State of strain in the Italian crust from geodetic data

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Abstract

The area bounded by the Alpine chain to the North and Mediterranean/Ionian sea to the South is characterized by a wide range of tectonic phenomena, such as the indentation of the Adria block into the Eastern Alp, lateral extrusion of the Tauern Window, unbending of the Adriatic lithosphere, opening of the Thyrrenian sea and subduction of the Ionian lithosphere beneath the Calabrian arc. This ongoing tectonics is accompanied by a relatively intense volcanism and seismicity, which justify the expectation of small but measurable horizontal and vertical displacements. We report on surface horizontal displacements determined at discrete locations by analyzing time series of permanent GPS stations with data coverage from one to five years of continuous operation. The horizontal velocities are defined consistently with the ITRF97 velocity datum. We show that the residual velocities relative to rigid rotations about Eulerian poles are never larger than 5 mm yr^{-1} and in several cases do reflect qualitatively the expected kinematics. Areas characterized by fracturing and faults with orientations changing on a short scale (Tauern window, Southern Alps) exhibit a more irregular distribution of velocities, probably associated with local phenomena. Eigenvalues and eigenvectors of a mean strain rate tensor are computed by optimally -in a least squares collocation sense -interpolating the station velocities to locations baricentric to clusters of stations. The estimated strain is everywhere smaller than 41 10^{-9} yr^{-1} with a mean uncertainty of 20 10^{-9} yr^{-1} (1σ). The areas with largest strain rate are the Central Apennines and Eastern Alps, while in the Western Alps the estimated strain rate is smaller than 15 -20 10^{-9} yr^{-1}, hence comparable with its uncertainty. The azimuths of the strain rate ellipse are qualitatively compared with the directions of the stress estimated from fault plane mechanisms and borehole breakouts, and with the strike of major faults. The orientations of the strain rate and stress ellipses show remarkable consistency, within the estimated uncertainties. We conclude in favor of evidence of a yet qualitative but significant correlation between broad scale (~300 km) stress and strain rate patterns, and orientation of large scale active lineaments.

Introduction

Temporal changes of the coordinates of geodetic satellite and VLBI stations worldwide correlate with the large scale drift pattern of major lithospheric units in rigid rotation about Eulerian poles. Intraplate velocities or departures from rigidity near plate margins tend to be small (Argus and Gordon, 1996), but quite considerable is their potential relevance for a quantitative understanding of the crustal deformation within a plate, plate margin or minor unit. The correlation in time and space of the estimated displacements of a network of GPS stations yields a residual (relative to Eulerian rotation) velocity field which, in a number of examples (e.g. Ward, 1998; Kahle et al., 2000, McKlusky et al., 2000), has proven to be a sensitive indicator of the present day strain rate field in the portion of upper crust covered by the geodetic network. Areas where several processes are taking place, perhaps interacting with each other in a complicated manner, are ideal candidates for GPS-based investigations. Italy is certainly a good example. Rigid plate models predict in this area (De Mets et al, 1990, 1994) a northwards convergence of the African and Eurasian lithospheres at a rate of approximately 7 mm yr^{-1}, but this convergence alone is only one element of a puzzle made up of short scale (few hundreds of km) processes such as, to name the most important, the northwards indentation of the Adria Block into the Eastern Alps, the counter-clockwise rotation of the Italian peninsula towards the Dinarids, volcanism and the opening of the Tyrrhenian basin, and the active subduction of the Ionian crust beneath the Calabrian Arc (Mueller et al. 1992, Rebai et al., 1992, Montone et al., 1999). Several authors have pointed out that in the past 20 Ma seismic activity (Amato et al., 1993, Frepoli et al., 1996) and volcanism (Barberi et al., 1973) in Italy have only indirectly been related to the Africa -Eurasia convergence. Malinverno and Ryan (1986) and Royden et al. (1987) have suggested that the subduction of the Adriatic and Ionian lithosphere beneath the Calabrian arc is related to the opening of the Thyrrenian sea. Because the subduction takes place at a rate larger than the convergence between Africa and Europe (Patacca et al., 1993), several mechanisms such as 'slab pull and roll back' (Kruse and Royden, 1994), lateral extrusion of crustal blocks (Mantovani et al., 1996) or eastward

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asthenospheric flow (Doglioni, 1991) have been suggested to explain the puzzling parallelism of the convergence of Eurasia and Africa, and the direction of subduction. Numerical models based on finite elements (Bassi et al., 1997; Mantovani et al., 2000) have only partly been successful in accommodating all the independent pieces of information into one consistent evolutionary picture. On the other hand, the knowledge of active stress in Italy has recently increased in detail and reliability (Montone et al., 1999; Frepoli and Amato, 2000) relative to the description given in earlier works (Udias, 1982; Mueller, 1989), or in the World Stress Map (Zoback, 1992), and extend to most of Italy the agreement between the different data types and depths which was found earlier over more limited areas (Amato and Montone, 1997). Earlier geodetic work based on VLBI (Ward, 1994) and Satellite Laser Ranging data (Cenci et al., 1993; Noomen et al., 1996), particularly within the WEGENER Project (Wilson and Reinhardt, 1993), have successfully constrained present day plate-scale kinematics, but have been unable to detail an intraplate strain rate field in the Mediterranean, due to an insufficient distribution of continuously tracking stations and to uncertainties in the orientation of a common reference system. The analysis of time series of GPS-derived coordinates of stations in Italy and surrounding countries has the potential of better constraining such models, due to the existence of several permanent GPS stations with a multi-year tracking history. Some stations are co-located with independent observing techniques such as Satellite and Lunar Laser Ranging, DORIS and Very Long Baseline Interferometry, and contribute to the periodic realization of an International Terrestrial Reference Frame (ITRF) (Boucher et al., 1999) and of its European densification EUREF (Bruyninx, 2000; Becker et al., 2000). The purpose of this paper is to present estimates of horizontal velocities of permanent GPS stations in the rectangle comprised between 5 and 20 degrees longitude East and 34 to 49 degrees latitude North (Figure 1). We confine to those stations with a tracking history of about one year or longer, up to five years. Because only permanent stations are considered, one can investigate in detail the noise model affecting the time series of the coordinates, and hence the velocity estimates. Finally, the inferred strain rate is examined in the context of independent structural and seismological data, and of evolutionary models, focusing in particular on the Alpine Arc and North - Central Apennines, where the useful stations are more dense.

The velocity and strain rate field

We summarize in Table 1 the velocities of the stations and the basic statistical information, referring to a companion paper (Caporali and Baccini, 2001) for the analysis method and the discussion of the uncertainties. The structural units which are covered by the network of permanent GPS stations are described in Figure 1. The residual velocities of these stations relative to the rigid plate velocities predicted by the NUVEL1A - NNR (De Mets et al., 1990, 1994) model are shown in Figure 2. All stations are assumed in the Eurasian plate except NOTO and LAMP, assumed in the African plate. Before attempting a geophysical interpretation of the departures from rigid rotation, we need to estimate the strain rate field which is implied by the station velocities. To do this we introduce an isotropic covariance function of the full network (the densified network plus all the over 100 stations in the European Permanent Network) :

$$C_{ij}(d) = \frac{C_{ij}(0)}{1+\left(d/d_0\right)^2} \quad i, j = e(ast), n(orth); \qquad (1)$$
$$C(d) = \begin{bmatrix} C_{nn} & C_{en} \\ C_{en} & C_{ee} \end{bmatrix}$$

The covariance function depends on the distance *d* between pairs of station, with a scale distance d_0 assumed equal to 250 km, the mean separation over the entire network. $C_{ij}(0)$ represents for $i=j$ the variance of the corresponding velocity components, otherwise the covariance between the east and north velocities. From Table 1, for each velocity estimate a weight factor is computed:

$$W = \frac{\frac{1}{s^2}}{\sum \frac{1}{s^2}} \qquad (2)$$

where the sum extends to all the stations in Table 1, for a given component.
The velocity interpolated at a point P is finally:

$$\begin{bmatrix} v_n \\ v_e \end{bmatrix}_P = \sum_s C(d_{P,s}) \sum_{s'} \left[C(d_{s,s'}) + W_{ss'}\right]^{-1} \cdot \begin{bmatrix} v_n \\ v_e \end{bmatrix}_{s'}$$
$$s, s' = station \quad indeces \qquad (3)$$

