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SATELLITE POSITIONING FOR GEOSCIENCES

# The velocity field of the Italian area

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**Abstract** The rapid development of several permanent GNSS networks in Italy has made available a huge amount of GNSS observations, giving the chance to figure out and significantly improve the spatial and temporal resolutions of the crustal deformation in the Italian area. More than 20 GNSS networks, promoted and managed by different institutions, constitute the grid of monitoring stations that includes over 1000 permanent stations, mainlydevoted to real-time positioning services but that has proven to be suitable for monitoring slow deforming processes, such as for instance, intraplate deformation processes. The whole set of raw GPS data is routinely processed at INGV providing daily solutions of station coordinates and estimating linear velocities for each station. The information content of coordinate time series is wide, the station position variations incorporate linear and non-linear effects caused by geophysical phenomena of different nature, of which we show some evidences. The sectors where the permanent network is augmented with non-permanent sites allows to study tectonic processes with a finer resolution.

**Keywords** GPS velocity field · Italy · Tectonic deformation

## 1 GNSS networks and data analysis

INGV manages the Italian RING network (http://ring.gm.ingv.it), a GPS network of about 200 stations that meet strict instrumental standardization in terms of monument, receiver and antenna types. Moreover, daily data from 32 different Italian GNSS networks are currently archived and processed routinely. The GNSS database is further augmented with other 57 sites belonging to EUREF and/or IGS networks that are homogeneously distributed in Europe and used for the ITRF2008 reference frame definition (Fig. 1). The number of analyzed sites grew exponentially in the last decade, following the deployment of new GNSS stations (Fig. 2). At present we process, on average, data from about 1000 sites per day, this number is variable because of data gaps due to different causes (missing data, bad data not passing a preliminary quality check, etc.).

The monument types, antenna and receiver types and the environmental operating conditions are not uniform (Devoti et al. 2016), nor geodetic standards are well advised, nevertheless the networks cover the Italian area in an almost uniform way. Figure 3 shows all the analyzed GPS stations (black dots) and the color maps the distance from the nearest GPS site: in most sections this distance ranges between 10 and 20 km with an overall maximum value lower than 40 km. In this picture, northwest Italy is slightly sparser populated, since most of the INGV stations were planned to monitor the seismically active Apennines chain, nevertheless the number of new contributing stations is always in evolution according to the different owner needs.

This continuous monitoring effort, carried out by various institutions, is of great value to better understand the large-scale plate kinematics and to shed light on the physics that governs tectonic deformation and seismic and aseismic faulting. The GPS data are currently archived and fully processed

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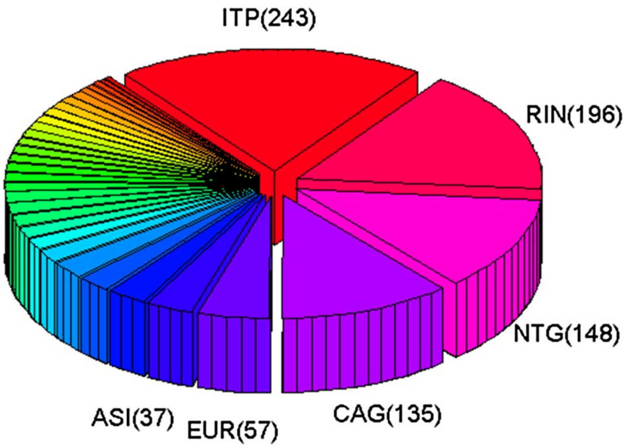


**Fig. 1** Number of analyzed sites for each network. *RIN* RING (Istituto Nazionale di Geofisica e Vulcanologia), *ASI* Agenzia Spaziale Italiana, *FRE* FREDNET (Istituto Nazionale di Oceanografia e di Geofisica Sperimentale), *EUR* EUREF and IGS. The remaining acronyms represent networks established by regional administrations and private companies

