BOLLETTINO DI GEOFISICA TEORICA ED APPLICATA VOL. 43, N. 3-4, PP. 195-219; SEP.-DEC. 2002

Combination of permanent and non-permanent GPS networks for the evaluation of the strain-rate field in the central Mediterranean area

E. SERPELLONI[1, 2], M. ANZIDEI[2], P. BALDI[1], G. CASULA[2], A. GALVANI[2], A. PESCI[2] and F. RIGUZZI[2]

[1] *Dipartimento di Fisica, Settore di Geofisica, Università di Bologna, Italy*
[2] *Istituto Nazionale di Geofisica e Vulcanologia, Centro Nazionale Terremoti, Roma, Italy*

(Received, February 21, 2002; accepted September 18, 2002)

Abstract - The deformation pattern of the Mediterranean is characterized by a complex space-time distribution of compressional and tensional events, in part related to the collision between the African and Eurasian plates. The present day appearance of this complex evolution consists of a high number of crustal wedges, interacting with one another. In the central Mediterranean, and in particular in the Adriatic/Tyrrhenian and Ionian domains, the present number of permanent GPS stations, and the relatively short observation time span of most of them, do not allow a detailed description of the kinematics of this complex tectonic framework. For this reason, non-permanent GPS networks play an important role for improving the determination of the deformation pattern of this area, if rigorously combined with information provided by permanent GPS stations. We combined non-permanent GPS observations, collected during more than ten years, surveying regional and sub-regional geodetic networks in the central Mediterranean, and the ITRF2000 velocity solution of the European Permanent GPS Network. We used the final velocities of 32 IGS stations to constrain a stable Europe reference frame. The residual velocity field with respect to this reference frame shows remarkable features for the relatively higher rate deforming zones, such as the Italian peninsula and the Aegean area, and suggests that the Aegean area, Calabrian arc and Central-Southern Apennines are subject to strain rates higher than that of longer wavelength in the rest of the Mediterranean area.

Corresponding author: E. Serpelloni, Dipartimento di Fisica, Settore di Geofisica, Università di Bologna, Viale B. Pichat 8, 40127 Bologna, Italy. Phone: +39 0512095009; fax: +39 0512095058; e-mail: serpelloni@ingv.it

1. Introduction

During the past decade, space geodesy became a new fundamental source of information on the kinematics of tectonically active areas. Geodetic measurements of crustal deformation provide direct tests of geodynamics and seismotectonic models. Nowadays, GPS is having a major impact on geodynamic studies in the Mediterranean, especially in the Italian area, where this work focuses. In this paper, we make a revision of most of the GPS data available for the study area, collected on regional and sub-regional networks in a time span of more than 10 years. Most of the data used in this work have been processed and analyzed in the recent past by other authors, but each network was studied independently from the others, following different processing approaches, obtaining solutions in different reference frames, and thus avoiding any possible rigorous combination of solutions. The recent improvements and developments of the GPS technique required a re-analysis of the earlier data, in order to apply more recent algorithms and models during the processing. With this aim, we re-processed the original GPS data, following a homogeneous scheme and considering each network as a local densification of the global IGS network.

Subduction and collision in the Mediterranean basin lead to a variety of stress states, from compressive to extensional and associated with strike-slip faulting (Fig. 1), within areas of varying size (Müller et al., 1992; Rebaï et al., 1992; Montone et al., 1999). A thickened continental lithosphere is present in continental collision zones such as the Alps and the Carpathians (Spakman et al., 1993; Piromallo and Morelli, 1997; Lucente et al., 1999), which are characterized by intense thrusting sub-perpendicular to the local convergence direction. Convergence may also lead to lateral expulsion of large lithospheric blocks along large-scale strike-slip faults, depending on the crustal fragmentation level. A thinned continental lithosphere localizes extensional deformation and can be associated with different tectonic contexts, as in the back-arc basins of the Aegean and Tyrrhenian subduction zones, which are also characterized by recent volcanic activity. In addition, both young and old oceanic lithosphere is present, and characterized by a greater rigidity with respect to the continental one. Usually, the oceanic lithosphere is little or weakly deformed and the deformation is mainly concentrated in continental areas adjacent to the oceanic lithosphere, as indicated by the distribution of seismicity (Fig. 2). In fact, from the analysis of the spatial distribution of instrumental seismicity in the Mediterranean, several large zones, limited by lithospheric scale structures such as subduction fronts and large strike-slip faults, can be identified at the regional and sub-regional scales. In particular, the central Mediterranean is a very complex region which makes it difficult to understand the present kinematic displacement field (Albarello et al., 1995).

At present the Mediterranean seems to consist of an assemblage of relatively small lithospheric blocks, with different thicknesses and rheologies, trapped between the relatively rigid African and north European plates, which have been converging during the past 70 My. The direction of the Africa/Eurasia convergence is still a matter of debate and the geodynamical evolution of the Mediterranean has been described in several papers with different approaches and assumptions and various hypotheses have been advanced (Tapponier, 1977; Le Pichon and Angelier, 1979; Boccaletti and Dainelli, 1982; Malinverno and Ryan, 1986; Royden, 1993;

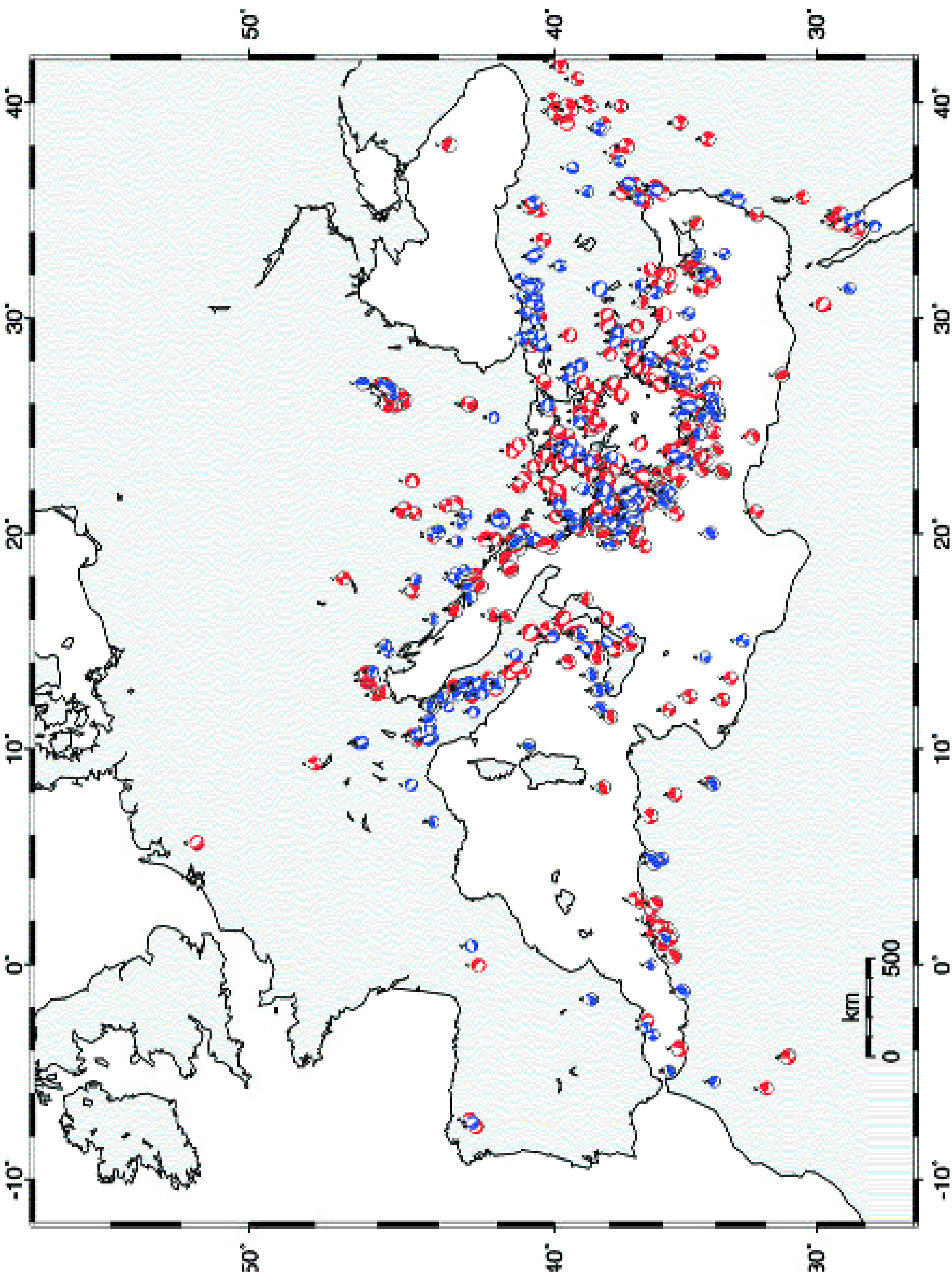


Fig. 1 - Spatial distribution of seismicity in the Mediterranean area: earthquake focal mechanisms are taken from the Harvard CMT catalog (red) and from the 1997-2000 INGV Rapid Centroid Moment Tensor data base (Pondrelli et al., 2002; http://www.ingv.it/seismoglo/RCMT).

