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# Tectonic interpretation of large scale geodetic measurements (VLBI, SLR) in the Central Mediterranean region: constraints and uncertainties

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**Abstract**
Some considerations are reported on the tectonic setting and microplate mosaic in the Mediterranean zones where VLBI and SLR stations are located. In particular, the possible sources of ambiguity in the determination of the Africa-Eurasia and Adriatic-Eurasia relative motions from geodetic data are discussed. Possible alternative kinematic interpretations, with respect to those reported in the literature, are then proposed.

**Key words** *space geodesy – plate kinematics – Central Mediterranean*

## 1. Introduction

The Mediterranean region is constituted by a complex mosaic of plates and microplates (see fig. 1), which move one with respect to the other to accommodate the relative approach between the Africa/Arabia and Eurasia blocks (Dewey *et al.*, 1973, 1989; Biju-Duval *et al.*, 1977; Dewey and Sengor, 1979; Dercourt *et al.*, 1986; Le Pichon *et al.*, 1988; Mantovani *et al.*, 1990, 1993, 1994).

Until recently, the only way to attempt a reconstruction of the kinematic pattern of such a system was based on the analysis of types and rates of deformation along plate boundaries inferred from geological and geophysical observations and from earthquake focal mechanisms. Now, a new powerful tool is available to approach this problem, *i.e.* high precision large scale geodetic measurements (VLBI, SLR, GPS), which can provide direct indications on the relative motions between a number of sites in the Mediterranean region. However, this new possibility should be utilized with due caution, by carefully considering the real uncertainties of geodetic data and the possible ambiguities in the plate mosaic, to avoid the scientific authority of such «direct information» being used to support unreliable kinematic hypotheses.

This work reports some considerations on the constraints which can (or cannot) be imposed to the Central Mediterranean kinematic/tectonic pattern on the basis of the most recent SLR and VLBI data sets reported in literature (Noomen *et al.*, 1993; Smith *et al.*, 1994; Zarraoa *et al.*, 1994; Ward, 1994).

## 2. General remarks

The number of parameters which are required to fully define the kinematic pattern of the complex Mediterranean plate mosaic (fig. 1 only shows the major plates and microplates), is very high and cannot be simply constrained by a limited number of baseline rates or motion vectors. It is thus necessary to use geologi-

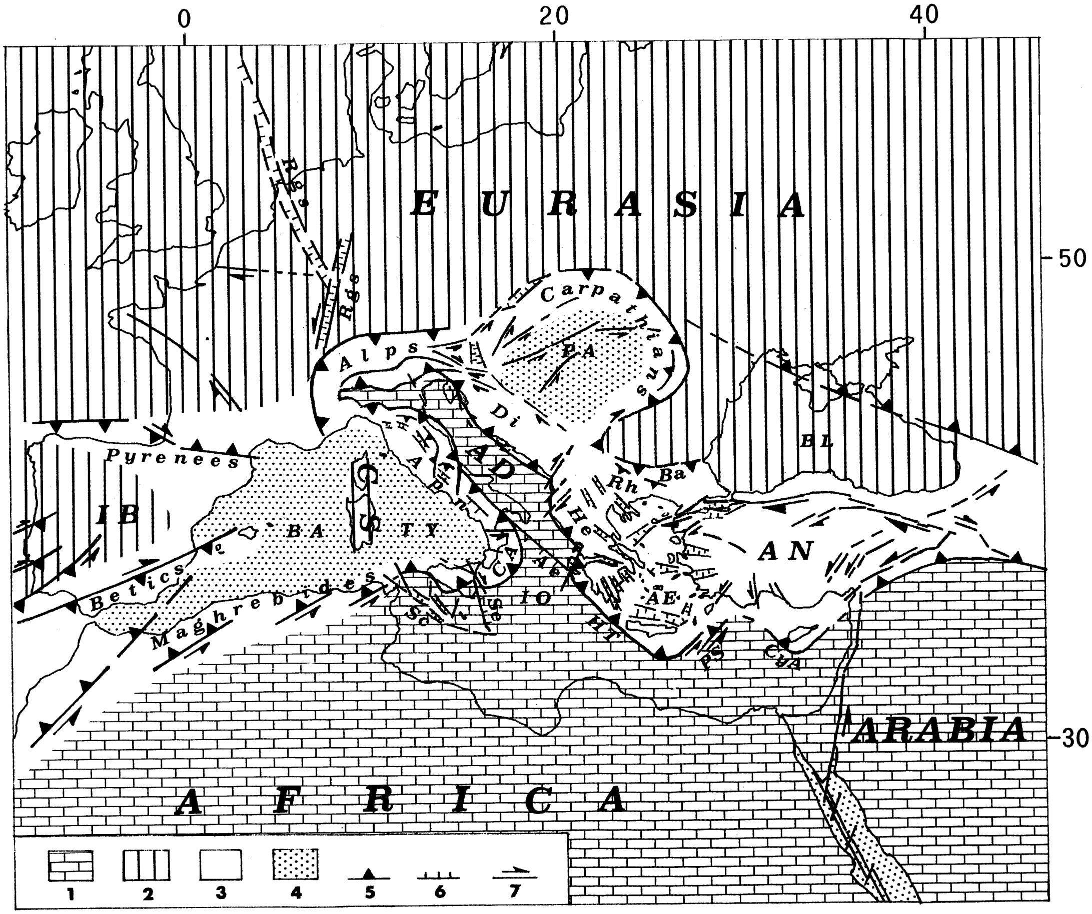


**Fig. 1.** Major tectonic features in the Mediterranean region. 1) African domain; 2) Eurasian domain; 3) orogenic belts; 4) Neogenic basins; 5, 6, 7) main compressional, tensional and transcurrent features. AD: Adriatic block; AE: Aegean; Ae: Apulian escarpment; AN: Anatolia; Apn: Apennines; BA: Balearic basin; Ba: Balkanides; BL: Black sea; CA: Calabrian arc; CyA: Cyprus arc; CS: Corsica-Sardinia; Di: Dinarides; HT: Hellenic trench; He: Hellenides; IB: Iberia; IO: Ionian basin; PA: Pannonian basin; PS: Pliny-Strabo trenches; Rgs: Rhine graben system; Rh: Rhodope; Sc: Sicily channel; Se: Siracusa escarpment; TY: Tyrrhenian basin.

cal and geophysical information to establish a number of assumptions about some aspects of the deforming system, in order to reduce the number of kinematic parameters. However, the reliability of the resulting kinematic pattern is conditioned by the reliability of tectonic choices. For example, if one station is taken as representative of the wrong block, any kinematic indication derived from the relevant data is misleading. Some considerations on this point, based on practical examples in the Mediterranean region, are reported in the next section.

Another source of ambiguity is related to the fact that the uncertainty associated with the observed vertical motion is so high that most authors (see *e.g.*, Ward, 1990) do not take this component into account and assume that the relative motion between the stations only occurs in the horizontal plane parallel to the relevant chord. Following Robbins *et al.* (1993), the total contribution of the vertical component to the local horizontal motion between sites can be expressed in percentage as 100 $d/(2r)$ where $d$ is the baseline length and $r$ is the radius of the earth (≈ 6371 km). This suggests that, for a baseline length of a hundred km, when vertical rates are one order of magnitude greater than the horizontal ones, a significant bias in the geodetic rates estimate is introduced when the vertical component is neglected.

Another arbitrary assumption which is generally adopted in the interpretation of geodetic data is that plate motions are continuous in time. The time distribution of seismicity along important plate boundaries (see *e.g.*, Anderson, 1975) suggests that relative plate motion is mainly constituted by coseismic and postseismic slippage along the border. The phases of accelerated drifting are separated by periods of very slow motion. If this hypothesis is realistic, the motion rates deduced by geodetic data cannot be simply extrapolated to time intervals different from the measuring period.

