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# Relative motions of Africa, Iberia and Europe during Alpine orogeny

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## Abstract

A revised kinematic model for the motions of Africa and Iberia relative to Europe since the Middle Jurassic is presented in order to provide boundary conditions for Alpine–Mediterranean reconstructions. These motions were calculated using up-to-date kinematic data predominantly based on magnetic isochrons in the Atlantic Ocean and published by various authors during the last 15 years. It is shown that convergence of Africa with respect to Europe commenced during the Cretaceous Normal Superchron (CNS), between chrons M0 and 34 (120–83 Ma). This motion was subjected to fluctuations in convergence rates characterised by two periods of relatively rapid convergence (during Late Cretaceous and Eocene–Oligocene times) that alternated with periods of slower convergence (during the Paleocene and since the Early Miocene). Distinct changes in plate kinematics are recognised in the motion of Iberia with respect to Europe, indicated by: (1) a Late Jurassic–Early Cretaceous left-lateral strike–slip motion; (2) Late Cretaceous convergence; (3) Paleocene quiescence; (4) a short period of right-lateral strike–slip motion; and (5) final Eocene–Oligocene convergence. Based on these results, it is speculated that a collisional episode in the Alpine orogeny at ca. 65 Ma resulted in a dramatic decrease in the relative plate motions and that a slower motion since the Early Miocene promoted extension in the Mediterranean back-arc basins.

*Keywords:* Alpine orogen; Convergence; Iberia; Plate kinematics; Africa

## 1. Introduction

The relative motions of Africa, Iberia and Europe have provided a kinematic framework for numerous tectonic reconstructions of the Alpine–Mediterranean region (e.g. Smith, 1971; Dewey et al., 1973, 1989; Biju-Duval et al., 1977; Dercourt et al., 1986; Savostin et al., 1986; Stampfli et al., 1998; Wortmann et al., 2001). In these reconstructions, the motion of Africa with respect to Europe is usually based on rotation parameters (poles of rotation and rotation angles) as calculated, for example, by Dewey et al. (1973, 1989). In the latter, convergence is considered to commence in the Late Cretaceous and has been accommodated since by subduction processes, continental collision and lithospheric deformation. The accuracy of these data is extremely important in order to set boundary conditions for future reconstructions, and it is the aim of this paper to provide revised kinematic constraints for these motions based on a comprehensive list of up-to-date rotation parameters.

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Table 1
Euler poles of rotation and finite rotation angles as inferred from fitting of magnetic isochrons by the listed authors

| Magnetic anomaly | Age (Ma) | Latitude | Longitude | Rotation | Reference |
|---|---|---|---|---|---|
| *Africa with respect to North America* | | | | | |
| 5 | 9.9 | 80.12 | 50.80 | –2.52 | Müller et al. (1990) |
| 6 | 19.2 | 81.07 | 56.51 | –5.21 | Srivastava et al. (1990a) |
| 13 | 33.1 | 75.37 | 1.12 | –10.04 | Müller et al. (1990) |
| 21 | 46.3 | 75.30 | –3.88 | –15.25 | Müller et al. (1990) |
| 24 | 52.4 | 78.33 | –2.64 | –16.91 | Müller et al. (1990) |
| 25 | 55.9 | 79.68 | –0.46 | –18.16 | Müller et al. (1990) |
| 30 | 65.6 | 82.90 | 4.94 | –20.76 | Müller et al. (1990) |
| 31 | 67.7 | 82.51 | –0.63 | –20.96 | Klitgord and Schouten (1986) |
| 32 | 71.1 | 81.35 | –9.15 | –22.87 | Klitgord and Schouten (1986) |
| 33 (young) | 73.6 | 80.76 | –11.76 | –23.91 | Klitgord and Schouten (1986) |
| 33 (old) | 79.1 | 78.30 | –18.35 | –27.06 | Klitgord and Schouten (1986) |
| 34 | 83.0 | 76.55 | –20.73 | –29.60 | Klitgord and Schouten (1986) |
| M0 | 120.2 | 66.09 | –20.18 | –54.45 | Srivastava et al. (1990a) |
| M4 | 126.0 | 65.97 | –19.43 | –56.63 | Roest et al. (1992) |
| M10 | 130.2 | 65.95 | –18.50 | –57.40 | Klitgord and Schouten (1986) |
| M11 | 131.1 | 66.14 | –18.72 | –58.03 | Roest et al. (1992) |
| M16 | 137.9 | 66.24 | –18.33 | –59.71 | Roest et al. (1992) |
| M21 | 146.7 | 66.24 | –18.33 | –62.14 | Roest et al. (1992) |
| M25 | 154.0 | 66.70 | –15.85 | –64.90 | Roest et al. (1992) |
| | 170.0 | 67.02 | –13.17 | –72.10 | Klitgord and Schouten (1986) |
| | 175.0 | 65.97 | –12.76 | –76.44 | Srivastava et al. (1990a) |
| *Europe with respect to North America* | | | | | |
| 5 | 9.9 | 65.38 | 133.58 | –2.44 | Lawver et al. (1990) |
| 6 | 19.2 | 68.92 | 136.74 | –4.97 | Lawver et al. (1990) |
| 13 | 33.1 | 65.64 | 136.95 | –7.51 | Lawver et al. (1990) |
| 21 | 46.3 | 66.15 | 135.40 | –10.87 | Srivastava and Roest (1996) |
| 24 | 52.4 | 63.89 | 139.27 | –12.89 | Srivastava and Roest (1996) |
| 25 | 55.9 | 63.14 | 141.66 | –14.22 | Srivastava and Roest (1989) |
| 30 | 65.6 | 64.84 | 143.96 | –16.95 | Srivastava and Roest (1989) |
| 33 (old) | 79.1 | 66.17 | 147.74 | –19.00 | Srivastava and Roest (1989) |
| 34 | 83.0 | 66.54 | 148.91 | –19.70 | Srivastava and Roest (1989) |
| Labrador Sea | 92 | 66.67 | 150.26 | –20.37 | Srivastava and Roest (1989) |
| M0 | 120.2 | 69.67 | 154.26 | –23.17 | Srivastava et al. (2000) |
| M18 | 142.5 | 68.99 | 154.75 | –23.05 | Srivastava and Roest (1989) |
| M25 | 154.0 | 69.03 | 155.44 | –23.26 | Torsvik et al. (2001) |
| | 170 | 69.1 | 156.70 | –23.64 | Royer et al. (1992) |
| | 175 | 71.61 | 156.70 | –25.27 | Torsvik et al. (2001) |
| *Iberia with respect to North America* | | | | | |
| 5 | 9.9 | 65.38 | 133.58 | –2.44 | Lawver et al. (1990) |
| 6 | 19.2 | 68.00 | 138.20 | –4.75 | Srivastava et al. (1990a) |
| 13 | 33.1 | 76.34 | 117.33 | –7.98 | Srivastava et al. (1990a) |
| 21 | 46.3 | 74.70 | 126.96 | –11.05 | Srivastava et al. (1990a) |
| 24 | 52.4 | 72.98 | 133.28 | –12.94 | Srivastava et al. (1990a) |
| 25 | 55.9 | 73.29 | 133.88 | –14.25 | Srivastava et al. (1990a) |
| 31 | 67.7 | 74.96 | 135.34 | –17.19 | Srivastava et al. (1990a) |
| 33 (old) | 79.1 | 85.49 | 110.28 | –22.41 | Srivastava et al. (1990a) |
| 34 | 83.0 | 87.18 | 57.43 | –24.67 | Srivastava et al. (1990a) |
| M0 | 120.2 | 64.71 | –18.94 | –58.11 | Srivastava et al. (2000) |
| M25 | 154.0 | 66.90 | –12.93 | –60.45 | Srivastava et al. (1990a) |
| | 175 | 65.72 | –12.82 | –66.32 | Srivastava and Verhoef (1992) |

