ANNALI DI GEOFISICA, VOL. XL, N. 6, December 1997

Spatial distribution of scalar seismic moment release in Italy (1983-1996): seismotectonic implications for the Apennines

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Abstract
We analyzed the distribution of seismic moment in Italy, computed from instrumental seismicity recorded by the Italian National Seismic Network in the past 14 years, to map the areas where seismic deformation processes have been active in this time interval. Seismic moment is the most suitable parameter to quantify earthquake size. It is related to the geometric characteristics of faults, to seismic energy and it is a quantity that can be summed and represented in its cumulative value. The maps of seismic moment distribution display more information than epicentral maps, better showing actively deforming regions. They provide further and original evidence for the existence, within the Apenninic belt, of two regions (north and south) characterized by different seismic energy release. The seismic moment is almost continuously and homogeneously distributed all along the belt in the Northern Apennines, whereas in the Southern Apennines it is concentrated in the zones recently activated by mainshock-aftershock seismic sequences. Seismic deformation takes place in a 30 km narrow belt along the Apennines, while in the transition zone between the Northern and Southern Apennines this belt is about 100 km wide. Comparing instrumental seismic moment release with the areas struck by the largest historical earthquakes which have occurred in the past six centuries, we qualitatively extended back to the past the information on where the seismic deformation occurs. In the Southern Apennines background energy release from instrumental seismicity is very low in the several areas hit by large historical earthquakes, suggesting that these seismogenic zones are currently quiescent.

Key words *scalar seismic moment – seismotectonic – Apennines*

1. Introduction

The purpose of this paper is to image the areas where seismic deformation takes place along the Italian peninsula. Seismic deformation is a discontinuous process which contributes to the total deformation and involves faulting in the upper crust (McKenzie and Jackson, 1983; Jackson and McKenzie, 1988). The deformation produced by large and small earthquakes reflects the kinematic boundary conditions. Moment tensors of large earthquakes can be used to describe how and to what extent a region is seismically deformed, while small earthquakes, although their contribution to the deformation is not significant, provide useful information on where deformation takes place. The importance of seismicity to plate tectonics, evident since the world seismicity map of crustal and deep earthquakes was published by Barazangi and Dorman (1969), refers mainly to space and time distribution of earthquakes, earthquake size, fault plane solutions, and the estimate of the average

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strain rate tensor. However, epicentral maps do not emphasize the fundamental characteristic of the earthquake source. The size of earthquakes is represented by symbols which have little to do either with the geometric characteristics of faults or with the energy released. In this paper, we use the scalar seismic moment to represent earthquake size. The images show the cumulated seismic moment interpolated over a square-cell grid covering the Italian peninsula. Scalar seismic moment, better than magnitude, represents the earthquake size, it is proportional to energy when stress drop is constant, and it is a parameter that can be summed and represented in its cumulative value for a given region. Once obtained, this representation of the recent (1983-1996) seismic activity, is used to discuss the tectonic implications for the Apennines.

2. Seismotectonic framework of the Apennines

The steady increase in the number of seismic stations installed in the past decade in Italy better outlines the main features of spatial seismicity patterns in Italy. More than 2000 earthquakes per year are recorded at the present time by the Italian National Seismic Network with a magnitude threshold of about 2.5. The crustal seismicity is mainly concentrated in a belt running along the Apenninic chain (fig. 1).

The pattern of instrumental seismicity delineates two distinct seismic areas, the Northern and the Southern Apennines (hereafter NA and SA, respectively). In NA, seismicity follows an arcuate belt convex toward the Adriatic Sea. The SA, where the largest earthquakes occur, are characterized by a narrow straight NW-SE striking seismic belt. In the past 20 years a few earthquakes with magnitude larger than 5.0 occurred there, including the $M_s = 6.9$, 1980 Irpinia earthquake (Deschamps and King, 1984; Gasparini *et al.*, 1985; Anderson and Jackson, 1987; Cocco *et al.*, 1993).

An offset in the seismicity distribution in the central section of the belt was observed by Cocco *et al.* (1993). This offset roughly coincides with the «Ancona-Anzio» line that, from a geological point of view, separates the northern from the southern arc. The «Ancona-Anzio» line also marks the transition in the seismicity pattern. Geological studies pointed out a right-lateral strike-slip or a reverse mechanism for such structural line (*e.g.*, Royden *et al.*, 1987; Patacca and Scandone, 1989). The seismicity distribution does not indicate that this structure is seismically active (Cocco *et al.*, 1993).

Fault plane solutions are the most useful source of information, and currently the only data available for the Apennines which allow the shape and orientation of the strain tensor to be determined. Here, we summarize the main features that can be derived from focal mechanisms of the largest earthquakes ($5.0 < M < 7.0$) which occurred in this century along the Apenninic belt (fig. 2). They have been computed either from P-wave polarities (Martini and Scarpa, 1983; Gasparini *et al.*, 1985; Frepoli and Amato, 1997), some of them are inferred from levelling measurements, such as the Messina 1908 and the Avezzano 1915 earthquakes (Capuano *et al.*, 1988; Valensise, 1988; Ward and Valensise, 1989) or from CMT solutions (Dziewonsky *et al.*, 1983). All the largest magnitude events ($M > 6.0$, larger circles in fig. 2) show normal faulting, pointing out a NE-SW extension in the Apennines in agreement with the minimum stress orientation resulting from borehole breakout data (Amato *et al.*, 1995a; Montone *et al.*, 1996) and structural geology (Hyppolite *et al.*, 1994). Fault plane solutions for smaller earthquakes show both normal and strike slip mechanisms. The minimum compression axis (T) of these earthquakes is generally oriented NE-SW. Thus, for smaller earthquakes the P axis is either vertical or horizontal while for the largest ones it is almost vertical, at least for the available 100 year time window.

