ANNALS OF GEOPHYSICS, VOL. 48, N. 2, April 2005

Geodetic deformation across the Central Apennines from GPS data in the time span 1999-2003

Marco Anzidei (1), **Paolo Baldi** (2), **Arianna Pesci** (1), **Alessandra Esposito** (1), **Alessandro Galvani** (1),
Fabiana Loddo (1), **Paolo Cristofoletti** (1), **Angelo Massucci** (1) **and Sergio Del Mese** (1)
(1) *Istituto Nazionale di Geofisica e Vulcanologia, Roma, Italy*
(2) *Dipartimento di Fisica, Università degli Studi di Bologna, Italy*

Abstract
During the time span 1999-2003, a temporary GPS network located across one of the highest seismic areas of the Central Apennines (Italy) was set up and repeatedly surveyed. The Central Apennines Geodetic Network (CA-GeoNet) extends across Umbria, Abruzzo, Marche and Lazio regions, in an area of ~180 × 130 km, from the Tyrrhenian to the Adriatic Sea. It consists of 125 GPS stations distributed at 3-5 km average grid and includes 7 permanent GPS stations operated by the Italian Space Agency (ASI) and the Istituto Nazionale di Geofisica e Vulcanologia (INGV). With the aim to estimate the active strain rate across this part of the chain, the GPS sites were located on the main geological units of the area and across the typical basin and range structures, related to the main seismogenic faults. In this paper we show the network and the first results obtained for a subset of 23 stations occupied at least during three repeated campaigns, in the time span 1999-2003. Data analysis, performed by Bernese 4.2 software, shows an extensional rate normal to the chain, in agreement with geological and seismic data. The strain rates in the inner chain range from $12\times10^{-9}\pm11\text{yr}^{-1}$ to $16\times10^{-9}\pm11\text{yr}^{-1}$ and from $-14\times10^{-9}\pm11\text{yr}^{-1}$ to $-3\times10^{-9}\pm11\text{yr}^{-1}$. This result provides an improved estimation of the ongoing deformation of this area with respect to previous studies and is in agreement with the style of deformation inferred from seismicity and with the features of the main seismogenic sources from recent geological and seismological investigations.

Key words *GPS – crustal deformations – Central Apennines – Italy*

1. Introduction

The development of geodetic space techniques and particularly of the NAVSTAR Global Positioning System (GPS), yelded to the realization of high precision geodetic networks devoted to geodynamic investigations in areas affected by recent active tectonics. This technique defines the relative positioning of the observation sites located on the Earth's surface within centimetric precision even for baselines of hundreds of kilometers and without the limitation of the terrestrial techniques, such as the mutual visibility between the observation sites. This enables us to study a new classes of tectonic processes both on regional and local scale, which previously were difficult to approach with the conventional geodetic techniques. On this basis, we set up a new GPS geodetic network across an intensely faulted area of the Central Apennines (Central Italy), designed to measure the detailed pattern of the current crustal deformations. During the last 25 years, several geological, seimological and geodetic studies have been performed in the Central

---

Mailing address: Dr. Marco Anzidei, Istituto Nazionale di Geofisica e Vulcanologia, Via di Vigna Murata 605, 00143 Roma, Italy; e-mail: anzidei@ingv.it

Apennines, to assess the seismic hazard of this region (Bosi *et al.*, 1975; Amato and Selvaggi, 1992; Amato *et al.*, 1993; Blumetti *et al.*, 1993, 1996; Galadini and Messina, 1993; Calamita *et al.*, 1994a,b, 1999; Ghisetti and Vezzani, 1996; Pantosti *et al.*, 1996; Amato *et al.*, 1998; Boschi *et al.*, 1998, 1999; Basili *et al.*, 1999; Peruzza, 1999; Barchi *et al.*, 2000; Galadini and Galli, 2000). However, this sector of the chain has never been investigated in detail through a tailor made GPS geodetic network devoted to an accurate estimation of the ongoing crustal deformation of this region. For this reason the Central Apennines Geodetic Network (CA-GeoNet) was planned and set up with mean distances between stations at 3-5 km and able to estimate the sub regional and near field strain rates across the main seismogenic structures and faults, which are supposed to drive the crustal dynamics of this area.

2. Geological and structural setting

The Apennines formed since the end of Miocene and developed in a chain-foredeep-foreland dynamic system. They are characterized by the overlying of several mesozoic and cenozoic paleogeographic domains, NE migrating (Bigi *et al.*, 1990; Calamita *et al.*, 1999) (fig. 1). Since Miocene the Central Apennines have displayed several tectonic phases and the geological units of the Umbria-Marche area were bent and thrust on those of the Lazio-Abruzzo carbonatic platform. The latter have been subsequently thrust on the Marche-Abruzzo formations. All these structures defines a thrust edifice NW-SE trending, with N-S dextral and WNW-ESE left lateral strike slip systems (Alfonsi *et al.*, 1991; Mattei *et al.*, 1995), as evidenced by independent geophysical data (Speranza *et al.*, 1997).

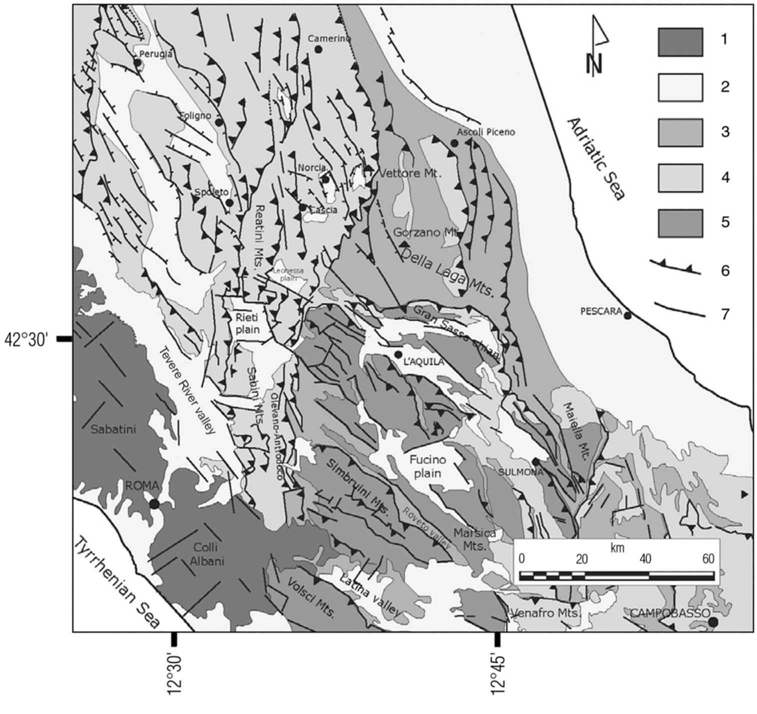

Fig. 1. Geological and structural sketch of the Central Apennines (modified from Cello *et al.*, 1997; Mazzoli *et al.*, 1997).

