different anomalies. We therefore include interpolated poles in our calculation of the relative motion of Africa with respect to Iberia for each of the whole series of anomalies involved (Tables 2 and 3). We then calculate

$$\mathrm{R}\,(\mathrm{AFR/IB})\;0 \rightarrow \mathrm{t} = \mathrm{R}\,(\mathrm{AFR/NAM})\;0 \rightarrow \mathrm{t} + \mathrm{R}\,(\mathrm{NAM/IB})\;0 \rightarrow \mathrm{t}$$

and use these poles, listed in Table 3, to monitor the extension in the PL domain east of Iberia assuming that Adria moved with Africa, by means of the motion paths of two markerpoints (Fig. 5). The results show that ∼450 km of Iberia–Adria extension opened the western PL domain in an ENE direction (with respect to Iberia in its present position) from BSMA (170 Ma) till M21 (∼148 Ma) times. Subsequent Iberia–Adria motion is negligible as shown by variably directed small motions of less than 30 km, i.e. within typical errors of marine magnetic anomaly analyses, and lasting till

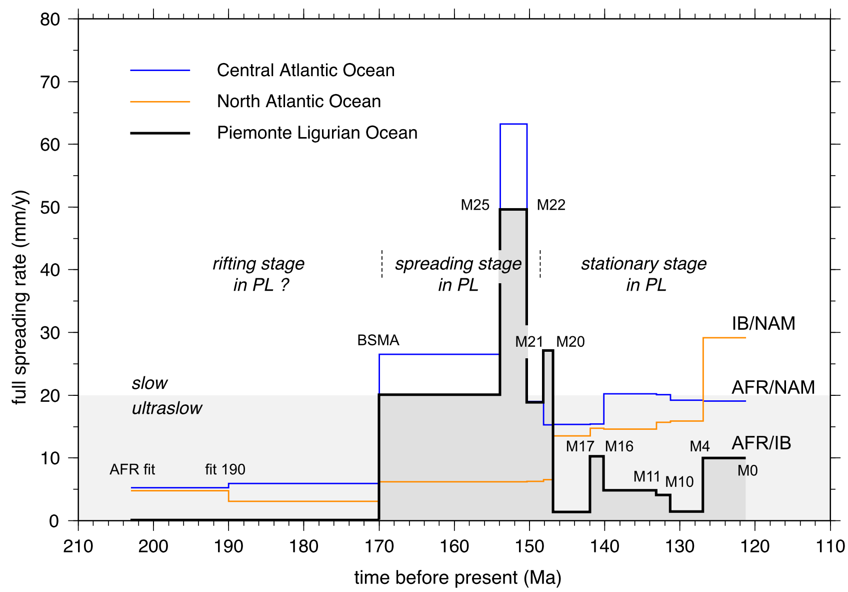

Fig. 6. Diagram showing full spreading rate with time for the central Atlantic, north Atlantic between N America and Iberia, and Piemonte Ligurian (PL) domain. Boundary between slow and ultraslow spreading regimes at 20 mm/yr according to Snow and Edmonds (2007).

M0 times. This suggests that the main spreading in the PL domain ended by M21 or M20.

The associated spreading rates in the central and northern Atlantic and the calculated spreading rates in the PL domain are shown in Fig. 6. Except for the time interval spanned by the BSMA and M22, full spreading rates in the central Atlantic are ultraslow, i.e. below 20 mm/yr (Dick et al., 2003; Snow and Edmonds, 2007). A high value for the M25–M22 interval has also been reported by Labails et al. (2010), but as noted by those authors, the inferred rate is sensitive to the time scale used. The early motions of Iberia with respect to North America are poorly constrained, with typical continental extension rates below 10 mm/yr in the early rifting stages and ultra-slow spreading between 10 and 15 mm/yr between M25 and M4. This latter result confirms previous half-spreading rate estimates by Srivastava et al. (2000) of 6.7 mm/yr for the M20–M4 interval. Inherent to our assumption that Iberia rifted with Africa from north America, we observe no differential motion of Africa/Adria relative to Iberia in the PL domain before BSMA times. The full spreading rate during the subsequent stage of spreading is close to 20 mm/yr till M25, followed by a short peak value close to 48 mm/yr between M25 and M22. Very small full spreading rates below 10 mm/yr prevail since M20.

