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A note on central-northern Marche seismicity: new focal mechanisms for events recorded in years 2003-2009

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ABSTRACT A focal mechanism study was carried out for seismic events that occurred in the central-northern Marche region between 2003 and 2009. The study is based on earthquake data, having magnitude $M \leq 3.5$, recorded by the seismic network of the Istituto Nazionale di Geofisica e Vulcanologia. The results show that events tend to cluster into different sectors, each being characterized by a roughly homogeneous seismological behaviour. The new data confirm the occurrence of an extensional stress regime in the axial zone of the mountain belt, generally characterized by vertical or sub-vertical P-axes. On the other hand, a different stress regime appears to dominate in the outer Apennine sector, extending from the high valley of the Marecchia River to the foothills west of Ancona. Here, the well-known extensional domain of the axial zone of the Apennine mountain belt gives way, through an area characterized by oblique-slip faulting and variably plunging P-axes, to a regime dominated by roughly horizontal P-axes along the Adriatic onshore. Roughly horizontal P-axes characterize also the adjacent Adriatic Sea sector, although some variability in the maximum compression direction occurs in the offshore area.

Key words: seismicity, focal mechanisms, central Italy, Marche.

1. Introduction

The seismicity of the northern Marche region, as recorded over the past 27 years (1983-2009) by the Istituto Nazionale di Geofisica e Vulcanologia's (INGV) seismic network, is characterized by low- to medium-magnitude ($M \leq 5.0$), dominantly shallow events that tend to cluster along the Apennine belt and adjacent foothills. Deep earthquakes (located at depths locally in excess of 40 km) are few and scattered. On the other hand, no earthquake with magnitude $M > 5$ has occurred in the Adriatic offshore of central-northern Marche in recent times (Montone *et al*., 2004; Chiarabba *et al*., 2005; Pondrelli *et al*., 2006; Boncio and Bracone, 2009; Piccinini *et al*., 2009).

Due to the low level of seismicity in the study area, it is fundamental to analyze in detail even moderate seismic activity and to obtain focal mechanisms from low- to medium-magnitude earthquakes. As a matter of fact, new seismological constraints are needed for an effective integration with geological, geomorphic and further geophysical information in order to obtain useful insights into the stress field controlling active deformation in the study area. This study is intended to update available seismological evidence, with the aim of adding new information to previous studies (e.g., Frepoli and Amato, 1997, 2000; Santini, 2003; Santini and Martellini, 2004). Possible geodynamic implications for the active tectonic behaviour of the central-northern Marche region are also briefly addressed.

The active tectonic behaviour of the study area has been intensely investigated (e.g., Dramis, 1992; Lavecchia *et al*., 1994; Meletti *et al*., 2000; Di Bucci *et al*., 2003; Borraccini *et al*., 2004). As already mentioned by Di Bucci and Mazzoli (2002), an active NE–SW extension along the axial zone of the Apennine chain is well established and widely documented (Mariucci *et al*., 1999; Boncio *et al*., 2000 and references therein). On the other hand, although all workers agree on the occurrence of active deformation in the external zone of the fold and thrust, the size of active structures – and consequently maximum expected earthquake magnitude – and their kinematics are still a matter of debate and require further investigation. Furthermore, based on available seismological and geological constraints, the active tectonic behaviour of this outer Apennine sector cannot be straightforwardly interpreted in terms of a simple geodynamic model. In particular, the issue of activity vs. inactivity, and/or modes of reactivation of Apennine fold-and-thrust belt-related structures is particularly controversial [compare, e.g., Boncio *et al*. (2000) with Di Bucci and Mazzoli (2002)]. In order to obtain a more detailed picture of the seismological behaviour of the study area and to contribute to a better definition of its active tectonic behaviour, 11 new fault plane solutions of crustal events with $M \leq 3.5$ have been calculated, using data recorded by the INGV national seismic network in the years 2003-2009.

2. Previous seismological data

In order to obtain a comprehensive picture of the seismological behaviour of the northern Marche area, the new data set provided in this study needs to be integrated with pre-existing information within the framework of a larger regional context. To this purpose, a review of pre-existing seismological data is carried out in this section, taking into account focal mechanisms of events from the whole central-northern Apennines. Two distinct periods of observation are considered: 1970-1989 and 1990-2002.

2.1. The years 1970-1989

Fault plane solutions for the years 1970-1989, based on first motion polarities obtained from waveforms and listed in seismic bulletins, have been determined from Gasparini *et al*. (1985). Fig. 1 shows the Centroid Moment Tensor (CMT) solutions of the Norcia (1979) and Perugia (1984) earthquakes, the solutions for the four larger events of the July 1987 Porto San Giorgio sequence (Riguzzi *et al*., 1989), and the solutions for the six larger events of the September-October 1997 Colfiorito sequence (Santini *et al*., 2004). The two CMT solutions indicate an extensional regime along the Apennine mountain chain, whereas the strike-slip solution for the 1972 Ancona (1972) event is characterized by an ENE-WSW-oriented, horizontal maximum compression (P) axis (Frepoli and Amato, 1997).

