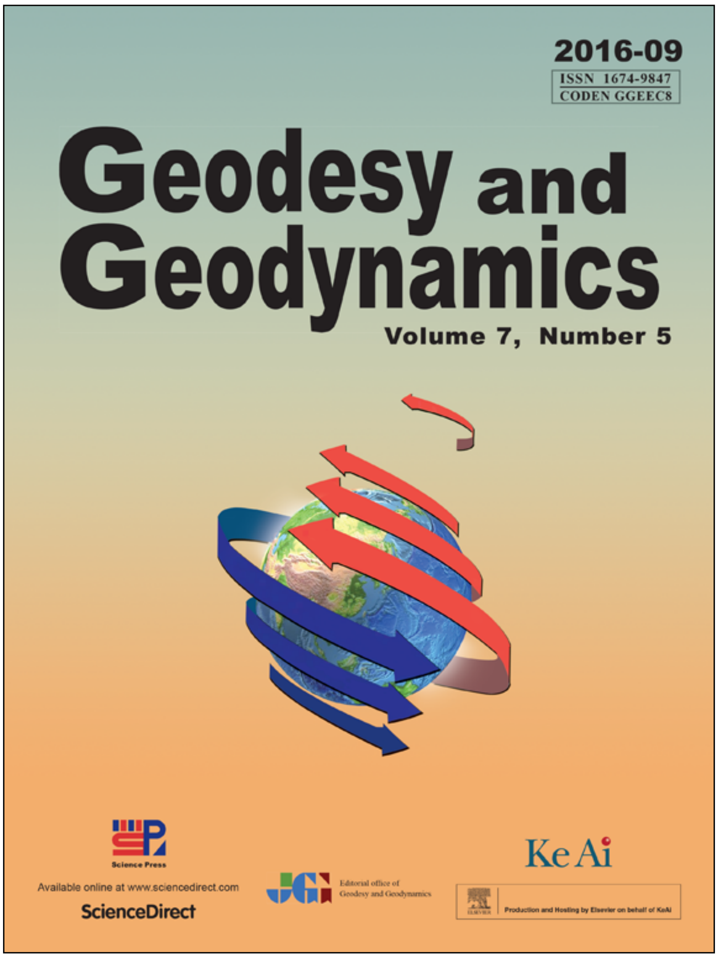
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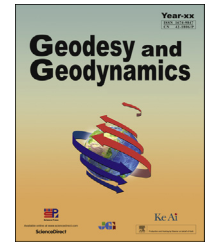

Comparison of the historic seismicity and strain-rate pattern from a dense GPS-GNSS network solution in the Italian Peninsula

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We present a dense crustal velocity field and corresponding strain-rate pattern computed using Global Positioning System (GPS)- Global Navigation Satellite System (GNSS) data from several hundred permanent stations in the Italian Peninsula. GPS data analysis is based on the GAMIT/GLOBK 10.6 software, which was developed and maintained mainly by Massachusetts Institute of Technology (MIT), using tools based on the distributed-sessions approach implemented in this package. The GPS data span the period from January 2008 to December 2012 and come from several different permanent GPS networks in Italy. The GLOBK package implemented in the last version of the GAMIT package is used to compute the position time-series and velocities registered in the International Terrestrial Reference Frame (ITRF) 2008. The resulting high-density intra-plate velocity field provides indications of the tectonics of the Mediterranean region. A computation of the strain-rate pattern from GPS data is performed and compared with the map of the epicentral locations of historical earthquakes that occurred in the last 1000 years in the Italian territory, showing that, in general, higher crustal deformation rates are active in regions affected by seismicity of greater magnitude.

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1. Introduction

Recently, several technological improvements have been implemented in hardware and software applied to Global Positioning System (GPS) technology. Modern receivers can be easily operated from remote sites and directly connected to the Internet. In particular, practically all of the standard modern instruments for permanent GPS stations available for the commercial user are provided with ftp and web servers and can be connected directly to the Internet with the aid of mobile phone technology, and in this way, they can be remotely operated. Facilities for real-time monitoring and positioning with GPS techniques are thus freely available to the user. Modern receivers can be operated by means of user-friendly, object-oriented utilities that are implemented as graphic user interfaces. Static and kinematic positioning applications are widely used to determine the positioning of aircraft in the sky or cars on roads. In Italy, more than 600 permanent GPS stations, which are available for different purposes, are relatively uniformly distributed throughout the territory.

Several continuous GPS (CGPS) station networks are operated by different public and private organizations to provide services to the user, such as correction of kinematic ambiguity and determination of real-time positioning of cars and aircraft. Furthermore, these networks can be used for real-time monitoring of environmental phenomena, including crustal deformation; geodynamic phenomena, such as the subsidence or uplift of the Apennines or Alps chains due to post-glacial rebound; or volcanic activity. High-rate, real-time kinematic applications are useful for computations of coseismic crustal movement and the consequent characterization of seismogenetic structures.

In this work, we begin by describing the methodology applied for the computation of CGPS data solutions that are used to estimate stable high-quality velocity fields from approximately 383 permanent stations that are densely distributed throughout the Italian Peninsula; GPS data are processed for the time span between January 2008 and December 2012. We process the data following a distributed-session multi-step procedure to achieve the task of computing dense velocity fields as well as the strain-rate pattern of the total network. Moreover, the results of the computation of the strain-rate magnitude pattern are presented based on the method developed by Hackl et al. [1] and references therein, which interpolates the horizontal components of the velocity fields by means of the spline in tension technique [2], and then, we calculate the velocity gradient using Generic Mapping Tools (GMT) version 4.5.13 [3]. The strain pattern shows interesting similarities with the map of seismic hazard for the Italian Peninsula, published on the web as "Mappa di pericolosità sismica del territorio nazionale" [4].

Finally, a comparison with the historical seismicity that occurred in the Italian Peninsula during the last 1000 years is presented, showing good analogies with the strain-rate pattern derived from geodetic data.

2. Experimental section

2.1. GPS permanent site data

We built an archive of daily data in Receiver Independent Exchange (RINEX) format, compressed the data with a Hatanaka compressor [5] and finally stored the data using software tools written in Unix c-shell and b-shell languages, as fortran and c subroutines and main programs. Using these tools, we built and maintained our GPS data archive.

From the Internet, we downloaded GPS data from different networks maintained by various public and private organizations. We started with the Rete Integrata Nazionale GPS (RING) [6], maintained by the National Center of Earthquakes of the Istituto Nazionale di Geofisica e Vulcanologia (INGV-CNT) [7]. This network is maintained by INGV-CNT personnel to manage the data from many CGPS stations, which are available also for Italpos, the Leica Geosystems® Italy permanent GPS network [8].

The RING network was established for the routine computation of the strain of the Italian Peninsula, mainly for seismological and volcanic studies. The quality of the RING network data is better than that of the data from the other networks. In particular, the geodetic monuments are built using high-quality scientific standards. Italpos is a network of approximately 150 CGPS sites that is maintained by Leica Geosystems Italy S.p.A. for commercial purposes to transmit kinematic corrections and ambiguities to interested users who are interested in kinematics and rapid-static positioning points in the territory with the aid of a single receiver. An agreement between INGV and Leica regarding several sites that belong to the RING network in ItalPos involves the INGV personnel as well for the maintenance of the ItalPos network sites.