To avoid biases, the differences of the station velocities relative to the mean are interpolated . Then, the mean is added back. The velocity gradient tensor is obtained by horizontal differentiation of the interpolated velocity, which involves the derivative of the assumed covariance function (eq.1):

$$\begin{bmatrix} v_{n,n} & v_{n,e} \\ v_{e,n} & v_{e,e} \end{bmatrix}_P =$$
$$\sum_s \begin{bmatrix} \frac{\partial C}{\partial n} & \frac{\partial C}{\partial e} \\ \frac{\partial C}{\partial n} & \frac{\partial C}{\partial e} \end{bmatrix}_{P,s} \sum_{s'} \left[C(d_{s,s'}) + W_{ss'}\right]^{-1} \cdot \begin{bmatrix} v_n \\ v_e \end{bmatrix}_{s'}$$
$$s, s' = station \quad indeces \qquad (4)$$

The same equation can be used to map the variances in the velocities a the locations of the GPS stations (Table 1) to uncertainties in the velocity gradient at the interpolation point P. The contribution to the total variance from the interpolation algorithm is negligible, if the interpolation point P is baricentric to a cluster of stations with mean distance <d_0, but would be important away from the data points, as it happens for example in grids. As a last step we compute in P the eigenvalues (σ_1,σ_2) of the strain rate tensor, and the azimuth θ of σ_1:

$$\sigma_1 = \frac{v_{n,n} + v_{e,e}}{2} + \sqrt{\left(\frac{v_{e,e} - v_{n,n}}{2}\right)^2 + \left(\frac{v_{e,n} + v_{n,e}}{2}\right)^2}$$

$$\sigma_2 = \frac{v_{n,n} + v_{e,e}}{2} - \sqrt{\left(\frac{v_{e,e} - v_{n,n}}{2}\right)^2 + \left(\frac{v_{e,n} + v_{n,e}}{2}\right)^2} \qquad (5)$$

$$sin2\theta = \frac{v_{e,n} + v_{n,e}}{\sigma_2 - \sigma_1}; \cos 2\theta = \frac{v_{e,e} - v_{n,n}}{\sigma_1 - \sigma_2}$$

Basic seismological and structural data

Constraining evolutionary models with velocities of scattered geodetic stations, although very precisely determined, requires some knowledge of the horizontal and vertical scales at which the crust can be considered as rigid. The vertical scale depends on whether the upper and lower crust are coupled. If the lower crust has a power law rheology, then the vertical scale could be as small as 10 - 20 km. This depends on the local geotherm and, hence, the depth at which diabase or -depending on crustal composition- diorite will flow. This depth determines the thickness of the brittle upper crust and the typical depth of earthquakes which, in seismically active regions, are candidate counterparts of surface displacements. For example, below the northern Alpine foreland the seismic activity is uniformly distributed up to 30 km depth, but the hypocenters below the Swiss Alps, where the Moho is 50 km deep, are not deeper than 15-20 km (Deichmann and Baer, 1990). Defining a horizontal scale of rigidity is more debatable, especially when stations are non uniformly distributed. The existence of active faults in the neighborhood of a station needs to be carefully evaluated before drawing conclusions on the significance of the velocity of that station to the present day kinematics of the surrounding area. In the Alps (Figure 3) there is a remarkable difference in tectonic style between the West-Central and Eastern sectors: backfolding, backhrusting and foreland imbrication prevails in the West Central part (Dal Piaz, 1995). Strike slip and normal faults are dominant in the Eastern part. Focal mechanism studies of earthquakes in the Central Alps (Pavoni, 1980) indicate that the axes of maximum horizontal compression are perpendicular to the Alpine arc. Mueller (1984) has interpreted this focal mechanism as a reaction of the rigid Alpine upper crust to the continuing counterclockwise rotation of the Apennines. Recent seismological studies have indicated that a belt of extensional deformation is also present in the Western Alps (Eva et al., 1998; Sue et al., 1999). The belt is bounded to the W by the external cristalline massifs of Argentera, Pelvoux, Belledonne and Mont Blanc, and to the E by the Western Po Plain. Both the sandwiching Eastern and Western areas are under compression, implying a geodynamical model not restricted to simple collisional tectonics. On the Ligurian coast, the focal mechanism of two earthquakes which occurred in 1989 and 1990 suggested to Béthoux et al. (1992) a reactivation in compression of the Ligurian sea, possibly driven by extrusion associated with the northwards indentation of the Adriatic plate. The Central Alps are characterized by northward extrusion of hot and deep-seated material, imbrication of European crust, erosion of Austroalpine nappes in the foreland and backthrusting over the Southern Alps. These phenomena are absent in the Eastern Alps, because of the unconstrained lateral boundary represented by the Pannonian basin, acting as a stress sink. The eastwards escape (Figure 4) is facilitated by conjugated strike slip faults and gravitational spreading (Ratschbacher et al., 1991). Seismic activity is evident in the Friuli area, with foci distributed between 7 and 13 km depth (Bressan et al., 1998), and principal axes of horizontal compression oriented N-S in a 'inner wedge' and NW-SE in a 'outer wedge'. The Friuli and Slovenia appear still involved into a compressive regime historically interpreted as due to the Africa (or Adria) push against Europe (Renner and Slejko, 1994). This compression induced the decoupling and shortening of the Adriatic upper crust through a foreland fault-and-fold system propagating towards the Po Plain foreland. The remaining Adriatic lithosphere moved towards North, against and over the European lower plate and related orogenic belt. (Venturini and Fontana, 1992; Castellarin et al. 1992, Pondrelli et al., 1995, Mueller et al. 1992). In the Tyrrhenian sea, Corsica and Sardinia are separated by the western Apennines by extensional grabens filled with sediments. The Apenninic - Sicilian collisional chain was deformed in several phases during Neogene. Close to the end of the Tortonian (~ 9 Ma), a phase of extension and subsidence set in, which finally led to the formation of the Thyrrenian sea. This extensional phase appears to be contemporaneous with the compression of Apenninic Sicilian arc and is possibly related to the subduction of the Ionian lithosphere beneath the Calabrian Arc (Mueller and Kahle, 1993, Bassi et al., 1997). In the Apennines (Figure 3) the differential retreat of the Adriatic plate flexing beneath the northern Apennines and Calabrian Arc was responsible for the formation of the two distinct arcs (Patacca and Scandone, 1987). In the Northern Apennines the eastward migration of the compressional and extensional back arcs observed since Miocene is consistent with the observed stress regimes inferred from seismicity data. The rapidly changing orientation of stress in the extensional Peri - Tyrrhenean zone suggests great care. This area has been considered under extension (Frepoli and Amato, 1997), but the coexistence of normal and strike slip faults, and a re-evaluation of the orientation and relative magnitude of the principal stresses has recently led to the hypothesis of a radially extending zone (Frepoli and Amato, 2000). Based on instrumental and historical seismicity, Westaway (1992) estimated small, equal rates of extension and compression, ~0.3 mm yr^{-1} north of latitude 42.5°. The Southern Apennines are under a larger extension, as much as 5 mm yr^{-1} south of 41°N. For the Adriatic lithosphere the few reverse faulting earthquakes suggest a compressional regime which, according to Mantovani et al. (1997), could be driven by the unbending of the plate, in the underthrusting beneath the Dinarides.

From the point of view of a very general tectonic setting of the whole Italian area, the provinces indicated as under extension or compression correlate very well with zones of shallow or respectively deeper Moho isobaths, and high and, respectively, low heat flow. According to Nicolich and Dal Piaz (1991), the thickness of the crust ranges from 10 to 15 km on the Tyrrhenean sea, to a maximum of 25 km on the S and SW flank of the Apennines, in the regions of Toscana and Lazio. On the N and NW side, values as large as 30 to 50 km indicate a thicker crust, which is consistent with the inferred compression. Mongelli et al. (1991) likewise report heat flow values exceeding 120 mW m^{-2} in the extensional areas, and values not larger than 80 mW m^{-2} in the compressional areas.

