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# Nubia-Eurasia kinematics: an alternative interpretation from Mediterranean and North Atlantic evidence

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**Abstract**
It is argued that the Plio-Quaternary deformation pattern in the Mediterranean region is compatible with a SSW-NNE convergence between Africa (Nubia) and Eurasia and that the significant difference between this kinematics and the one provided by global models (SSE-NNW convergence *e.g.*, the NUVEL-1) may be due to the fact that those models interpret North Atlantic data by adopting an oversimplified two-plate configuration, which cannot account for the occurrence of significant seismotectonic activity inside the presumed Nubia and Eurasia blocks. It is shown that the adoption of a new plate configuration involving the Iberia and Morocco microplates, strongly suggested by geological and seismotectonic evidence, makes it possible to identify a kinematic model compatible within errors with the constraints recognized in the Mediterranean region and with the NUVEL-1 North Atlantic data set. Some considerations are made about why the present-day Nubia-Eurasia kinematic models inferred from geodetic observations are significantly different from long-term models, such as model NUVEL-1 and the one proposed in this work.

**Key words** *Nubia-Eurasia kinematics – Mediterranean region – Plio-Quaternary deformation*

## 1. Introduction

The huge amount of geological, volcanological and geophysical evidence now available in the Mediterranean region allows a fairly accurate reconstruction of the Neogene time-space distribution of deformation in that area, involving various tectonic processes, such as back-arc basin generation, lithosphere subduction, arc migration and orogenic accretion (*e.g.*, Sengor and Yilmaz, 1981; Dercourt *et al.*, 1986; Finetti, 2005). The features of major observed tectonic events, such as the strain involved, location, timing of initiation development and cessation, impose tight constraints on the driving mechanism. In a number of papers (Mantovani *et al.*, 1997, 2001a, 2002, 2006a,b; Babbucci *et al.*, 2004; Viti *et al.*, 2004, 2006; Mantovani, 2005) we argue that the best agreement between predicted and observed Pliocene-Quaternary deformation is obtained when the Mediterranean region is stressed by a NE to NNE-ward motion of Nubia (the stable part of Africa, *e.g.*, Gordon, 1995) and a roughly westward motion of the Anatolian block with respect to Eurasia.

A significantly different Nubia-Eurasia motion trend (NNW to NW ward) is suggested by global kinematic models which have been inferred from North Atlantic evidence (*e.g.*, Minster and Jordan, 1978; Argus *et al.*, 1989; De Mets *et al.*, 1990, 1994), and by the kinematic models inferred from geodetic data (*e.g.*, Sella *et al.*, 2002; Calais *et al.*, 2003; McClusky *et al.*, 2003; Kreemer *et al.*, 2003; Nocquet and Calais, 2004; Prawirodirdjo and Bock, 2004).

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In this work we present some considerations on the possible causes of such differences and propose a new kinematic model which is compatible with Mediterranean evidence and the NUVEL-1 North Atlantic data set. In Section 2, we describe the most significant tectonic features in the Eastern, Central and Western Mediterranean area, which in our opinion may be used as major constraints on the Nubia-Eurasia relative motion. Section 3 points out major seismotectonic evidence in the western part of the study area that suggests the presence of two independent microplates, Iberia and Morocco. In Section 4, we describe the proposed kinematic model and the constraints that have been used. In Section 5, we make some remarks about the uncertainties that might affect the Nubia-Eurasia Euler poles inferred from the presently available geodetic data.

## 2. Mediterranean constraints on the Plio-Quaternary Nubia-Eurasia kinematics

The most direct information on the relative motion between two plates is provided by the analysis of the deformation pattern observed at their boundary zone, that in the case of Nubia and Eurasia corresponds to the Mediterranean area (fig. 1). A detailed description of the available evidence in that region and a discussion about its possible geodynamic implications are given by Mantovani *et al.* (1997, 2002, 2006a) and Mantovani (2005). In this section, we point out some major aspects of the Pliocene-Quaternary Mediterranean deformation pattern which may lead to define quantitative constraints on the average Nubia-Eurasia relative motion during that period.

### 2.1. *Eastern Mediterranean*

It is widely recognized that during the Pliocene and Quaternary the northern oceanic margin of Nubia, the Ionian-Levantine Neotethys domain, has subducted under the Anatolian-Aegean system, which has extruded W to SW-ward with respect to Eurasia in response to the indentation of the Arabian promontory (*e.g.*, McKenzie, 1978; Dewey and Sengor, 1979; Robertson, 2000; Aksu *et al.*, 2005). The related consuming boundary (fig. 1) is formed by thrust fronts oriented SE-NW, such as the Hellenic and Pytheus-Cyprus trenches, and left-lateral transpressive fault systems trending SW-NE, such as the Pliny-Strabo in the Aegean Arc and the Tartus-Latakia, Larnaka-Amanos and Kyrenia-Misis ones in the Cyprus Arc (*e.g.*, Le Pichon *et al.*, 1981; Kempler and Garfunkel, 1994; Chaumillon and Mascle, 1997; Mascle and Chaumillon, 1997; Papazachos and Papaioannou, 1999; Robertson, 2000; Vidal *et al.*, 2000; Hall *et al.*, 2005a,b; Wdowinski *et al.*, 2006). The orientation of these major tectonic features indicates that Nubia and the Aegean-Anatolian system have converged along a roughly SW-NE to SSW-NNE direction in the Pliocene and Quaternary, as recognized by several authors (*e.g.*, Aksu *et al.*, 2005 and references therein).

To understand what implications this evidence may have on the Nubia-Eurasia convergence trend, one should know the coeval kinematics of the Anatolian-Aegean system with respect to the same reference frame. As regards motion trends, most authors agree that in the Pliocene and Quaternary Anatolia has moved roughly westward and Aegea roughly SW-ward with respect to Eurasia (*e.g.*, Le Pichon and Angelier, 1979; Hempton, 1987; Barka, 1992; Armijo *et al.*, 1999, 2003). Analyses of geological offsets along the North Anatolian Fault (NAF) provide values of right-lateral motion rate ranging between 5 and 10 mm/yr (*e.g.*, Barka, 1992; Dhont *et al.*, 1998; Hubert-Ferrari *et al.*, 2002; Polonia *et al.*, 2004). Comparable values of slip rate (10 mm/yr) are suggested by the recurrence times of major seismic activations of the entire NAF (*e.g.*, Barka, 1992, 1996). Estimates of fault offsets at the Eastern Anatolian fault system (*e.g.*, Cetin *et al.*, 2003) suggest an average slip rate of 11 mm/yr in the last 2.5 Myr.

Much higher velocities are indicated by geodetic observations, which suggest 15-25 mm/yr for Anatolia and 30-40 mm/yr for Aegea (*e.g.*, McClusky *et al.*, 2000). However, one should be aware that geodetic velocities are only representative of present-day plate motions. The fact that