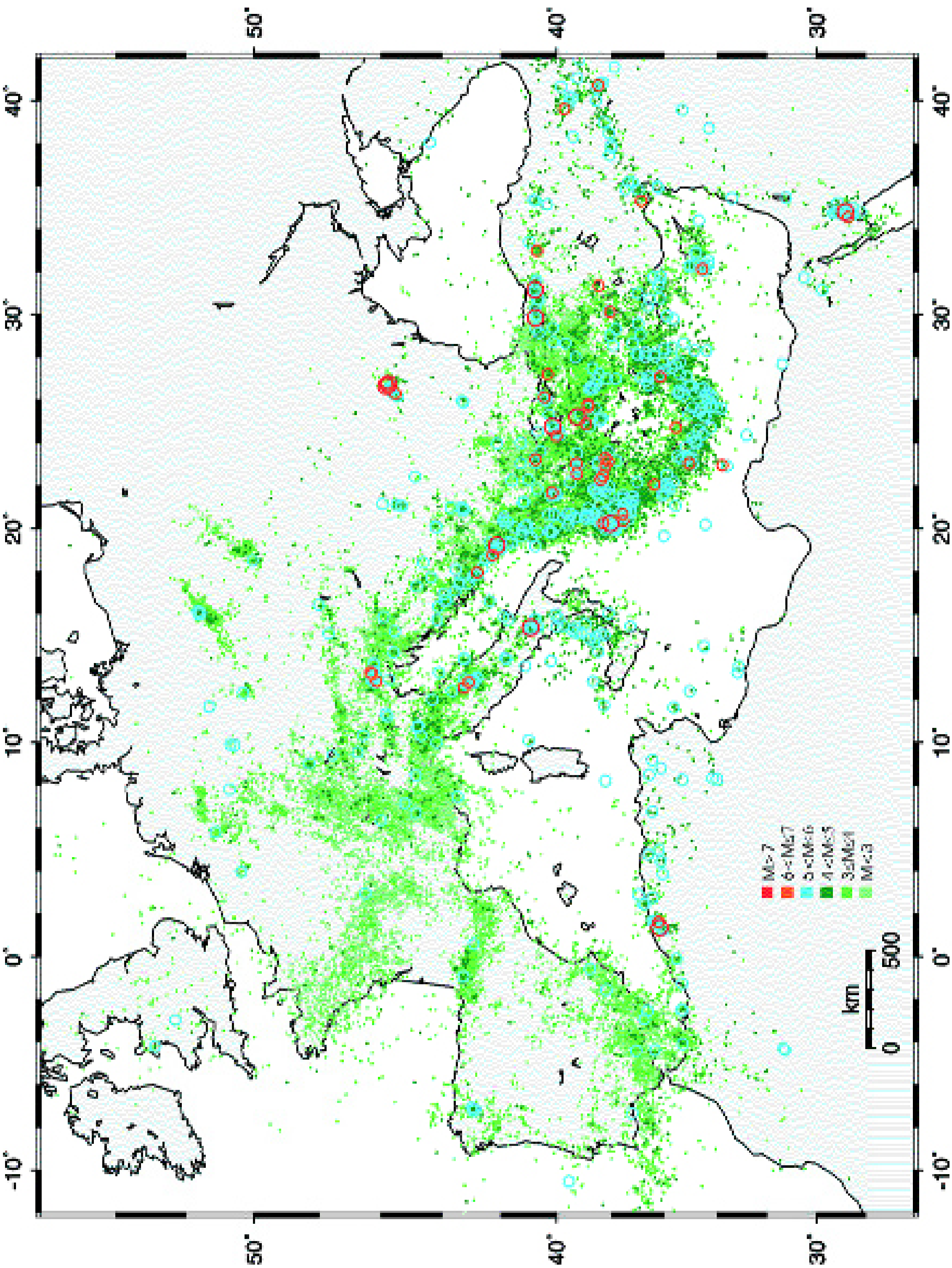


Fig. 2 - Spatial distribution of seismicity in the Mediterranean area: epicentral data are taken from the National Earthquake Information Center (NEIC) of the US Geological Service (USGS), which is a database of global earthquakes from 1973 to 2001 (http://neic.usgs.gov/neis/bullettin).

Bassi and Sabadini, 1994; Faccenna et al., 1996; Mantovani et al., 1996, 1997; Babucci et al., 1997; Bassi et al., 1997; Cianetti et al., 1997; Hatzfeld et al., 1997; Meijer and Wortel, 1997). The controversial aspect of the deformation patterns that has mainly determined the divergence of interpretations is the opening of basins in a zone of plate convergence. The ambiguity between the different dynamic interpretations, which respectively postulate the importance of subduction-related forces (as slab-pull) or kinematically induced horizontal forces, seems to be a major problem in the Mediterranean geodynamics. Moreover, the most appropriate way of describing continental deformation (i.e., continuum deformation versus micro-plate or block behavior) is another problem of the ongoing debate.

2. GPS networks

An important and independent constraint on the kinematic pattern of the Mediterranean area can be obtained by space geodetic measurements (SLR, VLBI and GPS), which provide information on the motion of a number of points on the Earth's surface with respect to a common geocentric reference frame. It is widely accepted that the NAVSTAR GPS (NAVigation Satellite Timing And Ranging Global Positioning System) technique can be successfully used to detect crustal deformation at different scales, so that permanent and non-permanent GPS arrays are currently used for this purpose all over the world (e.g., Bock et al., 1997). Due to the low deformation rates in most of the Mediterranean area, an accurate estimate of such parameter would require relatively long observation time spans, which may be reduced using permanent GPS stations. Unfortunately, the number of such stations in the Mediterranean region, and in particular in the Italian one, is too limited to provide significant information on the kinematics and the strain rate field of such a tectonically complex area; only after 1995, the Agenzia Spaziale Italiana (ASI) established some permanent GPS stations to constitute the Italian GPS Fiducial Network (IGFN; Vespe et al., 1999; see Fig. 3). For this reason, geophysical dedicated non-permanent GPS networks play an important role in supplying relevant tectonic information, both at regional and local scales. In this paper, we used GPS data collected on non-permanent stations to densify the European Permanent GPS Network (EPN-EUREF). The EUREF network is the European densification of the global GPS network involved in the International GPS Service for Geodynamics (IGS), which provides orbits, tracking data, positions and velocities for all stations in the International Terrestrial Reference Frame (ITRF). The EUREF network covers the European and Mediterranean region with more than 100 stations and its ITRF2000 solution, in full SINEX format, has been obtained from http://lareg.ensg.fr/ITRF2000.

Since 1987, the University of Bologna and the Istituto Nazionale di Geofisica (ING: currently Istituto Nazionale di Geofisica e Vulcanologia, INGV), in cooperation with several Italian and foreign agencies and universities, began to set up local and regional GPS networks in the Mediterranean area, and to collect GPS measurements just on some existing geodetic sites, belonging mainly to the Italian first order geodetic network, or to connected local networks. The first GPS survey carried out in the Italian area was performed in 1987 using single-frequency receivers set up on the terrestrial geodetic network of the Messina Strait (Southern Italy) (Achilli

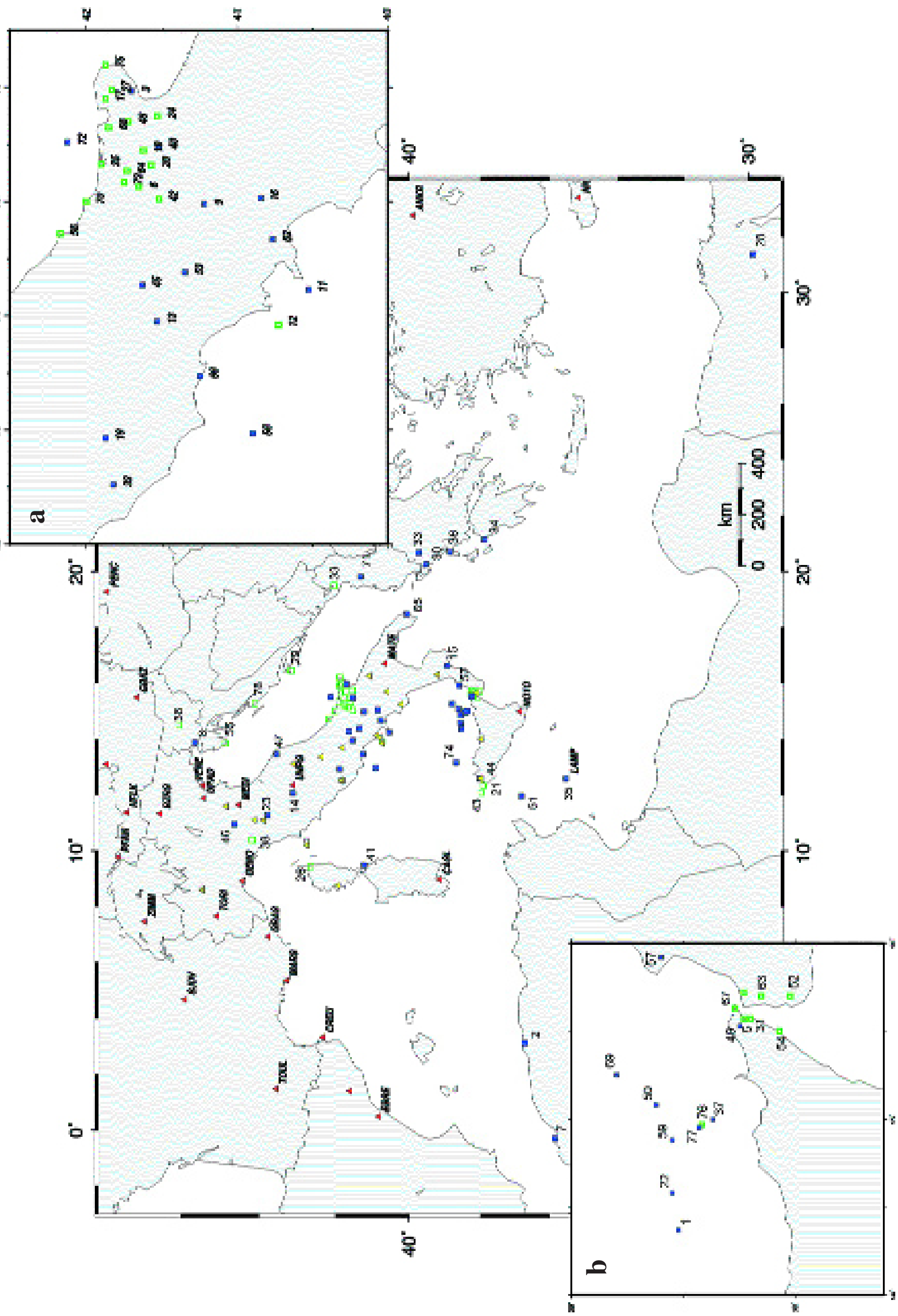


Fig. 3 - Non-permanent GPS stations in the Mediterranean area (blue squares), managed by the Istituto Nazionale di Geofisica e Vulcanologia (INGV) and the University of Bologna. Green open squares represent GPS stations not included in the final velocity adjustment. The TYRGEONET network is the widest of the ones described in this work and extends to all the Central Mediterranean area. a) GEOMODAP and Gargano networks; b) Eolie Islands and Messina Strait networks. Red triangles show the distribution of the EUREF permanent stations and yellow triangles represent some of the presently operational permanent GPS stations in the Italian area.

et al., 1988; Anzidei et al., 1998). Most of the new GPS monuments were built following the most restrictive requirements needed for geophysical purposes, adopting, when available, stable outcrops or concrete pillars, and using self-centering tools to improve position repeatability with an easy GPS antenna mounting. Fig. 4 shows two examples of GPS antenna self-centering devices, the first one used during the earlier GPS surveys (a) and the second one used during more recent surveys (b).

2.1. TYRGEONET GPS network:

The TYRGEONET network (TYRrhenian GEOdetic NETwork; see Fig. 3, Table 1 and Table 2) was set up in 1990 in the frame of a scientific project devoted to crustal deformation monitoring (Achilli et al., 1992a; Anzidei et al., 1995a). This network is composed of 50 vertices, 34 of which located in Italy and 16 in the surrounding countries, partially surveyed from 1990 to 2001 (Table 2). Some of them belong to already existing geodetic networks (the