## 3. VLBI data

The last results obtained by the VLBI European network (see Ward, 1994; Zarraoa *et al.*, 1994) are reported table I, in terms of baseline rates between the relevant stations. The velocities at the VLBI stations with respect to a North European frame are reported in fig. 2a,b.

In our opinion, the only indication which can be inferred from the above data is that the sites of Matera and Noto show a significant motion with respect to a North European reference frame, as underlined by Ward (1994) and Zarraoa *et al.* (1994). Any other inference seems to be mainly speculative, given the possible uncertainties on geodetic data and on the tectonic setting in each station site.

First of all, we suspect that the data relative to Medicina might be affected by noticeable uncertainty, much greater than the formal error indicated in fig. 2a,b, because Medicina lies in an alluvial basin, the Po plain, which seems to be affected by significant vertical movements. Leveling campaigns (Salvioni, 1957; Arca and Beretta, 1985) have indicated for the area of Medicina an average subsidence rate (mea-

**Table I.** Baseline rates in Europe obtained from VLBI observations by Ward (1994) and Zarraoa *et al.* (1994). For each baseline, the rate (mm/yr) and the standard deviation are reported. The differences between the baseline rates and motion vectors given by the two works are mainly related to the fact that Zarraoa *et al.* (1994) took into account a longer data set for the Matera station and also considered vertical movements in the analysis of VLBI data.

| Baselines | Ward (1994) | | Zarraoa *et al.* (1994) | |
|---|---|---|---|---|
| | Rate | St. dev. | Rate | St. dev. |
| Matera-Noto | 0.4 | 2.6 | −2.5 | 1.4 |
| Wettzell-Medicina | −1.9 | 0.4 | −2.2 | 0.5 |
| Medicina-Matera | −2.0 | 1.4 | −5.4 | 1.3 |
| Medicina-Noto | −5.9 | 1.1 | −6.6 | 0.9 |
| Wettzell-Onsala | −0.7 | 0.2 | −1.1 | 0.4 |
| Wettzell-Matera | −4.2 | 1.2 | −8.0 | 1.3 |
| Wettzell-Noto | −6.7 | 1.1 | −7.5 | 0.8 |
| Onsala-Medicina | −2.4 | 0.6 | −2.9 | 0.6 |
| Onsala-Matera | −5.3 | 3.8 | −11.7 | 1.5 |
| Onsala-Noto | −7.3 | 2.7 | −7.6 | 0.9 |

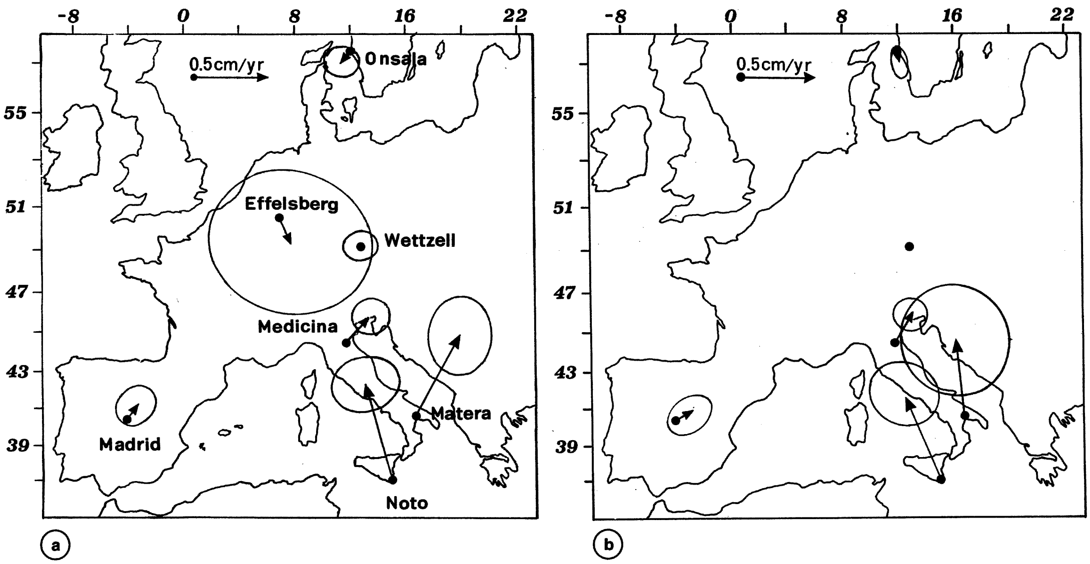


**Fig. 2a,b.** VLBI site velocities in a fixed European frame. a) Motion vectors reported by Ward (1994). These vectors are referred to a frame which minimizes the rates of Wettzell, Onsala, Madrid and Effelsberg. b) Motion vectors reported by Zarraoa *et al.* (1994). The reference frame fixes the coordinates of Wettzell, the directions from Wettzell to Onsala and a null vertical motion in Madrid.

sured with respect to the average sea level) of 2 mm/yr in the time interval 1877-1957. This estimate can be considered a lower boundary value since, in the last 30 years, the intense exploitation of water and gas resources in the Po plain has produced a significant increase of man-induced subsidence phenomena (Arca and Beretta, 1985). Preliminary data from recent leveling campaigns indicate subsidence rates in the order of 10 mm/yr in the Medicina area (Regione E.R.-IDROSER, 1994). Since the horizontal velocity field obtained by Ward (1994) has been determined on the assumption that vertical movements can be ignored (Ward, 1990), the motion rates reported in fig. 2a,b might be biased. Moreover, the variable character of water exploitation during each year may result in discontinuous subsidence rates, and thus they cannot be easily predicted and removed from the observed baseline variations. In addition, it must be taken into account that Medicina lies over the external nappes of the Apenninic belt, buried below the Po Plain (fig. 3), and that, consequently, the motion of this site might be kinematically connected with the Northern Apenninic arc rather than with the Adriatic plate. Geological and volcanological evidence clearly indicates that, since the Miocene, the Northern Apennines have migrated roughly NEward with respect to the Adriatic foreland (see *e.g.*, Elter *et al.*, 1975; Pieri and Groppi, 1981; Boccaletti *et al.*, 1985; Castellarin and Vai, 1986; Vai, 1987). The distribution of seismicity and the recent/present deformations along the internal and external margins of the belt (Gasparini and Praturlon, 1981; Bartolini *et al.*, 1983; Boccaletti *et al.*, 1985; Lavecchia, 1988) suggest that the relative motion between the chain and the adjacent foreland is still going on. Other evidence in this sense may be the occurrence of subcrustal earthquakes beneath the Northern Apennines (Selvaggi and Amato, 1992; Cimini and Amato, 1993), which are most probably related with the downward flexure of the Adriatic foreland beneath the migrating Apenninic belt

(Patacca *et al.*, 1990, 1993; Mantovani *et al.*, 1992, 1993). It is interesting to note that the direction of the geodetic vector in Medicina (NEward) is fairly coherent with the drifting trend of North Apennines nappes indicated by seismological and geological data.

As far as the station of Noto is concerned, the main problem is understanding which block this site represents. Some authors have tentatively supposed that Noto belongs to the African plate (Ward, 1994; Zarraoa *et al.*, 1994). However, this choice does not take into account that the Iblean block, where Noto is located, is surrounded by tectonic belts, such as the troughs in the Sicily channel, and the Syracuse escarpment, which are characterized by recent activity (see *e.g.*, Finetti and Del Ben, 1986; Boccaletti *et al.*, 1987; Cello, 1987; Reuther *et al.*, 1993). Some authors (see *e.g.*, Finetti and Del Ben, 1986 and Mantovani *et al.*, 1992, 1993, 1994) argued that the complex pattern of tensional, compressional and transcurrent deformations in Sicily and surrounding regions can be coherently explained by the hypothesis that the Iblean block moves independently from the African, Adriatic and Eurasia blocks (see fig. 4). These arguments are also supported by the results of finite element modeling experiments (Albarello *et al.*, 1994).