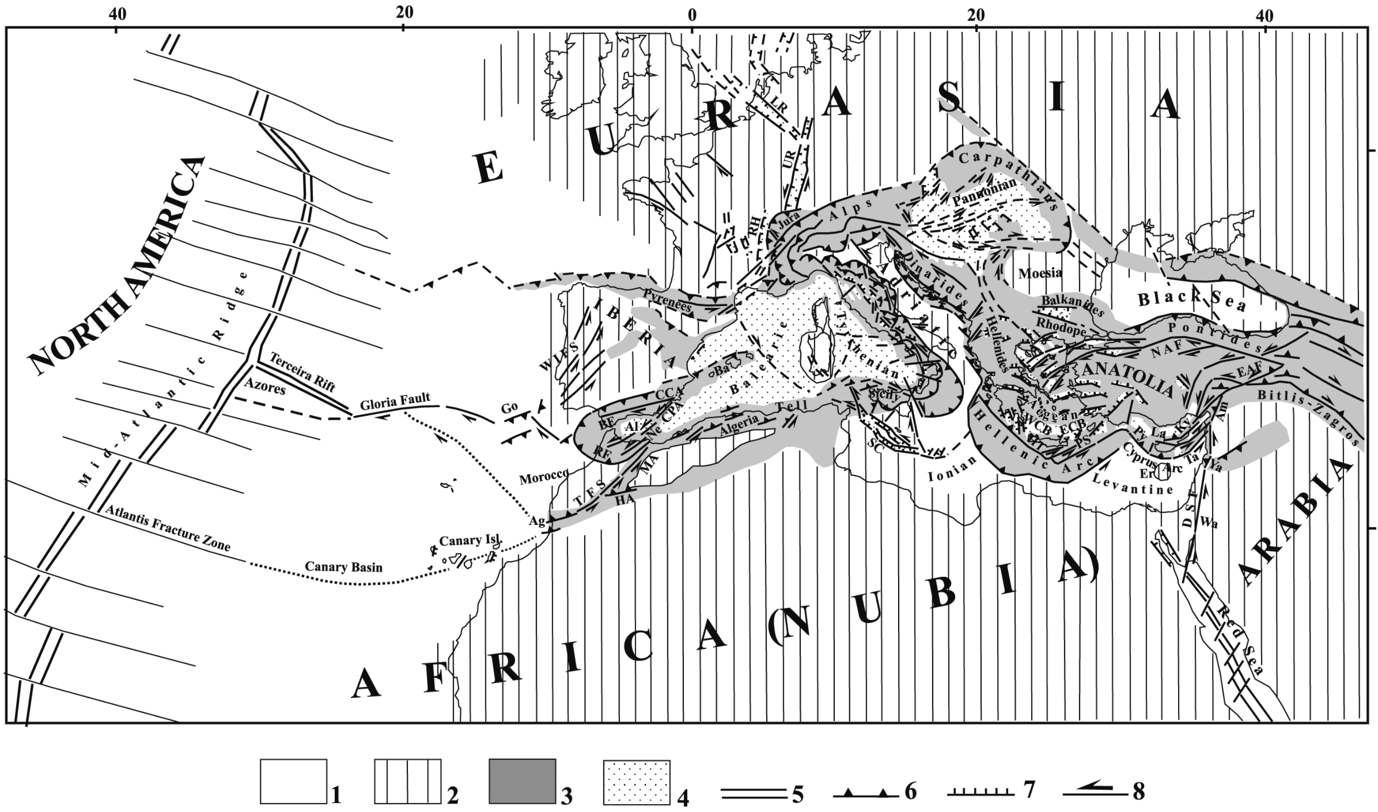

**Fig. 1.** Tectonic sketch of the Mediterranean area and the adjacent Atlantic domain. 1 – Oceanic domains; 2 – Continental domains; 3 – Orogenic belts; 4 – Cenozoic basins; 5 – Oceanic ridges; 6, 7, 8 – Compressional, tensional and strike-slip features. Dotted and dashed lines indicate presumed and inactive tectonic features, respectively. Ag = Agadir; Al = Alboran Basin; Am = Amanos Fault; Ba = Balearic Promontory; BE = Betics; CCA = Cadiz-Crevillente-Alicante fault zone; CPA = Carboneras-Palomares-Alhama de Murcia fault zone; DSF = Dead Sea Fault system; EAF = East Anatolian fault system; ECB = Eastern Cretan basin; Er = Eratosthene Seamount; Go = Gorringe thrust; HA = High Atlas; HT = Hellenic Trench; Ky = Kyrenia-Misis fault zone; La = Larnaka-Amanos fault zone; LR = Lower Rhine graben; MA = Middle Atlas; NAF = North Anatolian Fault; Ne = Nékor fault; Py = Pytheus trench; PS = Pliny-Strabo fault zone; RF = Rif; RH = Rhone graben; SC = Sicily Channel; Ta = Tartus-Latakia fault zone; TFS = Transmoroccan (Transalboran) Fault System; UR =Upper Rhine graben; Wa = Wadi Araba Fault; WCB = Western Cretan Basin; WIFS = Western Iberia Fault System; Ya = Yammuneh fault.

such motions do not coincide with the long-term geological ones should not be a surprise, since it is reasonable to expect significant effects of post-seismic relaxation in the Anatolian-Aegean zones after the last strong seismic activation of the North Anatolian decoupling fault system (*e.g.*, Barka *et al.*, 1992, 1996). In particular, one can presume a progressive migration of maximum velocities from Eastern Anatolia to the Aegean region, with a migration rate controlled by the rheological properties of the structures involved. The quantification of post-seismic relaxation induced by the activation of the NAF since the 1939 Erzincan earthquake (Mantovani *et al.*, 2001b; Cenni *et al.*, 2002) predicts that at present the Aegean zone is moving faster than Anatolia, with respective motion rates that fairly agree with the geodetic velocity field. Another reason to believe that the geodetic velocity field in the Aegean region is significantly different from the one which occurred during the Pliocene-Quaternary time is that such field, almost homogeneous (*e.g.*, McClusky *et al.*, 2000; Nyst and Thatcher, 2004), can hardly account for the occurrence of extension in the Eastern and Western Cretan basins (fig. 1), which are the most stretched areas of the Aegean region (Angelier *et al.*, 1982; Li *et al.*, 2003).

On the basis of the arguments mentioned above, it seems highly probable that in the Pliocene-Quaternary the Aegean zone moved SW ward at a rate comparable to that of Nubia. If so, the orientation of trenches and strike-slip faults at the Hellenic boundary zone can hardly be explained if a coeval Nubia-Eurasia motion trend significantly different from NE to NNE-ward is assumed. This conclusion is also suggested by the Plio-Quaternary evolution of the Cyprus Arc, in particular by the fact that in such arc tectonic activity has slowed down considerably since the Pliocene, after collision of the arc with the Eratosthenes continental fragment (*e.g.*, Robertson, 1998; Vidal *et al.*, 2000; Galindo-Zaldivar *et al.*, 2001). Furthermore, one could note that in the Cyprus Arc there is no discrepancy between long and short-term behaviour since geodetic measurements (*e.g.*, Kahle *et al.*, 2000; McClusky *et al.*, 2000; Wdowinsky *et al.*, 2006) indicate a convergence rate (9-14 mm/yr) comparable to the estimated motion rate of Nubia. Thus, assuming a NE to NNE ward motion of Nubia during the Pliocene-Quaternary period seems to be the only possibility to explain the morphology of the Cyprus Arc.

## 2.2. *Central Mediterranean*

An important constraint on the Nubia-Eurasia kinematics can be inferred from the Adria-Eurasia relative motion, since no significant decoupling zone can be recognized between Nubia and Adria since the late Pliocene/Early Pleistocene (*e.g.*, Babbucci *et al.*, 2004; Mantovani, 2005; Argnani, 2006; Mantovani *et al.*, 2006a). The fact that the motion of Adria with respect to Eurasia suggested in the literature (*e.g.*, Anderson and Jackson, 1987), involving a roughly NNE ward motion of the Southern Adriatic region, is not compatible with the NNW ward motion of Nubia predicted by the NUVEL-1 model led a number of authors to look for a decoupling zone between Nubia and Adria (*e.g.*, Anderson and Jackson, 1987; Westaway, 1990; Console *et al.*, 1993; Favali *et al.*, 1993; Oldow *et al.*, 2002; Battaglia *et al.*, 2004; Serpelloni *et al.*, 2005). However, the considerable dispersion of the decoupling zones so far proposed, concerning location (from the Central Adriatic Sea to Eastern Sicily), trend (from S-N to WSW-ENE) and tectonic nature (from strike slip to extensional), underlines the ambiguity of the respective supporting evidence (Argnani *et al.*, 2001; Babbucci *et al.*, 2004; Argnani and Bonazzi, 2005; Argnani, 2006). Significant seismotectonic activity is recognized in the Gargano zone, belonging to the Apulian structural high, but no evident eastward prosecution of this activity is recognized in the Southern Adriatic region (Argnani, 2006). A similar consideration has been made for the presence of minor deformation, with folds and reverse faults, in the offshore of Central Italy (Argnani and Frugoni, 1997). Strike slip faults possibly associated with seismicity are recognized south of the Salento peninsula, but also in this case a Adria-Nubia decoupling zone can hardly be recognized since in the Southernmost Adriatic domain Plio-Quaternary sediments are almost undeformed (Argnani *et al.*, 2001).

The NNE ward motion trend of southernmost Adria (*e.g.*, Anderson and Jackson, 1987; Babbucci *et al.*, 2004) and the lack of decoupling between Nubia and Adria indicate a motion trend of Nubia in the Central Mediterranean region that is consistent with the NNE ward Nubia-Eurasia convergence suggested by the geometry of the Hellenic and Cyprus boundary zones. This Nubia's kinematics is also quantitatively supported by the results of numerical modelling (Mantovani *et al.*, 2001c, 2006b), which show that the strain field in the central-eastern Mediterranean region, deduced from neotectonic and seismological data, is satisfactorily reproduced when kinematic boundary conditions are constituted by a NNE ward motion of Nubia and a westward motion of Anatolia.

### 2.3. *Western Mediterranean*

A significant constraint on the Nubia-Eurasia relative motion can be inferred from the seismotectonics of the Transmoroccan (or Transalboran) fault system. Some authors (*e.g.*, Jacobshagen, 1992 and references therein; Andeweg and Cloetingh, 2001) recognize that this fault system develops from the Betic region in Southern Spain to Agadir in Southern Morocco, crossing the Alboran Sea and the Middle and High Atlas belts (fig. 1). In spite of the fact that this tectonic feature is composed of many single faults, it is widely recognized as a continuous sinistral strike-slip decoupling zone between Nubia and the Morocco microplate (*e.g.*, Jacobshagen, 1992; Andeweg and Cloetingh, 2001).

Detailed investigations on the left-lateral fault pattern along the Transmoroccan belt (fig. 1) reveal the presence of NNE-SSW to NE-SW faults crossing the Betic-Alboran-Rif domain (*e.g.*, Hatzfeld *et al.*, 1993; Medina, 1995; Ait-Brahim *et al.*, 2002, 2004; Faulkner *et al.*, 2003; Gracia *et al.*, 2006), NE-SW faults in the Middle Atlas, locally associated with extensional and compressional features (*e.g.*, Brede, 1992; Bernini *et al.*, 2000, Gomez *et al.*, 1996, 1998) and ENE-WSW trending transpressional features between the High Atlas and Agadir (*e.g.*, Brede *et al.*, 1992; Mustaphi *et al.*, 1997; Sebrier *et al.*, 2006). Present activity along this

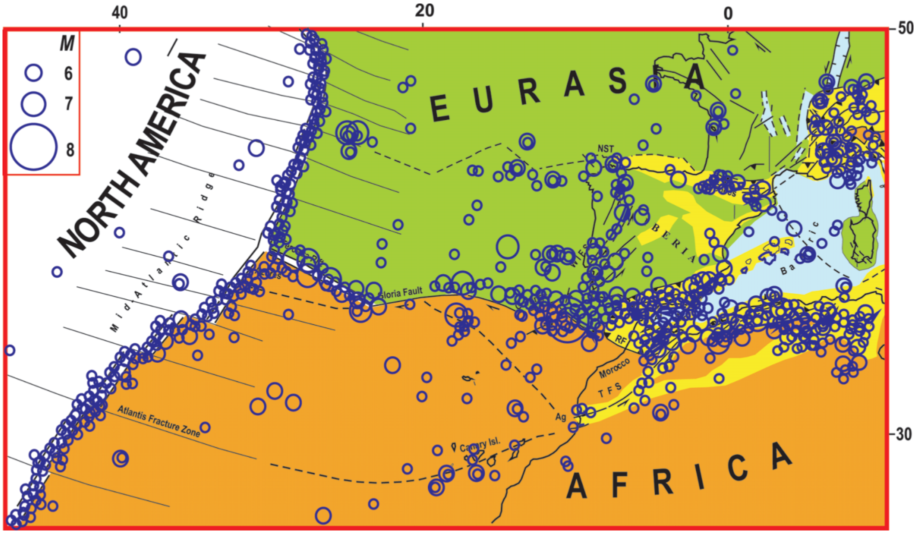

**Fig. 2.** Seismicity distribution in the Western Mediterranean-Atlantic region ($M$>4.5, 1964-2006) from the database of the Incorporated Researcher Institutions for Seismology (IRIS), available at <http://www.iris.washington.edu>. NST=North Spanish Trench; TFS=Transmoroccan Fault System.

major fracture is testified by crustal and subcrustal seismicity (*e.g.*, Medina and Cherkaoui, 1991; Deffontaines *et al.*, 1992; Lopez-Casado *et al.*, 2001; El Alami *et al.*, 2004), as shown in fig. 2. The existence of a deep decoupling zone between Nubia and Morocco is also suggested by the presence throughout the Atlas belt of abundant Pliocene-Quaternary alkaline basaltic volcanism (*e.g.*, Harmand and Moukadiri, 1986; El Azzab and Wartiti, 1998; Piqué *et al.*, 1998; El Azzouzi *et al.*, 1999).