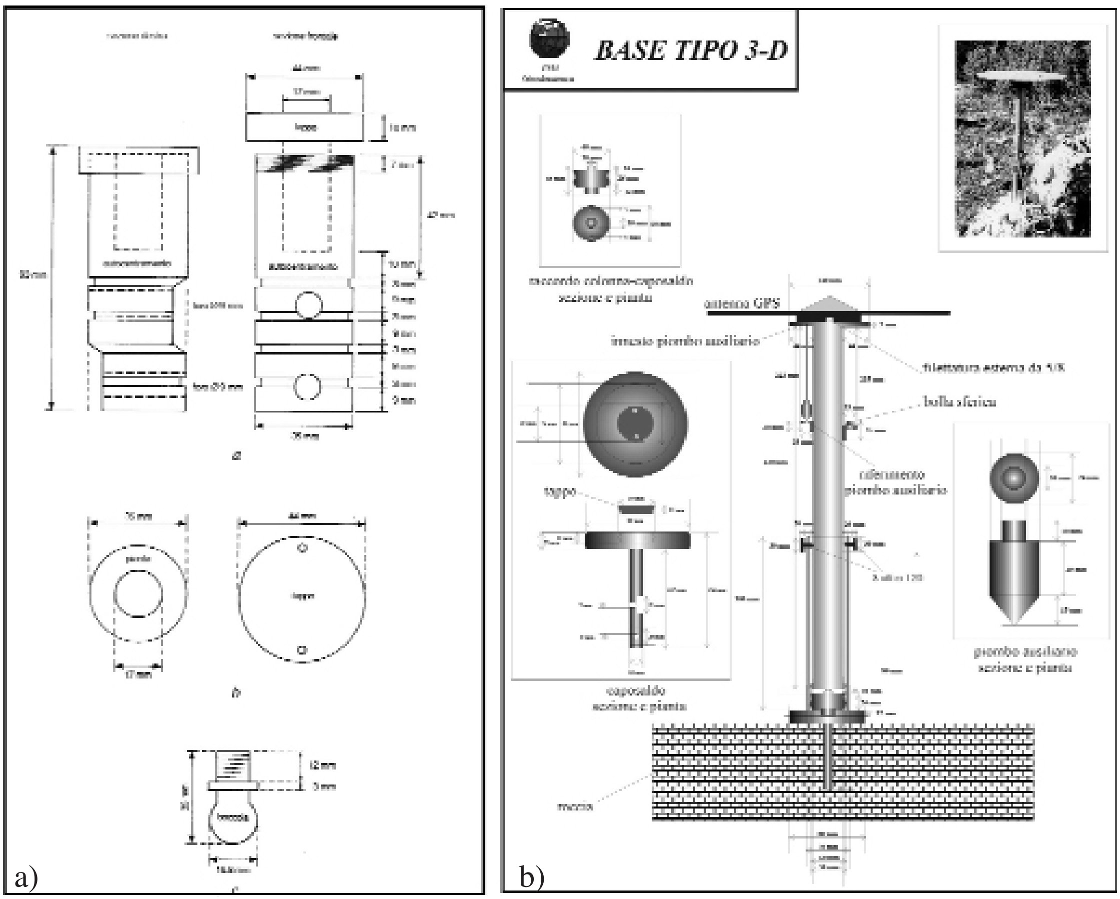


Fig. 4 - Schemes of the self-centering tools used for most of the non-permanent GPS sites monumented in the last decade: a) an old device used in the past; b) a more recent device, projected and built by INGV, that is also, nowadays, used for the new permanent GPS stations managed by INGV.

Table 1 - General information on non-permanent GPS stations. From left to right: complete station name (ecc = eccentricity with respect to present IGS stations); ID number as reported in Fig. 5; 4 characters station code; name of other connected geodetic networks; GPS networks within which the station has been observed (TYRG = TYRGEOENET; GEOM = GEOMODAP; GARG = GARGANO; EOLI = EOLIE; STRT = STRETTO; IGM95 = IGM95 National GPS Network); monument type: A = concrete pillar on outcrop, B = marker on outcrop, C = marker on concrete platform, D = marker on stable building, E = concrete pillar on stable building, F = marker on stable concrete wall, G = marker on roof of stable building, H = 3-D marker on stable building, I = iron pillar on outcrop, M type includes a wide variety of monuments used in geodetic networks for mapping and cadastral function, usually of a much lower quality with respect to geophysical dedicated markers. (* monuments no longer existing).

Station Names	ID	Code	Connected Networks	GPS Surveys	Monument.
Alicudi	1	ALCD	Eolie	EOLI	H
Algeri	2	ALGE		TYRG	D
Monte S. Angelo	3	ANGE	IGM 1thOrd.-IGM95	TYRG+GEOM+IGM95+GARG	E
Apostoli	4	APOS	Stretto di Messina	STRT	G
Arena	5	AREN	Stretto di Messina	STRT	D
Colle d’Armi	6	ARMI	IGM95	IGM95	M
Arzew	7	ARZE		TYRG	D
Basovizza	8	BASO	IGM-SLR	TYRG	B
Buonalbergo	9	BUON		GEOM	B
Cagliari (ecc.)	-	CAG1	SLR	GEOM	C
Cagliari (ecc.)	-	CAG_	SLR	TYRG	C
Contrada Cantatore	10	CANT	IGM95	IGM95	M
Capri (ecc.)	-	CAP1	IGM 1thOrd.-IGM95	GEOM	D
Capri	11	CAPR	IGM 1thOrd.-IGM95	GEOM+TYRG	D
Casamicciola	12	CASM		GEOM	D
Cassino	13	CASS	ENEA-IGM	GEOM+TYRG	A
Castiglion del Lago	14	CAST	IGM95	TYRG	D
Catanzaro	15	CATA	Fossa Catanzaro-IGM95	TYRG	A
Cassano Irpino	16	CIRP	Napoli	GEOM	A
Civita	17	CIVI	IGM95	IGM95	M
Corfino	18	CORF		TYRG	M
Caprinica Prenestina	19	CPRN	Colli Albani	GEOM	B
Monte Doro	20	DORO	IGM95	IGM95	B
Favignana	21	FAVI		TYRG	H
Filicudi	22	FILI	Eolie	EOLI	H
Firenze (IGM)	23	FIRE	IGM95	TYRG	G
Fossetta	24	FOSS	IGM95	IGM95+GARG	M
Torre Fortore	25	FRTR	IGM95	IGM95+GARG	E
Furiani – Corsica (F)	26	FURI		TYRG	B
Monte Giovannicchio	27	GIOV	IGM95	IGM95+GARG	A
Grasse (F) (ecc.)	-	GRA_	SLR-VLBI	TYRG	D
Helwan	28	HELW		TYRG	G
Hvar (CRO)	29	HVAR		TYRG	D
Igoumenitsa (GR)	30	IGOU		TYRG	A
ING Messina	31	INGM	Stretto di Messina	STRT	G
ING Roma (INGV)	32	INGR		GEOM+TYRG	E
Karitsa	33	KARI		TYRG	A
Kastro Illias (GR)	34	KAST		TYRG	E
Lampedusa	35	LAMO	SLR	TYRG	C
Lefkas (GR)	36	LEFK		TYRG	A
Lipari	37	LIPA	Eolie	EOLI	I
Lubiana (SLO)	38	LUBI		TYRG	E
Lucca *	39	LUCC	IGM95	TYRG	D
Lucera	40	LUCE	IGM 1thOrd.-IGM95	GEOM+TYRG+IGM95+GARG	A

Table 1 - continued.

Station Names	ID	Code	Connected Networks	GPS Surveys	Monument.
Maddalena	41	MADD	Magnetic Italian Network	TYRG	A
Marco	42	MARC	IGM95	IGM95	M
Marettimo	43	MARE		TYRG	D
Matera (ecc.)	-	MAT_	IGM95-SLR	TYRG	E
Milo	44	MILO	Etna-IGM95	TYRG	C
Miranda	45	MIRA		GEOM	B
Modena	46	MODE		TYRG	E
Monte Sicuro	47	MSIC	Ancona	TYRG	D
Monte Nero	48	NERO	IGM95	IGM95+GARG	A
Noto (ecc.)	-	NOT_	IGM95-SLR	TYRG	A
Pace	49	PACE	Arco Calabro-IGM95	TYRG+STRT	E
Panarea	50	PANA	Arco Calabro IGM 1thOrd.-IGM95	EOLI	D
Pantelleria	51	PANT		TYRG	G
Paterriti	52	PATE	Arco Calabro IGM 3rdOrd.-IGM95	STRT	D
Piedimonte Matese	53	PIED		GEOM	B
Placido	54	PLAC	IGM95-SLR Stretto di Messina	STRT	D
Pola (HR)	55	POLA		TYRG	E
Ponza	56	PONZ	Italian Magnetic Network	GEOM+TYRG	A
Monte Poro	57	PORO	Arco Calabro	TYRG+STRT+EOLI	A
Punta Penna	58	PPEN	IGM95	IGM95	M
Salina	59	SALI	Eolie	EOLI	H
Scrisi	60	SCRI	Stretto di Messina	STRT	A
Scutari (ALB)	61	SCUT		TYRG	E
San Giorgio	62	SGIO	Napoli	GEOM	B
San Nicola	63	SNIC	Stretto di Messina	STRT	G
San Paolo di C.	64	SPAO	IGM95	IGM95	M
Specchia Cristi	65	SPEC	IGM 1thOrd.-IGM95	TYRG	E
Sperlonga	66	SPER		GEOM	B
Spuria	67	SPUR	Stretto di Messina	STRT	E
Statale 89	68	SS89	IGM95	IGM95+GARG	M
Stromboli	69	STRO	Eolie	EOLI	F
Termoli	70	TERM	IGM95	IGM95	M
Tirana (ALB)	71	TIRA		TYRG	E
Tremiti	72	TREM	IGM 1thOrd.-IGM95	GEOM+TYRG+IGM95+GARG	E
Masseria del Tronco	73	TRO_	IGM95	IGM95	M
Ustica	74	USTI	Arco Calabro	TYRG	D
Vieste	75	VIES	IGM95	IGM95+GARG	F
Vulcano (Carapezza)	76	VUCA	OSVE	EOLI	B
Vulcano	77	VULC	IGM 1thOrd.-IGM95	EOLI	A
Zara (HR)	78	ZARA		TYRG	A

IGM National Geodetic Network, the Italian Magnetic Network and the more recent IGM95). Some stations coincide with the mobile Satellite Laser Ranging (SLR) sites or markers linked to them (Baldi and Marson, 1981; Achilli et al., 1985, 1992b; Nunnari and Puglisi, 1990; Surace, 1997). Many papers regarding results obtained by comparing different surveys in this network have been published in the last decade (Anzidei et al., 1996, 1997). Recently Anzidei et al. (2001) estimated the regional velocity field using data collected in the time span 1991-1998.

Table 2 - Observation table for all the non-permanent GPS stations included in the primary GPS data analysis.

yr	1991	1993	1994	1995	1996	1997	1998	1999	2000	2001
	000000000 000000000 123456789	00000000000 11111111112 01234567890	000000000000000000000 222222222333333333344 123456789012345678901	00000000000000000000000 44444444555555555566666 23456789012345678901234	0000000000000000000 6666677777777778888 5678901234567890123	00000000000000001 88888899999999990 45678901234567890	11111111 00000000 12345678	111111111111111 011111111112222 901234567890123	111111111111111111111 222222333333333344444 456789012345678901234	11111111 44444555 56789012
ALCD						•••• •••••			•••	••••
ALGE				••••••	••••••	••••••	••••••	••••••	•• ••	
ANGE	••••	•••••	•••• •••••	•••••••••••••••••••	•••••••••• ••••••••			•••••••	••••••••	
APOS			•							
AREN			••							
ARMI			•							
ARZE				••	••	• ••	••••••••	•••••••	•••••• •	
BASO		•• ••••••••	••••••••		••••••••					
BUON			••••	•••	•••			•••	••••	
CAG1			••••							
CAG_	•••••••••	• ••• •								
CANT			•							
CAPR	•••	••••	•• ••	•••••• ••••••••	••••••	••••••		••••••	••••••••••	
CASM				•						
CASS	••• •		••••	•••••	•••			••••	••••	
CAST	•••	•••••		••••••	•• ••			•••		
CATA	•••••••••		••••••••	••••••	•••••••					
CIRP			•••••	•••••	•••			••••••	•••••••••••	
CIVI			•							
CORF		•••••								
CPRN				••					•••••	
DORO			•							
FAVI						••••				
FILI						•••• •• •••			••••	
FIRE	•• ••••••			••••••	•••••••					
FORI								••••••		
FOSS			•		•					
FRTR			• •		•••					
FURI	•••••••									
GIOV			•		••					
GRA_	•••••••••									
HELW								•••••••	•••••••	
HVAR					•••					
IGOU	••••••••		•••••••	•••••	•••••••					
INGM			• •••							
INGR				•••••• •• •	••••••• ••••••	••••••		••••••• •••••••	••••••••••••••••••	•••••••
KARI			•••••••	•••••	•••••••					
KAST	••••••••		••••••••	••••••	•••••••					
LAMO	• ••• •••		••••••••	••••••	•••••••	••••••	•••••••	••••••		
LEFK	•• • •		•• •••••	••••••	•••••••					
LIPA						•••				••••
LUBI	•••••••••									
LUCC	••• •••									
LUCE	••••• •		• ••		• • •••			•••		
MADD	•••	••••• •••••			•••••				••••••	
MARC			•							
MARE						•••				
MAT_	•••••••••									
MILO			••• ••••			••••••	••••••	•••••••	•••••••	••••••
MIRA			••	•••••	••• ••			••••	••••••	