Station velocities and tectonic flow

Comparison the velocities in Figure 2 with the map of the tectonic units in Figure 1 shows that the very low velocities, relative to rigid rotation of stations, of OBER, WTZR, ZIMM, PFAN, KARL fit well the expectation of a stable crust, subject to negligible tectonic flow north of the Austro Alpine Front, in the Sub Alpine Molasse. The station HFLK is located north of Innsbruck and of the Tauern window. It is uncertain whether it already belongs to the stable Austro alpine. Its velocity relative to Eurasia is small, but is unfortunately biased by annual and semiannual variations, likely to be caused by a local water cycle. There are unfortunately no stations inside the extruded block in Figure 4: VILH, SBGZ, and RTMN exhibit nearly opposite velocities, which are apparently controlled by local, strike slip faults. As shown in Figure 4, these faults are a consequence of the push of the indenter against stable Eurasia. The stations in the North East WIEN, STPO and MOPI, as well as GRAZ, are already outside the extruded wedge and appear coherent with each other in a NNW motion. Quite incoherent are instead the velocities of BZRG and TREN, located east of the Giudicarie line, within just 80 km from each other. Both are reasonably well constrained by over two years of data, yet they exhibit nearly orthogonal velocities. By contrast, the northwards velocities of UPAD and VENE, two sites located on a several km thick sediment cover, are quite consistent with each other and have good chances to be representative of the northwards indentation of the Adria Block. It is unclear how this motion is accommodated laterally. A good candidate is the Schio Vicenza line, visible in Figure 5 just West of UPAD, a yet poorly understood fault which could be reactivated and play an active role in the accommodation of regional scale displacements (Mantovani et al., 2000). In the Western Alps and NW Italy the stations SJDV GRAS, MARS, GENO, and TORI seem to exhibit a WSW motion, which remains spatially quite coherent on a scale of a few hundreds of km. The AJAC site, in the stable Sardinia Corsica block, exhibits a westward motion which is compatible with the opening of the Tyrrhenian and the strike of normal faults between Corsica and Tuscany. The Apenninic stations MEDI, UNPG, and PRAT all exhibit a northwards velocity relative to the rigid plate model, with different azimuths. The stations MATE and VLUC are located on opposite sides of the Southern Apennines thrust. MATE is on the stable Apenninic foredeep. VLUC is on the edge of the Calabrian Arc, and COSE is well within the Calabrian arc, undergoing active subduction. The V shaped velocity pattern of VLUC on the W side and MATE on the E side is consistent with the strike of normal faults inbetween, and leads to expect a roughly EW extensional strain in the southern Apennines. Finally, now on the African plate, the velocity gradient between NOTO and LAMP implies a deformation in the Channel of Sicily, south of the margin between Africa and Eurasia (Farugia et al., 1987).

Patterns of active strain rate in the Italian crust

To examine this rather complex kinematic situation from the point of view of strain rate, we plot in Figure 5 the mean compressional and extensional eigenvalues of the strain rate ellipse. The plotting locations of the strain rate symbols are chosen so that each domain is baricentric relative to three or more well constrained stations within a radius d_0~250 km assumed in collocation. Western Alps, Southern Apennines between MATE and UNPG and Sicily are unfortunately ruled out by this criterion. Figure 5 shows that the Eastern Alps are generally subjected to a transtension which embodies the NS compression caused by the Adria indenter, and the E-W extension associated to the lateral escape. The compressional eigenvalue in the Southern Alps drifts in azimuth to a NW-SE direction, matching quite well the fan shaped pattern of the seismic stress described by Bressan et al. (1998). The Ligurian Alps, on the West side of Italy, appear to be subject to a smaller deformation, and this is quite well constrained by the long term stations of MARS, GRAS, TORI and GENO. Their velocities are small in comparison to their estimated uncertainties. Had the uncertainties been smaller, then the collocation algorithm would yield a ~EW extension between MARS and GRAS, and a ~EW compression between GRAS and GENO, as is evident in Figure 2. Quite interesting is the change from compression to extension moving south, from the Eastern Po Plain near latitude 45N across the Apennines. Because the station PRAT is relatively recent, we tested the inclusion of additional sites with similar uncertainties in the velocities, but at different locations. The tests indicated that the final orientation and size of the eigenvectors did not change appreciably. Finally, in Figure 5 we show the large extensional eigenvalue resulting from the triangle MATE VLUC and COSE. The large differential velocity of COSE relative to the two other stations is the responsible of the extension. This deformation pattern is not consistent with what one expects on account of the subducting and retreating

Calabrian arc on the one hand, and the opening of the Thyrrenian sea on the other hand, although the velocities of the individual stations are consistent with the expected kinematics. Unfortunately the distribution of stations is insufficient to give the full picture from the point of view of strain.

Stress vs. Strain rate

Recently, improved maps of the horizontal stress in Italy have been published by Bèthoux et al. (1992), Eva et al. (1998), Bressan et al. (1998), Montone et al. (1999), Frepoli and Amato (2000) and Sue et al. (1999). The principal stress directions resulting from these studies are summarized in Figure 2. In attempting a comparison of the orientation of stress and strain rate ellipses, some *caveat* is necessary. First, the diversity of the data sets. The stress maps result from a combination of different types of data: borehole breakouts give stress orientation, while fault plane solutions refer to strain. Secondly, depths and data quality may vary. Thirdly, the geographic distribution of data points is far from homogeneous, as for GPS stations. Fourthly, uncertainties in the orientation of the inferred principal axes of stress are often unknown, only the r.m.s. misfit of the fault plane solutions is given. Hence it is difficult to estimate the confidence level of an agreement or disagreement. A comparison in a qualitative sense is therefore the best one can attempt. The extensional patterns in the Molasse basin, Pannonian margin and Eastern Alps are not covered by these maps. The compressional regime in the Ligurian coast is marginal in comparison with our error estimates, but is consistent with independent results of Calais et al. (1999, 2000), based on a comparison between old triangulation data and satellite data, and by Caporali and Martin (2000), based on individual baselines. The compressional regime would lend support to the hypothesis of a closing Ligurian sea proposed by Bèthoux et al. (1992) on seismological grounds. The compression in the Eastern Alps is in excellent agreement with seismological data and expected plate kinematics (Ratschbacher et al., 1991; Bressan et al., 1998). The extension in the inner part of Central Apennines, and compression in the outer part of the arc, in the Eastern Po plain are consistent with the stress regimes inferred seismologically. The station VLUC is on the margin between Apennines and Calabrian arc. COSE belongs to the Calabrian Arc. With MATE they define a changing strain regime, where the northern part is transtensional and typically Apenninic, while the southern part, controlled by COSE, is more in keeping with the extensional regime of the Calabrian arc. In Sicily the stress field is such that no single stress tensor can be computed for the entire region from seismic and borehole breakout data. Not less than four distinct areas have been identified by Frepoli and Amato (2000). On the other hand, the only GPS stations NOTO and LAMP are available, thus insufficient to constrain a strain pattern which, on the basis of the features of the Pantelleria graben, we expect extensional and very nearly aligned along the line joining the two stations.

Conclusion

The strain rate inferred from GPS measurements defines over Italy a smooth pattern, which correlates with the large scale map of Quaternary to Plio-Pleistocenic tectonics. Based on up to five years of data from permanent satellite stations, the kinematical model features large scale deformation patterns comprising extensional and compressional regimes that are in most cases accommodated by pre-existing, large scale faults. Homogeneous strain provinces, from the Molasse basin to the North down to the Calabrian arc to the South are identified and the mean estimated strain rate is correlated with the corresponding tectonics. The estimated strain value never exceeds (41 +/-20) 10^{-9} yr^{-1}, recorded in the Eastern Alps and in the Calabrian Arc, a rather small value when compared e.g. with Anatolia where it exceeds 100 10^{-9} yr^{-1} (Kahle et al., 2000). These low values would be too small to be detected with epoch like stations, but are in this study sufficiently well constrained because permanent stations are used and a detailed noise model can be estimated for each time series. The agreement between the geodetically inferred strain rate and independent structural and geophysical data such as fault plane solutions or borehole breakouts is qualitatively good in the Northern regions, but weakly constrained by lack of stations in the Southern part. Overall, both in the North and the South, the velocities are small relative to the rigid model, but the horizontal gradients can be large. As these first estimates begin to constrain the amount of deformation on the surface, it becomes very urgent to know the strain inferred from the seismic moment summation (Westaway, 1992), so that an estimate of seismic/aseismic ratio for velocities can be attempted.