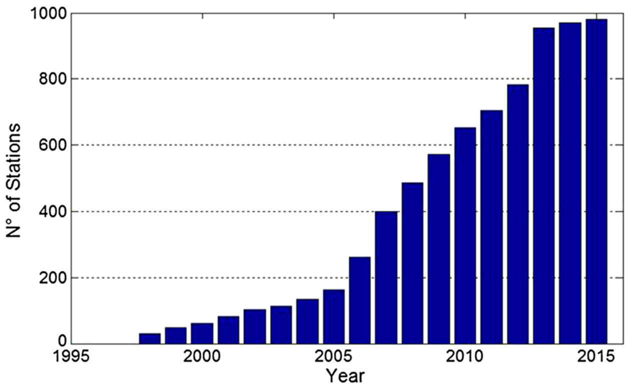


**Fig. 2** Bar chart showing the growth of analyzed site number in the Italian area per year

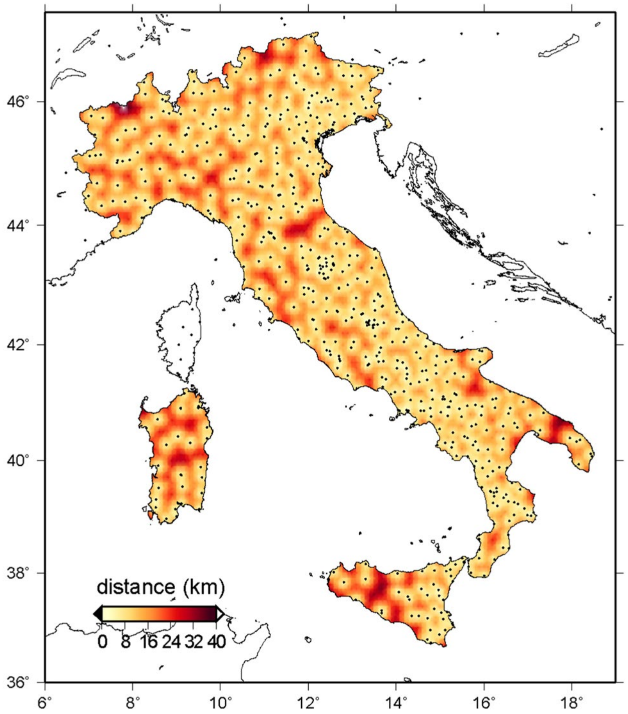


**Fig. 3** Distance from the nearest permanent GPS site on a regular grid of 0.1° × 0.1°. Black dots are the stations

by three Analysis Centers (AC) at INGV, in which different processing approaches are adopted (Devoti et al. 2017). The combination of those independent solutions provides a unique velocity field that can be validated and assessed through a feedback technique.

In particular, the three ACs process and analyze routinely all the available European GPS data using, respectively, the Bernese (Beutler et al. 2007), Gamit (Herring et al. 2015) and Gipsy (Zumberge et al. 1997) software. They produce daily position solutions for up to 2000 stations located mostly in the Mediterranean area and on the central and western European continent. Figure 4 shows the flowchart of the data processing scheme, starting from the raw GNSS observations acquired at the remote stations and transmitted over different transmission systems (GSM, UMTS, VSAT, WiFi, etc.) to the control centers, going through the quality control and archiving into databanks, and finally undergoing the processing and the products generation.

Each AC usually produces an independent velocity solution of a different grid of networks, so that most sites overlap among the other two. The site velocities are estimated fitting simultaneously a linear drift, episodic offsets and annual sinusoids to the coordinate time series. Offsets are estimated whenever a change in the GPS equipment induces a significant transient in the time series, or whenever a constant offset has been detected in the raw time series. Whereas seasonal oscillations are filtered out by fitting annual sinusoids. The three velocity solutions are then combined to obtain a complete velocity field expressed in a unique reference frame. The velocity combination procedure is a generalization of the loosely constraints approach (Devoti et al. 2017) in which each velocity field is considered as a sample of the true velocity field while the combined velocity, is the best estimate of the true velocity field. The availability of different samples of the station velocities allows a sort of validation in which the velocity repeatability can be truly assessed.

The combined horizontal velocity field (Fig. 5) highlights with unprecedented details the kinematics of a large portion of the European region, with dense spatial sampling of crustal deformation across the Mediterranean plate boundary and active fault systems.