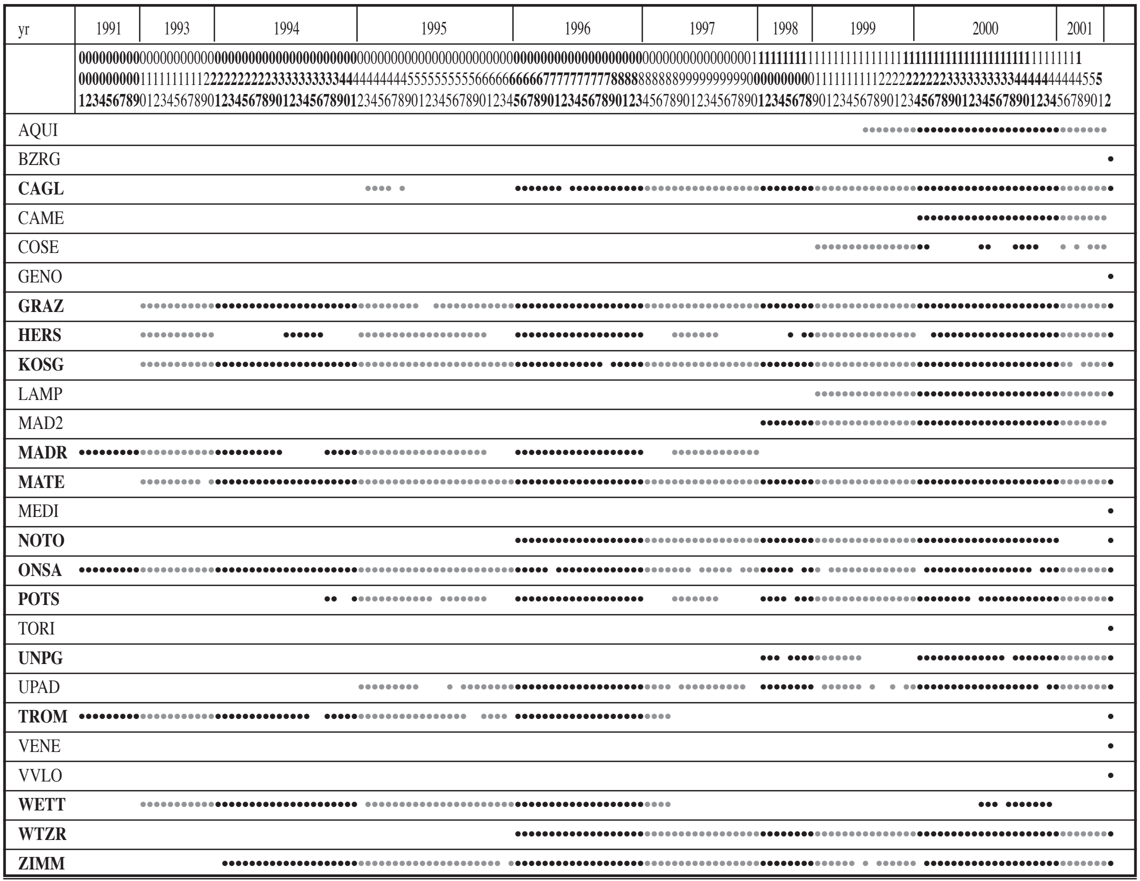
Table 2 - continued.

yr	1991	1993	1994	1995	1996	1997	1998	1999	2000	2001
	000000000	00000000000	000000000000000000000	00000000000000000000000	0000000000000000000	00000000000000001	11111111	111111111111111	111111111111111111111	11111111
	000000000	11111111112	222222222333333333344	44444444555555555566666	6666677777777778888	88888899999999990	00000000	011111111112222	222222333333333344444	44444555
	123456789	01234567890	123456789012345678901	23456789012345678901234	5678901234567890123	45678901234567890	12345678	901234567890123	456789012345678901234	56789012
MODE		••••• •••••	•••••••		•••••••			••••••		
MSIC	•••••••••	•• ••								
NERO			••		••					
NOT_			••••••							
PACE	•••••••••		••••						•••••	
PANA				••••		••••••••••		••••••	•••••••	•••
PANT	••••		••••••••			•••••	•••••••	••••••	••••••	
PATE			••							
PIED				•••••••	•••••			•••••••	••••••••	
PLAC			••							
POLA	••••••									
PONZ	•••••		•••••	••••••	••••••			••••••	••••••••••	
PORO	•••••••		•••••	•••••• ••••	•••••••	• ••••	••••••	••••••	••••••	•••••
PPEN			•							
QUAR								••••••		
SALI				••••		•••• ••••••			••••••	••••
SCRI			••							
SCUT				•••••						
SGIO				••••	•••• •			••••	•••	
SNIC			••							
SPAO			•							
SPEC	•••••••••	•••••	••••••••	••••••	••••••••				••••••	
SPER				•••••	••••••••			••••••	•••••	
SPUR			•							
SS89			•		• •					
STRO			••••			••• ••••			•••••••	•••••
TERM			••							
TIRA				••••••	•••••••					
TREM	•••••	•••••	• •••••	•••••• ••• ••	••••••••• •••• •			•••	•••••••••••	
TRO_			•							
USTI			•• •••••	••••••	•••••••	••••••	••••••	••••••	•••••••	••••
VIES			•		••					
VUCA									••••••	••••
VULC			•••	••••		••••••••• ••			•••••••	•••••••
WTM2	•••• ••••									
ZARA	••••••									

2.2. GEOMODAP GPS network

With the aim of detecting the present-day crustal motions of the central-southern Apennines, a densification of the TYRGEONET network in this area was established and repeatedly surveyed, in the frame of an EC project (the GEOdynamic MODeling of the APennines project; see Fig. 3a and Table 1). The 14 GPS sites of the GEOMODAP network (Anzidei et al., 1995b, 2001; Serpelloni et al., 2001) were occupied during several week-long campaigns in 1994, 1995, 1996, 1999, 2000, and 2001 (Table 2). Recently Serpelloni et al. (2001) estimated velocity and strain-rate fields of this region, using the whole data set.

Table 3 - Observation table for the permanent GPS stations included in the primary GPS data analysis (first step of the GAMIT/GLOBK processing scheme adopted in this work). Station names in bold are the ones used to define the reference frame, constraining their ITRF2000 positions for time series analysis and their horizontal ITRF2000 velocities for the velocity adjustment.



2.3. Messina Strait and Aeolie Islands GPS networks

In 1970, the Messina Strait area was included in an important engineering project commissioned by the Italian government for the construction of a bridge connecting Sicily to Calabria. To evaluate vertical and horizontal deformations in the Strait area, a leveling route and a geodetic network were established and repeatedly measured with terrestrial techniques (see Fig. 3b and Table 1). In 1987 and 1994, some sites belonging to this network were surveyed using the GPS technique (Table 2), but the 1987 observations have been discarded in the present work, because single frequency receivers were used and the accuracies obtainable from these instruments, significantly lower that the ones reachable using the more recent double frequency receivers, cannot be used for regional analysis. In 1987, the Messina Strait network was enlarged to the Aeolian Islands (Baldi et al., 1988) and was connected with the TYRGEONET network (see Fig. 3b).

2.4. IGM95 GPS network

IGM95 was a geodetic project started in 1992 in order to determine a new, fundamental network covering the whole of Italy (Surace, 1997). The aim of this project was the establishment of a 3D geodetic network of about one thousand points, distributed along the Italian territory, most of them belonging, or directly connected, to the national fundamental triangulation and leveling networks, using also all the SLR, VLBI and EUREF-GPS sites. Even if one of the aims of this network was to give a geometric reference for geophysical purposes to the scientific community, most of the IGM95 sites do not follow all the restrictive requirements, in terms of monumentation and data acquisition, to produce accuracies and repeatability suitable for geophysical applications. All IGM95 sites have been measured at least once in the 1992-1995 time span, and during the year 1996, the sites monumented in 1992 have been resurveyed in order to get the whole network measured using the same GPS instruments. After a seismic sequence that struck the Gargano area in September 1995 (Frepoli and Amato, 2000), in 1996 some geodetic monuments (Fig. 3a) of relatively good quality, belonging to the IGM95-GPS network were reoccupied (Table 1 and Table 2). In this work, IGM95 RINEX data have been reprocessed, following the same approach used for the other networks.

3. GPS data analysis

In this work the data processing has been performed using the GAMIT/GLOBK 10.05 software package (Herring, 2000; King and Bock, 2000), following the Distributed Session Mode approach (Blewitt et al., 1993; Zhang, 1996). The Quasi Observation approach (Dong, 1993; Dong et al., 1998) was adopted in the post processing steps in order to combine different network solutions into a unique, final global solution, where the reference frame is defined by computing the velocity field.

Each observable step of the analysis of GPS is characterized by a different software package. In the first step, the GAMIT software (Gps At MIT) has been used to remove or minimize the effects of outliers and cycle slips in the phase and pseudorange observations and to perform a weighted least-square adjustment of the observations. We processed the regional and local non-permanent networks together with some of the Italian permanent GPS stations and some IGS sites (see Table 3). We adopted the IGS_1 model in the data processing, in order to take into account the antenna phase center variations as a function of the elevation of satellites (Rothacher and Mader, 1996). This model arbitrarily assumes no elevation-dependent terms for Dorne-Margolin choke ring antennas and applies elevation-dependent variations for other antennas. A priori satellite orbits were obtained by numerically integrating the initial conditions (g-files; http://sopac.ucsd.edu/processing/orbits) obtained from the Scripps Orbit and Permanent Array Center, San Diego, CA (SOPAC). Using these satellite ephemerides, along with a-priori values for station coordinates, Earth rotation parameters and standard expressions for the precession and nutation, GAMIT computes theoretical values for the carrier phase observations at both the L1 and L2 frequencies for each station-satellite combination. These values are then subtracted from the observed ones to form phase residuals and combined as double differences (between satellites and between sites) in a least square analysis to estimate satellite orbit, site coordinates, Earth Orientation Parameters (EOP), atmospheric refraction and phase ambiguities (Bock et al., 1986; Shaffrin and Bock, 1988). Residual tropospheric effects relative to a reference model (e.g. Saastamoinen, 1972) are parameterized by a combination of zenith delay parameters. The first step of the processing is the ambiguity resolution, that is the evaluation of their correct integer numbers, in order to eliminate them from the observation equations. This is performed through a series of three intermediate solutions, as described by Dong and Bock (1989) and Feigl et al. (1993):

1. all parameters are estimated using the ionospheric-free (L3) combination of the L1 and L2 phase, imposing tight constraints on the position of some well-known IGS stations;
2. holding the station coordinates fixed at the values obtained previously, the wide-lane (L5) ambiguity parameters are estimated iteratively and, if possible, constrained to integer values. Effects of ionospheric refraction are constrained by the introduction, for each epoch, of an additional observation equation (Dong and Bock, 1989); if precise pseudoranges at both the L1 and L2 frequencies are available, they are used to help the determination of the wide-lane ambiguities;
3. keeping fixed the wide-lane ambiguities, the equations of "iono-free" combination are solved, resolving iteratively the residual biases of these observables (narrow lane).