As regards Matera, the assumption that this site belongs to the Adriatic plate seems to be reasonable, at the light of geological and tectonic evidence, even if Matera is located very close to the border between the outcropping

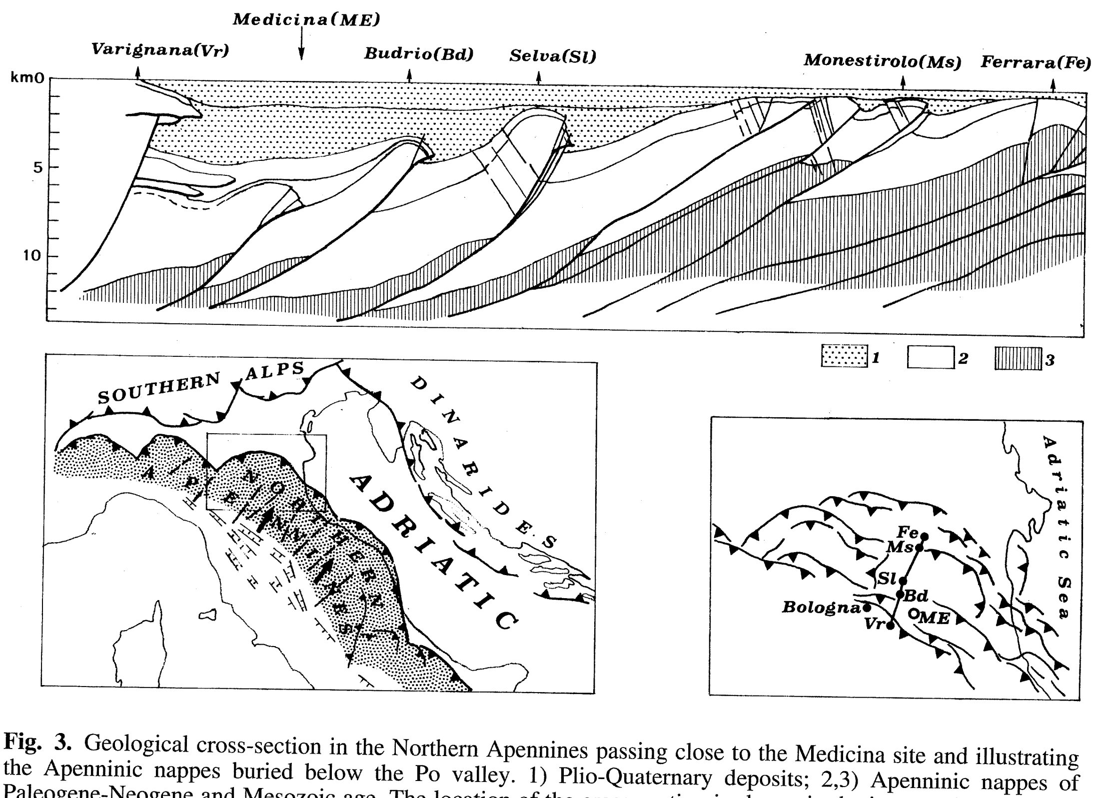


**Fig. 3.** Geological cross-section in the Northern Apennines passing close to the Medicina site and illustrating the Apenninic nappes buried below the Po valley. 1) Plio-Quaternary deposits; 2,3) Apenninic nappes of Paleogene-Neogene and Mesozoic age. The location of the cross-section is shown in the inset to the right. The left inset shows the Northern Apenninic Arc and its motion trend with respect to Adriatic foreland, as inferred from geological and seismological evidence (Mantovani *et al.*, 1992, 1993).

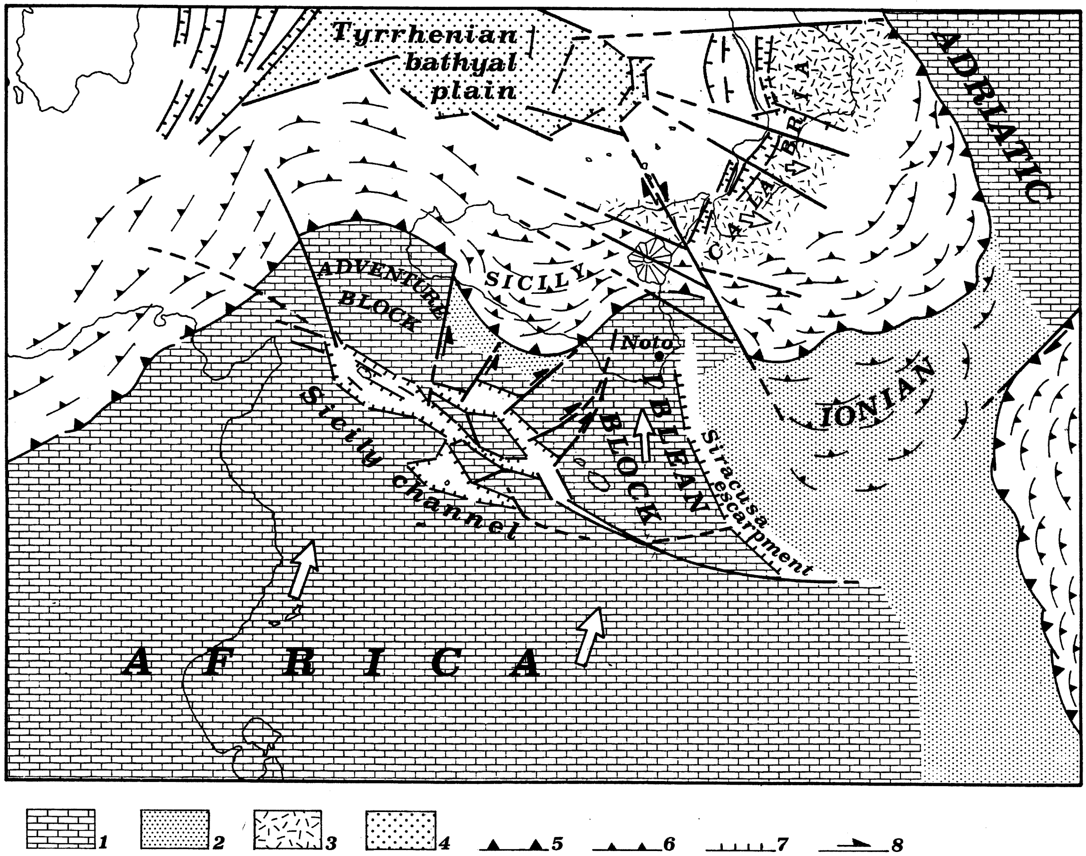


**Fig. 4.** Tectonic sketch of the Northern African margin and Calabrian arc. 1) African/Adriatic continental foreland; 2) thinned/intermediate foreland zones; 3) Calabrian block; 4) zone of crustal stretching in the Tyrrhenian area; 5) external front of the Alpine-Apenninic-Maghrebian belt; 6,7,8) compressional, tensional and transcurrent features. Big white arrows show the direction of the Africa-Adriatic convergence, which is assumed as the driving mechanism of the proposed evolutionary pattern (Mantovani *et al.*, 1992, 1993, 1994; Albarello *et al.*, 1994) and the drifting of the extruding Iblean and Calabrian wedges.

mesozoic platform and the adjacent trough. Neotectonic information indicates that this zone has undergone Quaternary vertical motion, with maximum rates of 1-1.5 mm/yr (see *e.g.*, Ciaranfi *et al.*, 1983; Westaway, 1993). Relatively intense vertical motions at the Matera station are also indicated by preliminary VLBI measurements (Zarraoa *et al.*, 1994). This could account for the significant discrepancy between the estimates of horizontal displacements supplied by Ward (1994) and Zarraoa *et al.* (1994).