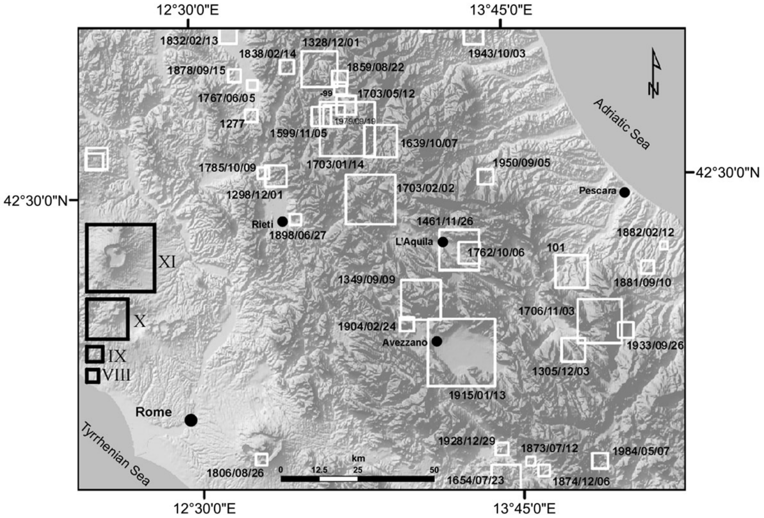

Fig. 2. Historical seismicity (white squares) of the Central Apennines from 179 B.C. to 1979 and $I \geq$ VIII MCS (from Boschi *et al.*, 1995, 1998, 1999). Black squares for intensity legend.

Since Upper Pliocene and Lower Pleistocene, the Apennines underwent an extensional tectonic phase that produced NW-SE trending normal faults (Bigi *et al.*, 1990; Calamita *et al.*, 1994a,b, 1999). The combined action of the Plio-quaternary faults produced several intermontane basins, filled with continental deposits. These basins are of great importance for the assessment of the Quaternary tectonics because the largest earthquakes and active tectonics are located within these zones (Bosi *et al.*, 1975; Lavecchia *et al.*, 1994; Boschi *et al.*, 1995, 1999; Cello *et al.*, 1997; Calamita *et al.*, 1999; Galadini and Galli, 2000; Galadini and Messina, 2001; Valensise and Pantosti, 2001).

The Umbria-Marche area displays Mesozoic and Cenozoic formations (limestones with silica and marls) NE-ward bent and thrust, with axis ranging from NW-SE to NNE-SSW in the northern and southern sectors, respectively. The Quaternary faults downlifted SW-ward trending blocks, (Calamita *et al.*, 1999) and the sedimentary basins (fig. 2). The Lazio-Abruzzo sector, which consists in Mesozoic and Cenozoic carbonatic units NW-SE thrusted with E-W trending planes (Accordi and Carbone, 1988; Ghisetti and Vezzani, 1990), during Quaternary experienced extensional tectonics that produced normal faults (Ghisetti and Vezzani, 1996). Active faults, with geological slip rates up to ~1 mm/yr (Barchi *et al.*, 2000; Galadini and Galli, 2000; Valensise and Pantosti, 2001) have been identified in this area. High angle faults systems, NW-SE striking, are located in the external sector of the Apennines Chain (Southern Laga, Sibillini and Gran Sasso Mts.) and produce differential lowering toward SE. Active faults border the Quaternary basins of Amatrice and Campotosto (Bigi *et al.*, 1990; Barchi *et al.*, 2000; Galadini and Galli, 2000; Valensise and Pantosti, 2001).

3. Seismicity

The seismicity of the Central Apennines, known by historical information and modern instrumental recordings, shows maximum magnitudes at 7.1 and macroseismic intensities up to XI MCS scale (Postpischl, 1985; Westaway, 1992; Boschi *et al.*, 1995, 1998, 1999) (fig. 2). Among the largest earthquakes that struck this region during the last two millennia, the 1703 seismic sequence is the most remarkable. Although the spatial and temporal evolution of this sequence is still a debated matter, the main shocks occurred in a wide area between Norcia and L'Aquila with intensities up to XI MCS and produced much damage and many casualties. Finally, in 1915, the Fucino area was subjected to a $M = 7.1$ (XI MCS) destructive seismic event, with epicentral location near Avezzano (Boschi *et al.*, 1995).

In recent times, from crustal and subcrustal earthquakes, Amato and Selvaggi (1992), defined three main seismogenetic belts in the Central Apennines: the first running along the western margin (Tyrrhenian), with earthquake hypo centres < 7 km and high geothermal gradients; the second within the chain, with extensional mechanisms and hypocentres between 5 and 15 km; the last, which is the least active and releases less energy, borders the Adriatic Sea and displays compressive and strike slip earthquakes. The maximum seismic energy is released in the inner part of the chain, along a belt

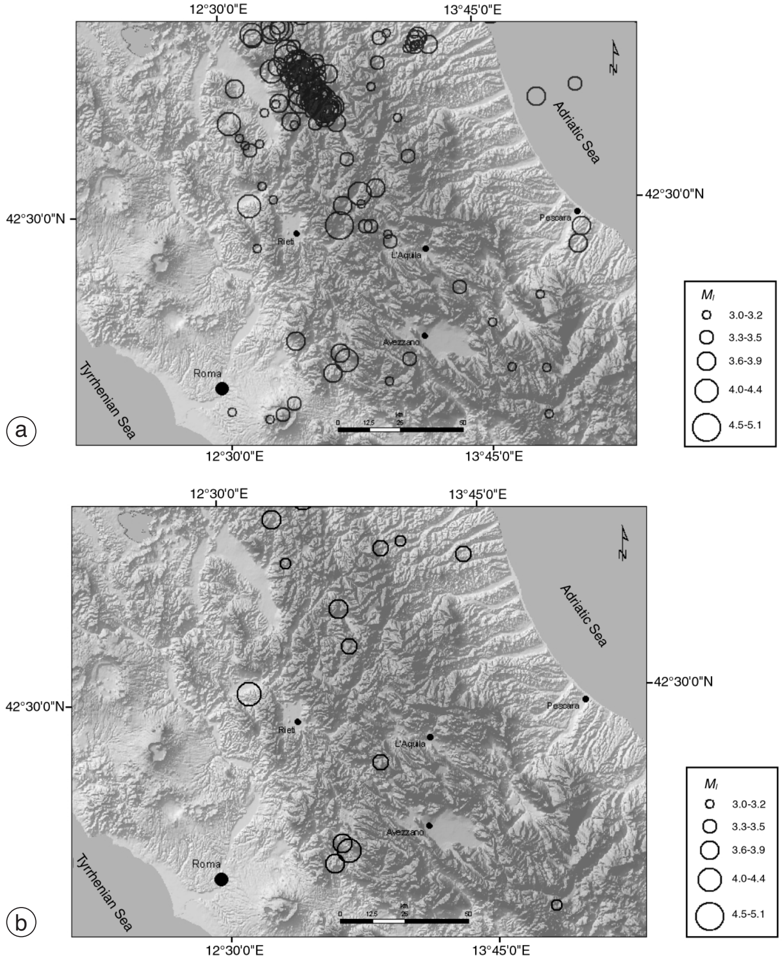

Fig. 3a,b. Instrumental seismicity during the time span (a) 1986-2003 and (b) 1999-2003 ($M_l > 3.0$ from the INGV Seismic Bullettin).