As in solution 1, a reference frame is defined by imposing tight constraints on some well-know IGS station coordinates. Using the resolved values of both the wide-lane and narrow-lane ambiguities held fixed, the final values of geodetic parameters are estimated from L3 observations. In practice, other two additional solutions are generated during this procedure. These are very loosely constrained solutions, in which the terrestrial reference frame is undefined (essentially free adjustments), and are obtained with orbit and position constraints sufficiently tight, to avoid numerical singularity, but sufficiently loose to avoid the introduction of a significant bias in the estimated parameters (Dong and Bock, 1989; Dong et al., 1998). Using this processing scheme, loosely constrained solutions (parameter adjustments and full covariance matrices) for each session of the surveys from 1991 to 2001 were obtained.

In the second step, the GLOBK software (GLOBal Kalman filter) has been used to combine all the daily regional and local-loose constrained solutions, obtained by the GAMIT processing, with the global, loosely constrained solutions provided by SOPAC (h-files) for the same period, solving the commonly shared parameters, such as the satellite orbits and the coordinates of the global IGS permanent stations included in both the subsets, by means of the Kalman filter procedure included in the GLOBK software. Oral (1994) and Zhang (1996) have demonstrated that the combination of global and regional solutions through an adjustment of their corresponding estimates, and using full covariance matrices, yields parameter estimates that are statistically equivalent to a simultaneous adjustment using all the data; this approach is significantly more efficient and maintains reasonably homogeneous solutions.

The third step was performed by using all the loosely constrained combined daily solutions, obtained by the GLOBK, as quasi observations (qob, Dong et al., 1998), to model the velocity of each station, assumed to be constant in time, by means of the Quasi Observation

Combination Analysis software (QOCA; http://gipsy.jpl.nasa.gov/qoca). The combination was performed through a sequential Kalman filtering algorithm, allowing global translation and rotation for each daily solution. Random walk style perturbations were allowed for some parameters whose errors were correlated with time, such as the EOP and the antenna heights (Feigl et al., 1993; Dong et al., 1998; Zhang et al., 1997; Mao et al., 1999). We first analyzed the position time series ("separate-mode" analysis), in order to detect outliers due, for example, to missing antenna height record, wrongly fixed cycle slip, severe multipath, poor satellite

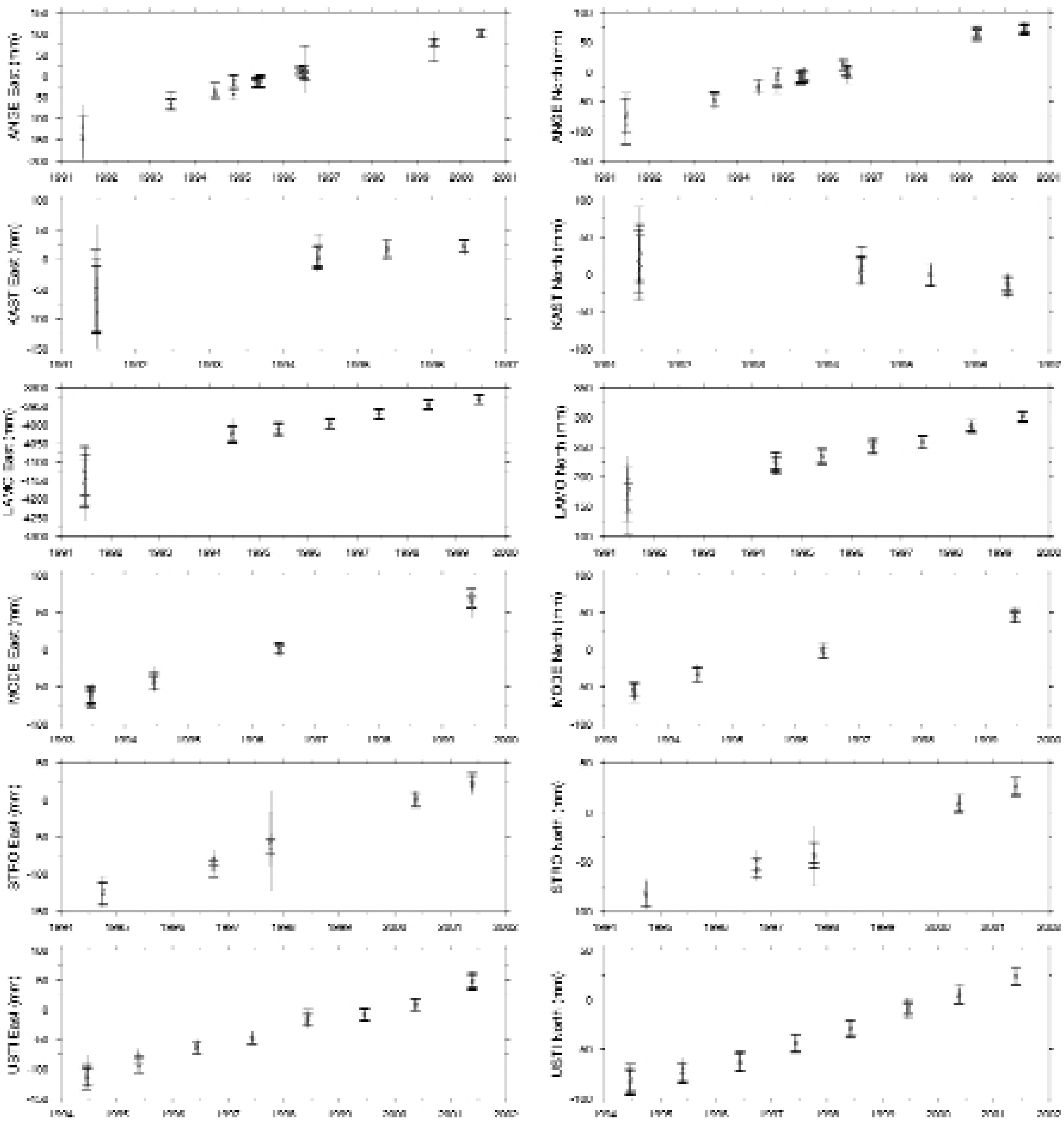


Fig. 5 - Position time series of the east and north components for some non-permanent GPS stations (Monte Sant'Angelo, Kastro Ilias, Lampedusa, Modena, Stromboli and Ustica), obtained constraining at a 2 cm level the ITRF2000 positions of some of the IGS stations reported in Table 3. Error bars indicate the 1 sigma error of each adjusted position.

configuration and other blunders not evidenced during the first step analysis. As a rule of thumb, we adopted the self-consistency, so, if one quasi observation is significantly inconsistent with the other, this data is likely to be an outlier and is checked and/or removed from the following analysis. At the moment, and with the data available, the analysis of the station position time series does not allow any assumption which differs from that of a constant velocity (Fig. 5 shows examples of position time series for some non-permanent GPS sites analyzed in this work). It is worth noting that the reference frame is defined only in this last step, and the approach adopted in this work affords a rigorous solution to the problem of an inhomogeneous tracking network, where the set of stations changes from day to day and year to year. The velocity adjustment approach adopted in this work ("global-mode" analysis) minimizes the effect of the shifting fiducial geometry by imposing the constraints on the coordinates and on the velocities in a consistent manner. We obtained the velocity field in the ITRF2000 reference frame constraining the horizontal velocities of some European IGS permanent stations, listed in Table 3, observed continuously as much as possible during the observation time span 1991-2001. To assess the accuracy of the velocity field obtained in this last step, we took into account the complexity of the error spectra of GPS data, following the error analysis proposed by Dong et al. (1998), and described in Shen et al. (2000). At each step, when a new data file was added, we considered the increment of the post fit χ^2 due to the addition of the new data file and the increase of degrees of freedom in data space, evaluated in a conventional way (observation number subtracted by the estimated parameters number). Each data file was then re-weighted after the iteration using the square root per quasi-observation data file averaged from forward and backward Kalman filtering. This procedure allows adequate relative weighting for each individual data file. The next step was to evaluate the increase of the number of parameters caused by allowing the parameter perturbation in the Kalman filtering process. The total normalized RMS was then re-evaluated with an updated estimate of the number of degrees of freedom and then the velocity variance-covariance matrix was rescaled.

4. Discussion and conclusions

Following the processing scheme described above we have analyzed 152 daily observation sessions and a total amount of 72 non-permanent GPS sites belonging to regional, sub-regional and local GPS networks (see Tables 1 and 2). All 72 stations have been used in the "separate-mode" analysis, but only stations observed in at least three surveys (with the exception of HELW) have been used in the velocity adjustment, "global-mode" analysis, after removing outliers and rescaling the qob files. In the regional analysis, the residual velocities with respect to a stable tectonic plate or crustal block are used for kinematics and geodynamics interpretations. The best approach for dealing with residual velocities with respect to a stable plate is that of extracting the rigid component, on a spherical Earth, of the plate or crustal block in consideration, using the "Earth's fixed point" theorem (Euler's theorem). Usually the reference frame for geodynamics and tectonics studies in the Mediterranean area is the stable portion of the Eurasian plate. A first attempt to compute the residual velocity field with respect

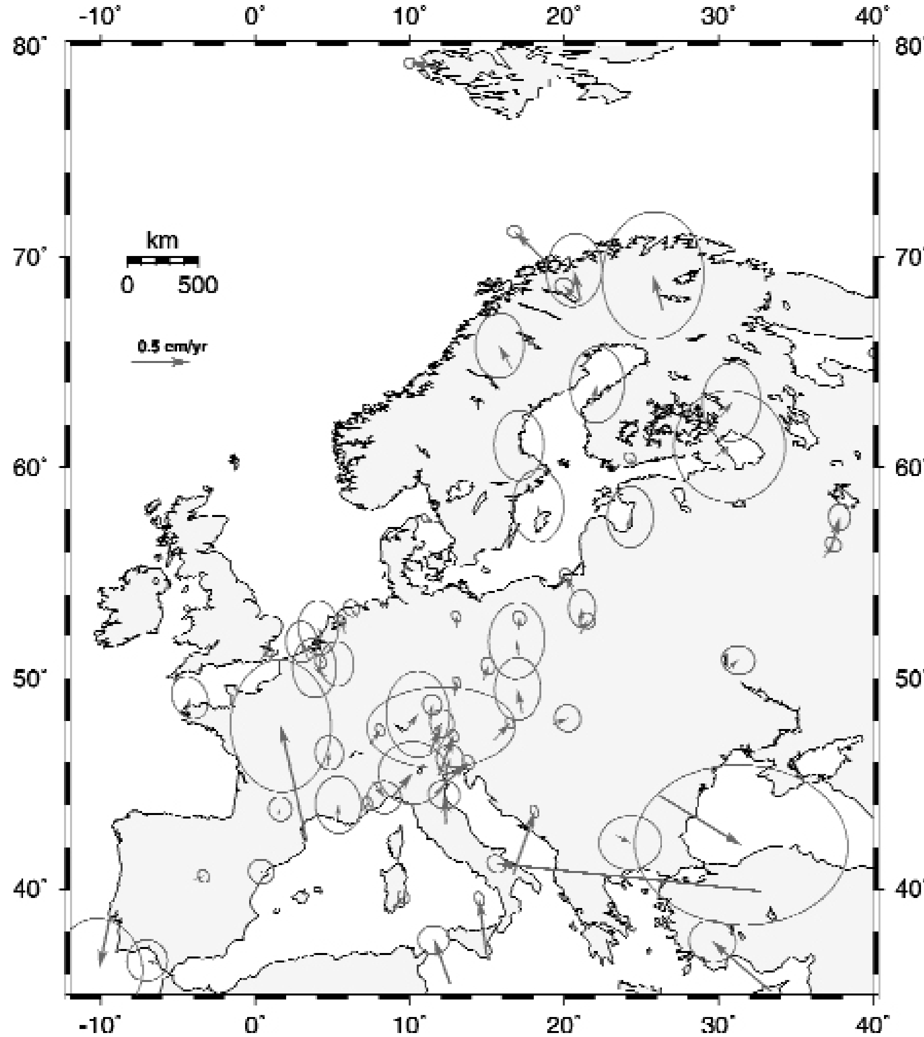


Fig. 6 - Residual velocity field computed with respect to the stable Eurasian reference frame defined by NNR-NUVEL-1A global model. Error ellipses are at the 95% confidence level.

