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Geodetic and seismological investigation in the Ionian area

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Abstract
Geodetic and seismic evidence of crustal deformations in the Ionian area are shown in this paper. The Ionian GPS network, composed of nine sites crossing the Ionian Sea from Calabria, Southern Italy, to Northwestern Greece, was established and surveyed in 1991, 1994, 1995 within the framework of the TYRGEONET project (Anzidei *et al.*, 1996). In 1996 a return campaign was carried out after the occurrence of seismic activity in 1995. The displacement pattern obtained for the Greek side of the network agrees well with those previously displayed, both in magnitude and direction, confirming a mean displacement rate of about 1-2 cm/yr. The same agreement is not found for the Italian side of the network, where no significant deformations were detected between 1994 and 1996. Seismic deformation was also studied for the same area, starting from the moment tensors of events which occurred in the last 20 years with magnitude greater than 5.0; evident similarity with the displacement field exhibited by the Greek side of the Ionian Sea by geodetic surveys was inferred. On the contrary, the motion detected for the Italian area cannot be simply related to seismic activity.

Key words *GPS – crustal deformations – seismicity – Ionian Sea*

1. Introduction

The Tyrrhenian-Apennines tectonic system, controlled by the collision process between the African and Eurasian plates and by the west-dipping subduction of the Adriatic-Ionian lithosphere, is one of the most complex structures of the whole Mediterranean basin. For this area geodynamical models based on geological and geophysical observations (Argus *et al.*, 1989; DeMets *et al.*, 1992) give a general view of the estimated crustal dynamics of the structures involved and provide a mean relative velocity of about 1 cm/yr. More recently a contribution to the definition of the deformation processes at local and regional scales has been by geodetic surveys carried out by terrestrial and space techniques (Billiris *et al.*, 1991; Stiros, 1993; Kahle *et al.*, 1993; Robbins *et al.*, 1993; Smith *et al.*, 1994; Noomen *et al.*, 1996; Anzidei *et al.*, 1996); in this context the Eurasia-Africa convergence was estimated at a rate of about 6-8 mm/yr (Noomen *et al.*, 1996).

In the Ionian area, a north-south extension of the Gulf of Corinth (1-2 cm/yr) (Rigo *et al.*, 1992) and two different displacement fields separated by the right lateral tectonic style of the Kephalonia fault system (fig. 1) was evidenced by many geophysical and geodetic

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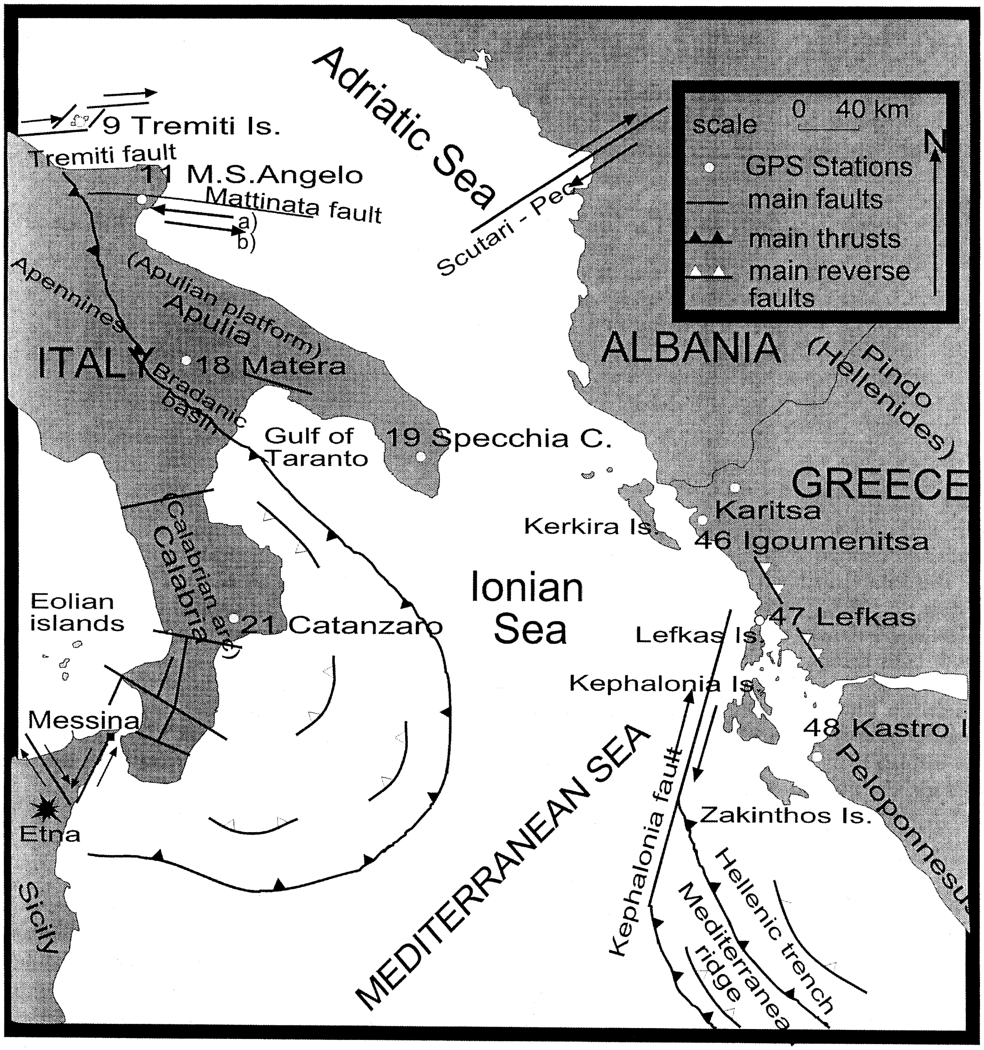