2.2. The years 1990-2002

Many focal mechanisms of low and moderate magnitude have been determined for the northern Apennines in the years 1990-2002. For the northern Marche region (box in Fig. 1),

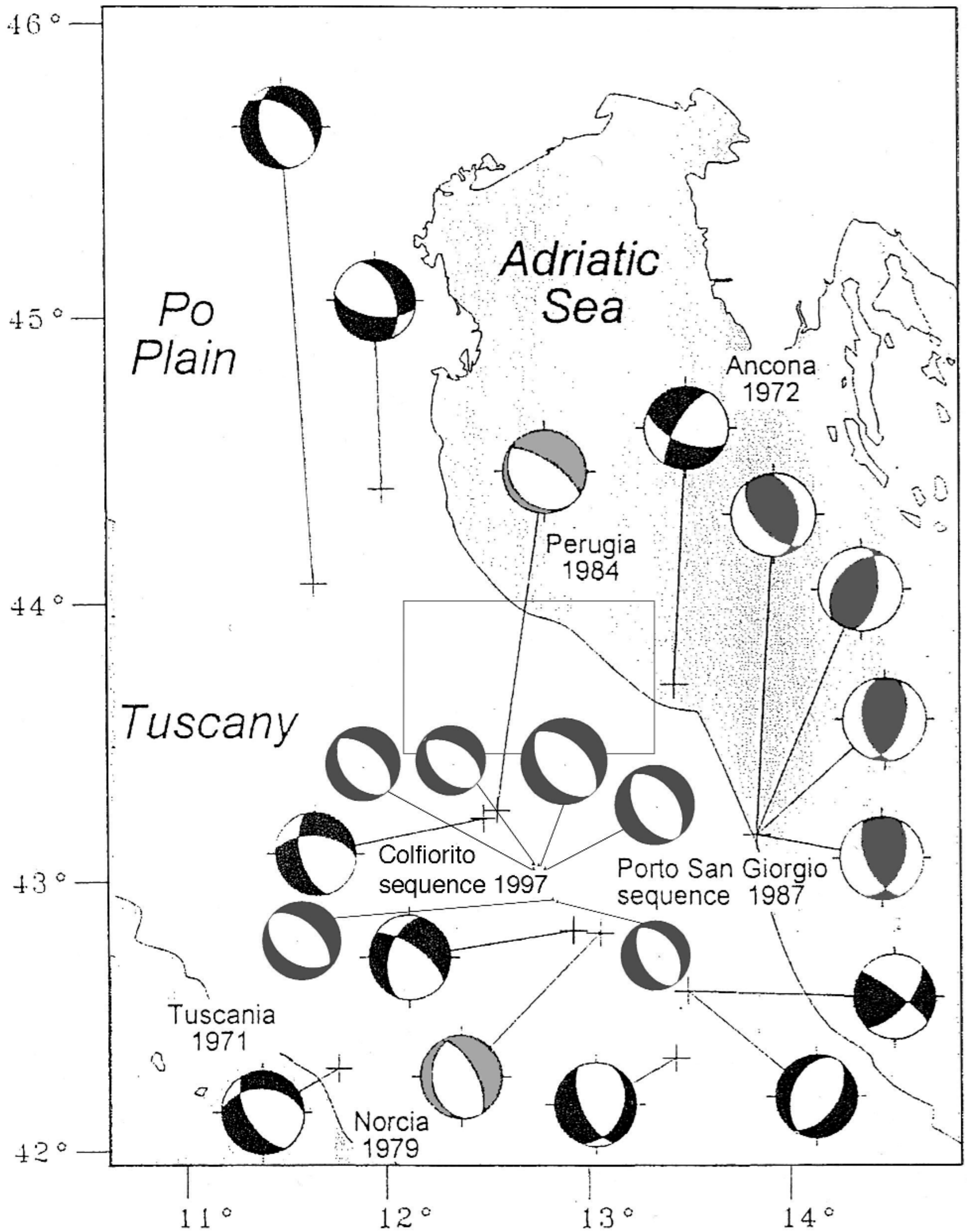


Fig. 1 - Map of NE Italy showing fault-plane solutions (in black) from Gasparini *et al*. (1985), CMT solutions (in light grey) for the Norcia and Perugia events, focal mechanisms (in dark grey) for the four largest events of the July 1987 Porto San Giorgio sequence (Riguzzi *et al*., 1989) and for the six largest events of the September-October 1997 Colfiorito sequence (Santini *et al*., 2004), [after Frepoli and Amato (1997), modified]. The box represents the area studied by Santini and Martellini (2004).

Table 1 - Summary of event parameters for seismicity recorded in years 1990-2002. Event time, hypocentre coordinates and depth, duration magnitude, fault plane solution, rms residuals, and quality factor F are shown (from Santini and Martellini, 2004).