In the following, some remarks are reported on how the uncertainties discussed above can influence the reliability of kinematic inferences.

### 3.1. *Africa-Eurasia pole*

Ward (1994) tentatively suggested an Africa-Eurasia rotation pole by using the geodetic vectors of Noto and Johannesburg (see fig. 5). In our opinion, this pole is not only

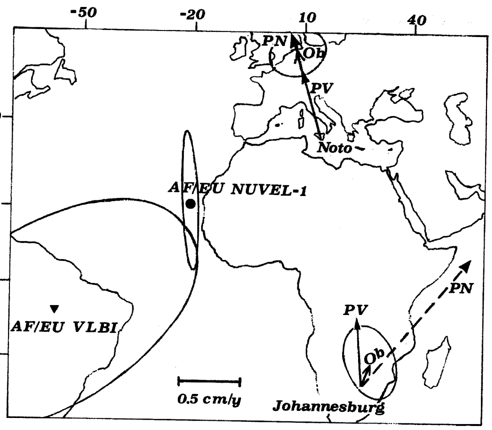


**Fig. 5.** Map showing the locations of the VLBI Africa-Europe rotation pole (black triangle) suggested by Ward (1994) and of the Nuvel-1 pole (black dot) given by DeMets *et al.* (1990). Vectors marked by PV are the motions predicted by the VLBI pole. Vectors marked by Ob indicate the motions derived from geodetic measurements; ellipses indicate the 3$\sigma$ errors (after Ward, 1994). Vectors marked by PN are those predicted by the Nuvel-1 pole.

poorly constrained, as admitted by Ward, but might be completely unreliable, since it is based on two motion vectors which are both affected by great uncertainty: the vector of Noto, as argued earlier, might not be representative of the African kinematics and the vector of Johannesburg is covered by its formal error. It is surprising that this very rough determination has led Ward to state: «it is safe to conclude that Africa-Europe convergence in the Central Mediterranean is northwesterly directed». Even though one assumes that Noto belongs to the African block, it does not seem safe at all to draw such a definitive conclusion on this crucial problem on the basis of only one geodetic site vector deduced after a relatively short observation period.

Most probably Ward's convinction is more based on the other major features which are generally used to support the hypothesis that Africa moves NWward with respect to Eurasia, *i.e.* the kinematic indicators in the North Atlantic (spreading rates, transform fault azimuths and seismic slip vectors) and the NWward direction of shortening in the Maghrebian-Betic regions, clearly testified by geological and seismological evidence (McKenzie, 1972; Philip and Meghraoui, 1983; Buforn *et al.*, 1988). However, it has been demonstrated by Mantovani *et al.* (1992, 1993) and Albarello *et al.* (1993, 1995) that the above evidence can be reconciled with different Africa-Eurasia kinematics, for instance a SSW-NNE relative motion, if one assumes that in Western Europe there are microplates not closely connected with stable Eurasia. The possible presence of mobile blocks, such as Iberia and Morocco, in the Western Mediterranean region is suggested by the significant tectonic activity and seismicity which occur in the North Atlantic, the Pyrenees, the Balearic and Alboran basins, in the Maghrebian-Betic-Rif belts and even in the western part of the Iberian peninsula. Similar considerations have been reported by other authors (see *e.g.*, Biju-Duval *et al.*, 1977; Le Pichon *et al.*, 1977; Vegas and Banda, 1982; Klitgord and Shouten, 1986; Philip, 1987; Buforn *et al.*, 1988; Cabral, 1989; Nicolas *et al.*, 1990). In addition, it must be considered that the main features of a large scale tectonic belt running from the Mediterranean to the North sea, *i.e.* the Rhine graben system (see *e.g.*, Ahorner, 1975; Pavoni, 1988), have been interpreted as effects of a past relative motion between the Western European domain and stable Eurasia (Le Pichon *et al.*, 1988; Bergerat, 1987).

### 3.2. *Adriatic plate*

For the reasons explained, we think that to constrain the Adriatic kinematics it is more cautious, for the moment, not to use the data relative to the Medicina station. Thus, to approach this problem, the motion vector in Matera remains the only indication. However, the orientation of this vector is rather uncertain, since it is indicated roughly NEward by Ward and roughly Northward by Zarraoa and coworkers (fig. 2a,b). This ambiguity precludes any precise hypothesis on the existence of an «Adriatic plate» moving independently from Africa and Europe.

The main evidence which led Ward (1994) to favour the idea of an independent Adriatic block is the difference between the drifting trends of Matera and Noto (fig. 2a). However, as argued earlier, this divergence might be explained by the independent motion of the Iblean microplate with respect to the African and Adriatic domains. Furthermore, as underlined by Ward (1994), the Adriatic-Europe rotation pole determined on the basis of the Matera and Medicina site rates, implies a relative motion of about 7 mm/yr between Africa and Adriatic along the presumed border between these two blocks, which, however, has no geological or seismological support.

It is interesting to note that the geodetic motion rate and drifting trend of Noto are both in very good agreement with the corresponding parameters of the Iblean block (figs. 4 and 8) deduced from geological and seismological data (Mantovani *et al.*, 1992, 1993; Albarello *et al.*, 1994).

### 3.3. *Estimates of the strain field in Italy from geodetic data*

From the theoretical point of view, the computation of the strain field in a triangular zone whose vertices have known motions (Ward, 1994) is certainly correct, but the practical usefulness of this kind of average estimates in a highly tectonized and fragmented region, as the Italian one, seems to be very limited. In fact, it is evident that the local strain fields in the subzones of the triangular area considered by Ward (see fig. 6a), *i.e.* Northern, Central, Southern Apennines, Calabrian Arc and Sicily may be completely different from the average one derived from geodetic data in the triangu-

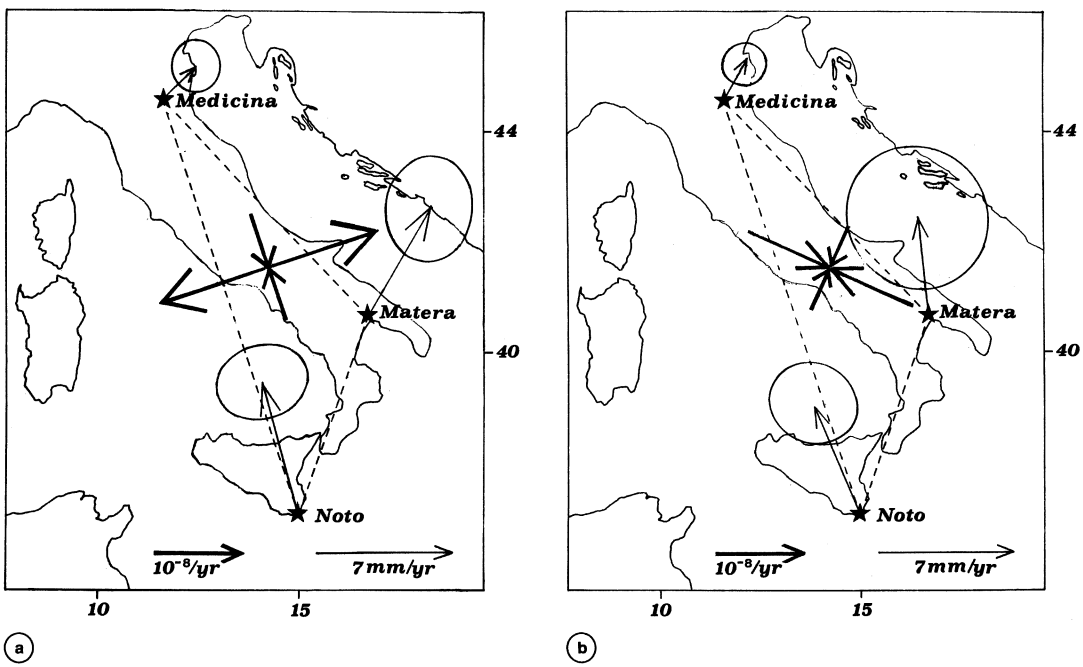


**Fig. 6a,b.** a) Horizontal principal strain rate axes (big arrows) in the area between Medicina, Matera and Noto, computed from baseline rates (table I) given by Ward (1994). b) Horizontal principal strain rate axes (big arrows) computed from the baseline rates (table I) given by Zarraoa *et al.* (1994).