Some authors (*e.g.*, Anguita and Hernan, 1975, 2000; Brede *et al.*, 1992; Mezcua *et al.*, 1992), on the basis of geological, seismological and volcanological evidence, suggest that the Transmoroccan fault system further propagates West to SW ward through the Canary islands, up to longitude 25°W in the Canary basin close to the Hierro and Atlantis mid-Atlantic fracture zones reported by Banda *et al.* (1992) and Ranero *et al.* (1997).

The occurrence of a major active deep fracture, like the Transmoroccan one, raises an important problem for global kinematic models, since it is not compatible with the two-plate configuration adopted by those models. Attempts at reconciling the left-lateral shear observed at that fault system with the NW ward Nubia-Eurasia convergence trend predicted by the NUVEL-1 model (*e.g.*, Piqué *et al.*, 1998; Bernini *et al.*, 2000; Andeweg and Cloetingh, 2001) suggest that this feature is due to the west to SW ward extrusion of the Morocco microplate with respect to Eurasia. However, this explanation presents obscure aspects, mainly related to the fact that the active boundaries of the invoked Morocco block are not defined. For instance, the proposed kinematics of this microplate would require shortening somewhere in the adjacent Atlantic zone, which is not recognized. In addition, the presumed westward motion of the Morocco block with respect to Eurasia is not compatible with the NW to NNW ward relative motion between the Moroccan offshore zone and Eurasia, indicated by the structural and seismotectonic features of the Gorringe thrust zone (fig. 1). The above hypothesis about the kinematics of the Morocco microplate could be influenced by another contemporaneous tectonic process which is taking place in that zone, *i.e.* the westward escape of the Betic-Rif orogenic wedge with respect to the surrounding regions (fig. 1). However, this small orogenic wedge, characterized by well recognized active boundaries and only involving shallow structures (*e.g.*, Rebai *et al.*, 1992; Buforn *et al.*, 1995; Meghraoui *et al.*, 1996; Maldonado *et al.*, 1999), should not be confused with the much larger Morocco microplate. On the other hand, a relative motion between the Betic-Rif wedge and the Morocco microplate is well documented by the compressional deformation recognized at the border between these two blocks (*e.g.*, Moratti *et al.*, 2003; Bargach *et al.*, 2004; Medialdea *et al.*, 2004).

The Mediterranean evidence described in this section and the arguments reported by Mantovani *et al.* (1997, 2002, 2006a) and Mantovani (2005) suggest that in the last few million years Nubia and Eurasia have undergone a SSW-NNE convergence. A similar kinematics is suggested by other authors (*e.g.*, Dercourt *et al.*, 1986; Cetin *et al.*, 2003; Hall *et al.*, 2005a; Aksu *et al.*, 2005 and references therein).

## 3. Iberia and Morocco microplates

In our opinion, the fact that the analysis of North Atlantic data led to a Nubia-Eurasia convergence trend (NNW ward, see *e.g.*, De Mets *et al.*, 1990) significantly different from the one suggested by the Mediterranean evidence (NNE ward) is due to the oversimplified two-plates configuration adopted by the NUVEL-1 approach. This hypothesis is suggested by the occurrence of seismotectonic activity in some zones lying inside the Africa and Eurasia blocks adopted by DeMets *et al.* (1990), such as the Pyrenees, Western Iberia, Morocco and the adjacent Atlantic region (fig. 2). In particular, we argue that seismotectonic evidence in the Western Mediterranean suggests the presence of at least two major intervening microplates, Morocco and Iberia (fig. 3).

The Morocco (MOR) microplate is delimited by the Azores-Gibraltar tectonic belt, the Canary-Transmoroccan fault system, and by the sector of the Mid Atlantic Ridge running from Azores to the Atlantis fracture zone (fig. 3). The decoupling of this microplate from Nubia is accommodated by overall sinistral strike-slip motion at the Ca-

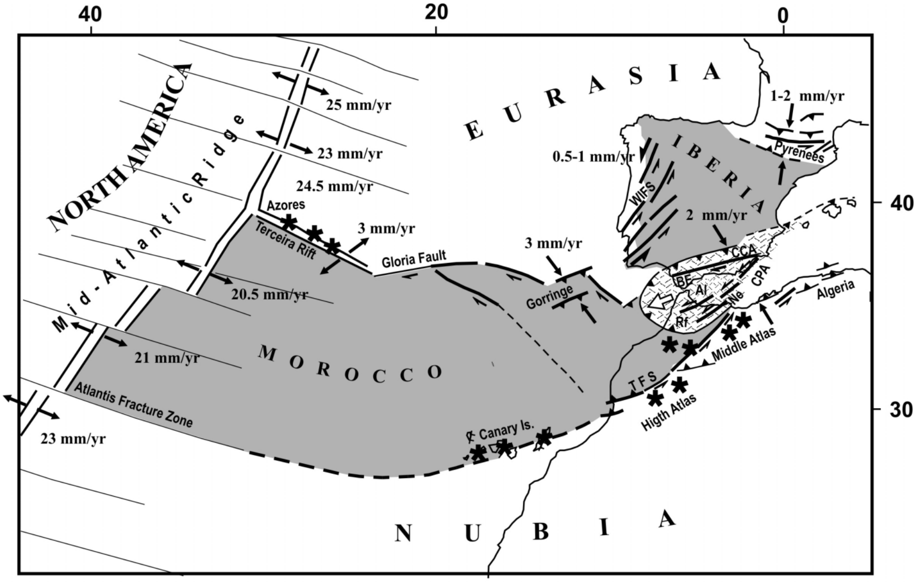

**Fig. 3.** Geometry of the Iberia and Morocco microplates (shaded areas) and the respective boundaries zones with respect to Nubia and Eurasia. Thick and dashed lines indicate seismically active and presumed plate boundaries, respectively. The stippled zone identifies the Betic-Rif orogenic wedge (extruding westward, as indicated by the empty arrow). Black stars indicate Pliocene-Quaternary alkaline-basaltic volcanism (see text for references). The strain regimes recognized at the various plate boundaries (see table IIa-i) are indicated by converging, diverging and anti-parallel arrows, respectively. Symbols and abbreviations as in fig. 1.

nary-Transalboran fault system, locally transtensional or transpressional as discussed in Section 2. The tentative westward prosecution of this fault system to the Mid Atlantic transform zones, such the Atlantis one, is suggested by the spatial distribution of seismicity (*e.g.*, Wysession *et al.*, 1995 and fig. 2). The decoupling between MOR and Eurasia is accommodated by tectonic activity at the Azores-Gibraltar tectonic belt, NE-SW lengthening at the Terceira ridge, dextral strike-slip at the Gloria fault and roughly NNW-SSE thrusting at the Gorringe zone (*e.g.*, Buforn *et al.*, 1988, 2004; Kiratzi and Papazachos, 1995; Morel and Meghraoui, 1996; Hayward *et al.*, 1999). Roughly E-W lengthening occurs along the sector of the Mid Atlantic Ridge, which forms the boundary between MOR and North America (*e.g.*, DeMets *et al.*, 1990 and references therein). Seismic activity (Lynnes and Ruff, 1985; Buforn *et al.*, 1988) suggests that some dextral strike-slip deformation occurs within MOR, along a NNW-SSE belt running from the Gloria Fault to Agadir (figs. 2 and 3).

The relative motion between the Iberia (IBE) microplate and Eurasia is accommodated by roughly N-S shortening, accompanied by minor sinistral strike-slip, at the Pyrenean belt (*e.g.*, Grellet *et al.*, 1993; Goula *et al.*, 1999; Pauchet *et al.*, 1999; Mauffret *et al.*, 2001; Alasset and Meghraoui, 2005), and by sinistral shear at the NNE-SSW trending fault system (WIFS in fig. 3) recognized in the Portugal region (*e.g.*, Cabral, 1989; Ribeiro *et al.*, 1996; Jabaloy *et al.*, 2002; Vilanova and Fonseca, 2004; Martinez-Diaz *et al.*, 2006). Both the above borders are affected by significant seismic activity (Souriau and Pauchet, 1998; Souriau *et al.*, 2001; Borges *et al.*, 2001).