A rigorous quantification of the uncertainty attached to the inferred rates would require as a start specific error bars on all anomaly picks. Lacking these we can still obtain a rough estimate of the uncertainty. This is based on the insight that, in the end, our velocities derive from the distance between anomalies, divided by their age difference. Typically, anomalies are localized with an uncertainty on the order of 10 km (e.g., Gaina et al., 2002; Doubrovine et al., 2012). With distance between the anomalies on the order of 100 km, difference in age between consecutive anomalies of ∼10 Myr, and errors in the dating of anomalies of order 1 Myr, the uncertainty in the inferred velocity is found to be of order 1 mm/yr, i.e. an order of magnitude smaller than our inferred spreading rates in the PL ocean.

Aside the existing uncertainties surrounding the early stages of motion before BSMA times, we interpret the Adria motion path as the expression of some 450 km of extension, largely between 170 Ma and M21 (∼148 Ma) during which oceanic spreading may have occurred in the western PL domain. Using one single stage pole for the time span from 170 Ma till M21 we arrive at a time-averaged, slow full spreading rate of 22.7 mm/yr. In line with the onset of spreading between Iberia and north America at least since anomaly M20 times, this was followed by a stationary stage of essentially no significant motion in the western PL domain from around M21 until M0 (Fig. 5).

5. Discussion

We now address three aspects of the above analysis. First, we discuss how our analysis may be subject to errors and uncertainties. Secondly, we address the evolution of the PL ocean farther to the east, where Africa–Europe rather than Africa–Iberia motion determined its opening. Finally, we evaluate the predictions of our reconstruction against geological data on the PL ocean.

5.1. Uncertainties in the model

The modeled motion path of Adria relative to Iberia critically depends on the accuracy of the inferred motions of Africa and Iberia with respect to N America. Whilst the motion of Africa with respect to North America is well constrained, there are many uncertainties surrounding the motion of Iberia. Except for the pioneering study by Srivastava and Verhoef (1992) no Euler poles have been published for the early part of the Iberian motion history, while the poles proposed by Srivastava and Verhoef (1992) imply a significant component of geologically undocumented Africa–Iberia shortening during much of the motion history. At this point we note that aside any lack of geological evidence for such shortening there is no evidence for a significant extensional component across the AGFZ either, and our analysis presented above thus hinges on the arbitrary assumption that Iberia moved coherently with Africa. A small component of either shortening or extension across the AGFZ, however, would admittedly affect the direction of extension in the PL domain but the effect on the magnitude of extension would probably be small.

Aside these uncertainties surrounding the Jurassic motion of Iberia, most stages in the motion paths of Africa and Iberia are based on total reconstruction poles assessed for *different* anomalies, such that our analysis required the use of interpolated poles not constrained by magnetic anomalies on either side of the AGFZ. This may also affect the accuracy of the Iberia poles calculated for M20, M17, M11 and M4, whilst reconstruction poles for Iberia for M16 and M10 were subsequently calculated via interpolation as well. As stage poles are strongly sensitive to errors in the reconstruction poles used for their calculation, the above uncertainties in these reconstruction poles may affect the AFR/IB stage poles describing Adria motion. We note as well that the early motions of Africa prior to the BSMA and of Iberia prior to M20 are not constrained by clear magnetic anomalies, which likely induces errors in the calculated motion of Adria (Africa/Meseta) with respect to Iberia.

