Active seismic deformation in the Italian peninsula and Sicily

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Abstract
Recent and historical seismicity as well as reliable fault plane solutions are used in order to perform a moment tensor analysis and estimate the active crustal and sub-crustal deformation of the Italian peninsula and Sicily. The results show that in Northern Italy, along the Alps, the deformation is taken up by compression at N162°E and a rate of 1 mm/yr. The thickening of the seismogenic layer is taking place at a rate of 0.1 mm/yr. In Central Italy, along the Apennines, extension is prevailing at N28°E and a rate of 3 mm/yr which causes thinning of the seismogenic layer at a rate 0.5 mm/yr. In Southern Italy, at Calabria, the deformation is taken up as extension at N40°E and a rate of 11 mm/yr. At the island of Sicily, compression is occurring at N25°E and a rate of 1 mm/yr. These results are in agreement with plate motion models for the area. The analysis of the deep seismicity of the Tyrrhenian Sea showed that the descending slab is in a state of down dip compression at N146°E and a rate of 2 mm/yr.

Key words *deformation – seismicity – Italy – Sicily – Tyrrhenian Sea*

1. Introduction

The Italian peninsula and Sicily (fig. 1), located at the center of the Mediterranean Sea between two compressive zones belonging to the African and the Eurasian plates, is a region of interest from the geodynamical point of view. The Alps in the north take up some of the northward convergence of the African and Eurasian plates. This rate of convergence is 8 mm/yr at Western Sicily, as it is predicted by plate motions (DeMets *et al.*, 1990).

Along the chain of the Apennines, which were formed mainly in Miocene time by thrusting, geological and geophysical evidence suggests that the tectonics are characterized by extensional features, related to both the opening of the Tyrrhenian Sea and the alkali-potassic volcanic activity (McKenzie, 1972; Mantovani and Boschi, 1983; Gasparini *et al.*, 1982, 1985; Westaway and Jackson, 1987).

The structural setting of Southern Italy is the result of complex geodynamic events which succeeded from late Tortonian up to the present (Patacca and Scandone, 1989). In the Calabrian arc, the tectonic setting is related to active volcanism and remnants of a northwest-dipping Benioff zone. This Benioff zone is part of a broader subduction zone active since Oligocene (30 Ma ago). Earthquakes as deep as 500 km are reported to occur in this area (McKenzie, 1972; Anderson and Jackson, 1987b among many others). The subduction rates range from 1.4 cm/yr to 2.5 cm/yr (McKenzie, 1972; LePichon *et al.*, 1973).

The present paper is intended to examine the active deformation of the Italian peninsula and Sicily, crustal and subcrustal, as it is deduced from seismicity and does not address the driving forces responsible for the motions. Opinions concerning the

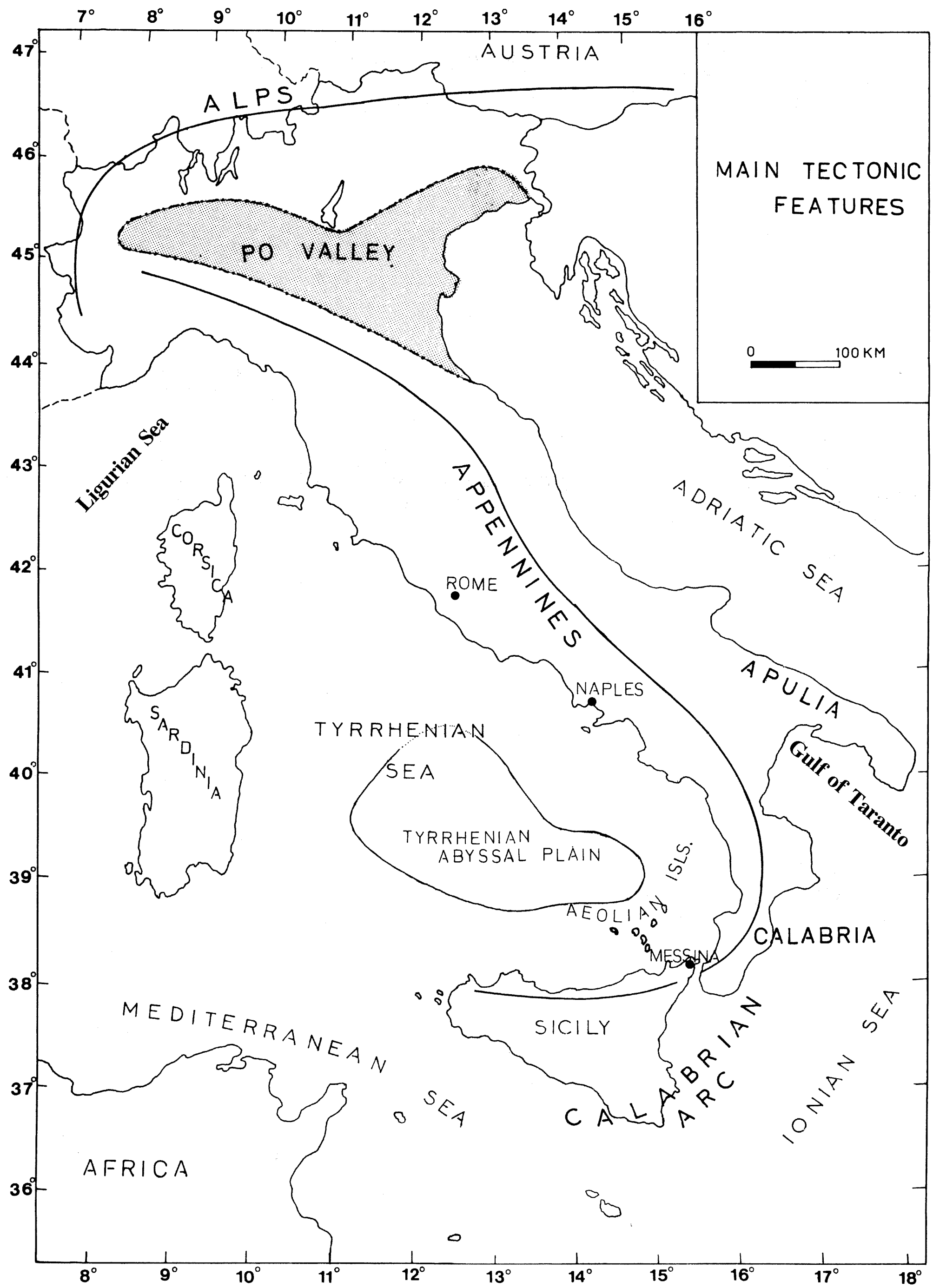

Fig. 1. Major tectonic features of the Italian peninsula and Sicily.

geodynamic processes involved in the broader Adriatic area are diverse and discussed extensively elsewhere in the literature. Previous studies concerning the tectonic pattern of the Adriatic area have been carried out by McKenzie (1972), Papazachos (1973), Gasparini *et al.* (1982, 1985); Anderson and Jackson (1987a,b), Jackson and McKenzie (1988), Westaway (1990, 1992), Cinque *et al.*, (1993) among others.

Actually, this study is part of a series of papers dealing with the active deformation of the Mediterranean area along the Africa-Eurasia plate boundary (Papazachos and Kiratzi, 1992; Papazachos *et al.*, 1992; Kiratzi, 1991, 1993).