to this frame has been made comparing the ITRF2000 velocity solution of the IGS stations in Europe with the NNR-NUVEL-1A plate motion model (Argus and Gordon, 1991; DeMets et al., 1994), by removing the NNR-NUVEL-1A rotation for Eurasia from the ITRF2000 velocities. The residuals, obtained in this way, display a general counterclockwise rotation of some IGS stations in central and northern Europe with values of up to several mm/yr, introducing consequently a bias in the following kinematic and geodynamic analysis of tectonically active areas (Fig. 6). To overcome this problem, we used ITRF2000 velocity solution to constrain a plate kinematic model for the Eurasian plate. Following the approach of Shen et al. (2000), we used some IGS stations located on a stable portion of the Eurasian plate to compute a Euler rotation pole that defines a stable Europe reference frame (Serpelloni, 2002). The residual velocity field, with respect to this stable Europe reference frame (Fig. 7), shows clear features for the more rapidly deforming areas, such as the Aegean/Anatolian, Adriatic and Tyrrhenian areas. Geodetic velocities in the remaining parts of the study areas, such as central Europe and the western Mediterranean are small or not significant.

A remarkable feature of the residual velocity field is a discontinuity in the transition zone between the Aegean/Balkan and the Adriatic-Ionian/Tyrrhenian domains, which is marked by the Kephallinia tectonic lineaments (Khale et al., 1993). Here the Hellenic units overthrust the Adriatic platform and the discontinuity is characterized by an abrupt change in the residual velocity directions and rates, moving from westwards to SW-wards cm/yr level motion trends to the mm/yr level rates of the Adriatic and Tyrrhenian regions, characterized by only two dominant motion trends, NNE-wards and NNW-wards. A simple explanation for this behaviour is the considerably different resistances that the westward drifting Aegean system encounters north and south of the Kephallinia discontinuity, due to the continental character of the Adriatic plate and the oceanic character of the Ionian basin. The motion trend of the Aegean/Anatolian

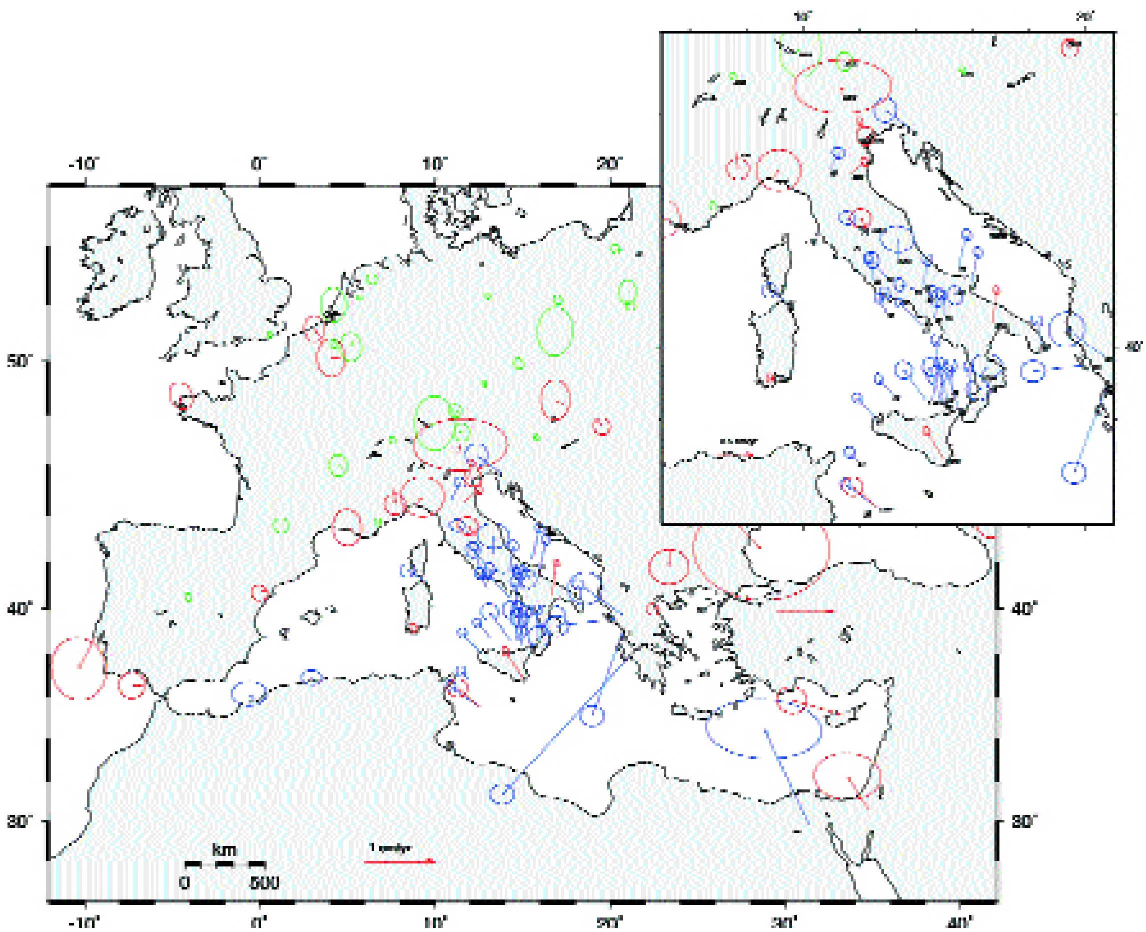


Fig. 7 - Residual velocity field with respect to the stable European reference frame obtained in this work, characterized by the following parameters: Ω = 0.257 ± 0.001 (°/My); Lat = 56.9 ± 0.71(°N); Lon = -100.3 ± 0.5 (°E). Green arrows are the residual velocities of IGS stations used to compute the Euler pole; red arrows are the residual velocities of the remnant EUREF stations; blue arrows are the residual velocities of non-permanent and non-IGS permanent GPS stations. Error ellipses are at the 95% confidence level.

domain indicates a westward escape of this block with respect to Eurasia, at an average rate of 20-25 mm/yr, as clearly provided by more extensive GPS measurements in this area (Khale et al., 2000; McKlusky et al., 2000; and references within). A second clear feature is that, using the GPS data available, the motion of the African plate seems to be oriented NNW-wards to NW-wards, a direction that seems to characterize the whole Tyrrhenian sector. This observation agrees well with the mean NNW-SSE direction of the SHmax, recovered by in situ stress measurements, whose areal extent lets some authors suppose to be representative of the converging direction between Africa and Eurasia (Müller et al., 1992; Rebaï et al., 1992; Zoback, 1992; Montone et al., 1999). This motion agrees well also with the prediction of other global models (Dewey et al., 1973, 1989; Minster and Jordan, 1978; DeMets et al., 1994). It is worth noting that the motion of the African plate with respect to the stable Europe reference frame obtained in this work may be constrained only using sites that are located mostly on non tectonically stable areas of the northern African margin. The two TYRGEONET stations of ALGE and ARZE, are located on the Maghrebian belt, which may be affected by local tectonic deformations, and their small residual velocities are not significant at a 95% confidence level. The sites of HELW and RAMO, respectively a non-permanent TYRGEONET station and an IGS permanent station, are located near the Dead Sea rift area and the Dead Sea-Levant fault zone; areas that are still undergoing active tectonics, consequently their motions might be not representative of the African plate kinematics. Moreover, the velocity of HELW is not well constrained since it has been obtained using only two repeated GPS campaigns. The site of PANT is located within the Sicily Strait tectonic zone, which has recently undergone, and is probably still undergoing, extensional deformation (Finetti and Del Ben, 1986). The only GPS station lying on a relatively undeformed African foreland is Lampedusa, which is, however, located very close to the troughs of the Sicily Channel. If we consider the motion of Lampedusa as representative of the African plate relative motion with respect to Eurasia, the stations located on the Adriatic lithological domain, SPEC, MATE, ANGE and TREM, BASO and UPAD clearly evidence a microplate-like kinematics for the Adriatic block, which seems to move independently, or semi-independently, from the African plate. In fact, its motion can be described by a counterclockwise rotation, with respect to stable Europe. It is worth noting that BASO displays an anomalous residual velocity, with respect to what expected from this rotation pole, and only future surveys or deployments of new permanent GPS stations will provide enough information to better constrain the kinematics of the Adriatic micro-plate. Concerning the residual velocity field of the Adriatic and Tyrrhenian domains, it is remarkable the presence of only two prevalent motion trends is noteworthy: NNE-wards for the station located in the Adriatic domain and in the southern Apennines, NW- to NNW-wards for the stations located on the Tyrrhenian side. The kinematic behaviour seems to be more complicated in the Calabrian and Aeolian area. As regards the analysis of the residual velocity field in the Tyrrhenian/Adriatic domains, it is not an easy task to understand if the relatively simple velocity field obtained, is related to the NW-ward motion of the African plate, as predicted by geological and geophysical global models, or to the kinematics of crustal blocks, like the Adriatic microplate or smaller ones still to be detected, in response to the boundary forces of this complex system, obviously involving the Aegean/Anatolia westward escape. To answer this question we first need to better constrain the present kinematics of the African plate. This can only be obtained by deploying new GPS stations.