The focus on the Italian area allows to evidence peculiar features both in the horizontal and vertical velocities

**Fig. 4** Scheme of the data flow. Courtesy of Maria Brovelli

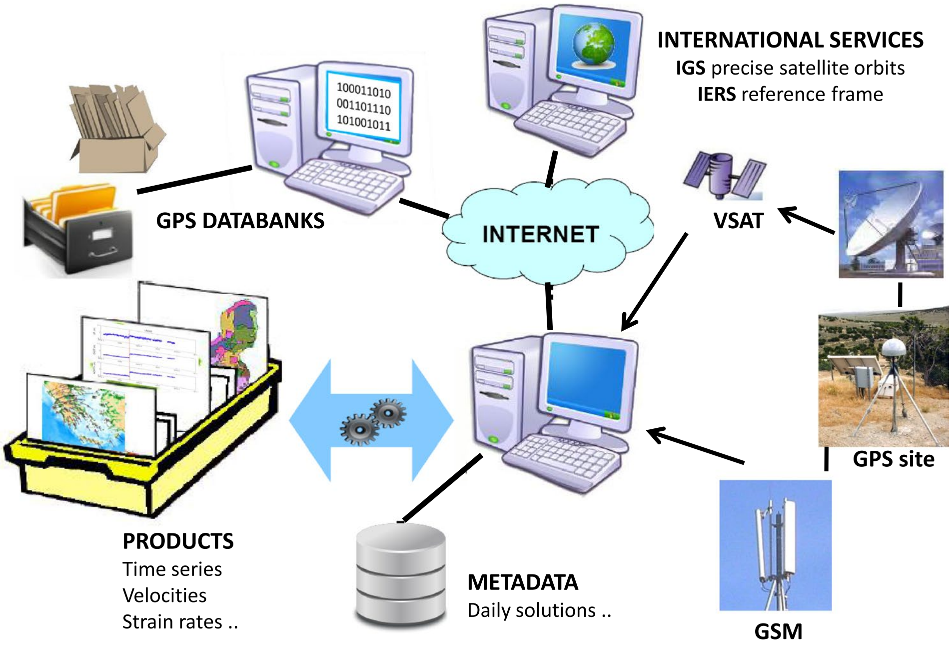
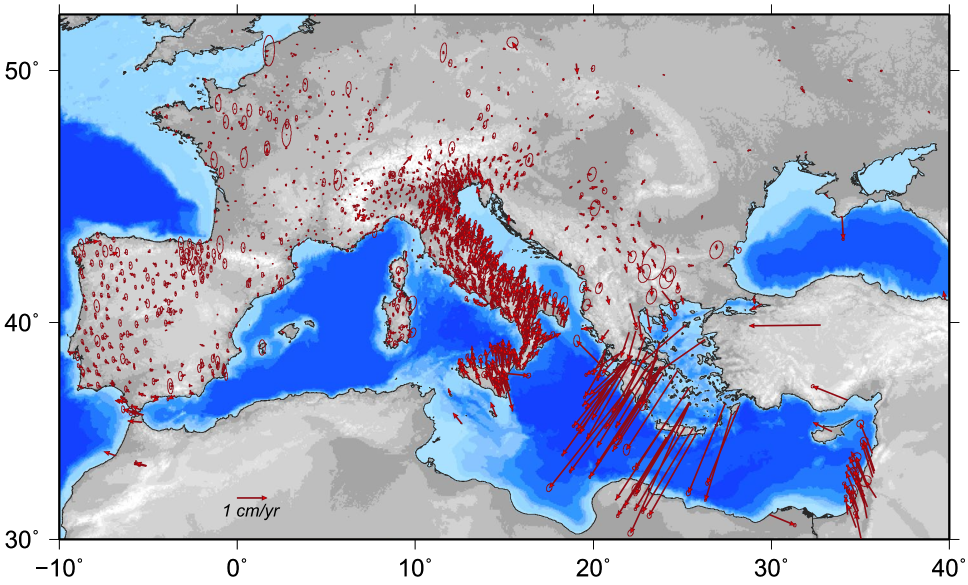


**Fig. 5** Horizontal velocity field of the Mediterranean area estimated with respect to the stable Eurasian plate. After Devoti et al. (2017)



(Fig. 6a, b); the error ellipses show the one-sigma region and range from 0.1 mm/year for the long lasting sites, to about 1 mm/year. The average horizontal and vertical velocity uncertainties are 0.3 and 0.5 mm/year, respectively. Each GPS site spans different life times, so that we show in the figure all those with a minimum observation time of 3 years, the mean station lifetime being 7 years. The reference Eurasian plate has been realized by minimizing the rigid motion of 15 selected EUREF stations located in stable central Europe.