Fig. 1. Map of the area under investigation with the main tectonic structures. The two different vector directions (a and b) of the Mattinata fault are derived from different interpretations given for the first by Gasparini *et al.* (1980), Finetti (1982) and Underhill (1989) and for the second by Favali *et al.* (1993); (after Anzidei *et al.*, 1996).

investigations (Finetti, 1982; Scordilis, 1985; Kiratzi and Langston, 1991; Kahle *et al.*, 1993).

The Ionian area was also studied by three GPS campaigns carried out in 1991, 1994 and 1995 on a network consisting of nine sites from Calabria (Southern Italy) to Northwestern Greece (Anzidei *et al.*, 1996), in the framework of the TYRGEONET project (Achilli *et al.*, 1992).

The results obtained, extensively reported in Anzidei *et al.* (1996), show a displacement pattern for the Greek side of the Ionian area in agreement with the above-mentioned tectonic

Table I. General features of the GPS campaigns.

Network		1991		1994		1995		1996	
ID	Site	Period (day)	Session (hour)	Period (day)	Session (day)	Period (day)	Session (hour)	Period (day)	Session (day)
9	Tremiti	10	8	–	–	6	24	6	24
11	M.S. Angelo	10	8	4	12	6	24	6	24
18	Matera	10	8	8	24	6	24	6	24
19	Specchia	10	8	8	12	6	12	6	24
21	Catanzaro	10	8	7	12	6	24	6	24
46	Igoumenitsa	9	8	7	12	5	12	6	24
47	Lefkas	8	8	8	12	6	12	6	24
48	Kastro I.	8	8	8	24	6	24	6	24
51	Karitsa	–	–	6	12	6	24	6	24

features. Concerning the Italian side of the Ionian Sea area, geodetic evidence of a right lateral activity of the Mattinata fault (Northern Apulia, fig. 1) was assessed for the first time (Anzidei *et al.*, 1996) and the greatest displacement vector was found in the site of Specchia Cristi (Southern Apulia), leading to the hypothesis of a counterclockwise rotation of the Apulia with respect to the Adriatic plate, as already hypothesized by some authors (Finetti, 1982; Kahle *et al.*, 1993).

In 1996 a return GPS campaign was carried out on the same network to study the Ionian area again, after the occurrence of seismic activity in 1995 (table I).

The ING Seismological Bulletin reports seismic activity in the Gargano area ranging from the low level of 1991 (some earthquakes with low magnitudes) to the maximum level reached in September 1995 with an event of moderate magnitude (M_l = 4.6, September 30, 10.14 GMT). A higher level of seismic activity also occurred in the Ionian side of Greece (CMT Catalogue) in 1995.

In this paper the displacement field of the Ionian area from 1991 to date, after the 1996 GPS data processing, is discussed together with a study on seismic deformation based on the moment tensor summation method (Kostrov, 1974; Jackson and McKenzie, 1988).