Acknowledgment: this research is supported by a grant of the Ministry of University and Scientific Research and by ASI.

References

Amato, A., B. Alessandrini, G.B. Cimini, A.Frepoli and G.Selvaggi, Active and remnant subducted slabs beneath Italy: Evidence from seismic tomography and seismicity, *Ann. Geofis., 36, 201-214,1993.*

Amato, A. and P. Montone, Present - day stress field and active tectonics in southern peninsular Italy, *Geophys. J. Int., 130, 519-534, 1997.*

Argus, D.F. and R.G. Gordon, Tests of the rigid-plate hypothesis and bounds on intraplate deformation using geodetic data from very long baseline interferometry, *J. Geophys. Res., 101B6, 13555-13572, 1996.*

Barberi, F., P. Gasparini, F. Innocenti and L. Villari, Volcanism of the southern Thyrrenian sea and its geodynamic implications, *J. Gephys. Res. 78, 5221-5232, 1973.*

Bassi, G., R. Sabadini and S. Rebai, Modern tectonic regime in the Tyrrhenian area: observations and models, *Geophys. J. Int., 129, 330-346, 1997.*

Becker, M. , P. Franke, G. Weber, D. Ineichen, L. Mervart, EUREF contribution to ITRF2000 and Analysis Coordinator Report for 8/99 - 6/00, *Report on the Symposium of the IAG Subcommission for Europe (EUREF), Tromsoe, 22-24 June 2000, Ed. by J.A. Torres and H. Hornik, Veroeffentlichungen der Bayerischen Kommission fuer di Internationale Erdmessung der Bayerischen Akademie der Wissenschaften, Astronomisch Geodaetische Arbeiten, Heft n. 61, 31-36, Munich 2000.*

Bethoux, N., J. Frechet, F. Guyoton, F. Thouvenot, M. Cattaneo, C. Eva, M. Nicolas and M. Granet, A closing Ligurian sea?, *Pageoph, 139, 179-194, 1992.*

Beutler, G., E. Brockmann, S. Fankhauser, W. Gurtner, J. Johnson, L. Mervart, M. Rothacher, S. Schaer, T. Springer and R. Weber, Bernese GPS software version 4.0, *ed. by M. Rothacher and L. Mervart, Astronomical Institute of the University of Bern, September 1996, 418 pp.*

Bigi G., D. Cosentino, M. Parotto, R. Sartori and P. Scandone, Structural model of Italy. Sheet n. 1 *Edited by Castellarin A., Coli M., Dal Piaz G.V., Sartori R., Scandone P. and Vai G.B. CNR, progetto finalizzato Geodinamica, Roma 1990.*

Boucher, C., Z. Altamimi and P. Sillard, The 1997 International Terrestrial Reference Frame (ITRF97), *IERS Technical Note n. 27, Observatoire de Paris, 191 pp., May 1999.*

Bressan, G., A. Snidarcig and C. Venturini, Present state of tectonic stress of the Friuli area (Eastern Southern Alps), *Tectonophysics, 292, 211-227, 1998.*

Bruyninx, C., Overview of the EUREF permanent network and the network coordination activities, *Report on the Symposium of the IAG Subcommission for Europe (EUREF), Tromsoe, 22-24 June 2000, Ed. by J.A. Torres and H. Hornik, Veroeffentlichungen der Bayerischen Kommission fuer di Internationale Erdmessung der Bayerischen Akademie der Wissenschaften, Astronomisch Geodaetische Arbeiten, Heft n. 61, 24-30, Munich 2000.*

Burrus, J., Contributions to a geodynamic synthesis of the Provencal basin (North-Western Mediterranean), *Marine Geology, 55, 247-269, 1984.*

Calais, E., Continuous GPS measurements across the Western alps, 1996-1998, *Geophys. J. Int., 138, 221-230, 1999.*

Calais, E. , L. Galisson, J.-F. Stéphan, J. Delteil, J. Deverchère, C. Larroque, B. Mercier de Lépinay, M. Popoff and M. Sosson, Crustal strain in the Southern Alps, France, 1948-1998, *Tectonophysics, 319, 1-17, 2000.*

Caporali, A. and S. Martin, First results from GPS measuements on present day Alpine kinematics, *J. of Geodyn., 30, 275-283, 2000.*

Caporali, A. and S. Baccini, Average strani rate in the Italian crust inferred from a permanent GPS network, Part 1: Statistical analysis of time series of permanent GPS stations, *this issue, 2001.*

Castellarin A., L. Cantelli, A.M. Fesce, J.L. Mercier, V. Picotti, G.A. Pini, G. Prosser, and L. Selli, Alpine compressional tectonics in the Southern Alps. Relationships with the N-Apennines. *Annales Tectonicæ, 6, 62-94, 1992.*

Cenci, A., M. Fermi, C. Sciarretta, R. Devoti and A. Caporali, Tectonic motion in the Mediterranean Area from Laser Ranging to LAGEOS, in *Contributions of Space Geodesy: Crustal Dynamics, D. E. Smith and D.L. Turcotte editors, Geodynamics Series volume 23, 347-358, American Geophysical Union, Washington D.C., 1993.*

Dal Piaz, G.V., Plate Tectonics and Mountain Building: The Alps, in Plate Tectonics: The First Twenty five Years, *Proc. of the VIII Summer School on Earth and Planetary Sciences, Ed. by G. Ranalli, pp. 171-251, 1995.*

Deichmann, N. and M. Baer, Earthquake focal depths below tha alps and northern alpine foreland of Switzerland, in: *The European Geotraverse: Integrative Studies, Ed. by R. Freeman, P. Giese and St. Mueller, pp.277-288, European Science Foundation, Strasbourg, France 1990.*

De Mets, C., R.G. Gordon, D.F. Argus and S. Stein, Current plate motions, *Geophys. J. Int., 101, 425-478, 1990.*

De Mets, C., R.G. Gordon, D.F. Argus and S. Stein, Effect of recent revisions to the geomagnetic reversal time scale on estimates of current plate motions, *Geophys. Res. Lett., 21, 2191-2194, 1994.*

Doglioni, C., A proposal of kinematic modeling for W-dipping subductions : Possible applications to the Thyrrenian Apennines system, *Terra Nova,3 , 423-434, 1991.*

Eva E., S. Pastore and N. Deichmann, Evidence for ongoing extensional deformation in the Western Swiss Alps and Thrust-faulting in the SouthWestern Alpine foreland. *J. Geodyn, 26, 27-43, 1998.*

Farrugia, P., I. Apopei and K.P. Bonjer, Observations of seismicity of the Sicily channel, *Mem. Soc. Geol. It., 38, 329-340, 1987*

Frepoli, A., G. Selvaggi, G. Chiarabba and A. Amato, State of stress in the southern Thyrrenian subduction zone from fault plane solutions, *Geophys. J. Int., 125, 879-891,1996.*

Frepoli, A. and A. Amato, Contemporaneous extension and compression in the northern Apennines from earthquake fault plane solutions, *Geophys. J. Int., 129,368-388, 1997.*

Frepoli, A. and A. Amato, Spatial variation in stresses in peninsular Italy and Sicily from background seismicity, *Tectonophysics, 317, 109-124, 2000*.

Kahle, H.G., M. Cocard, Y. Peter, A. Geiger, R. Reilinger, A. Barka and G. Veis, GPS-derived strain rate field within the boundary zones of the eurasian, African and Arabian Plates, *J. Geophys. Res. 105B10, 23353-23370, 2000.*

Kruse, S.E. and L.H. Royden, Bending and unbending of an elastic lithosphere: The Cenozoic history of the Apennine and dinaride foredeep basins, *Tectonics, 13, 278-302, 1994*.

Malinverno, A. and W.B.F. Ryan, Extension in the Thyrrenean sea and sfortening in the Apennines as result of arc migration driven by sinking of the lithosphere, *Tectonics, 5, 227-245, 1986*.