The magnitude of deformation rates across the Apennines has been quantified by several authors (Anderson and Jackson, 1987; Jackson and McKenzie, 1988; Westaway, 1992; Pondrelli *et al.*, 1995) who estimated the average strain rate tensor applying Kostrov's equation (1974). Although these authors considered

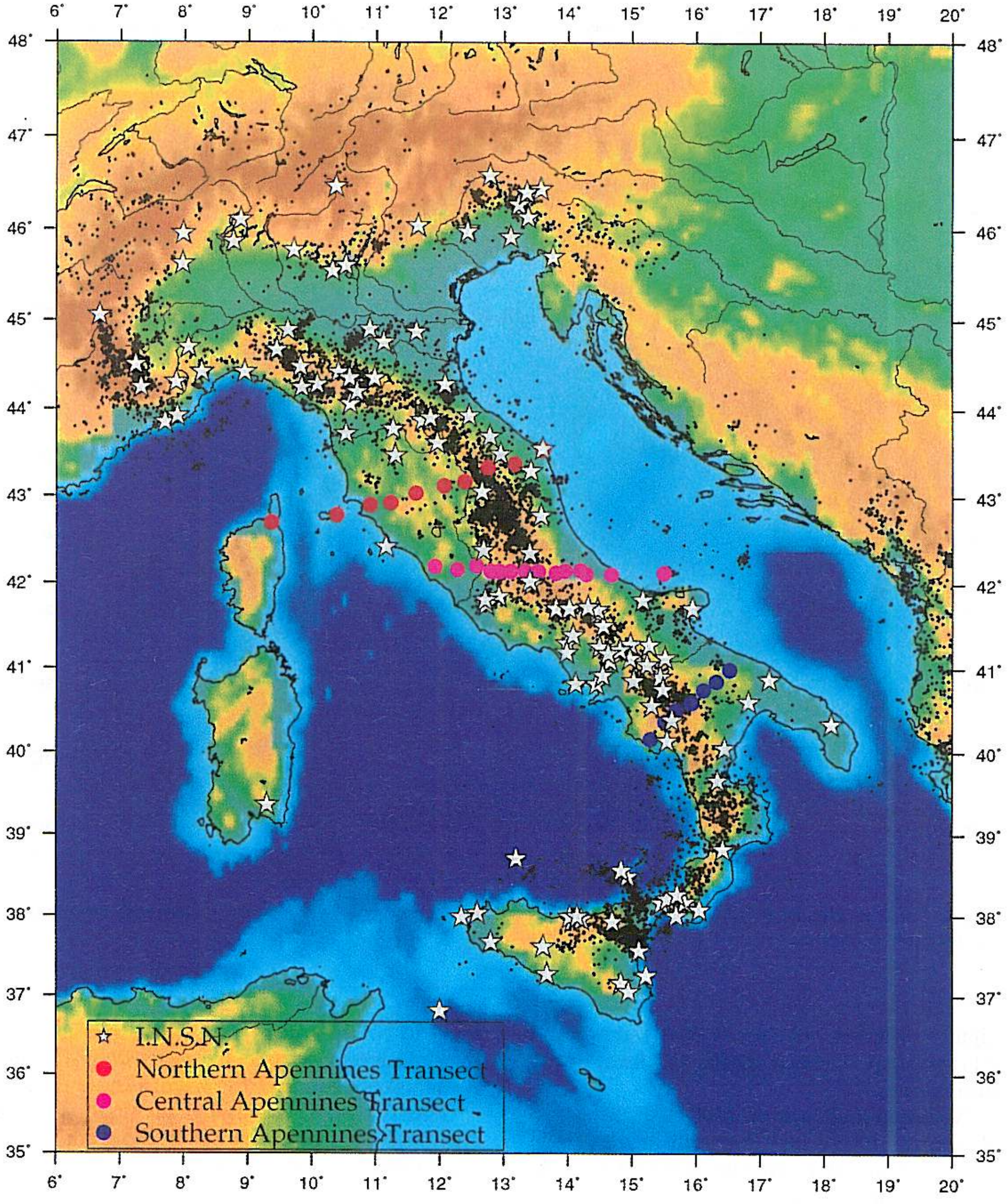


Fig. 1. Seismicity distribution of the well-located earthquakes in the ING bulletin. Selection criteria refer to the geometry of the network and rms of the solution. Also shown are the Italian National Seismic Network (stars) and station locations of the three temporary arrays installed in the Apennines (coloured circles).