NNW-SSE striking and 50-60 km width. It is worth nothing that in the Umbria-Marche region, deep earthquakes have been located up to 90 km in depth, supporting the hypothesis of a subducting Adriatic lithosphere under peninsular Italy. This seems in agreement with seismic tomography data, although a lack of deep seismicity in the other sectors of the Central Apennines prevented us extrapolating this interpretation to the whole chain (Spakman, 1990; Amato *et al.*, 1993). The instrumental seismicity recorded during the time span 1982-2003 (fig. 3a) is mainly located in the Umbria-Marche area and along the Olevano-Antrodoco-Posta structural lineament (Salvini and Vittori, 1982). The former is addressed to the Umbria-Marche 1997 seismic sequence, while the the latter is located along the border between the regional tectonic structures of the Umbria-Marche-Sabina in the west and of the Gran Sasso in the east (fig. 1). The available focal mechanisms of the largest earthquakes occurred in the 1939-1980 time span (Gasparini *et al.*, 1985) and the seismic sequences of Norcia, in 1979 (Deschamps *et al.*, 1984), Lazio-Abruzzo, in 1984 (Westaway *et al.*, 1989) and Colfiorito, in 1997 (Amato *et al.*, 1998), show a general extensional tectonic regime, with *T* axis NE-SW trending (Frepoli and Amato, 1997; Montone *et al.*, 1997). After these earthquakes, the region was subjected only to a few low energy seismic events, especially during the time span 1999-2003 (fig. 3b), the same epochs as the GPS surveys.

4. The CA-GeoNet and GPS campaigns

The CA-GeoNet, established in 1999 and completed in 2001, consists in 124 GPS stations, distributed with an average grid at 3-5 km (Anzidei *et al.*, 2003). Siting was performed taking into account the geological and structural features of the region, and the geodetic benchmarks have been located on significant outcropping units. Most GPS stations are located across the Plio-Quaternary basins and the main seismogenic sources, inferred from geological and seismological data (Valensise and Pantosti, 2001) (fig. 4).

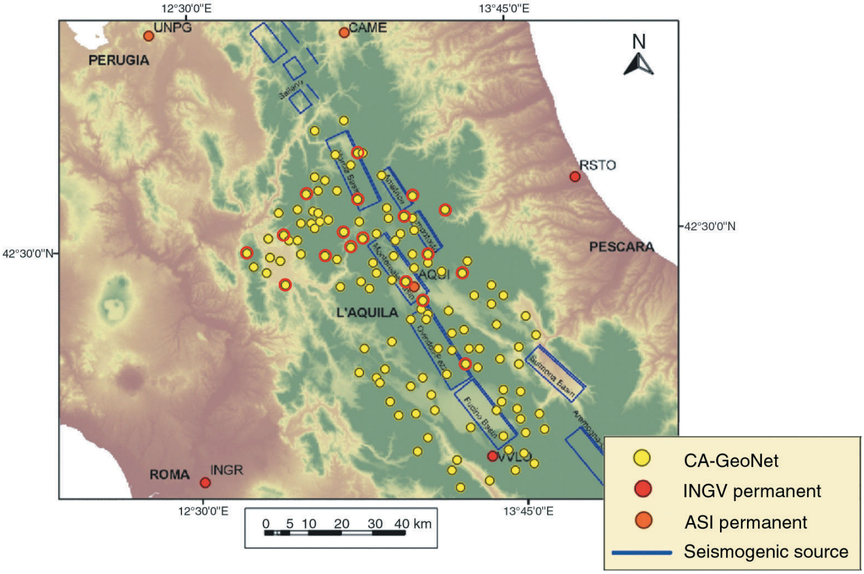

Fig. 4. Distribution of the CA-GeoNet stations with respect to the seimogenetic sources, as reported in Valensise and Pantosti (2001). Red circles show the set of stations used in this paper.

We used 3D type GPS monuments for the 125 temporary stations. The network includes 7 permanent GPS stations managed by the Italian Space Agency (AQUI, CAME, UNPG) and by the Istituto Nazionale di Geofisica e Vulcanologia (INGR, VVLO, RSTO, INGP).

During the time span 1999-2003 all the stations of the network were occupied and 23 of them repeatedly measured during at least three campaigns (fig. 5a,b). We used Trimble 4000SSi dual frequency receivers, equipped with Trimble L1/L2 Ground Plane geodetic antenna (22020-00 type). Surveys were rigorously planned taking into account network grid, number of stations to be measured simultaneously (up to 11), and time required to move receivers through the

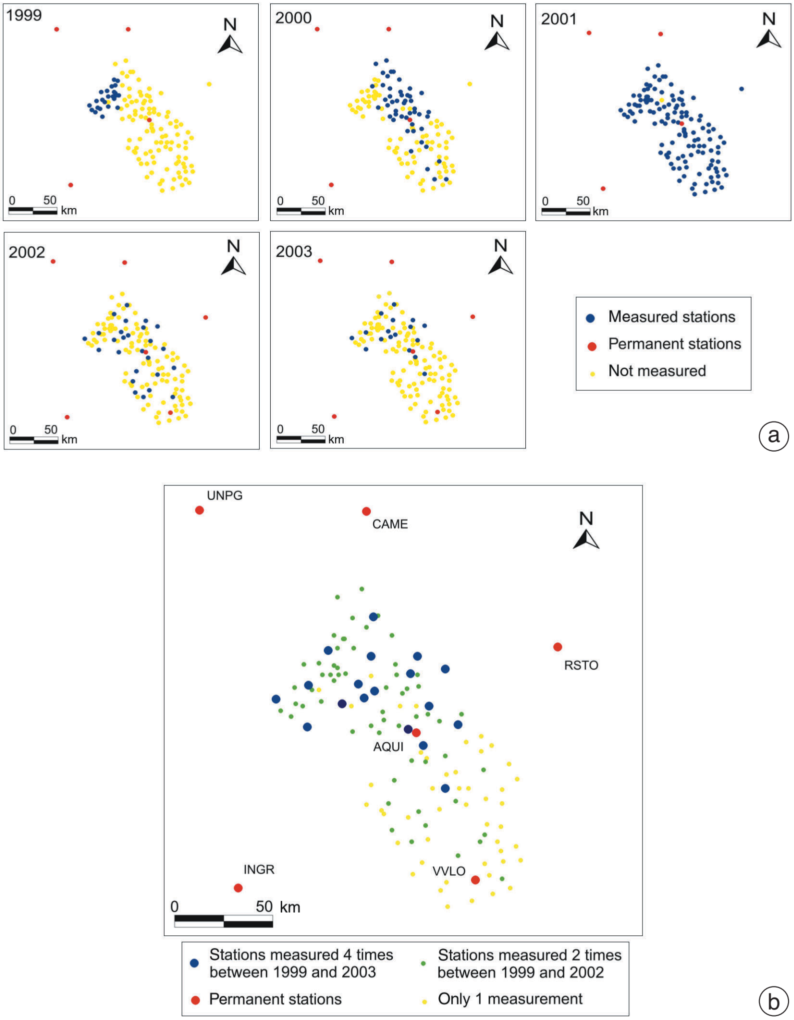

Fig. 5a,b. Sketch of the CA-GeoNet occupations during the repeated campaigns performed in the time span 1999-2003: a) distribution of measured station for each campaign; b) state of the art: blue circles display the stations measured at least three times between 1999 and 2003.

network. Each station was occupied for an average observation window of 48 h, for at least two survey sessions per station. GPS data were collected at 30 s sample rate during each observation session of at least 12 to 24 h duration. To constrain the daily solutions and to include the network in a unique reference frame, we used data collected at permanent stations (CAME, UNPG, AQUI, RSTO, INGR, VVLO and INGP). Moreover, for the whole campaign duration, TERM and PRET stations continuously operated as semi-permanent stations.

