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**Pure and Applied Geophysics**

# Geodetic Measurements of Crustal Deformation in the Western Mediterranean and Europe

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*Abstract*— Geodetic measurements of crustal deformation over large areas deforming at slow rates ( < 5 mm/yr over more than 1000 km), such as the Western Mediterranean and Western Europe, are still a challenge because (1) these rates are close to the current resolution of the geodetic techniques, (2) inaccuracies in the reference frame implementation may be on the same order as the tectonic velocities. We present a new velocity field for Western Europe and the Western Mediterranean derived from a rigorous combination of (1) a selection of sites from the ITRF2000 solution, (2) a subset of sites from the European Permanent GPS Network solution, (3) a solution of the French national geodetic permanent GPS network (RGP), and (4) a solution of a permanent GPS network in the western Alps (REGAL). The resulting velocity field describes horizontal crustal motion at 64 sites in Western Europe with an accuracy on the order of 1 mm/yr or better. Its analysis shows that Central Europe behaves rigidly at a 0.4 mm/yr level and can therefore be used to define a stable Europe reference frame. In that reference frame, we find that most of Europe, including areas west of the Rhine graben, the Iberian peninsula, the Ligurian basin and the Corsica-Sardinian block behaves rigidly at a 0.5 mm/yr level. In a second step, we map recently published geodetic results in the reference frame previously defined. Geodetic data confirm a counterclockwise rotation of the Adriatic microplate with respect to stable Europe, that appears to control the strain pattern along its boundaries. Active deformation in the Alps, Apennines, and Dinarides is probably driven by the independent motion of the Adriatic plate rather than by the Africa-Eurasia convergence. The analysis of a global GPS solution and recently published new estimates for the African plate kinematics indicate that the Africa-Eurasia plate motion may be significantly different from the NUVEL1A values. In particular, geodetic solutions show that the convergence rate between Africa and stable Europe may be 30–60% slower than the NUVEL1A prediction and rotated 10–30° counterclockwise in the Mediterranean.

**Key words:** Plate motions, plate boundary zone, crustal deformation, Mediterranean, geodesy, GPS.

## *Introduction*

The boundary between the African and Eurasian plates in the Mediterranean area consists of a broad zone of deformation, extending from north Africa to central Europe (Fig. 1). Active deformation in the Africa-Eurasia plate boundary zone is generally interpreted as the result of the convergence between the African and

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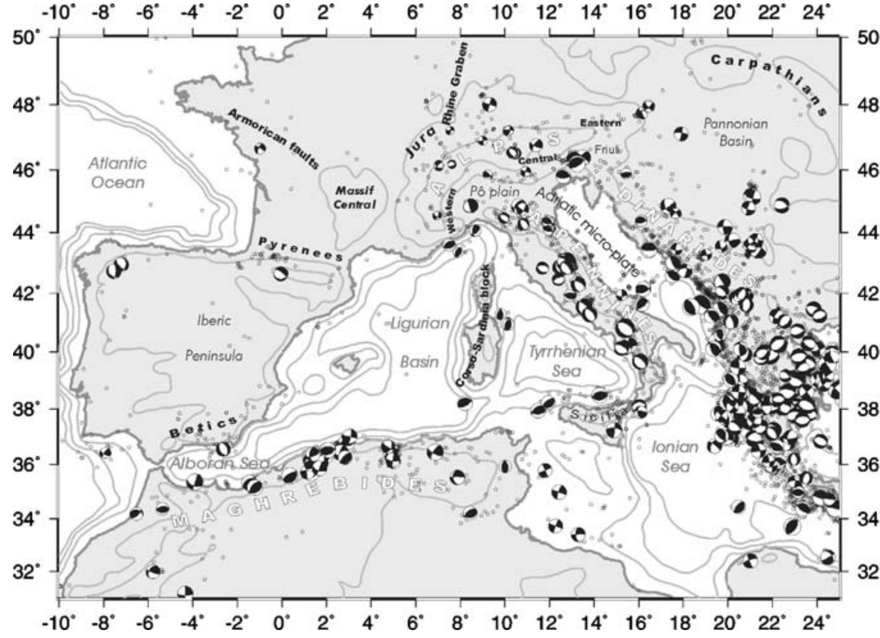

Figure 1
Seismicity map of Europe and the Western and Central Mediterranean. Epicenter locations for the 1973–2002 period ($M_s > 3.0$, NEIC catalog). Earthquake focal mechanism from Harvard (http://www.seismology.harvard.edu/CMTsearch.html) and Swiss tensor Moment Project (http://seismo.ethz.ch/info/mt.html) for the 1997–2002 period, $M > 5$.

Eurasian plates, ranging from ~10 mm/yr at the longitude of Turkey to ~4 mm/yr in the Gibraltar Strait according to the NUVEL1A global plate kinematic model (DEMETS *et al.*, 1990, 1994). In addition, geodetic measurements in Greece and Turkey reveal the existence of a separate Anatolian plate, moving west to southwestward at 20–30 mm/yr with respect to Eurasia (e.g., MCCLUSKY *et al.*, 2000). In contrast with the eastern part of the Africa-Eurasia plate boundary zone in Greece and Turkey, with large velocities and strain rates, little is known yet regarding the kinematics of crustal deformation in the Western Mediterranean.

The Western Mediterranean area is part of the plate boundary between Africa and Eurasia (Fig. 1). It is surrounded by Alpine mountain ranges (Betics, Atlas and Maghrebides, Apennines, Dinarides, Alps), usually thought to accommodate the Africa-Eurasia plate convergence. However, the Western Mediterranean-Alps domain also includes significant strike-slip (e.g., Western Swiss Alps, EVA and SOLARINO, 1998) and extensional (e.g., Apennines, D'AGOSTINO *et al.*, 2001) active tectonic features. In addition, several aseismic domains are embedded in the plate boundary zone, interpreted either as rigid blocks or microplates (Corsica-Sardinian block, Adriatic and Iberian microplates), or as undeformed sedimentary basins (Ligurian and Pannonian basins). The relatively low plate motion and strain rates in the Western Mediterranean and the long recurrence time for large earthquakes make seismological and geomorphological indicators of active deformation scarce and difficult to interpret. As a consequence, strain distribution across the Africa-Eurasia plate boundary in the Western Mediterranean and strain accumulation on the major seismogenic structures are still largely unknown.

In addition to active deformation in the Africa-Eurasia plate boundary zone, instrumentally recorded seismicity shows a moderate but non-negligible activity in some intraplate areas in Europe such as the Rhine graben and the Armorican faults (Fig. 1). Both structures are located hundreds to thousands of kilometers away from the major plate boundary and penetrate deeply inside the Eurasian plate interior, suggesting that some of the Africa-Eurasia convergence could be transferred as far north as Central Europe. Measuring possible intraplate deformation of the Eurasian plate in Western Europe is therefore important to understand how stress is transferred across plate boundaries. Assessing the level of rigidity of the Eurasian plate in Europe is also important to define an unbiased plate-fixed reference frame for mapping geodetic velocities.