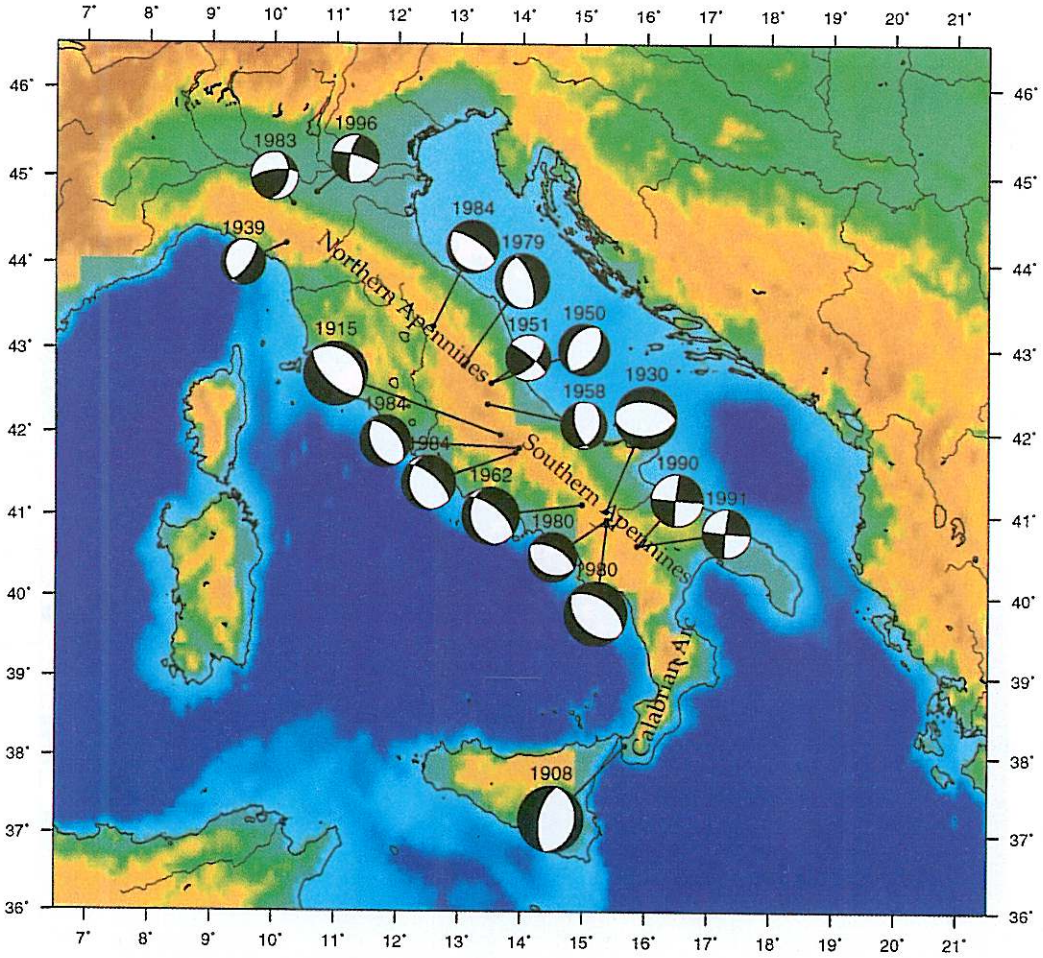


Fig. 2. Focal mechanisms for $M > 5.0$ earthquakes in the last century. Symbols are scaled with magnitude. See text for references.

slightly different volumes, time windows and data sets, they obtained similar estimates of extension rates.

Anderson and Jackson (1987), Jackson and McKenzie (1988), and Pondrelli *et al.* (1995) quantified an extension rate, perpendicular to the Apennines, ranging from 1 to 3 mm/yr for the whole seismic belt and in a relative short time interval (16-85 years).

Westaway (1992) found an extension rate of one order of magnitude greater in SA with respect to NA in a nearly 400 year time interval by considering seismic moments of historical earthquakes estimated by macroseismic data.

Finally, both seismicity distribution and magnitude of the largest earthquakes point out a difference in the seismotectonic features of NA with respect to SA, while fault plane solutions show that the whole Apenninic chain is undergoing NE-SW extension. At greater depth there is strong evidence that beneath NA there is a still active subduction process (Selvaggi and Amato, 1992; Amato *et al.*, 1993), while beneath SA both the lack of intermediate depth and deep earthquakes and clear P-wave velocity anomalies suggest the absence of subduction processes. These observations will drive the discussion and particularly the interpretation of the Ancona-Anzio line as the border of the two Apenninic sectors.

3. Seismic moment distribution

Our data base contains earthquake locations and magnitudes from 1983 to date reported by the ING seismic bulletins which provide duration magnitudes and, less frequently, local magnitudes. We evaluate the seismic moment for instrumental seismicity by using an empirical regression between scalar seismic moment and magnitude. Among many empirical relations between magnitude and scalar seismic moment (see Di Donato and Giardini, 1995, for a review) none have been calibrated for the Italian seismicity, except for those involving m_b or M_s. Our first step is to assess a reliable regression between seismic moment and duration magnitude (M_d) or local magnitude (M_L) for the Apennines. We calculated the seismic moment from the digital recordings of several local earthquakes recorded during three temporary arrays composed of 7 to 15 digital broadband seismic stations (coloured circles in fig. 1) installed from the Adriatic to the Tyrrhenian coast in the framework of the GeoModAp project (contr. EV5V-CT94-0464, Amato *et al.*, 1995b, 1996). For these local earthquakes we estimated the scalar seismic moment using spectral analysis. We determined the average S wave low frequency spectral level ($\overline{\Omega}_s$), after correction for anelastic attenuation using a value of k equal to 0.07 (see Rovelli *et al.*, 1988, for details), of ground displacement from the horizontal components recorded at each station and we estimated the scalar seismic moment through the expression (Brune, 1970; Bonamassa *et al.*, 1984; Rovelli *et al.*, 1988):

$$M_o = \frac{4\pi \rho D V_s^3 \overline{\Omega}_{(s)}}{F_s < R_s\,(\theta,\ \varphi) > P}.$$

Where ρ is the density (2.7 gr/cm^3), V_s is the S-wave velocity (chosen to be 3.2 km/s), D is the epicentral distance, $F_s = 2$ accounts for the free surface effect, $< R_s(\theta, \varphi) >$ is the average radiation pattern (0.63), and P is the partition of energy between the two horizontal components ($P = 1/\sqrt{2}$). Finally, the seismic moment for each earthquake is obtained averaging the single station estimates. Table I summarizes the results. The M_d and M_L are taken from the ING bulletin and range between 1.5 and 4. This range of values includes most of the seismicity recorded in Italy. Only few earthquakes exceeded this magnitude threshold during the past 14 years. Figure 3 shows the two empiri-