2. GPS data processing and deformation analysis

The 1996 GPS data processing was performed by the Bernese software (v. 3.5, Rothacher *et al.*, 1993) following the criteria used in the data processing of the 1991, 1994 and 1995 campaigns (Anzidei *et al.*, 1996). In brief, the procedure can be summarized in: use of code pseudoranges to calibrate the receiver clocks with respect to GPS time; use of the satellite ephemerides provided by the International GPS Service (IGS) to define the standard orbits; limitation of the effects of tropospheric refraction by the use of the Saastamoinen standard model and by discarding all the observations having an elevation angle lower than 20° in order to reduce the atmospheric noise; single baseline initial processing by single, double and triple differences to re-

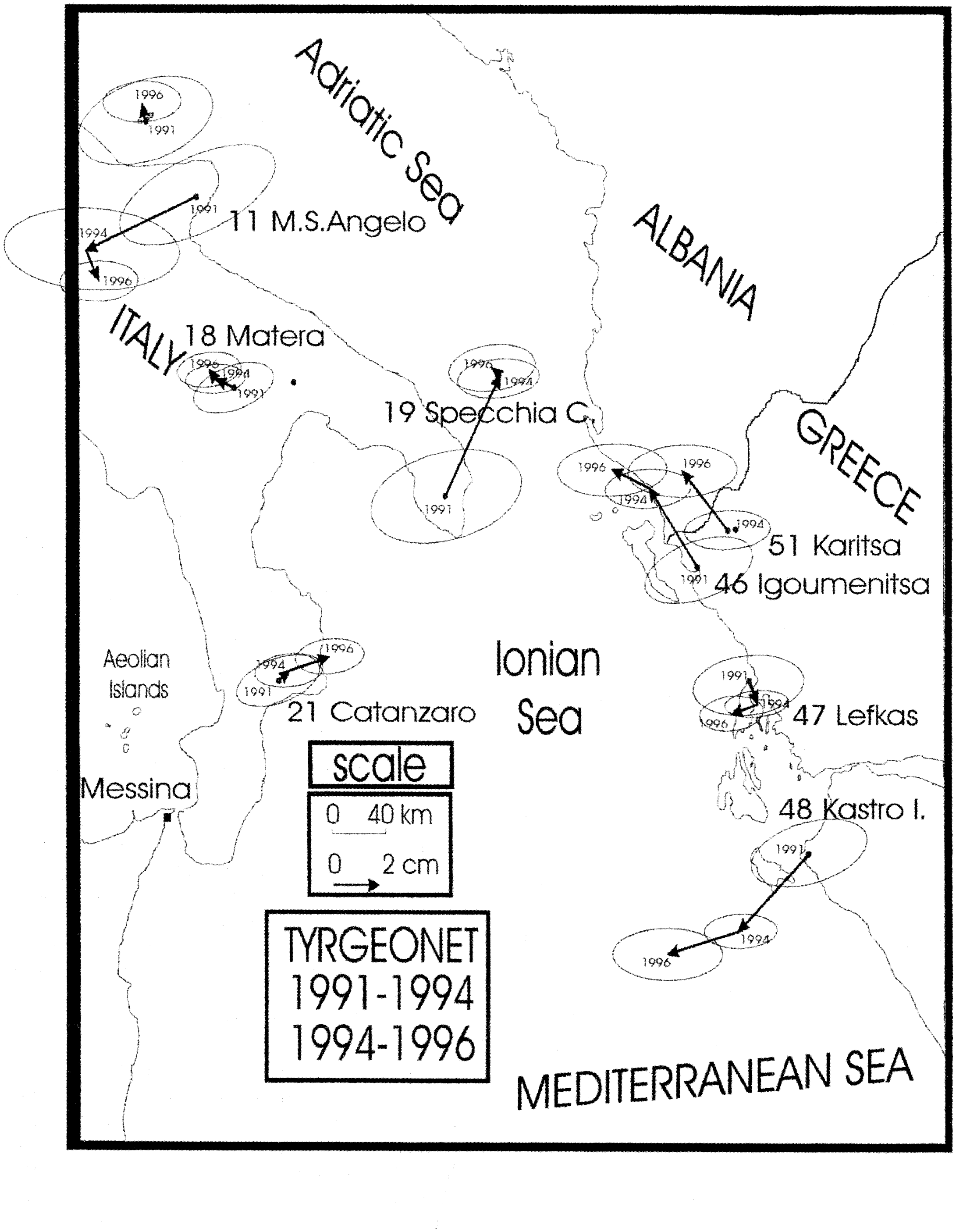

Fig. 2. Displacements vectors and error ellipses for the 1991-1994 and 1994-1996 comparisons.