lar zone of fig. 6a. In fact, neotectonic and seismological data indicate that the Northern Apennines are affected by a SW-NE tensional strain in the internal (Tyrrhenian) margin and a similarly oriented compressional strain in the external (Padanian) margin (see *e.g.*, Elter *et al.*, 1975; Boccaletti *et al.*, 1985); the zone of contact between the Northern and Central Apennines is undergoing SE-NW compression accompanied by dextral shear (Castellarin *et al.*, 1978, 1982; Calamita and Deiana, 1988; Lavecchia *et al.*, 1988); the Southern Apennines show a dominant tensional field oriented SW-NE (Ortolani, 1979; Ciaranfi *et al.*, 1983; Pantosti and Valensise, 1990); in the Calabrian Arc, a SSW-NNE to N-S compressional regime accompanied by a WNW-ESE to E-W distension is indicated by seismic and neotectonic data (Barbano *et al.*, 1978; Philip, 1987; Lo Giudice and Rasà, 1986; Van Dijk and Okkes, 1991; Albarello *et al.*, 1994). In this context, the principal strain rate axes computed by Ward (1994) from geodetic data in the triangle Medicina-Matera-Noto (see fig. 6a and table IIA) indicating a transtensional domain characterized by a principal tensional axis having anti-Apennine trend, cannot be taken as representative of any local tectonic framework. Furthermore, the strain pattern obtained from the baseline rates proposed by Zarraoa *et al.* (1994) gives a considerably different result (fig. 6b and table IIB), consisting in an isotropic compression with a principal shortening axis directed along the Apenninic belt. This noticeable difference, in spite of the fact that the data of Ward and Zarraoa are almost compatible with each other within the relative errors, clearly testifies the high sensitivity of strain parameters to the uncertainty of geodetic data.

In order to evaluate the mutual consistency of independent observations on the present strain field, Ward (1994) compared the average strain tensor obtained by geodetic data with the one deduced from seismic moment tensor analysis (Kostrov, 1974; Jackson and McKenzie, 1988). In this regard, it must be considered that the estimate of seismic strain tensors might be affected by significant uncertainties. One is connected with the lack of direct information on moment tensors associated to the oldest earthquakes (1900-1950) which constitute, for the Italian region, the most significant contribution to the global strain release (see *e.g.*, Jackson and McKenzie, 1988). Another source of uncertainty is related to the choice of the time interval considered for the comparison between seismic and geodetic data: short time in-

**Table II.** Horizontal principal strain rate axes in Italy deduced from geodetic and seismological data. Parameters $\lambda$ and $\phi$ respectively represent the modulus (in units $10^{-9}$ $yr^{-1}$ with negative values representing shortenings) and orientation (degrees clockwise from north) of principal horizontal strain rate axes ($\varepsilon_1$ and $\varepsilon_2$) computed from baseline rates following Turcotte and Schubert (1982). Positive horizontal principal strain rate axes indicate a radial extension, negative values radial compression and alternate signs strike slip (see *e.g.*, Philip, 1987). Columns A and B respectively report principal strain rate axes deduced from the baseline rates of Ward (1994) and Zarraoa *et al.* (1994). Columns C and D report principal strain rate axes deduced from seismic moment tensor analysis (Kostrov, 1974). The results in column C were obtained in this work by considering the available fault plane solutions of earthquakes in the triangle Noto-Matera-Medicina from 1908 to 1990 (Riuscetti and Schick, 1975; D'Ingeo *et al.*, 1980; Gasparini *et al.*, 1982, 1985; Giardini *et al.*, 1984; Benina *et al.*, 1985; Dziewonski *et al.*, 1985, 1991a,b; Anderson and Jackson, 1987; Jackson and McKenzie, 1988). The geometric and mechanical parameters to be included in the Kostrov's formula, were taken from Ward (1994). Column D reports the results obtained by Jackson and McKenzie (1988) for the Apennines in the area between latitudes 40°N and 45°N.

| | A | | B | | C | | D | |
|---|---|---|---|---|---|---|---|---|
| | $\lambda$ | $\phi$ | $\lambda$ | $\phi$ | $\lambda$ | $\phi$ | $\lambda$ | $\phi$ |
| $\varepsilon_1$ | +13.6 | 068 | −5.5 | 020 | +6.8 | 068 | +1.8 | 043 |
| $\varepsilon_2$ | −6.5 | 158 | −9.7 | 110 | +1.5 | 158 | +0.0 | 133 |

tervals, comparable with the duration of VLBI campaigns (10-20 years), are not representative of the effective tectonic loading due to the relatively long interseismic periods characteristic of large earthquakes in Italy, whereas long time intervals (70-100 years) are possibly more representative of the average tectonic strain, but are not directly comparable with geodetic estimates. Furthermore, to avoid misleading conclusions on the present tectonic setting, the comparison between geodetic and seismic strain tensors should be performed taking into account both the horizontal principal strain rate axes.

Table II shows the principal horizontal strain rate axes deduced from geodetic data and two estimates of seismic strain rate tensor in Italy; the first (C) was obtained in this work, taking into account the earthquakes which occurred in the triangle Noto-Medicina-Matera from 1900 to 1990; the other estimate (D) was obtained by Jackson and McKenzie (1988) using seismic data in the Apennines (from latitude 40°N to 45°N) in the time interval 1908-1981. The results are mutually compatible and suggest the presence of an isotropic tensional regime characterized by strain rate axes having NE-SW and NW-SE trends respectively. This indication contrasts with both strain rate tensors obtained by geodetic data which indicate transtensional and isotropic compressive regimes respectively.

## 4. SLR data

Figure 7 shows the motion vectors derived from SLR data in a number of sites in the Central Mediterranean region, reported in the latest literature (Smith *et al.*, 1994).