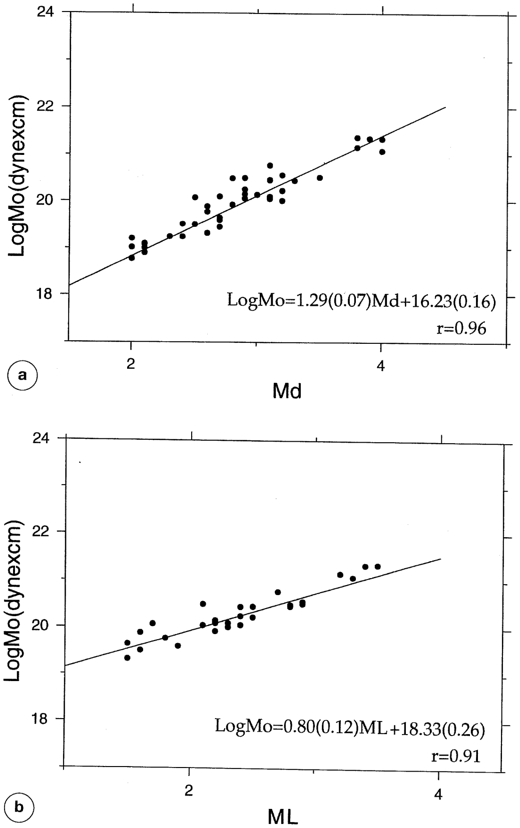


Fig. 3a,b. Linear regressions between Log (M_o) and (a) duration coda magnitude, (b) local magnitude. M_d and M_L are from ING bulletins.

Table I. Earthquakes used for calibrating the Log (M_o)-M_d and Log (M_o)-M_L regressions.

Event	M_o (dyne·cm) 10^{19}	Log (M_o)	σ Log (M_o)	M_d	M_L
1	230.0	21.36	0.30	3.8	
2	220.7	21.34	0.48	3.9	3.5
3	215.2	21.33	0.47	4.0	3.4
4	143.0	21.15	0.88	3.8	3.2
5	118.0	21.07	0.58	4.0	3.3
6	57.9	20.76	0.40	3.2	2.7
7	36.1	20.56	0.44	3.2	2.9
8	32.0	20.51	0.40	3.5	2.1
9	31.3	20.50	1.33	2.9	2.8
10	30.6	20.49	0.58	3.1	2.8
11	28.3	20.45	0.28	3.2	2.5
12	28.0	20.45	0.36	3.1	2.4
13	27.1	20.43	0.34	3.3	
14	17.5	20.24	0.24	2.9	2.4
15	16.6	20.21	0.27	3.2	2.5
16	14.1	20.15	0.36	2.9	2.2
17	13.6	20.13	0.21	3.0	
18	12.5	20.10	0.34	3.1	2.2
19	12.4	20.09	0.29	2.7	2.3
20	12.2	20.09	0.20	3.0	
21	11.8	20.07	0.29	2.5	1.7
22	11.4	20.06	0.32	2.8	2.4
23	11.2	20.05	0.20	3.1	2.1
24	10.1	20.01	0.32	3.2	2.3
25	8.3	19.92	0.32	2.7	2.2
26	7.7	19.89	0.28	2.6	1.6
27	5.8	19.77	0.28	2.6	1.8
28	4.3	19.64	0.19	2.7	1.5
29	3.9	19.59	0.19	2.7	1.9
30	3.2	19.51	0.20	2.4	
31	3.1	19.50	0.43	2.5	1.6
32	2.8	19.44	0.23	2.7	
33	2.0	19.31	0.25	2.6	1.5
34	1.7	19.24	0.12	2.4	
35	1.7	19.24	0.43	2.3	
36	1.6	19.20	0.17	2.0	
37	1.2	19.09	0.20	2.1	
38	1.2	19.08	0.52	2.1	
39	1.0	19.01	0.43	2.0	
40	1.0	19.00	0.10	2.1	
41	0.8	18.90	0.04	2.1	
42	0.6	18.77	0.35	2.1	

cal regressions. The correlation coefficients are 0.96 and 0.91, for M_d and M_L respectively. The two relations are:

$$\mathrm{Log}(M_o = 16.23\ (\pm\ 0.16) + 1.29\ (\pm\ 0.07)\,M_d$$

$$\mathrm{Log}(M_o = 18.33\ (\pm\ 0.26) + 0.80\ (\pm\ 0.12)\,M_L$$

4. Results

The seismic moment rate resulting from 14 years of instrumental seismicity, is $4.1 \cdot 10^{22}$ dyne · cm/yr in NA and slightly higher in SA ($6.8 \cdot 10^{22}$ dyne · cm/yr). Figure 4 shows the cumulative time distribution of seismic moment for the two sectors of the Apennines. In SA, the occurrence of Val Comino 1984, Isernia 1986, Benevento 1990, Potenza 1990, and Irpinia 1996 seismic sequences produces the steps in the trend shown in fig. 4. The linear increase in seismic moment between these sequences is almost equal to the increase in the NA, suggesting that the larger moment rate in SA is only related to the limited time window covered by our data set, and thus, preventing us considering it as a characteristic feature of the Apennines. The higher moment rate of SA is meaningful only considering the historical seismicity.

To map the seismic moment release, we divided the Italian territory into square cells of 5.5 × 5.5 km. The seismic moment of all the earthquakes located within each cell were added and represented as a cumulative value. The dimensions of the cells were chosen to ac-