5. GPS data processing, velocity field and strain analysis

The GPS data were processed by means of the Bernese 4.2 software, performing the following steps: generation of satellite orbits using precise ephemeredes from CODE (Center of Orbit DEtermination); computation of the best value for point positions from code pseudo-range observables and receiver clocks correction; creation of undifferenced phase data from receiver carrier phase readings; creation of single difference phase data and computation of their correlations; coordinate estimation from triple-differences processing and cycle slips detection; computation of the double-difference solution solving for baseline components and real phase ambiguity values; integer ambiguity values estimation (iterative procedure); computation of the fixed bias solution starting from previous estimates, adopting different acceptance or rejection criteria. The strategy used for baselines computation (step 3) was based on network geometry and station distribution, taking into account measurement sessions. Single difference daily observations were formed between the available fiducial stations, continuously operating during the campaign, to the other CA-GeoNet stations. The tropospheric zenith delay was computed and corrected using the standard Saastmoinen model and estimating a set of time-dependent parameters for each site. The elevation-dependent antenna phase center corrections were applied, according to the IGS_1 model. The ionospheric effect was reduced introducing the estimation of the global TEC (Total Electronic Content) obtained by the L4 (geometry-free) linear combination analysis. The ambiguities were computed adopting the wide-lane technique. In the first step, the linear combination L5 was processed and the wide-lane ambiguities were stored; in the second, the L3 (iono-free) combination was used, the wide-lane ambiguities were introduced as known and the narrow-lane ambiguities were solved.

Daily solutions were computed and combined for each campaign by a least-square sequential adjustment and finally combined (Koch, 1988). A free network solution approach was adopted to avoid ‘distorsions’ (Brockmann and Gurtner, 1996).

Table I lists the root mean square values of daily solutions with respect to the adjusted values for each campaign, providing the repeatability of the north, east and up components. To estimate velocities at the CA-GeoNet stations, we combined the normal equation solutions of the four campaigns, adding new station parameters: coordinates at reference epochs and mean velocities.

Errors were obtained after matrix inversion (solving the equation system) from residual statistical distribution with respect to the combined solution. The large amount of available data produced the underestimation of the real uncertainties and the standard deviation values that were both considered in the subsequent analysis (table II).

Figure 6 shows the time series for the north and east components of 23 stations of the network, computed with respect to INGR station. Error bars show the standard deviation of horizontal components of the station coordinates, related to each campaign (table I).

Table I. Root mean values of the daily solutions with respect to the adjusted values of each campaign.

Year	North (mm)	East (mm)	Up (mm)
1999	2.1	3.5	7.8
2000	2.7	3.5	5.9
2001	2.0	1.6	7.1
2002	2.1	1.6	7.7
2003	2.2	2.2	8.0

Table II. GPS site, approximate geographic coordinates (WGS84), velocities (mm/yr) and related errors at 95% confidence level, computed with respect to the continuous monitoring INGR station. Data have been estimated after four repeated campaigns (1999-2003).

CA-GeoNet relative velocity field respect to INGR station

No.	Station	Longitude (° ′ ″)	Latitude (° ′ ″)	Height (m)	V_E (mm/yr)	V_N (mm/yr)
4	AQUI	13 21 0.8911	42 22 5.6611	712.47	−1.7 ± 0.6	−0.9 ± 0.6
10	BORB	13 9 44.7927	42 30 40.9554	859.87	−7.9 ± 1.8	−2.1 ± 1.4
14	CAME	13 7 26.3895	43 6 43.1463	498.07	4.1 ± 0.8	1.4 ± 0.6
18	CASB	12 50 57.3613	42 23 22.8759	447.65	−2.3 ± 1.4	0.8 ± 1.0
21	CEPP	12 51 17.9712	42 31 48.3242	990.06	1.3 ± 1.0	−1.0 ± 0.8
32	CROG	13 29 6.2189	42 35 10.5275	1118.19	0.9 ± 1.4	1.8 ± 1.2
39	FAVI	13 5 12.0416	42 32 5.0215	1033.86	−4.4 ± 1.4	−4.0 ± 1.0
46	INGR	12 30 53.2758	41 49 41.1006	103.83	0.0 ± 0.4	0.0 ± 0.4
47	IPRA	12 42 18.6001	42 29 3.3114	973.57	0.7 ± 1 .0	0.6 ± 0.8
49	LACU	13 6 41.5153	42 29 15.9050	1140.26	−2.3 ± 1.2	1.3 ± 1.0
60	MOSP	12 56 57.9180	42 38 48.3459	983.66	−2.0 ± 1.4	2.2 ± 1.0
64	MTSN	13 9 15.2060	42 45 39.7934	994.79	0.6 ± 1.6	−6.1 ± 1.2
76	POCA	13 19 34.2957	42 34 14.0445	1365.31	0.3 ± 1.2	2.3 ± 1.0
80	PRET	13 18 58.6325	42 22 56.9605	731.77	−2.8 ± 0.8	−0.8 ± 0.8
90	ROFA	13 32 27.8156	42 23 50.1564	1546.80	−0.9 ± 4.2	5.0 ± 3.2
91	ROIO	13 23 9.2925	42 19 36.5285	1042.14	−2.0 ± 1.4	−2.4 ± 1.2
96	SCUO	13 21 31.9419	42 37 45.6348	1433.32	−1.7 ± 1.4	−4.1 ± 1.0
100	SFRA	13 24 29.9572	42 27 35.5929	1879.35	−3.0 ± 1.4	−2.3 ± 1.2
108	SROT	13 8 30.4860	42 37 39.1611	1442.06	0.0 ± 1.6	−8.2 ± 1.2
115	TERM	13 0 36.0723	42 28 10.0081	1851.15	−1.2 ± 0.6	−0.8 ± 0.6
126	VPEZ	13 29 4.4420	42 10 54.9826	1543.70	−2.7 ± 1.2	−4.2 ± 1.0
129	VVLO	13 37 23.6215	41 52 10.7275	1045.19	1.2 ± 0.6	0.5 ± 0.6
131	RSTO	14 0 5.3208	42 39 30.1835	102.59	1.5 ± 1.0	0.0 ± 0.8
303	UNPG	12 21 20.5314	43 7 9.8078	351.07	−4.0 ± 0.8	0.4 ± 0.4

The strain rate estimation was performed by a least square adjustment under the uniform field condition, using station velocities as observables

$$\begin{pmatrix} 1 & 0 & \Delta x_1 & \Delta y_1 & 0 & 0 \\ 0 & 1 & 0 & 0 & \Delta x_1 & \Delta y_1 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & 0 & \Delta x_1 & \Delta y_1 & 0 & 0 \\ 0 & 1 & 0 & 0 & \Delta x_1 & \Delta y_1 \end{pmatrix} \begin{pmatrix} U \\ V \\ L_{11} \\ L_{12} \\ L_{21} \\ L_{22} \end{pmatrix} = \begin{pmatrix} u_1 \\ v_1 \\ \vdots \\ u_n \\ v_n \end{pmatrix}.$$

