

ACTIVE CRUSTAL DEFORMATION IN THE ITALIAN PENINSULA AND SICILY

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A B S T R A C T

A moment tensor analysis is performed in order to estimate the active crustal deformation of the Italian peninsula and Sicily. In northern Italy, along the Alps, the deformation is taken up as compression performed at an azimuth of 162° and a rate of 1 mm/yr. In central Italy, along the Apennines, extension is prevailing at an azimuth of 28° 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 an azimuth of 40° and a rate of 11 mm/yr. At the island of Sicily, compression is occurring at an azimuth of 25° and a rate of 2 mm/yr. These results are in agreement with plate motion models for the area.

ΕΝΕΡΓΟΣ ΠΑΡΑΜΟΡΦΩΣΗ ΤΟΥ ΦΛΟΙΟΥ ΣΤΗΝ ΠΕΡΙΟΧΗ ΤΗΣ ΙΤΑΛΙΑΣ ΚΑΙ ΣΙΚΕΛΙΑΣ

Κυρατζή, Α.

Π Ε Ρ Ι Λ Η Ψ Η

Η μελέτη της παραμόρφωσης της Ιταλίας και της Σικελίας έδειξε ότι στο βόρειο τμήμα, κατά μήκος των Αλπεων, επικρατεί συμπίεση με διεύθυνση 162° και ταχύτητα 1 mm/yr. Στο κεντρικό τμήμα των Απεννίνων, ο φλοιός εκτείνεται κατά διεύθυνση 28° και ταχύτητα 3 mm/yr. Στη Καλαβρία, η παραμόρφωση του φλοιού πραγματοποιείται πάλι σαν εφελκυσμός με ταχύτητα 11 mm/yr. Στη Σικελία, επικρατεί συμπίεση με ταχύτητα 2 mm/yr και διεύθυνση 25° . Τα αποτελέσματα αυτά είναι σε καλή συμφωνία με τα τεκτονικά μοντέλα για την περιοχή.

INTRODUCTION

The Italian peninsula and Sicily, 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.

Geological and geophysical evidence suggests that the tectonics is characterized by extensional features along the Apennines, which were formed mainly in Miocene time by thrusting. In the Calabrian arc, the tectonic setting is related to active volcanism and remnants of a northwest-dipping Benioff zone. Earthquakes as deep as 500 Km are reported to occur in this area. The Alps in the north, take up some of the northward convergence of the African and Eurasian plates. This convergence is taken up

faster at western Sicily at a rate of 8 mm/yr, predicted by plate motions (DeMets et al., 1990).

The present paper examines the active deformation of the Italian peninsula and Sicily, as it is deduced from the seismicity and does not address the driving forces responsible for the motions. 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), among others.

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 contribution of the work of Papazachos and Kiratzi (1992) was to separate the focal mechanism from the scalar moment and to use historical as well as instrumental data to define the moment rate released in an area for the longest possible time period. The reader will find a more detailed description of the procedure in Papazachos and Kiratzi (1992), Papazachos et al. (1992) and Kiratzi (1992). In Papazachos and Kiratzi (1992) was found that a factor of 3 uncertainty is mapped on the estimated velocity rates.

THE DATA

All the shallow earthquakes that occurred in the Italian peninsula and Sicily, for the period 1873 - 1991, were collected. The main source of information for the period 1901-1974 was the catalogue of Comninakis and Papazachos (1978). 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), Mantovani and Boschi (1983), Anderson and Jackson (1987a, b), Console and Favali (1988), Jackson and McKenzie (1988), Margottini et al. (1991), were also used.

For the demands of this paper, the Italian peninsula and Sicily have been separated in relatively homogeneous sub-regions in order to investigate the deformation patterns. Thus, four areas are separately examined: a) the region of northern Italy, which consists of the Alps and part of northern Apennines, b) the region of central Italy, south of 43°N, along central Apennines, c) the region of southern Apennines and Calabria, south of about 40.2°N and d) Sicily.

Figure (1) shows the distribution of the shallow seismicity for the Italian peninsula and Sicily. Different sizes are used to denote different earthquake magnitudes.