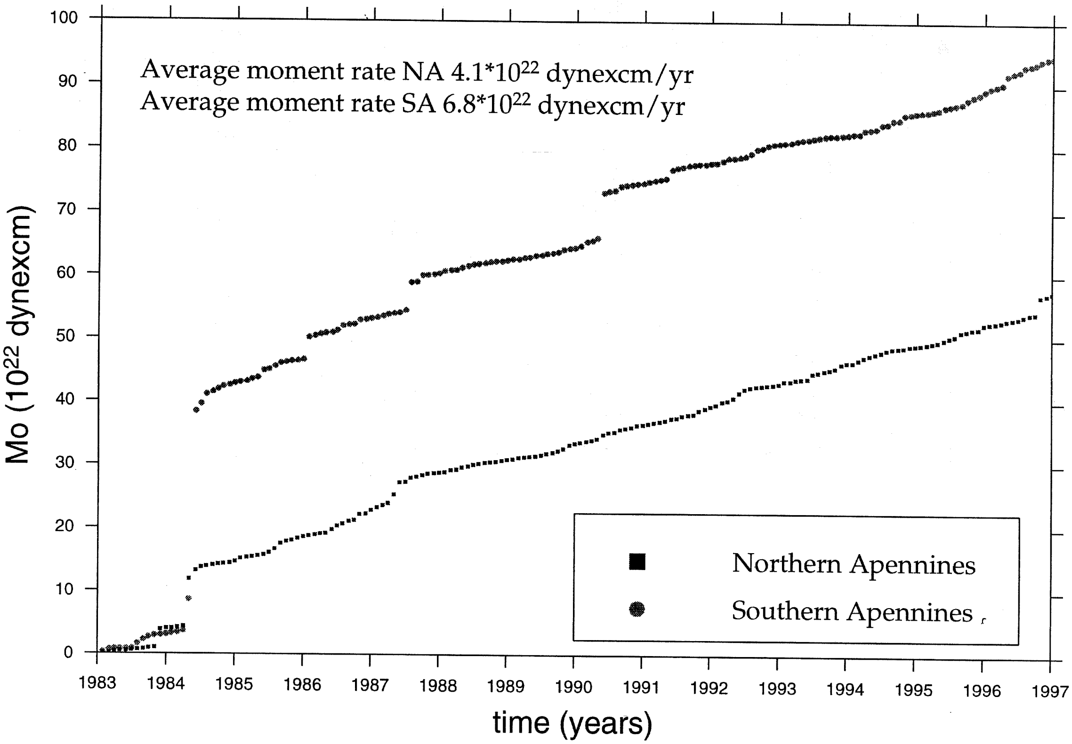


Fig. 4. Cumulate time distribution of seismic moment for the Northern Apennines (solid squares) and Southern Apennines (solid circles).

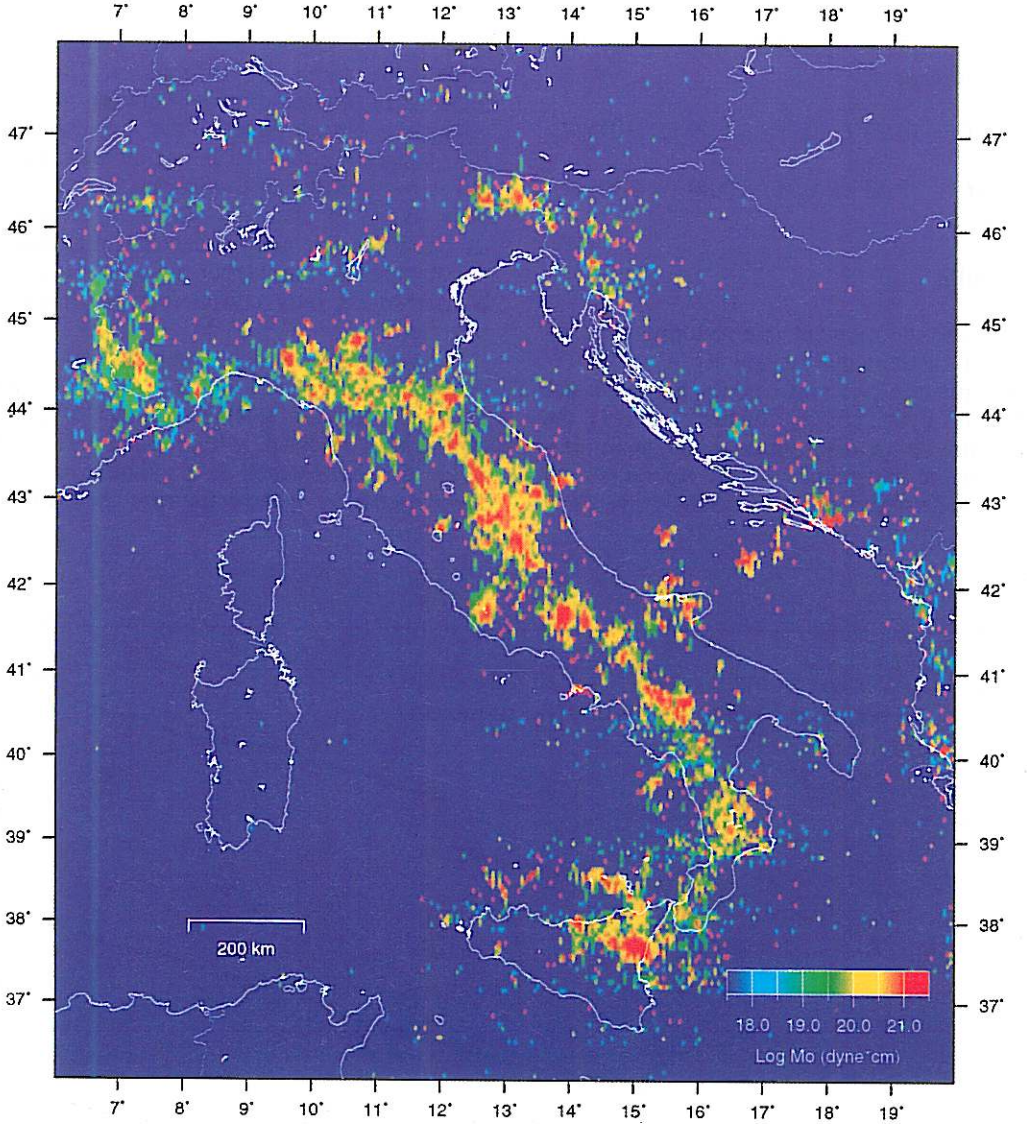


Fig. 5a. Seismic moment distribution map: non interpolated image.