move cycle slips and outliers from the data sets. Finally, a double difference multibaseline processing was performed to estimate parameters (coordinates with respect to one fixed points and phase ambiguities of each site) and covariance matrices. A set of independent baselines was computed for each day of measurements. All the baseline sets were adjusted to obtain the final set of 1996 coordinates with the corresponding covariance matrix. The adjustment was made by the software NETGPS, developed at DIIAR of Politecnico di Milano (Crespi and Sguerso, 1993), that allows a rigorous posterior statistical analysis based on complete parameter covariance matrix. The mean precision of the 1996 network results of the same order of magnitude of the 1994 and 1995 ones, ranging between 2.0 to 2.5 cm at a 95% confidence level (fig. 2) (Anzidei *et al.*, 1996). After the network adjustment a four-parameter conformal transformation among the four sets of coordinates was made to avoid any systematic effects due to possible differences in reference systems. The four parameters (scale and rotations) were estimated fixing the center of gravity of the networks and used to express the coordinates in a unique reference system defined by the 1996 ones, before the final statistical analysis.

The deformation analysis starts from the evaluation of the significance of the displacements (coordinate differences) of repeated surveys, with respect to the associated error ellipsoids, by an iterative procedure based on the F (Fisher) test (Crespi, 1996). This procedure allows for a separation of the points into two groups: those whose coordinate differences are significantly changed from those whose coordinates are not.

The test is based on the assumption that the observations (Cartesian components of the GPS baselines) and their differences $\delta x = x_2 - x_1$ are normally distributed. Starting from the null hypothesis

$$H_0 : x_2 = x_1,$$

it is possible to define a statistic that, if H_0 is true, follows a Fisher distribution (Koch, 1984):

$$\frac{\delta x^T Q_{\delta\delta}^{-1} \delta x}{m\sigma_0^2} = F_0 \sim F_{m,\,(r_1,\,r_2)} = F_t,$$

where $Q_{\delta\delta}$ is the cofactor matrix of the coordinate differences, (r_1, r_2) the redundancies of the two adjustments, m the number of the unknown parameters to be tested and:

$$\sigma_0 = \frac{r_1\,\sigma_{01}^2 + r_2\,\sigma_{02}^2}{r_1 + r_2}$$

with $(\sigma_{01}^2, \sigma_{02}^2)$ the variances of the unit weight of the two surveys compared.

If $F_0 \sim F_{m,\,(r_1,\,r_2)}$ the hypothesis H_0 is true, and then the coordinates do not show any significant differences at the chosen significance level; on the contrary, when the hypothesis H_0 is false, the coordinates are significantly changed.

The Fisher test results for the 1991, 1994, 1995 (Anzidei *et al.*, 1996) and 1996 (this paper) coordinates at 5% and 1% significance level are listed in table II.

As reported in Anzidei *et al.* (1996), the coordinate comparisons 1991-1994 and 1991-1995 showed significant differences in five sites (Tremiti, M.S. Angelo, Specchia, Igoumenitsa and Kastro) reaching the maximum value in Specchia (5 cm with 3 cm confidence interval at the 95% level) while most of the sites remain in the *datum* (set of stable points) in the comparison 1994-1995. Concerning the 1994-1996 comparison, the 5% significance level values are slightly different from those of the 1% one (table II). In any case, making the conservative choice (1% level) of Anzidei *et al.* (1996), only Igoumenitsa and Karitsa display significant coordinate differences. Figure 2 reports the displacement vectors and error ellipses (95% confidence level) for the 1991-1994 (Anzidei *et al.*, 1996) and 1994-1996 comparisons. Note that the displacements are referred to an intrinsic reference system, whose origin is placed at the cen-

Table II. Results of Fisher test at significance level of 5% and 1%. Flag (*) indicates the sites with $F > F_t$ for which the coordinate differences are significant.