Event	Date	Lat. N (°)	Lon. E (°)	Depth (km)	M_D	Strike (°)	Dip (°)	Rake (°)	rms	F
1	1990/08/27	44.020	13.177	5.0	3.9	115	50	0	0.10	0.00
2	1991/11/22	43.842	12.062	5.9	3.0	165	60	-70	0.02	0.03
3	1996/06/28	43.769	12.995	27.5	3.4	155	40	110	0.16	0.12
4	2000/02/22	43.790	12.083	8.0	3.0	265	65	-120	0.0	0.13
5	2000/05/05	44.014	13.192	5.0	4.1	195	25	30	0.25	0.20
6	2000/06/25	43.886	13.147	5.0	3.5	130	90	-50	0.16	0.18
7	2000/06/27	43.883	13.200	5.0	3.4	115	85	40	0.06	0.14
8	2000/08/01	43.929	12.318	5.0	4.2	160	70	130	0.02	0.10
9	2000/12/27	43.678	12.245	5.0	3.2	115	30	-80	0.13	0.12
10	1999/02/23	43.700	12.830	20.0	2.8	140	60	-30	0.08	0.04
11	2002/09/08	43.470	12.440	18.0	3.0	120	76	-40	0.15	0.13

available fault-plane solutions for this time span - calculated from arrival times and polarities - are reported by Santini and Martellini (2004). Event parameters and the best focal mechanisms are shown in Table 1 and in Fig. 2. In Fig. 2, moreover, we also show the focal mechanisms determined by Frepoli and Amato (1997), indicated by the same label numbers used by the authors. Two events - May 8, 1990 (grey label 8) and January 17, 1993 (grey label 50) - are indicative of an extensional regime in the Toscana and Umbria foothills adjacent to the northern Marche region. On the other hand, the January 26, 1990 (grey label 5) and December 15, 1991 (grey label 26) events record a compressional regime, whereas the April 6, 1993 event (grey label 56) is of strike-slip type. Based on these results, Santini and Martellini (2004) recognized three sectors characterized by specific seismological characteristics in the Pesaro-Urbino province (Fig. 2): a) an extensional Apennine chain area; b) a compression-dominated area comprised between the high valley of the Marecchia River and the low valley of the Metauro River; and c) a further compressional area located in the Adriatic offshore.

3. New focal mechanisms

The seismic events analyzed in this study are located in the central-northern Marche region, between latitudes 43.5° to 44.0° N and longitudes 12.0° to 13.5° E. The area extends from the town of Ancona to that of Gabicce Mare along the coast and from the town of Fabriano to the Montefeltro area along the Apennine mountain belt (Fig. 3a).

The analyzed events, spanning from January 2003 to December 2009, have been selected from the INGV Seismic Bulletin (http://bollettinosismico.rm.ingv.it/). Events with local magnitude (and/or duration) equal or larger than 3.5 have been relocated, and the related focal mechanisms calculated. The velocity model used for the hypocentre location (HYPOINVERSE; Klein, 1989) is that adopted by Santini (2003) for the northern Marche area (Table 2a). For the focal