In this study, we present a newly combined velocity field for Western Europe and the Western Mediterranean and a critical analysis of recent geodetic results published for this area.

## *A Combined Velocity Field for Western Europe and the Western Mediterranean*

In the past decade, geodetic measurements have been widely used to monitor crustal motions, from tectonic plates to local surveys of active faults, with precision levels on the order of 2–3 mm/yr (horizontally) routinely achieved. In the last few years, the increasing accuracy and density of space geodetic measurements have also permitted the testing of plate rigidity at a 2 mm/yr level (ARGUS and GORDON, 1996; DIXON *et al.*, 1996; DEMETS and DIXON, 1999; KOGAN *et al.*, 2000). However, 1–2 mm/yr of motion within several hundreds of kilometers can still lead to significant deformation over recent geological times. In particular, it may result in sufficient elastic stress accumulation to cause moderate to large earthquakes on faults with long recurrence intervals (1000 years and more, e.g., NEWMAN *et al.*, 2001). In addition, 1–2 mm/yr of internal deformation within a block or plate chosen as a "stable" reference frame for the purpose of a geophysical interpretation may introduce a significant bias in the velocity field, in particular in areas deforming at very slow rates (DIXON *et al.*, 1996). However, the determination of a dense and consistent velocity field at a continental scale, accurate at a sub-millimeter per year level, still remains a challenge.

This study is based on a newly combined velocity field for Western Europe and the Western Mediterranean. Indeed, combining the results from several networks and/or analysis centers provides a number of advantages over the analysis of each solution independently. First, it minimizes possible systematic errors associated with each processing strategy taken individually. Second, sites shared by several solutions provide a way to tie these solutions into a single and consistent velocity field and permit comparison of individual solutions for the detection of outliers. Third, reference frame constraints applied in individual geodetic solutions can significantly affect velocities (and positions), making direct comparisons between such solutions inadequate (SILLARD and BOUCHER, 2001).

We use a combination methodology that handles reference frame constraints simultaneously for all individual solutions in a rigorous way (e.g., BROCKMANN, 1997; DAVIES and BLEWITT, 2000; ALTAMIMI *et al.*, 2002). Because we use 14-parameter transformations and minimally constrained solutions in the combination and no additional constraints, relative positions and velocities of individual solutions are not affected by the reference frame definition. Finally, we apply a weighting scheme that rescales the variance-covariance matrices of each individual solution and provides realistic formal errors. The combination methodology is similar to the one used for the determination of the ITRF. It is fully described in ALTAMIMI *et al.* (2002) and NOCQUET and CALAIS (submitted). We include in the combination (1) a selection of 36 sites from the ITRF2000 solution, (2) a solution from a subset of sites of the European Permanent GPS Network (EUREF-EPN), (3) a solution of the French national geodetic permanent GPS network (RGP), and (4) a solution of a permanent GPS network in the western Alps (REGAL; CALAIS *et al.*, 2000). The input data to the combination consist of individual solutions with minimal constraints applied. The combination model consists in estimating simultaneously, a position at a reference epoch and a velocity for each site, and a 14-parameter transformation between the individual and the combined solution (see ALTAMIMI *et al.*, 2002 for details). The reference frame definition in the combination is implemented by imposing the 14–parameter transformation between ITRF2000 and the combined solution to be zero (no translation, scale factor, or rotation and no rate of change of these parameters). The resulting velocity field is therefore expressed in the ITRF2000 reference frame. From this preliminary combination, an *a posteriori* variance factor $\sigma_s^2$ for each individual solution $s$ is estimated in the inversion, which is then applied to the variance-covariance matrix of the corresponding individual solution iteratively until both individual $\sigma_s^2$ and the global *a posteriori* variance factor equals 1. Normal residuals in the combination are used for outlier detection. For most of the sites common to several individual solutions we find an agreement in horizontal velocities on the order of 0.5 mm/yr, with formal errors in horizontal velocities less than 1 mm/yr. The best determined sites have a formal error of about 0.2 mm/yr on horizontal velocities. Once the combined velocity field is obtained, we analyze it for plate rigidity following a procedure fully described in NOCQUET *et al.* (2001). We first use an algorithm that searches, over all possible site combinations, the subset of four sites whose velocities best fit a rigid rotation. We use $\chi^2$ tests and minimal variance criteria to rank the site subsets according to their fit to a rigid rotation. We then progressively augment this initial subset of sites by adding one site at a time and testing the consistency of the new site subset with a rigid rotation using $\chi^2$ and *F*-ratio tests. Following this procedure, we find a 29-site subset that defines a rigid domain extending from Central Europe to the westernmost part of Europe, including Spain and Sardinia (Fig. 2). This 29-site subset defines a stable Europe-ITRF2000 rotation pole located at 56.0°N/–101.5°W with an angular rate of 0.25 ± 0.003°/Ma. The weighted rms of the residuals at the sites used to define stable Europe is 0.4 mm/yr. It makes use of all the available geodetic techniques and of the full covariance matrix of the ITRF2000 SINEX file. This approach is independent from the NNR-NUVEL-1A plate motion model and benefits from the consistency of our velocity field combination over Europe. Although the 29-sites rigid subset extends to the east as far as Moscow, we cannot assert that the rigid motion defined by this subset is representative of the whole Eurasian plate motion. We therefore use the expression "stable Europe" rather than "Eurasia" to refer to the region encompassing our 29 sites hereafter in the text. We find no significant residual motion with respect to central Europe at the 0.5 mm/yr level at the continuous GPS

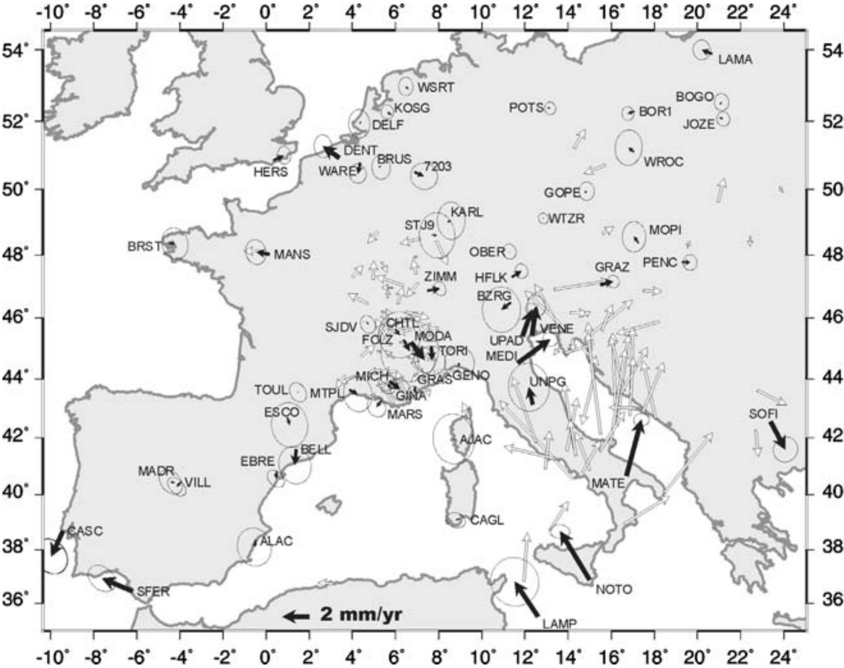

Figure 2
Combined velocity field for Western Europe and the Western Mediterranean, with respect to stable Eurasia (definition in the text). Black arrows show velocities at continuous sites. Error ellipses are 95% confidence and account for the variance of the data and the variance of the Eurasia Euler parameters. White arrows show velocities at campaign sites.