The oblique convergence between IBE and Nubia is accommodated by overall NNW-SSE to NW-SE shortening in a relatively large and complex deforming zone (fig. 3), including the Betic-

Rif orogenic belt, the Alboran zone, the Balearic promontory and the Maghrebian belt in Northern Algeria (*e.g.*, Meghraoui *et al.*, 1986, 1996; Rebai *et al.*, 1992; Buforn *et al.*, 1995, 2004; Morel and Meghraoui, 1996; Stich *et al.*, 2003, 2006; Yelles-Chaouche *et al.*, 2006). The westward extrusion of the Betic-Rif wedge is one of the effects of the IBE-Nubia convergence. The relative motion between IBE and that wedge is accommodated by ENE-WSW dextral transpressional faults in Southern Spain, such as the Cadiz-Crevillente-Alicante, one (*e.g.*, Buforn *et al.*, 1995; Alfaro *et al.*, 2002; Gracia *et al.*, 2006). The decoupling of the Betic-Rif wedge from Nubia is allowed by NNE-SSW to NE-SW sinistral strike-slip and trans-tensional faults in the Alboran Sea and southeastern Spain, such as the Alhama de Murcia-Palomares-Carboneras system, almost aligned with the Transmoroccan fault system (Andeweg and Cloetingh, 2001; Faulkner *et al.*, 2003; Stich *et al.*, 2003, 2006; Gracia *et al.*, 2006). The above sinistral shear zone could continue in the Eastern Rif, where seismically active features such the Nekor Fault (*e.g.*, Hatzfeld *et al.*, 1993; Medina, 1995; Ait Brahim *et al.*, 2004) are recognized. The roughly E-W extension, recognised from southeastern Spain to eastern Rif through the Alboran Sea (*e.g.*, Buforn *et al.*, 1995, 2004; Medina, 1995; Ait Brahim *et al.*, 2002; Martinez-Martinez *et al.*, 2006; Reicherter and Peters, 2005; Gracia *et al.*, 2006) most probably occurs in the wake of the extruding Betic-Rif wedge. The compressional fronts recognized in the Atlantic offshore of Gibraltar, at the western border of the Betic-Rif wedge (*e.g.*, Maldonado *et al.*, 1999; Moratti *et al.*, 2003; Bargach *et al.*, 2004; Medialdea *et al.*, 2004; Gutscher *et al.*, 2006; Thiebot and Gutscher, 2006) mark the zone where this wedge overthrusts the Morocco microplate.

## 4. Proposed kinematic model

To define the new kinematic model for the Mediterranean Nubia-Eurasia boundary zone we assume a plate configuration (fig. 4) that involves three major blocks, Nubia, Arabia and Eurasia, and two microplates, MOR and IBE, as discussed in the previous section. The Anatolian-Aegean and the Rif-Betic systems are considered as extruding orogenic wedges rather than rigid blocks, in line with the interpretation of other authors (*e.g.*, Maldonado *et al.*, 1999; Piper and Perissoratis, 2003; Piper *et al.*, 2006). As discussed earlier, the Adriatic promontory is assumed as connected with Nubia.

Eurasia is taken as a rigid and unique plate in spite of the occurrence of seismotectonic activity in France and the Rhine-Rhone graben system (*e.g.*, Sebrier *et al.*, 1997). We assume that this intraplate deformation is mainly due to the indentation of the Adriatic promontory, as suggested by some authors (*e.g.*, Dezes *et al.*, 2004 and references therein). In particular, the push of Adria in the Eastern Alps (fig. 4) is compatible with the sinistral transtension and NE-SW extension observed at the Upper and Lower Rhine Graben systems respectively (*e.g.*, Plenefisch and Bonjer, 1997; Hinzen, 2003) and with the active NW-SE compression in the eastern Swiss Alps and the Jura belt (*e.g.*, Nivière and Winter, 2000; Persaud and Pfiffner, 2004). This driving mechanism, combined with the push of Iberia, could be also responsible for the compressional regime which affects several zones of France, evidenced by a considerable uplift rate (1-2 mm/yr) of the Massif Central, and the seismotectonic activity of several transcurrent and reverse faults from Brittany to Aquitaine (*e.g.*, Grellet *et al.*, 1993; Dezes *et al.*, 2004; Mazabraud *et al.*, 2005).

The occurrence of significant intraplate deformation in Central Europe and the fact that the relatively complex distribution of strain styles in this zone is consistent with the effects expected from the indentation of the Adriatic promontory could provide further support to the hypothesis that Adria moves in connection with Nubia. If the Northern Adriatic domain were decoupled from the Southern Adriatic/Nubia system and were moving very slowly, as suggested by some authors (*e.g.*, Westaway, 1990; Oldow *et al.*, 2002), it would be quite problematic explaining the occurrence of seismotectonic activity in such a broad region, lying just in front of the Adriatic promontory.

At the Hellenic and Cyprus arcs, Nubia interacts with the Anatolian-Aegean system. Along the Dinarides, Adria interacts with the Carpatho-Pannonian region, which is still char-

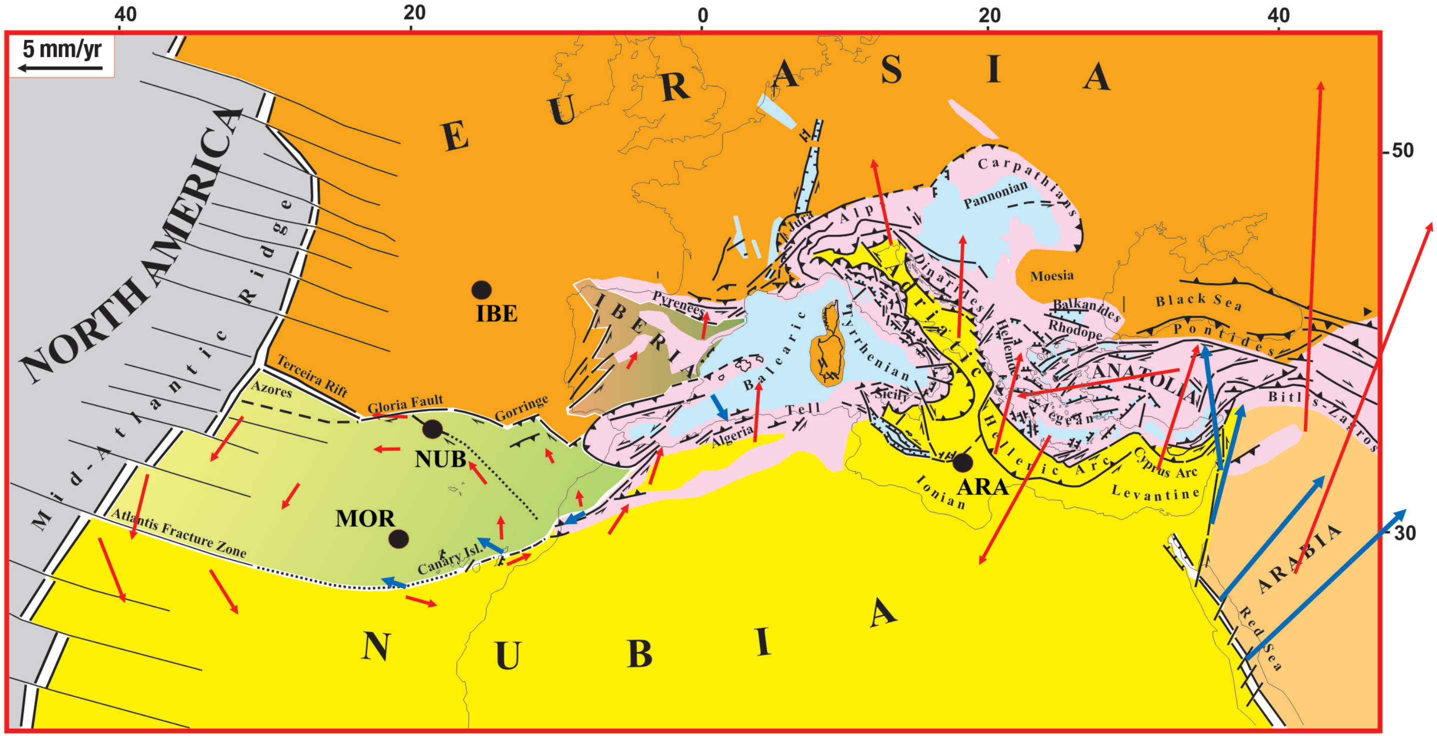

**Fig. 4.** Proposed plate configuration and kinematics in the Mediterranean region. The abbreviations ARA, IBE, MOR and NUB close to black dots indicate the location of the Euler poles of the Arabia, Iberia, Morocco and Nubia plates with respect to an Eurasian reference frame (see table I). Red arrows show the motions of plates with respect to Eurasia predicted by the respective Eulerian poles. Blue arrows along plate borders show relative plate motions with respect to Nubia. The velocity field shown in the Anatolian-Aegean system is compatible with geological evidence (see text). Other symbols as in fig. 1.

acterized by considerable deformation. Further east, Nubia interacts with the Arabia plate along the mid-ocean-like Red Sea Ridge and the Dead Sea Transform Fault Zone.

Taking into account the plate configuration mentioned above (fig. 4), we looked for the set of Euler poles (table I) which satisfactorily account for the observed features at the various plate borders (table IIa-i), by inverting the available kinematic indicators in a weighted least-square approach (De Mets *et al.*, 1990). The constraints considered in this search are represented by spreading rates (Mid Atlantic Ridge and Red Sea), transform fault azimuths (Mid Atlantic Ridge and Gloria Fault) and relative plate velocity vectors (all other boundaries). Velocity vectors have been obtained from seismic moment tensor summation, structural analysis of neotectonic faults and numerical modelling of recent/present deformation patterns observed at plate borders (table IIa-i). Given the relatively large uncertainty which may affect the results of these last estimates (*e.g.*, Argus *et al.*, 1989; Marret and Allmendinger, 1990; Viti *et al.*, 2001), we have assigned a relatively large error level (10°-20° and 1.5-4 mm/yr, respectively) to azimuth and rate of velocity vectors.