2. Method of data analysis

The method of data analysis followed here is the one suggested by Papazachos and Kiratzi (1992), which is mainly based on Kostrov's (1974), Molnar's (1979) and Jackson and McKenzie's (1988) formulations. The main difference arises in how to make use of the historical and pre-1964 data, when the magnitudes of the earthquakes are reasonably well known but the focal mechanisms are not. One approach, used by others (*i.e* Jackson and McKenzie, 1988) is to assume a mechanism for these older events. The approach followed here is to use these older events only to estimate a scalar seismic moment rate and apply this to an average focal mechanism determined from the post-1964 earthquake population. For practical purposes, in places where there are adequate numbers of earthquakes the two methods produce much the same results. Where there are not many post-1964 earthquakes, however, we are forced to assume an average focal mechanism determined from post-1964 events. The reader will find a detailed description of the procedure in Papazachos and Kiratzi (1992), Papazachos *et al.* (1992) and Kiratzi (1993).

Briefly, the data analysis has been carried out as follows: first, the annual scalar moment rate, $\dot{M}_0$, is calculated for a region (Molnar, 1979),

$$\dot{M}_0 = \frac{A}{1 - B} \cdot M_{0,\max}^{(1-B)} \qquad (2.1)$$

where $M_{0,\max}$ is the moment of the largest ever observed earthquake of the region and

$$A = 10^{(a + \frac{bd}{c})} \quad \text{and} \quad B = \frac{b}{c} \qquad (2.2)$$

where a and b are the constants of the Gutenberg-Richter relation and c and d are the constants of the moment magnitude relation applicable to the area:

$$\log M_0 = cM + d \qquad (2.3)$$

Then the components of a «representative focal mechanism tensor», $\bar{\boldsymbol{F}}_{ij}$, for the area, are estimated, using the following relation:

$$\bar{\boldsymbol{F}}_{ij} = \frac{\sum_{n=1}^{N} M_0^n \boldsymbol{F}_{ij}^n}{\sum_{n=1}^{N} M_0^n} \qquad (2.4)$$

where $\boldsymbol{F}_{ij}^n$ is a function only of the strike, dip and rake of the focal mechanism of the nth earthquake (Aki and Richards, 1980), N is the number of all the focal mechanisms available, and M_0^n is the corresponding scalar moment of the nth focal mechanism. We see that the tensor, $\bar{\boldsymbol{F}}_{ij}$, is just a weighted M_0 average of the $\boldsymbol{F}_{ij}^n$ tensors.

Then the strain rate tensor and the velocity tensors are calculated using the corresponding relations as these are shown in the previously referenced papers.

Papazachos and Kiratzi (1992) performed a most detailed error analysis and found that a factor of 3 uncertainty is mapped on the estimated strain rate and velocity tensors.

3. The data

For the purposes of this paper, the Italian peninsula and Sicily have been separated in four relatively homogeneous sub regions (see fig. 2) in order to investigate the crustal deformation pattern. The deformation caused by the deep seismicity of the Tyrrhenian Sea is examined separately. Thus, as far as the crustal deformation is concerned, the areas examined separately are: a) the region of Northern Italy, which consists of the Alps and part of the Northern Apennines; b) the region of Central Italy, south of 43°N, along the Central Apennines; c) the region of Southern Apennines and Calabria, south of about 40.2°N and d) Sicily. This separation is mainly based on the distribution of the shallow seismicity, on the geological and tectonic features and on previous work (mainly Mantovani and Boschi, 1983). Moreover, the distribution of the fault plane solutions plays an important role in the separation of an area in different seismogenic volumes. From equation (2.4) it is clear that if all fault plane solutions within a region are identical, then the eigenvalues of $\boldsymbol{F}$ should be 1, 0 and -1. Hence, the deviation of the eigenvalues of $\boldsymbol{F}$ from these values is a measure of the similarity of the fault plane solutions (specifically, of the P, T and null axis) for the area. Thus, for the four seismogenic volumes chosen here the eigenvalues of the tensor $\boldsymbol{F}$ are as follows: a) 0.92, 0.25, -0.95 for Northern Italy; b) 0.98, -0.01, -0.97 for the Central part and Calabria and c) 0.76, -0.41, -0.82 for Sicily.

Two catalogues were compiled for the present paper. The first is a catalogue of all the earthquakes, both shallow and intermediate depth, that have occurred in the area of interest during 1870-1991. These data were used to determine the parameters a and b of the Gutenberg-Richter relation and to define the geometry of the deforming volumes. The second catalogue consists of the best fault plane solutions, preferably determined by waveform modeling, of recent (post 1964) earthquakes and their corresponding scalar seismic moments. These data were used to determine a moment-magnitude relation applicable to the area and to get the components of the tensor, $\bar{\boldsymbol{F}}_{ij}$.

Thus, all the earthquakes of shallow and intermediate focal depth that occurred in the Italian peninsula and Sicily over the period 1870-1991 were collected. The main source of information for the period 1901-1974 was the catalogue of Comninakis and Papazachos (1978). This catalogue was based on information given by Gutenberg and Richter (1954), Karnik (1969, 1971), Shebalin *et al.* (1974), as well as the ISS and ISC bulletins. For the period 1975-1991 the data were mainly collected from the regional bulletins of ISC. Other sources were used to enrich our data, especially with information on historical earthquakes. Thus, information from catalogues included in the work of Ambraseys (1976), Cagnetti and Pasquale (1979), Cipar (1980), Gasparini *et al.* (1982, 1985), Martini and Scarpa (1983), Mulargia and Boschi (1983), Anderson and Jackson (1987a,b), Console and Favali (1988), Jackson and McKenzie (1988), Margottini *et al.* (1991), were also used.

Plots of the variation of the seismicity rate with time for different magnitudes were used to determine the time periods of data completeness. Thus, as is shown in table I for the area of Northern Italy, for instance, the catalogue samples all earthquakes with $M \geq 6.8$ for the period 1873-1991, with $M \geq 6.0$ for the period 1900-1991, with $M \geq 5.5$ for 1910-1991 and with $M \geq 5.0$ for 1950-1991. Table I also lists other parameters that are used in the analysis, to be described later. The dimensions of each deforming volume, length and width, as well as the azimuth of each volume with the north, are determined from the seismicity distribution, in the way described by Papazachos and Kiratzi (1992).