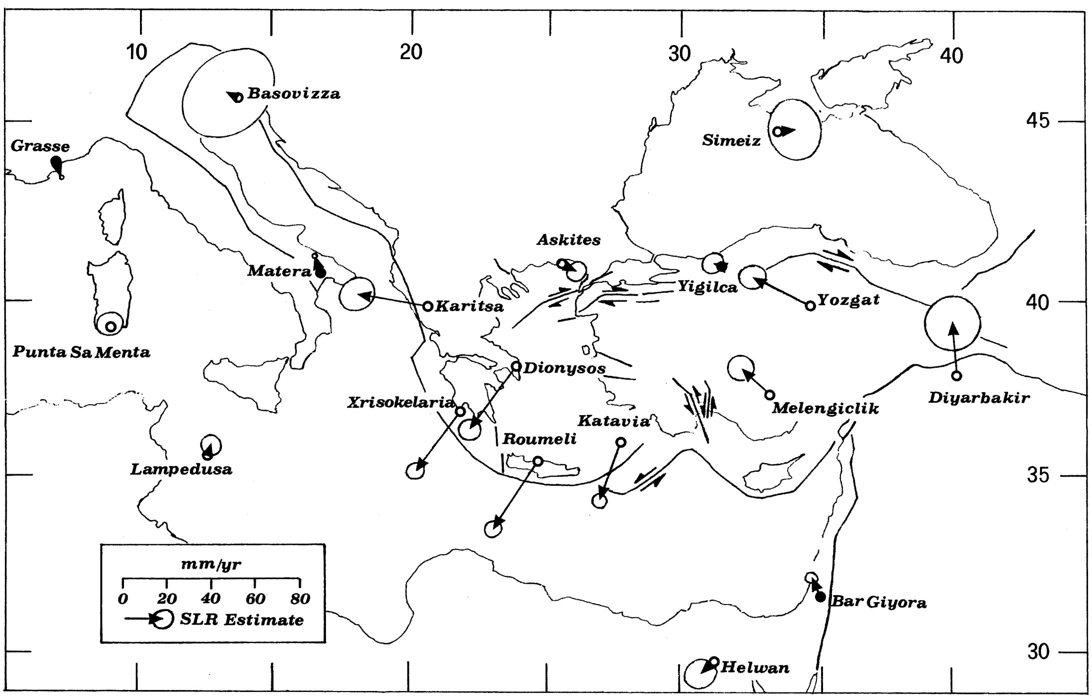


**Fig. 7.** Estimates of horizontal motions relative to Northern Europe for SLR tracking sites in the Central-Eastern Mediterranean. Permanent tracking sites are indicated with black symbols. White symbols indicate sites periodically visited by transportable systems. Ellipses represent $1\sigma$ errors (after Smith *et al.*, 1994).

It can be noted that the trend (NWward) of the Matera motion inferred by this kind of data is significantly different from those derived by VLBI observations (Northward and NEward, see fig. 2a,b). This spreading of orientations clearly indicates that to know the motion of this site and to deduce the kinematics of the Adriatic plate it is necessary to wait for a longer data set.

The motion trend of Basovizza (fig. 7) cannot be easily reconciled with the VLBI vector of Medicina (fig. 2a,b) if both sites are assumed to belong to the Adriatic plate. This discrepancy could be easily attributed to the large uncertainty affecting the SLR vector of Basovizza. However, since the motion of Medicina is most probably not representative of the Adriatic kinematics, as argued earlier, a scarce coherence between the motion trends of Medicina and Basovizza, if confirmed by more significant data, could have a tectonic explanation.

The fact that Grasse presents a significant motion with respect to North European stations is not easily reconcilable with the basic assumptions of the Nuvel-1 model (DeMets *et al.*, 1990), *i.e.* the hypothesis that Eurasia is a unique coherent block from the North Atlantic ridges to the Pacific trenches.

The high rates observed in the Eastern Mediterranean regions confirm the indications of geological and seismological data on the fact that the Aegean-Anatolian system is deforming much more rapidly than the African-Adriatic one. A result which seems scarcely compatible with seismicity rates is the high velocity of Karitsa (32 mm/yr). In fact, strain rates deduced from moment tensor analysis carried out using available fault plane solutions in the area comprised between the Ionian islands and Albania indicate a much lower shortening (directed WSW-ENE) of about 2 mm/yr (Papazachos *et al.*, 1992). Very recent results (August 1994 CDDIS bulletin) allowed a reassessment of SLR estimates at Karitsa which supports the hypothesis that rates so far estimated were significantly biased and that, at present, no significant motion with respect to Eurasia is observed at this station.

A very encouraging result, concerning our kinematic predictions in this region, is the motion vector of Lampedusa (fig. 7). This vector, in fact, is fairly coherent with the hypothesis that Africa is moving NNEward with respect to Eurasia (Mantovani *et al.*, 1990, 1992, 1993; Albarello *et al.*, 1993, 1995). Unfortunately, the great uncertainty which still affects this vector prevents any precise hypothesis on this problem.

Other interesting information provided by SLR data, which confirms the indications of current geodynamic hypotheses (Cohen, 1980; Montigny *et al.*, 1981; Rehault *et al.*, 1984) is the fact that the site of Punta Sa Menta does not show a significant motion with respect to Eurasia (see fig. 7 and table III).

## 5. Discussion and conclusions

Geodetic observations can make a fundamental contribution to the reconstruction of present tectonic processes in the Mediterranean area. However, a correct geodynamic interpretation of this kind of data requires a reliable estimate of the uncertainties which affect baseline rates or motion vectors and the identification of major active discontinuities (as possible plate borders) in the structural system under investigation. If these two basic conditions are not fulfilled, any geodynamic inference from geodetic data might be misleading.

As concerns the first problem, we only know the formal error which is associated to each baseline, but it is still poorly understood what fraction of the true uncertainty it represents. To develop a more precise idea about this aspect, we collected the results of SLR geodetic measurements so far reported in the literature (see table III). From this table several baselines present a considerable spreading of results, which often even involve inversion of movements. In the majority of cases, the range between the minimum and maximum value is much greater than the formal errors associated to the baseline rates. In order to estimate how this spreading is due to differences in the length of the data set used by different authors, we computed a number of baseline rates from SLR information reported in CDDIS bulletin

**Table III.** Baseline rates (mm/yr) in the Central Mediterranean obtained by a number of authors from SLR measurements and combined SLR and VLBI inversions. Negative values are shortening. 1,2,3) Gendt *et al.*, 1993; 4) Cenci *et al.*, 1993; 5) Reigber *et al.*, 1993; 6) Noomen *et al.*, 1993; 7) Smith *et al.*, 1994. The different values reported by Gendt *et al.* (1993) are associated to different treatments of the same data set. Parentheses show reported estimated errors (1$\sigma$). In most cases, this information is lacking due to the fact that data reported by the cited authors were not sufficient for the estimate of experimental errors. For each author, the observation period is reported.

| Baseline | 1<br>1983-1990 | 2<br>1983-1990 | 3<br>1983-1990 | 4<br>1983-1989 | 5<br>1980-1990 | 6<br>1986-1990 | 7<br>1980-1993 |
|---|---|---|---|---|---|---|---|
| Basov.-Dionysos | | | | −2 | 13 | 1 | 13 |
| Basov.-Grasse | | | | | 2 | −2 | −4 |
| Basov.-Karitsa | | | | −21 | −18 | −20 | −18 |
| Basov.-Lampedusa | | | | 0 | 20 | −18 | −3 |
| Basov.-Matera | | | | | 4 | −14 | 0 |
| Basov.-P.Sa Menta | | | | −33 | 9 | −10 | −2 |
| Basov.-Roumeli | | | | 34 | 29 | 18 | 18 |
| Basov.-Xrisokellaria | | | | 15 | 18 | −6 | 18 |
| Dion.-Grasse | 1 | 5 | 7 (05) | | −5 | 4 | −9 |
| Dion.-Karitsa | | | | 5 | 32 | 25 | 28 |
| Dion.-Lampedusa | | | | −66 | −9 | −42 | −29 |
| Dion.-Matera | 7 | 12 | 6 (06) | | 0 | −4 | −2 |
| Dion.-P.Sa Menta | −15 | −16 | | −47 | −14 | −11 | −15 |
| Dion.-Roumeli | 6 | 15 | | 20 | 16 | 8 | 2 |
| Dion.-Xrisokellaria | 11 | 14 | 11 (02) | −42 | 7 | 16 | −2 |
| Grasse-Karitsa | | | | | −36 | −21 | −35 |
| Grasse-Lampedusa | | | | | 2 | 10 | −11 |
| Grasse-Matera | −7 | −8 | −4 (02) | −12 (05) | −7 | 5 | −8 |
| Grasse-P.Sa Menta | 4 | 3 | 5 (06) | | 0 | 4 | −10 |
| Grasse-Roumeli | 12 | 9 | 9 (18) | −4 (23) | 7 | 26 | −4 |
| Grasse-Xrisokellaria | −9 | −13 | 0 (03) | −4 (16) | −6 | −9 | −6 |
| Kari.-Lampedusa | | | | −17 | −15 | −56 | −28 |
| Kari.-Matera | | | | | −31 | −32 | −28 |
| Kari.-P.Sa Menta | | | | −29 | −37 | −35 | −31 |
| Kari.-Roumeli | | | | 55 | 48 | 38 | 36 |
| Kari.-Xrisokellaria | | | | 38 | 33 | 14 | 34 |
| Lamp.-Matera | | | | | 15 | −7 | −3 |
| Lamp.-P.Sa Menta | | | | 29 | −1 | 9 | −1 |
| Lamp.-Roumeli | | | | −24 | −4 | −16 | −20 |
| Lamp.-Xrisokellaria | | | | −22 | −16 | −61 | −25 |
| Mate.-P.Sa Menta | −7 | −17 | −7 (06) | | −4 | 5 | −1 |
| Mate.-Roumeli | 23 | 22 | 24 (08) | 32 (13) | 19 | 23 | 9 |
| Mate.-Xrisokellaria | 6 | 1 | 10 (05) | 26 (10) | 7 | −6 | 9 |
| P.Sa Me.-Roumeli | −4 | −17 | | 4 | −4 | 14 | −7 |
| P.Sa Me.-Xrisokellaria | −28 | −36 | | −3 | −18 | −27 | −10 |
| Roum.-Xrisokellaria | 22 | 21 | | 10 | 14 | 36 | 2 |
| Wett.-Basovizza | | | | | −16 | | |
| Wett.-Dionysos | 20 | 24 | 22 (06) | | 4 | | |
| Wett.-Grasse | 0 | 2 | −1 (03) | −13 (07) | −2 | | |
| Wett.-Karitsa | | | | | −27 | | |
| Wett.-Lampedusa | | | | | 4 | | |
| Wett.-Matera | −6 | 0 | −7 (03) | −13 (02) | −12 | | |
| Wett.-P.Sa Menta | 2 | 1 | −2 (07) | | −3 | | |
| Wett.-Roumeli | 28 | 35 | 32 (07) | 37 (13) | 20 | | |
| Wett.-Xrisokellaria | 15 | 12 | 18 (04) | 24 (02) | 7 | | |