The horizontal velocity field permits to figure out some important features at regional scale: the distinct patterns between the Tyrrhenian and Adriatic domains, represented, respectively, by the NW- and NE-directed velocities marking the active extension along the Apennines chain; the ongoing compression in NE Alps and northern Sicily; the extension across the Northeastern Sicily and the Sicily Channel; the Corsica–Sardinia block demonstrating no residual motion with respect to the Eurasian plate. Moreover, significant subsidence is evident in the eastern Po plain and Aeolian islands area, whereas a striking uplift along the Alps and Apennines chain is detected. This complex puzzle reflects the rather complicated geodynamic processes involved in the Italian peninsula, its tectonics is dominated by the active

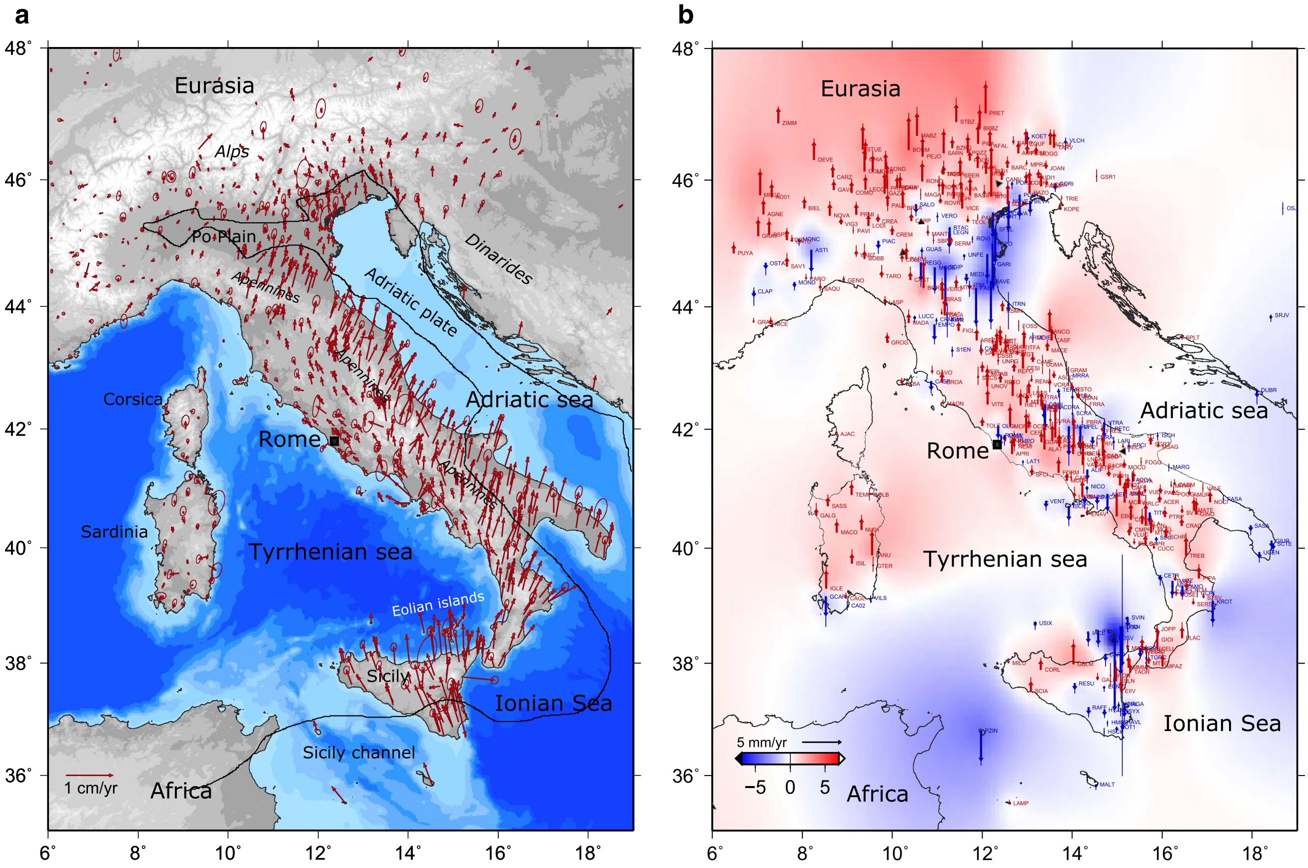


**Fig. 6** **a** Horizontal velocity field of the Italian area in the Eurasian frame; **b** vertical velocity field. The background color map has been obtained by interpolating the vertical velocities by GMT (Wessel et al. 2013)

subduction of the Adriatic microplate along the Apennines and Dinarides, and overriding the Eurasian plate along the Alps (Devoti et al. 2008). Earthquakes with extensional mechanisms mainly occur along the Apennines, while compressive mechanisms are detected near the active fronts (Pondrelli et al. 2006).

Actually GPS time series contain more interesting signatures (Fig. 7a) than linear trend useful to study geodynamic processes. In fact, they are often affected by earthquakes, both as instant offsets (Figs. 7a, b, 8), useful to model the seismic source (i.e., Anzidei et al. 2009; Cheloni et al. 2016) or post-seismic non-linear behavior, as shown in Fig. 7a (Devoti 2012).