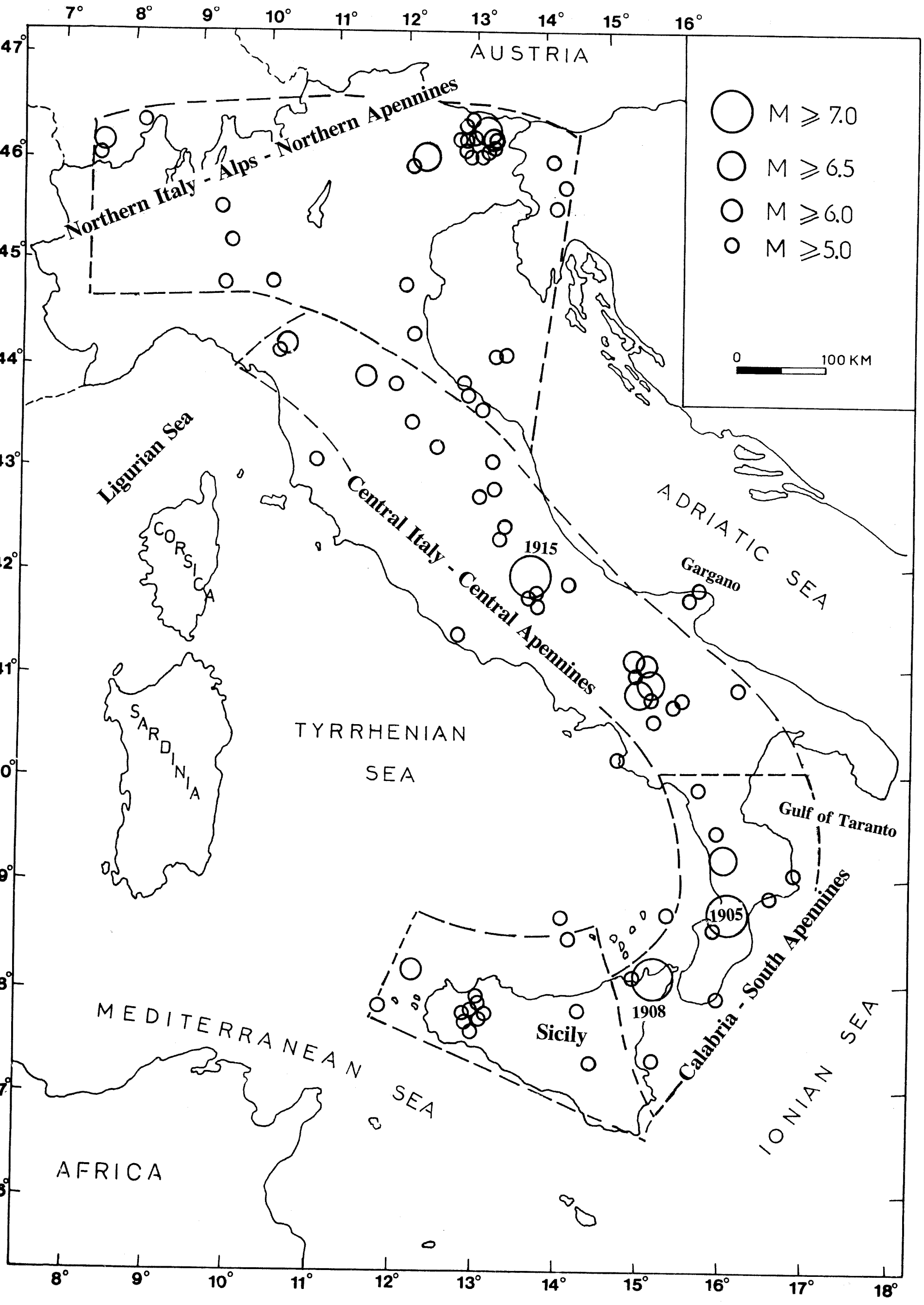

Fig. 2. Distribution of the shallow seismicity of the Italian peninsula and Sicily, for the period 1870-1991. The dashed lines include the four areas that are studied.

Table I. Information on the time period of data completeness for each region and on the seismicity parameters that were used in the present analysis.

T	M_{min}	M_{max}	Length (km)	Width (km)	Az^o	b	a(yr)	$\dot{M}_0$ dyn. cm/yr
				Northern Italy – Alps – Northern Apennines				
1873	≥6.8	6.8	500	180	76	1.13	5.61	$0.96*10^{25}$
1900	≥6.0							
1910	≥5.5							
1950	≥5.0							
				Central Italy – Central Appenines				
1873	≥6.0	7.1	550	100	145	0.90	4.28	$0.15*10^{26}$
1910	≥5.5							
1950	≥5.0							
				Calabria – Southern Apennines				
1870	≥6.0	7.3	300	100	40	0.75	3.06	$0.12*10^{26}$
1900	≥5.5							
1965	≥5.0							
				Sicily				
1870	≥6.0	6.0	230	90	40	0.75	3.05	$0.13*10^{25}$
1900	≥5.5							
1965	≥5.0							
				Deep seismicity – Tyrrhenian Sea				
1900	≥6.0	7.1	220	280	40	0.76	3.45	$0.19*10^{26}$
1925	≥5.5							
1950	≥5.0							
1970	≥4.5							

T: year since when the data are complete for a certain threshold magnitude, M_{min}, M_{max}: maximum magnitude ever observed; Az: azimuth of each deforming zone, in respect to north. The thickness of the seismogenic layer was assumed to be 15 km for the shallow seismicity and 50 km for the deep and intermediate depth seismicity of the Calabrian arc (Anderson and Jackson, 1987b); b, a: b-value and annual a-value of the Gutenberg-Richter relation, respectively; $\dot{M}_0$: seismic moment rate, shear modulus, $\mu = 3*10^{11}$ dyn./cm^2 and $\mu = 5*10^{11}$ dyn./cm^2 for crustal and mantle seismicity, respectively.

The thickness of the seismogenic layer for the crustal seismicity was assumed to be 15 km and for the mantle seismicity of the Tyrrhenian Sea was taken 50 km based on the work of Anderson and Jackson (1987b).

Figure 2 shows the distribution of the shallow seismicity for the Italian peninsula and Sicily and the limits of the seismogenic volumes that are studied. Figure 3 shows the distribution of the deep seismicity of the Tyrrhenian Sea. The complete data are shown in both figures, and different symbol sizes are used to denote different earthquake magnitudes.

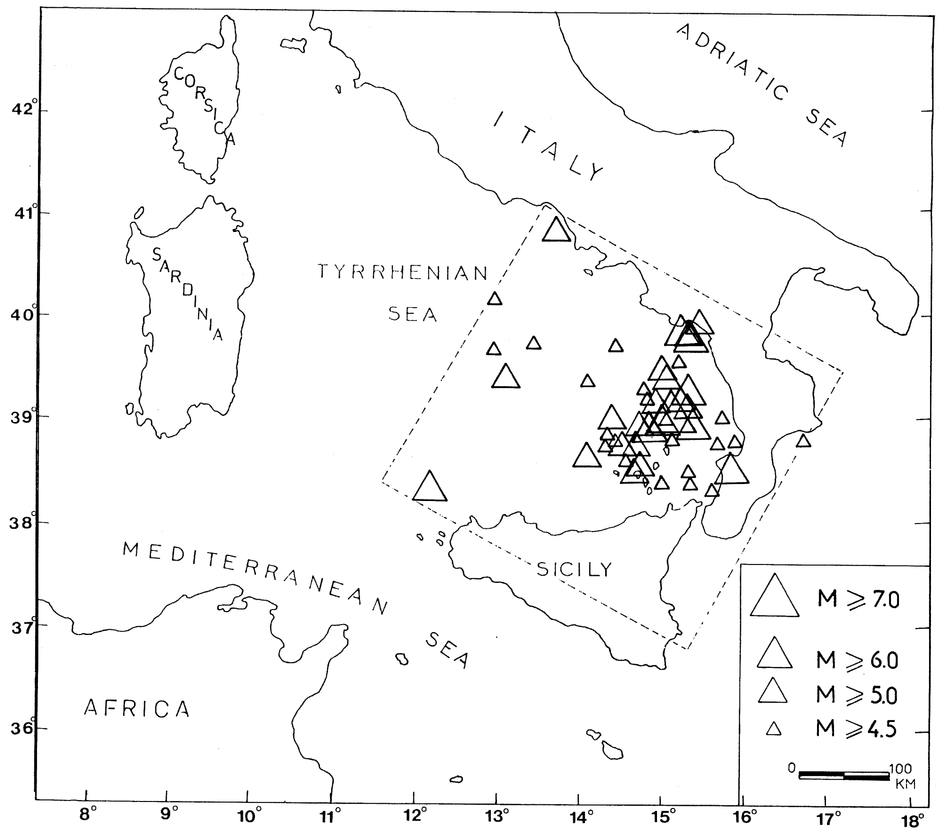

Fig. 3. Distribution of the deep and intermediate depth seismicity of the Tyrrhenian Sea for the period 1900-1991.

3.1. *The Gutenberg-Richter relation*

Figure 4 shows the Gutenberg-Richter relation determined for each area of study, using the corresponding complete data, for the period 1870-1991. It is seen that the *b*-value is higher in Northern Italy (1.13), decreases to 0.90 in Central Italy and becomes 0.75 in Calabria and Sicily. The *b*-value for the deep seismicity of the Calabrian arc is about the same (0.76) as in the shallow seismicity. The annual values of the *a*-value are also shown in the figure.