In any case, a marked motion of Africa relative to North America from BSMA till M21 times contrasts with at best very small motions of Iberia, and this results in a clear ENE-ward motion of Adria relative to Iberia during that time span. The details of this motion path may be subject to uncertainties regarding the early stages, but the overall trend illustrated here via the stage pole motion between 170 Ma and M21, seems clear and not seriously affected by errors in the pertinent reconstruction poles.

It needs also be emphasized that the lack of any motion in the modeled PL domain before BSMA times relates entirely to our assumptions on the early rifting of Iberia. If that rifting would be smaller than implied by a motion together with Africa, a differential motion would result in the PL domain. In view of the lack of any further constraints on this early part of the Iberian motion history, the effects on the PL system can hardly be elucidated, and we refrain from further analysis.

The modeled ENE motion of Adria is followed by a stage of very small motions between M21 and M0 in variable directions and at very small rates. These very small motions are close to those expected for small errors in the reconstruction poles and this may suggest that the spreading between Adria and Iberia essentially came to an end.

In a recent paper by Bronner et al. (2011), a much younger initiation age of seafloor spreading in the Northern Atlantic is proposed. The authors reinterpreted the first magnetic anomaly (J-anomaly) in the Newfoundland–Iberia rift system, considered in previous studies as the beginning of the M series (M0–M3), as the result of a magmatic pulse associated with breakup close to the Aptian–Albian boundary (112 Ma). This alternative interpretation, however, is difficult to reconcile with onland paleomagnetic data from the Iberian Peninsula (Gong et al., 2008) as these latter data indicate that most of the 35° anticlockwise rotation of Iberia occurred during the Aptian. Paleomagnetic data from Iberia are thus consistent with the interpretation of the J anomaly as M0 and inconsistent with the younger break-up advocated by Bronner et al. (2011). As matters stand, we therefore prefer to follow previous kinematic studies (e.g. Srivastava et al., 2000) in which the J anomaly is interpreted to reflect breakup around M0.

5.2. Rifting and oceanization in the Piemonte–Ligurian domain

The above kinematic analysis of opening in the PL basin can clearly not discriminate between rifting of continental crust and full-blown oceanic spreading, such that the model shown in Fig. 7 illustrates the cumulative effect of both rifting and oceanization. Several studies in the Piemonte Ligurian ophiolite zone of SE Switzerland (e.g. Manatschal, 2004; Manatschal et al., 2006; Manatschal and Müntener, 2009) have shown that the ocean–continent transition in the PL basin was quite broad and was characterized by exhumed sub-continental mantle lithosphere. This is not dissimilar to the magma-poor North Atlantic rifted margin, but unlike the Atlantic, it seems that the PL ocean had barely developed into a "real" ocean. Our model calculations show that the PL ocean was a relatively small basin indeed, and that the rate of opening was very slow. Given the common lack of standard oceanic crust in the Piemonte–Ligurian ophiolites it may be questioned if a clear spreading ridge did ever develop, or that most of the oceanic domain was formed via extensional denudation of (serpentinized) mantle rocks.

5.3. Evolution of the eastern Piemonte–Ligurian domain

We now address possible consequences of our analysis of differential Africa–Iberia motion for the evolution of the eastern PL ocean between southern Europe and Africa. To this end, we calculate AFR–EUR total reconstruction poles using the AFR–NAM poles of Table 3 for 170 Ma (BSMA times) and M0, in combination with pertinent NAM–EUR pre-drift Euler poles of respectively Torsvik et al. (2012) and Vissers and Meijer (2012). The resulting reconstructions are shown in Fig. 7.