The velocity gradient tensor was computed and its strain and rotational parts separated. Eigenvalues were obtained from matrix diagonalization, providing strain rate values along the two principal axis ($E_{\max}$, $E_{\min}$) and the orientation (azimuth φ)

$$E_{\max} = \left(L_{11} + L_{22} + \sqrt{(L_{11} - L_{22})^2 + (L_{12} + L_{21})^2} \right) \Big/ 2$$

$$E_{\min} = \left(L_{11} + L_{22} - \sqrt{(L_{11} - L_{22})^2 + (L_{12} + L_{21})^2} \right) \Big/ 2$$

$$\varphi = \frac{1}{2} \operatorname{arctg} \left(- \frac{L_{12} + L_{21}}{L_{11} - L_{22}} \right).$$

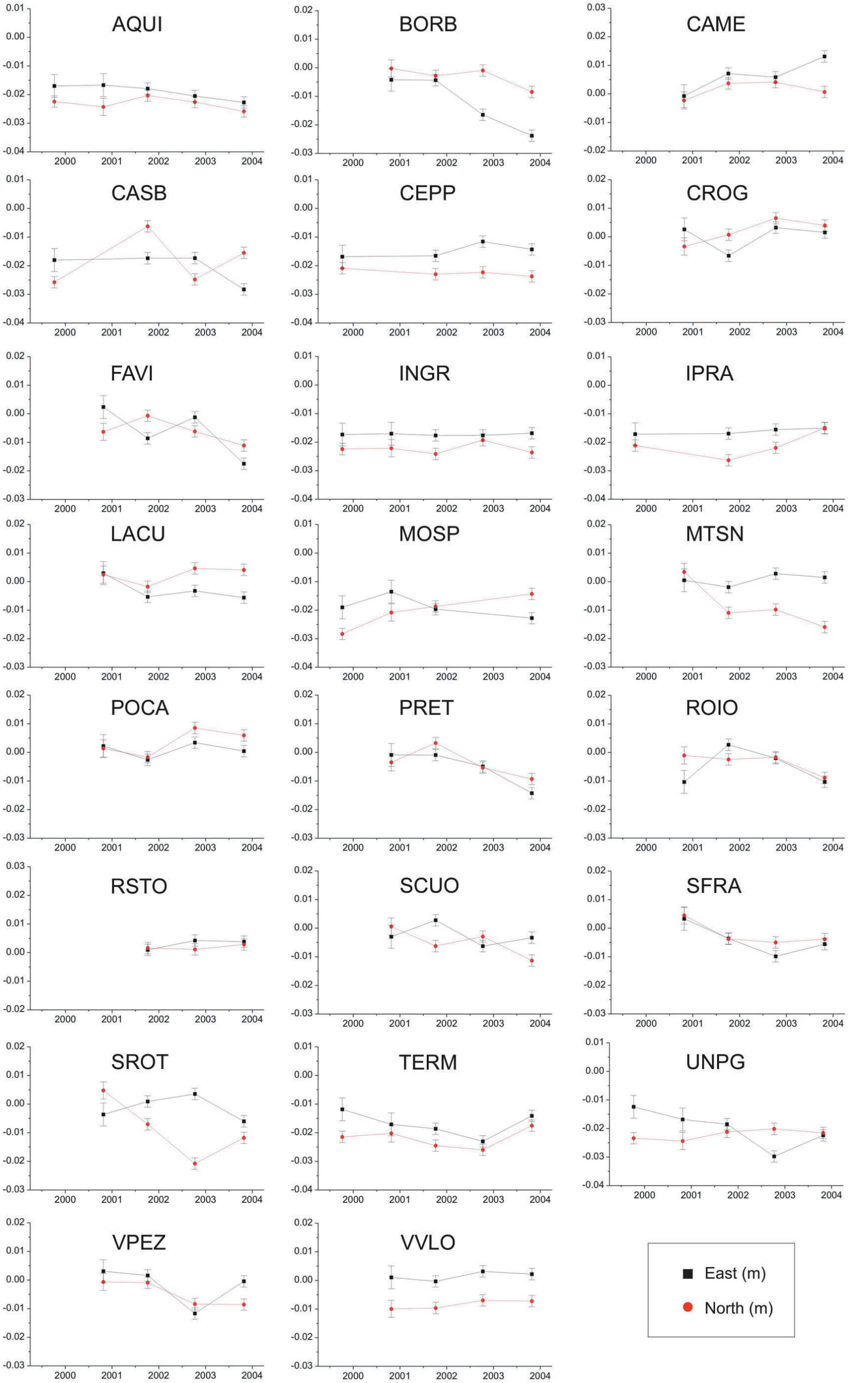

Fig. 6. Horizontal GPS position time series, for the North (N), East (E) components with respect to INGR station.

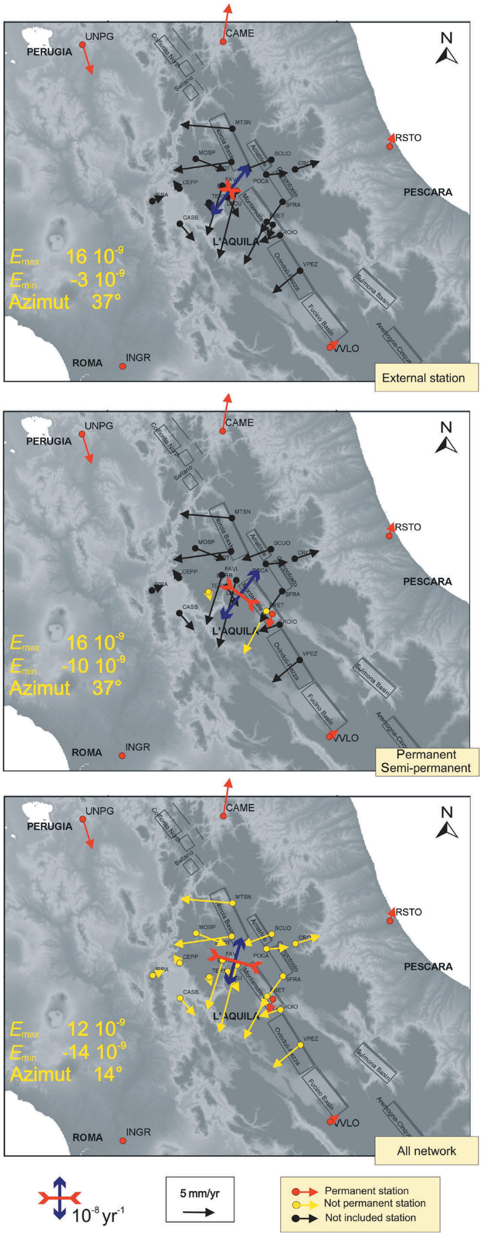

Fig. 7. Velocity (black arrows) and strain (double blue and red arrow) fields, estimated during the time span 1999-2003, after four repeated campaigns (red dots – permanent stations, and yellow dots – non permanent stations). Maximum strain is at $16\times10^{-9}\pm11$ yr^{-1}; minimum strain is at $-14\times10^{-9}\pm11$ yr^{-1}. Seismogenic sources from Valensise and Pantosti (2001).