Information about the present strain field, averaged at a regional scale, may be obtained by an integrated analysis of earthquake fault plane solutions (Jackson and McKenzie, 1988) and summation of moment tensors (Kostrov, 1974). Such type of investigation has been carried out in the Mediterranean region by a number of authors (Westaway, 1992; Anderson and Jackson, 1987; Jackson and McKenzie, 1988; Ekström and England, 1989; Kiratzi, 1994; Pondrelli et al., 1995; Papazachos and Kiratzi, 1996; Selvaggi, 1998; Viti et al., 2001). However, the results obtained by using this approach may be affected by uncertainties, due to the assumptions and simplifications adopted in the model and the approximate knowledge of the observed strain field. Moreover, since the amount of average seismic strain estimated by Kostrov's approach is strongly dependent on some poorly known parameters, such as thickness of the seismogenetic layer and the reliability of magnitudes of seismic events, this approach might be used to obtain information about the deformation style, without taking into account the modulus of the strain

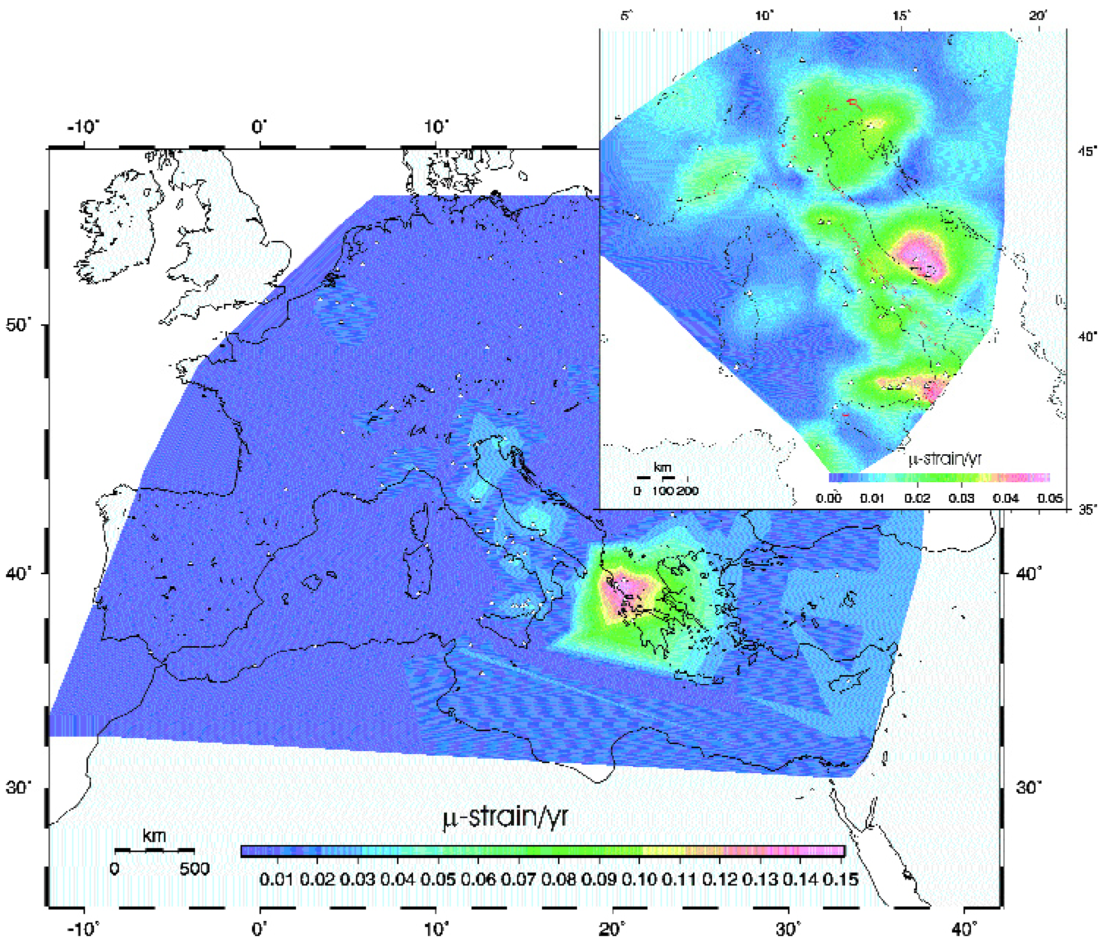


Fig. 8 - Contouring by optimal Delaunay triangulation of the interpolated maximum scalar strain rates defined by Savage and Simpson (1997). White triangles represent GPS stations whose velocities have been used in the strain computation.

rate (Viti et al., 2001). Information about regional strain regimes might also be inferred from neotectonic and geomorphological data (Hippolyte et al., 1994, 1995; Valensise and Pantosti, 2001), where this evidence is coherent over sufficiently large zones. However, in some geodynamic contexts, when shortening at a given collisional border occurs through strike-slip faulting and microblock rotations, possibly accompanied by tensional features in the wake of extruding or rotating crustal wedges, the use of neotectonic and geomorphological data may lead to a partial recognition of the related kinematics of the surrounding plates. In an attempt to obtain the present-day strain rate field, we used the damped least square method described by Shen et al. (1996) to compute the long wavelength strain rate field at the Mediterranean scale. We used the parameterization given by Savage and Simpson (1997) to plot a contour map of the maximum strain rates (defined as MAX ($|e_{max}|$, $|e_{min}|$, $|e_{max} + e_{min}|$). Fig. 8 shows that high strain rates are located only in the central and eastern Mediterranean, and, in particular, in the Aegean area, with a relative maximum in the transition zone between the Aegean-Balkan system and the Adriatic-Tyrrhenian system, corresponding to the Kephallinia fault zone. Relatively high strains are located along the Italian peninsula, especially in the Calabrian Arc, central-southern Apennines, Gargano area, central sector of the northern Apennines, Liguria and north-eastern Italy, Friuli, and Istria. The values plotted in Fig. 8 can be related to the potential seismic moment release (Ward, 1998; Kagan, 2002). The strain rate field computed from geodetic data measures the contribution of both seismic and aseismic deformation of the crust, whereas the strain rate field derived from historical and/or instrumental seismicity is a measurement of the seismic contribution to tectonic deformations. That is, the comparison of the geodetically-derived crustal deformations with the seismically derived ones can provide new insights into the balance between seismic and aseismic deformations, contributing significantly to the seismic hazard reduction in a seismogenetic area. It is worth noting that geodesy and seismology work on different time spans, so results can be different, and can be compared only if one assumes that rates of deformation remain stable for a long time in the study area; assumption that is generally acceptable. This "first order" image of the strain rate field clearly shows the great potential of geodetic measurements in helping to constrain the seismic hazard of tectonically active areas. In the near future, the combination of GPS data provided by continuously operating regional networks and local non-permanent networks, will significantly improve the determination of the current strain rate field in the Mediterranean area.

Acknowledgments. We are grateful to all Agencies, Universities, technicians and single researchers involved in field surveys and to SOPAC for providing h-file global solutions. Thanks are due to Dr. D. Dong and Dr. Z. K. Shen for discussions about data elaboration and strain rate analysis. The maps were created using the Generic Mapping Tools (GMT) software (Wessel and Smith, 2001). This paper was partially supported by the Italian Space Agency and the UE.

References

Achilli V., Anzidei M., Baldi P., Gasparini C., Marsella M. and Riguzzi F.; 1992a: *TYRGEONET: a global positioning system geodetic network for geodynamical survey of the Italian peninsula*. Ann. Geofis., **36**, 191-200.

Achilli V., Baldi P., Cagnetti V., De Marco R., Gazziano S., Marcucci S., Marsan P., Milana G. and Screpanti A.; 1985: *Attività sismica nell'area del Lazio meridionale*. In: Atti IV Convegno GNGTS, Esagrafica, Roma, pp. 121-133.

Achilli V., Baldi P., Zerbini S., Broccio F., Cagnetti V., Marsan P., Gubellini A. and Unguendoli M.; 1988: *Comparison between GPS and ground based distance measurements in the Messina Straits area*. Boll. Geof. Teor. Appl., **30**, 119-120.

Achilli V., Crespi M., Di Filippo S. and Vettore A.; 1992b: *Misure GPS sul poligono di Lucera: campagne 1989 e 1990*. Rivista del Catasto e Servizi Tecnici Erariali, **47**, 51-68.

Albarello D., Mantovani E., Babbucci D. and Tamburelli C.; 1995: *Africa-Eurasia kinematics: main constraints and uncertainties*. Tectonophys., **243**, 25-36.

Anderson H.J. and Jackson J.A.; 1987: *Active tectonics of the Adriatic region*. Geophys. J. R. Astr. Soc., **91**, 937-983.

Anzidei M., Baldi P., Bonini C., Casula G., Gandolfi S. and Riguzzi F.; 1998: *Geodetic surveys across the Messina straits (Southern Italy) seismogenetic area*. J. Geodyn., **25**, 85-97.

Anzidei M., Baldi P., Casula G., Crespi M. and Riguzzi F.; 1996: *Repeated GPS surveys across the Ionian Sea: evidence of crustal deformations*. Geophys. J. Int., **127**, 257-267.

Anzidei M., Baldi P., Casula G., Galvani A., Mantovani E., Pesci A., Riguzzi F. and Serpelloni E.; 2001: I*nsights into present-day crustal motion in the central Mediterranean area from GPS surveys*. Geophys. J. Int., **146**, 98-110.

Anzidei M., Baldi P., Casula G., Pondrelli S., Riguzzi F. and Zanutta A.; 1997: *Geodetic and seismological investigation in the Ionian area*. Ann. Geofis., **40**, 587-610.

Anzidei M., Baldi P., Casula G., Riguzzi F. and Surace L.; 1995a: *La Rete Tyrgeonet*. Boll. Geod. Sci. Affini, Spec. Suppl., **54**, 2, 115 pp.

Anzidei M., Baldi P., Casula G., Riguzzi F. and Zanutta A.; 1995b: *GEOMODAP project GPS network*. Istituto Nazionale di Geofisica, Roma, Italy, Pubb. Num. **570**, 71 pp.

Argus D.F. and Gordon R.G.; 1991: *No-Net Rotation model of current plate velocities incorporating plate rotation model NUVEL-1*. Geophys. Res. Lett., **18**, 2039-2042.

Babbucci D., Tamburelli C., Mantovani E. and Albarello D.; 1997: *Tentative list of major deformation events in the Central-Eastern Mediterranean region since the middle Miocene*. Ann. Geofis., **40**, 645-669.

Baldi P., Drewes H., Reigberg Ch., Zerbini S. and Achilli V.; 1988: *Combined terrestrial and space techniques in the Calabrian Arc Project*. Bulletin of International Coordination of Space Techniques for Geodesy and Geodynamics, **10**, 115-120.

Baldi P. and Marson I.; 1981: *Gravity and geodetic network for the study of crustal deformation in seismic area (Ancona)*. Boll. Geod. Sci. Affini, **40**, 189-196.

Bassi, G. and Sabadini R.; 1994: *The importance of subduction for the modern stress field in the Tyrrhenian area*. Geophys. Res. Lett., **21**, 329-332.

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

Blewitt G., Bock Y. and Gendt G.; 1993: *Regional clusters and distributed processing*. In: Kouba J. (ed), Proc. of the IGS Analysis Center Workshop, Int. Assoc. of Geodesy, Ottawa, Canada, pp. 61-92.

Boccaletti M. and Dainelli P.; 1982: *Il sistema reumatico neogenico-quaternario nell'area Mediterranea: esempi di deformazione plastico-rigida post collisionale*. Mem. Soc. Geol. It., **24**, 465-482.

Bock Y., Gourevitch S.A., Counselman C.C., King R.W. and Abbot R.I.; 1986: *Interferometric analysis of GPS phase observation*. Manuscripta Geodaetica, **11**, 282-288.

Bock Y., Wdowinski S., Fang P., Zhang J., Williams S., Johnson H., Behr J., Genrich J., Dean J., van Domselaar M., Agnew D., Wyatt F., Stark K., Oral B., Hudnut K., King R., Herring T., Dinardo S., Young W., Jackson D. and Gurtner W.; 1997: *Southern California permanent GPS geodetic array: continuous measurements of crustal deformation between the 1992 Landers and 1994 Northridge earthquakes*. J. Geophys. Res., **102**, 18,013-18,033.

Cianetti S., Gasperini P., Boccaletti M. and Giunchi C.; 1997: *Reproducing the velocity and stress fields in the Aegean region*. Geophys. Res. Lett., **24**, 2087-2090.

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

Dewey J.F., Pitman W.C., Ryan W.B.F. and Bormin J.; 1973: *Plate tectonics and the evolution of the Alpine system*. Geol. Soc. Am. Bull., **84**, 3137-3180.