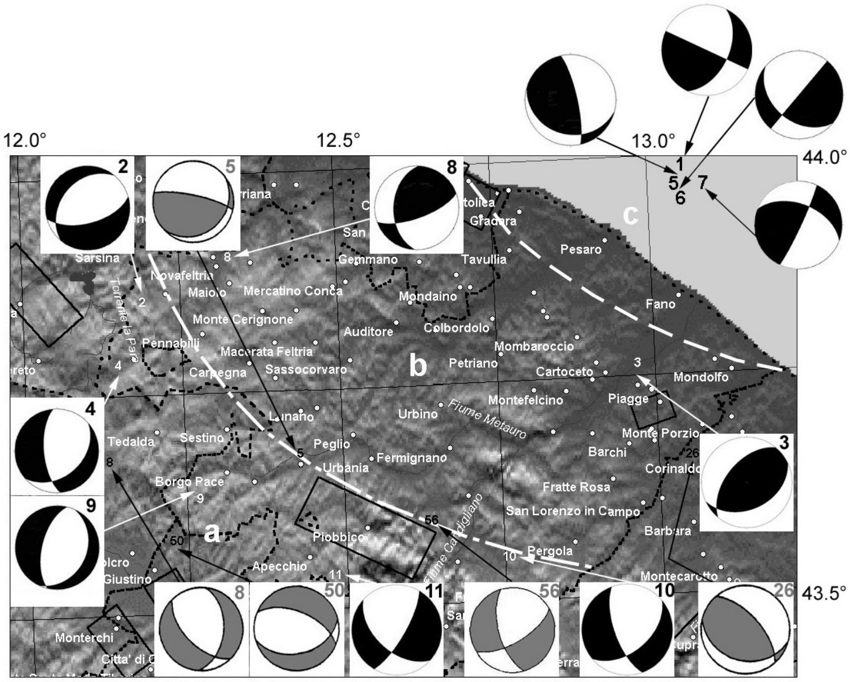
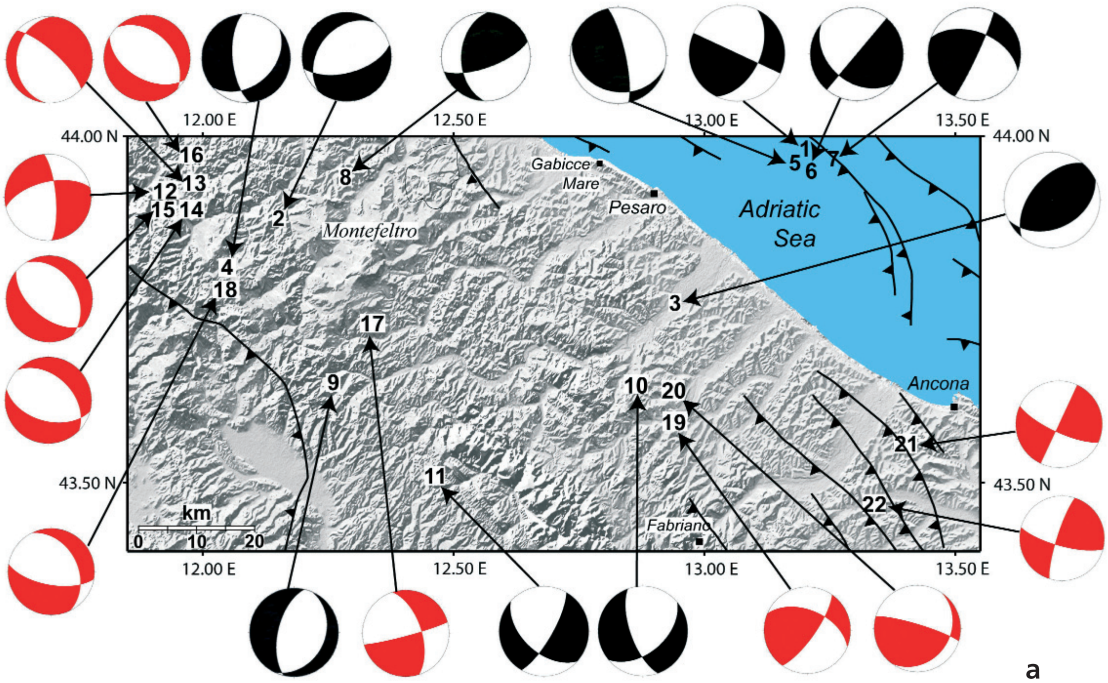
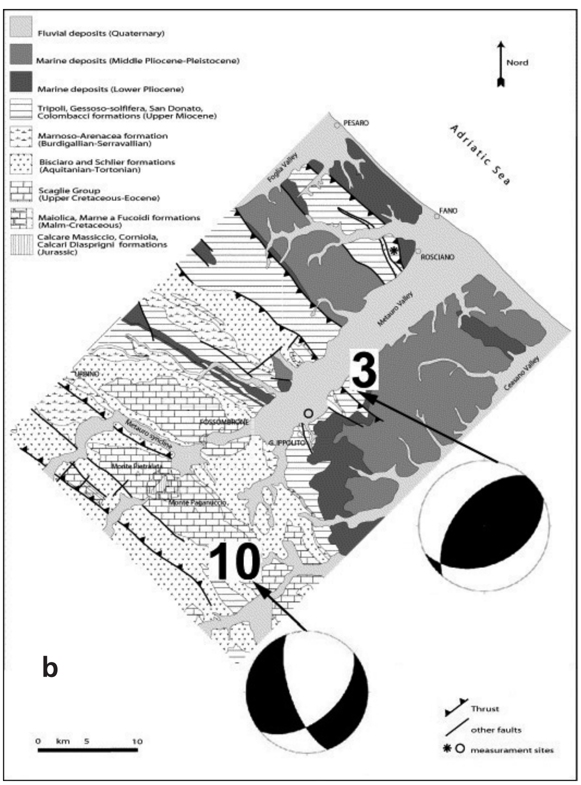
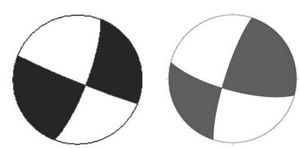


Fig. 2 - Focal mechanisms for events recorded in the years 1990-2002 [from Santini and Martellini (2004) in black, and Frepoli and Amato (1997) in grey]. 'a', 'b' and 'c' are seismogenic belts as defined by Santini and Martellini (2004) (see text).

mechanism determination, the FPFIT algorithm of Reasenberg and Oppenheimer (1985) has been used. The new focal mechanisms (Fig. 4) provide double solutions (labelled A and B) for three events (August 30, 2006; October 21, 2006, UTC 8:55; and January 25, 2007). In these instances, multiple solutions are due to the low azimuth cover of data onto the focal sphere. The main seismological parameters are summarized in Table 3. This includes: (i) the main focal plane parameters, (ii) plunge of P and T axes, (iii) fault type (according to the classification scheme of Zoback, 1992), (iv) the residual (rms) for the hypocentre calculation, and (v) the misfit (F) related to the polarity for the resolution of the focal mechanism (F = 0.0 representing a perfect fit, and F = 1.0 representing a complete misfit). These data show that rms values are ≤ 0.20 s for three events, while three rms values are in the range of 0.20 s < rms ≤ 0.30 s and the remaining rms values are larger than 0.30 s. For the resolution of the focal mechanisms, the polarity quality factor (F) is characterized by values lower than 0.23. For cases with double solutions, we have chosen the solution with the lower residual and/or misfit F values. A particular case is the August 30, 2006 event for which the two solutions show similar rms and F; however, for this event the different plunges of the principal (P and T) axes do not change the focal mechanism types obtained (FPS), substantially. Taking into account the first solutions only, three events display F values below 0.11, and six are characterized by F values comprised between 0.11 and 0.20. The calculation of the plunge of P and T axes gives a result of five focal mechanisms of normal fault (NF) type, four focal mechanisms of strike-slip (SS) type, and one of "Unknown Category" (UC).