Mantovani, E., D. Albarello, C. Tamburelli and D. Babbucci, Evolution of the Thyrrenian basin and surrounindg regions as a result of the Africa-Eurasia convergence, *J. Geodyn., 21, 35-72, 1996*.

Mantovani, E., D. Albarello, C. Tamburelli, D. Babbucci and M. Viti, Plate Convergence, crustal delamination, extrusion tectonics and minimization of shortening work as main controlling factors of the recent Mediterranean deformation pattern, *Ann. Geof. 40, 611-643, 1997*.

Mantovani, E., M. Viti, D. Albarello, C. Tamburelli, D. Babbucci and N. Cenni, Role of kinematically induced horizontal forces in Mediterranean tectonics: insight from numerical modeling, *J. Geodyn. 30, 287-320, 2000.*

McKlusky, S., S. Balassanian, A. Barka, C. Demir, S. Ergintav, I. Georgiev, O. Gurkan, M. Hamburger, K. Hurst, H. Kahle, K. Kastens, G. Kekelidze, R. King, V. Kotzev, O. Lenk, S. Mahmoud, A. Mishin, M. Nadariya, A. Ouzounis, D. Paradissis, Y. Peter, M. Prilepin, R. Reilinger, I. Sanli, H. Seeger, A. Tealeb, M.N. Toksoz, and G. Veis, Global Positioning System constraints on plate kinematics and dynamics in the eastern Mediterranean and Caucasus, *J. Geophys. Res., 105B3, 5695-5719, 2000.*

Mongelli, F., G. Zito, B. Della Vedova, G. Pellis, P. Squarci and L. Taffi, Geothermal regime in Italy and surrounding areas, in *Exploration of the Deep Continental Crust, eds. V. Cermak and L. Rybach, Springer Verlag, Berlin, 1991.*

Montone, P., A. Amato and S. Pondrelli, Active stress map of Italy, *J. Geophys. Res., 104B11, 25595-25610, 1999.*

Mueller, B., M.L. Zoback, K. Fuchs, L. Mstin, S. Gregersen, N. Pavoni, O. Stephansson and C. Ljunggren, Regional patterns of tectonic stress in Europe, *J. Geophys. Res., 97, 11,783-11803, 1992.*

Mueller, St., Dynamic processes in the Alpine Arc, *Ann. Geophys., 2, 161-164, 1984*.

Mueller, St., Deep-reaching geodynamic processes in the Alps, in *Alpine Tectonics, ed. by M.P. Coward, D. Dietrich and R.G. Park, Spec. Publ. Geol. Soc. London, 45, 303-328, 1989.*

Mueller, St. and H.G. Kahle, Crust- Mantle evolution, structure and dynamics of the Alpine Mediterranean region, in: *Contributions of Space Geodesy to Geodynamics: Crustal dynamics, Ed. by D.E.Smith and D.L. Turcotte, AGU Geodynamics Series vol.23, pp.249-298, 1993.*

Nicolich, R. and G.V. dal Piaz, Isobate della Moho in Italia, in *Structural Model of Italy, 6 Sheets, 1:500000, CNR Progetto finalizzato Geodinamica, 1991*.

Noomen, R., T.A. Sprinter, B.A.C. Ambrosius, K. Herzberger, D.C. Kuijper, G.J. Mets, B. Overgaaw and K.F. Wakker, Crustal deformation in the Mediterranean area computed from SLR and GPS observations, *J. Geodyn, 21, 73-96, 1996*.

Patacca, E. and P. Scandone, Post Tortonian mountain building in the Apennines: the role of the passive sinking of a relic lithospheric slab, in *The Lithosphere in Italy: advances in Earth Science research, ed. by A. Boriani, M. Bonafede, G.B. Picardo and G.B. Vai, Accademia Nazionale dei Lincei, Mid Term Conference, Rome 5-6 May 1987, pp.157-176.*

Patacca, E., R. Sartori and P. Scandone, Tyrrhenian basin and apennines kinematic evolution and related dynamic constraints, In: *Boschi, E. (Ed.), Recent evolution and seismicity of the Mediterranean region, Kluwer Academic, Dordrecht, 161-171, 1993.*

Pavoni, N., Crustal stresses inferred from fault plane solutions of earthquakes and neotectonic deformation in Switzerland, *Rock Mechanics, Suppl. 9, 63-68, 1980*.

Pondrelli, S., A. Morelli, and E. Boschi, Seismic deformation in the Mediterranean area estimated by moment tensor summation, *Geophys. J. Int., 122, 938-952, 1995.*

Ratschbacher, L., O. Merle, P. Davy and P. Cobbold, Lateral Extrusion in the Eastern Alps, Part 1: Boundary conditions and experiments scaled for gravity, *Tectonics, 10, 245-256, 1991*.

Ratschbacher, L., W. Frisch, H.G. Linzer, and O. Merle, Lateral Extrusion in the Eastern Alps, Part 2: Structural analysis, *Tectonics, 10, 257-271, 1991.*

Rebai, S., H. Philip and A. Taboada, Modern tectonic stress field in the Mediterranean region: evidence for variation in stress directions at different scales, *Geophys. J. Int., 110, 106-140, 1992.*

Renner, G. and D. Slejko, Some comments on the seismicity of the Adriatic region, *Bollettino di Geofisica Teorica ed Applicata, 36, 141-144, 1994.*

Royden, L. and G. Karner, Flexure of lithosphere beneath Apennine and Carpathian foredeep basins: evidence for an insufficient topographic load, *Am. Assoc. Petrol. Geol. Bull., 68, 704-712, 1984.*

Sue, C., F. Thouvenot, J. Fréchet and P. Tricart, Widespread extension in the core of the western Alps revealed by earthquake analysis, *J. Geophys. Res. 104B11, 25611-25622, 1999*.

Udias, A., Seismicity and seismotectonic stress-field in the Alpine Mediterranean region, *in Alpine-Mediterranean geodynamics, ed. by H. Berckhemer and K. Hsu, AGU-GSA Geodynamics Series, 7, 75-82, 1982*.

Venturini C. and C. Fontana, The Neoalpine phase in the Carnic Alps: secondary E-W compressions, *Studi Geologici Camerti volume speciale CROP 1-1A, 271-274, 1992*.

Ward, S.N., Constraints on the seismotectonics of the Central Mediterranean sea from Very Long Baseline Interferometry, *Geophys. J. Int., 117, 441-452, 1994*.

Ward, S.N., On the consistency of earthquake moment release and space geodetic strain rates: Europe, *Geophys. J. Int., 135, 1011-1018, 1998.*

Westaway, R., Seismic moment summation for historical earthquakes in Italy: Tectonic implications, *J. Geophys. Res. 97B11, 15437-15464, 1992*.

Wilson, P., and E. Reinhardt, The WEGENER-Medlas Project: preliminary results on the determination of the geokinematics of the Eastern Mediterranean, in *Contributions of Space Geodesy: Crustal Dynamics, D. E. Smith and D.L. Turcotte editors, Geodynamics Series volume 23, 299-309, American Geophysical Union, Washington D.C., 1993.*

Zoback, M.L. and al. (29 authors), Global patterns of tectonic stress, *Nature, 341, 291-298, 1989.*

Zoback, M.L., First and second order patterns of stress in the lithosphere: The World Stress Map Project, *J. Geophys. Res., 97, 11703-11728, 1992*.

Table 1: horizontal velocities (mm yr^{-1}) of permanent GPS stations in or near Italy. First column identifies the network: E=Euref, D=Densification. The first pair of velocity columns lists the velocities predicted by the model NUVEL1A NNR of De Mets et al. (1994). NOTO and LAMP are assumed in the African plate, all the remaining stations are assumed in the Eurasian plate. The following sub-table lists the velocities and uncertainties, in the sense of two sample Allan variance. The velocities are estimated as the slope of the time series, assuming time correlated measurements according to the normalized autocorrelation computed from each time series.