The opening of the Atlantic Ocean at the expense of the disappearing Tethys Ocean was deduced in early reconstructions based on the least-square fitting of continental platforms across the Atlantic (Carey, 1958; Bullard et al., 1965). These reconstructions, however, only provided constraints for the positions of the plates prior to the opening of the Atlantic Ocean and could not provide a time-dependent incremental path that describes the relative motions of the surrounding plates. The latter was made possible in the pioneering work of Pitman and Talwani (1972), who used fracture zones and magnetic anomalies on both side of the Atlantic spreading ridge to reconstruct the kinematic evolution of the Atlantic Ocean. Their work provided sets of a limited number of poles of rotation (Euler poles) and their finite rotation angles for the motions of Africa and Europe relative to North America.

The occurrence of linear magnetic anomalies is limited to divergent plate boundaries where sea floor spreading and formation of new oceanic crust took place. Therefore, the motions of Africa and Iberia with respect to Europe cannot be directly determined but are calculated instead by using published or derived motions of Africa, Europe and Iberia with respect to North America (Dewey et al., 1973, 1989; Savostin et al., 1986; Mazzoli and Helman, 1994). With the emergence of new data that better constrain the evolution of the Atlantic Ocean, these motions have been revised and modified (Srivastava and Roest, 1989, 1996; Lawver et al., 1990; Srivastava et al., 1990a, 2000; Roest and Srivastava, 1991; Roest et al., 1992; Srivastava and Verhoef, 1992; Torsvik et al., 2001), and it is therefore necessary to incorporate these additional data in a revised kinematic model for the relative motions of Africa, Iberia and Europe.

This paper presents revised rotation parameters for the motions of Africa and Iberia with respect to Europe. In the scope of this work, the complex kinematics of microplates within the Alpine orogeny is not discussed. Rather, we aim to provide a framework for the implied motions around the Mediterranean as obtained from plate kinematics of the North Atlantic. These motions can provide kinematic boundary conditions for more detailed reconstructions of the Alpine–Mediterranean region.

## 2. Methodology

Kinematic analysis has been performed using PLATYPLUS, a software package developed in the School of Geosciences Australian Crustal Research Centre at Monash University (see web site http://www.virtualexplorer.com.au/PlatyPlus). PLATYPLUS provides an interactive platform for plate reconstruction by reading and applying motion files (with either absolute or relative motions) and by interpolating rotation parameters at any required stage.

Kinematic data applied in this study have been derived from published rotation parameters predominantly based on geometrical fits of linear magnetic anomalies and fracture zones (Klitgord and Schouten, 1986; Srivastava and Roest, 1989, 1996; Lawver et al., 1990; Müller et al., 1990; Srivastava et al., 1990a, 2000; Roest et al., 1992; Royer et al., 1992; Srivastava and Verhoef, 1992; Torsvik et al., 2001) (Table 1). These data describe the relative motions of Europe, Iberia and Africa with respect to North America. Unfortunately, only a limited number of magnetic anomalies are recognised in the Atlantic Ocean. No information exists for anomalies younger than anomaly 5 (9.9 Ma) and the oldest recognised magnetic anomaly in the central Atlantic is M25 (154 Ma). A significant problem arises from the existence of a quiet period with no magnetic reversals during the Cretaceous Normal Superchron (CNS), between chron 34 (83 Ma) and chron M0 (120.2 Ma). In Table 1, the only rotation parameters from this period are derived from extrapolation of the motion of Europe with respect to North America at 92 Ma (the assumed age of the opening of Labrador Sea) based on the rate of spreading between anomalies 31 and 34 (67–83 Ma) (Srivastava and Roest, 1989).