Event parameters	RCMT	this study
Date (dd/mm/yy)	20/09/09	20/09/09
Time (UTC)	03:50	03:50
Lat (N)	43.48	43.42
Long (E)	13.48	13.39
Depth (km)	33.00	36.57
Magnitude	4.6	4.6
Strike (°)	112	105
Dip (°)	87	75
Rake (°)	-168	170
FPS	*SS*	*SS*

c

Fig. 3 - (a) Fault-plane solutions from Santini (2003) (in black), and fault plane solutions calculated in this study (in red). (b) Simplified geological sketch map of the Metauro River valley area, showing FPS for earthquake epicentres located in the area (from Santini, 2003), and Neogene thrusts and Quaternary faults (from Di Bucci *et al*., 2003). (c) Focal mechanism for the September 20, 2009 event. Fault plane solution calculated in this study (light grey) is compared with the fault plane solution (dark grey) from RCMT (http://www.bo.ingv.it/RCMT).

Table 2 - Velocity models used for focal mechanism computation: a) northern Marche velocity model [from Santini (2003); b) central Adriatic velocity model [modified after Cassinis *et al*. (2003) and Chiarabba *et al*. (2005)].

a

V_p (km/s)	Layer top (km)
5.7	0.0
6.0	12.0
6.2	18.0
6.7	26.0
7.5	35.0

b

V_p (km/s)	Layer top (km)
5.7	0.0
6.0	8.0
6.2	12.0
7.0	24.0
8.0	35.0

The focal mechanisms relative to the January-February 2003 seismic swarm of Montefeltro (five events labelled as nos. 12 to 16) are of dominant normal type, consistent with the extensional tectonic regime characterizing the Apennine foothills. The focal mechanism for event no. 18 is also of normal type, compatible with its location along the axial zone of the Apennine chain. On the other hand, event no. 17, of strike-slip type, is also located along the same 'a' sector (northern Apennine belt, Fig. 2) as defined by Santini and Martellini (2004). However, it should be noted that this is a deeper event (hypocentre depth of 34.52 km) with respect to those located along the Apennine foothills (characterized by hypocentre depth < 20 km). Hypocentre depths of about 29 km are obtained for events nos. 19 and 20. The calculation of the plunge of P-and T-axes results in a strike slip-type focal mechanism for event no. 19, whereas the plunge of the T-axis obtained for the first focal solution is a few degrees off with respect to the strike-slip category for event no. 20. Event no. 21, located near the Ancona coast at a depth of about 23 km, is also of strike-slip type. It is worthy of note that the latter three events, as well as event no. 17, are located in the 'b' (onshore, Fig. 2) area of Santini and Martellini (2004) and are characterized by a greater hypocentre depth with respect to the Apennine chain and Apennine foothills areas.

3.1. The September 20, 2009 Montefano event

In order to analyze the M_L 4.6, September 20, 2009 Montefano event, located at a latitude of 43.420° N and a longitude of 13.386° E, a different velocity model has been used taking into account the variation in crustal structure. As this event is located along the central Adriatic coast (Figs. 3a and 3b), the model adopted (with some modification, as explained in the following) is that of Cassinis *et al*. (2003) and Chiarabba *et al*. (2005) (Table 2b).

The rms values were too high in order to localize event 22 using the same velocity model applied to localize the other events. Therefore, we considered different velocity models with the aim of obtaining a lower rms value. We finally obtained rms residuals reduced by about 50% by varying layer depths and considering the presence of upper mantle rocks at depths deeper than 30 - 35 km. In the central Adriatic model, differently from the model of Table 2a, the shallower layers are characterized by a reduced thickness and the lower crust consists of a 12-km thick single layer having a velocity of 7.0 km/s. We used this second model also for event 21; in this case, the rms residuals do not change significantly with respect to the first model, due to the similarity of the two considered models from the Earth's surface to the hypocentre depth of 23 km.