The Italian Space Agency (ASI) maintains a permanent CGPS network in the Italian territory, as well as some sites in Greece. These data are available via file transfer protocol (ftp) at the ASI site [9], with solutions computed mainly using Bernese [10] and Gipsy-Oasis [11] software. These data are made available to the scientific community and to all users who can freely access the ASI ftp server.

The ASI solutions and stations are also involved in the European Reference Network (EUREF) Global Navigation Satellite Systems (GNSS) EUREF Permanent Network (EPN) project [12,13], a European network of CGPS stations that are distributed mainly in the territory of the Eurasia Plate and extend longitudinally from Asiatic and Russian sites to sites in Greenland as well as latitudinally from north African sites to polar stations located in Iceland, Norway and other places. The network solutions and data are made available to the scientific community via free ftp access [14], together with metadata that describe the characteristics of the instrumentation used in the sites and their antenna mounts. Solutions are available for more than 400 permanent stations from the IGB08 reference frame sites of the International GNSS Service (IGS) for the Geodynamics Tracking Network, the International Terrestrial Reference Frame2008 (ITRF2008), and other reference frames. Intraplate velocities are available (ITRF2008), and successful comparisons can be made between our solutions and the

EUREF solutions for coordinates and velocities. Contributions are given by the EUREF project for the definition of reference frames, Earth orientation parameters, and precise orbits for the IGS for Geodynamics.

Together with the previously described network data, we also made use of the CGPS sites of different regions and provinces of the Italian networks in our solutions. In particular, we gathered data from the best-quality permanent sites of the following regional institutions into which the Italian territory is divided administratively: Emilia Romagna, Toscana, Liguria, Piemonte, Lombardia, Veneto, Friuli Venezia Giulia, Calabria, Puglia, and the Provincia Autonoma of Trento and Bolzano [6]. As for the ItalPos network sites, the quality of the data determined the choice of whether to combine these data solutions with those of scientific institutions, such as INGV, EUREF and ASI [15].

2.2. *Processing of the data*

We used the GAMIT 10.6 (GPS Analysis at MIT) data processor developed at the Harvard Smithsonian Center of Astrophysics, Massachusetts Institute of Technology (MIT), and the Scripps Institution of Oceanography of the University of California at San Diego [16]. The GAMIT software is composed of different programs for GPS data processing that can be applied sequentially using Unix c-shell utilities. It is mainly used to compute loosely constrained daily solutions of all clusters by also estimating the coordinates, variance-covariance matrices, ambiguities, atmospheric delays, and sometimes orbital parameters. For the sake of convenience, we divided the data to be processed into 20 clusters of 15 CGPS sites each. The data from eight trusted EUREF sites (CAGL, GENO, MATE, NOT1, PADO, WTZR, GRAZ and POTS) were added into all of the cluster solutions to constrain the solutions as best as possible. To improve the stability of the solutions and to facilitate the combination process, we adopted the same set-up file to model all of the biases. Moreover, the chosen set-up was compatible with the Scripps Orbit and Permanent Array Center (SOPAC) regional clustering [17–22].

The Saastamoinen (1972) model [23] was used to estimate the dry and wet parts of the atmospheric delays; moreover, to model the a priori zenith delay corrections, we adopted the global pressure and temperature "50" model that was implemented and discussed by Boehm et al. [24]. Finally, for every site, the values of the zenith delay corrections were extrapolated from the a priori global grid file that was computed with the aid of the Vienna Mapping functions [25,26].

The iono-free observable is a phase linear combination that is inherently free of 90% of the ionospheric effects, and for this reason, it was used during processing. However, it was still necessary to reduce the contribution of the ionosphere by modelling and stochastically adjusting this bias.

To account for the main components of the solid Earth tides (i.e., diurnal, semi-diurnal, ter-diurnal, weekly, monthly, semi-annual, and annual), we applied the global model implemented by Petit and Luzum [27]. Pole-tide corrections were applied according to IERS03 standards [28].

The tidal effects of oceanic loading were modelled using the finite element solution (FES) 2004 tide model implemented at the Centre National d'Etudes Spatiales, France [29].

Different types of receivers with different antennae were mixed in our solution, in such a way that it was necessary to introduce the upgraded version of the absolute antenna phase centre correction models into the processing. These were provided by IGS and have been made available on the University of California at San Diego, USA, Garner, ftp site [30].

2.3. *Solution creation and adjustment*

To compute the position time-series of the CGPS stations together with the station velocities, we adopted a multi-step procedure, starting from the so-called quasi-observations, i.e., the cluster solutions computed during the GAMIT processing (h-files) that contained loosely constrained weighted least-squares estimates of the site coordinates, variance-covariance, atmospheric models, orbits, and so on [31,32,17]. The first step was to form observations from the quasi-observations by combining our solutions with the regional cluster solutions of SOPAC. This operation was performed using the GLOBK program, by down-weighting the h-files with appropriate weights, taking into account the noise of the solutions.

The robust combination process, as stated by Dong et al. [33], was obtained when precise IGS orbits were used during the processing, and at least two, preferably three, trusted sites were common to all of the solutions (i.e., the h-files). After the combination process, the daily combined observations of all 20 clusters were obtained. After robust combination sessions, a first compensation of the network was performed to compute the site-by-site position time-series for the northeast-up components in a known reference frame. It is possible to register the network sites in the ITRF2008 or IGB08 reference frames by loosely constraining the known positions and velocities of the trusted sites made available by the EUREF or SOPAC facilities in ITRF2008 or IGB08 during the GLOBK solution of the network [34–36].

Interactive editing with the Herring Matlab Tools [37] and processing with the Williams Create and Analyze Time Series [38] packages based on maximum likelihood methods were necessary to estimate the site-by-site noise, to subtract annual and semi-annual components, and to estimate both offsets and outliers.

First, we operated GLOBK to remove the almost-rigid rotation of the Eurasian Plate by means of the pole published in ITRF2008 [36]. Second, using our estimate of the rotation pole of the Eurasian Plate. Finally, the χ^2 parameter of the single daily network solution was used to estimate more realistic error ellipses of the sites considered [31,32]. Fig. 1 shows some of the 188 continuous GPS permanent sites of the IGS used in this study. In this work, we represent the uncertainty of the GPS-derived velocity field in the figures with error ellipses that are at the 68% (1.5 σ) level of confidence.