Kinematic indicators along the Mid Atlantic Ridge, which form the boundary between North America and the Eurasia, Morocco and Nubia blocks are taken from the NUVEL-1 database (DeMets *et al.*, 1990). From the same source also come the kinematic constraints assumed at the Gloria Fault, which in our plate configuration is a sector of the MOR-Eurasia boundary. The western and eastern part of that boundary, *i.e.* the Terceira rift and the Gorringe thrust zone are instead constrained by seismotectonic velocity vectors (table IIe). The relative motion at the MOR-Nubia boundary is constrained by 6 velocity vectors, two located offshore (Canary Basin and Canary Islands) and four along the long NE-SW Transmoroccan tectonic belt (Agadir, Tizi n'Test Fault, High Atlas and Middle Atlas). Since these vectors are inferred from the geometrical pattern of faults, folds and joints, only the azimuth of the relative plate motion is defined (table IIg). The relative motion at the IBE-Eurasia boundary is tentatively constrained by two velocity vectors derived from neotectonic faulting, one located in the Western Iberian fault system and the other in the Pyrenean orogenic belt (fig. 3). Along the Nubia-IBE boundary, we use one velocity vector, representative of the shortening axis recognized in the wide collision zone from Southern Spain to the Algerian Maghrebian belt.

As discussed in Section 2, we think that a significant constraint on the Nubia-Eurasia relative motion can be deduced from the motion of Adria, that we take as a promontory of Nubia. The constraints we adopt in this zone are represented by two velocity vectors, located in the northern and southern parts of Adria (fig. 4 and table IIf), which are taken from the velocity field derived by numerical experiments (Mantovani *et al.*, 2001c).

**Table I.** Relative Euler poles (latitude, longitude and angular velocity) of the plates shown in fig. 4, obtained by inverting the kinematic indicators reported in table IIa-i. ARA = Arabia; EUR = Eurasia; IBE = Iberia; MOR= = Morocco; NAM = North America; NUB = Nubia. See text for explanations.

| | EUR | | | NAM | | | NUB | | | MOR | | | ARA | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Lat (°) | Long (°) | ω (°/Ma) | Lat (°) | Long (°) | ω (°/Ma) | Lat (°) | Long (°) | ω (°/Ma) | Lat (°) | Long (°) | ω (°/Ma) | Lat (°) | Long (°) | ω (°/Ma) |
| NAM | 62.4 | 135.8 | −0.200 | | | | | | | | | | | | |
| NUB | 36.2 | −18.0 | 0.100 | 80.2 | 75.4 | 0.240 | | | | | | | | | |
| MOR | 28.5 | −21.0 | 0.123 | 79.6 | 36.9 | 0.240 | −0.8 | −29.7 | 0.028 | | | | | | |
| ARA | 34.4 | 18.0 | 0.500 | 50.5 | 30.5 | 0.595 | 32.5 | 25.8 | 0.416 | 33.7 | 29.7 | 0.403 | | | |
| IBE | 43.5 | −14.2 | 0.074 | 76.8 | 105.6 | 0.234 | −16.5 | 154.5 | 0.029 | −8.0 | 152.4 | 0.056 | −32.2 | −157.5 | 0.435 |

**Table IIa-i.** Mediterranean and North Atlantic constraints (ridge spreading rates, transform fault azimuths and plate velocity vectors) considered in the search of the kinematic solution reported in table I. For each plate boundary (see figs. 3 and 4), the relevant kinematic constraints, along with the related standard deviation σ and the respective values predicted by the related Euler pole (table I), are reported. The differences between predicted and observed values are given in brackets. See text for explanations.

ⓐ **North America – Eurasia**

Spreading rates – Mid-Atlantic Ridge

| Latitude (°) | Longitude (°) | Observed ± σ (mm/a) | Predicted (mm/a) | Source |
|---|---|---|---|---|
| 86.50 | 43.00 | 12 ± 3 | 10.4 (–1.6) | DeMets *et al.* (1990) |
| 84.90 | 7.50 | 13 ± 3 | 11.5 (–1.5) | = |
| 84.10 | 00.00 | 13 ± 2 | 11.8 (–1.2) | = |
| 83.40 | –4.50 | 15 ± 3 | 12.1 (–2.9) | = |
| 73.70 | 8.50 | 17 ± 4 | 14.1 (–2.9) | = |
| 72.50 | 3.00 | 15 ± 4 | 14.7 (–0.3) | = |
| 71.80 | –2.50 | 14 ± 3 | 15.1 (+1.1) | = |
| 69.60 | –16.00 | 17 ± 2 | 16.1 (–0.9) | = |
| 69.30 | –16.00 | 17.5 ± 2 | 16.2 (–1.3) | = |
| 68.50 | –18.00 | 18 ± 2 | 16.5 (–1.5) | = |
| 67.90 | –18.50 | 18 ± 2 | 16.6 (–1.4) | = |
| 61.60 | –27.00 | 19 ± 2 | 18.3 (–0.7) | = |
| 60.20 | –29.10 | 19 ± 2 | 18.6 (–0.4) | = |
| 44.50 | –28.20 | 25 ± 4 | 21.2 (–3.8) | = |
| 43.80 | –28.50 | 24 ± 3 | 21.3 (–2.7) | = |
| 43.30 | –29.00 | 23± 3 | 21.3 (–1.7) | = |
| 42.90 | –29.30 | 25.5 ± 2 | 21.4 (–4.1) | = |
| 42.70 | –29.30 | 23 ± 2 | 21.4 (–1.6) | = |
| 42.30 | –29.30 | 23.5 ± 2 | 21.4 (2.1) | = |
| 41.70 | –29.20 | 24.5 ± 3 | 21.5 (–3.0) | = |

Transform azimuths – Mid-Atlantic Ridge

| Latitude (°) | Longitude (°) | Observed ± σ (°) | Predicted (°) | Source |
|---|---|---|---|---|
| 80.00 | 1.00 | 125.5 ± 5 | 124.7 (–0.8) | DeMets *et al.* (1990) |
| 78.80 | 5.00 | 127 ± 10 | 126.8 (–0.2) | = |
| 71.30 | –9.00 | 114 ± 3 | 112.6 (–1.4) | = |
| 52.60 | –33.20 | 95.9 ± 3 | 95.6 (–0.3) | = |
| 52.10 | –30.90 | 95.5 ± 2 | 96.8 (1.3) | = |

ⓑ **North America – Nubia**

Spreading rates – Mid-Atlantic Ridge

| Latitude (°) | Longitude (°) | Observed ± σ (mm/a) | Predicted (mm/a) | Source |
|---|---|---|---|---|
| 29.60 | –43.00 | 23 ± 3 | 24.3 (+1.3) | DeMets *et al.* (1990) |

**Table IIa-i** (*continued*).

Spreading rates – Mid-Atlantic Ridge

| Latitude (°) | Longitude (°) | Observed ± σ (mm/a) | Predicted (mm/a) | Source |
|---|---|---|---|---|
| 27.50 | –44.20 | 24 ± 3 | 24.7 (+0.7) | DeMets *et al.* (1990) |
| 26.90 | –44.50 | 26 ± 4 | 24.8 (–1.2) | = |
| 26.20 | –44.80 | 22 ± 3 | 24.9 (+2.9) | = |
| 25.70 | –45.00 | 24 ± 4 | 25.0 (+1.0) | = |
| 25.30 | –45.40 | 22.5 ± 2 | 25.1 (+2.6) | = |
| 25.10 | –45.40 | 24.5 ± 2 | 25.1 (+0.6) | = |
| 24.50 | –46.10 | 23 ± 4 | 25.2 (+2.2) | = |
| 24.20 | –46.30 | 24.5 ± 2 | 25.2 (+0.7) | = |
| 23.00 | –45.00 | 25 ± 4 | 25.4 (+0.4) | = |
| 22.80 | –45.00 | 25 ± 2 | 25.4 (+0.4) | = |

Transform azimuths – Mid-Atlantic Ridge

| Latitude (°) | Longitude (°) | Observed ± σ (°) | Predicted (°) | Source |
|---|---|---|---|---|
| 23.70 | –45.70 | 98.0 ± 2 | 98.9 (+0.9) | DeMets *et al.* (1990) |

ⓒ **North America – Morocco**

Spreading rates – Mid-Atlantic Ridge

| Latitude (°) | Longitude (°) | Observed ± σ (mm/a) | Predicted (mm/a) | Source |
|---|---|---|---|---|
| 36.80 | –33.20 | 20.5 ± 2 | 20.5 (+0.0) | DeMets *et al.* (1990) |
| 36.50 | –33.70 | 22 ± 3 | 20.6 (–1.7) | = |
| 36.00 | –34.10 | 20 ± 3 | 20.8 (+0.8) | = |
| 35.00 | –36.50 | 21 ± 4 | 21.2 (+0.2) | = |
| 34.30 | –37.00 | 21 ± 3 | 21.4 (+0.4) | = |
| 31.90 | –40.50 | 23 ± 4 | 22.2 (–0.8) | = |
| 30.90 | –41.70 | 23 ± 4 | 22.5 (–0.5) | = |
| 30.50 | –41.90 | 22 ± 3 | 22.6 (+0.6) | = |

Transform azimuths – Mid-Atlantic Ridge

| Latitude (°) | Longitude (°) | Observed ± σ (°) | Predicted (°) | Source |
|---|---|---|---|---|
| 35.20 | –35.60 | 104.5 ± 2 | 102.5 (–2.0) | DeMets *et al.* (1990) |
| 33.70 | –38.70 | 104.5 ± 2 | 102.4 (–2.1) | = |
| 30.00 | –42.40 | 101.5 ± 3 | 101.9 (+0.4) | = |

ⓓ **Arabia – Nubia**

Spreading rates – Red Sea

| Latitude (°) | Longitude (°) | Observed ± σ (mm/a) | Predicted (mm/a) | Source |
|---|---|---|---|---|
| 25.77 | 35.73 | 9.7 ± 1.6 | 8.8 (–0.9) | Chu and Gordon (1998) |