The fundamental questions for which geodesy provides useful clues to disclose our understanding of geodynamic processes are not trivial indeed, here we propose a few key issues for which the measurement of displacements may help clarifying pending issues.

The first question concerns the possibility of measuring a possible precursor: is there any geophysical process that produces measurable effects on the surface, which can trigger or modify the occurrence of earthquakes? It is generally thought that elastic strain accumulates in the crust gaining a critical stress value after which an unavoidable rupture occurs (Fig. 8). However, many other phenomena may alter the constant strain build-up, promoting or retarding the fault rupture. Pore pressure changes caused by deep-seated fluids or shallow water table fluctuations induced by climate changes (Hoffmann et al. 2001; Longuevergne et al. 2009; Jacob et al. 2010; Wahr et al. 2013; Amos et al. 2014; Devoti et al. 2015; Silverii et al. 2016), stress variations caused by nearby earthquakes (Lin and Stein 2004; Thompson and Parsons 2016) but also indirect mantle flow caused by subduction or continental collision such as delamination and tear faults (D’Agostino et al. 2001; Pérouse et al. 2010; Devoti et al. 2011; Cowie et al. 2013). Recognizing all these processes represent a challenge for the scientific community and will by all means constrain future earthquake hazard.

This discussion is related to another basic scientific problem: do we have a complete tectonic model that explains the observed inter-seismic deformation? In other words, how well do we know the mechanics and the importance of different processes that control the strain and stress accumulation in active fault zones. It is thought that tectonic deformation