3. Results and discussion

3.1. *General remarks*

Many papers have been published concerning the study of the strain rate derived from the GPS data of continuous

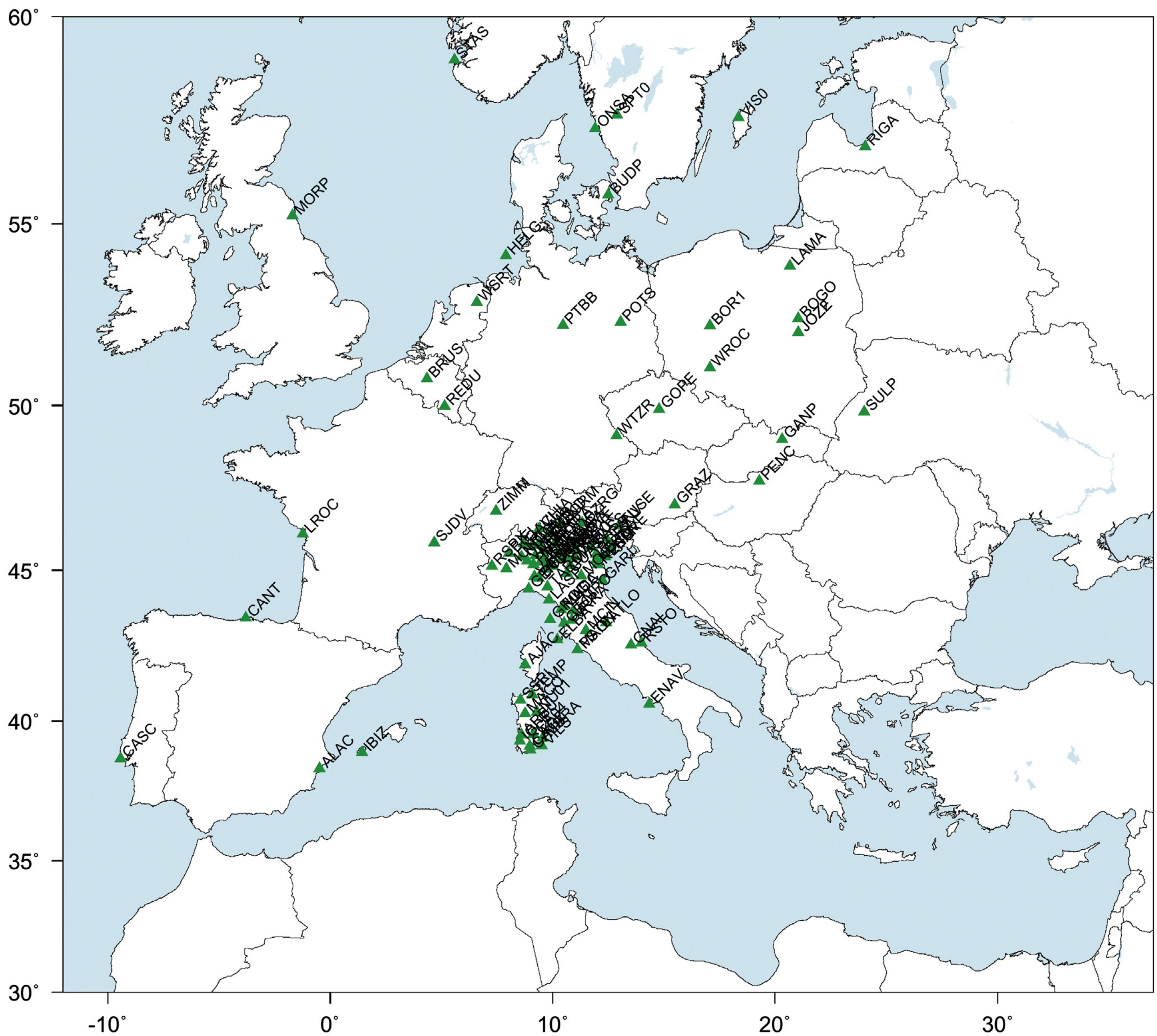

Fig. 1 – 111 of the 188 permanent GPS stations used in this work to define the reference frame.

operating permanent stations in the Italian Peninsula [7,39–46]; the novelty of our work is the usage of GLOBK 10.6 to simultaneously adjust a network of 383 permanent GPS sites and to compute the corresponding strain-rate field by means of the Hackl et al. [1] computational approach based on spline in tension methodology [2]. This procedure can be automated easily and applied effectively to computer clusters; moreover, an interesting comparison with the historical seismicity may be performed as, for example, in the study published recently by Koulali et al. [40] in Geophysical Research Letters, in which some data regarding the historical seismicity of the last century in northern Indonesia were compared with the strain-rate pattern computed from GPS data with a block modelling approach to estimate the seismic hazard in this area. In fact, either the historical seismicity or the strain-rate pattern can give interesting indications about the areas of maximum seismic hazard in the Italian Peninsula and other regions [see also [39,42,46,5]].

As stated above, combined daily solutions of an Italian regional cluster of approximately 383 permanent GPS sites were realized starting from our solution h-files and using regional cluster solutions taken from the Garner facility. Daily combined solutions were stabilized using a priori coordinated EUREF and velocities in ITRF2008 to loosely constrain our combined whole network of daily h-files. The almost-rigid rotation of the Eurasian Plate was removed using the GLOBK global origin (glorg) tool to compute the intra-plate residual horizontal velocities for all of the sites. More than 100 sites (111) showed residual horizontal velocities < 0.95 mm/yr, which demonstrates the good quality of the solutions and shows that the applications of the Altamimi ITRF2008 definition of the Eurasian absolute rotation pole first and our estimation of the rotation pole second were correctly implemented (see Fig. 2).