Figure (2) shows the Gutenberg-Richter relation determined for each area of study. It is seen that the b-value is higher in

northern Italy (1.13), reduces to 0.90 in central Italy to becomes 0.75 in Calabria and Sicily.

In order to determine the moment-magnitude relation we assumed that the slope of the best-fitting line equals 3/2, experimentally defined by Kanamori and Anderson (1975). Figure (3) shows the data used (scalar moments and magnitudes listed in table I), and the relation obtained is the following:

$$\text{Log}M_0 = 1.5M_s + 16.27$$

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.

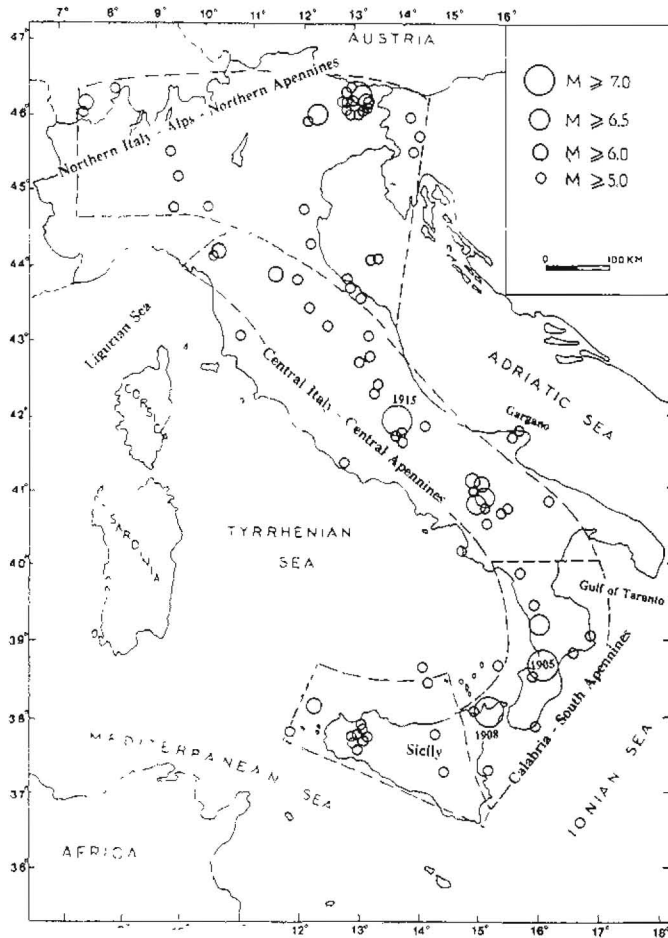


Fig.1. Distribution of the shallow seismicity (complete data) of the Italian peninsula and Sicily. The regions studied are also shown.

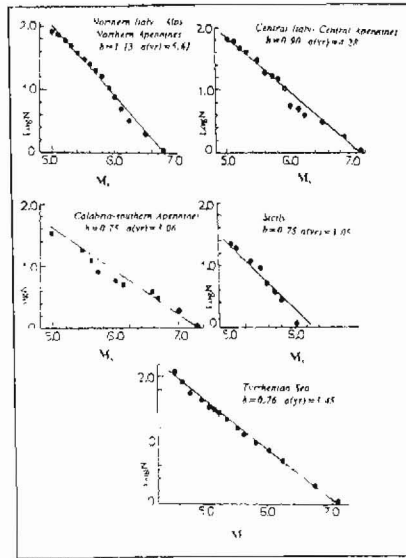


Fig.2. The frequency magnitude relation for each area of study.

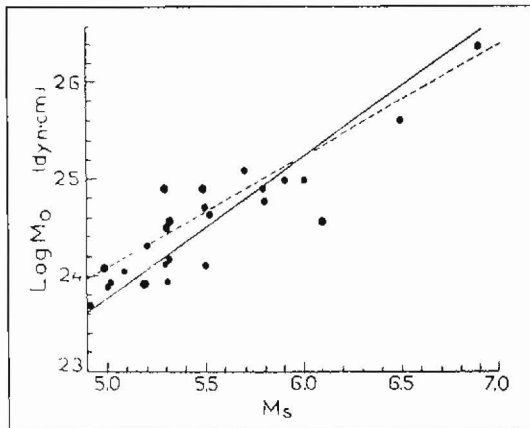


Fig.3. The moment-magnitude relation applicable to the area of study (straight line). The dashed line represents the relation of Giardini et al. (1984) for the Mediterranean region.