sites located in France, outside of the seismically active areas of the Alps and Jura (BRST, SJDV, TOUL, MTPL). This indicates that the stable part of France (outside the Alps and Jura) is rigidly attached to Central Europe and places an upper bound of 0.5 mm/yr (1 sigma) on possible horizontal motion across the Rhine graben.

In addition to solutions from continuous GPS networks, we also use results from GPS campaign measurements because they provide denser spatial sampling of the actively deforming areas. We used a selection of sites from (1) ANZIDEI *et al.* (2001; 1991–1998 surveys in Italy and North Africa), (2) ALTINER (2001; 1994–1996 surveys in the Dinarides), (3) VIGNY *et al.* (2002; 1993–1998 surveys in the Western Alps), and (4) GRENERCZY *et al.* (2000; 1994–1997 surveys in Central Europe and the Friuli area). We had access to VIGNY *et al.*'s (2002) full solutions (estimated parameters and full covariance) and were therefore able to combine them rigorously with the continuous GPS solutions, following the methodology described above. Since we did not have access to the full solution (including reference frame constraints information and full covariance matrix) for the other campaign results, we chose to account for the fact that they use different processing strategies and/or definitions of the stable Europe-fixed frame, by estimating a rotation between each solution and the ITRF2000, using sites common with the ITRF and verifying the obtained residuals. We find no significant rotation and residuals between GRENERCZY *et al.*'s (2000) results and ITRF2000. We find a significant rotation between ANZIDEI *et al.*'s (2001) results and the ITRF2000 and a poor agreement with the ITRF2000 velocities, suggesting an incorrect implementation of the reference frame in the GPS analysis. This is confirmed by a new analysis of this data set (SERPELLONI *et al.*, 2001). ALTINER'S (2001) velocities are mapped with respect to the IGS station GRAZ (Graz, Austria). We therefore added the ITRF2000 velocity for GRAZ and imposed a continuity constraint of the velocity field along the Trimiti line where Altiner's data merge Anzidei *et al.*'s data. The resulting velocity field is shown in Figure 1.

We emphasize the fact that, besides Vigny *et al.*'s solution, the campaign velocities used here are not derived from a homogeneous processing or a rigorous geodetic combination. In addition, the simplistic procedure used here to join the campaign solutions does not allow us to produce reliable uncertainties. However, when rigorously combining VIGNY *et al.*'s (2002) campaign solutions with continuous data, we found that the campaign-only results underestimate the velocity formal errors by a factor of 2 to 5. Consequently, the campaign velocities presented here should be interpreted with caution and only general trends could be considered as reliable.

## *Africa-Eurasia Convergence in the Western Mediterranean*

The relative motion between the African and Eurasia plates is the kinematic boundary condition of the Alpine-Mediterranean active deformation system. It is therefore a key parameter for understanding the dynamics of active deformation in the Africa-Eurasia plate boundary zone. Because of the lack of geodetic sites on the African plate, its current motion is usually taken from plate models derived from oceanic magnetic anomalies and transform azimuths directions along the mid-Atlantic ridge, such as ARGUS *et al.*'s model (1989) or, more often, the NUVEL1A global plate model (DEMETS *et al.*, 1990, 1994). Only recently, new permanent GPS stations installed on the African plate have allowed for the first direct estimates of its rotation parameters (Fig. 3).

We computed rotation parameters of Africa with respect of stable Europe using the IGS02P09 combined IGS solution, updated for GPS-week 1155 (March 2nd, 2002). This solution is a combination of weekly global solutions provided by the 7 IGS data analysis centers. It contains positions and velocities in ITRF2000 for 11

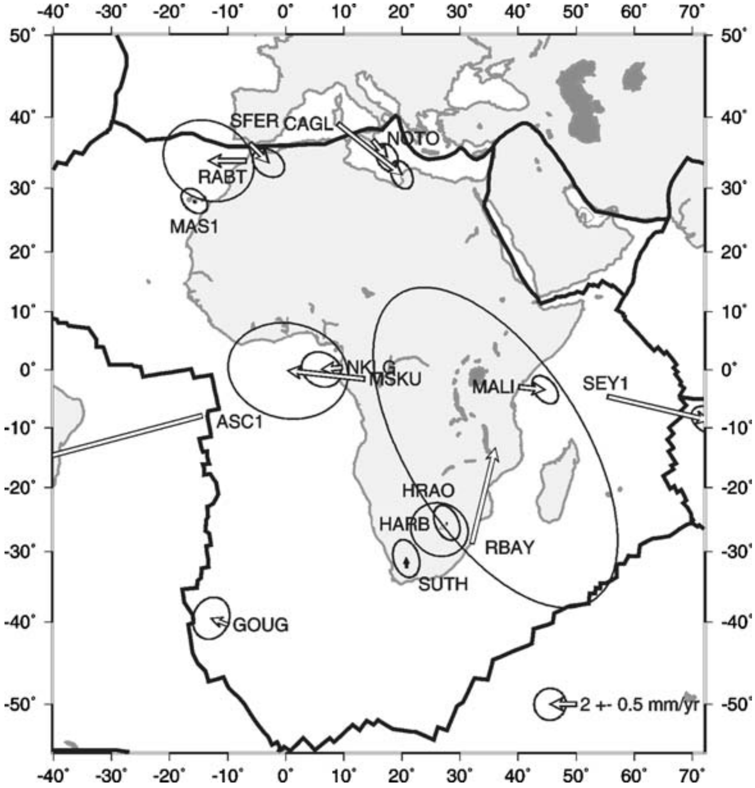

Figure 3
Residual velocities in Africa and some surrounding sites, after removing the rigid rotation defined by GOUG, HARB, NKLG, MAS1, HRAO, SUTH (M2 model, Table 1). This solution based on the IGS combined solution IGS02P09. The 95% confidence ellipses account for the data variance and the variance of the African Euler parameters. A rigid rotation estimated for (GOUG, HARB, NKLG, MAS1) (M1 model, Table 1) shows no significant difference with the one presented here.

