Short Note

A note on Northern Marche seismicity: new focal mechanisms and seismological evidence

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Abstract
A geodynamic interpretation of the Northern Marche region is difficult, the zone being characterized by complex structures which cannot be defined in the form of a simple, standard model. It is unquestionable that the geodynamic setting, whatever it is, bears a strong influence on the seismic hazard assessment of a region, and this is the background reason for the present note. In order to obtain a more detailed picture of seismological evidence in this zone, 11 new fault plane solutions of crustal events with $2.9 < M < 4.3$ were calculated, using data recorded by the national seismic network of the Istituto Nazionale di Geofisica e Vulcanologia in the period 1990-2000. The aim is to add local information to the previous studies by Frepoli and Amato (1997, 2000). A possible result of this new study is the division of the Northern Marche region into three areas with different focal mechanism categories: the inner area of the Apenninic belt, the Adriatic on-shore and the Adriatic off-shore. This note is intended to be a contribution to update seismological evidence in the Northern Marche region.

Key words *focal mechanisms – Northern Apennines – Adriatic off-shore – seismological evidence*

1. Introduction

For the Northern Apennines, available data consistently indicate active extension in the axial zone of the chain, where the main active structures consist of border faults to a series of NW-SE oriented intramontane basins (Lunigiana, Garfagnana, Mugello, Casentino, high Tiber Valley; *e.g.*, Galadini *et al.*, 2001). A general agreement exists on the fact that a roughly NE-SW oriented minimum stress axis (σ_3) is dominant in this part of the orogen (Borghini *et al.*, 2000).

In the studied rectangular area (outer Northern Apennines and related Adriatic off-shore; fig. 1), thrust tectonics has been widely documented by field surveys and by the interpretation of seismic reflection lines and deep wells (*e.g.*, Bally *et al.*, 1986; Barchi *et al.*, 1998).

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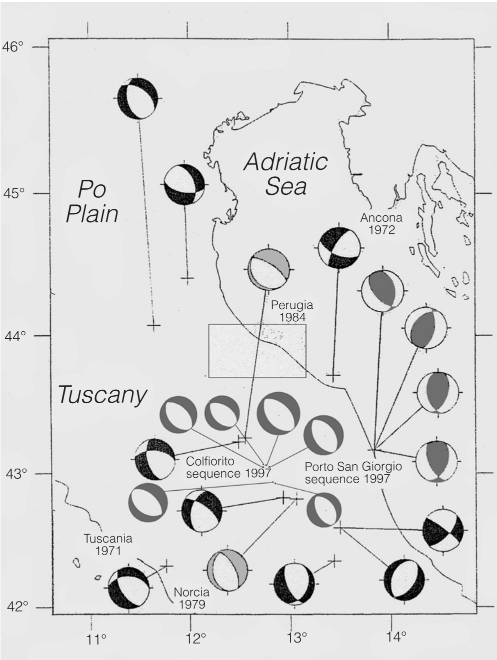

Fig. 1. Fault-plane solutions from Gasparini *et al.* (1985) (in black), CMT solutions (in light grey), solutions of the four largest events of the Porto San Giorgio sequence of July 1987 from Riguzzi *et al.* (1989) and of the six largest events of the Colfiorito sequence of September-October 1997 from Santini *et al.* (2003) (dark grey), and the studied area (in the box) of the Northern Marche region.

On-shore, available field data show that the most important evidence of active tectonics in the studied area is a well documented and generalised Pleistocene uplift (*e.g.*, Dramis, 1992; Borraccini *et al.*, 2002).

The studied area is the locus of a moderate – yet significant – tectonic activity, as also witnessed by historical and instrumental seismicity (I_{max} = IX MCS; M_{max} = 6; Gruppo di Lavoro CPTI, 1999; Frepoli and Amato, 2000). The sources of these earthquakes are not well known (Galadini *et al.*, 2000) and the possible existence and size of currently silent sources is a matter of study (Valensise and Pantosti, 2001).

2. Seismic data

Many focal mechanisms of moderate events with magnitudes ranging between 4.0 and 5.8 have been determined for the Northern Apennines. The available fault-plane solutions of the period 1939-1980, calculated from arrival times and polarities read from seismic bulletins, were reported by Gasparini *et al.* (1985): the best focal mechanisms are shown in fig. 1 as selected by Zoback (1992), which used *P* and *T* axes to divide the data into five main stress regime categories and an unknown category when the data provide no information on relative stress magnitudes (see table I).