The motion of Africa and Iberia relative to Europe was calculated using a plate circuit analysis with a fixed European coordinate system (Dewey et al.,

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Note to Table 1:
Latitudes and longitudes are in degrees with positive values for N and E; rotation angles are in degrees with positive values for clockwise rotations.

Table 2
Ages of magnetic anomalies used in calculations of plate motions in this paper

| Anomaly | Age (Ma) | Reference | Anomaly | Age (Ma) | Reference |
|---|---|---|---|---|---|
| 5 | 9.9 | Huestis and Acton (1997) | 33 (old) | 79.1 | Cande and Kent (1995) |
| 6 | 19.2 | Huestis and Acton (1997) | 34 | 83.0 | Cande and Kent (1995) |
| 13 | 33.1 | Huestis and Acton (1997) | M0 | 120.2 | Gradstein et al. (1994) |
| 21 | 46.3 | Cande and Kent (1995) | M4 | ~ 126.0 | Channell et al. (1995) |
| 24 | 52.4 | Cande and Kent (1995) | M10 | 130.2 | Gradstein et al. (1994) |
| 25 | 55.9 | Cande and Kent (1995) | M11 | 131.1 | Gradstein et al. (1994) |
| 30 | 65.6 | Cande and Kent (1995) | M16 | 137.9 | Gradstein et al. (1994) |
| 31 | 67.7 | Cande and Kent (1995) | M18 | 142.5 | Gradstein et al. (1994) |
| 32 | 71.1 | Cande and Kent (1995) | M21 | 146.7 | Gradstein et al. (1994) |
| 33 (young) | 73.6 | Cande and Kent (1995) | M25 | 154.0 | Gradstein et al. (1994) |

Ages indicate the initiation of magnetic chrons.

1973). For example, the rotation of Africa relative to Europe at time $t$ can be expressed as:

$$_{\mathrm{AF}}\mathrm{ROT}_{\mathrm{EU}}(t) = _{\mathrm{AF}}\mathrm{ROT}_{\mathrm{NA}}(t) + _{\mathrm{NA}}\mathrm{ROT}_{\mathrm{EU}}(t)$$

Where $_{\mathrm{A}}\mathrm{ROT}_{\mathrm{B}}(t)$ is the rotational parameters (latitude, longitude and angle) of plate A relative to B at a given time.

Ages of magnetic anomalies taken here are the youngest ages (initiations) of the geomagnetic chrons after Gradstein et al. (1994), Channell et al. (1995), Cande and Kent (1995) and Huestis and Acton (1997) (Table 2).

## 3. Motion of Africa with respect to Europe

Poles of rotation and rotation angles for the motion of Africa relative to Europe are summarised in Table 3 along with rotation parameters derived from the models of Dewey et al. (1989) (for 170–25 Ma) and Mazzoli and Helman (1994) (for 25–0 Ma). This motion is also shown as trajectories and convergence rates of sets of three points moving with Africa as a function of time (Fig. 1).

The motion of Africa with respect to Europe during the Late Jurassic and Early Cretaceous is characterised by left-lateral strike–slip motion (Fig. 1A). According to our results, this motion changed to relative convergence between chrons M0 and 34, which is a long period with no magnetic reversals (Cretaceous Normal Superchron). Using these data alone, it is therefore not possible to determine when convergence commenced. Dewey et al. (1989) suggested that convergence commenced at 92 Ma based on Late Cretaceous ages obtained in early geochronological studies of high-pressure rocks from the western Alps (Bocquet et al., 1974). However, this assumption is rather weakened by much younger (Cenozoic) ages of high-pressure metamorphism in the Alps reported in recent contributions (e.g. Duchene et al., 1997; Gebauer et al., 1997; Rubatto and Hermann, 2001). Therefore, geological evidence from the western Alps is not considered in this model to support kinematic changes during the CNS.

A prominent feature recognised in Fig. 1B is two periods of rapid convergence: between chrons M0 and 31 (120–67 Ma), and between chrons 24 and 6 (52.4–19.2 Ma). These periods are terminated by rapid decreases in convergence rates, which are particularly evident at 67–65 Ma when convergence basically ceased for a period of 10–15 my. Convergence recommenced during chron 25 ( ~ 55 Ma) and seemed to reach its maximum rate during Eocene–Oligocene times. Subsequently, convergence has significantly decreased and remained relatively slow at least since chron 6 (19 Ma).