continuous GPS sites in Africa and the surroundings (Fig. 3), with the full associated covariance matrix. We first select the sites that best represent stable Africa, following the procedure described above for Europe (NOCQUET *et al.*, 2001). We find the "most rigid" site subset to be GOUG, HARB, NKLG, and MASP, with residual velocities less than 0.7 mm/yr (Model IGS02P09-M1 in Table 1). Residual velocities are 2 to 8 mm/yr at the sites located east of the East African rift on the Somalian plate and can therefore not be used to estimate a rigid rotation for the African plate. SUTH, located southwest of HARB, has a residual velocity of 1.8 mm/yr. Adding this site to the estimation of the African plate rotation parameters has a negligible impact on predicted velocities in the Mediterranean area ($<$ 0.5 mm/yr, Model IGS02P09-M2 in Table 1, Fig. 3). Fischer and $\chi^2$ tests indicate that both NOTO (Sicily, 1.4 ± 0.5 mm/yr residual velocity with respect to Africa) and SFER (Southern Spain, 2.0 ± 0.7 mm/yr residual velocity with respect to Africa) can be distinguished from Africa at the 95% confidence level but not at the 99% level. CAGL (Cagliari, Sardinia) shows a large residual (6.0 ± 1.5 mm/yr) clearly indicating that Sardinia does not belong to the African plate.

We then subtract the stable Europe-ITRF2000 rotation parameters defined above from the Africa-ITRF2000 rotation parameters from our model (IGS02P09-M2, Table 1) to obtain the Africa-stable Europe rotation parameters. Figure 4 shows predicted velocities along the Africa-Eurasia plate boundary in the Mediterranean, according to these Africa-stable Europe rotation parameters and to recently published Africa-Eurasia models. All models besides ALBARELLO *et al.* (1995) indicate N0 to N45W convergence between the African and Eurasian plate in the Mediterranean, from convergence in the eastern part of the plate boundary,

Table 1

*Recently published Africa-Eurasia rotation parameters*

| Source | Lat. (degrees) | Long. | Ang. vel. (deg./Myr) | Data used |
|---|---|---|---|---|
| ARGUS *et al.* (1989) | 18.8 | −20.3 | 0.10 ± 0.02 | Magnetic anomalies and transform azimuths directions along the mid-Atlantic ridge |
| DEMETS *et al.* (1994) | 21.0 | −20.6 | 0.13 ± 0.02 | Same as above plus plate circuit closure |
| CRÉTAUX *et al.* (1998) | 26.1 | 20.2 | 0.139 ± 0.03 | 4 sites, DORIS solution |
| ALBARELLO *et al.* (1995) | 41.6 | −11.8 | 0.117 | Same as ARGUS *et al.*, (1989) |
| SELLA *et al.* (2002) | 18.2 | −20.0 | 0.060 ± 0.005 | 5 sites, GPS solution |
| KREEMER and HOLT (2001) | 2.6 | −21.0 | 0.036 ± 0.005 | 7 sites, GPS solution |
| This study (IGS02P09 M1) | 2.1 | −20.0 | 0.07 ± 0.02 | 4 sites (GOUG, MAS1, HARB, NKLG), GPS IGS global solution |
| This study (IGS02P09 M2) | 7.7 | −18.3 | 0.07 ± 0.02 | 6 sites (same as above + HRAO, SUTH), GPS IGS global solution |

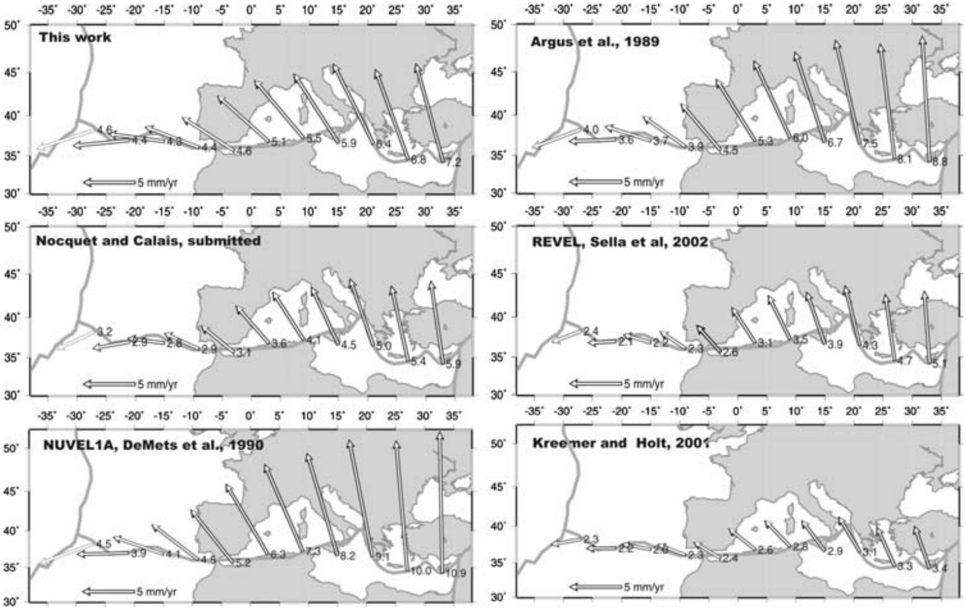

Figure 4
Predicted velocities for the African plate with respect to stable Europe along the Africa-Eurasia plate boundary in the Mediterranean (Table 1). Panel labelled "this work" corresponds to the IGS02P09 M1 solution of Table 1. Numbers by the arrows are velocities in mm/yr.

progressively transitioning westward to transpression (Tunisia-Algeria-Morocco), strike-slip (Gloria transform fault), and transtension (Azores). The convergence velocity varies between models in the 3–10 mm/yr range for the eastern Mediterranean, and in the 3–8 mm/yr range for the Western Mediterranean. The comparison between geological and geodetic models shows an Africa-stable Europe convergence rate 30 to 60% slower for the geodetic models. Also, the geodetic estimates are rotated 10° to 30° counterclockwise compared to the geological model values. The differences among the geodetic estimates themselves are significant, ranging from 3 to 5.7 mm/yr at the longitude of Sicily to 2.5 to 4.5 mm/yr in the Gibraltar Strait. In particular, we find a significant difference between our IGS02P09-derived Euler parmeters and those of SELLA *et al.* (2002) (Table 1).