Table III. Strain rate tensor estimation from three different velocity data set: external network (CAME, INGR, RSTO, UNPG, VVLO); fiducial network (AQUI, CAME, INGR, PRET, RSTO, TERM, UNPG, VVLO) and global network (all the used CA-GeoNet stations). Maximum and minimum engein values are given together with associated errors and azimuths.

Network data set	$E_{\max}$ (yr^{-1})	e$E_{\max}$ (yr^{-1})	$E_{\min}$ (yr^{-1})	e$E_{\min}$ (yr^{-1})	Az (°)	eAz (°)
External	$16\cdot10^{-9}$	$11\cdot10^{-9}$	$-3\cdot10^{-9}$	$11\cdot10^{-9}$	37°	18°
Fiducial	$16\cdot10^{-9}$	$13\cdot10^{-9}$	$-10\cdot10^{-9}$	$13\cdot10^{-9}$	37°	16°
Global	$12\cdot10^{-9}$	$12\cdot10^{-9}$	$-14\cdot10^{-9}$	$12\cdot10^{-9}$	14°	24°

The procedure was applied to different data sets (fig. 7), using AQUI, CAME, INGR, PRET, RSTO, TERM, UNPG and VVLO permanent stations (table III). The first computation concerns only a set of (external) stations (CAME, INGR, RSTO, UNPG and VVLO continuous monitoring stations located around the not permanent network), to estimate the sub-regional strain rate values across this area.

A further computation was carried out adding to the previous set of stations AQUI, PRET and TERM (permanent or semi-permanent), which are located in the inner chain (fiducial network). A more accurate result in terms of coordinate estimation was obtained and a compressive component was computed along the chain axis.

Finally, all the velocity data set was considered and a global mean strain rate tensor was estimated, but weakly anti-clockwise rotated with respect to the previous solutions.

Results show an extensional behaviour of the chain, in agreement with geological and seismic data, and a significant compression in its inner part. Strain rates range from $12\times10^{-9}\pm11$ yr^{-1} to $16\times10^{-9}\pm11$ yr^{-1} and from $-14\times10^{-9}\pm11$ yr^{-1} to $-3\times10^{-9}\pm11$ yr^{-1}, normal and along the chain axis, respectively.

The computed deformation trend represents a significant improvement of earlier results published in previous papers by D'Agostino *et al.* (2001) from the reoccupation of part of the IGM95 network (Surace, 1993, 1997), by Serpelloni *et al.* (2001) and Anzidei *et al.* (2001) from the Tyrgeonet and GeoModAp networks, by Hunstad and England (1999) and Hunstad *et al.* (2003) from historical IGM triangulation network. These previous geodetic studies estimate maximum strain rates for the Central Apennines at $180\pm30\times10^{-9}$ (D'Agostino *et al.*, 2001), $57\pm13\times10^{-9}$ (Caporali *et al.*, 2003), from $3.7\pm29\times10^{-9}$ to $116\pm32\times10^{-9}$ (Hunstad *et al.*, 2003), $4.1\pm0.8\times10^{-9}$ (Ward, 1994), $31\pm8\ \times10^{-9}$ (Serpelloni *et al.*, 2002), generally higher but with similar strikes with respect to those shown in this paper. The different time span used in the data, the available data set, the network size, geometry and finally the number of stations analysed, can be partially responsible of such differences in the obtained results.

6. Conclusions

Our data provide a more detailed view on the present-day sub-regional and near deformation field of this region, thanks to the high number of stations and the short baselines (3-5 km) among stations. The striking of the strain axes show that the area is undergoing an active deformation with NE-SW prevailing extension, normal to the chain. No relevant seismic activity has occurred in recent years in the surveyed area, even if the region experienced destructive earthquakes in the past.

Moreover if the post-seismic deformations related to the last largest earthquakes (Fucino, 1915, M_s=6.9; and Umbria-Marche, 1997, M_s=5.9), located in the southernmost and northernmost sides of the network respectively, are ended or weak and confined within a few km across the fault (Aoudia *et al.*, 2003), the observed deformation is interseismic, thus describing the regional and purely elastic deformation field of the region. The extensional behaviour of the area, normal to the chain, is in agreement with the distribution and trend of the main seismogenic sources reported in Valensise and Pantosti (2001) that could play a major role in the observed deformations and in the kinematics of the peninsular Italy.

New surveys, planned in 2004 to add new velocity data, will improve the knowledge of the active strain rate estimation in this high risk seismic area.

The local deformation field, that can be representative of the accumulating deformation on the faults, will allow us to estimate the present day slip rate related to the single faults or structures and to distinguish their temporal and spatial variations from repeated surveys. The network grid at 3-5 km, which is optimal with respect to the average seismogenic fault size of the Central Apennines, will yield affordable geodetic data to constrain eventual coseimic dislocation models. Finally the combination with DinSAR data will provide an accurate spatial deformation pattern of this region, related with seismic cycle (Massonnet *et al.*, 1993, 1996; Massonnet and Feigl, 1998), as recently performed in the Apennines during the 1997 Umbria-Marche earthquakes 1997 (Hunstad *et al.*, 1998; Anzidei *et al.*, 1999; Stramondo *et al.*, 1999; Salvi *et al.*, 2000; Santini *et al.*, 2004).

Ackowledgements

This reasearch was performed under the Italian Space Agency Project «Applicazione delle tecniche spaziali per la valutazione del campo di deformazione crostale e della pericolosità sismica dell'Appennino Centro Meridionale». We are grateful to Prof. Enzo Boschi who encouraged this work, Dr. Paolo Marsan, of the National Seismic Service who made available the occupation of the Aquilano Geodetic Network, Dr. Andrea Tertulliani for the helpful scientific discussion on the historical seismicity.

REFERENCES

ACCORDI, G. and F. CARBONE (1988): Sequenze carbonatiche meso-cenozoiche, in *Note Illustrative della Carta delle Litofacies del Lazio-Abruzzo ed Aree Limitrofe*, edited by G. ACCORDI, F. CARBONE, G.,CIVITELLI, L. CORDA, D. DE RITA, D. ESU, R. FUNICIELLO, T. KOTSAKIS, G. MARIOTTI and A. SPOSATO, *Quad. Ric. Sci.*, **114** (5), 11-92.

ALFONSI, L., R. FUNICIELLO and M. MATTEI (1991): Strike-slip tectonics in the Sabina area*, Boll. Soc. Geol. It.*, **110**, 481-488.

AMATO, A. and G. SELVAGGI (1992): Terremoti crostali e subcrostali nell'Appennino settentrionale, *Studi Geologici Camerti*, vol. spec. 1991/1, 75-82.

AMATO, A., B. ALESSANDRINI, G.B. CIMINI, A. FREPOLI and G. SELVAGGI (1993): Active and remnant subducted slabs beneath Italy: evidence from seismic tomography and seismicity, *Ann. Geofis.*, **XXXVI** (2), 201-214.

Amato, A., R. Azzara, C. Chiarabba, G.B. Cimini, M. Cocco, M. Di Bona, L. Margheriti, S. Mazza, F. Mele, G. Selvaggi, A. Basili, E. Boschi, F. Courboulex, A. Deschamps, S. Gaffet, G. Bittarelli, L. Chiaraluce, D. Piccinini and M. Ripepe (1998): The 1997 Umbria-Marche, Italy, earthquake sequence: a first look at the main shocks and aftershocks, *Geophys. Res. Lett.*, **25** (15), 2861-2864.