3.2. *The moment-magnitude relation*

In order to determine the moment-magnitude relation we assumed that the slope of the line equals 3/2, experimentally defined by Kanamori and Anderson (1975). Figure 5 shows the scalar moments and the magnitudes for both shallow and intermediate-depth earthquakes (listed in tables II and III), and the relation thus obtained is the following:

$$\text{Log } M_0 = 1.5\, M_s + 16.27 \qquad (3.1)$$

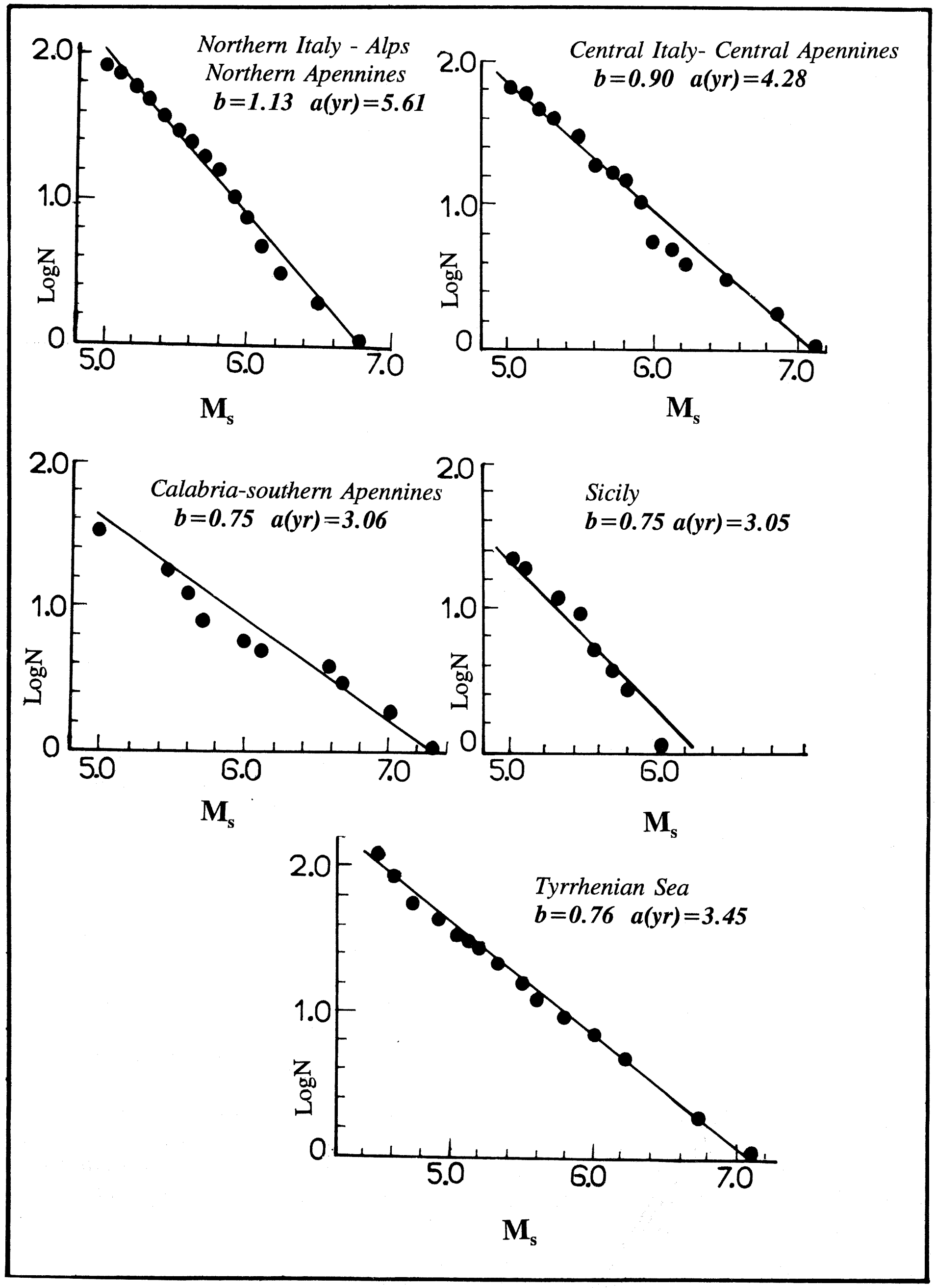

Fig. 4. The frequency-magnitude relation for: Northern Italy – Alps – Northern Apennines; Central Italy – Central Apennines; Calabria – Southern Apennines; Sicily and Tyrrhenian Sea (deep focus seismicity).

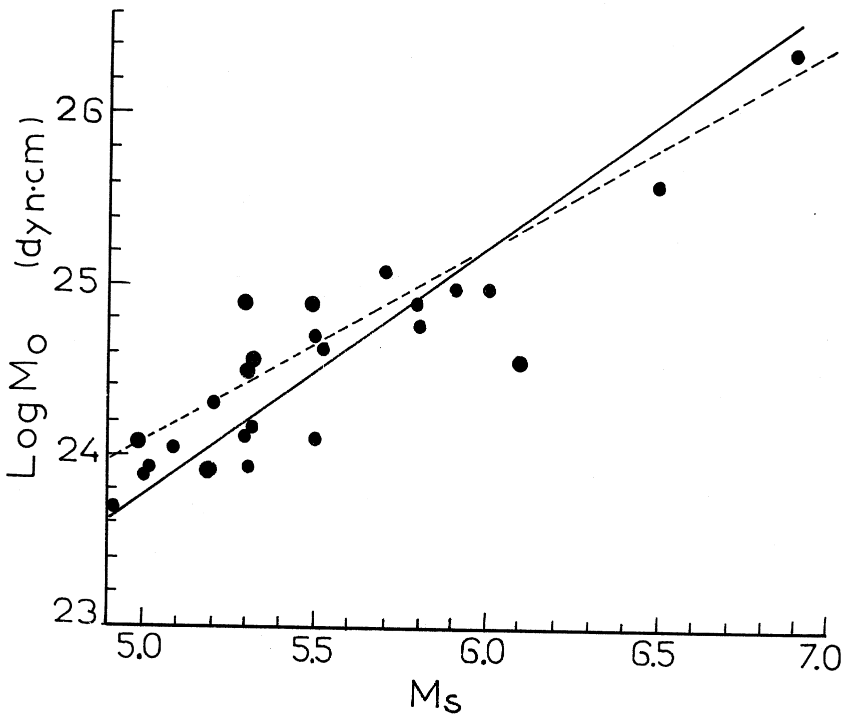

Fig. 5. The moment-magnitude relation applicable to the area of study, represented by the straight line. The dashed line represents the relation of Giardini *et al.* (1984) for the Mediterranean region. Seismic moments and magnitudes are listed in tables II and III.

The dashed line in this figure is the relation of Giardini *et al.* (1984) proposed for the shallow and deep seismicity of the Mediterranean area, and is shown for comparison.

3.3. *The fault plane solutions*

Tables II and III list the fault plane solutions and the scalar moments (determined independently by waveform analysis), of the shallow and deep earthquakes, respectively. The majority of these solutions are determined by waveform modelling. In general, we include those solutions that either showed the polarity data or (having magnitudes greater than 5.5) were examined using waveform analysis. Anderson and Jackson (1987a,b) have done a great deal of work as concerns the reliability of the focal mechanisms of the area and, in many cases, we adopted their solutions.