Table I. Fault Plane Solutions (FPS) categories of Zoback (1992) used for classification of events shown in fig. 4.

Plunges of axes (pl)		FPS categories by Zoback (1992)	Figure 4 notation (label color)	Legenda
P	*T*			
pl ≥ 52°	pl ≤ 35°	NF	blue labels	normal-fault
40° ≤ pl ≤ 52°	pl ≤ 20°	NS	blue labels	with small-slip-component
pl < 40°	pl ≤ 20°	SS	red labels	strike-slip
pl ≤ 20°	pl < 40°	SS	red labels	strike-slip
pl ≤ 35°	pl ≥ 52°	TF	green labels	thrust-fault
pl ≤ 20°	40° ≤ pl ≤ 52°	TS	green labels	with small-slip-component
others	others	UC	black labels	unknown category

The figure displays also two Centroid Moment Tensor (CMT) solutions of the Norcia (1979) and Perugia (1984) earthquakes, the focal mechanisms of four events of the Porto San Giorgio seismic sequence of July 1987 (Riguzzi *et al.*, 1989) and the focal mechanisms of six events of the Colfiorito seismic sequence of September-October 1997 (Santini *et al.*, 2003). The two CMT solutions show an evident normal-fault regime along the portion of the Apenninic belt, while the strike-slip solution of the Ancona (1972) event, shows a compressional axis (P) with ENE-WSW orientation (Frepoli and Amato, 1997).

The only events in previous studies suggesting an evident active compression along the outer part of the Apenninic belt in the Northern Marche occurred on January 26, 1990, and December 15, 1991, as recolored in dark grey in fig. 2 by Frepoli and Amato (1997).

The earthquakes analyzed in this study are located in the Northern Marche from 43° to 44°N and from 12° to 13.5°E (table II). Arrival times and polarities were accurately re-picked from digital seismic waveforms recorded by the seismic network of the INGV in the period 1990-2000.

The duration magnitudes M_d of these events range between 3.0 and 4.2. The smaller events are not considered because their mechanism cannot be calculated with good accuracy due to the lack of off-shore seismograph stations: therefore it is advisable to consider magnitudes greater than 3-3.5. The locations of considered

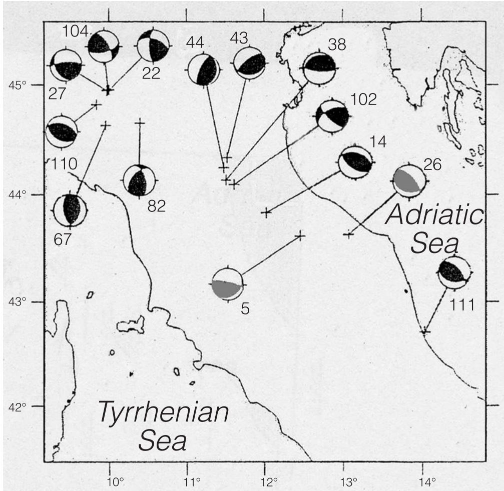

Fig. 2. Thrust-fault solutions from Frepoli and Amato (1997): the solutions of seismic events which occurred in the studied area are recolored in dark grey.

Table III. Velocity model adopted for focal mechanism computation.

Velocity (km/s)	Depth (km)
5.7	0-12
6	12-18
6.2	18-26
6.7	26-35
7.5	35-

Table II. Parameters of the seismic events whose epicentres and focal mechanisms are shown in fig. 4.

Label	Year	Month	Day	Lat (°N)	Long (°E)	Depth (km)	M_d	Strike	Dip	Rake	rms (s)	F
1	1990	August	27	44.02	13.177	5.0	3.9	115°	50°	0°	0.10	0.00
2	1991	November	22	43.842	12.062	5.9	3.0	165°	60°	−70°	0.02	0.03
3	1996	June	28	43.769	12.995	27.5	3.4	155°	40°	110°	0.16	0.12
4	2000	February	22	43.79	12.083	8.0	3.0	265°	65°	−120°	0.01	0.13
5	2000	May	5	44.014	13.192	5.0	4.1	195°	25°	30°	0.25	0.20
6	2000	June	25	43.886	13.147	5.0	3.5	130°	90°	−50°	0.16	0.18
7	2000	June	27	43.883	13.200	5.0	3.4	115°	85°	40°	0.06	0.14
8	2000	August	1	43.929	12.318	5.0	4.2	160°	70°	130°	0.02	0.10
9	2000	December	27	43.678	12.245	5.0	3.2	115°	30°	−80°	0.13	0.12