Anzidei, M., P. Baldi, A. Galvani, A. Pesci, I. Hunstad and E. Boschi (1999): Coseismic displacement of the 26th september 1997 Umbria-Marche (Italy) earthquakes detected by GPS: campaigns and data, *Ann. Geofis.*, **42** (4), 597-607

Anzidei, M., P. Baldi, G. Casula, A. Galvani, E. Mantovani, A. Pesci, F. Riguzzi and E. Serpelloni (2001): Insights on present-day crustal motion in the Central Mediterranean area from GPS surveys, *Geophys. J. Int.*, **146**, 98-110.

Anzidei, M., A. Galvani, A. Esposito, P. Cristofoletti, A. Pesci, P. Baldi, G. Casula, N. Cenni, F. Loddo and E. Serpelloni (2003): The Central Apennines Geodetic Network (CA-Geonet): description and preliminary results, in *XXVIII European Geophysical Society General Assembly*, *Geophys. Res. Abstr.*, vol. 5, abstr. EAE03-A-05288.

Aoudia, A., A. Borghi, R. Riva, R. Barzaghi, B.A.C. Ambrosius, R. Sabadini, L.L.A. Vermeersen and G.F. Panza (2003): Postseismic deformation following the 1997 Umbria-Marche (Italy) moderate normal faulting earthquakes, *Geophys. Res. Lett.*, **30** (7), 1390.

Barchi, M., F. Galadini, G. Lavecchia, P. Messina, A.M. Michettti, L. Peruzza, A. Pizzi, E. Tondi and E. Vittori (2000): *Sintesi delle Conoscenze sulle Faglie Attive in Italia Centrale: Parametrizzazione ai Fini della Caratterizzazione della Pericolosità Sismica* (CNR-GNDT, Roma) pp. 62.

Basili, R., F. Galadini and P. Messina (1999): The applicatiion of palaeolandsurface analysis to the study of recent tectonics in Central Italy, in *Uplift, Erosion and Stability: Perspectives on Long-Term Landscape Development*, edited by B.J. Smith, W.B. Whalley and P.A. Warke, *Geol. Soc. London Spec. Publ. 162*, 109-117.

Bigi, G., D. Cosentino, M. Partotto, R. Sartori and P. Scandone (1990): *Structural Model of Italy (scala 1:500000),* sheet no. 4, CNR-PFG.

Blumetti, A.M., F. Dramis and A.M. Michetti (1993): Fault-generated mountain fronts in the Central Apennines (Central Italy): geomorphological features and seismotectonic implications, *Earth Surf. Processes Landforms*, **18**, 203-223

Blumetti, A.M., G.P. Cavinato and M. Tallini (1996): Evoluzione plio-quaternaria della conca di L'Aquila-Scoppito: studio preliminare, *Il Quaternario*, **9** (1), 281-286.

Boschi, E., G. Ferrari, P. Gasperini, E. Guidoboni, G. Smriglio and G. Valensise (1995): *Catalogo dei Forti Terremoti in Italia dal 461 a.C. al 1980* (ING, Roma - SGA, Bologna), vol. 1, pp. 974.

Boschi, E., E. Guidoboni, G. Ferrari and G. Valensise (1998): *I Terremoti dell'Appennino Umbro-Marchigiano. Area Sud Orientale dal 99 a.C. al 1984* (INGV, Roma - SGA, Bologna), pp. 267.

Boschi, E., P. Gasperini, G. Valensise, R. Camassi, V. Castelli, M. Stucchi, A. Rebez, G. Monachesi, M.S. Barbano, P. Albini, E. Guidoboni, G. Ferrari, D. Mariotti, A. Comastri and D. Molin (1999): *Catalogo Parametrico dei Terremoti Italiani* (Editrice Compositori, Bologna), pp. 92.

Bosi, C. (1975): Osservazioni preliminari su faglie probabilmente attive nell'Appennino Centrale, *Boll. Soc. Geol. It.*, **94**, 827-859.

Brockmann, E. and W. Gurtner (1996): Combination of GPS solutions for densification of European network: concepts and results derived from 5 European associated analysis centers of the IGS, in *EUREF Workshop*, Ankara, May 1996.

Calamita, F., G. Cello, G. Deiana and W. Paltrinieri (1994a): Structural styles, chronology rates of deformation, and time-space relationships in the Umbria-Marche thrust system (Central Apennines, Italy), *Tectonics*, **13**, 873-881.

Calamita, F., M. Coltorti, P. Farabollini and A. Pizzi (1994b): Le faglie normali quaternarie nella dorsale appenninica Umbro-Marchigiana. Proposta di un modello di tettonica d'inversione, *Studi Geologici Camerti*, vol. spec. 1994, 211-225.

Calamita, F., M. Coltorti, P. Pieruccini and A. Pizzi (1999): Evoluzione strutturale e morfogenesi plio-quaternaria dell'Appennino Umbro-Marchigiano tra il preappennino Umbro e la costa Adriatica, *Boll. Soc. Geol. It.*, **118**, 125-139.

Caporali, A., S. Martin and M. Massironi (2003): Average strain rate in the Italian crust inferred from a permanent GPS network, II. Strain rate *versus* seismicity and structural geology, *Geophys. J Int.*, **155**, 254-268

Cello, G., S. Mazzoli, E. Tondi and E. Turco (1997): Active tectonics, in the Central Apennines and possible implications for seismic hazard analysis in peninsular Italy, *Tectonophysics*, **272**, 43-68.

D'Agostino, N., R. Giuliani, M. Mattone and L. Bonci (2001): Active crustal extension in the Central Apennines (Italy) inferred from GPS measurements in the interval 1994-1999, *Geophys. Res. Lett.*, **28** (10), 2121-2124.

Deschamps, A., G. Iannaccone and R. Scarpa (1984): The Umbrian earthquake (Italy) of 19 September 1979, *Ann. Geophysicae*, **2** (1), 29-36.

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

Galadini, F. and P. Galli (2000): Active tectonics in the Central Apennines (Italy) – input data for seismic hazard assessment, *Nat. Hazard,* **22**, 225-270.

Galadini, F. and P. Messina (1993): Stratigrafia dei depositi continentali, tettonica ed evoluzione geologica quaternaria dell'Alta Valle del fiume Sangro (Abruzzo Meridionale), *Boll. Soc. Geol. It.*, **112**, 877-892.

Gasparini, C., G. Iannaccone and R. Scarpa (1985): Fault-plane solutions and seismicity of the Italian Peninsula, *Tectonophysics*, **117**, 59-78

Ghisetti, F. and L. Vezzani (1990): Stili strutturali nei sistemi di sovrascorrimento della Catena del Gran Sasso (Appennino Centrale), *Studi Geologici Camerti*, vol. spec., 37-50.

GHISETTI, F. and L. VEZZANI (1996): Geometrie deformative ed evoluzione cinematica dell'Appennino Centrale*, Studi Geologici Camerti*, **XIV**, 127-154.

HUNSTAD, I. and P. ENGLAND (1999): An upper bound on the rate of strain in the Central Apennines, Italy, from triangulation measurements between 1869 and 1963, *Earth Planet. Sci. Lett.,* **169**, 261-267.