**Table IIa-i** (*continued*).

| Latitude (°) | Longitude (°) | Observed ± $\sigma$ (mm/a) | Predicted (mm/a) | Source |
|---|---|---|---|---|
| 25.36 | 36.02 | 10.0 ± 1.6 | 9.2 (−0.8) | Chu and Gordon (1998) |
| 22.22 | 37.86 | 13.6 ± 0.8 | 11.8 (−1.8) | = |
| 22.19 | 37.89 | 10.8 ±0.8 | 11.9 (+1.1) | = |
| 22.16 | 37.91 | 11.8 ±0.8 | 11.9 (+0.1) | = |
| 22.13 | 37.97 | 12.7 ±0.8 | 12.0 (−0.7) | = |
| 21.92 | 37.86 | 12.4 ±0.8 | 12.0 (−0.4) | = |
| 20.96 | 38.19 | 11.0 ±0.8 | 12.7 (+1.7) | = |
| 20.94 | 38.23 | 11.6 ± 0.8 | 12.8 (+1.2) | = |
| 20.87 | 38.10 | 12.6 ± 0.8 | 12.7 (+0.1) | = |
| 20.21 | 38.29 | 12.2 ± 0.8 | 13.2 (+1.0) | = |
| 20.02 | 38.42 | 13.8 ± 0.8 | 13.4 (−0.4) | = |
| 20.00 | 38.53 | 12.6 ± 0.8 | 13.5 (+0.9) | = |
| 19.97 | 38.56 | 12.0 ± 0.8 | 13.5 (+1.5) | = |
| 19.94 | 38.61 | 13.2 ± 0.8 | 13.5 (+0.3) | = |
| 19.77 | 38.68 | 13.6 ± 0.8 | 13.7 (+0.1) | = |
| 19.61 | 38.77 | 13.8 ± 0.8 | 13.8 (+0.0) | = |
| 19.58 | 38.81 | 13.0 ± 0.8 | 13.8 (+0.8) | = |
| 19.55 | 38.86 | 14.7 ± 0.8 | 13.9 (−0.8) | = |
| 19.52 | 38.89 | 15.0 ± 0.8 | 13.9 (−1.1) | = |
| 19.39 | 38.95 | 14.0 ± 0.8 | 14.0 (+0.0) | = |
| 19.36 | 38.99 | 14.6 ± 0.8 | 14.0 (−0.6) | = |
| 19.31 | 39.00 | 14.8 ± 0.8 | 14.1 (−0.7) | = |
| 19.28 | 39.05 | 15.0 ± 0.8 | 14.1 (−0.9) | = |
| 19.19 | 39.16 | 14.8 ± 0.8 | 14.2 (−0.6) | = |
| 19.16 | 39.08 | 15.2 ± 0.8 | 14.2 (−1.0) | = |
| 19.06 | 39.30 | 15.2 ± 0.8 | 14.4 (−0.8) | = |
| 19.02 | 39.33 | 15.3 ± 0.8 | 14.4 (−0.9) | = |
| 18.99 | 39.37 | 15.6 ± 0.8 | 14.5 (−1.1) | = |
| 18.95 | 39.40 | 14.6 ± 0.8 | 14.9 (+0.3) | = |
| 18.92 | 39.43 | 15.4 ± 0.8 | 14.5 (−0.9) | = |
| 18.85 | 39.48 | 15.2 ± 0.8 | 14.6 (−0.6) | = |
| 18.82 | 39.53 | 15.4 ± 0.8 | 14.6 (−0.8) | = |
| 18.80 | 39.62 | 15.0 ± 0.8 | 14.7 (−0.3) | = |
| 18.78 | 39.55 | 15.0 ± 0.8 | 14.7 (−0.3) | = |
| 18.74 | 39.59 | 15.2 ± 0.8 | 14.7 (−0.5) | = |
| 18.71 | 39.62 | 14.8 ± 0.8 | 14.7 (−0.1) | = |
| 18.63 | 39.69 | 15.4 ± 0.8 | 14.8 (−0.6) | = |
| 18.55 | 39.75 | 15.2 ± 0.8 | 14.9 (−0.3) | = |
| 18.48 | 39.78 | 15.5 ± 0.8 | 14.9 (−0.6) | = |
| 18.42 | 39.83 | 15.5 ± 0.8 | 15.0 (−0.5) | = |

**Table IIa-i** (*continued*)**.**

| Latitude (°) | Longitude (°) | Observed ± $\sigma$ (mm/a) | Predicted (mm/a) | Source |
|---|---|---|---|---|
| 18.35 | 39.88 | 16.1 ± 0.8 | 15.1 (–1.0) | Chu and Gordon (1998) |
| 18.31 | 39.79 | 15.2 ± 0.8 | 15.1 (–0.1) | = |
| 18.04 | 40.04 | 14.8 ± 0.8 | 15.3 (+0.5) | = |
| 17.96 | 40.06 | 15.9 ± 0.8 | 15.4 (–0.5) | = |

Velocity vectors – Dead Sea fault zone

| Zone | Latitude (°) | Longitude (°) | Observed ± $\sigma$ Azimuth (°) | Rate (mm/a) | Predicted Azimuth (°) | Rate (mm/a) | Source |
|---|---|---|---|---|---|---|---|
| Wadi Araba Fault | 30.8 | 35.4 | 15 ± 10 | 5 ± 2 | 14.3 (–0.7) | 6.7 (+1.7) | Klinger *et al.* (2000a,b) |
| Yamunneh Fault | 34.0 | 36.0 | 355 ± 10 | 7.5 ± 1.5 | 353.0 (–2.0) | 7.0 (–0.5) | Gomez *et al.* (2003, 2006); Rukieh *et al.* (2005) |

ⓔ **Morocco – Eurasia**

Transform azimuths – Gloria Fault

| Latitude (°) | Longitude (°) | Observed ± $\sigma$ (°) | Predicted (°) | Source |
|---|---|---|---|---|
| 36.90 | –23.50 | 257 ± 5 | 255.3 (–1.7) | DeMets *et al.* (1990) |
| 37.00 | –22.60 | 265 ± 3 | 260.6 (–4.4) | = |
| 37.10 | –21.70 | 265 ± 3 | 265.9 (+0.9) | = |
| 37.10 | –20.50 | 270 ± 7 | 272.9 (+2.9) | = |

Velocity vectors

| Zone | Latitude (°) | Longitude (°) | Observed ± $\sigma$ Azimuth (°) | Rate (mm/a) | Predicted Azimuth (°) | Rate (mm/a) | Source |
|---|---|---|---|---|---|---|---|
| Terceira Rift | 38.80 | –27.20 | 45 ± 20 | 3 ± 1 | 61.6 (+16.6) | 2.7 (–0.3) | Buforn *et al.* (1988); Kiratzi and Papazachos (1995) |
| Gorringe Thrust | 36.00 | –10.50 | 340 ± 20 | 3 ± 2 | 322.7 (17.3)* | 1.0 (–2.0)* | Buforn *et al.* (2004) |

ⓕ **Nubia – Eurasia**

Velocity vectors

| Zone | Latitude (°) | Longitude (°) | Inferred from numerical modelling ± $\sigma$ Azimuth (°) | Rate (mm/a) | Predicted Azimuth (°) | Rate (mm/a) | Source |
|---|---|---|---|---|---|---|---|
| South-eastern Alps | 45.80 | 14.80 | 358 ± 20 | 3 ± 2 | 350.3 (–7.7) | 4.9 (+1.9) | Mantovani *et al.* (2001c) |
| Southern Adriatic | 40.50 | 17.60 | 7 ± 20 | 5 ± 3 | 2.8 (–4.2) | 5.2 (+0.2) | = |
| Sirte Basin | 34.64 | 20.40 | 24 ± 20 | 8 ± 4 | 14.2 (–9.8) | 5.7 (–2.3) | = |
| Levantine Basin | 33.77 | 31.60 | 27 ± 20 | 11 ± 4 | 18.0 (–9.0) | 7.2 (–3.8) | = |

**Table IIa-i** (*continued*).

ⓖ **Nubia – Morocco**

Velocity vectors – Canary-Transmoroccan Fault Zone

| Zone | Latitude (°) | Longitude (°) | Observed ± $\sigma$ | | Predicted | | Source |
|---|---|---|---|---|---|---|---|
| | | | Azimuth (°) | Rate (mm/a) | Azimuth (°) | Rate (mm/a) | |
| Canary Basin | 27.0 | −21.0 | 106 ± 20 | – | 108.2 (+2.2) | 1.50 | Wysession *et al.* (1995) |
| Canary Islands | 29.0 | −14.0 | 120 ± 20 | – | 119.5 (−0.5) | 1.70 | Feraud *et al.* (1985);<br>Day *et al.* (1999);<br>Marinoni (2001) |
| Agadir | 30.5 | −9.7 | 70 ± 10 | – | 68.1 (−0.9)* | 1.4* | Sebrier *et al.* (2006) |
| TizinTest Fault | 31.0 | −8.0 | 60 ± 10 | – | 61.7 (+1.7)* | 1.4* | Jacobshagen (1992);<br>Sebrier *et al.* (2006) |
| High Atlas | 31.7 | −6.5 | 60 ± 10 | – | 55.8 (−4.2)* | 1.4* | Brede (1992);<br>Beauchamp *et al.* (1999);<br>Teixell *et al.* (2003) |
| Middle Atlas | 33.0 | −5.0 | 40 ± 10 | – | 48.0 (+8.0)* | 1.4* | Deffontaines *et al.* (1992);<br>Gomez *et al.* (1996, 1998) |

ⓗ **Nubia – Iberia**

Velocity vectors – Algeria

| Latitude (°) | Longitude (°) | Observed ± $\sigma$ | | Predicted | | Source |
|---|---|---|---|---|---|---|
| | | Azimuth (°) | Rate (mm/a) | Azimuth (°) | Rate (mm/a) | |
| 36.80 | 3.70 | 325 ± 10 | 2 ± 1 | 329.6 (+4.6) | 1.7 (−0.3) | Meghraoui and Doumaz (1996);<br>Buforn *et al.* (2004);<br>Yelles-Chaouche *et al.* (2006) |

ⓘ **Iberia – Eurasia**

Velocity vectors

| Zone | Latitude (°) | Longitude (°) | Observed ± $\sigma$ | | Predicted | | Source |
|---|---|---|---|---|---|---|---|
| | | | Azimuth (°) | Rate (mm/a) | Azimuth (°) | Rate (mm/a) | |
| Portugal | 41.0 | −7.0 | 20 ± 10 | < 1 | 27.5 (+7.5) | 0.8 | Cabral (1989);<br>Ribeiro *et al.* (1996);<br>Jabaloy *et al.* (2002) |
| Pyrenees | 43.0 | 1.0 | 0 ± 20 | < 2 | 7.9 (+7.9) | 1.6 | Herraiz *et al.* (2000);<br>Alasset and Meghraoui (2005) |

(*) Computed by adopting the 33% of the Morocco-Eurasia angular velocity reported in table I.