				NUVEL1A NNR		This Solution			
Net	Station	ϕ	λ	v_N	v_E	v_N	σ_{VN}	v_E	σ_{VE}
E	AJAC	41.933	8.763	14.11	20.64	13.18	4.81	18.26	4.63
E	BZRG	46.3069	11.3368	13.71	20.49	13.75	1.69	18.77	1.71
E	CAGL	38.9477	8.9728	14.08	21.01	13.01	0.61	20.87	0.7
D	COSE	39.0131	16.3104	12.87	22.09	12.32	1.34	22.71	1.71
E	GENO	44.7271	8.9212	14.08	20.36	13.75	1.54	18.52	1.59
E	GRAS	43.5626	6.9206	14.37	20.11	13.79	0.39	19.52	0.36
E	GRAZ	46.8752	15.4935	13.01	21.11	13.87	0.57	21.27	0.57
E	HFLK	47.1212	11.3861	13.7	20.38	13.88	1.31	20.37	0.73
E	KARL	49.0111	8.4111	14.15	19.54	13.68	1.21	18.4	1.51
E	LAMP	35.3181	12.6057	20.48	19.72	16.62	5.63	17.86	2.86
E	MARS	43.0868	5.3538	14.59	19.91	12.68	1.23	17.88	1.21
E	MATE	40.4591	16.7045	12.81	22.02	17.49	0.58	21.47	0.87
E	MEDI	44.3276	11.6468	13.66	20.81	15.62	0.98	23.47	1.2
E	MOPI	48.3725	17.2739	12.85	21.07	14.27	0.65	20.5	0.69
E	NOTO	36.6916	14.9898	19.85	20.51	16.87	0.67	21.91	0.7
E	OBER	47.8948	11.2799	13.72	20.24	13.83	0.47	19.78	0.59
E	PFAN	47.3237	9.7847	13.95	20.07	14.35	0.54	19.71	0.68
D	PRAT	43.6933	11.0991	13.75	20.8	15.21	4.81	21.39	3.32
D	RTMN	47.524	14.677	13.15	20.89	11.02	3.01	20.66	2.93
E	SBGZ	47.6119	13.1104	13.42	20.61	11.94	1.91	16.94	2.63
E	SJDV	45.6868	4.6766	14.68	19.4	13.64	1.11	18.21	1.23
E	SRJV	43.8678	18.4139	12.48	21.94	10.85	3.94	23.55	4.59
D	STPO	48.203	15.633	12.98	20.95	14.53	3.32	20.48	1.84
E	TORI	44.8714	7.6613	14.27	20.06	12.9	1.67	18.43	1.75
D	TREN	45.8802	11.1224	13.74	20.51	11.28	2.07	20.54	1.35
E	UNPG	42.9275	12.3557	13.55	21.11	14.42	1.86	19.64	2.05
E	UPAD	45.2143	11.8779	13.62	20.73	15.77	0.54	20.29	0.75
E	VENE	45.4369	12.3319	13.62	20.73	15.34	0.75	20.78	0.72
D	VILH	46.4149	13.8505	13.29	20.91	16.11	4.07	21.3	2.25
D	VLUC	40.0411	15.2659	13.05	21.85	15.85	3.91	20.6	6.75
D	WIEN	48.219	16.373	12.85	21.07	14.58	2.11	19.46	3.69
E	WTZR	48.9537	12.8789	13.45	20.36	13.73	0.46	20.03	0.65
E	ZIMM	46.6851	7.4652	14.29	19.75	14.42	0.45	19.54	0.54

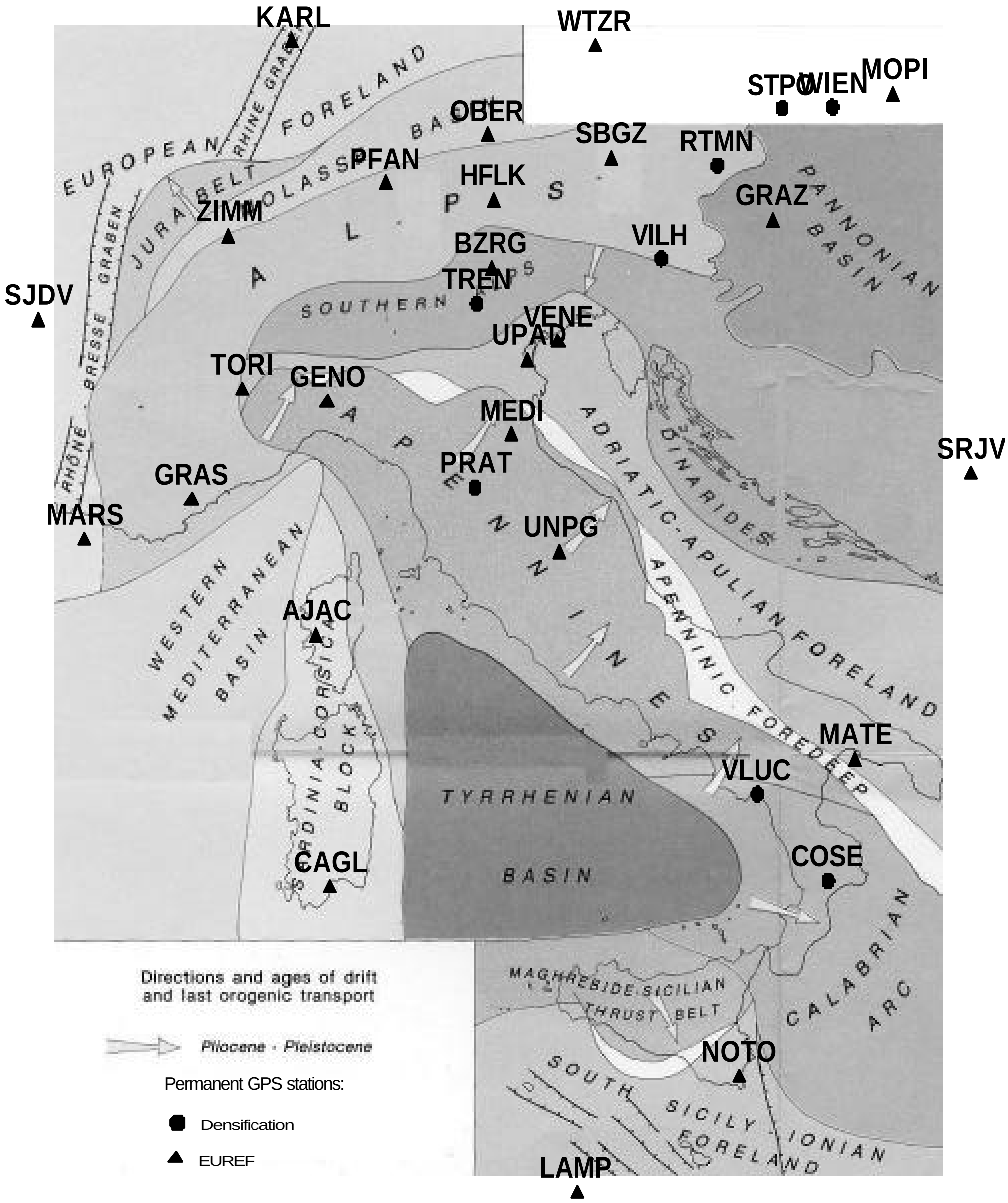

Figure 1: distribution of EUREF and Densification permanent GPS stations in the studied area, with an indication of the major structural units, after Bigi et al. (1990).