Figure 6 shows the fault plane solutions of the shallow earthquakes, while fig. 7 shows the focal mechanisms of eight deep earthquakes of the Tyrrhenian Sea. Equal area lower hemisphere projection of the focal sphere is used and the black quadrants denote compression.

4. Strain rates and deformation rates

As already mentioned, table I lists the parameters used in the data analysis for

Table II. Information on the seismic moments and on the focal mechanisms of the shallow earthquakes occurred at the Adriatic area.

N.	Date		Time	ϕ°N	λ°E	h(km)	M_s	M_0 (dyn. cm)	Strike°	Dip°	Rake°	Ref.
1	Dec.	12, 1908	04:20	38.10	15.35	10	7.0		208	55	−67	2
2	Aug.	21, 1962	18:09	41.00	15.00	8	5.6		310	65	−130	3
3	Aug.	21, 1962	18:19	41.02	15.02	8	6.1	$3.5 * 10^{24}$	310	65	−110	3
4	Jan.	15, 1968	02:01	37.75	12.98	10	5.8		270	50	35	2
5	Jan.	16, 1968	16:42	37.86	12.98	36	5.5		250	58	18	2
6	Jan.	25, 1968	09:56	37.69	12.97	3	5.5		270	64	31	2
7	July	15, 1971	01:33	44.78	10.34	8	5.2		250	84	132	2
8	May	6, 1976	20:00	46.25	13.24	8	6.5	$2.9 * 10^{25}$	76	75	90	1
9	Sept.	11, 1976	16:31	46.28	13.16	16	5.5		76	73	90	2
10	Sept.	11, 1976	16:35	46.30	13.20	20	5.4		91	80	90	2
11	Sept.	15, 1976	03:15	46.30	13.20	10	6.0	$1.0 * 10^{25}$	270	40	126	2
12	Sept.	15, 1976	09:21	46.32	13.13	17	5.9	$1.0 * 10^{25}$	56	67	70	1
13	Aug.	15, 1977	21:10	38.85	16.98	40	5.0	$8.2 * 10^{23}$				4
14	March	11, 1978	19:20	38.10	16.03	15	5.0	$8.4 * 10^{23}$				4
15	April	15, 1978	23:33	38.39	15.07	21	5.7	$1.39 * 10^{25}$	148	55	153	2
16	Sept.	19, 1979	21:35	42.81	13.06	16	5.8	$6.92 * 10^{24}$	212	55	−30	2
17	Dec.	8, 1979	04:06	38.28	11.74	15	5.3	$1.3 * 10^{24}$	254	56	136	2
18	May	28, 1980	19:51	38.48	14.25	12	5.5	$3.84 * 10^{24}$	278	37	130	2
19	Nov.	23, 1980	18:34	40.76	15.33	10	6.9	$2.43 * 10^{26}$	116	30	−108	2
20	Nov.	25, 1980	18:28	40.15	15.36	15	5.3	$1.5 * 10^{24}$	129	26	−65	4
21	Jan.	16, 1981	00:37	40.13	15.23	15	5.3	$8.5 * 10^{23}$	115	30	−93	4
22	Nov.	9, 1983	16:29	44.73	10.40	37	4.9	$4.5 * 10^{23}$	262	71	129	4
23	April	29, 1984	05:03	43.26	12.56	12	5.3	$3.4 * 10^{24}$	143	21	−72	4
24	May	7, 1984	17:49	41.77	13.90	10	5.8	$7.82 * 10^{24}$	312	66	−110	4
25	May	11, 1984	10:41	41.83	13.96	14	5.2	$2.03 * 10^{24}$	317	49	−103	4
26	April	26, 1988	00:53	42.37	16.61	8	5.5	$1.4 * 10^{24}$				5
27	May	5, 1990	07:21	40.73	15.86	5	5.5	$5.7 * 10^{24}$	184	73	13	5
28	Dec.	13, 1990	00:24	37.20	15.50	10	5.3	$3.3 * 10^{24}$				4

1: Cipar (1980); 2: Anderson and Jackson (1987a); 3: Westaway (1987); 4: centroid moment tensor solution; 5: ISC bulletins.

each area of study. In all cases the coordinate system 1 : North, 2 : East, 3 : Down, is used for the calculation of the strain rate and velocity tensors. The use of the terms extension and shortening rate in this paper refers to the corresponding horizontal component of the velocity vector.

Table IV summarizes the results on the deformation rates for each region which are discussed below.

4.1. *Crustal deformation*

a) *Northern Italy – Alps – Northern Apennines* – Seven fault plane solutions

Table III. Information on the seismic moments and on the focal mechanisms of the intermediate depth and deep earthquakes of the Tyrrhenian Sea.

N.	Date	Time	ϕ°N	λ°E	h(km)	M_s	M_0 (dyn. cm)	Strike°	Dip°	Rake°	Ref.
1	April 13, 1938	02:45	39.20	15.20	290	7.1		30	89	−74	2
2	Febr. 2, 1956	15:10	39.03	15.63	234	6.2		188	13	−115	1
3	Jan. 3, 1960	20:19	39.26	15.29	283	6.2		179	13	−99	1
4	Dec. 20, 1973	17:44	38.79	14.82	272	5.2		203	30	−117	3
5	June 28, 1977	07:12	38.63	14.71	261	5.1	$1.02*10^{24}$	175	44	−137	4
6	Dec. 30, 1977	18:08	40.00	15.42	283	5.5	$8.8*10^{24}$	304	19	−32	3
7	Dec. 27, 1978	17:46	41.11	13.58	390	5.3	$7.7*10^{24}$	192	73	32	3
8	March 21, 1984	01:12	39.42	15.23	281	5.2	$8.11*10^{23}$	227	90	69	5
9	Dec. 14, 1990	03:21	39.30	15.38	249	5.0	$1.1*10^{24}$	129	7	−107	6

1: Gasparini *et al.* (1982); 2: Martini and Scarpa (1983); 3: Anderson and Jackson (1987b); 4: Giardini *et al.* (1984); 5: Dziewonski *et al.* (1984); 6: centroid moment tensor solution.

were used in the analysis listed with numbers 7, 8, 9, 10, 11, 12 and 22 in table II. In the northeastern part, the fault plane solutions used in the analysis are derived from the 1976 Friuli sequence and are all well studied. In the northwestern part, along the Northern Apennines, there are only two solutions used, which show thrusting with a considerable strike-slip component. Actually, these events represent the only clear reverse faulting activity in the Northern Apennines. The magnitude of these events is small but, nevertheless, the focal mechanisms were determined by waveform modeling. The maximum magnitude for this region was taken equal to 6.8 (event of June 29, 1873). The seismic moment rate determined for this area is equal to $0.96*10^{25}$ dyn. cm/yr. The T axis of the «representative focal mechanism» of the area trends in an azimuth of 157° and plunges at a 63° angle. The P axis trends at an azimuth of 162° and plunges at a 26° angle.

As is seen from the results of table IV, the deformation in Northern Italy is expressed as compression at an azimuth of 162° and a rate of 1.3 mm/yr.

b) *Central Italy – Central Apennines* – Ten fault plane solutions were used in the analysis listed with numbers 2, 3, 16, 19, 20, 21, 23, 24, 25 and 27 in table II. These focal mechanisms indicate normal faulting in WNW-ESE striking planes following the trend of the Apenninic chain. The Irpinia event of 23 November 1980 is the most important and most damaging one (Del Pezzo *et al.*, 1983; Deschamps and King, 1983, Westaway and Jackson, 1984 among many others). The maximum magnitude for this region was taken equal to 7.1 (event of January 13, 1915). The seismic moment rate was found equal to $0.15*10^{26}$ dyn. cm/yr. The T axis of the «representative focal mechanism» for this region trends in an azimuth of 42° and plunges at a 17° angle. The P axis is nearly horizontal and trends at an azimuth of 42°.