Eastward, the Alpine Tethys continued along the area of the Alps, where Adria and its northeastern, now intensely deformed promontory 'AlCaPa' became separated from Eurasia. This separation was accommodated by opening of the Valaisan basin and PL Ocean separated by the Briançonnais microcontinental sliver (e.g. Frisch, 1979; Schmid et al., 2004) (Fig. 7). Farther to the east, the Alpine Tethys domain continued into the area presently occupied by the Carpathian–Pannonian region, where the Tisza–Datca blocks and the Moesian platform rifted away from the Bohemian Massif (Ozclon et al., 2007; Schmid et al., 2008) (Fig. 7). Most models propose that motion of the Moesian platform along the East European platform (Fig. 7) occurred along the Tornquist–Tesseyre line – a former passive margins of Baltica (Cocks and Torsvik, 2005) – acting as a transform bounding the Alpine Tethys to the east. Motion of the Moesian platform led to the left-lateral transpressional Dobrogea orogen (Fig. 7) (e.g. Ozclon et al., 2007). After the Early Cretaceous, the Tisza, Datca, AlCaPa and the northern Adriatic regions of the Alps and present-day Carpathian back-arc region have been intensely deformed, rotated and translated over large distances during the closure of the Alpine Tethys (Schmid et al., 2008), and restoration to their positions during the Jurassic opening of the Alpine Tethys is therefore complicated. The Moesian platform, however, has largely escaped major Alpine deformation and may have been in a stable position since the end of the Jurassic–Earliest Cretaceous opening of the Alpine Tethys (van Hinsbergen et al., 2008).

The simplest scenario for the opening of the eastern Alpine Tethys is that it hosted the Africa–Europe plate boundary, accommodating all AFR–EUR and AFR–IB motion since 170 Ma until M0. Our plate circuit shows that the bulk of AFR–EUR extension occurred along a small circle almost parallel to the orientation of the Tornquist–Tesseyre line, albeit with a small net component of convergence consistent with the transpressional character of the Dobrogea orogen. Comparable to the Africa–Iberia case, the bulk of extension between Africa and Europe occurred between 170 and M21 ($\sim$148 Ma), after which the Africa–Eurasia pole became located within or close to the Moesian platform (Fig. 7). In this simplest-case scenario, which corresponds to the maximum amount of extension in the PL that can be explained by Africa–Europe motion, the total amount of 170 Ma–M0 Moesia–Europe extension is 315 km along the Tornquist–Tesseyre line. To the west, in the domain of the present-day western Alps, Africa–Europe extension was at best $\sim$675 km, part of which was accommodated in the Valaisan basin (e.g. Schmid et al., 2004) (Fig. 7). Although the partitioning of the extension between the Valaisan and PL domains is difficult to assess, we infer from these values that the spreading rates across the entire PL domain were slow to ultraslow.

Geological evidence suggests that the Moesia, Datca, Tisza and Alcapa blocks that made up the southern margin of the PL domain were separated by narrow oceanic basins of Jurassic age (e.g. the Severin ocean) (Schmid et al., 2008). Our analysis shows that Africa–Eurasia motions do not allow for any ENE–WSW extension. Because these basins trend parallel to small circles de-