## 4. Iberia

The motion of the Iberian microplate during the opening of the Atlantic Ocean has been previously discussed by Srivastava et al. (1990a,b) and Roest and Srivastava (1991). Here we present calculated rotation parameters for the motion of Iberia relative to Europe (Table 4) and trajectories of the motion of two points

Table 3
Euler poles for the motion of Africa relative to Europe as calculated in this study and compared with motions calculated by Dewey et al. (1989) for 175–25 Ma and Mazzoli and Helman (1994) for 25–0 Ma

| Time (Ma) | This study | | | Dewey et al. (1989) and Mazzoli and Helman (1994) | | |
|---|---|---|---|---|---|---|
| | Latitude | Longitude | Rotation | Latitude | Longitude | Rotation |
| 5 | −13.99 | 158.23 | 0.55 | −8.13 | 165.07 | 0.51 |
| 10 | −13.91 | 158.94 | 1.09 | −3.15 | 164.83 | 1.03 |
| 15 | −14.77 | 162.89 | 1.53 | −10.99 | 161.26 | 1.67 |
| 20 | −17.27 | 164.31 | 2.13 | −21.71 | 162.41 | 2.44 |
| 25 | −24.32 | 161.90 | 3.57 | −26.84 | 164.01 | 3.06 |
| 30 | −27.24 | 161.11 | 5.04 | −28.48 | 161.07 | 4.70 |
| 35 | −28.89 | 160.77 | 6.41 | −29.21 | 159.45 | 6.47 |
| 40 | −30.10 | 160.57 | 7.60 | −31.87 | 161.53 | 7.90 |
| 45 | −30.96 | 160.61 | 8.80 | −33.91 | 163.36 | 9.31 |
| 50 | −30.02 | 160.71 | 9.61 | −34.72 | 164.63 | 10.46 |
| 55 | −28.83 | 161.90 | 10.39 | −33.24 | 165.32 | 10.73 |
| 60 | −28.73 | 163.02 | 10.58 | −32.44 | 166.98 | 10.97 |
| 65 | −28.82 | 163.93 | 10.64 | −31.75 | 168.71 | 11.21 |
| 70 | −29.70 | 163.75 | 11.87 | −32.43 | 169.41 | 11.43 |
| 75 | −32.66 | 164.46 | 13.84 | −33.67 | 169.43 | 11.91 |
| 80 | −35.02 | 165.10 | 16.46 | −34.37 | 168.77 | 13.43 |
| 85 | −36.88 | 166.30 | 19.35 | −36.21 | 168.26 | 16.98 |
| 90 | −38.68 | 167.70 | 22.56 | −39.77 | 168.05 | 28.77 |
| 95 | −40.01 | 168.88 | 25.77 | −41.29 | 168.60 | 34.39 |
| 100 | −41.03 | 169.89 | 28.99 | −42.51 | 169.56 | 35.89 |
| 105 | −41.85 | 170.77 | 32.23 | −43.62 | 170.48 | 37.41 |
| 110 | −42.51 | 171.59 | 35.12 | −44.65 | 171.36 | 38.95 |
| 115 | −43.09 | 172.35 | 37.95 | −45.59 | 172.20 | 40.51 |
| 120 | −43.60 | 173.04 | 40.78 | −46.47 | 173.01 | 42.07 |
| 125 | −44.46 | 173.71 | 42.65 | −47.27 | 173.79 | 43.65 |
| 130 | −44.94 | 174.58 | 43.75 | −48.02 | 174.54 | 45.24 |
| 135 | −46.03 | 174.82 | 45.25 | −48.71 | 175.25 | 46.83 |
| 140 | −46.66 | 175.09 | 46.50 | −49.36 | 175.95 | 48.44 |
| 145 | −47.22 | 175.28 | 47.81 | −49.96 | 176.61 | 50.05 |
| 150 | −48.06 | 176.43 | 49.29 | −50.53 | 177.26 | 51.67 |
| 155 | −48.99 | 177.90 | 50.98 | −51.06 | 177.88 | 53.30 |
| 160 | −49.81 | 178.93 | 53.00 | −51.56 | 178.48 | 54.93 |
| 165 | −50.56 | 179.92 | 55.03 | −52.02 | 179.06 | 56.57 |
| 170 | −51.26 | 180.88 | 57.07 | −52.46 | 179.62 | 58.21 |
| 175 | −50.57 | 182.00 | 59.82 | −52.88 | 180.16 | 59.86 |

in Iberia relative to fixed points in Europe (Figure 2). These results are generally in agreement with the kinematic analysis described in Roest and Srivastava (1991).

The reconstruction shows that during Middle Jurassic–Early Cretaceous (170–120 Ma), the plate boundary between Iberia and Europe accommodated more than 200 km of left-lateral strike–slip motion (Fig. 3a–d). This motion commenced during rifting of Iberia from the Grand Banks, prior to the initiation of sea floor spreading in this region (see Srivastava and Verhoef, 1992). A major change in plate kinematics occurred with the onset of sea floor spreading in the Bay of Biscay sometime during the CNS (120–83 Ma), leading to left-lateral strike–slip motion in the Pyrenees and approximately 115 km of convergence in more easterly parts of the 'Greater' Iberian microplate (e.g. Sardinia and Corsica; Fig. 3e). The relative motion of Iberia and Europe changed to wholesale convergence at chron 34 (83 Ma) (Fig. 3e and f), whereas after chron 31 Iberia stopped moving with respect