THE FOCAL MECHANISMS

Table 1 lists the fault plane solutions and the scalar moments (determined by waveform analysis) of the earthquakes.

Figure (4) shows these focal mechanisms.

a) Northern Italy - Alps - Northern Apennines

Seven fault plane solutions were used in the analysis listed with numbers 7, 8, 9, 10, 11, 12 and 22 in table 1. The maximum magnitude for this region was taken equal to 6.8 (event of June 29, 1873).

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 1. These focal mechanisms indicate normal faulting in WNW-ESE striking planes following the trend of the Apenninic chain.

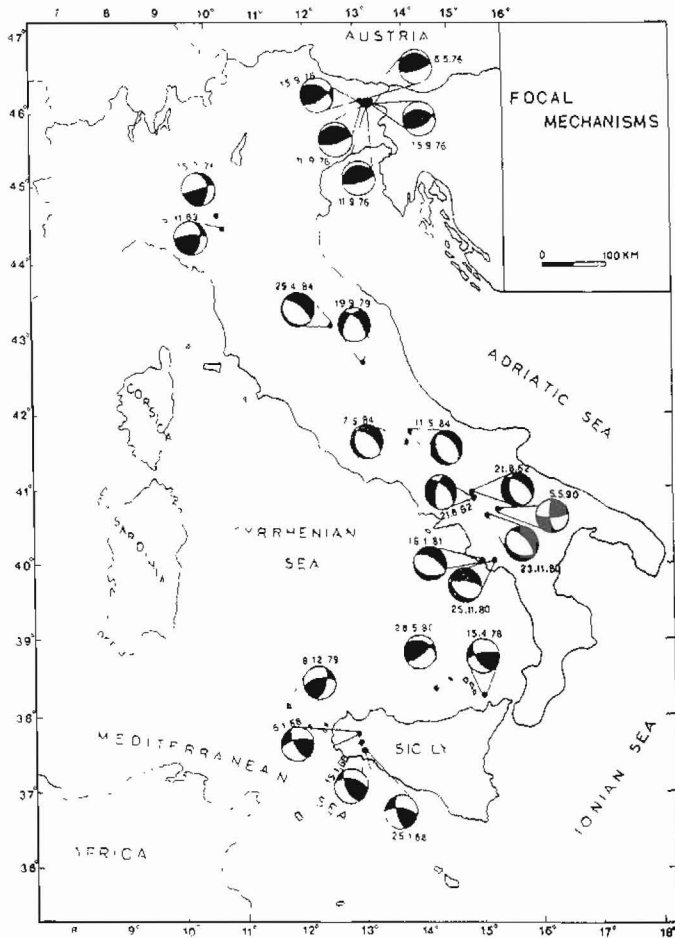


Fig.4. Fault plane solutions of the shallow earthquakes of the Italian peninsula and Sicily.

Table 1. Information on the seismic moments and on the focal mechanisms of the shallow earthquakes occurred at the Adriatic area.