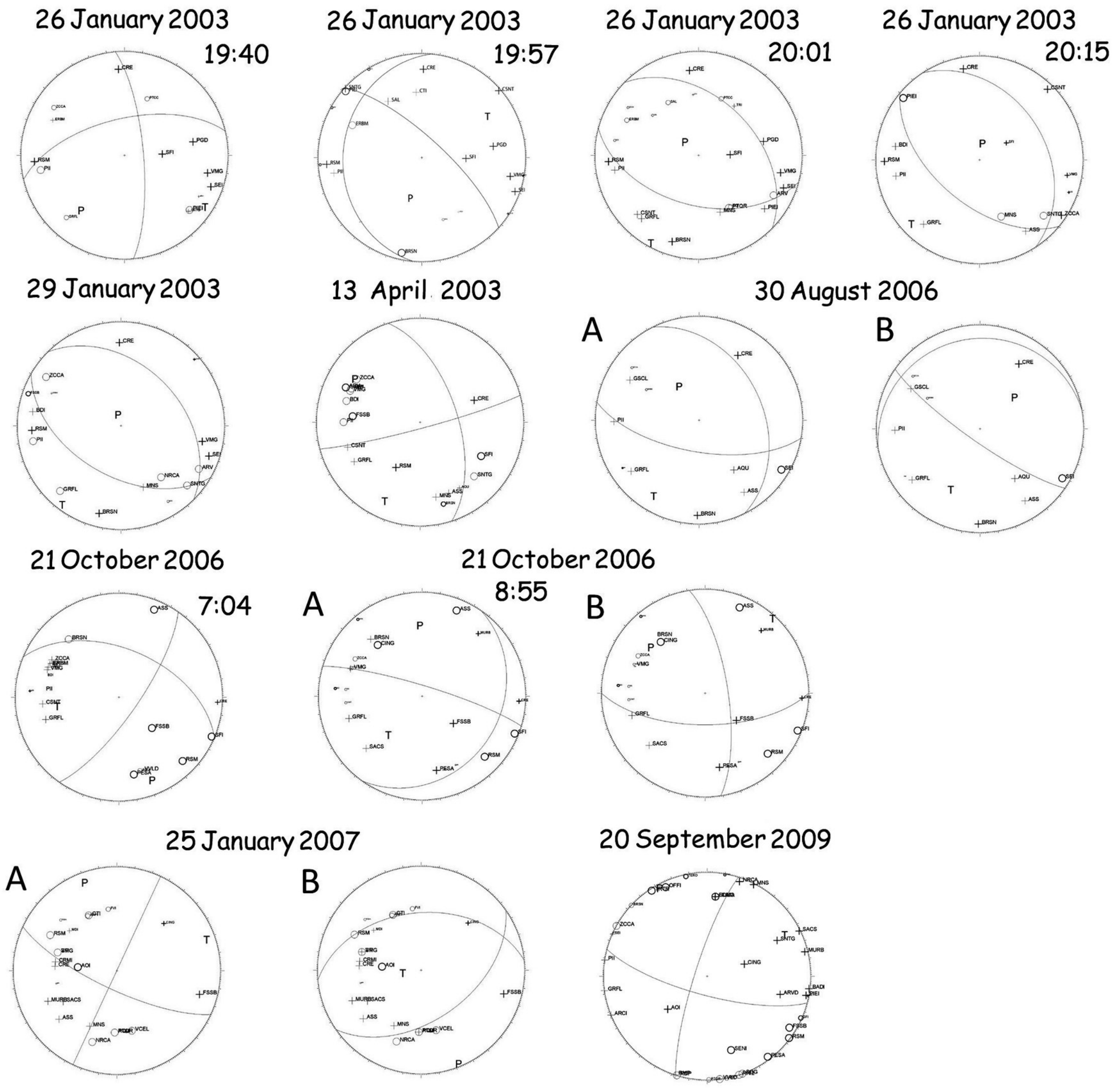


Fig. 4 - New focal mechanisms for events recorded in years 2003-2009, with double solutions for 3 out of 11 events (A and B labels).

The focal mechanism obtained for the Montefano event is comparable to that extracted from the RCMT catalogue (http://www.bo.ingv.it/RCMT). Comparing the two focal mechanisms (Fig. 3c) it may be observed that, although different techniques have been used, the obtained results are similar and are characterized by a dominantly horizontal, NW oriented compression.

4. Concluding remarks

The new focal mechanisms obtained in this study (Fig. 3a, in red) contribute to a better, more detailed definition of the composite picture outlined by previous studies for the seismotectonics

Table 3 - Summary of event parameters for seismicity recorded in the years 2003-2009. Event time, hypocentre coordinates and depth, magnitude, fault plane solution, plunge of P-and T-axes, FPS categories, rms residuals, and quality factor F are shown.

Event	Date	Time	Lat. N (°)	Lon. E (°)	Depth (km)	Magnitude	Strike (°)	Dip (°)	Rake (°)	P-axis (°)	T-axis (°)	FPS	rms	F
12	2003/01/26	19:40	43.906	11.925	10.83	3.5 M_L	355	75	-150	31.64	9.12	SS	0.20	0.14
13	2003/01/26	19.57	43.903	11.956	13.40	4.3 M_L	185	25	-40	56.40	26.66	NF	0.43	0.12
14	2003/01/26	20:01	43.905	11.912	11.47	4.0 M_L	105	50	-110	74.48	3.12	NF	0.18	0.11
15	2003/01/26	20:15	43.921	11.884	7.69	4.3 M_L	130	55	-100	77.42	9.49	NF	0.30	0.05
16	2003/01/29	23:50	43.910	11.945	15.87	3.7 M_d	120	50	-100	81.10	4.53	NF	0.22	0.22
17	2003/04/13	22:54	43.725	12.299	34.52	3.6 M_d	75	85	-150	24.45	16.89	SS	0.36	0.07
18	2006/08/30	10:01	43.755	12.061	9.55	3.7 M_L	100	65	-120	58.63	14.84	NF	0.17	0.13
							125	80	-80	53.96	34.26	NF	0.17	0.13
19	2006/10/21	7:04	43.583	12.939	28.84	42 M_L	35	75	40	14.83	38.47	SS	0.34	0.22
20	2006/10/21	8:55	43.594	12.934	29.73	3.6 M_L	35	25	20	32.59	47.99	UC	0.33	0.20
							90	65	-160	31.20	4.57	SS	0.33	0.22
21	2007/01/25	21:36	43.560	13.444	22.85	3.7 M_L	115	75	-180	10.54	10.54	SS	0.22	0.14
							55	50	70	3.12	74.48	TF	0.22	0.22
22	2009/09/20	3:50	43.420	13.386	36.57	4.6 M_L	105	75	170	3.69	17.55	SS	0.39	0.05