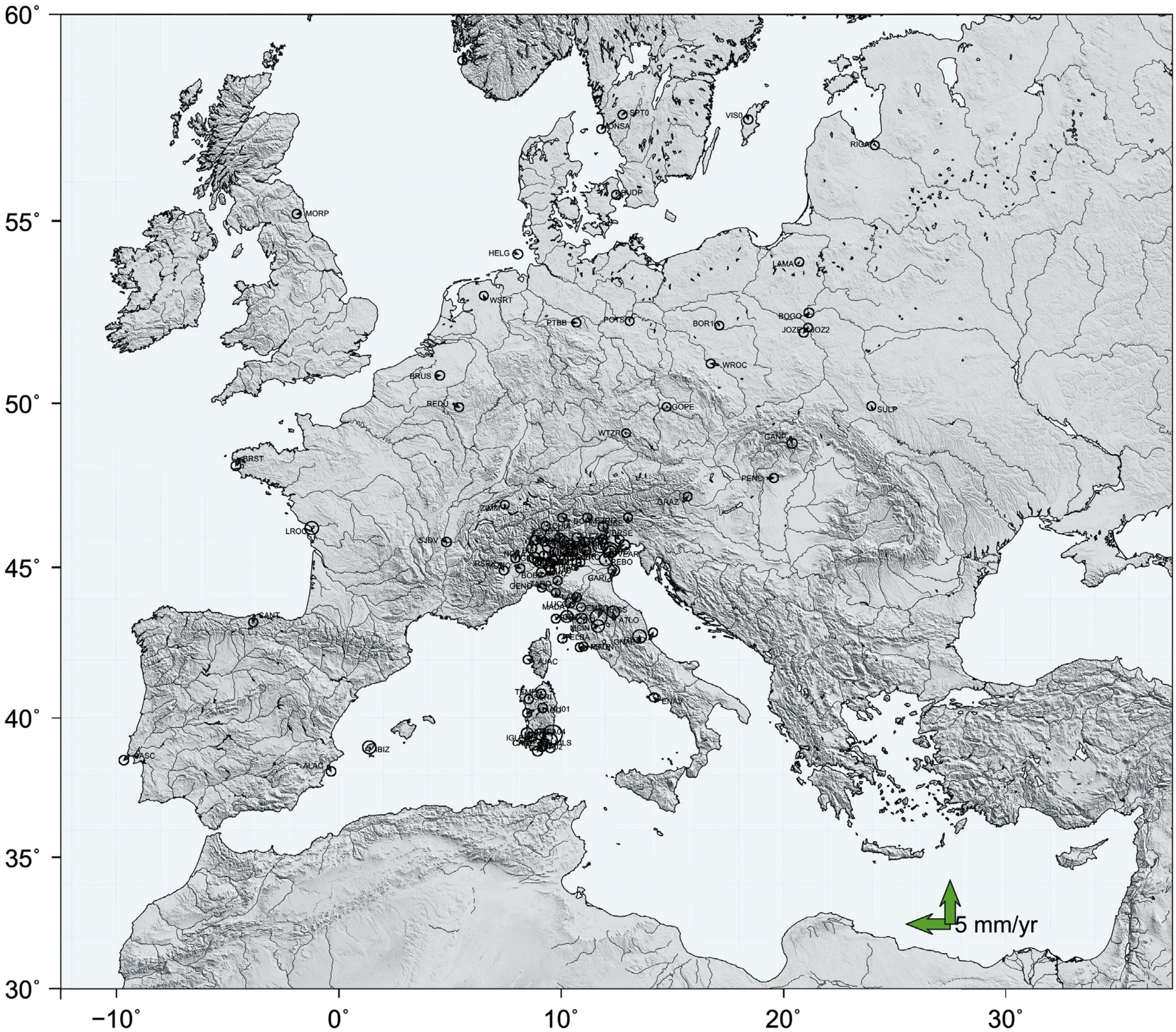

Fig. 2 – Residual horizontal intra-plate Eurasian velocities of the 111 sites of our solutions with residual velocity values <0.95 mm/yr; for the sake of convenience, the authors omit the corresponding data table. Uncertainty ellipses represent the 68% level of confidence.

Using this procedure, data from several hundred permanent GPS stations can be processed and combined. The horizontal and vertical velocities contain the effects of slow-moving cm- to mm-per-year tectonic and environmental phenomena, such as micro-plate motion, subsidence, post-glacial rebound, and sometimes, movements in volcanic areas.

In particular, looking at the whole network solution (see Figs. 3–5), evidence of the northeastern motion of the Nubian Plate is visible for the stations located in the southern part of the Mediterranean Sea: LAMP, MALT and PZIN. This is also evident by looking at the residual velocities of the south-eastern part of Sicily (see Fig. 5).

The sites belonging to Sardinia and Corsica show very little or no significant residual horizontal velocities, which demonstrates that these regions are very stable and move with the Eurasian Plate [39,43–45].

In the continental area of the Italian Peninsula, some interesting large-scale effects may be appreciated by looking at the network dense-residual velocity solutions. In particular, at a scale of 50 km, the Messina Strait sites show 6–7 mm/yr residual velocities and an extensional movement along the northeast to southwest direction (Fig. 5).

In the southern Italian Apennines area, where the RING network is denser and the quality of the sites is better, we can observe residual horizontal velocities of approximately

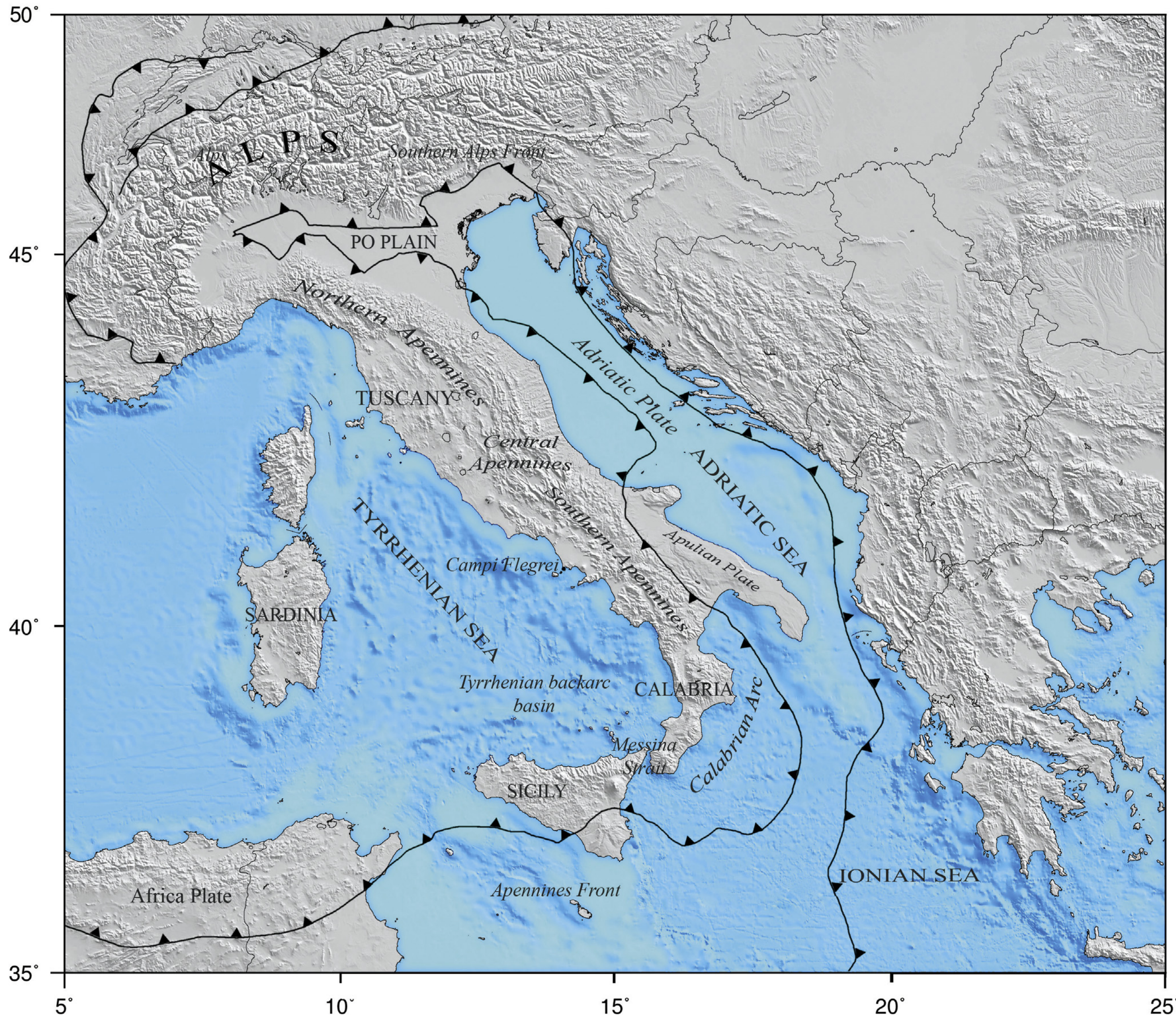

Fig. 3 – The geodynamic map of the Italian Peninsula; major tectonic structures are represented (modified from reference [45]).