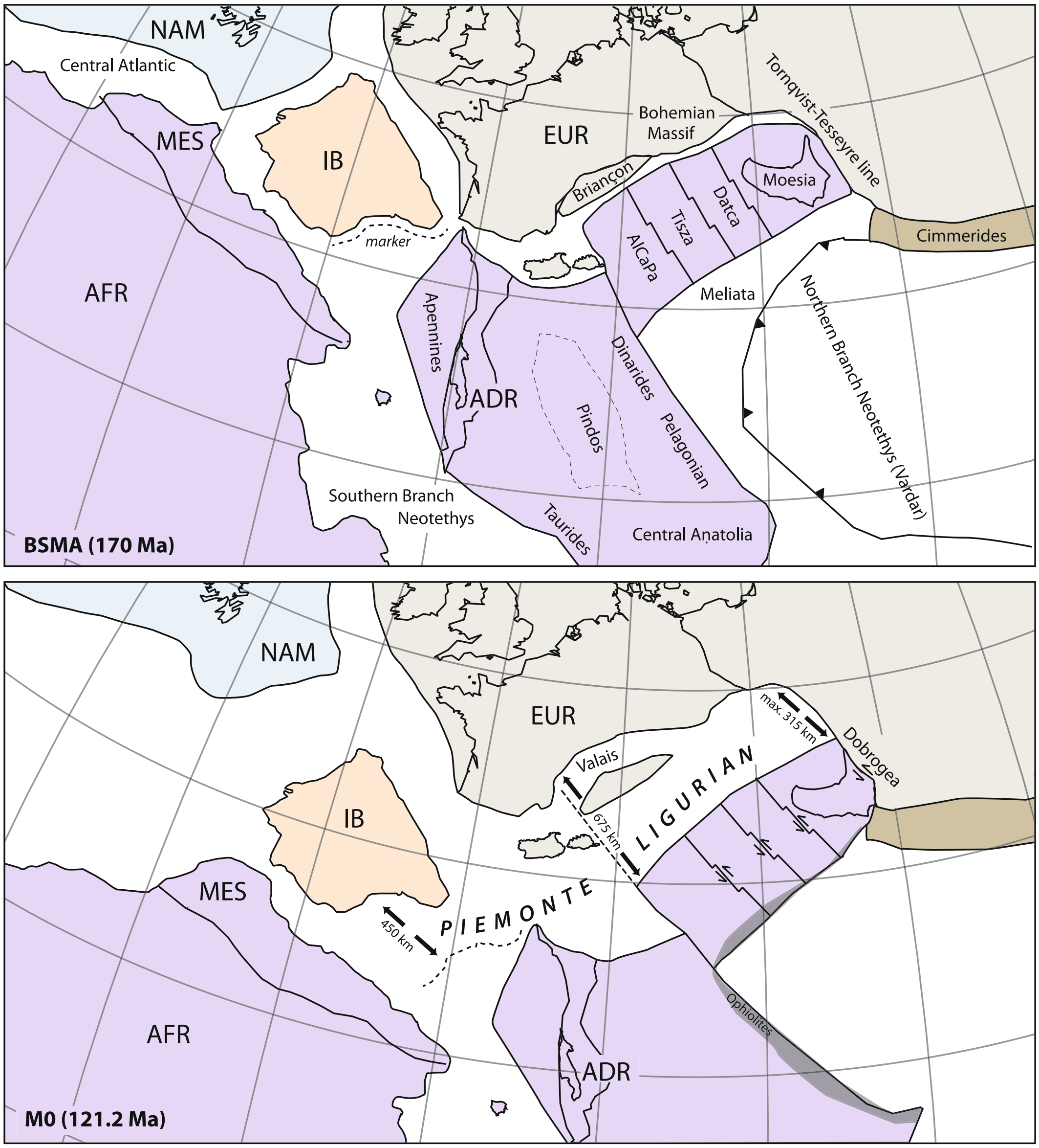

Fig. 7. Simplified paleogeography of the opening of the entire PL ocean shown relative to Europe fixed. It is assumed that Adria and the AlCaPa, Tisza, Datca and Moesia blocks of the northern and northeastern Mediterranean region were fixed relative to Africa in the Jurassic–Early Cretaceous, and that one single plate boundary was located in the PL ocean and along the Tornquist–Tesseyre line. (a) Reconstruction for 170 Ma (BSMA times), with R (AFR/EUR) 50.91° N 0.29° W −55.66 calculated from AFR/NAM (Table 2) and the pre-drift NAM/EUR pole for 170 Ma of Torsvik et al. (2012). (b) Reconstruction for M0 times, R (AFR/EUR) 43.47° N 8.05° W −41.54, using the AFR/NAM pole (Table 2) and NAM/EUR pole for M0 of Vissers and Meijer, 2012. The reconstruction shows a maximum width of the PL ocean; more likely a diffuse plate boundary existed between the northeastern Mediterranean blocks. See text for further discussion.

scribing Africa–Europe motion in the Jurassic, it seems more likely that such oceanic corridors formed as left-lateral pull-apart basins (Fig. 7). In such a scenario, the amount of extension in the PL domain would decrease northeastward and the 300–400 km of extension calculated above for the PL domain between the Moesian Platform and Europe should represent a maximum value.