of the investigated area (e.g., Santini, 2003; Borraccini *et al*., 2004; Santini and Martellini, 2004). The new focal mechanisms obtained in this study confirm the well-known extensional activity along the axial zone of the Apennine mountain belt. This extensional domain gives way, toward the NE, to an area characterized by oblique-slip faulting and variably plunging P-axes. This belt extends in a NW-SE direction from the high valley of the Marecchia River to the foothills west of Ancona, the new focal mechanisms obtained in this study allowing one to further extend the 'transitional area' already proposed by Santini and Martellini (2004) towards the SE.

Further to the NE, a mainly compressional domain occurs along the Adriatic onshore and adjacent offshore areas. This domain, displaying both reverse and strike-slip fault plane solutions, is also characterized by variable orientation of the maximum compression, therefore outlining a complex tectonic behaviour. The new focal mechanisms calculated for the Adriatic onshore area effectively integrate the pre-existing pattern of very deep crustal – possibly upper mantle for Montefano – seismicity, ranging from a 23 to a 37 km depth. Taking into account their epicentral location, these earthquakes would be probably located in the footwall in the easternmost thrust of the Apennine system, should a thin-skinned thrusting model be adopted for the outer Marche Apennines (e.g., Boncio *et al*., 2000). In this case, these events would represent a deformation within the Adria foreland block, rather than within the deformed Apennine crust. On the other hand, in the case of a thick-skinned [basement-involved tectonic inversion; Coward *et al*. (1999)] model being adopted for the outer fold-and-thrust structures (Mazzoli *et al*., 2001), these deep earthquakes would be located in the orogenic basement of the Marche Apennines.

In any case, the related focal mechanisms (including the September 20, 2009, M = 4.6, deep Montefano earthquake) indicate a dominant NW-SE to N-S oriented compression in the Adriatic onshore area, not compatible with a NE-directed shortening that would be expected for an actively building fold-and-thrust belt, nor with a rolling-back Adria lithosphere in front of an advancing Apennine thrust front. On the other hand, it should be noted that the two new focal mechanisms obtained for the area just SW of the town of Ancona (including the deep Montefano event; Fig. 3c) are fully compatible with the seismotectonic behaviour inferred for the whole Adria block, including the activity of dextral, roughly E-W trending, deep (lithospheric), long-lived faults (Di Bucci and Mazzoli, 2003).

Pre-existing focal mechanisms from the Adriatic offshore (cluster of events 1, 5, 6 and 7) display a marked variability in the orientation of the P-axis. These events are shallow focus (5 km) and probably represent deformation within the Apennine deformed crust (i.e., in the hanging wall, or anyway SW of the outer thrust of the system) independently of the model – thin-skinned or thick-skinned – adopted for fold-and-thrust structures. Within this cluster, the seismic moment, and therefore the deformation, is dominated by the 2000 main shock (event 5), that is the one compatible with a NE-directed compression. Its seismic moment is ~ 4.5 times the summed moment of the two 2000 aftershocks (events 6 and 7) and it is ~ 1.5 times the summed moment of events 1, 6 and 7. Therefore, a weighted analysis of this cluster bears important seismotectonic implications, as it leaves the possibility of active, though cryptic, Apennine NE directed thrusting open.

In any case, although the complex, inherited fault structure characterizing the investigated area (Coward *et al*., 1999) may trigger significant local variations of the stress field resolved by seismological analysis, the gathering of new earthquake focal mechanisms is progressively improving our understanding of the seismotectonic behaviour of the central-northern Marche region.

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REFERENCES

Boncio P. and Bracone V.; 2009: *Active stress from earthquake focal mechanisms along the Padan–Adriatic side of the Northern Apennines (Italy), with considerations on stress magnitudes and pore-fluid pressures.* Tectonophysics, **476**, 180-194.

Boncio P., Brozzetti F. and Lavecchia G.; 2000: *Architecture and seismotectonics of a regional low-angle normal fault zone in Central Italy.* Tectonics, **19**, 1038–1055.

Borraccini F., Di Bucci D., De Donatis M., Megna A., Nesci O., Santini S., Savelli D. and Tramontana M.; 2004: *Quaternary tectonics of the northern Marche region and implications for active deformation in the outer northern Apennines*. Studi Geologici Camerti, 2002 workshop COST-ACTION 625, Special Issue, pp. 39-44.