5 mm/yr in the northeast direction, which indicate the delineation and counter-clockwise rotation of the Apulian Plate at a large scale [39,43,44].

Moreover, in general, along the Apennine chain, the residual velocities of our solution show an extensional regime from west to east. The three stations LICO, IPRO and RITE show an anomalous trend of expansion due to the movement of the Phlegrean fields caldera during the period of 2008–2012 [47].

The residual horizontal velocities of sites on the Adriatic Plate show a relative motion of approximately 3–4 mm/yr in the northeast direction, as indicated by other studies, which are useful to delineate this tectonic structure [48,49].

The Po plain vertical velocities are affected by a negative or subsidence trend with scattering in the range of −1 to −4 mm/yr essentially due to the extraction of water for industrial and civil use that occurred in this area (see Fig. 6) [48,49].

The same phenomenon is noticeable in some areas of Sicily, where water is extracted daily from wells for civil use [50].

Fig. 5 illustrates northeast movement residuals of approximately 3–4 mm/yr for the horizontal velocities of the Po valley, which thus shows a compressional trend in the area that was struck by the Emilian seismic sequence of May to June 2012 [51,52].

In the areas of the Apennines and Alps chains, the vertical GPS velocities are positive, with a small (1–2 mm/yr) post-glacial rebound signal (Fig. 6) [48].

In the areas of the northwestern sites in the regions of Piemonte, Liguria and Lombardia, the residual horizontal velocities show very little or no relative motion. Conversely, in the central Apennine areas near the Toscana, Lazio and Abruzzo regions, we can observe that moving from west to

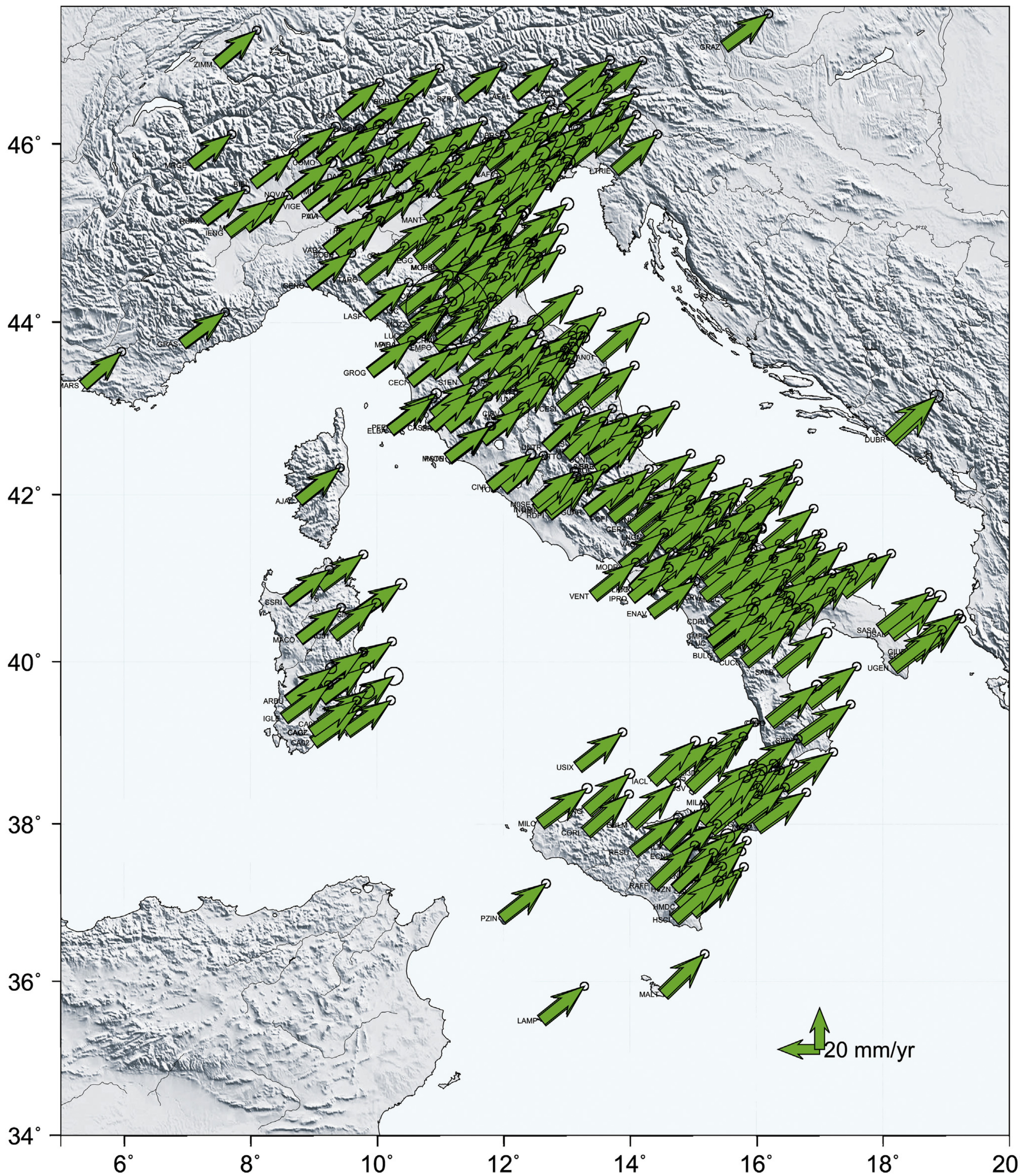

Fig. 4 – **ITRF2008-registered permanent GPS sites velocity data of the whole network solution presented in this study. The northeastern general motion of approximately 25 mm/yr of the Eurasian Plate is clearly evident. Uncertainty ellipses are shown which represent the 68% level of confidence.**