count for the average horizontal errors associated to the location reported by the ING bulletin. We used all the earthquakes, without any selections on the location, in order to keep the completeness of the data set. We show two different maps: a discrete distribution of the cells (fig. 5a), and an interpolated image (fig. 5b). The discrete image resembles an epicentral map, scaled with the magnitude, where different colors are used for earthquake size. As we use the complete data set without selection on the quality of the solution, we see a sparse dis-

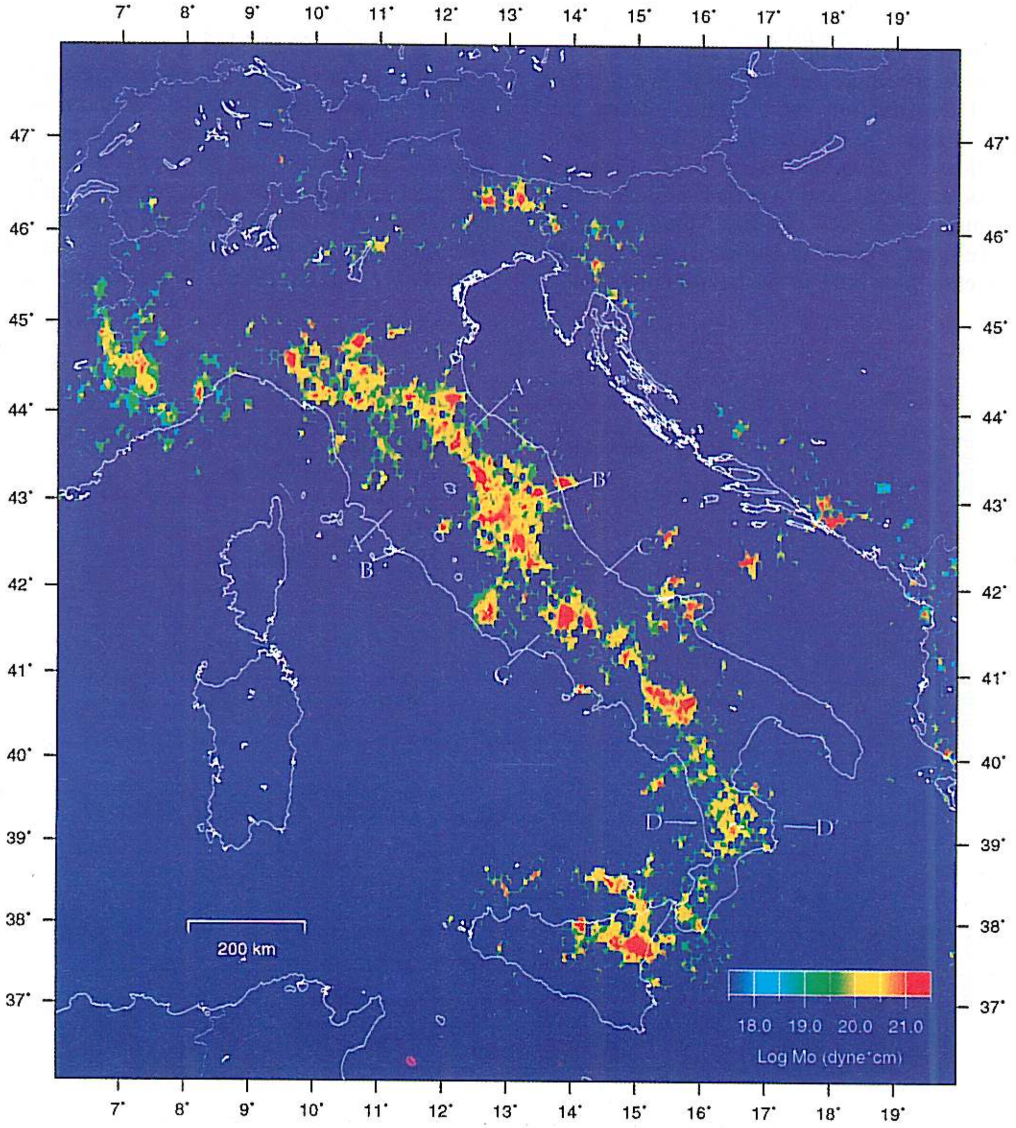


Fig. 5b. Seismic moment distribution map: interpolated image.

tribution of seismicity that, however, delineates the larger moment release on the Apenninic belt with respect to adjacent areas. The interpolated image (fig. 5b) points out only the areas with a significant moment release, and thus, where seismic deformation is more active. Tectonic implications will be restricted to the latter representation. Figure 5b points out those regions where seismic sequences have occurred. Some areas, characterized by a large number of earthquakes (*e.g.*, Western Alps in fig. 1), do not have a significant seismic release (this is easily explained by the presence of a dense local network operating there that lowers the magnitude threshold for location). We see that internal deformation within the Adriatic microplate cannot be neglected, and that a significant release is also associated to Mt. Etna and Phlegraean Fields and Aeolian Islands or to Quaternary volcanoes like the Alban Hills. All these regions appear as isolated spots of seismic release with little or no lateral continuity.