(June, 1994) referring to increasing lengths of the data sets (table IV). Most baselines show a spreading of values lower than that in table III. This suggests that an important role in determining the noticeable differences in baseline rates reported by various authors is probably played by the different strategies followed for the elaboration of original data. Another example of this effect is given by the differences in VLBI motion vectors of Matera obtained by Ward (1994) and Zarraoa *et al.* (1994).

As concerns the uncertainties connected with an insufficient knowledge of the plate mosaic and tectonic setting, several considerations can be made. Geological and seismological evidence suggests that the observed motion of Medicina might be representative of the kinematics of the Northern Apennines rather than of the Adriatic platform. Furthermore, the results of geodetic leveling indicate that this site may be affected by vertical movements (subsidence) much greater than the estimated horizontal motion.

A reasonably low ambiguity seems to affect the location of Matera in the Adriatic plate, but the motion trend of this site is still surrounded by considerable uncertainty, since the proposed vectors, derived by VLBI and SLR data within their relative $2\sigma$ errors, allow the drifting trend to vary from roughly ENE to WNW (see *e.g.*, Ward, 1994; Zarraoa *et al.*, 1994; Smith *et al.*, 1994).

The above remarks and the fact that the motion vector of Basovizza is not significant again suggest that to attempt a reliable estimate of the Adriatic motion it is necessary to wait for a longer data set. This is confirmed by the fact that, on the basis of currently available data, opposite conclusions could be drawn from the VLBI data reported by Ward (1994), who suggests an independent motion of the Adriatic block with respect to Africa, and those given by Smith *et al.* (1994) who instead suggest a coherent motion of the two plates.

The main ambiguity about the station of Noto concerns whether or not this site belongs to the African plate. The analysis of the Plio-Quaternary deformation pattern in Sicily and surrounding regions led some authors (Finetti, 1984; Jongsma *et al.*, 1985; Finetti and Del

**Table IV.** Baseline rates (in mm/yr) here deduced from SLR data reported in the CDDIS bulletin (June, 1994) concerning a number of stations in the Central Mediterranean. Each column reports the rates estimated for the relevant baselines using data up to 1992, 1993 and 1994 respectively. Negative values represent shortenings.

| Baseline | 1992 | 1993 | 1994 |
|---|---|---|---|
| Basov.-Dionysos | 3.6 | 5.8 | 7.8 |
| Basov.-Grasse | −7.3 | −8.7 | −7.9 |
| Basov.-Karitsa | −23.2 | −22.6 | −22.8 |
| Basov.-Lampedusa | −9.9 | −14.7 | −13.1 |
| Basov.-Matera | −15.0 | −10.7 | −10.1 |
| Basov.-P.Sa Menta | −7.0 | −7.4 | −4.7 |
| Basov.-Roumeli | 17.4 | 4.9 | 12.9 |
| Basov.-Xrisokellaria | −0.1 | 2.3 | 10.7 |
| Dion.-Grasse | −2.9 | −6.7 | −3.6 |
| Dion.-Karitsa | 28.8 | 29.4 | 31.0 |
| Dion.-Lampedusa | −30.9 | −27.2 | −26.2 |
| Dion.-Matera | −0.7 | −3.7 | −1.9 |
| Dion.-P.Sa Menta | −1.9 | −4.0 | −1.3 |
| Dion.-Roumeli | 11.6 | 1.8 | 3.0 |
| Dion.-Xrisokellaria | 12.0 | 12.7 | 0.8 |
| Grasse-Karitsa | −31.5 | −35.6 | −33.9 |
| Grasse-Lampedusa | 5.7 | −8.5 | −5.8 |
| Grasse-Matera | −3.9 | −4.8 | −3.5 |
| Grasse-P.Sa Menta | −4.6 | −9.1 | −6.3 |
| Grasse-Roumeli | 11.7 | −9.5 | 2.7 |
| Grasse-Xrisokellaria | −10.3 | −14.6 | −0.7 |
| Kari.-Lampedusa | −42.8 | −39.3 | −37.4 |
| Kari.-Matera | −31.8 | −34.7 | −33.9 |
| Kari.-P.Sa Menta | −27.4 | −28.5 | −25.9 |
| Kari.-Roumeli | 40.7 | 27.6 | 35.7 |
| Kari.-Xrisokellaria | 21.4 | 24.3 | 29.8 |
| Lamp.-Matera | 2.5 | 0.3 | 0.6 |
| Lamp.-P.Sa Menta | 15.1 | 4.5 | 5.0 |
| Lamp.-Roumeli | −18.8 | −29.9 | −16.4 |
| Lamp.-Xrisokellaria | −43.8 | −39.6 | −24.2 |
| Mate.-P.Sa Menta | 11.2 | 11.6 | 13.0 |
| Mate.-Roumeli | 20.5 | 0.6 | 10.7 |
| Mate.-Xrisokellaria | 1.6 | −1.1 | 9.7 |
| P.Sa Me.-Roumeli | 12.8 | −7.1 | 6.6 |
| P.Sa Me.-Xrisokellaria | −11.8 | −14.1 | 1.6 |
| Roum.-Xrisokellaria | 23.1 | 5.6 | 3.9 |
| Wett.-Basovizza | 10.9 | 7.7 | 7.3 |
| Wett.-Dionysos | 11.2 | 11.0 | 12.8 |
| Wett.-Grasse | 4.4 | 4.4 | 4.0 |
| Wett.-Karitsa | −12.5 | −15.1 | −15.7 |
| Wett.-Lampedusa | 3.9 | −4.5 | −3.4 |
| Wett.-Matera | −6.5 | −5.6 | −5.3 |
| Wett.-P.Sa Menta | 4.9 | 2.4 | 4.4 |
| Wett.-Roumeli | 24.9 | 11.1 | 17.5 |
| Wett.-Xrisokellaria | 10.1 | 9.8 | 16.3 |

Ben, 1986; Mantovani *et al.*, 1992, 1993) to suggest that the Iblean block moves independently from Africa. Even though one does not accept this hypothesis, the occurrence of recent/present deformations and volcanic activity in all regions surrounding the Iblean block, clearly documented by seismic investigations and seismological evidence (Carbone *et al.*, 1982; Grasso *et al.*, 1990; Reuther *et al.*, 1993), cannot be neglected.