The differences among the geodetic estimates may be due to the different data span and data processing strategy used, or to the list and geographic distribution of the sites used to invert for the Eurasian and African plate rotation parameters. In order to separate these two effects, we have used the IGS02P09 solution and inverted for the Eurasia and Africa plate motion using the same site selection as SELLA *et al.* (2002). We find Euler parameters that are statistically indistinguishable from SELLA *et al.* (2002) and velocity predictions in the Mediterranean that differ by less than 0.5 mm/yr. However, we find that the Sella *et al.*'s rotation parameters for Eurasia lead to significant residual velocities in the IGS02P09 solution at the sites located on the Eurasian plate (up to 3 mm/yr). We therefore suspect that the difference between the Sella *et al.* and IGS02P09 parameters for the Africa–Eurasia relative motion results primarily from the choice of sites used to define Eurasia. Our tests indeed show that the definition of the Eurasian plate (i.e., the subset of sites chosen to represent stable Eurasia) influences geodetic velocities in the Mediterranean by up to 2.5 mm/yr. This is 50% of the expected signal in the Western Mediterranean and, therefore, cannot be neglected.

### *The Adriatic Microplate and its Boundaries*

The Adriatic indenter (or Apulian promontory) is a prominent feature in the Mediterranean area. It is a relatively aseismic domain, bounded by actively deforming areas (Apennines, Alps, Friuli, Dinarides). Anderson and Jackson (1987) first proposed that the Adriatic indenter may actually be an independent microplate, detached from the African plate and rotating counterclockwise with respect to stable Europe around a pole located at 45.8°N/10.2°E. Using VLBI results at MATE and MEDI, Ward (1994) reached a similar conclusion but proposed a rotation pole located at 46.8°N/6.3°E and an angular rate of 0.30 ± 0.06°/Ma. Westaway (1990) used tectonic information and earthquake focal mechanisms to infer a rotation of the Adriatic microplate at 0.3°/Ma around a pole at 44.5°N/9.5°E. More recently, Calais *et al.* (2002) inverted simultaneously geodetic velocities from a combination of permanent GPS arrays in Western Europe and Anderson and Jackson's (1987) slip vectors of major earthquakes in Italy. They find a rotation pole at 45.36°N/9.10°E and an angular rate of 0.52°/Ma (Fig. 5). Figure 6 compares, in a stable Europe-fixed frame, the observed velocities from the combined solution described above with velocities predicted by each of these models. We find that the geodetic data generally agree with a counterclockwise rotation of the Adriatic plate with respect to stable Europe. However, the fit of the GPS-derived velocities to a rigid plate model is fair, at best. This is due, in part, to the lower quality of the campaign solutions in the combination presented here. It may also reflect internal deformation of the Adriatic microplate. Anderson and Jackson (1987), Westaway (1990), and Calais *et al.* (2002) models fit the GPS data equally well.

These models imply NE-SW extension in the Apennines at a rate that increases from North (1–2 mm/yr) to South (4–6 mm/yr), in good agreement with the extension rates derived from independent geodetic studies (Anzidei *et al.*, 2001; D'Agostino *et al.*, 2001; Hunstad and England, 1999). This rotation of the Adriatic microplate implies NE-SW shortening in the Dinarides and the N-S compression in the Friuli area, consistent with recently published focal mechanisms (Montone *et al.*, 1999; Pondrelli *et al.*, 2002) and neotectonic studies (Benedetti *et al.*, 2000). The velocity of UPAD and VENE with respect to stable Europe (Fig. 5)

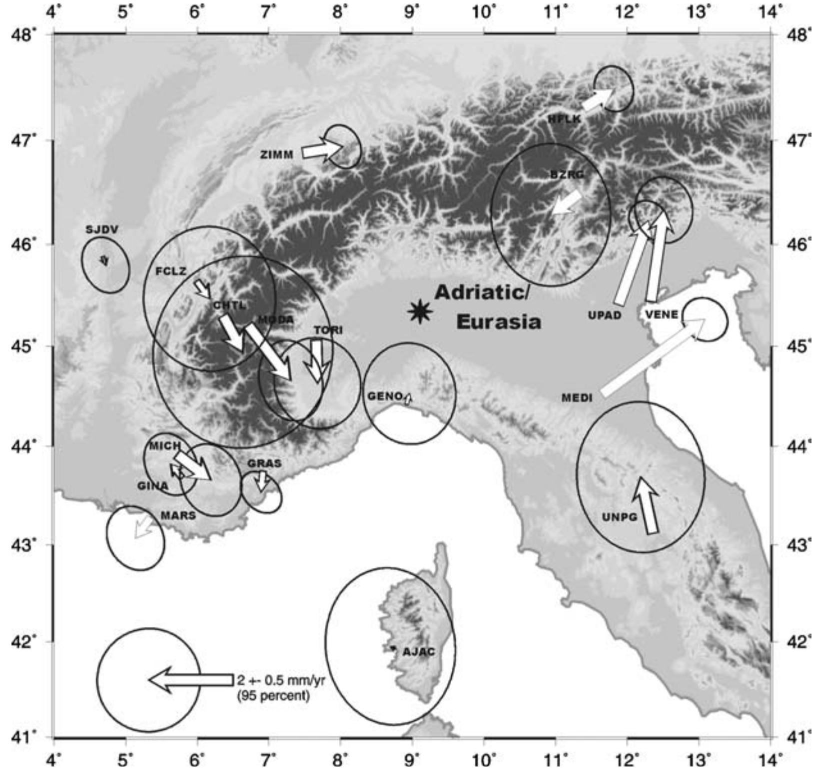

Figure 5
Close-up on the Alps and the northern part of the Apennines and the Adriatic plate, velocities derived from permanent GPS networks with respect to stable Eurasia (definition in the text). Error ellipses are 95% confidence and account for the variance of the data and the variance of the Eurasia Euler parameters. The star indicates the location of the Adriatic/Eurasia Euler pole computed from UPAD and TORI velocities and earthquake slip vector data used by ANDERSON and JACKSON (1987).

indicates NS shortening at ~2 mm/yr (2.2 ± 0.6 mm/yr at UPAD). The corresponding strain rate is on the order of $10^{-8}$ $\text{yr}^{-1}$, consistent with GRENERCZY *et al.*'s (2000) result of $8.6 \pm 2.5 \times 10^{-9}$ $\text{yr}^{-1}$ in the same area. Further west, the rotation of the Adriatic microplate implies NW-SE compression, transitioning to dextral shear between 8°E and 10°E, consistent with seismotectonic data (MAURER, 1997; EVA and SOLARINO, 1998). In the Western Alps (west of 8°E), the rotation of the Adriatic microplate, together with the arcuate shape of the contact between the Po plain and the Alps, implies dextral shear kinematic boundary conditions, with an additional divergent component in their central part and in Switzerland, and a convergent component in their southern part. Earthquake focal mechanisms in the western Alps show right-lateral motion on NE-SW and NS trending faults, combined with extension in the northern and central parts (EVA *et al.*, 1997; EVA and SOLARINO, 1998; SUE *et al.*, 1999), and compression in the southern part (MADDEDU *et al.*, 1997;