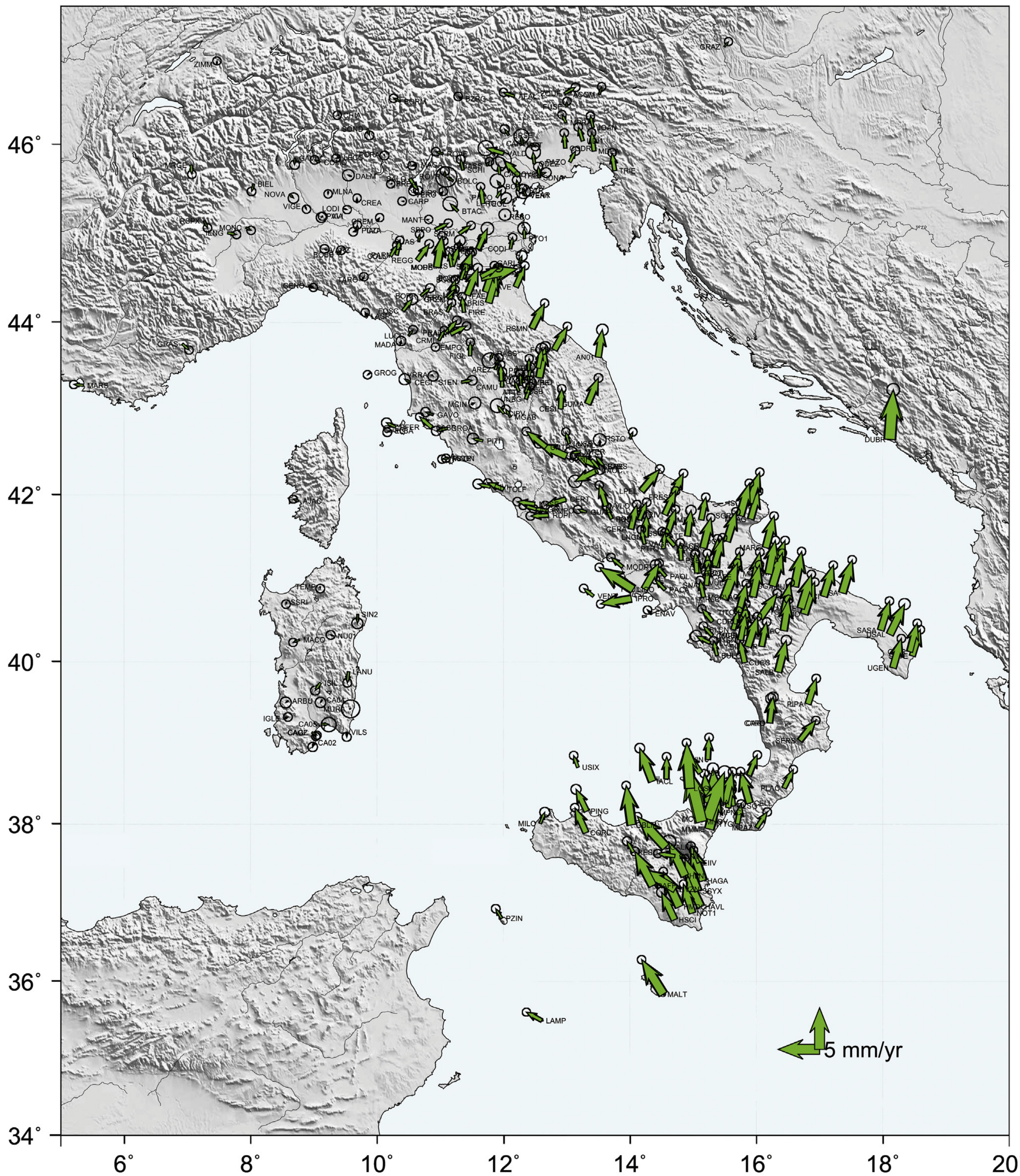

Fig. 5 – Residual horizontal intra-plate velocities of the >300 CGPS stations discussed in this study. The rigid rotation of Eurasian Plate indicated in the Altamimi et al. [36] definition has been subtracted. In this figure, error ellipses are shown with the 68% level of confidence.

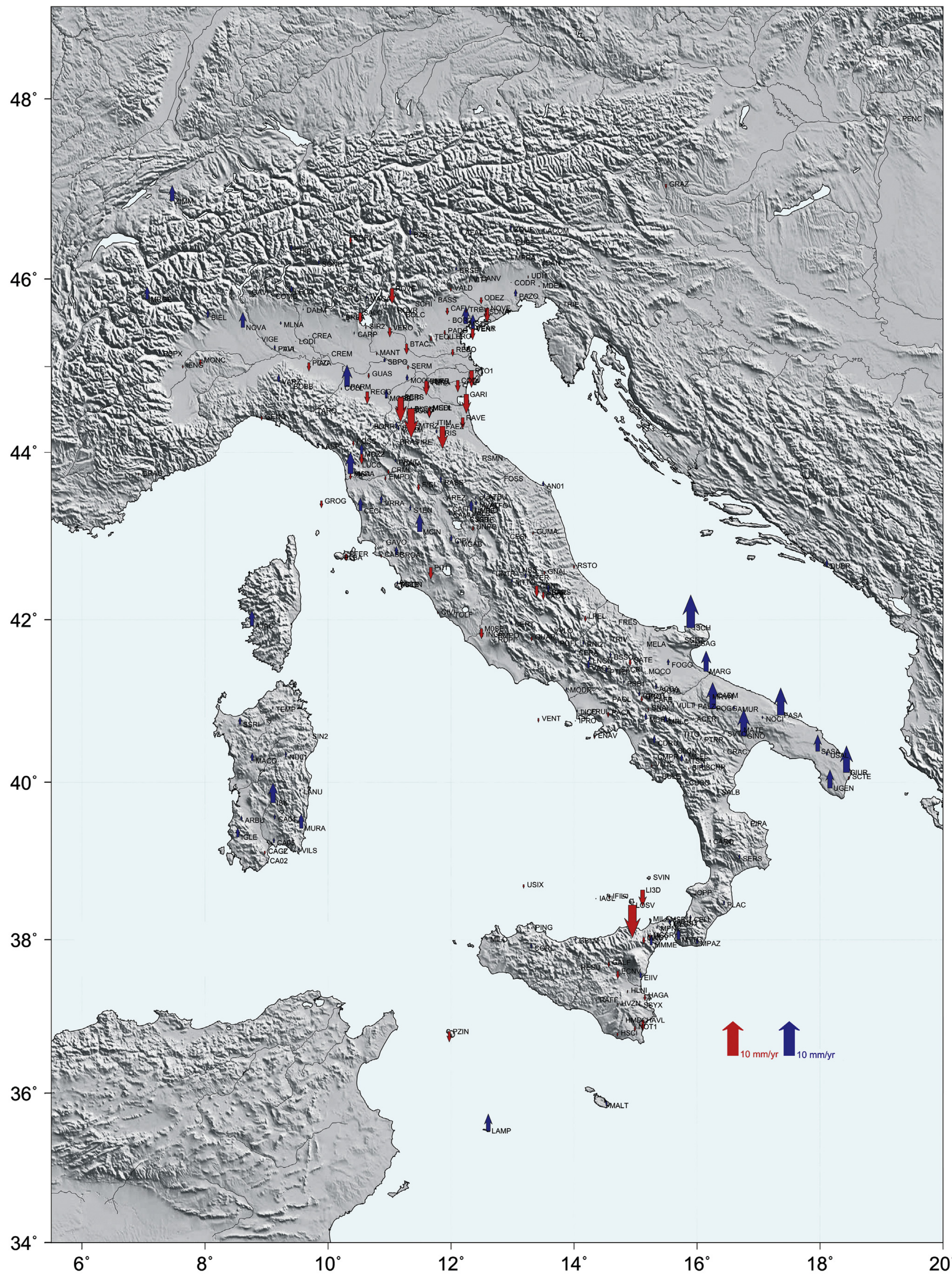

Fig. 6 — Vertical GPS velocities computed in this study. The error ellipses have been omitted for simplicity. Red denotes subsidence (negative velocity); blue denotes uplift (positive velocity).

east along the Apennine chain, the directions and intensities of the velocities range from westward residual motion to northeastward residual movement, testifying to an extensional tectonic regime along this mountain chain.