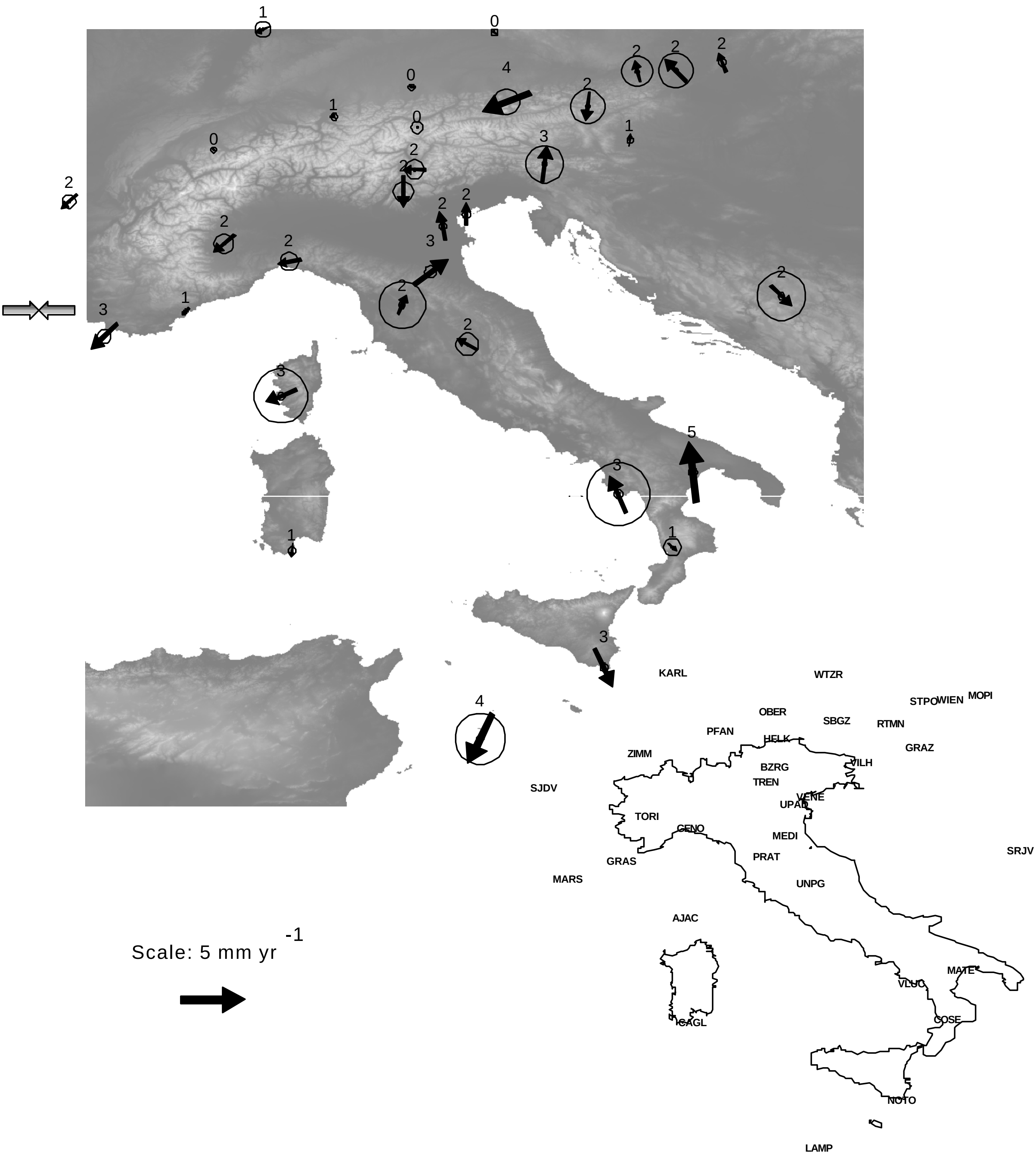

Figure 1: estimated residual velocities of the permanent GPS stations relative to the predictions of the rigid plate model NUVEL1A NNR. Reference velocity datum is realized by constraining to their ITRF97 values the velocity of stations falling outside the study box in stable areas [see Caporali and Baccini (2001) for details]. All stations are assumed in the Eurasian plate except NOTO and LAMP, assumed in the African plate. Values of the velocities in mm yr^{-1} label the arrows, which are centered on the station location. Error ellipses refer to estimates done by Caporali and Baccini (2001) and are also centered on the station location. Double headed arrows indicate the directions of maximum compressional or extensional stress derived from fault plane solutions by Eva et al. (1998) and Sue et al. (1999) (Western Alps), Bressan et al. (1998) (Eastern Alps), Frepoli et al. (1997, 2000) and Montone et al. (1999) (Italian peninsula and islands). Topographic data base: GTOPO30 1-km elevation grid of National Oceanic and Atmospheric Administration.

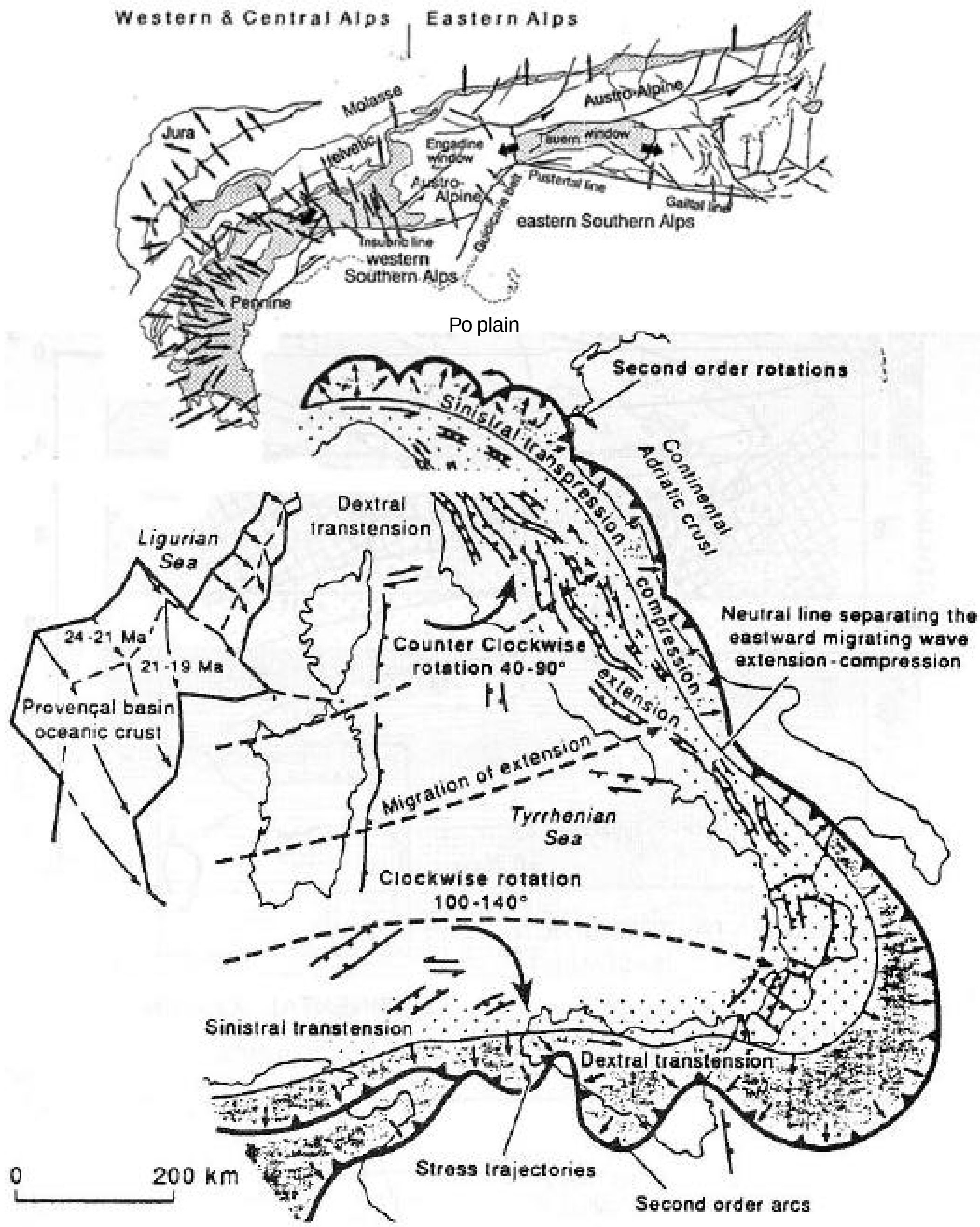

Figure 1: kinematic sketch of the Alps and Italian peninsula, adapted from Ratschbacher et al.(1991), Doglioni (1991), Mueller and Kahle (1993) and Burrus (1984).