It is clear (table IV) that deformation here is expressed as horizontal extension at an azimuth of 28° and a rate of 3.1 mm/yr. The thinning of the seismogenic layer is taking place at a rate of 0.5 mm/yr.

c) *Calabria – Southern Apennines* – Unfortunately in this region there were no fault plane solutions for any earthquake after 1964. The occurrence of the 1908 Messina earthquake and the normal faulting involved (see table II) dominates. This

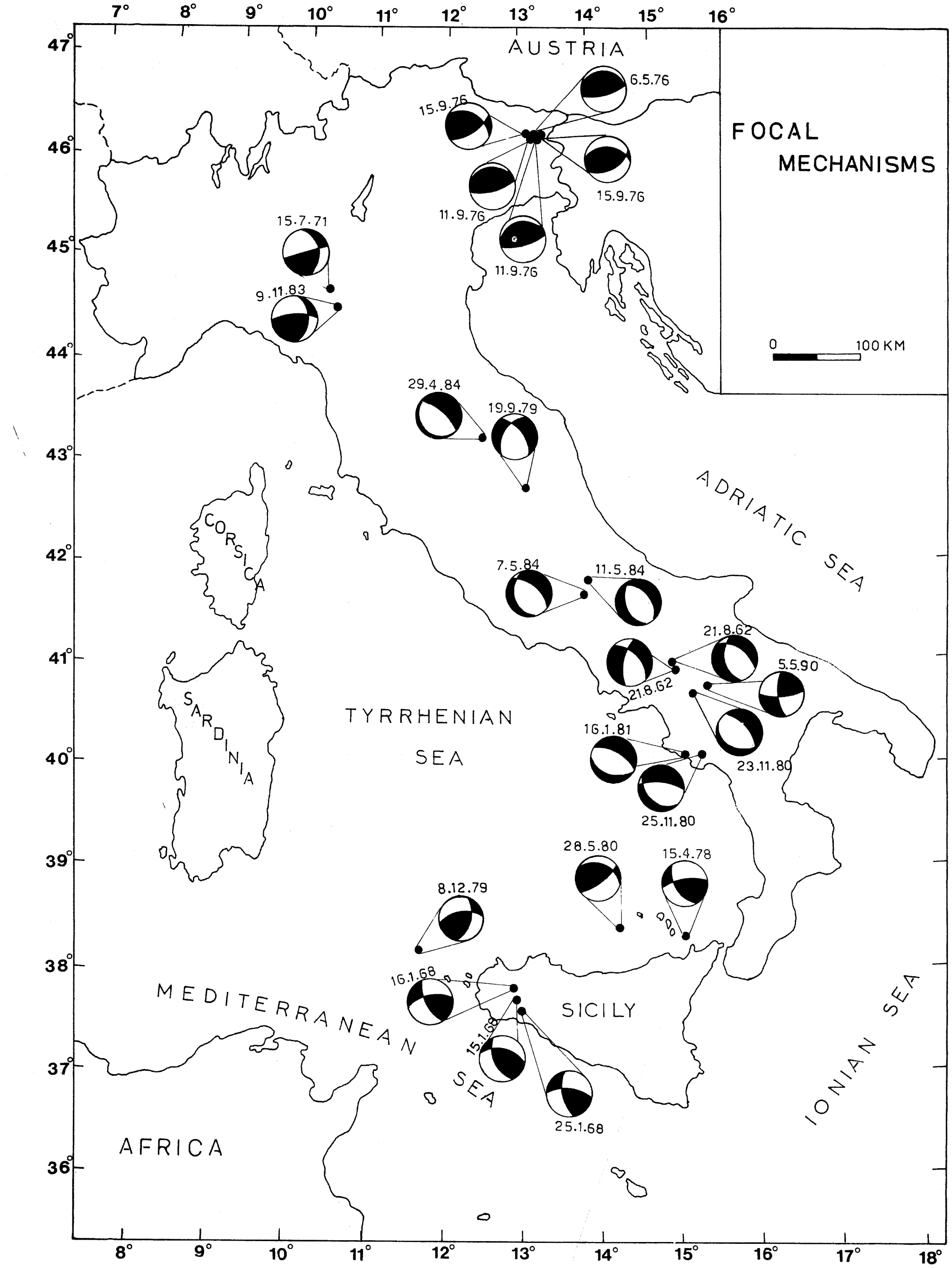

Fig. 6. Fault plane solutions of the shallow earthquakes of the Italian peninsula and Sicily as they are listed and referenced in table II.

Table IV. Components of the strain rate tensor, $\dot{\epsilon}_{ij}$ (in 10^{-8} yr^{-1}) and of the velocity tensor, v_{ij} (in mm/yr) for the Italian peninsula and Sicily.

Northern Italy – Alps – Northern Apennines

Strain rate tensor ($*10^{-8}$/yr)

$\dot{\epsilon}_{11}$	$\dot{\epsilon}_{12}$	$\dot{\epsilon}_{13}$	$\dot{\epsilon}_{22}$	$\dot{\epsilon}_{23}$	$\dot{\epsilon}_{33}$
−0.63	0.19	0.83	−0.02	−0.31	0.65

Velocity tensor (mm/yr)

v_{11}	v_{12}	v_{13}	v_{22}	v_{23}	v_{33}
−1.11	0.41	0.25	0.03	−0.09	0.98

Eigenvalues of the velocity tensor:

λ_i: (mm/yr)	Azimuth°	Plunge°
−1.29	162	11
0.17	77	−24
0.14	50	63

Central Italy – Central Apennines

Strain rate tensor ($*10^{-8}$/yr)

$\dot{\epsilon}_{11}$	$\dot{\epsilon}_{12}$	$\dot{\epsilon}_{13}$	$\dot{\epsilon}_{22}$	$\dot{\epsilon}_{23}$	$\dot{\epsilon}_{33}$
1.46	1.28	1.07	1.01	1.34	−2.47

Velocity tensor (mm/yr)

v_{11}	v_{12}	v_{13}	v_{22}	v_{23}	v_{33}
2.40	1.28	0.32	0.56	0.40	−0.37

Eigenvalues of the velocity tensor:

λ_i:(mm/yr)	Azimuth°	Plunge°
3.11	28	8
−0.53	102	−64
0.01	121	25

Calabria - Southern Apennines

Strain rate tensor ($*10^{-8}$/yr)

$\dot{\epsilon}_{11}$	$\dot{\epsilon}_{12}$	$\dot{\epsilon}_{13}$	$\dot{\epsilon}_{22}$	$\dot{\epsilon}_{23}$	$\dot{\epsilon}_{33}$
2.12	1.86	1.55	1.47	1.94	−3.59

Velocity tensor (mm/yr)

v_{11}	v_{12}	v_{13}	v_{22}	v_{23}	v_{33}
6.44	5.49	0.46	4.52	0.58	−0.54

Eigenvalues of the velocity tensor:

λ_i: (mm/yr)	Azimuth°	Plunge°
11.09	40	4
−0.63	117	−74
−0.05	131	16

Sicily

Strain rate tensor ($*10^{-8}$/yr)

$\dot{\epsilon}_{11}$	$\dot{\epsilon}_{12}$	$\dot{\epsilon}_{13}$	$\dot{\epsilon}_{22}$	$\dot{\epsilon}_{23}$	$\dot{\epsilon}_{33}$
−0.43	−0.28	−0.09	0.09	0.21	0.34

Velocity tensor (mm/yr)

v_{11}	v_{12}	v_{13}	v_{22}	v_{23}	v_{33}
−0.98	−0.56	−0.03	−0.02	0.06	0.05

Eigenvalues of the velocity tensor:

λ_i: (mm/yr)	Azimuth°	Plunge°
−1.23	25	−0
0.26	115	18
0.03	115	−72

Table IV. (*continued*) Components of the strain rate tensor, $\dot{\epsilon}_{ij}$ (in 10^{-8} yr^{-1}) and of the velocity tensor, v_{ij} (in mm/yr) for the Italian peninsula and Sicily.