The residual velocities of our solutions are characterized by error ellipses at the 68% confidence level, with scattering in the range of 0.2–0.3 mm/yr for the horizontal axis, and <1 mm/yr for the vertical axis, which testifies to the high quality of both the data and solutions.

3.2. *Horizontal strain-rate pattern computation from GPS data*

We applied the fast, simple and immediate technique implemented by Hackl et al. [1] to evaluate the patterns of deformation and strain rate in the Italian Peninsula based on a simple interpolation procedure using our GPS intraplate velocities as input.

This method can be applied even if precise local geologic settings are not available; in fact, we needed a method that could be immediately applied in cases in which a dense GPS network was available, and in particular, when the local geology was not completely accessible.

For this computation, a three-step procedure was implemented; first, the interpolation of the horizontal components of the velocity field on a regular grid was performed using the spline according to the tension method of Wessel and Bercovici [2]. Second, the velocity gradient was computed with the partial spatial derivatives of the interpolated velocity field. Finally, we computed the strain-rate patterns according to a linear combination of the velocity gradient horizontal component, following the theory published by Hackl et al. [1]. This multi-step procedure has been implemented on a Linux Bash shell calling GMT routines.

By interpolating the velocity horizontal component fields using splines in tension [2], it is possible to underline regions with a high strain rate related to tectonic activity or deformation due to anthropogenic activities (i.e., oil and water pumping, see reference [48]). We applied this method to the velocity field detrended by the inherently rigid rotation of the Eurasian Plate, following the definition of Altamimi [36].

As noted before, this relatively dense velocity field was computed starting from our archive of GPS data collected in the Italian Peninsula, an area that is strongly characterized by active tectonic phenomena and located between the African and Eurasian plates.

The strain rate is a good indicator of the deformation accumulated in a region, but it is not a direct indicator of the occurrence of seismic events. Strain-rate patterns can only provide additional information for supporting estimates of seismic hazards and for implementing maps [1]. The most promising usage of geodetic data to support seismic prediction is to study the seismic transients in the regions close to seismogenetic structures [56].

As mentioned earlier, to obtain a continuous and dense strain-rate pattern using only our GPS relative velocity data, we first perform an interpolation of the east and north velocity components on a regular grid of $0.05^\circ \times 0.05^\circ$ using the splines in tension algorithm [2]. A parameter T is defined, varying between 0 and 1, to control the tension; the parameter T is set to 0 for a minimum curvature and to 1 for a maximum curvature, giving maxima and minima only at observation points. For instance, the results are not very sensitive to the value of T when the distance between the sites from which the velocity computed is comparable to the dimension of the grid cells [1,53,54]. To obtain a dense enough velocity field, we set $T = 0.3$, the value suggested by Wessel and Bercovici [2], for topographic interpolation. In other words, during the interpolation, the investigated area is divided into a regular grid with a cell size comparable to the average distance between geodetic sites.

The algorithm can manage the redundancy of sites inside a cell because we used a velocity field derived from dense GPS network data. In such a way, the values of the multiple velocities are replaced by the value of the corresponding computed median. This operation results also in an automatic correction of the outliers.

Moreover, as noted by the work published by D'Agostino et al. [53,54], the second invariant of the resulting horizontal strain-rate pattern is independent of the noise caused by the reference frame definition.

Finally, we added the direction and magnitude of the maximum strain rate to the map shown in Fig. 7a to better represent the strain-rate tensor. These data are very effective in characterizing the position of the deformation and direction along which crustal faulting may occur. In Fig. 7a, the colour scale indicates the magnitude of the maximum strain rate, while the white arrows indicate the amplitude and directions of the maxima.

The horizontal strain ranges from 5 to $10 \times 10^{-9}\ \mathrm{yr}^{-1}$ in areas where less seismicity occurs to approximately $1 \times 10^{-7}\ \mathrm{yr}^{-1}$ in more deformed areas. Moreover, looking at the historical seismicity of the Italian Peninsula, in the areas characterized by a $10^{-7}\ \mathrm{yr}^{-1}$ level of strain rate, we can expect seismic events with magnitudes from 6.5 up to a maximum of 7; conversely, where the strain rate reaches $0.05 \times 10^{-7}\ \mathrm{yr}^{-1}$, such as in the Emilia Romagna region, we can expect up to magnitude of 6 seismic events (see Fig. 7b).

Here, we define the seismic risk of a region as the product of the probability that an earthquake of a given magnitude occurs in this area and the risk of damage to buildings, systems, or other entities; alternatively, the seismic hazard can be defined as the probability that an earthquake occurs in a given geographic area, within a given time span, and with an intensity of ground motion that exceeds a defined threshold.

Taking into account these definitions, the map of the strain-rate tensor is one of the elements that are useful to evaluate the seismic hazard of a territory. The map is helpful for monitoring purposes oriented to evaluating the seismic hazard and for giving information regarding ground deformation of tectonic and volcanic origins, enabling appreciable advances in geodetic and geophysical research. In the last 1000 years, Italy has been struck by over 1600 earthquakes of an intensity greater than VI on the MCS scale (CPTI11), namely, an approximate magnitude *Mw* greater than 4.7. Fig. 7a shows some analogies with Fig. 7b, which represents the epicentral location of the sites in Italy that have suffered damage of at least VI on the MCS in the last 1000 years [55].