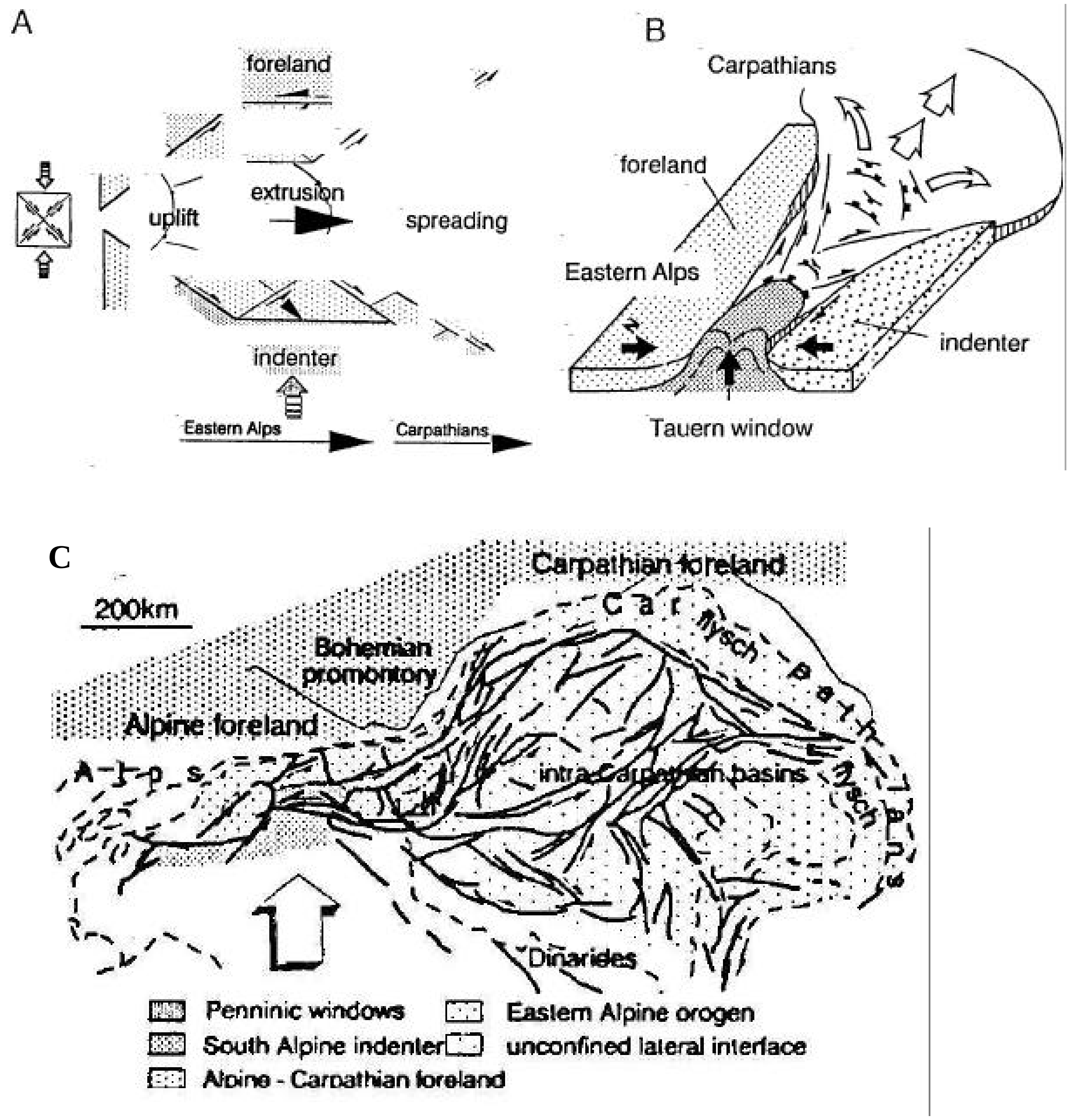

Figure 1: A)sketch model of stress and strain in a block squeezed between an indenter (Adria plate or promontory), a fixed Eurasian foreland and a lateral stress sink; B) compression, uplift and gravitational spreading of the Tauern window; C) geographic index map.

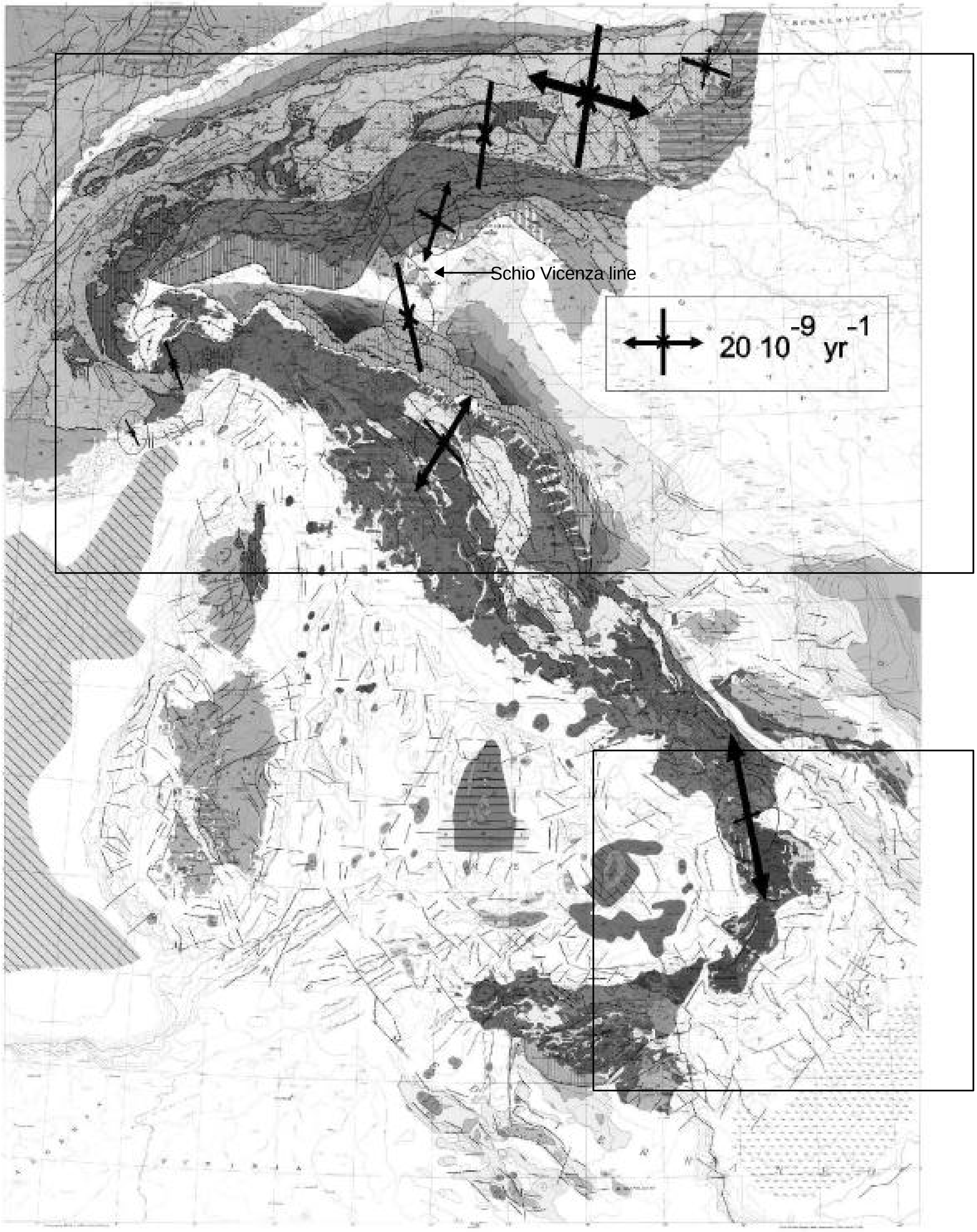

Figure 1: map of the geodetically inferred strain rate, computed at locations baricentric to three or more stations falling within a radius of ~250 km. Eastern and Ligurian Alps, Northern Apennines and the portion of the Southern Apennines/ Calabrian arc covered by the stations MATE, VLUC and COSE. In this case the large extension is likely to be the resultant of differently oriented strain regimes. The expected direction is always radial to the arc. Uncertainties in the strain rate eigenvalues are 1σ. Base map: Structural Model of Italy (Bigi et al., 1990).