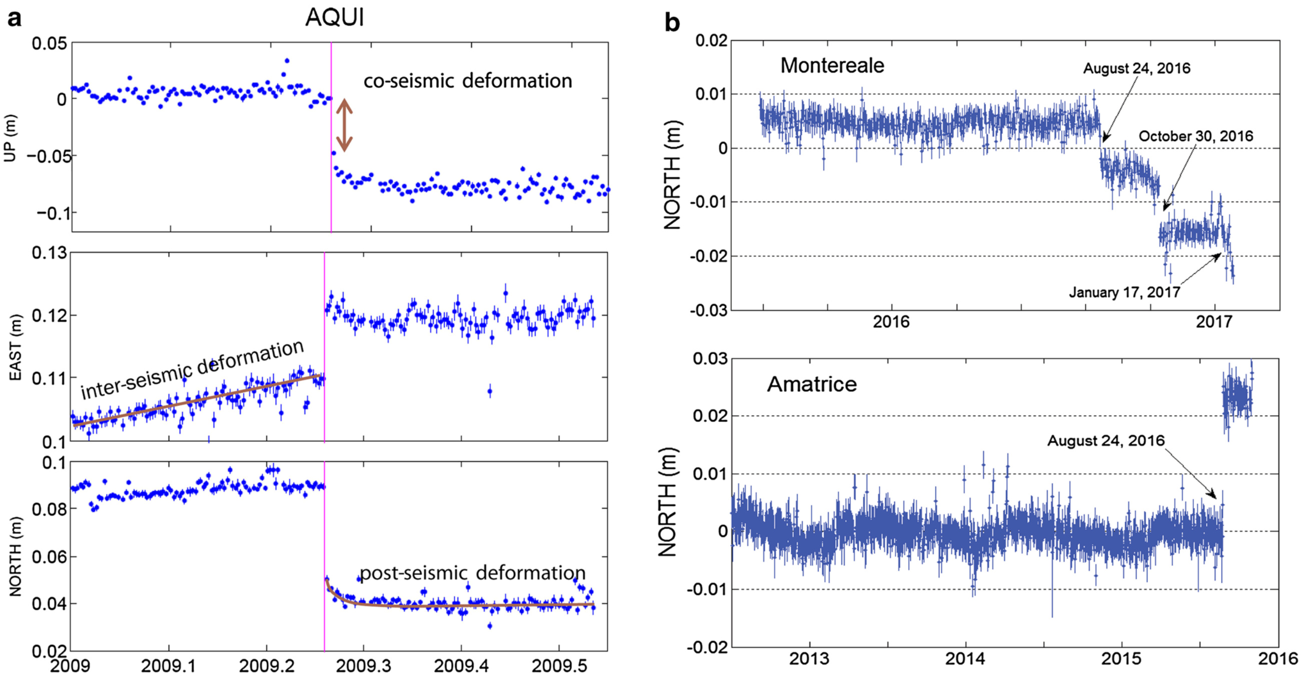


**Fig. 7** **a** Time series of the Up, East and North components of L'Aquila station from January 01, 2009 to the end of July, the red bar marks the epoch of the April 6 Mw 6.1 earthquake; **b** time series of the North component of Montereale and Amatrice stations crossing the epoch of the recent seismic sequence started on August 26, 2016