The only site which can be safely assumed as a point of the African plate is Lampedusa. In fact, no evidence exists on possible decoupling discontinuities between this zone and the main continent. All solutions concerning this crucial point (Noomen *et al*, 1993; Smith *et al.*, 1994) indicate a significant eastward component of motion (7 to 12 mm/yr), which is not in line with that (characterized by a westward component of 2 mm/yr) predicted by the Nuvel-1 kinematic model (DeMets *et al.*, 1990). Unfortunately, this datum is still affected by a great uncertainty.

Only to draw some attention to a possible geodynamic reference which might be useful for the interpretation of future geodetic observations, we would like to make some comments on the kinematic scheme proposed by Mantovani *et al.* (1992, 1993) and Albarello *et al.* (1993, 1995), in connection with the VLBI and SLR data here considered (see fig. 8). It can be noted that the Africa-Eurasia rotation vector shown in this figure predicts motion trends and drifting rates in the Central Mediterranean which are fairly coherent with the geodetic vector in Lampedusa. The hypothesis that the Iblean microplate moves independently from Africa along a SSE-NNW direction may explain the trend of the geodetic vector of Noto. As concerns the Adriatic plate, fig. 8 reports the vectors predicted by the Adriatic-Eurasia rotation pole proposed by Anderson and Jackson (1987). This prediction would favour the solution proposed by Ward (1994). However, we do not know what significance this result has since, in our opinion, the pole here considered is not well constrained. It is based on slip vectors derived from focal mechanisms in the Eastern Alps, in the Apennines and in the Southern Dinarides (see Anderson and Jackson, 1987; Jackson and McKenzie, 1988), but actually it is far from clear whether seismic activity in the above zones, especially Southern Apennines, can be safely assumed as representative of the Adriatic-Eurasia relative motion. However, we think that the geological-seismological constraints currently available, do not allow a better definition of the Adriatic kinematics.

From the arguments discussed above, one could try to derive some indications on the geodetic measurements in the Central Mediterranean which should be privileged in the near future. In our opinion, a priority problem is a better constraining of the relative motion between Africa and stable Eurasia in order to remove, or at least mitigate, the present ambiguity about this crucial aspect of the Mediterranean tectonic pattern. For this purpose, the systematic monitoring of the baselines between Lampedusa and North European stations, such as Wettzell, Onsala and Effelsberg, or a frequent occupation with mobile stations of another site in the African foreland, would also be of basic importance. The kinematics of the Corsica-Sardinia block with respect to the surrounding regions represents an important constraint on the dynamic mechanism responsible for deformations in the Central Mediterranean (see Mantovani, 1982; Mantovani *et al.*, 1985). The available data indicate a negligible movement of this block with respect to stable Eurasia. However, the present significance of this result, with respect to the uncertainty involved, is very low, so the continuation of geodetic measurements in the site of Punta Sa Menta would be useful. The analysis of past deformations in the Balkan regions suggests that a fast relative motion occurs between the Southern Dinarides and Hellenides (Mantovani *et al.*, 1992, 1993). The decoupling of these two regions is accommodated by the dextral transpressional deformations which occur in the Albanian area (see *e.g.*, Philip, 1987). At present, the motion of the Hellenides with respect to Northern Europe is monitored by the observations in Karitsa, whereas the Dinaric belt is uncovered. Thus, the occupation in the ex-Yugoslavian territory should be very suitable, when the political situation will allow it.

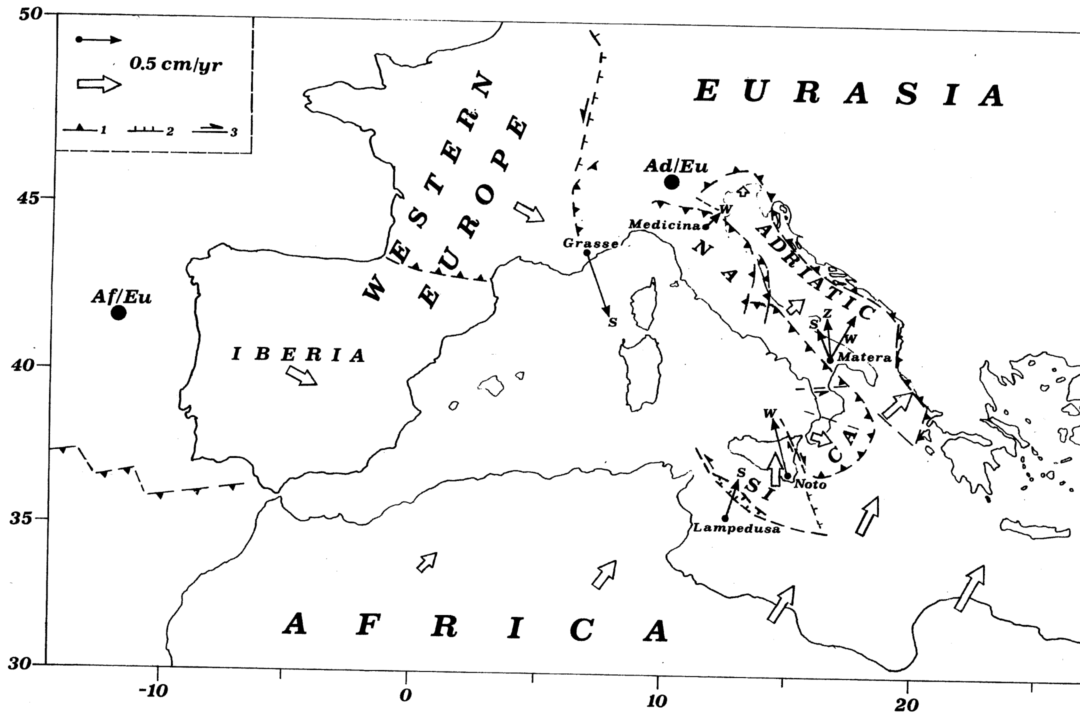


**Fig. 8.** Proposed kinematic pattern in the Mediterranean area on the basis of geological and geophysical evidence (Mantovani *et al.*, 1985, 1990, 1992, 1994; Albarello *et al.*, 1993, 1995). The vector in Sicily is taken from the microplate kinematic scheme shown in fig. 4. The vectors in the Adriatic plate are compatible with the Adriatic-Eurasia pole proposed by Anderson and Jackson (1987) and Jackson and McKenzie (1988). Small arrows marked with W, S or Z show the site rates respectively proposed by Ward (1994), Smith *et al.* (1994) and Zarraoa *et al.* (1994). 1,2,3: Compressional, tensional and transcurrent features. CA: Calabrian Arc; NA: Northern Apennines; SI: Sicilian block; Ad/Eu: Adriatic/Eurasia pole; Af/Eu: Africa/Eurasia pole.

Finally, we suggest that for the determination of geodetic motion vectors from baseline rates, with respect to stable Eurasia, the assumed reference frame should only involve north European stations lying east of the Rhine graben system, since, as argued by Mantovani *et al.* (1992, 1993) and Albarello *et al.* (1993, 1995), the stations lying west of the Rhine graben might not be representative of the stable Eurasia. The motion of blocks in the area considered might be discontinuous in time, especially around seismic periods and this could introduce a significant bias in the motion rates determined from geodetic data without considering this problem.


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