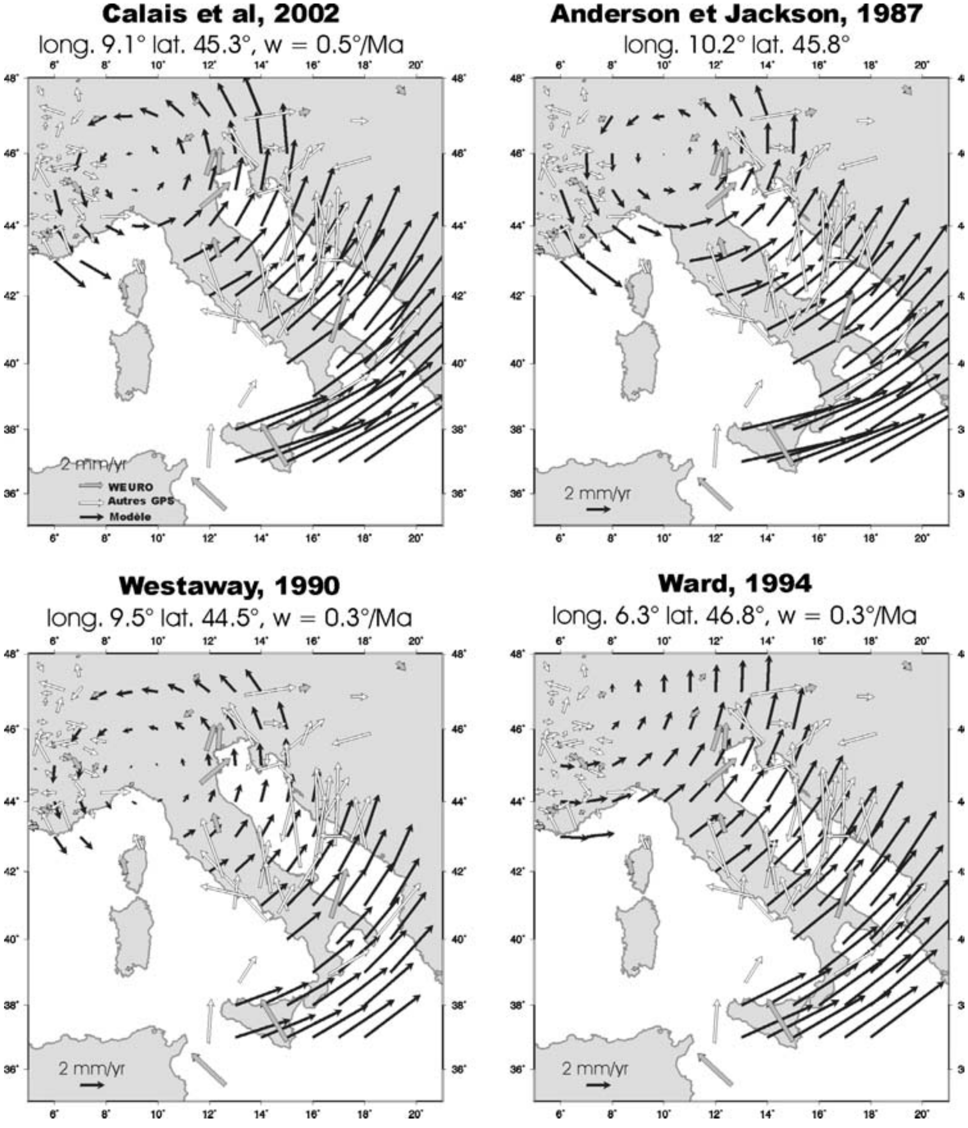

Figure 6

Kinematics of the Adriatic microplate. Black arrows show the velocities predicted by four different models. Grey arrows show observed velocities from continuous GPS stations. White arrows show GPS campaign results from Anzidei *et al*. (2001), Altiner *et al*. (2001), Grenerczy *et al*. (2000) and Vigny *et al*. (2002).

Baroux *et al*., 2001). In addition, continuous GPS data in the western Alps show east to southeastward velocities with respect to stable Europe, indicating a strain regime that combines right-lateral shear with E-W extension in the northern and central part of the range, and N-S to NW-SE compression in the southern part

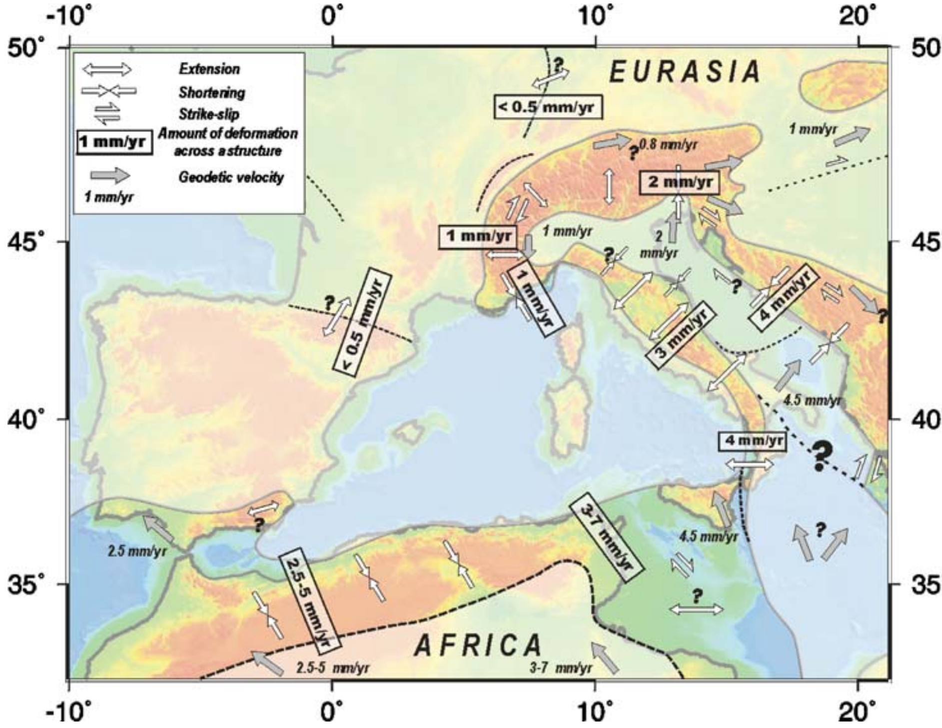

Figure 7
Schematic map of the Africa-Eurasia plate boundary zone in the Western Mediterranean. Areas of active deformation are highlighted, they correspond to the main seismically active areas. Numbers indicate amounts of deformation across highlighted areas. Open arrows indicate strain regime, grey arrows indicate direction of motion with respect to the Eurasian plate.