No	Date	Time	$\varphi^{\circ}N$	$\lambda^{\circ}E$	h(km)	M_s	M_0 (dyncm)	str ^o	dip ^o	rake ^o	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	"	18:19	41.02	15.02	8	6.1	$3.5 \cdot 10^{24}$	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	Jul 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	$2.9 \cdot 10^{25}$	76	75	90	1
9	Sept 11, 1976	16:31	46.28	13.16	16	5.5		76	73	90	2
10	"	16:35	46.30	13.20	20	5.4		91	80	90	2
11	Sep 15, 1976	03:15	46.30	13.20	10	6.0	$1.0 \cdot 10^{25}$	270	40	126	2
12	"	09:21	46.32	13.13	17	5.9	$1.0 \cdot 10^{25}$	56	67	70	1
13	Aug 15, 1977	21:10	38.85	16.98	40	5.0	$8.2 \cdot 10^{23}$				4
14	Mar 11, 1978	19:20	38.10	16.03	15	5.0	$8.4 \cdot 10^{23}$				4
15	Apr 15, 1978	23:33	38.39	15.07	21	5.7	$1.39 \cdot 10^{25}$	148	55	153	2
16	Sep 19, 1979	21:35	42.81	13.06	16	5.8	$6.92 \cdot 10^{24}$	212	55	-30	2
17	Dec 8, 1979	04:06	38.28	11.74	15	5.3	$1.3 \cdot 10^{24}$	254	56	136	2
18	May 28, 1980	19:51	38.48	14.25	12	5.5	$3.84 \cdot 10^{24}$	278	37	130	2
19	Nov 23, 1980	18:34	40.76	15.33	10	6.9	$2.43 \cdot 10^{26}$	116	30	-108	2
20	Nov 25, 1980	18:28	40.15	15.36	15	5.3	$1.5 \cdot 10^{24}$	129	26	-65	4
21	Jan 16, 1981	00:37	40.13	15.23	15	5.3	$8.5 \cdot 10^{23}$	115	30	-93	4
22	Nov 9, 1983	16:29	44.73	10.40	37	4.9	$4.5 \cdot 10^{23}$	262	71	129	4
23	Apr 29, 1984	05:03	43.26	12.56	12	5.3	$3.4 \cdot 10^{24}$	143	21	-72	4
24	May 7, 1984	17:49	41.77	13.90	10	5.8	$7.82 \cdot 10^{24}$	312	66	-110	4
25	May 11, 1984	10:41	41.83	13.96	14	5.2	$2.03 \cdot 10^{24}$	317	49	-103	4
26	Apr 26, 1988	00:53	42.37	16.61	8	5.5	$1.4 \cdot 10^{24}$				5
27	May 5, 1990	07:21	40.73	15.86	5	5.5	$5.7 \cdot 10^{24}$	184	73	13	5
28	Dec 13, 1990	00:24	37.20	15.50	10	5.3	$3.3 \cdot 10^{24}$				4

1 Cipar (1980), 2 Anderson and Jackson (1987a), 3 Westaway (1987), 4 Centroid Moment Tensor solution, 5 ISC bulletins.

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 I), dominates. This event, resembling the 1783 Calabrian event, caused many casualties especially in Reggio Calabria, 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. Since we did not have any fault plane solutions for the area and there is evidence of active normal faulting, we assumed that the solutions for this area will be similar to the ones observed 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).

d) Sicily

Six fault plane solution were used listed with numbers 4, 5, 6, 15, 17 and 18 in table I. The fault plane solutions in western Sicily show thrusting with considerable strike slip motion in WNW-ESE oriented planes. There was no earthquake greater than 6.0 in the present century, nor ever reported in catalogues spanning 2000 years (Gasparini et al., 1985), so we assumed that the maximum magnitude for the area equals 6.3 (6.0 plus the standard error in the magnitude calculation).

RESULTS AND DISCUSSION

Table 2 summarises the results on the deformation rates for each region. The length, the width and the azimuth of each deforming zone were calculated from the distribution of the seismicity. The thickness of the seismogenic layer was assumed to be 15 Km.

Figure (5) is a sketch map which summarizes the maximum seismic velocities in 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 an azimuth of 162° 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).

Central Italy and central Apennines are undergoing crustal extension at $N28^\circ E$ and a rate of 3.1 mm/yr. This extensional tectonics cause thinning of the seismogenic layer at a rate of 0.5 mm/yr. Anderson and Jackson (1987a) and Jackson and McKenzie (1988) calculated rates of 1.3-3.5 mm/yr, while 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 $N40^\circ E$. If we include the event of 1908 in the moment tensor summation then this rate reduces to 7 mm/yr and the azimuth becomes $N77^\circ E$. The occurrence of the 1908 Messina event suggests that the compressional tectonics related to the subduction are not occurring in Calabria. 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 an azimuth of 25° and a rate of 2.1 mm/yr. It seems 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

Table 2. Strain rates and velocity rates for the Italian peninsula and Sicily Northern Italy - Alps - northern Apennines.