Our confidence in such constraints is based on the fact that the adopted velocity field can quantitatively account for the Quaternary deformation pattern in the central-eastern Mediterranean region inferred from a large amount of geological and geophysical data. We also impose that the Nubian domain lying in front of the Hellenic and Cyprus arcs moves NNE ward, as discussed in

Section 2. This condition is defined by the velocity vectors located in the Syrte and Levantine basins (table IIf), taken from the velocity field resulting from numerical modelling (Mantovani *et al.*, 2001c). Considering the significant uncertainty which may affect these constraints, we assign them a relatively large error (20°).

The relative motion between Nubia and Arabia is constrained by spreading rates in the Red Sea (Chu and Gordon, 1998) and by velocity vectors deduced by seismological and geological information in two sectors of the Dead Sea fault system (Wadi Araba and Yammuneh fault zones; fig. 1). Chu and Gordon's (1998) dataset allows for a much more reliable computation of the Arabia-Nubia Euler poles with respect to the data used by DeMets *et al.* (1990), which are all located in Gulf of Aden, now largely believed to represent the Somalia-Arabia plate boundary (*e.g.*, Fournier *et al.*, 2001). In fact, in the Dead Sea shear zone the NUVEL-1 model predicts shortening rates considerably larger than those observed (*e.g.*, Klinger *et al.*, 2000a,b; McClusky *et al.*, 2003). The velocity vectors in the Anatolian-Aegean system shown in fig. 4 are consistent with the considerations given in Section 2.1. The motion trends of Anatolia and Aegea are westward and SW ward respectively, as suggested by most authors, while the rates are compatible with the geological evidence discussed in Section 2.1 (5-10 mm/yr).

To better illustrate the plate kinematics predicted by the Euler poles given in table I, both the predicted velocity fields in plate interiors (red arrows) and the relative velocity at plate boundaries (blue arrows) are shown in fig. 4.

In our opinion, the kinematic solution here proposed can help to overcome several major outstanding problems of the NUVEL-1 Nubia-Eurasia kinematics:

– For instance, the hypothesis that Nubia has moved NNE ward in the recent history does not require the very unlikely drastic change of motion trend, from NE ward to NW ward, which is instead implied by the Nubia-Eurasia kinematics provided by global kinematic models (see *e.g.*, Dewey *et al.*, 1989). A discussion about this problem is given by Mantovani (2005).

– The two-plates configuration adopted by the NUVEL-1 model cannot account for the occurrence of intense earthquakes in the Transmoroccan-Canary fault system, in Portugal and in the Pyrenean belt. In particular, the major features of the Transmoroccan tectonic belt, such as the occurrence of sinistral strike-slip faulting, alkaline basaltic volcanism, and strong lithospheric thinning (*e.g.*, Piqué *et al.*, 1998; Seber *et al.*, 1996; Ramdani, 1998; Teixell *et al.*, 2005; Fullea *et al.*, 2007) and the seismotectonic features in the adjacent Atlantic zone can hardly be reconciled with the Nubia-Eurasia relative motion predicted by the NUVEL-1 model.

– The incompatibility between the widely recognized Adria kinematics and the NUVEL-1 Nubia-Eurasia relative motion cannot be reconciled with the lack of a reliable decoupling zone between Nubia and Adria (Babbucci *et al.*, 2004; Argnani, 2006).

– The SW-NE relative motion between Nubia and the Anatolian-Aegean system, implied by the morphological features of the Hellenic and Cyprus arcs, can be reconciled with a NNW ward motion of Nubia only if the Plio-Quaternary motion rate of the Anatolian-Aegean system was much higher than the one of Nubia. However, such hypothesis is not consistent with Pliocene-Quaternary geological evidence in that system.

Furthermore, it must be pointed out that the kinematic pattern we propose (fig. 4) is compatible with many other features of the Pliocene-Quaternary deformation pattern observed in the Mediterranean region, as discussed in previous papers (Mantovani *et al.*, 1997, 2002, 2006a; Mantovani, 2005) and supported by the results of numerical modelling (Mantovani *et al.*, 2001c).

On the other hand, it cannot be ignored that our kinematic solution is significantly different from the models derived by geodetic data. A discussion about this possible problem is given in the next section.

## 5. Geodetic measurements

A number of attempts at determining the Nubia-Eurasia relative motion by using space geodetic data have so far been made (*e.g.*, Sella *et al.*, 2002; McClusky *et al.*, 2003; Calais *et al.*, 2003; Kreemer *et al.*, 2003; Nocquet and Calais,

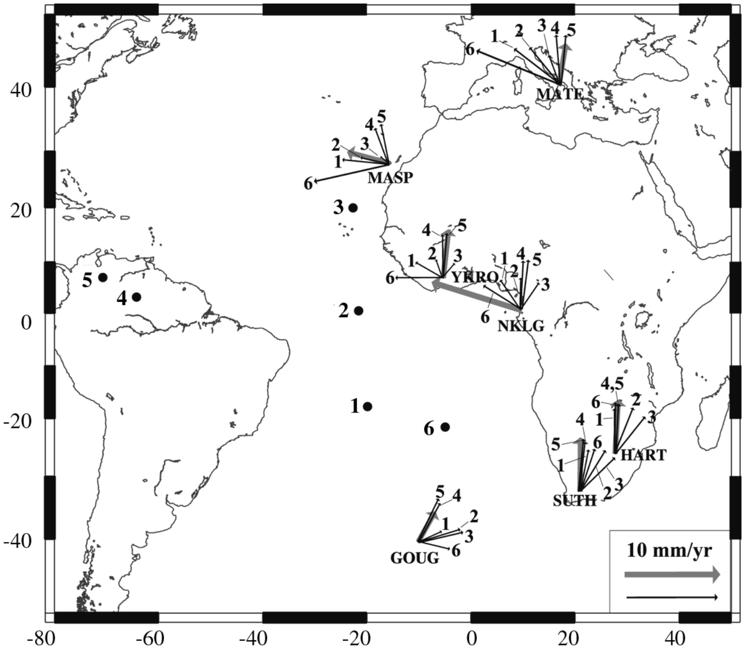

**Fig. 5.** Nubia-Eurasia Euler poles derived from geodetic data (black dots numbered from 1 to 6) and respective velocities (thin arrows with numbers) predicted by such poles at the African GPS sites reported in table IIIa. Thick grey arrows show the residual ITRF2000 velocities (table IIIa) with respect to the Eurasia absolute pole provided by Prawirodirdjo and Bock (2004). Poles 1 to 3 are taken from literature, while the poles 4 to 6 are computed in this work taking into account slightly different data sets with respect to the first 3 poles (see table IIIb).

2004; Prawirodirdjo and Bock, 2004). The Nubia-Eurasia Euler poles proposed by the above authors (some of them are given in fig. 5 and table IIIa,b) considerably differ from one another and are mostly located south of the NUVEL-1 pole, implying an even more westward motion trend of Nubia in the Mediterranean region with respect to the model here proposed.

We do not have any simple explanation for the fact that the present-day kinematics inferred from geodetic data is significantly different from the long-term kinematic models, the NUVEL-1 and the one here proposed. One could consider the possibility that such difference is due to a variation of plate kinematics in the recent evolution. For instance, Calais *et al.* (2003) tentatively relate the presumed recent deviation and slowdown of the Nubia-Eurasia convergence to the increasingly collisional resistance in the Mediterranean region. However, even if this explanation cannot be ruled out, it is not easy to believe that the change of motion trend of Nubia from NNE to NNW ward has occurred without leaving clear geological imprints throughout the Mediterranean region (Mantovani, 2005). Even Calais *et al.* (2003) admit that neither convincing Mediterranean tectonic evidence nor dynamic causes responsible of the above change may easily be recognized. Significant discrepancies between geodetic velocities and global kinematic models have been recognised along other major plate boundaries, as the Andes and the Himalaya-Tibet (Yang and Mian, 2002), but such discrepancies have been tentatively explained as effects of different short and long-term mechanical behaviour of the lithosphere.