(Fig. 5; Calais *et al.*, 2002). The velocity gradient across the Western Alps does not exceed 2 mm/yr, corresponding to strain rates on the order of $10^{-8}$ $\text{yr}^{-1}$ or less.

### *The Corsica-Sardinia Block*

Corsica and Sardinia constitute a narrow continental domain, relatively aseismic, bounded by two oceanic basins, the Ligurian basin to the west and the Tyrrhenian Sea to the east. Corsica and Sardinia have sometimes been interpreted as an independent tectonic block, moving northward and colliding with continental Europe. This hypothesis is derived from earthquake focal mechanisms and microtectonic observations of neogene faulting, that show N-S shortening along the northern margin of the Ligurian basin in the southern part of the French Alps, and in Provence (Ritz, 1992; Maddedu *et al.*, 1997; Baroux *et al.*, 2001). The current geodetic results do not support that conclusion (Figs. 2 and 5). The best determined geodetic site in this domain is CAGL (Cagliari, Sardinia, Fig. 2). Its velocity is determined from SLR and continuous GPS measurements since 1995. All the geodetic solutions used here exhibit a residual velocity for CAGL less than 0.5 mm/yr in a stable Europe-fixed frame as found by DEVOTI *et al.* (2002). Similarly, continuous GPS site AJAC, although less well determined than CAGL, shows a negligible residual velocity ( < 0.3 mm/yr) with respect to stable Europe (Figs. 2 and 5).

It therefore appears that Corsica and Sardinia, and probably the entire Ligurian basin, are rigidly attached to stable Europe. We propose that the N-S shortening observed along the northern margin of the Ligurian basin, in the southern part of the French Alps and in Provence, results from the counterclockwise rotation of the Adriatic microplate, as explained above, rather than from the motion of an independent Corsica-Sardinia block. Furthermore, the fact that Corsica-Sardinia and the Ligurian basin are part of stable Europe implies that the convergence between Africa and stable Europe in the Western Mediterranean must be accommodated south of Sardinia, most probably by active deformation in the Maghrebides ranges in North Africa. This is also suggested by the velocities at CAGL and LAMP (Fig. 2), that indicate between 3 and 5 mm/yr of NW-SE shortening, possibly taken up by transpressional deformation in North Africa (MEGHRAOUI *et al.*, 1986).

## *The Iberian Peninsula*

The Iberian peninsula is a relatively aseismic area separated from the rest of Europe by the Pyrenées mountain range. The Pyrenées have a moderate seismicity with some instrumentally recorded earthquakes reaching magnitude 5, mostly located in the northwestern part of the range (DELOUIS *et al.*, 1993; SOURIAU and PAUCHET, 1998). Geodetic VLBI observations in Europe, including the VLBI station of Madrid, have been performed on a regular basis since the early 1990s. They indicate a negligible velocity of Madrid with respect to Wettzel, located on stable Europe (0.1 ± 0.3 mm/yr; HAAS *et al.*, 2000). The analysis of the ITRF2000 velocity field, that includes these VLBI measurements, confirms this result (Fig. 2). In addition, the continuous GPS site VILL (Villafranca, near Madrid) shows a residual velocity less than 1.1 mm/yr relative to stable Europe (Fig. 2). This result is confirmed by an independent GPS-only solution recently published by SELLA *et al.* (2002). Residual velocities at other continuous GPS sites in Spain show no significant motion with respect to stable Europe at their uncertainty level (Fig. 2). Together with the velocity at site TOUL, located in France about 100 km north of the Pyrenées, these results imply an upper bound of 0.5 ± 1.5 mm/yr (95% confidence) for possible motion across the Pyrenées. We therefore consider the Iberian peninsula as rigidly attached to stable Europe. Consequently, stable Europe (at the ~0.5 mm/yr level) spans from central Europe to France, and includes the Iberian Peninsula, the Ligurian basin, Corsica, and Sardinia.

The southern part of the Iberian peninsula is characterized by a diffuse seismicity, well expressed in the Betics Cordillera and in southern Portugal. The velocity at SFER, the best determined site in the southern part of the Iberian peninsula, is 2.4 ± 1.1 mm/yr in a westward direction with respect to stable Europe (95% confidence, Fig. 2). We therefore suggest that the Africa-Eurasia plate boundary at the longitude of Iberia involves a relatively broad domain, encompassing the Betic Cordillera and possibly southern Portugal.

## *Summary and Discussion*

### *African Plate*

The motion of the African plate with respect to stable Europe is not fully established yet. Geodetic estimates agree on a N45W ± 20 ° convergence at the longitude of Sicily, transitioning progressively to a more E-W convergence direction toward the Gibraltar Strait. Estimates of convergence rates range between 3 to 7 mm/yr at the longitude of Sicily, decreasing westward to 2 to 5 mm/yr at the longitude of the Gibraltar Strait (Figs. 4 and 7). In spite of the fairly large scatter between the geodetic solutions, they consistently indicate an Africa-stable Europe convergence rate slower than the prediction of geological models by a factor ranging from 1.2 to 2. These differences between the geodetic solution and geological model may be due to inaccuracies in the model and/or in the geodetic data. CHU and GORDON (1999), found that splitting Africa into two plates (Nubia and Somalia) and removing the plate circuit closure condition in the Pacific significantly modified the angular velocity of India relative to Eurasia, compared to the original NUVEL-1A value. The updated version of NUVEL1 (MORVEL) is currently being produced and will include a Nubian and a Somalian plate. However, a preliminary version indicates a velocity of 6.9 mm/yr in a N341 direction at NOTO with respect to Eurasia (C. DEMETS, personal communication, 2002). If this was confirmed, it therefore seems unlikely that splitting Africa into two plates will reduce the mismatch between geodetic observations and global kinematic models in the Mediterranean.

### *North Africa*

The lack of deformation in the Western Mediterranean area north of the African coastline indicated by the seismicity distribution and the geodetic results, together with the NW-ward motion of the African plate with respect to stable Europe, imply that the Africa-stable Europe motion in the Western Mediterranean is essentially accommodated by deformation in North Africa and southern Iberia. Very little strain, if any, seems to be transferred to the north, into the Eurasian plate.