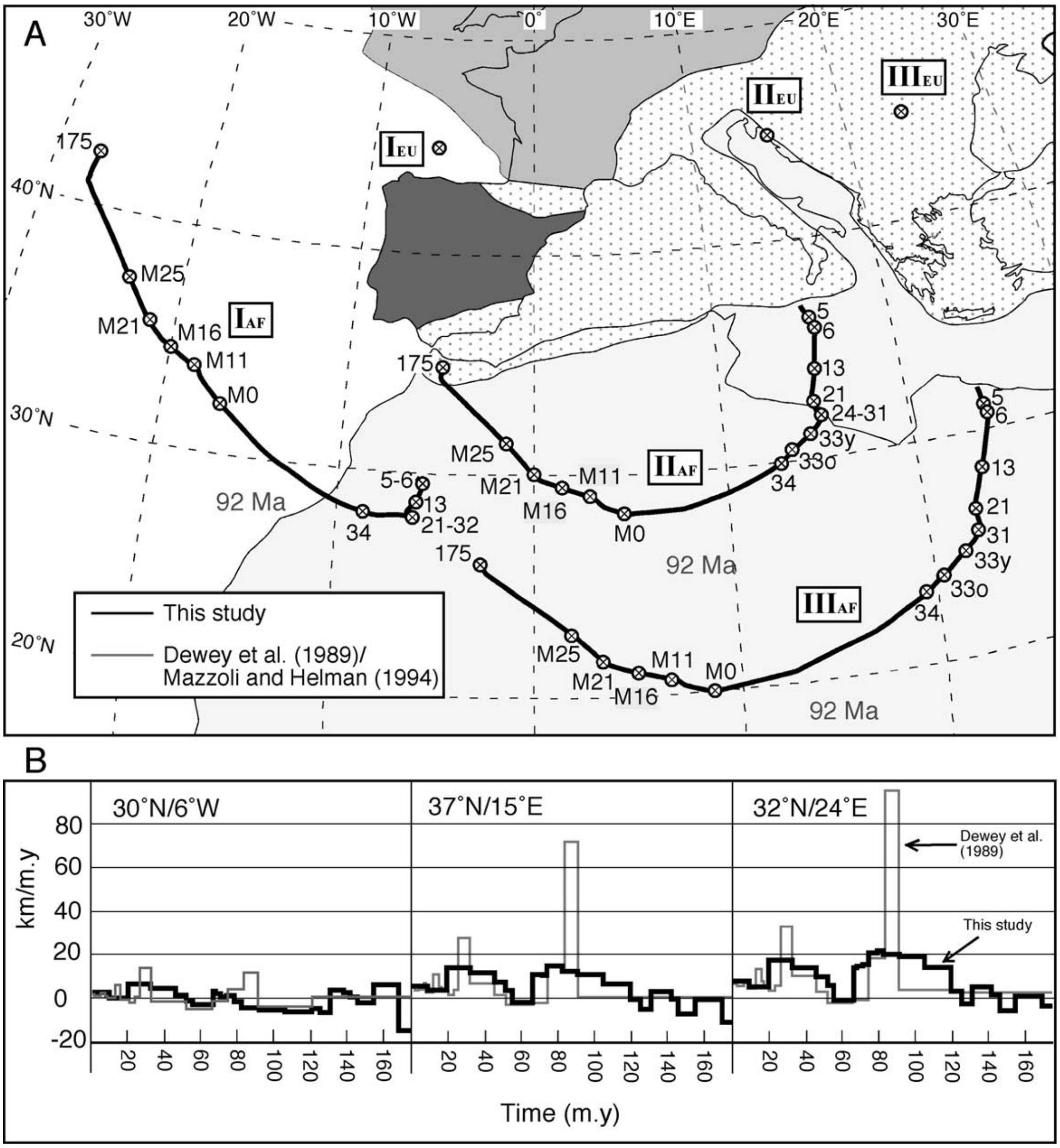

Fig. 1. (A) Trajectories of three points in Africa relative to fixed points in Europe ($I_{AF}$ = 30°N/6°W; $I_{EU}$ = 45°N/6°W; $II_{AF}$ = 37°N/15°E; $II_{EU}$ = 45°N/15°E; $III_{AF}$ = 32°N/24°E; $III_{EU}$ = 45°N/24°E) plotted as a function of time. Stippled area indicates regions of Mesozoic and Cenozoic deformation. (B) Calculated convergence rates of I, II and III. Compared trajectories and convergence rates after Dewey et al. (1989) and Mazzoli and Helman (1994) are also shown (grey lines).

to Europe for a period of 10–15 my (until chron 25; Fig. 2). An independent motion of Iberia resumed during the Eocene, identified by a right-lateral strike–slip motion with a total displacement of 60–70 km during anomalies 24–21 (55–46 Ma; Fig. 3g) followed by final convergence until the Oligocene (Fig. 3h; see also Roest and Srivastava, 1991).

Table 4
Rotation parameters for the motion of Iberia relative to Europe

| Anomaly | Age (Ma) | Latitude | Longitude | Rotation |
|---|---|---|---|---|
| 5 | 9.9 | 0 | 0 | 0 |
| 6 | 19.2 | 77.93 | 59.14 | 0.24 |
| 13 | 33.1 | −31.21 | 166.79 | 1.73 |
| 21 | 46.3 | −23.85 | 157.12 | 1.72 |
| 24 | 52.4 | −21.60 | 157.88 | 2.10 |
| 25 | 55.9 | −20.72 | 162.40 | 2.61 |
| 30 | 65.6 | −12.95 | 165.77 | 3.02 |
| 31 | 67.7 | −16.45 | 167.49 | 3.10 |
| 33 (old) | 79.1 | −37.17 | 169.00 | 8.04 |
| 34 | 83.0 | −38.86 | 169.85 | 10.28 |
|  | 92.0 | −42.64 | 173.20 | 16.56 |
| M0 | 120.2 | −43.86 | 174.17 | 44.77 |
| M18 | 142.5 | −46.19 | 177.47 | 45.91 |
| M25 | 154.0 | −47.12 | 179.45 | 46.29 |
|  | 170.0 | −47.55 | 180.35 | 50.62 |
|  | 175.0 | −46.80 | 181.10 | 50.33 |