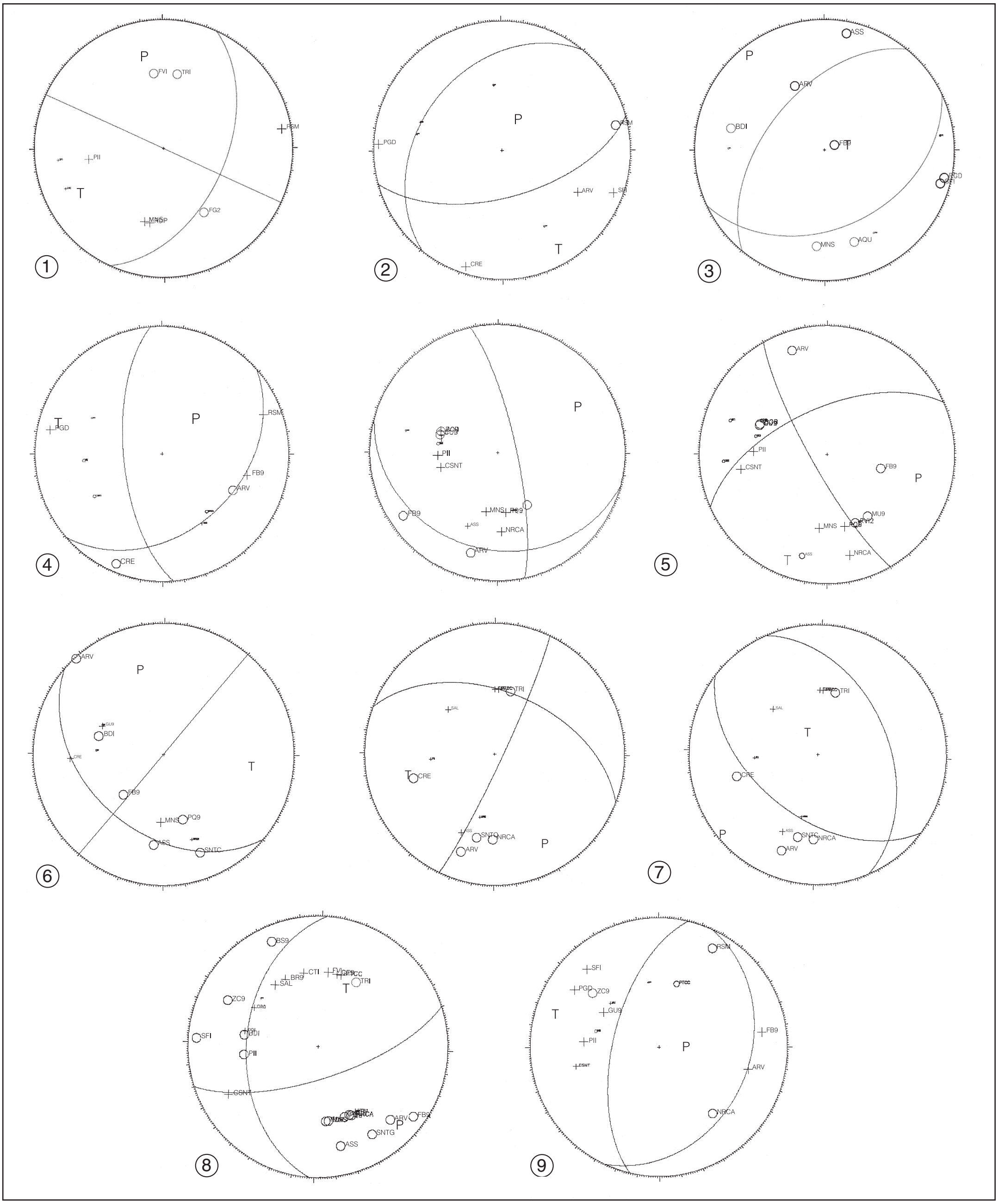

Fig. 3. Lower hemisphere, equal-area projection of the 11 selected fault plane solution presented in this study. Compression and dilatation polarities are indicated with crosses and circles, respectively. The 9 focal mechanisms of fig. 4 are the first solutions; in the case of double solutions (5 and 7), the second solutions with a worse stability are shown.

events were verified with the computer program HYPOINVERSE (Klein, 1989) using the velocity structure reported in table III.