East of about 2°W, the spatial distribution of the seismicity shows that most of the large earthquakes are concentrated along a relatively narrow crustal strip following the northern coast of Africa (Fig. 1). The NW-SE oblique convergence between Africa and Eurasia in the Western Mediterranean is consistent with the earthquake focal mechanisms, that show mostly reverse motion on NE-SW trending, and usually NW-dipping, faults, often combined with a strike-slip component. Geodetic and seismological data therefore suggest that the strain induced by the Africa-Eurasia oblique convergence concentrates at the northern edge of Africa. The sharp rheological transition between the oceanic crust of the Ligurian basin to the north, and the north of the African continental crust to the south may contribute significantly in focusing stress and strain, similarly as proposed by LOWRY and SMITH (1995) to explain the concentration of seismicity at the boundary between the Colorado Plateau and the Basin and Range province in the western United States. Interestingly, west of about 2°W, where this sharp rheological transition vanishes, active deformation seems to affect a broader area encompassing the Moroccan Riff as well as the southernmost part of the Iberian peninsula, including the Betics cordillera and possibly southern Portugal (MEGHRAOUI *et al.*, 1996). However, other processes such as mantle delamination could also play a significant role in the Alboran Sea area (SEBER *et al.*, 1996). Finally, independent estimates from geological observations (MEGHRAOUI *et al.*, 1996) or seismic moment summation (KIRATZI and PAPAZACHOS, 1995) indicate a shortening rate of 1.0–2.5 mm/an in the Algerian Tell Atlas and the Moroccan Riff. Since the total Africa-Eurasia plate convergence rate is likely to be (slightly) higher, it could indicate that some of this convergence is accommodated further in the Saharian Atlas in Morocco and Algeria. However, there is no evidence for active deformation in these areas, where the level of seismicity is low.

Further east, the role played by the deforming area located between Sicily and Tunisia and extending southward to the Lybian coast is unclear. It could accommodate a differential motion between Africa and the Ionian Sea, with a different convergence direction (with respect to Europe) for the Ionian Sea.

### *Adriatic Microplate*

Geodetic results clearly indicate that the Adriatic domain is not part of the African plate. They support, to the first order, the hypothesis of a counterclockwise rotation of an Adriatic microplate. This rotation implies 2.5 to 4–5 mm/yr of NE-SW extension along the Apennines from north to south, ~4 mm/yr of NE-SW shortening in the Dinarides, transitioning to ~2 mm/yr of NS shortening in the Friuli area, and ~1 mm/yr of combined extension and right-lateral shear in the Swiss and Western Alps. Geodetic and seismotectonic data in the Alps, Apennines, and Dinarides are consistent with this model. This suggests that active deformation in the Alps, Apennines, and Dinarides is controlled, and possibly dynamically driven, by the motion of the Adriatic microplate rather than by the convergence between Africa and Eurasia, as usually assumed. These results raise the issue of the driving mechanism for the motion of the Adriatic plate, which does not appear to be related to the African plate motion in a simple manner. A definite answer to this question is out of the scope of this study and would require dynamic geophysical models incorporating realistic boundary conditions (Africa–Eurasia plate motion and Aegean subduction, located just east of our study area), stresses induced by gravitational potential energy variations (e.g., MOLNAR and LYON-CAEN, 1988) and/or by the peri-Adriatic subducted slabs (WORTEL and SPAKMAN, 2000) and by the westward push of the Anatolian-Aegean-Balkan system (TAPPONNIER, 1977; MANTOVANI *et al.*, 2002).

The definition of the southern boundary of the Adriatic microplate also remains unclear. There has to be a tectonic discontinuity between southern Italy, with NE-ward velocities w.r.t. Europe (e.g., site MATE), and southern Sicily and the rest of the African plate, with NW-ward velocities w.r.t. Europe (e.g., sites NOTO and LAMP). WESTAWAY (1990) inferred that the southern boundary of the Adriatic microplate corresponds to an alignment of earthquakes along the "Trimiti line" between the Gargano and Dubrovnik. This is consistent with the velocity of NOTO, which does not fit that of the Adriatic microplate, therefore suggesting a major tectonic discontinuity between Sicily and continental Italy. However, the well determined velocity of MATE (Matera), located south of the Trimiti line, shows a velocity that fits reasonably well that of the rigid Adriatic microplate defined above. The southern boundary of the Adriatic plate should therefore be located south of Matera and north of Noto. Although there are active faults in that area, no active fault is known offshore across the Ionian Sea that could constitute the southern boundary of the Adriatic microplate. Data from additional continuous GPS sites in Italy, combined in a rigorously implemented reference frame, are necessary in order to understand the transition from the southern part of the Adriatic plate to the Ionian Sea and Sicily.

### *Eastern Alps and Pannonian Basin*

In the eastern Alps, we find a significant eastward residual velocity for GRAZ with respect to stable Europe (Fig. 2, 1.0 ± 0.4 mm/yr, 95% confidence level), in agreement with a previous study by GRENERCZY *et al.* (2000; 1.7 ± 0.8 mm/yr). We also find a similar residual velocity at station PENC, in the Pannonian basin (Fig. 2). These velocities, together with the campaign results of GRENERCZY *et al.* (2000) support the idea of an eastward motion of the easternmost part of the Alps and the northern Pannonian basin. This eastward motion has been interpreted as an extrusion process, in response to the collision of the Adriatic indenter in the Friuli region (BADA, 1999; GRENERCZY *et al.*, 2000). We suggest that the deforming areas in continental Greece and at the Aegean subduction may constitute a low friction boundary facilitating east and southeastward motions in southern central Europe. This far-field effect of the Aegean subduction may be indicated by the 2.4 mm/yr SE-ward residual velocity at SOFI (Bulgaria) with respect to stable Europe (Fig. 2).

## *Conclusion*

The combination procedure used here is an efficient and rigorous way to integrate several geodetic solutions into a single and consistent reference frame. The rigorous combination of campaign with continuous solutions is possible, but requires the availability of the associated statistical information (full variance-covariance matrix and explicit description of reference frame constraints) which was missing for most of the data used in the present work. We therefore stress that the most reliable results in this study are obtained using continuous GPS data. We also propose a rigorous definition of stable Europe, based on the combination of a redundant set of solutions from continuous geodetic networks in Europe. We then map velocities in this stable Europe reference frame.

Among the results presented here, we find that geodetic data consistently indicate an Africa-stable Europe convergence rate slower than the prediction of geological models. This, if confirmed by more geodetic data on the African plate and longer observation time series, has significant implications for the rigidity of the African plate and/or may imply recent variations of the African plate motion. Also, we find that the Africa-stable Europe oblique convergence in the Western Mediterranean is mostly accommodated by transpressional deformation in north Africa and southern Iberia. Very little strain, if any, appears to be transferred into the Eurasian plate. Active deformation in the Alps, Apennines, and Dinarides is probably driven by the independent motion of the Adriatic plate rather than by the Africa-Eurasia convergence. However, the forces responsible for the motion of the Adriatic plate and the relationship between extension in the Apennines and convergence between Africa and Eurasia remain open questions.

The kinematic description of crustal deformation in the Western Mediterranean and Western Europe presented here provide boundary conditions and validation data for studies aimed at modelling lithospheric-scale deformation processes in the Mediterranean (e.g., JIMENEZ-MUNT *et al.*, 2001a, b, in press). It remains however critical to increase the amount of geodetic observations in Africa in general, and North Africa in particular, in order to better estimate the kinematics of the African plate and complete the determination of strain distribution across the Africa-Eurasia plate boundary zone in the Mediterranean area.

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