In the following, to explore alternative explanations of the short-term/long-term discrep-

**Table IIIa,b.** Nubia-Eurasia kinematics from geodetic measurements. a) North (u) and east (v) components of absolute and residual velocity in 7 GPS continuous stations located in Nubia and in the Southern Adriatic (MATE), shown in fig. 5. Absolute velocities and standard deviations ($\sigma$), are provided by the Laboratoire de Recherches en Géodésie (LAREG), whose ITRF2000 solution is available at <http://lareg.ensg.ign.fr>. Residual velocities are obtained from absolute ones by subtracting Prawirodirdjo and Bock's (2004) Eurasia absolute pole (latitude 57.246°N, longitude −99.691°E and angular velocity 0.260°/Myr). b) Nubia-Eurasia Euler poles (fig. 5) taken from literature (1, 2 and 3) and determined in this work (4, 5 and 6) by the data set reported in a). All the above Nubia-Eurasia Euler poles have been obtained by difference from the related Nubia and Eurasia absolute poles (see text for explanations). For each case, the list of continuous GPS stations used to constrain the Nubia absolute pole is shown. Pole 2 has also been constrained by 1 non-continuous GPS site and 4 sites belonging to the DORIS network (*e.g.*, Willis *et al.*, 2005). The columns «Nubia» and «Eurasia» report basic information about the absolute Euler poles from which the above Nubia-Eurasia poles derive. $N$ is the number of geodetic stations used to constrain the respective absolute Euler pole, $\nu=2N-3$ is the related number of degrees of freedom, and $\chi_\nu^2$ is the reduced $\chi^2$ error (*e.g.*, Kreemer *et al.*, 2003).

| ⓐ Station | | | Absolute velocity | | Residual velocity | |
|---|---|---|---|---|---|---|
| Name | Lat (°) | Long (°) | $u$ (mm/yr) ± $\sigma$ | $v$ (mm/yr) ± $\sigma$ | $u$ (mm/yr) | $v$ (mm/yr) |
| GOUG | −40.35 | −9.88 | 18.51 ± 3.60 | 20.23 ± 1.89 | 2.87 | 1.61 |
| HART (HAR, HARB, HARK, HRAO) | −25.89 | 27.71 | 17.86 ± 0.41 | 18.09 ± 0.35 | 5.43 | 0.32 |
| MASP (MAS, MAS1) | 27.76 | −15.63 | 16.67 ± 0.54 | 16.66 ± 0.35 | 1.11 | −4.13 |
| MATE | 40.65 | 16.70 | 18.09 ± 0.36 | 23.70 ± 0.13 | 4.08 | 0.69 |
| NKLG | 0.35 | 9.67 | 17.73 ± 1.30 | 14.88 ± 2.39 | 2.97 | −9.47 |
| SUTH | −32.38 | 20.81 | 18.92 ±1.69 | 16.39 ±1.37 | 5.44 | 0.05 |
| YKRO | 6.83 | −5.24 | 20.42 ± 1.10 | 24.82 ± 1.10 | 4.83 | 0.53 |

| ⓑ Pole | Source and Nubian geodetic stations | Nubia-Eurasia rotation vector | | | Nubia | | Eurasia | |
|---|---|---|---|---|---|---|---|---|
| | | Lat (°N) | Lon (°E) | $\omega$ (°/Myr) | $N, \nu$ | $\chi_\nu^2$ | $N, \nu$ | $\chi_\nu^2$ |
| 1 | Sella *et al.* (2002): GOUG, HAR, HRAO, MAS, SUTH | −18.23 | −20.01 | 0.062 | 5, 7 | 0.82 | 15, 27 | 1.02 |
| 2 | Kreemer *et al.* (2003): GOUG, MAS, SUTH + MATR (GPS not continuous)+ + ARMA, DAKA, HELA, LIBA (DORIS network) | 1.1 | −21.3 | 0.060 | 8, 13 | 0.54 | 122, 241 | 1.05 |
| 3 | Prawirodirdjo and Bock (2004): GOUG, HARB, HARK, HRAO, MAS1, NKLG, SUTH | 20.09 | −22.09 | 0.051 | 7, 11 | 0.8 | 18, 33 | 1.1 |
| 4 | This work: GOUG, HART, SUTH | 3.21 | −62.57 | 0.049 | 3, 3 | 0.16 | as Pole 3 | |
| 5 | This work: GOUG, HART, SUTH, YKRO | 7.23 | −69.78 | 0.049 | 4, 5 | 0.11 | as Pole 3 | |
| 6 | This work: GOUG, HART, NKLG, SUTH | −21.76 | −5.14 | 0.099 | 4, 5 | 1.80 | as Pole 3 | |

ancy in the Mediterranean area, we make some considerations about the uncertainties that might affect the presently available geodetic data in that region. The main source of uncertainty may come from the fact that only few GPS permanent stations are currently operating in Nubia (fig. 5 and table IIIa) and that most of them are located along active deforming boundaries of this plate (figs. 1, 2 and 5), as also recognized by Altamimi *et al.* (2002) and Sella *et al.* (2002). The station of MASP (Mas Palomas, Gran Canaria Island, indicated in literature as MAS and MAS1 also) is located along an active tectonic belt affected by volcanic and seismic activity, Miocene to Quaternary giant landslides and considerable (about 1 cm/yr) vertical and horizontal ground motion (*e.g.*, Mezcua *et al.*, 1992; Carracedo *et al.*, 1999; Anguita and Hernan, 2000; Fernandez *et al.*, 2003; Gonzalez de Vallejo *et al.*, 2003). The station of GOUG lies very close to the South Atlantic spreading ridge. The station of NKLG (Libreville, Gabon), is located near the Cameroon line, where recent tectonic and volcanic activity is recognized (*e.g.*, Suleiman *et al.*, 1993; Ateba and Ntepe, 1997; Ubangoh *et al.*, 1997; Foster and Jackson, 1998). No recent seismotectonic activity is instead recognized in the zone where the stations of the South African Hartebeesthoek Observatory (HAR, HARB, HARK, HRAO and HART) are located. One should also consider that most African stations (all but HRAO and MASP) have been excluded from the network of core sites used for defining the ITRF2000 solution since they do not satisfy quality criteria adopted for site selection (Altamimi *et al.*, 2002).

In order to check the stability of the Nubia-Eurasia Euler poles with respect to the set of stations considered, we have carried out some experiments. The Nubia-Eurasia Euler poles obtained by such experiments (poles 4, 5 and 6, given in table IIIb and illustrated in fig. 5) are computed as the difference between the related Nubia and Eurasia absolute Euler poles, obtained by inverting sets of absolute geodetic velocities in a weighted least-squares approach which minimizes the parameter $\chi^2$ (*e.g.*, DeMets *et al.*, 1990). For each Euler pole, the goodness of fit is measured by the reduced $\chi^2$ error ($\chi_\nu^2=\chi^2/\nu$) where $\nu$ is the number of degrees of freedom, depending on the number of stations used in the inversion (*e.g.*, Kreemer *et al.*, 2003). For the computation of poles 4, 5 and 6 we have adopted the Eurasia absolute pole provided by Prawirodirdjo and Bock (2004). The Nubia-Eurasia Euler poles taken from literature (cases 1 to 3 in table IIIb) derive from Nubia and Eurasia absolute poles for which complete information about $\chi_\nu{}^2$ parameters is available.

The results given in table IIIb and fig. 5 raise doubts about the constraining power of the presently available data set in the Nubia plate, since the parameters of Euler poles show a strong dependence on the set of stations considered. In particular, it can be noted that the poles computed without taking MASP into account are characterized by locations and angular velocities considerably different from those of the first three poles and that including the station NKLG in the data set (pole 6 in table IIIb) provides a particularly bad fit.

At last, it is worth noting that the kinematics predicted by the Euler poles 4 and 5 (obtained without using MASP and NKLG) in the Southern Adriatic is fairly compatible with the geodetic velocity of MATE (fig. 5). This evidence, and the fact that the $\chi_\nu^2$ values related to poles 4 and 5 are much lower than those of poles 1, 2 and 3 (table IIIb) may imply that geodetic data could be reconciled with the Nubia-Eurasia kinematics suggested by Mediterranean evidence if the most uncertain geodetic vectors, as MASP and NKLG, are not considered. However, since recognizing the actual quality and geodynamic significance of geodetic data is not so simple, we believe that any attempt to derive Euler poles from the presently available data set in Nubia (defined as «geodetically poor» by Altamimi *et al.*, 2002) should be considered with caution.

## 6. Conclusions

We argue that current ideas on the recent (last few Myr) relative motion between Nubia and Eurasia, generally based on the analysis of North Atlantic data (*e.g.*, the NUVEL-1 model), might be not reliable. This hypothesis is suggested by the analysis of the Plio-Quaternary deformation pattern in the Mediterranean region, which coherently indicate a NNE ward Nubia-Eurasia convergence, rather different from the NNW ward convergence trend provided by the NUVEL-1 model. The possibility that NUVEL-1 Nubia-Eurasia kinematics is not reliable is also suggested by the fact that the two-plates configuration adopted by such approach cannot explain the occurrence of significant seismotectonic activity in some zones lying inside the presumed Nubia and Eurasia plates, such as Pyrenees, Portugal and the Transmoroccan-Canary fault system. In this paper it is shown that if a more reliable plate configuration, involving the Iberia and Morocco intervening microplates, is adopted, a kinematic pattern can be identified which accounts, within the respective errors, for both Mediterranean and North Atlantic (NUVEL-1) constraints.

Understanding why the Nubia-Eurasia convergence trend indicated by Mediterranean evidence is significantly different from the one inferred by geodetic data is not a simple task. In our opinion, the present network of permanent GPS stations in Africa may be still inadequate to determine Nubia's kinematics. The main problem is that no or very few stations are available in the stable part of Africa. In addition, the Nubia-Eurasia Euler poles so far proposed in the literature are considerably influenced by the set of stations considered. In particular, such poles are strongly conditioned by the use of the site (MASP) located at the Canary Island active tectonic belt, which is recognized as a possible westward prosecution of the Transmoroccan fracture zone. To explain the discrepancy between the Nubia-Eurasia kinematic models obtained by different approaches, one should also consider the possibility that the Mediterranean constraints we take into account are not as significant as we claim. However we think this is unlikely, since our point of view is supported by the major features we describe in this work and can also provide plausible and coherent explanations for the Mediterranean deformation pattern inferred from a large amount of geological, geophysical and volcanological evidence (Mantovani *et al.*, 1997, 2002, 2006a; Mantovani, 2005). Thus, we think that any conclusion about the reliability of the Nubia-Eurasia kinematics deduced by Mediterranean features should be drawn only after having considered the complete framework of evidence and arguments in support of that interpretation.

On the other hand, we think that any attempt to defend the reliability of the Nubia-Eurasia kinematics provided by the NUVEL-1 model or inferred from geodetic data should be accompanied by plausible explanations of how the major problems we raise in this work can be overcome. For instance, it does not seem scientifically opportune using a Nubia-Eurasia kinematic model which predicts no deformation in zones affected by strong seismicity, needs a decoupling between Adria and Nubia not documented by any significant evidence, and cannot provide any plausible explanation for the morphology and tectonic setting of the Cyprus Arc and for the sinistral shear observed at the Transmoroccan fault system and for many other features (*e.g.*, Mantovani, 2005).

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