Good values of rms residuals were obtained for most analyzed earthquakes; in particular the rms values of locations have residuals below 0.25 s; furthermore, a misfit of polarity quality factor (F) was below 0.20. The fault plane solutions were calculated with the program FPFIT (Reasenberg and Oppenheimer, 1985) and the 11 fault plane solutions were obtained with more than eight polarities.

3. New focal mechanisms

This classification is founded on the assumption that the earthquake focal mechanisms reflect the state of stress of the Northern Marche region, implying that the P- and T-axes, to a first approximation, correspond to the principal stress axes σ_1 and σ_3, respectively.

Figure 3 shows fault plane solutions for 9 events which occurred in the Northern Marche from 1990 to 2000. The multiple solutions are due both to the low weight of some polarities and to the low azimuthal coverage of data on the focal sphere. In fig. 4 the solutions with the smaller uncertainties were chosen, represented by the first solutions of the 9 focal mechanisms of fig. 3; if one considers the alternative solutions, the tectonic setting does not change much.

The 9 first solutions of fig. 3 are divided as follows:

– three solutions (labels 2, 4 and 9) belong to the pure normal-fault category (NF);

– two solutions (labels 3 and 5) belong to the pure thrust-fault category (TF);

– one solution (label 8) belongs to the thrust-fault with small strike-slip category (TS);

– three solutions (labels 1, 6 and 7) are included in the unknown-stress-field category (UC).

If plunges of the axes of solutions are inside or outside the ranges defined in table I with differences of only one degree these solutions were assigned to the appropriate category: in this case, one solution (label 5) belongs to the thrust-fault with small strike-slip category with a difference of 0.2 degrees, as it is possible to see in table II.

The eastern part of the examined area was also affected by a few historical events of magnitude larger than 5.5. The estimated sources of these events are shown in fig. 4. The northernmost box (west of Pesaro) represents the source of the Coriano earthquake (December 25, 1786;

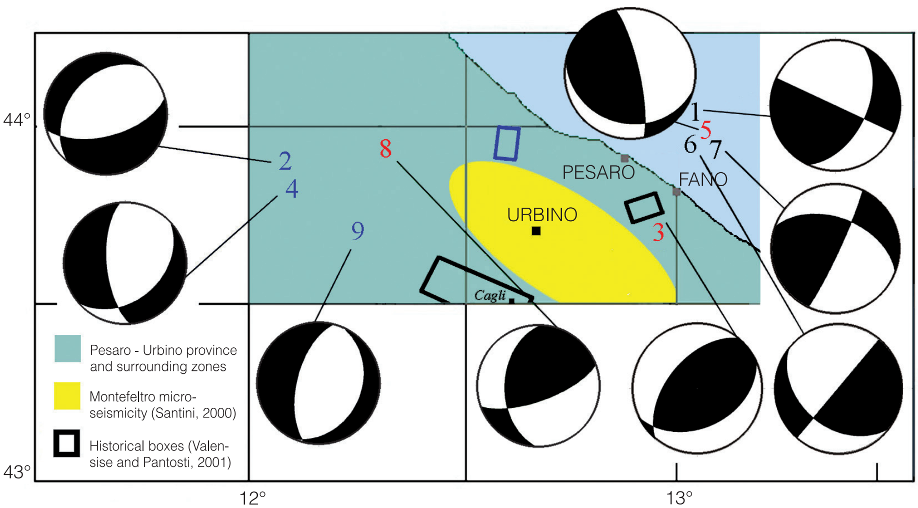

Fig. 4. Epicentre location and focal mechanisms of seismic events listed in table II. Fault Plane Solution (FPS) categories refer to Zoback (1992; table I). Historical boxes after Valensise and Pantosti (2001).