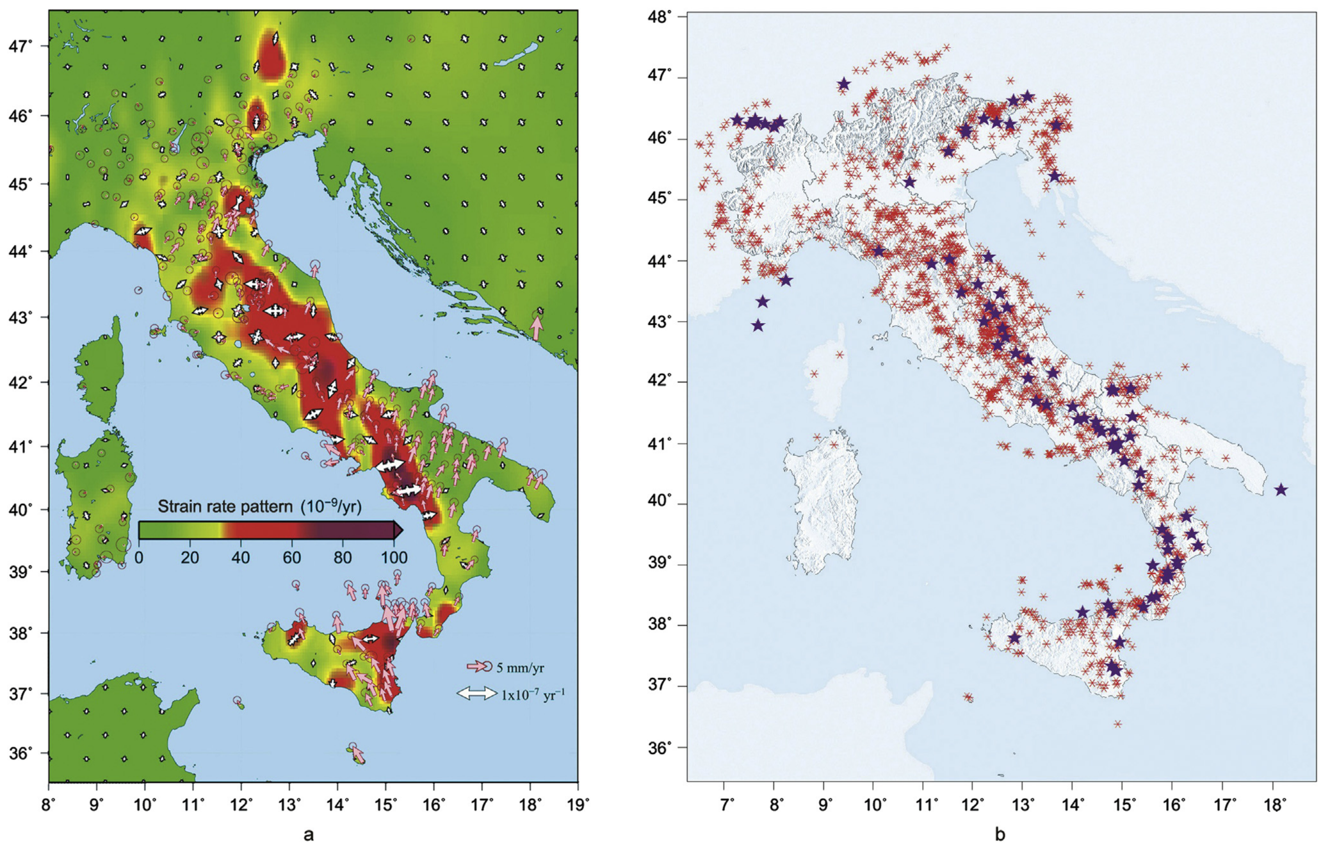

Fig. 7 — a) Pattern of magnitude of the strain-rate tensor of the Italian Peninsula computed by applying the method of Hackl et al. and D'Agostino et al. [1,53,54], after the interpolation of the computed velocity gradient with the technique of spline in tension using the GMT4 package [3]. Analogies with Fig. 7b are evident. b) Map of historical Italian earthquakes. In this map, we have selected the epicentral location of historical earthquakes that occurred in Italy during the last 1000 years. The data represented are selected from the CPTI11 database [55] with magnitude ≥4.5 (1887 events). The red asterisks represent all 1887 earthquakes, and the violet stars highlight the 86 events with magnitude ≥6.0. This map presents some similarity with the strain-rate map of Fig. 7a.

4. Discussion and conclusions

This work begins by presenting a methodology based on the distributed-sessions approach and on the GPS data-analysis software package GAMIT/GLOBK 10.6 written in the Fortran language, Unix c-shell and c, all of which running in Linux environments. The software package is effective for handling several hundred to one thousand GPS-GNSS site networks, provided that the appropriate strategy is adopted.

The data were gathered from the different GPS networks previously described, and the archive populations were routinely handled by dividing the whole network into smaller clusters that could be processed by small-architecture machine clusters (i.e., personal computer clusters). Combined stable good-quality solutions were obtained after the robust combination of our solutions and those of the Garner facility to obtain daily solutions (h-files) of the whole network of approximately 383 permanent GPS stations. The format of the solutions can be automatically converted into the solution independent exchange (SINEX) format and made available to the scientific community. The velocities and coordinates were stabilized in the ITRF2008 reference framework, and the residual intra-plate velocities were computed and showed interesting large-scale indications of the tectonics of the Mediterranean area.

Finally, we successfully applied the method of Hackl et al. [1] and D'Agostino et al. [53,54], as well as the references therein for computing the pattern of the magnitude of the strain-rate tensor derived from the GPS intra-plate velocity field based on the GMT 4.5.13 package, and we followed a continuous smoothed interpolation of the computed velocity field with the method of spline in tension implemented by Wessel and Bercovici [2] and a successive computation of the velocity gradient and the strain-rate tensor (see Fig. 7a).

The map of the strain-rate tensor gives useful information about ground deformation of tectonic and volcanic origins, enabling significant progress in geophysical and geodetic research and in monitoring activity that contributes in part to defining seismic hazards; in fact, interesting analogies are evident on the map of Italian seismicity shown in Fig. 7b.

With the exception of the Sardinia and Corsica regions, where our solution confirms the general movement of the Eurasian Plate and whose stations are sometimes used to define the reference frame, the Italian Peninsula is affected by tectonics activated by the long front of slow compression between the African and Eurasian plates, active in the southeast-northwest direction; the corresponding large-scale movement of Eurasia of approximately 25 mm/yr northeastward can be removed using the general definition of the absolute Eurasia rotation pole given by Altamimi for the ITRF2008 [36] (see Figs. 3 and 4). Moreover, with a high-density crustal velocity field, such as that presented in this paper, it is possible to carefully estimate a relative rotation pole by which the rigid rotation of Eurasia can be eliminated to improve the computation of the residual intra-plate velocity field.

Many large-scale tectonic features are evident in considering the residual velocity field represented in Fig. 5, such as the Messina Strait 50-km-scale extension, the northeast movement of the Adriatic Plate, the extension along the Apenninic chain going from west to east, and the compressional field still active between the Emilian-Tuscany Northern Apennines and the Po plain, which generated the May–June 2012 Emilia earthquakes (see Fig. 5) [51,52].

Evidence of the subsidence phenomenon is present, in particular, in the high negative trend of the Po plain stations represented in red in Fig. 6 [48].

The three stations located in the volcanic district of the Phlegrean fields show a residual expansive velocity trend due to the contemporary dilatation of the local caldera, also observed by other authors with GPS-GNSS, differential interferometric synthetic aperture radar (DinSAR) and, concerning the vertical component, spirit-levelling techniques [47] (see Figs. 3 and 5).

In general, the areas in which human industrial activities require the daily pumping of water from soils are affected by the subsidence phenomenon that can be sensed by accurate high-precision GPS-GNSS measurements; conversely, the areas of the Apennines and the Alps are affected by positive vertical velocities due to the post-glacial rebound phenomenon.

The comparison of the strain-rate pattern and historical earthquakes, as already noted in other areas by other authors, for example, Koulali et al. [40], Antonielli et al. [57], represents a new approach to defining the characteristics of seismogenetic areas but also provides a helpful tool to better implement the definition of seismic hazard areas, even if it is not effective for the prediction of earthquakes [1] (Fig. 7a, b).

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