Network		Experimental F-value	
Comparison	Site	$\alpha = 5\%$ $F_t = 2.64$	$\alpha = 1\%$ $F_t = 3.86$
1991-1994	Tremiti	–	–
	M.S. Angelo	3.27 *	3.27
	Matera	0.67	1.33
	Specchia	16.56 *	18.02 *
	Catanzaro	2.15	2.21
	Igoumenitsa	8.67 *	8.54 *
	Lefkas	1.55	1.94
	Kastro	9.25 *	7.54 *
	Karitsa	–	–
1991-1995	Tremiti	6.35 *	6.35 *
	M.S. Angelo	4.84 *	4.84 *
	Matera	0.80	0.80
	Specchia	11.61 *	11.61 *
	Catanzaro	1.33	1.33
	Igoumenitsa	11.42 *	11.42 *
	Lefkas	1.63	1.63
	Kastro	11.10 *	11.10 *
	Karitsa	–	–
1994-1995	Tremiti	–	–
	M.S. Angelo	6.35 *	8.00 *
	Matera	1.35	0.21
	Specchia	1.00	2.51
	Catanzaro	0.40	0.64
	Igoumenitsa	3.95 *	2.85
	Lefkas	2.45	1.91
	Kastro	1.66	3.64
	Karitsa	3.76 *	2.89
1994-1996	Tremiti	–	–
	M.S. Angelo	2.94 *	2.53
	Matera	0.37	2.20
	Specchia	0.11	1.33
	Catanzaro	1.27	2.37
	Igoumenitsa	3.55 *	6.15 *
	Lefkas	2.25	0.61
	Kastro	3.96 *	3.15
	Karitsa	5.93 *	8.34 *

ter of gravity of the *datum* defined by the sites of Matera, Catanzaro and Lefkas; vectors represent the relative behaviour of the points, and it is always possible to transform the displacement pattern with respect to any other fixed point only by a 3D translation (Crespi, 1996).

The deformation pattern exhibited by the Greek sites within the 1994-1996 analysis confirms the behaviour displayed in the 1991-1994 comparison (Anzidei *et al.*, 1996). The mean relative displacements of the Greek vertices are about of the same order of magnitude (1÷2 cm/yr) and the vector directions, changing clearly from the south (Kastro Ilias) to the north (Igoumenitsa), evidence the two tectonic domains defined by the presence of the Kephalonia fault system. Further, the site of Lekfas does not show any significant displacements either. Concerning the Italian sites of the network, the displacement pattern of the 1991-1994 analysis is not completely confirmed by the present comparison (1994-1996), apart from the sites of Matera and Catanzaro. The three Adriatic sites (Tremiti, M.S. Angelo and Specchia Cristi) do not show significant relative displacements, although an abrupt change of the vector direction of M.S. Angelo is evidenced. This deviation may be related to the higher seismic activity level (main shock on September 30 1995, $M_l = 4.6$, ING Seismological Bulletin) which occurred in this area between the 1995 and 1996 GPS campaigns, although the moderate magnitude of seismic events did not allow significant deformation detection.

3. Seismic deformation

An evaluation of the seismic deformation displayed by the Ionian area was carried out starting from seismological data extracted from the CMT Catalogue (Dziewonski *et al.*, 1983; all subsequent in P.E.P.I.). These data are the moment tensors of events which occurred between 1977 and 1996, with magnitudes greater than 5.0 and hypocentral depths lower than 33 km (focal mechanisms in fig. 3). Most of these events are concentrated in three areas along the eastern coast of the Adriatic Sea. In the Dinarides we find the first group, the second is around the Corinth Gulf and the third is along the Kephalonia fault. Within each group there is a certain homogeneity in seismic sources: in the first area compressive focal mechanisms prevail, in the Corinth Gulf seismic sources are mainly extensional, while along the Kephalonia fault strike slip and compressive sources are more frequent.

The moment tensor summation method (Kostrov, 1974; Jackson and McKenzie, 1988) was applied to these events for each seismogenetic area. It consists in the summation of the moment tensors of the great earthquake which occurred within a volume selected on the basis of seismicity distribution and tectonic setting. It may give different interesting information on the active deformation along a boundary zone, as the geometry of seismic deformation and an evaluation of the relative seismic velocity of plates. During the last 15 years, many studies have been proposed regarding calculations of seismic deformation (Jackson and McKenzie, 1988; Ekstrom and England, 1989; Papazachos and Kiratzi, 1992; Pondrelli *et al.*, 1995) and usually the results are compared with data of aseismic deformation computed by global plate motion or, mainly at present, obtained by geodetic measurements.