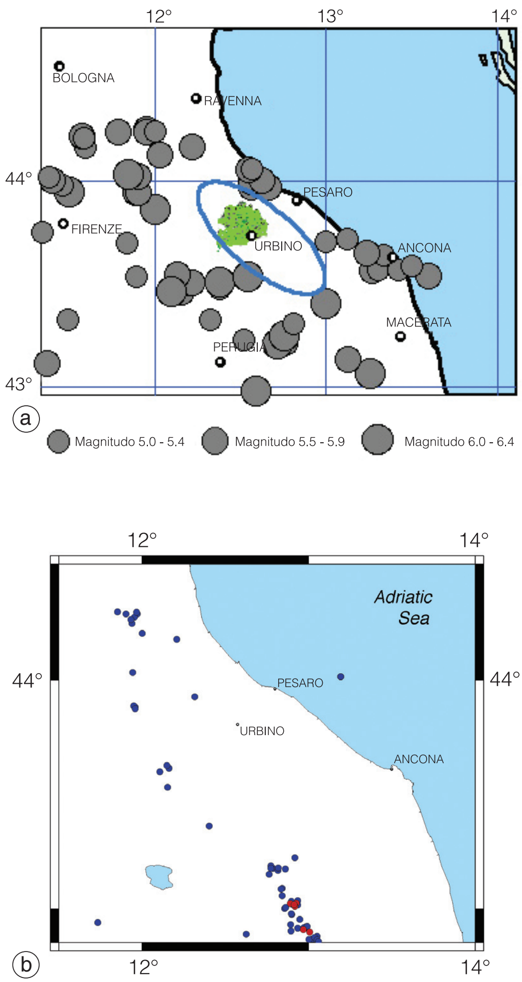

Fig. 5a,b. a) Historical seismicity examined by Santini (2000), from Boschi *et al.* (1997) and Gruppo di Lavoro CPTI (1999); The Montefeltro area (green zone) is characterized by limited values in terms of intensity and frequency (blue ellipse). b) Epicentres of seismic events with magnitude ≥ 4 recorded by the national seismic network of INGV from year 1990 to 2003 (blue circles with magnitude < 5 and red circles with magnitude ≥ 5).

43.98°N; 12.58°E), an event of intensity I_0=VIII and equivalent magnitude M_e = 5.5 (Gruppo di Lavoro CPTI, 1999). This source is derived by the analysis of the isoseismal map produced by Guidoboni and Ferrari (1986); it strikes 20º ± 15º and is 5.6 km long and 5.2 km wide.

The two other sources, instead, are exclusively derived from intensity data by applying the method proposed by Gasperini *et al.* (1999), as the quality of the obtained solution allowed the representation of the source by an oriented rectangular box (Valensise and Pantosti, 2001). The box south-west of Fano (43.71°N; 12.97°E) corresponds to the September 21, 1897 earthquake (I_0= VII and M_e = 5.4; Gruppo di Lavoro CPTI, 1999) and strikes 73º ± 48º. The southernmost box represents the seismic source for the Cagli event (43.59°N; 12.51°E) which occurred on June 3, 1781 (I_0= IX-X and M_e = 6.2; Gruppo di Lavoro CPTI, 1999). This source strikes 118º ± 17º.

4. Conclusions

The Northern Apennine chain was described as a tectonic belt characterized by extension (*e.g.*, Lavecchia, 1988; Decandia *et al.*, 1998). General agreement exists on the fact that a NE-SW oriented minimum stress axis (σ_3) is dominant in the axial zone of the chain (Mariucci *et al.*, 1999; Boncio *et al.*, 2000). A possible result of this study is the division of the Northern Marche region into three areas with different seismological evidences:

– the inner area of the Apenninic belt, which is caracterized by extension;

– the Adriatic on-shore, which shows evidence of active compression;

– the Adriatic off-shore, which shows not very clear evidence of active compression.

In the extensional area, the *T*-axes of normal solutions (2, 4 and 9 in fig. 4) do not have a homogeneous orientation, while in the compressional area the *P*-axes of thrust solutions (3 and 8 in fig. 4) have a dominant NW-SE direction (in agreement with compressive stress regime mapped by Montone *et al.* (1999) in northern surrounding zones of the Northern Marche).

Finally, the Adriatic off-shore zone shows not clear seismological evidence of nevertheless possible active compression; on the other hand no earthquake with magnitude ≥ 5 occurred during historical times in the off-shore zone of the Northern Marche region (fig. 5a,b).

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