Dewey J.F., Helman M.L., Turco E., Hutton D.H.W. and Knott S.D.; 1989: *Kinematics of the western Mediterranean*. In: Coward M.P. and Dietrich D. (eds), Alpine Tectonics, Geol. Soc. Spec. Pubbl., **45**, 265-283.

Dong D.; 1993: *The horizontal velocity field in southern California from a com-bination of terrestrial and space-geodetic data*. PhD Thesis, Mass. Ins. of Tech., Cambridge, 59 pp.

Dong D. and Bock Y.; 1989: *Global positioning system network analysis with phase ambiguity resolution applied to crustal deformation studies in California*. J. Geophys. Res., **94**, 3949-3966.

Dong D., Herring T.A. and King R.W.; 1998: *Estimating regional deformation from a combination of space and terrestrial geodetic data*. Jour. of Geod., **72**, 200-214.

Ekström G. and England P.; 1989: *Seismic strain rates in regions of distributed continental deformation*. J. Geophys. Res., **94**, 231-257.

Faccenna C., Davy P., Brun J.P., Funiciello R., Giardini D., Mattei M. and Nalpas T.; 1996: *The dynamics of back-arc extension: an experimental ap-proach to the opening of the Tyrrhenian sea*. Geophys. J. Int., **126**, 781-795.

Feigl K.L., Agnew D.C., Bock Y., Dong D., Donnellan A., Hager B.H., Herring T.A., Jackson D.D., Jordan T.H., King B.W., Larsen S., Larson K.M., Murray M.H., Shen Z.K. and Webb F.H.; 1993: *Space geodetic measurements of crustal deformation in central and southern California, 1984-1992*. J. Geophys. Res., **98**, 21,677-21,712.

Finetti I. and Del Ben A.; 1986: *Geophysical study of the Tyrrhenian opening*. Boll. Geof. Teor. Appl., **110**, 75-156.

Frepoli A. and Amato A.; 2000: *Fault plane solutions of crustal earthquakes in Southern Italy (1988-1995): seismotectonic implications*. Ann. Geofis., **43**, 437-467.

Hatzfeld D., Martinod J. and Bastet G.; 1997: *An analog experiment for the Aegean to describe the contribution of gravitational potential energy*. J. Geophys. Res, **102**, 649-659.

Herring T.A.; 2000: GLOBK: *Global Kalman filter VLBI and GPS analysis pro-gram, version 10.0*. Mass. Ins. of Tech., Cambridge, 98 pp.

Hippolyte J.C., Angelier J. and Barrier E.; 1995: *Compressional and extensional tectonics in an arc system: example of the southern Apennines*. J. Struct. Geol., **17**, 1725-1740.

Hippolyte J.C., Angelier J. and Roure F.; 1994: *A major geodynamic change revealed by Quaternary stress patterns in the southern Appennines (Italy)*. Tectonophysics, **240**, 199-210.

Jackson J. and McKenzie D.; 1988: *The relationship between plate motions and seismic moment tensors, and the rates of active deformation in the Mediterranean and Middle East*. Geophys. J., **93**, 45-73.

Kagan Y.Y.; 2002: *Seismic moment distribution revisited: II. Moment conservation principle*. Geophys. J. Int., **149**, 731-754.

Kahle H.G., Cocard M., Peter Y., Geiger A., Reilinger R., Barka A. and Veis G.; 2000: *GPS-derived strain rate field within the boundary zones of the Eurasian, African, and Arabian plates*. J. Geophys. Res., **105**, 23,353-23,370.

Khale H.G., Muller M.V., Mueller S. and Veis G.; 1993: *The Kheohalonia transform faul and rotation of the Apulian platform: evidence from satellite geodesy.* Geophys. Res. Lett., **20**, 651-654.

King R.W. and Bock Y.; 2000: *Documentation for the GAMIT GPS analysis software, version 10.01*. Mass. Ins. of Tech. and Scripps Institution of Oceanography, 203 pp.

Kiratzi A.; 1994: *Active seismic deformation in the peninsula and Sicily.* Ann. Geof., **37**, 27-35.

Kostrov V.V.; 1974: *Seismic moment and energy of earthquakes, and seismic flow of rocks*. Izv. Earth Phys., **1**, 23-40.

Le Pichon X. and Angelier J.; 1979: *The Hellenic Arc and trench system: a key to the neotectonic evolution of the eastern Mediterranean area*. Tectonophysics, **60**, 1-42.

Lucente F.P., Chiarabba C., Cimini G.B. and Giardini D.; 1999: *Tomographic constraints on the geodynamic evolution of the Italian region*. J. Geophys. Res., **104**, 20,307-20,327.

Malinverno A. and Ryan W.B.F.; 1986: *Extension in the Tyrrhenian Sea and shortening in the Apennines as results of arc migration driver by sinking of the lithosphere*. Tectonics, **5**, 227-245.

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

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

Mao A., Harrison C.G.A. and Dixon T.H.; 1999: *Noise in GPS coordinate time series*. J. Geophys. Res. **104**, 2797-2816.

McClusky S., Balassian S., Barka A., Demir C., Georgiev I., Hamburger M., Hurst K., Kahle H.G., Kastens K., Kekelidze G., King R., Kotzev V., Lenk O., Mahmoud S., Mishin A., Nadariya M., Ouzounis A., Paradissis D., Peter Y., Prilepin M., Reilinger R., Sanli I., Seeger H., Tealeb A., Tokzoz M. and Veis G.; 2000: *GPS constraints on plate kinematics and dynamics in the eastern Mediterranean and Caucasus*. J. Geophys. Res., **105**, 5695-5719.

Meijer P.Th. and Wortel M.J.R.; 1997: *Present-day dynamics of the Aegean region: a model analysis of the horizontal pattern of stress and deformation*. Tectonics, **16**, 879-895.

Minster J.B. and Jordan T.H.; 1978: *Present-day plate motions*. J. Geophys. Res., **83**, 5331-5354.

Montone P., Amato A. and Pondrelli S.; 1999: *Active stress map of Italy.* J. Geophys. Res., **104**, 25,595-25,610.

Müller B., Zoback M.L., Fuchs K., Mastin L., Gregersen S., Pavoni N., Stephansson O. and Ljunggren C.; 1992: *Regional patterns of tectonic stress in Europe*. J. Geophys. Res., **97**, 11,783-11,803.

Nunnari G. and Puglisi G.; 1990: *Risultati della campagna di misure GPS 1990 nell'area etnea*. In: Atti IX Convegno GNGTS, Esagrafica, Roma, pp. 251-263.

Oral M.B.; 1994: *Global Positioning System (GPS) measurements in Turkey (1988-1992): kinematics of the Africa-Arabia-Eurasia plate collision zone*. PhD thesis, Mass. Ins. of Tech., Cambridge, 115 pp.

Papazachos C.B. and Kiratzi A.A.; 1996: *A detailed study of the active crustal deformation in the Aegean and surrounding area*. Tectonophysics, **253**, 129-153.

Piromallo C. and Morelli A.; 1997: *Imaging the Mediterranean upper mantle by P-wave travel time tomography.* Ann. Geofis., **40**, 963-979.

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

Pondrelli S., Morelli A., Ekström G., Mazza S., Boschi E. and Dziewonski A.M.; 2002: *European-Mediterranean regional centroid-moment tensors: 1997-2000*. Phys. Earth Planet. Int., **130**, 71-101.

Rebaï S., Philip H. and Taboada A.; 1992: *Modern tectonic stress field in the Mediterranean region: evidence for variation in stress directions at different scale*. Geophys. J. Int., **110**, 106-141.

Rothacher M. and Mader G.; 1996: *Combination of antenna phase center offsets and variations: antenna calibration set IGS_01*. Anonymous ftp ubeclu.unibe.ch, June, 1996.

Royden L.H.; 1993: *Evolution of retreating subduction boundaries formed during continental collision*. Tectonics, **12**, 629-638.

Saastamoinen J.; 1972: *Atmospheric correction for the troposphere and stratosphere in radio ranging of satellites*. In: Henriksen S.W. (ed), The use of Artificial Satellites for Geodesy. Geophys. Monogr. Ser. 15, AGU, Washington DC, pp. 247-251.

Savage J.C. and Simpson R.W.; 1997: *Surface strain accumulation and the seismic moment tensor*. Bull. Seism. Soc. Amer., **87**, 1345-1353.

Schaffrin B. and Bock Y.; 1988: *A unified scheme for processing GPS phase observations*. Bull. Géod., **62**, 142-160.

Selvaggi G.; 1998: *Spatial distribution of horizontal seismic strain in the Apennines from historical earthquakes*. Ann. Geofis., **41**, 241-251.

Serpelloni E.; 2002: *Utilizzo di misure GPS per lo studio delle deformazioni crostali nell'area del Mediterraneo*. PhD thesis, University of Bologna, 257 pp.

Serpelloni E., Anzidei M., Baldi P., Casula G., Galvani A., Pesci A. and Riguzzi F.; 2001: *Geodetic deformations in the Central-Southern Apennines (Italy) from repeated GPS surveys*. Ann. Geofis., **44**, 627-647.

Shen Z.K., Jackson D.D. and Ge B.X.; 1996: *Crustal deformation across and be-yond the Los Angeles basin from geodetic measurements*. J. Geophys. Res., **101**, 27,957-27,980.

Shen Z.K., Zhao C., Yin A., Li Y., Jackson D.D., Fang P. and Dong D.; 2000: *Contemporary crustal deformation in east Asia constrained by Global Positioning System measurements*. J. Geophys. Res., **105**, 5721-5734.

Spakman W.S., Van Der Lee S. and Van Der Hilst R.; 1993: *Travel-time tomography of the European-Mediterranean mantle down to 1400 km*. Physics Earth Planet. Inter., **79**, 3-74.

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

Tapponier P.; 1977: *Evolution tectonique du système alpin en Méditerranée: poinconnements et écrasement rigide-plastique*. Bull. Soc. Geol. Fr., **7**, 437-460.

Valensise G. and Pantosti D.; 2001: *The investigation of potential earthquake sources in peninsular Italy: a review*. J. of Seismology, **5**, 287-306.

Vespe F., Bianco G., Fermi M., Ferraro C., Nardi A. and Sciarretta C.; 1999: *The Italian GPS Fiducial Network: services and products*. J. Geod., **30**, 327-336.

Viti M., Albarello D. and Mantovani E.; 2001: *Classification of seismic strain estimates in the Mediterranean region from a bootstrap approach*. Geoph. J. Int., **146**, 399-415.

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

Wessel P. and Smith W.H.F.; 2001: *The Generic Mapping Tools (GMT) version 3.4*. Technical Reference and Cookbook, SOEST/NOAA, 112 pp.

Westaway R.; 1992: *Seismic moment summation for historical earthquakes in Italy: tectonic implications*. J. Geophys. Res., **97**, 15,437-15,464.

Zhang J.; 1996: *Continuous GPS measurements of crustal deformation in southern California*. PhD thesis, University of California, San Diego, 110 pp.

Zhang J., Bock Y., Johnson H., Fang P., Williams S., Genrldi Y., Wolowinski S. and Bour Y.; 1997: *Southern California permanent GPS geodetic array: error analysis of daily position estimates and site velocities*. J. Geophys. Res., **102**, 18,035-18,055.

Zoback M.L.; 1992: *First and second order patterns of stress in the lithosphere: the World Stress Map Project*. J. Geophys. Res., **97**, 11,703-11,728.