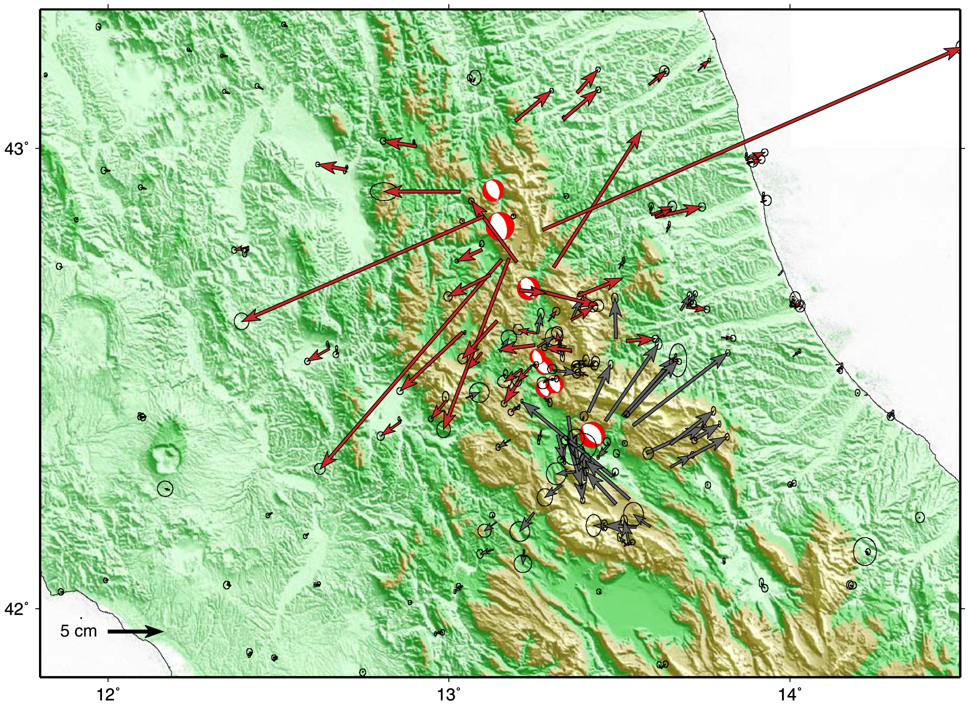


**Fig. 8** Horizontal displacements observed at permanent and non-permanent GPS stations after the L'Aquila earthquake (April 6, 2009 Mw 6.1,) gray arrows, and the cumulative displacements (in red) due to Amatrice (August 24, 2016 Mw 6.0), Visso (October 26, 2016 Mw 5.9), Norcia (October 30, 2016 Mw 6.5) and the four *M* > 5.0 Campotosto events (January 18, 2017) red arrows (colour figure online)

buildup is well approximated by a linear increase of strain with time and is generally termed inter-seismic deformation (Segall 2010). Thus, to study the earthquake cycle and improve the predictive power of the theory, it is crucial to figure out the corresponding components in each time series to assess the regional stress field variation. Another peculiar question arises after the earthquake occurs, it is worthwhile to assess what kind of seismic source and how the rupture evolves in time by observing the time-dependent surface displacements at different space–time scales. Although we already own a good theory of fault dislocation in a elastic half-space (i.e., dislocation theory, see for example Savage 1983), we still lack the details of the rupture style, the effect of listric geometries or secondary splay faults, non-elastic behavior of the lithosphere and if mature or incipient faults act differently. Finally, after an earthquake had occurred, we may ask how the lower crust will react to the fault dislocation and sudden stress drop, and what rheology explains the observed surface rebound. This effect, called post-seismic relaxation (Hampel and Hetzel 2015), may last for several decades after major earthquakes and overlaps to the inter-seismic tectonic deformation, thus it has to be carefully analyzed and assessed to separate the relative contributions.

The deployment of discontinuous GPS stations, in which repeated survey campaigns may be achieved with reasonable precision, represents a helpful and rather cost-effective monitoring technique allowing to densify the network in sectors of particular interest. The discontinuous stations materialized in central Italy, provide more than 200 benchmarks that, measured occasionally over the last 18 years, provide a