The above kinematic evolution of Iberia with respect to Europe is also supported by geological evidence that implies left-lateral strike–slip displacement along the North Pyrenean Fault at least since 110 Ma (Montigny et al., 1986; Costa and Maluski, 1988) and a change to transpressional regime at ca. 85 Ma (Puigdefabregas and Souquet, 1986; de Jong, 1990). Soula et al. (1986) have reported dextral offsets along oblique mylonites from the Pyrenees, which are found in Late Cretaceous rocks and are unconformably overlain by Eocene rocks. This may suggest that right-lateral strike–slip motion occurred in the time span between the Cretaceous and the Eocene as also implied from our reconstruction. Geological evidence for the final stage of convergence in the Pyrenees is found in successive Eocene to Early Oligocene thrust sheets and piggyback basins (e.g. Puigdefabregas and Souquet, 1986). Crustal balanced cross-sections in the Pyrenees show a decreasing amount of shortening from east to west (Seguret and Daignieres, 1986) with at least 147 km of minimum shortening in the central Pyrenees (Muñoz, 1992; Fitzgerald et al., 1999). This is comparable to an approximately 160–170 km of total convergence between Iberia and Europe since chron 34 calculated for points located in the central Pyrenees (around longitude 1°E) (Fig. 2).

## 5. Tectonic implications

Fig. 3 shows a schematic tectonic reconstruction of the western Tethys using the above motions of Africa and Iberia as well as additional information from Stampfli et al. (1998, 2001). In this reconstruction,

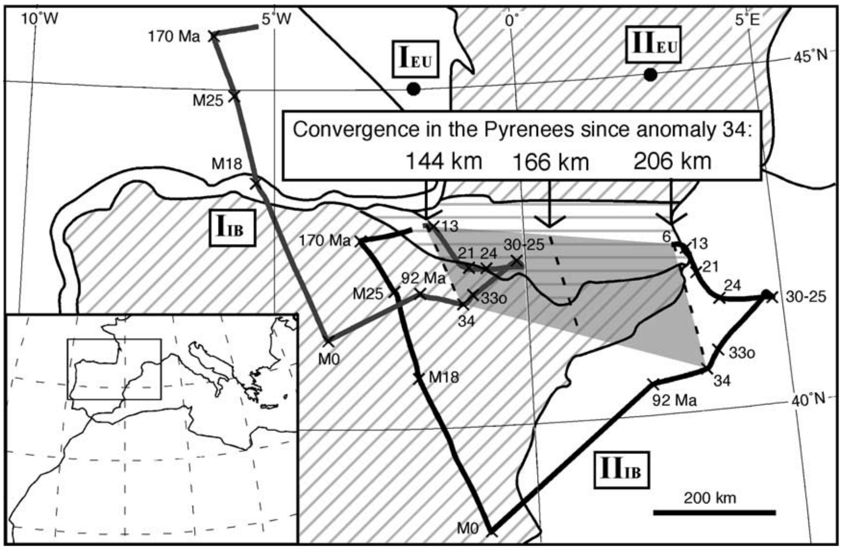

Fig. 2. Trajectories of two points in Iberia relative to fixed points in Europe plotted as a function of time ($I_{IB}$ = 43°N/2°W; $I_{EU}$ = 45°N/2°W; $II_{IB}$ = 42.5°N/3°E; $I_{EU}$ = 45°N/3°E). Shaded area and dashed lines indicates the amount of convergence in the Pyrenees since anomaly 34 (83 Ma).