M_{max}	Length(Km)	Width(Km)	Az ^o	b	a(yr)	M_0 dyncm/yr			
6.8	500	180	76	1.13	5.61	$0.96 \cdot 10^{25}$			
Strain rates $\cdot 10^{-8}$ /yr			ϵ_{11}	ϵ_{12}	ϵ_{13}	ϵ_{22}	ϵ_{23}	ϵ_{33}	
Velocity rates (mm/yr)			v_{11}	v_{12}	v_{13}	v_{22}	v_{23}	v_{33}	
Eigenvalues of the velocity tensor: λ_i :(mm/yr) Azimuth ^o Plunge ^o									
						-1.29	162	11	
						0.17	77	-24	
						0.14	50	63	
Central Italy - central Apennines									
M_{max}	Length(Km)	Width(Km)	Az ^o	b	a(yr)	M_0 dyncm/yr			
7.1	550	100	145	0.90	4.28	$0.15 \cdot 10^{26}$			
Strain rates $\cdot 10^{-8}$ /yr			ϵ_{11}	ϵ_{12}	ϵ_{13}	ϵ_{22}	ϵ_{23}	ϵ_{33}	
Velocity rates (mm/yr)			v_{11}	v_{12}	v_{13}	v_{22}	v_{23}	v_{33}	
Eigenvalues of the velocity tensor: λ_i :(mm/yr) Azimuth ^o Plunge ^o									
						3.11	28	8	
						-0.53	102	-64	
						0.01	121	25	
Calabria - southern Apennines									
M_{max}	Length(Km)	Width(Km)	Az ^o	b	a(yr)	M_0 dyncm/yr			
7.3	300	100	40	0.75	3.06	$0.12 \cdot 10^{26}$			
Strain rates $\cdot 10^{-8}$ /yr			ϵ_{11}	ϵ_{12}	ϵ_{13}	ϵ_{22}	ϵ_{23}	ϵ_{33}	
Velocity rates (mm/yr)			v_{11}	v_{12}	v_{13}	v_{22}	v_{23}	v_{33}	
Eigenvalues of the velocity tensor: λ_i :(mm/yr) Azimuth ^o Plunge ^o									
						11.09	40	4	
						-0.63	117	-74	
						-0.05	131	16	
Sicily									
M_{max}	Length(Km)	Width(Km)	Az ^o	b	a(yr)	M_0 dyncm/yr			
6.3	230	90	40	0.75	3.05	$0.21 \cdot 10^{25}$			
Strain rates $\cdot 10^{-8}$ /yr			ϵ_{11}	ϵ_{12}	ϵ_{13}	ϵ_{22}	ϵ_{23}	ϵ_{33}	
Velocity rates (mm/yr)			v_{11}	v_{12}	v_{13}	v_{22}	v_{23}	v_{33}	
Eigenvalues of the velocity tensor: λ_i :(mm/yr) Azimuth ^o Plunge ^o									
						-2.08	25	-0	
						0.44	115	18	
						0.05	115	-72	

(1988) and the NUVEL-1 model of DeMetts 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.

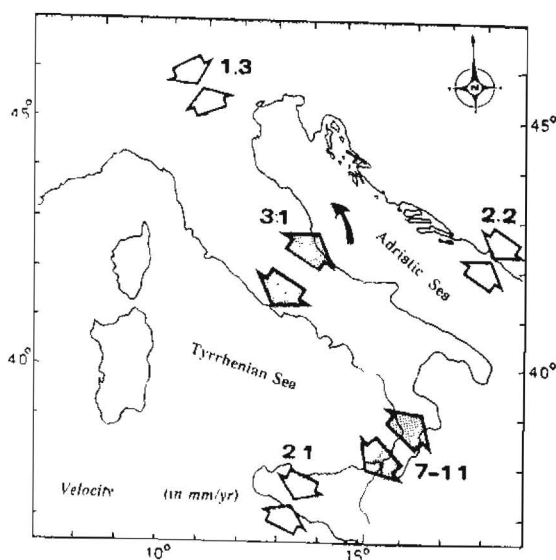


Fig.5. Schematic summary of seismic deformation rates (maximum velocities, in mm/yr) of the Italian peninsula and Sicily. Diverging arrows denote extension while converging ones denote shortening. The velocity rate for coastal Yugoslavia is from Papazachos et al. (1992).

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