Cassinis R., Scarascia S. and Lozej A.; 2003: *The deep crustal structure of Italy and surrounding areas from seismic refraction data. A new synthesis.* Boll. Soc. Geol. It., **122**, 365-376.

Chiarabba C., Jovane L. and Di Stefano R.; 2005: *A new view of Italian seismicity using 20 years of instrumental recordings.* Tectonophysics, **395**, 251-268.

Coward M.P., De Donatis M., Mazzoli S., Paltrinieri W. and Wezel F.C.; 1999: *Frontal part of the northern Apennines fold and thrust belt in the Romagna-Marche area (Italy): shallow and deep structural styles.* Tectonics, **18**, 559-574.

Di Bucci D. and Mazzoli S.; 2002: *Active tectonics of the Northern Apennines and Adria geodynamics: new data and a discussion.* Journal of Geodynamics, **34**, 687-707.

Di Bucci D. and Mazzoli S.; 2003: *The October-November 2002 Molise seismic sequence (southern Italy): an* *expression of Adria intraplate deformation*. Journal of the Geological Society, London, **160**, 503-506.

Di Bucci D., Mazzoli S., Nesci O., Savelli D., Tramontana M., De Donatis M. and Borraccini F.; 2003: *Active formation in the frontal part of the Northern Apennines: insights from the lower Metauro River basin area (northern Marche, Italy) and adjacent Adriatic off-shore.* Journal of Geodynamics, **36**, 213-238.

Dramis F.; 1992: *Il ruolo dei sollevementi tettonici a largo raggio nella genesi del rilievo appenninico.* Studi Geologici Camerti, Special Issue, **1**, 9-15.

Frepoli A. and Amato A.; 1997: *Contemporaneous extension and compression in the Northern Apennines from earthquake fault plane solutions*. Geophysical Journal International, **129**, 368-388.

Frepoli A. and Amato A.; 2000: *Spatial variations in stresses in peninsular Italy and Sicily from background seismicity*. Tectonophysics, **317**, 109-124.

Gasparini C., Iannaccone G. and Scarpa R.; 1985: *Fault-plane solutions and seismicity of the Italian peninsula*. Tectonophysics, **117**, 59-78.

Klein F.W.; 1989: *HYPOINVERSE, a program for Vax computers to solve for earthquake location and magnitude.* Open-File Rep., U.S. Geol. Surv., 226 pp.

Lavecchia G., Brozzetti F., Barchi M., Menichetti M. and Keller J.; 1994: *Seismotectonic zoning in east-central Italy deduced from an analysis of the Neogene to present deformations and related stress fields.* Geol. Soc. Am. Bull., **106**, 1107–1120.

Mariucci M.T., Amato A. and Montone P.; 1999: *Recent tectonic evolution and present stress in the Northern Apennines.* Tectonics, **18**, 108–118.

Mazzoli S., Lanci L. and De Donatis M.; 2001: *Paleomagnetic rotations in thrust belts: A case-study from the Marche-Romagna area (Northern Apennines, Italy).* Journal of Geodynamics, **32**, 373-393.

Meletti C., Patacca E. and Scandone P.; 2000: *Construction of a Seismotectonic model: the case of Italy*. Pure App. Geophys., **157**, 11-35.

Montone P., Mariucci M.T., Pondrelli S. and Amato A.; 2004: *An improved stress map for Italy and surrounding regions (central Mediterranean).* J. Geophys. Res., **109**, B10410, doi: 10.1029/2003JB002703.

Piccinini D., Piana Agostinetti N., Roselli P., Ibs-von Seht M. and Braun T.; 2009: *Analysis of small magnitude seismic sequences along the Northern Apennines (Italy)*. Tectonophysics, **476**, 136-144.

Pondrelli S., Salimbeni S., Ekstrom G., Morelli A., Gasperini P. and Vannucci G.; 2006: *The Italian CMT dataset from 1997 to the present.* Phys. Earth Planet. Inter., **159**, 286-303.

Reasenberg P. and Oppenheimer D.; 1985: *FPFIT, FPPLOT and FPPAGE: FORTRAN computer program for calculating and displaying earthquake fault-plane solutions*. Open-File Rep., U.S. Geol. Surv., 109 pp.

Riguzzi F., Tertulliani A. and Gasparini C.; 1989: *Study of the seismic sequence of Porto San Giorgio: Marche 3 July 1987.* Il Nuovo Cimento, **12C**, 453-466.

Santini S.; 2003: *A note on Northern Marche seismicity: new focal mechanisms and seismological evidences*. Annals of Geophysics, **46**, 725-731.

Santini S. and Martellini A.; 2004: *Meccanismi focali ed evidenze sismologiche dei movimenti tettonici nella provincia di Pesaro e Urbino*. Studi Geologici Camerti, **2**, 141-152.

Santini S., Baldi P., Dragoni M., Piombo A., Salvi S., Spada G. and Stramondo S.; 2004: *Monte Carlo inversion of DInSAR data for dislocation modeling: application to the 1997 Umbria-Marche seismic sequence (central Italy)*. Pure Appl. Geophys., **161**, 817–838.

Zoback M.L.; 1992: *First- and second-order patterns of stress in the lithosphere: the world stress map project*. J. Geophys. Res., **97**, 11703-11728.

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