5.4. Comparison with geochronological and petrological data

The modeled spreading in the PL domain is markedly consistent with modern geochronological data including U-Pb SHRIMP, Ar/Ar and Sm/Nd ages obtained from gabbros, diorites, albitites and plagiogranites from ophiolite exposures in the western Alps, Apennines and Corsica. A compilation of these data by Costa and Gaby (2001) shows that most of the resulting ages span the period from 168 till 148 Ma, whilst few Sm/Nd ages are higher but with large errors. Geochronological data from impregnated plagioclase peridotites (i.e. Sm–Nd cpx-plg isochron ages of 155 ± 6, 163 ± 20 and 165 ± 20 Ma) from Monte Maggiore (Corsica; Rampone and Piccardo, 2003) and Mt. Nero (External Ligurides; Rampone et al., 1995) have been interpreted to reflect a stage of MORB melt – peridotite interaction and MORB impregnation (Piccardo, 2008). These data are corroborated by U/Pb dating in zircons from the Platta and Err nappes in the eastern central Alps (Schaltegger et al., 2002) as well as by biostratigraphy of supraophiolitic radiolarites (Bill et al., 2001).

Whilst the modeled timing of spreading in the PL domain is consistent with the geochronological data, the nature of the ophiolites in the Alps–Apennine system seems to lend support to the slow-ultraslow full spreading rates inferred via our plate kinematic analysis as follows.

Recent marine studies of the South-West Indian and Arctic Ridges have recognized a class of ultra-slow spreading oceans with spreading rates lower than approximately 20 mm/yr characterized by extended rifted continental margins, and ridges marked by intermittent volcanism and by continuous emplacement of serpentinized mantle to the seafloor over large regions (Dick et al., 2003; Snow and Edmonds, 2007). They generally show a discontinuous cover of basaltic extrusions as well as amagmatic sectors, and seem to lack a gabbroic layer 3. Aside widespread exhumation of mantle rocks, the distinctive features of ultra-slow spreading ridges include a relative abundance of basalts, enriched in LREE and other incompatible elements and showing alkaline and/or isotopically enriched signatures related to melting of garnet-eclogite or veined mantle (e.g. Nauret et al., 2004, 2005). The exposed abyssal peridotites have a strong compositional variability (e.g. Hellebrand et al., 2006; von der Handt et al., 2006) varying from depleted harzburgites and dunites to enriched plagioclase peridotites related to melt migration and melt-peridotite interaction. Despite their relatively high abundance (30% of abyssal peridotites), few studies have been devoted to abyssal plagioclase peridotites, partly because intense alteration obliterates the microstructure, which sets limits to microstructurally controlled geochemical analysis. Available samples, however, of plagioclase-enriched peridotites and gabbro-norites from modern slow-ultraslow ridges (Mid-Atlantic, Gakkel and Southwest Indian Ridges) show mineral compositions strongly depleted of incompatible trace elements, very high An content in plagioclase and highly magnesian pyroxenes.