Figure 4 shows the total seismic moments obtained from each area. They confirm that in the northern zone a compressional tectonic prevails, in the second the extension is developing and the Kephalonia fault is characterized by a transpressive deformation. Comparing these results with geodetic measurements, we find an evident similarity between the direction of vectors of the eastern network and the directions of motion predictable from seismic data, mainly for the sites of Kastro, Karitsa and Igoumenitsa.

On the contrary, the deformation estimated for the Italian side of the network is difficult to relate to seismic activity, just because in this area the seismicity is lower during the same time interval and it is not so clustered. Even with events of smaller magnitude (*i.e.*, magnitude between 4.0 and 5.0, black dots of fig. 3) a stronger correlation is impossible. These

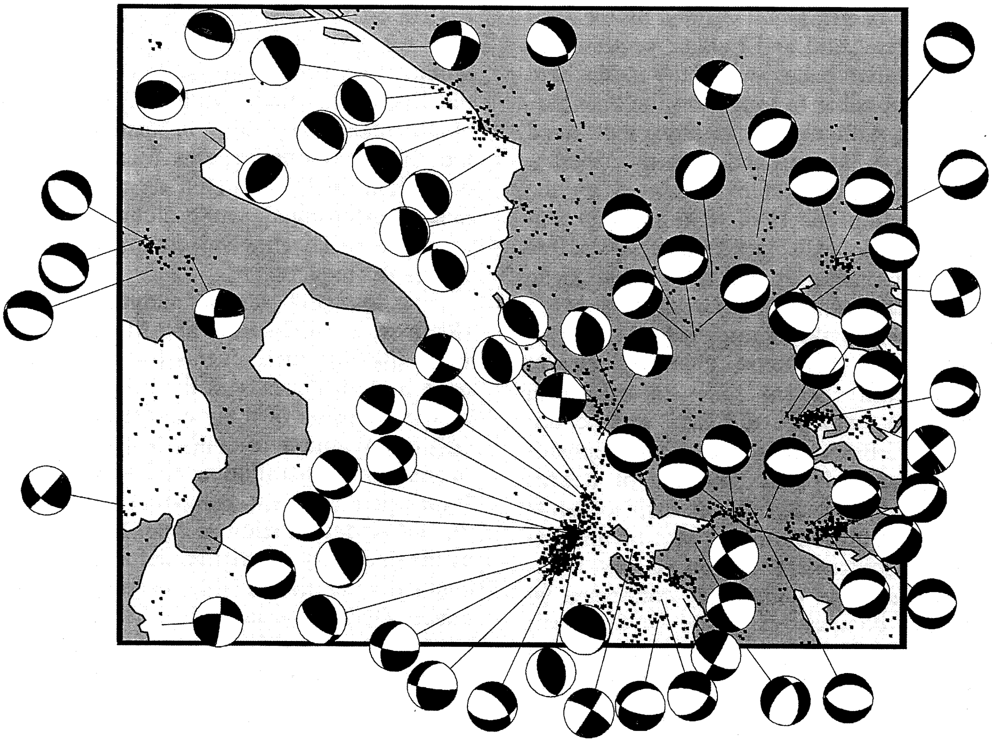

Fig. 3. Map of the seismic events of the Ionian area. Earthquakes which occurred between 1964 and 1996 with magnitudes ranging from 4.0 to 5.0 are represented by dots (I.S.C. and N.E.I.S. Catalogue). Focal mechanisms of the events which occurred between 1977 and 1996 with magnitudes greater than 5.0 and hypocentral depths lower than 33 km (CMT Catalogue) are also reported.

characteristics of the seismicity do not allow a seismic deformation representative of the regional stress field to be determined. From computations done to study larger areas of deformation in the Mediterranean Sea, for this zone a high rate of aseismic deformation is usually predicted, even reaching values greater than the 50% of the total amount (Jackson and McKenzie, 1988; Pondrelli *et al.*, 1995).

Furthermore, an evaluation of seismic velocity (the velocity of deformation deduced by seismicity) gives values that are clearly lower by at least an order of magnitude with respect to those obtained from geodetic measurements (fig. 4), even if seismic data refer to a data set 20 years long. This effect is not only due to the high rate of aseismic deformation of the Ionian area, but also to the fact that we are comparing values deduced by different methods. Seismic velocity is representative of an extensive area, where seismicity has occurred, while velocity vectors computed from geodetic measurements refer to the motion of one point. The comparisons of these different data may enhance the nature of the evaluated motion, underlining the presence and the importance of aseismic deformation.