Tyrrhenian Sea – descending slab

Strain rate tensor ($*10^{-8}$/yr)		$\dot{\epsilon}_{11}$	$\dot{\epsilon}_{12}$	$\dot{\epsilon}_{13}$	$\dot{\epsilon}_{22}$	$\dot{\epsilon}_{23}$	$\dot{\epsilon}_{33}$
		−0.18	0.24	−0.10	0.18	0.30	0.00
Velocity tensor (mm/yr)	v_{11}	v_{12}	v_{13}	v_{22}	v_{23}	v_{33}	
	−0.86	0.72	−0.58	−0.19	0.48	−0.37	
Eigenvalues of the velocity tensor:	λ_i: (mm/yr)	Azimuth°	Plunge°				
	−1.73	146	−29				
	0.29	65	15				
	0.02	180	57				

Positive eigenvalues represent dilatation (extension for the horizontal component of the velocity vector or thickening of the seismogenic layer for the vertical component of the velocity vector) while negative ones represent compression (shortening or thinning). Positive or negative plunge indicates that the eigenvector is directed into or out of the solid earth, respectively.

event, resembling the 1783 Calabrian event, caused many casualties, especially in the city of Messina, intensified by the tsunami that generated, and is the largest and most catastrophic earthquake in Italy of the last century. Its fault plane solution shows normal faulting in an almost NS trending plane. The event is obviously not related to any subduction process because thrust faulting would normally be expected. Even though the event was large and is considered as a shallow one there are no reports of surface faulting.

Since we did not have any fault plane solutions for the area and there was evidence of active normal faulting (Riuscetti and Schick, 1975), we assumed that the components of the tensor $\bar{F}_{ij}$ were the same as the ones of the extensional province in Central Italy, then we calculated the deformation rates for the corresponding seismogenic volume of Calabria. The maximum earthquake magnitude was taken equal to 7.3 (Pizzo Calabro event of September 8, 1905 in Southern Italy). Table IV shows that the area is dominated by extension at N40°E and a rate of 11.1 mm/yr. If we include the focal mechanism of the event of 1908 and put a weight equal to 1 to all the fault plane solutions (because if we normalize with the seismic moment the 1908 event would totally control the tensor $\boldsymbol{F}$), then the extension becomes at N53°E and the rate slightly reduces to 9 mm/yr.

The vertical component of the displacement field produced by the Messina earthquake of 1908 was recorded by colonel Loperfido, who finished a levelling campaign a few months before the earthquake and repeated the measurements right after it. Large vertical coseismic displacements were reported that reached a negative maximum (downlift) of 70 cm in Messina (from fig. 5 of Mulargia and Boschi, 1983). Actually, if we calculate the components of the seismic moment tensor of the Messina earthquake (using the fault plane solution of table II and scalar seismic moment $5.9*10^{26}$ dyn. cm) we simply see that the tensor is dominated by equal parts of E-W extension and negative vertical movement.

d) *Sicily* – Six fault plane solutions were used listed with numbers 4, 5, 6, 15, 17 and 18 in table II. The fault plane solutions in Western Sicily show thrusting with considerable strike slip motion in WNW-ESE oriented planes. Three of the fault plane solutions used are from the 1968 Belice earthquake sequence. There has been no earthquake greater than 6.0 in the present century, or ever reported in catalogues span-

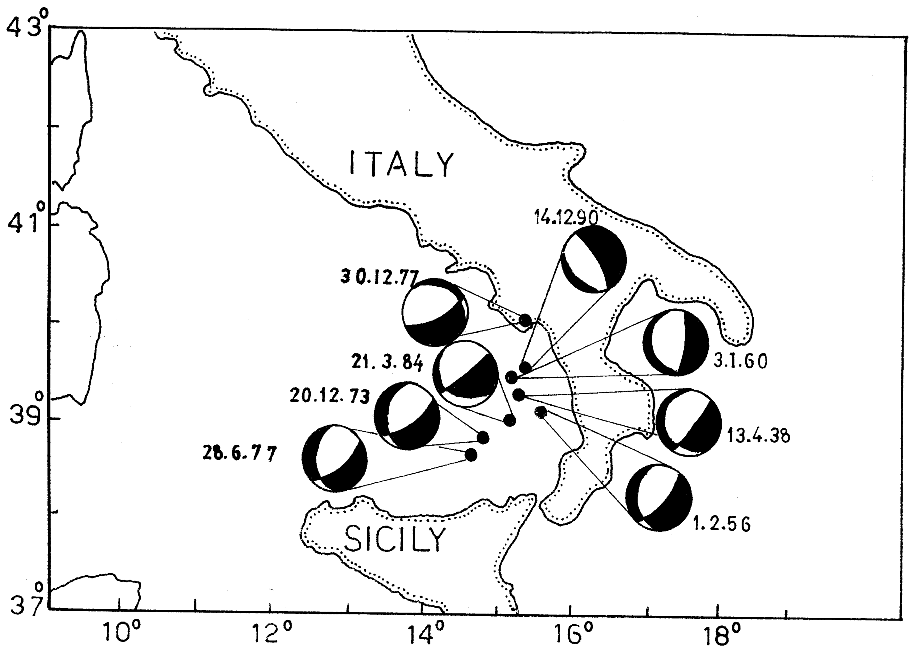

Fig. 7. Fault plane solutions of the deep-focus earthquakes of the Tyrrhenian Sea as they are listed and referenced in table III.

ning 2000 years (Gasparini *et al.*, 1985). So we assumed that the maximum magnitude for the area equals 6.0.

The seismic moment rate was found to be equal to $0.13*10^{25}$ dyn. cm/yr. The P axis of the «representative focal mechanism» has a shallow plunge and a trend of 24° while the T axis has a trend of 114° and a plunge of 53°.

Table IV shows that the dominant component of deformation is compression at an azimuth of 25° and a rate of 1.2 mm/yr.

4.2. *Deformation of the descending slab*

A similar analysis was performed in order to examine the deformation caused by the deep seismicity of the Tyrrhenian Sea. The current seismicity in Southern Italy appears to be characteristic of a subduction zone, although it is not known if subduction is presently occurring there. There are signs, however, like the absence of large thrust events at the surface, that support the idea of a terminated subduction process. The great depth reached by the earthquake hypocentres (500 km) suggests that subduction took place over a long period of time.