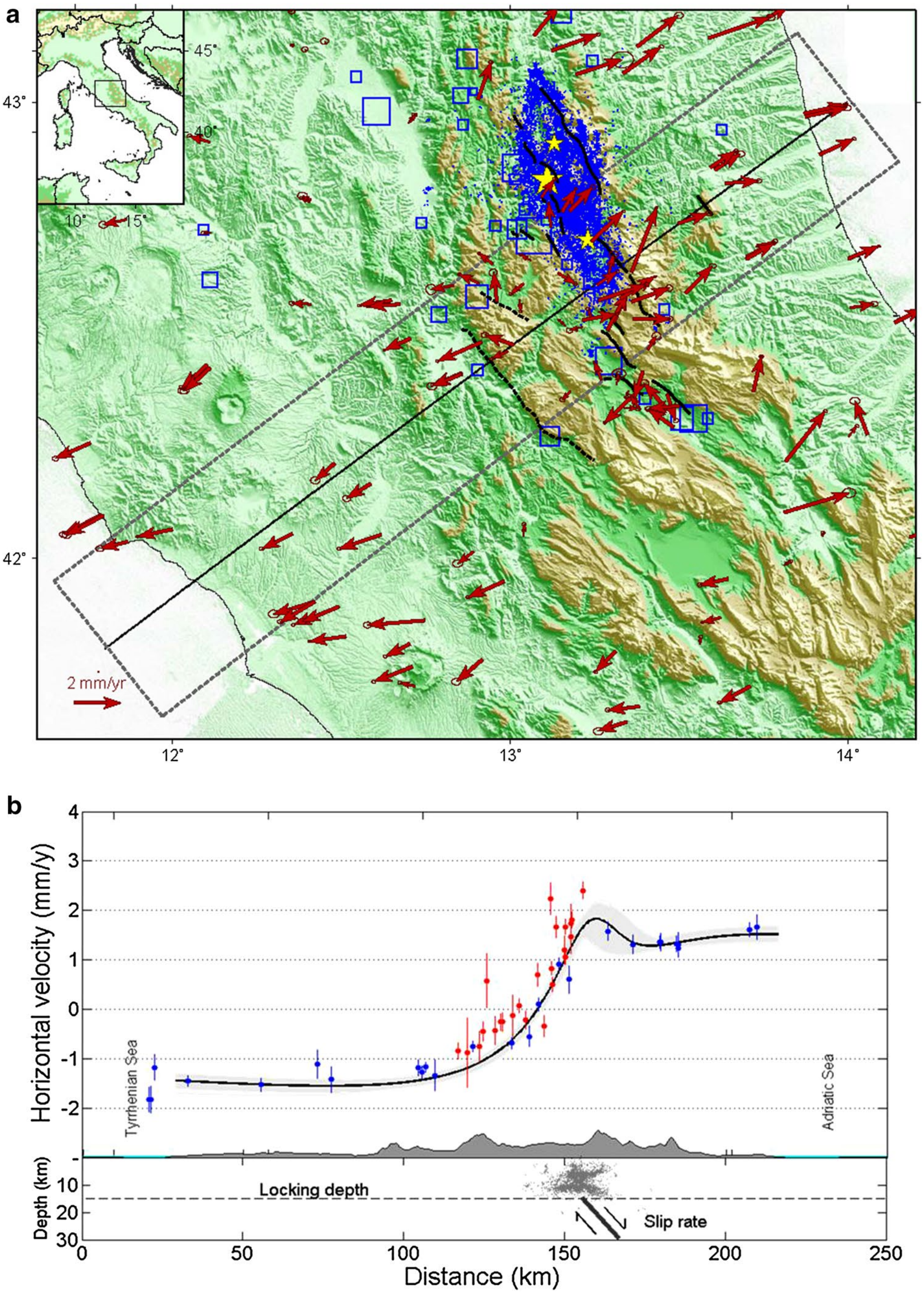


**Fig. 9** **a** GPS horizontal inter-seismic velocities (red) from permanent and non-permanent networks in a no-net-translation reference frame. In blue the seismicity (square historical, dot recent); **b** velocities projected along the profile within the rectangular box, in gray the topographic profile; the black line on the bottom is the best estimate from data of the dislocation surface occurring along a E-directed creeping source located below 15 km depth (colour figure online)

complementary set of observations for the linear trend evaluation (Galvani et al. 2012). Worth of note is the GPS transect crossing central Italy over the Amatrice area, for which we were able to estimate the horizontal velocities with enhanced details before the August 24, 2016 seismic sequence. The velocities enclosed in the rectangular box were projected along the profile shown in Fig. 9a; they are representative of the pre-seismic velocities (i.e., inter-seismic including post-seismic relaxation due to previous events), before the Amatrice earthquakes. The red dots in Fig. 9b shows the projected velocities obtained from the non-permanent GPS stations, in this particular profile the density of non-permanent stations is three times higher, and thus the recognition of second-order details in the deformation pattern becomes feasible. As an example of possible source for the observed surface inter-seismic strain, the solid line in Fig. 9b shows the modeled strain profile caused by a creeping dislocation embedded in an elastic half-space (Savage 1983) and locked at 15 km depth.

## 2 Conclusions

We show that a dense grid of GNSS stations, despite its inhomogeneous nature, represents a valuable scientific infrastructure that allows continuous monitoring of surface displacements and support significant geophysical studies in active plate boundary zones like the Italian peninsula. The mean inter-station distance ranges between 10 and 40 km but is not regular everywhere, this allows to figure out the long wavelength of the surface deformation pattern. Nevertheless to inspect the details and in some cases, to discriminate between competing theories, a further network densification is necessary. A good cost-effectiveness compromise may be the adoption of removable GNSS stations measuring the position in repeated survey campaigns. The network augmentation in particular sectors and across the Apennines shows still unknown and probably unexpected features of the deformation field at small spatial scales, thus suggesting the existence of short wavelength deformation patterns at distances comparable to the seismogenic layer (10 km or lower distances). We, therefore, strongly support the idea of a geodetic infrastructure (grid of GNSS networks) along and across the Apennines, capable to monitor geophysical processes at different spatial scales and continuously in time. Such an infrastructure will certainly grant fundamental understandings of crustal and sub-crustal processes in the Italian peninsula.

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