HUNSTAD, I., M. ANZIDEI, P. BALDI, M. COCCO, A. GALVANI and A. PESCI (1998): Modelling Coseismic displacements during the 1997 Umbria-Marche earthquake (Central Italy), *Geophys. J. Int.*, **139**, 283-295

HUNSTAD, I., G. SELVAGGI, N. D'AGOSTINO, P. ENGLAND, P. CLARKE and M. PIEROZZI (2003): Geodetic strain in peninsular Italy between 1875 and 2001, *Geophys. Res. Lett.,* **30** (4), 1181.

KOCH, K.R. (1988): *Parameter Estimation and Hypotesis Testing in Linear Models* (Springer, Berlin-Heidelberg-New York), pp. 377.

LAVECCHIA, G., F. BRONZETTI, M. BARCHI, J. KELLER and M. MENICHETTI (1994): Seismotectonic zoning in East-Central Italy deduced from analysis of the Neogene to present deformations and related stress field*, Bull. Geol. Soc. Am.*, **106**, 1107-1120.

MASSONNET, D. and K. FEIGL (1998): Radar interferometry and its applications to the changes in the Earth's surface, *Rev. Geophys.*, **36**, 441-500.

MASSONNET, D., M. ROSSI, C. CARMONA, F. ADRAGNA, G. PELTZER, K. FEIGL and T. RABAUTE (1993): The displacement field of the Landers earthquake mapped by radar interferometry*, Nature*, **364**, 138-142

MASSONNET, D., W. THATCHER and H. VADON (1996): Detection of postseismic fault-zone collapse following the Landers earthquake*, Nature,* **382**, 612-616

MATTEI, M., R. FUNICIELLO and C. KISSEL (1995): Paleomagnetic and structural evidence for Neogne block rotations in the Central Apennines (Italy), *J. Geophys. Res.,* **101**, 2835-2845.

MAZZOLI, S., S. CORRADO, M. DE DONATIS, D. SCROCCA, D.W.H. BUTLER, D. DI BUCCI, G. NASO, C. NICOLAI and V. ZUCCONI (1997): Time and space variability of the «thin-skinned» and «thick-skinned» thrust tectonics in the Apennines (Italy), *Rend. Fis. Acc. Lincei*, s. 9, v. 11, 5-39.

MONTONE, P., A. AMATO, A. FREPOLI, M.T. MARIUCCI and M. CESARO (1997): Crustal stress regime in Italy*, Ann. Geofis.,* **XL** (3), 741-757.

PANTOSTI, D., G. D'ADDEZIO and F.R. CINTI (1996): Paleoseismicity of the Ovindoli-Pezza Fault, Central Apennines, Italy: a history including a large, previously unrecord earthquake in the Middle Ages (860-1300 A.D.), *J. Geophys. Res.,* **101**, 5937-5959.

PERUZZA, L. (1999): *Progetto MISHA. Metodi Innovativi per la Stima dell'Hazard: Applicazione all'Italia Centrale* (CNR-GNDT, Roma), pp. 176.

POSTPISCHL, D. (1985): Catalogo dei Terremoti Italiani dall'Anno 1000 al 1980*, Quad. Ric. Sci.*, **114** (2B), pp. 239.

SALVI, S., S. STRAMONDO, M. COCCO, E. SANSOSTI, I. HUNSTAD, M. ANZIDEI, P. BRIOLE, P. BALDI, M. TESAURO, E. LANARI, F. DOUMAZ, A. GALVANI and A. PESCI (2000): Modelling coseismic displacement resulting from SAR interferometry and GPS measurements during the 1997 Umbria-Marche seismic sequence, *J. Seismol.*, **4**, 479-499.

SALVINI, F. and E. VITTORI (1982): Analisi strutturale della linea Olevano-Antrodoco-Posta (Ancona-Anzio Auct): metodologie di studio delle deformazioni fragili e presentazione del tratto meridionale*, Mem. Soc. Geol. It.*, **24**, 337-355.

SANTINI, S., P. BALDI, M. DRAGONI, A. PIOMBO, S. SALVI, G. SPADA and S. STAMONDO (2004*):* Monte Carlo inversion of DInSAR data for dislocation modeling: application to the 1997 Umbria-Marche seismic sequence (Central Italy), *Pure Appl. Geophys.*, **161**, 817-838.

SERPELLONI, E., M. ANZIDEI, P. BALDI, G. CASULA, A. GALVANI, A. PESCI and F. RIGUZZI (2001): Geodetic measurement of crustal deformations in Central-Southern Apennines (Italy)*, Ann. Geofis.*, **44** (3), 627-647

SERPELLONI, E., M. ANZIDEI, P. BALDI, G. CASULA, A. GALVANI, A. PESCI and F. RIGUZZI (2002): Combination of permanent and non-permanent GPS networks for the evaluation of the strain-rate field in the Central Mediterranean area, *Boll. Geofis. Teor. Appl.*, **43** (3/4), 195-219

SPAKMAN, W. (1990): Tomographic images of the upper mantle below Central Europe and the Mediterranean*, Terra Nova*, **2**, 542-553.

SPERANZA, F., L. SAGNOTTI and M. MATTEI (1997): Tectonics of the Umbria-Marche-Romagna Arc (Central Northern Apennines Italy): new paleomagnetic constrains*, J. Geophys. Res.*, **102**, 313-3166.

STRAMONDO, S., M. TESAURO, P. BRIOLE, E. SANSOSTI, S. SALVI, R. LANARI, M. ANZIDEI, P. BALDI, G. FORNARO, A. AVALLONE, M.F. BUONGIORNO, G. FRANCESCHETTI and E. BOSCHI (1999): The September 26,1997 Central Italy earthquakes: coseismic surface displacement detected by sar interferometry and GPS, and fault modeling, *Geophys. Res. Lett.*, **26** (7), 883-886.

SURACE, L. (1993): Il progetto IGM95, *Boll. Geod. Sci. Affini*, **3**, 220-230

SURACE, L. (1997): La nuova rete geodetica nazionale IGM95: risultati e prospettive di utilizzazione, *Boll. Geod. Sci. Affini*, **3**, 357-377

VALENSISE, L. and D. PANTOSTI (2001): Database of potential sources for earthquakes larger than M=5.5 in Italy, *Ann. Geofis.*, 44 (suppl. to n. 4), pp. 180 (with CD-ROM).

WARD, S.N. (1994): Constraints on the seismotectonics of the Central Mediterranean Sea from very long baseline interferometry, *Geohys. J. Int.*, **117**, 441-452.

WELLS, D.L. and K.J. COPPERSMITH (1994): New empirical relationships among magnitude, rupture length, rupture width and surface displacements*, Bull. Seismol. Soc. Am.*, **84** (4), 974-1002.

WESTAWAY, R., R. GAWTHORPE and M. TOZZI (1989): Seismological and field observations of the 1984 Lazio-Abruzzo earthquakes: implications for the active tectonics of Italy*, Geophys. J. R. Astron. Soc.*, **98**, 489-514.

WESTAWAY, R. (1992): Seismic moment summation for historical earthquakes in Italy: tectonic implication*, J. Geophys. Res.*, **97** (B11), 15437-15464.

(received June 18, 2004;
accepted December 09, 2004)