In NA, we observe an almost continuous belt of scalar seismic moment release larger than 10^{21} dyne · cm homogeneously distributed all along the chain, while in SA there are regions where seismic moment release is very low and is concentrated in the areas where the seismic sequences have occurred during the last 16 years (Irpinia 1980, Val Comino 1984, Isernia 1986, Benevento 1990, Potenza 1990 and 1991, Irpinia 1996). We also see, in the

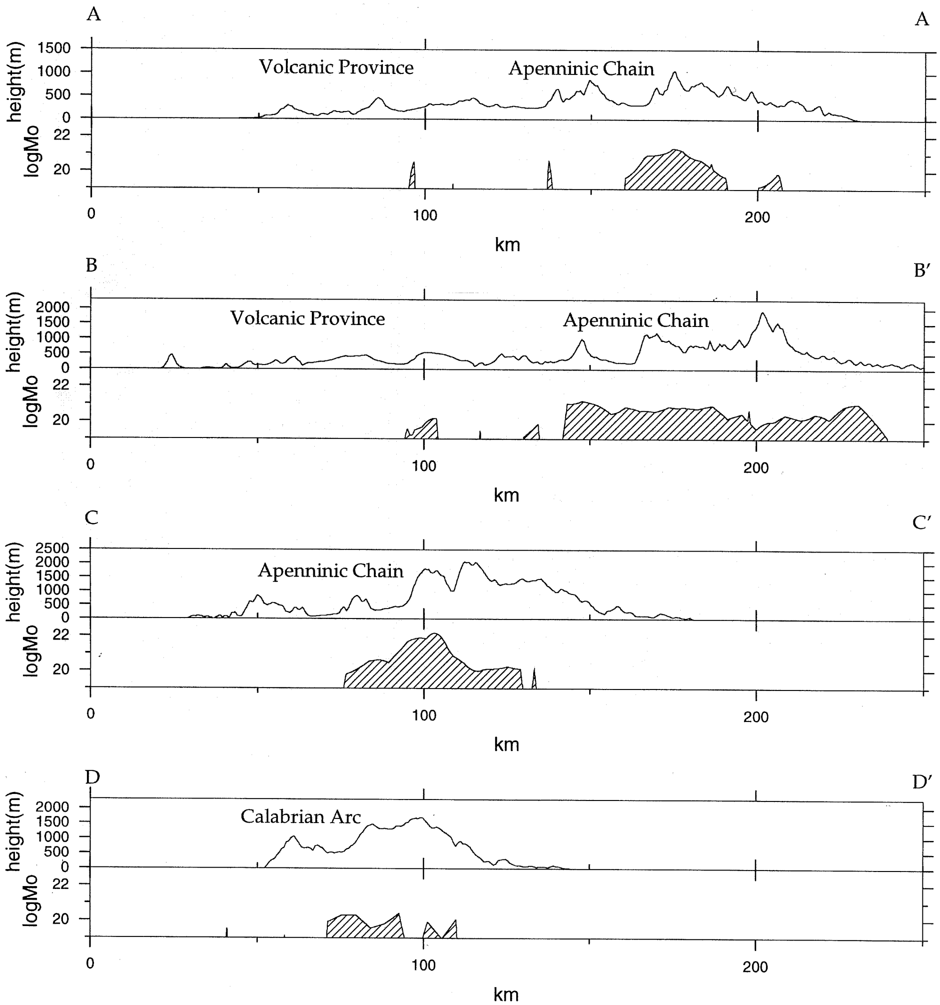


Fig. 6. Seismic moment distribution profiles perpendicular to the Apennines. See fig. 5b for profile traces.

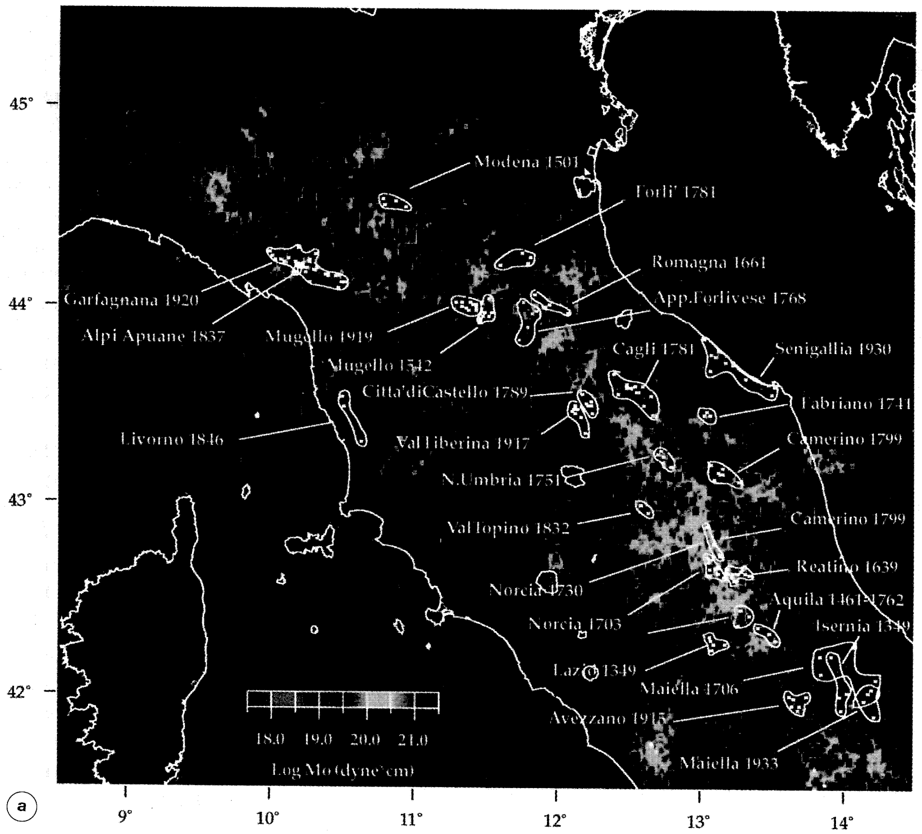
Irpinia region, a significant release related to aftershocks of the large 1980 event ($M_s = 6.9$), still some years later than the mainshock.