Eight fault plane solutions were used in the analysis, listed with numbers 1 to 6, 8 and 9 in table III. All these events are deep (> 200-400 km) and we assume that we examine the deformation only of this part of the descending slab. The focal mechanism of the event of December 27, 1978 was omitted because it clearly shows motion on a different plane (Anderson and Jackson, 1987b). The length of the deforming zone (along strike), is taken to be 220 km and the width of the zone 280 km. The thick-

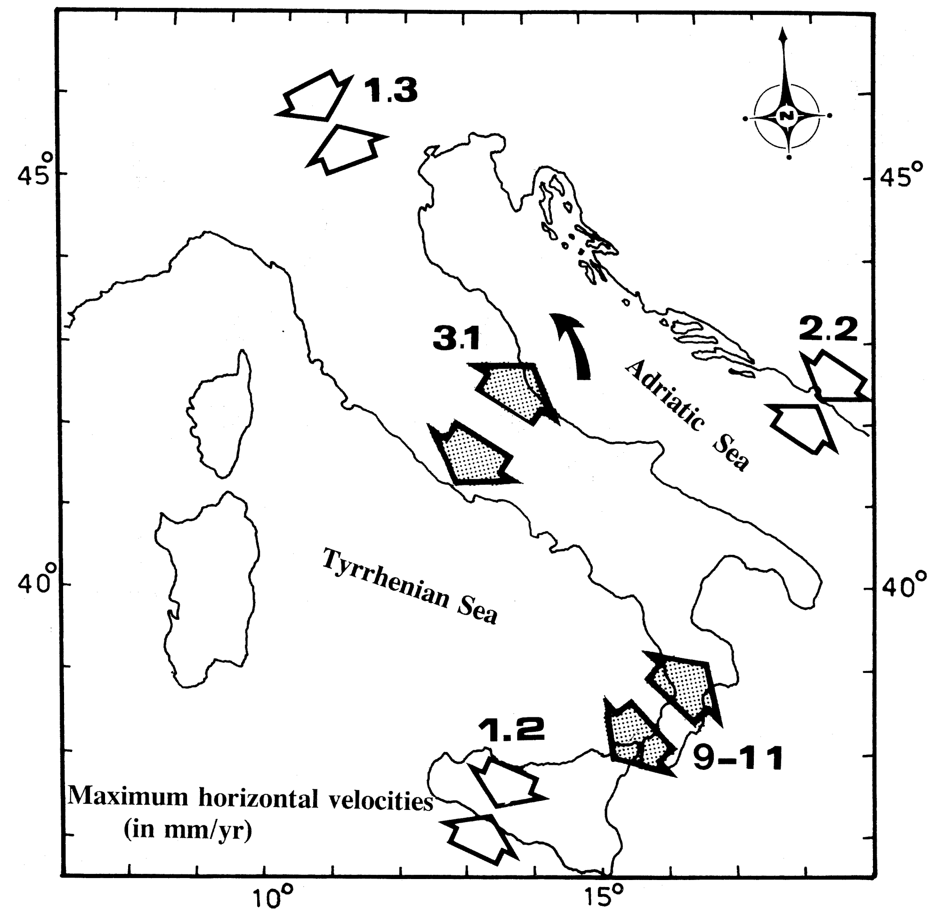

Fig. 8. Schematic summary of seismic deformation rates (maximum horizontal velocities, in mm/yr) of the Italian peninsula and Sicily. Diverging arrows denote extension while converging ones denote shortening. The velocity rate for coastal Yugoslavia is from Papazachos *et al.* (1992).

ness of the seismogenic layer is considered to be 50 km, while the dip angle of this part of the zone is taken to be 45° (Anderson and Jackson, 1987b). The seismic moment rate calculated is $0.19*10^{26}$ dyn. cm/yr. The maximum magnitude for this zone is taken as 7.1, that is, the magnitude of the April 13, 1938 event. The T axis of the «representative focal mechanism» has a trend of 105° and a plunge of 41°, while the P axis has a trend of 314° and a plunge of 45°, pointing above the solid earth.

The results of table IV indicate that the deformation of the descending slab is mainly expressed as compression at an azimuth of 146° and a rate of 1.7 mm/yr.

5. Conclusions and discussion

Figure 8 is a sketch map which summarizes the maximum horizontal velocities of the active crustal seismic deformation of the Italian peninsula and Sicily. Diverging arrows denote extension, while converging ones denote compression. Northern Italy, along the Alps and Northern Apennines, is undergoing compression at N162°E and a rate of 1.3 mm/yr. This compressional deformation pattern is in accordance with the counterclockwise rotation of the Adriatic Sea. Our results indicate a faster shortening in the Alps than the value of 0.1 mm/yr calculated by Westaway (1992). The extensive discussion as to whether the Adriatic Sea represents a promontory of the African plate or not is very well known. For instance, McKenzie (1972) suggested that the Adriatic Sea and the coastal areas of Italy and Yugoslavia form a tongue of the African plate which is underthrusting Eurasia in Northeastern Italy and Yugoslavia. Lort (1971), on the other hand, suggested that the Adriatic Sea is a separate microplate, the Apulian plate, which may move independently of the larger plates. At any rate, except from the existence of a plate boundary across the Adriatic Sea, the interpretations of Lort and McKenzie are quite similar. In both cases, compressional tectonics are expected in Northeastern Italy and adjacent Yugoslavia.

Central Italy and Central Apennines are undergoing crustal extension at N28°E and a rate of 3.1 mm/yr. This extensional tectonics causes thinning of the seismogenic layer at a rate of 0.5 mm/yr. Anderson and Jackson (1987a) calculated extension rates for Central Italy equal to 2.9 mm/yr in the direction N32°E, Jackson and McKenzie (1988) calculated rates of 1.3-3.5 mm/yr, and Westaway (1992) calculated an extension rate of 5 mm/yr. The seismic shortening in coastal Yugoslavia was calculated equal to 1.0-2.4 mm/yr (Jackson and McKenzie, 1988; Papazachos *et al.*, 1992). So, it looks that the extension rate in Central Italy and the shortening rate in southern coastal Yugoslavia are, within error limits, approximately the same.

In Calabria and Southern Apennines the crust is extended at a rate of 11 mm/yr at N40°E. If we include the event of 1908 in the moment tensor summation, then this rate reduces to 9 mm/yr and the azimuth becomes N53°E. The occurrence of the 1908 Messina event suggests that the compressional tectonics related to the subduction is not occurring in Calabria. The Calabrian arc, because of the continental interaction, experienced the most intense compressive stresses along the Apennine chain. However, within this compressional regime several zones having different seismic potentials and different tectonic characteristics can be identified as, for example, the Messina strait, probably a graben structure (Ghisetti, 1984), which is the most evident tectonic discontinuity crossing the southern part of the Calabrian arc. This normal faulting in Southern Italy is probably due to the lateral stretching of the crust produced by the strong curvature in this part of the arc (De Natale, 1989). It seems that the boundary between the normal faulting and the nearby thrusting is very sharp and it is not very easy to define it.

In Sicily, the deformation is taken up by compression performed at N25°E and a rate of 1.2 mm/yr. Our results show that the extension in Central Italy and the shortening in Sicily are performed at about the same azimuth, the extension being a little faster. The Africa-Eurasia pole of Jackson and McKenzie (1988) and the NUVEL-1 model of DeMets *et al.* (1990) predict a velocity of 8 mm/yr in Sicily. The results obtained here probably indicate that a part of the total deformation is expressed aseismically in this region.

A good test to our results would come from independent measures of the total deformation from geodetic measurements. To the best of our knowledge, geodetic networks were only recently installed in Italy. In 1986 a network was installed that covers the West Hellenic Arc and the Calabrian Arc, using GPS measurements. The project is being conducted by various institutions from Germany, Greece, Italy and Switzerland. In 1989 the TYRGEONET GPS network was installed that covered mostly the entire Italian peninsula. This network was installed by the University of Bologna with the cooperation of a number of institutions from other countries. Unfortunately, these networks have not been measured enough times to get the deformation field and the results are only preliminary. From a preliminary analysis of the data of the first network, a shift of the station coordinates towards SSE is observed in the Southeastern Tyrrhenian Sea, indicating an opening of the Tyrrhenian basin (Kahle *et al.*, 1992).

The study of the moment tensors of the deep seismicity of the Tyrrhenian Sea showed that the descending slab, at least for its deeper part from 230-400 km, is in a state of down dip compression at a rate of about 2 mm/yr.

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