4. Conclusions

The Ionian area GPS network was recently surveyed, after the occurrence of the 1995 seismic activity. The comparison between the old

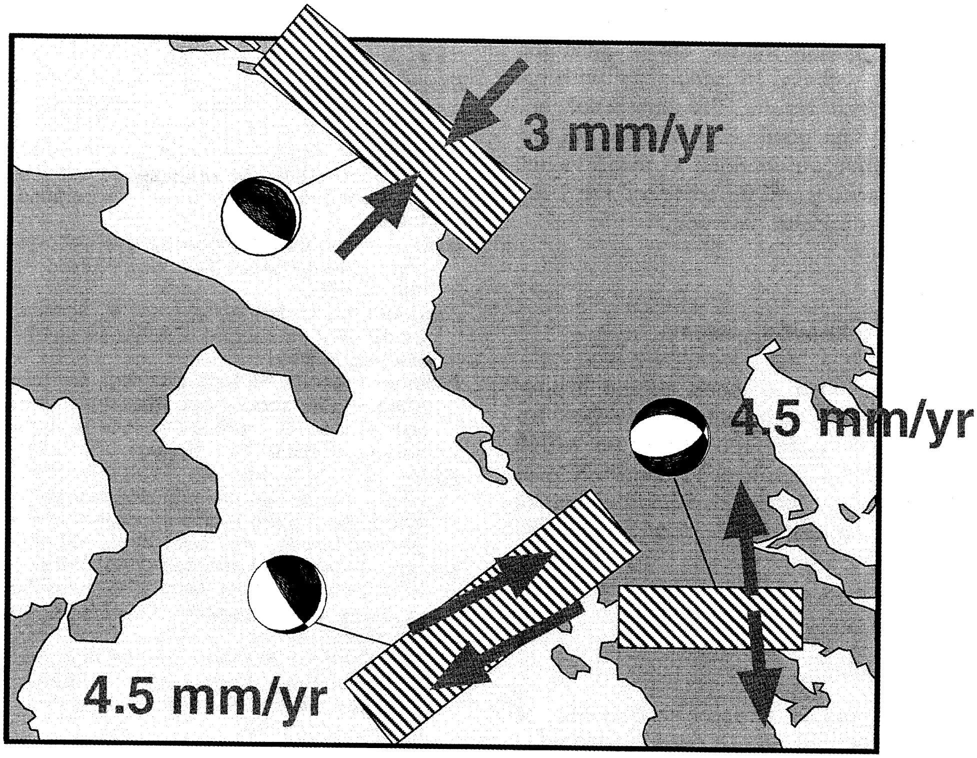

Fig. 4. Results of summation of moment tensors of great earthquakes. The area along the eastern coast of the Adriatic Sea exhibits a compressional seismic deformation, the Corinth Gulf is an area characterized by extensional seismic deformation and the Kephalonia fault shows a strike slip style moved by a transpressive regime. The seismic deformation styles agree with the main tectonic features recognized for this area.

coordinates of the 1991, 1994, 1995 surveys and the new ones of the 1996 survey was made following the criteria reported in Anzidei *et al.* (1996). The displacement pattern obtained for the Greek side of the network well agrees with those previously displayed, both in magnitude and direction, confirming a mean displacement rate of about 1-2 cm/yr. The same agreement was not found for the Italian side of the network where no significant deformations were detected between 1994 and 1996. The occurrence of moderate seismic activity in the Apulian area, may have changed the trend of the aseismic deformation found for the site of Specchia Cristi.

The comparison between the seismic deformation computed by the moment tensor summation method and the displacement pattern obtained by geodetic techniques shows a good similarity in the direction of motion for the Greek side of the network. The compressional regime that prevails in the eastern coast of the Adriatic Sea, the extension developing in the Corinth Gulf and the transpression which characterizes the Kephalonia fault are confirmed by the seismic data. On the contrary, the results obtained from the Italian side of the network do not have a definite correspondence with seismicity, leading us to hypothesize that most of the displacement observed in the site of Specchia Cristi from 1991 to 1995 has aseismic origin. This fact may be supported by the changes observed in the Apulian area after the occurrence of moderate seismic activity in 1995.

Concerning the difference observed in the magnitude of motion for the Greek area, the lower velocity deduced by seismicity with respect to geodetic results, the difference between seismic and geodetic data must be underlined: the first are obtained as mean values over a large area (some hundred of km^2) the second refer to a point network.

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