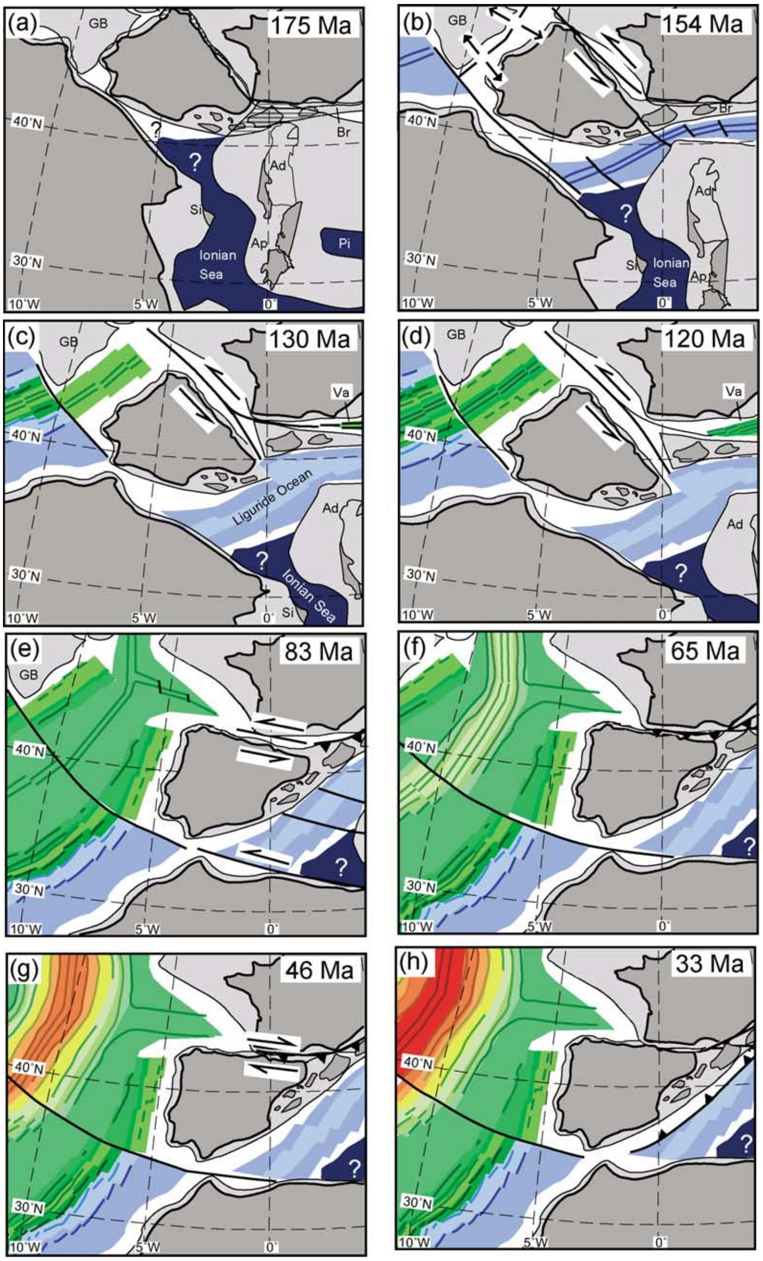

Fig. 3. Reconstruction of the western Tethys since Middle Jurassic using rotation parameters for Africa, Iberia and Europe. Additional information on Alpine Tethys is partly modified after Stampfli et al. (1998, 2001). Isochrons in the Atlantic Ocean are after Cande et al. (1989) (courtesy of R. Sutherland for providing the digital dataset) except of M11 off the Iberian and the Grand Banks coasts, which is after Srivastava et al. (2000). Shaded areas mark overlaps of adjacent plates. Abbreviations are: Ad = Adria; Ap = Apulia; Br = Briançonnais; GB = Grand Banks; Pi = Pindos; Si = Sicily; Va = Valais.

Europe is fixed and the Adriatic plate is attached to Africa as implied from palaeomagnetic studies (e.g. Channell, 1996).

The reconstruction of the western Tethys shows a relatively good fit of the continents since the Middle Jurassic using the revised kinematic constraints. This is particularly important for the Adriatic promontory, which overlapped with southern France and eastern Spain in earlier reconstructions (compare Fig. 2 in Wortmann et al., 2001 with Fig. 3a). A minor overlap exists between northern Adriatic terranes (Southern Alps and Sesia Zone) and eastern 'Great' Iberian terranes (Corsica, Sardinia, and Kabylies). This geometric problem was possibly a direct result of an assumption (which is not necessarily justified) that these terranes had a rigid connection with Iberia and Adria. The overlaps seen in the western margins of Iberia at 175 Ma (Fig. 3a) can be explained by the effect of syn-rift stretching prior to spreading in the northern Atlantic (Srivastava and Verhoef, 1992).

The reconstruction shows that the kinematic constraints considered here are sufficient to explain the opening of the Liguride Ocean during the Late Jurassic (Fig. 3b and c). Nevertheless, using these motions alone it is difficult to resolve the tectonic interactions between different terranes in the Alps (i.e. Briançonnais, Valais, Sesia–Lanzo Zone), which possibly acted as independent microplates during Alpine orogeny.

## 6. Discussion

### *6.1. Commencement of Africa–Europe convergence*

A key issue revisited in this paper, previously discussed by Dewey et al. (1989), considers when convergence between Africa and Europe commenced. The data suggest that this occurred sometime between chrons M0 and 34, when the motion of both Africa and Iberia with respect to Europe changed from overall left-lateral strike–slip to convergence. However, the existence of a quiet magnetic period at this time (the CNS) does not enable precise estimation of the age of the kinematic change. Dewey et al. (1989) suggested a swerve in the plate motion at 92 Ma based on the assumption that a change in the plate kinematics would mark the onset of Alpine deformation in Europe. Fig. 1B shows that this would have resulted in rapid convergence rates (in excess of 90 km/my in the eastern Mediterranean), but only during a relatively short period between 92 and 83 Ma.

The issue in respect to Dewey et al.'s (1989) interpretation concerns the timing of onset of Alpine collision. As indicated, eclogites and blueschists from the western Alps, previously considered to represent a Cenomanian–Turonian (100–90 Ma) metamorphic event, now reveal Cenozoic metamorphic ages using various dating techniques (Duchene et al., 1997; Gebauer et al., 1997; Rubatto and Hermann, 2001). This evidence does not contradict the possibility that rocks in the western Alps were also subjected to high-pressure metamorphism in earlier times. There is simply no agreement as to when these events took place. However, metamorphism may have occurred as early as ~ 120 Ma (Paquette et al., 1989; Monié and Chopin, 1991) suggesting that subduction and collisional processes took place earlier than previously thought. This may imply even earlier commencement of convergence between Africa and Europe.

The attempt to correlate orogenic processes with motions of the far-field plates is further complicated if we consider the limits of our current knowledge as to how orogens work. Recent reconstructions of the Tethyan belt (e.g. Hall, 2002; Stampfli and Borel, 2002) show the incorporation of a large number of continental ribbons (or allochthonous terranes) during orogenesis. Many of these terranes functioned as independent microplates detached from their origin plates during back-arc extension and subsequently drifted and collided with adjacent continents (Nur and Ben-Avraham, 1982). With such interactions, shortening in the collisional belt can be fully compensated by extension in the back-arc region, resulting in accretion of allochthonous terranes without convergence of the far-field plates taking place. If this style of tectonism has occurred, it becomes difficult to use metamorphic ages to infer the behaviour of the large-scale plate interactions. We must therefore conclude that timing of the onset of convergence of Africa with respect to Europe remains poorly constrained.