In our representation, the offset in correspondence of the «Ancona-Anzio» line is not detected but rather appears as a broadening area of seismic release. This part of the Apennines corresponds to the transition zone between NA and SA which are characterized by a different geodynamic evolution. This is also the region where the Apenninic chain is larger. Moreover, a strong correlation between topography and seismic release is found all along the Apenninic chain. Profiles across the Apennines in fig. 6 better show the correlation between topography and seimic release. In profile AA′, representative of the northern arc, the width of the deforming belt is about 30 km and lies beneath the highest elevations of this part of the chain. BB′ passes through the «Ancona-Anzio» line emphasizing the broader zone of seismic release. In CC′ the seismic belt is again narrow (35 km) showing, also here, a good correlation with topography. The Calabrian arc also shows the same features of the previous profiles. In our opinion, understanding the relation between seismic activity, topography, and tectonic forces is still an open question.

The seismic moment map shown in fig. 5b and the profiles shown in fig. 6 suggest a «localised» type of deformation for the Apennines and not «diffuse» and spread over great distances as typically observed in continental deformation areas, like Greece or Turkey (McKenzie and Jackson, 1983; McKenzie, 1986). These regions of continental deformation, where the width of the deforming belt is large compared to the largest faults, are characterized by a distributed deformation which involves fault-bounded blocks and a variety of focal mechanisms (McKenzie and Jackson, 1983; Jackson and McKenzie, 1988, Jackson *et al.*, 1995). Along the Apennines, because the fault length associated with the largest earthquakes (see Pantosti and Valensise, 1990) is comparable to the width of the deforming belt (about 30 km), the similarity of shape and orientation of the moment tensor is not surprising (fig. 2), with the exception of the central part of the Apennines where the seismic belt reaches a width of nearly 100 km. For smaller earthquakes along the Apennines ($M < 6$), the width of the deforming belt is much larger than the length of faults. Extension can be taken by either normal or strike slip faults, which is what we observe for smaller events.

The tectonic implications are limited due to the very short time window covered by the instrumental data set. We compared the seismic moment maps with the areas struck by the large historical earthquakes, to verify whether the distribution of small earthquakes is meaningful with respect to the long-term seismic behaviour of the Apennines. The macroseismic information comes from the recent ING catalogue of the largest earthquakes which occurred in Italy in the past two millennia (Boschi *et al.*, 1995). We chose to show the maximum intensity areas (IX or X MCS) of the largest earthquakes since 1400. The largest earthquakes occurred mainly inside the deforming belt delineated by the seismic moment distribution (fig. 7a,b), except for a few of them (*e.g.*, Gargano seismic zone). Qualitatively, we argue that the width of the deforming belt pointed out by the 14 year time window of seismic moment distribution coincides with the belt where the largest earthquakes occur.

Noteworthy is that, in SA, zones surrounded by the highest intensity areas are characterized by very low seismic moment release, suggesting a correlation between large fault location and lack of low magnitude seismicity. The instrumental seismicity is confined to the areas adjacent to the main seismogenic faults that are, indeed, not associated with background seismicity. This suggests that the large active faults of the Southern Apennines seismogenic belt are quiescent. In NA, where active faults are generally not longer than 10-15 km, background seismic release appears almost continuous and homogeneously distributed along the belt. NA faults, at the scale of our representation, cannot be distinguished because they are hidden by earthquake location errors and cell size.



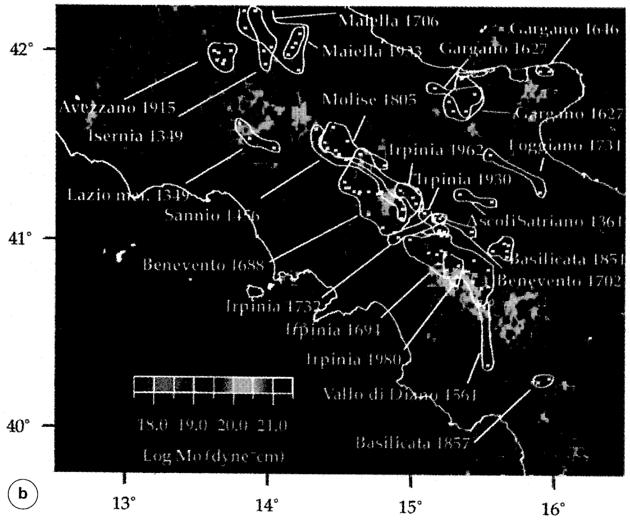


Fig. 7a,b. Comparison between seismic moment distribution and intensity points for the largest historical earthquakes since 1400 for: a) Northern Apennines; b) Southern Apennines. Only earthquakes with I_{max} equal to IX or X are shown. The intensity point data are from Boschi *et al.* (1995).

5. Conclusions

Seismicity patterns can be represented on maps using scalar seismic moment distribution. This furnishes original images which improve those provided by the symbolic representation of magnitudes. We have shown that such maps are useful to discriminate actively deformed regions. We point out that NA and SA are characterized by a different seismic release both in time and space, at least for the time window of 14 years of instrumental seismicity. NA are characterized by a rather constant moment rate of nearly $4.1 \cdot 10^{22}$ dyne · cm/yr while the rate for SA is larger and not constant in time, but dominated by the occurrence of sporadic seismic sequences. The spatial distribution of seismic moment shows that the seismic deformation along the Apennines is localized in a narrow belt of about 30 km, except for the transition zone between Northern and Southern Apennines where it is 100 km wide. This result is supported by the distribution of intensity points of historical earthquakes. In NA seismic release is continuous and homogeneous along the deforming belt; in SA we infer a correlation between the areas where large faults which ruptured during historical earthquakes are located and the lack of background seismicity. This suggests that during the investigated time period the seismic release is concentrated in the regions adjacent to the main seismogenic faults.

Acknowledgements

We thank F. D'Ajello Caracciolo and G. Valensise who collaborated in the early stage of this work. We also thank R. Console, P. De Natale, and M. Cocco for helpful suggestions and improvements to the paper. This work was partially funded by the EC project GeoModAp (contract EV5V-CT94-0464).

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(received July 21, 1997;
accepted December 30, 1997)