Field, microstructural, petrologic and geochemical evidence from the PL ophiolites indicate that the oceanic basin was characterized by (1) mantle exposure at the sea-floor, (2) both volcanic and a-volcanic domains, and (3) lack of sheeted dyke complexes and a gabbroic Layer 3 (see e.g., Piccardo, 2008, and references therein). These ophiolites, often indicated as lherzolite-type ophiolites (Nicolas, 1995) typically lack evidence for a 5–6 km thick magmatic crust characteristic for the model ophiolite succession (Anonymous, 1972), and include those in which the association of serpentinite, volcanic rocks and deep-sea sediment was first recognized and termed “ophiolite” in 1905 (Steinman, 1905). Recent studies on the ophiolitic peridotites from the PL ocean have shown that they were at least in part exhumed from the sub-continental lithospheric mantle to the sea floor by means of km-scale extensional shear zones (e.g. Drury et al., 1990; Vissers et al., 1991; Piccardo and Vissers, 2007; Mohn et al., 2012), that melts with alkaline affinity were present and that melt-modified peridotites with a strong m-scale compositional heterogeneity are abundant (Piccardo, 2008). This heterogeneity has been related to the effects of (1) widespread porous flow and focused infiltration of MORB-type asthenospheric melts, (2) melt/peridotite interaction, and (3) melt stagnation and storage in the shallow mantle lithosphere, during rifting and inception of the PL basin (e.g. Müntener and Piccardo, 2003; Piccardo et al., 2004, 2007). The majority of these melt-modified peridotites are plagioclase-enriched, with plagioclase contents up to more than 20% by volume. Plagioclase peridotites are characterized, moreover, by reactive orthopyroxene replacement on mantle olivine and by presence of veins, dykelets and decametric pods of gabbro-norites. The early crystallization of magnesian orthopyroxene suggests that the infiltrated melts were silica-saturated (see, e.g., Piccardo and Guarnieri, 2011, and references therein). These characteristics led to recognize: (1) presence and abundance of strongly depleted, silica saturated MORB-type melts during rifting and opening of the basin, (2) their stagnation and storage within the shallow mantle lithosphere, and (3) the impregnation and refertilizaton by basaltic components of the host peridotite.

The above characteristics, notably the exposure of mantle rocks at the sea-floor and the alternation of volcanic and a-volcanic segments, coupled with the petrologic features of the pertinent magmas and peridotites (i.e. the presence of alkaline melts, the extreme compositional heterogeneity of the mantle peridotites and the stagnation and storage of strongly depleted melts) seem entirely consistent with our plate kinematic results in that they support interpretations of the PL ocean as a Jurassic analogue of modern ultra-slow spreading oceans.

6. Summary and conclusions

A plate-kinematic analysis of the relative motion of Africa and Iberia during the Mesozoic based on marine magnetic anomalies and fracture zones of the Central and North Atlantic Ocean allows to estimate the amount, rate and direction of extension in the PL domain. The PL was a Mesozoic oceanic basin between Adria and Iberia/Europe, now represented by ophiolites in the Alps–Apennine system. Based on the critical assumption that Adria moved as a promontory of Africa, we conclude that between 170 Ma and ∼150 Ma ago some 450 km of extension must have taken place between Adria and Iberia.

The PL ocean stretched eastwards towards the area occupied by the Carpathian–Pannonian system, where it was bounded by the Tornquist–Tesseyre line along which the Moesian platform drifted southeastwards relative to Eurasia. We calculate that the maximum extension in the eastern end of the PL ocean was ∼315 km, if the Tornquist–Tesseyre line formed the discrete Africa–Europe plate boundary during the Jurassic. Geological evidence suggests, however, that the plate boundary was diffuse and distributed over several fault zones (e.g. forming the Severin oceanic basin to the west of the Moesian platform), and the calculated amount of eastern PL basin extension was probably less.

The modeling obviously does not reveal to what extent the PL basin extension was due to genuine ocean floor development, but it is clear that it was a slow process at maximum full spreading rates close to 20 mm/yr. The modeled timing of spreading is consistent with modern geochronological data from the PL ophiolites, whilst several characteristics of the ophiolites such as exposure of upper mantle rocks at the sea floor, the alternation of volcanic and a-volcanic segments, and the petrologic features of the pertinent magmas and peridotites lend support to such ultraslow spreading.

Acknowledgements

Figs. 2–6 were made using the Generic Mapping Tools (GMT) software (Wessel and Smith, 1991), Fig. 7 was made with Gplates software (Boyden et al., 2011). DJJvH acknowledges financial support through ERC Starting Grant 306810 (SINK) and an NWO VIDI grant. We thank Gideon Rosenbaum and Laurent Jolivet for thoughtful reviews of the manuscript that helped us to improve the paper.

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