The motion presented here for the period between chrons M0 and 34 has been derived from linear interpolation (except for a single point at 92 Ma that marks the opening of Labrador Sea; Srivastava and Roest, 1989). However, the validity of this interpolation can be doubted if a pirouette in plate kinematics occurred sometime during the CNS. We check this possibility by plotting the temporal distribution of Africa–Europe Euler poles (Fig. 4), which shows a continuous migration before and after the CNS. If an abrupt change from overall strike–slip to convergence took place during the CNS, we would expect to see these poles clustered in two groups. Nonetheless, the Euler pole gradually migrated northward. We can therefore assume, despite the lack of data, that ongoing northward migration of the Euler pole occurred during the CNS. It is therefore argued that such pirouette from overall strike–slip to convergence is unlikely and more smoothly varying trajectories are presented.

### *6.2. Fluctuation of plate motions*

An interesting aspect of the motions described in this paper is the fluctuation in convergence rates through time. This is best emphasised between chrons 31 and 24 (67–55 Ma), in which convergence of both Africa and Iberia virtually stopped for a period of 10–15 my (Figs. 1B and 2). In the latest Cretaceous (70–65 Ma), fragments of Gondwana were accreted against the European margin, resulting in obduction of ophiolites over the Arabian margin (Dercourt et al., 1986) and high-pressure metamorphism in the Sesia–Lanzo zone of the western Alps (Duchene et al., 1997; Rubatto et al., 1999). It is therefore possible that continental collision in Europe led to a temporary quiescence in plate motions followed by plate reorganisation. Similar behaviour involving a dramatic decrease in plate kinematics has also been reported by Molnar and Tapponnier (1975) for the velocity of the Indian plate following the India–Eurasia collision at ca. 50 Ma.

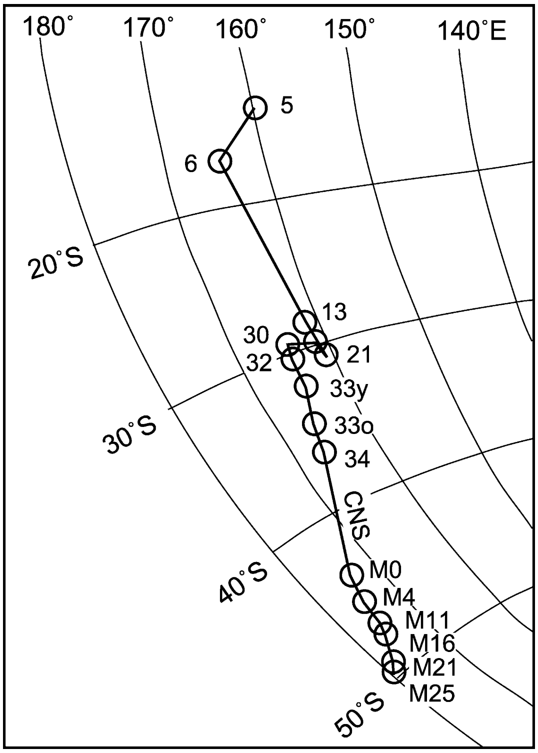

Fig. 4. Projection of Euler poles for the motion of Africa relative to Europe showing a continuous and gradual migration of the Euler pole through time.

A second period of relatively slow convergence rates is recognised since the Early Miocene ( ~ 20 Ma), although the exact chronology of this velocity decrease is not very well resolved. Since the Late Oligocene ( ~ 30 Ma), large areas in the interface between Africa and Europe have been subjected to extensional regime associated with the formation of back-arc basins in the Mediterranean region (e.g. Dewey et al., 1973, 1989; Biju-Duval et al., 1977; Durand et al., 1999; Jolivet and Faccenna, 2000; Rosenbaum et al., 2002). In the western Mediterranean, particularly rapid extension occurred between 21 and 16 Ma (Speranza et al., 2002). Royden (1993) has shown that back-arc extension can initiate by rollback of subduction hinges combined with slower convergence rates that do not exceed the rates of subduction rollback. Therefore, slower convergence rates can theoretically promote back-arc extension (Northrup et al., 1995; Jolivet and Faccenna, 2000). Accordingly, it is possible that subduction rollback and back-arc extension in the Mediterranean region commenced as a result of slower convergence between Africa and Europe.

## 7. Conclusions

This paper presents revised kinematic parameters for the motions of Africa and Iberia with respect to Europe in order to provide boundary conditions for

Alpine–Mediterranean reconstructions. The following conclusions can be drawn from this study:

(1) Convergence of Africa with respect to Europe commenced during the CNS between chrons M0 and 34 (120–83 Ma).
(2) Between chrons 31 and 24 (67–55 Ma), Africa and Iberia almost stopped moving relative to Europe, possibly as a consequence of continental collision in the Alps at ca. 65 Ma.
(3) The motion of Iberia relative to Europe has been characterised by alternation from left-lateral strike–slip motion, overall convergence and right lateral strike–slip motion.
(4) Since the Early Miocene, a relatively slow convergence has been taking place between Africa and Europe giving rise to wholesale extension in the Mediterranean back-arc basins.

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