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INPAR, CMT and RCMT seismic moment solutions compared for the strongest damaging events (M≥4.8) occurred in the italian region in the last decade

Summary - We consider moment tensor inversion solutions for a set of damaging earthquakes, with moment magnitude ≥4.8, that occurred in the Italian region during the period 1997-2005. The source parameters have been retrieved using a robust methodology (INPAR method), that performs a dynamic relocation of the hypocentre (latitude, longitude and depth) simultaneously with the determination of the focal mechanism. The INPAR method had successfully been applied over a quite broad range of magnitudes (1.5-6.0) and within a wide variety of tectonic, volcanic, and geothermal environments. The main methodological outcome is that INPAR is particularly useful for regional and local studies of seismic source moment tensor, especially when a limited number of stations makes it difficult to analyse relatively small magnitude events with global scale methodologies.

Keywords: moment tensor inversion, Italian region, focal depth, CLVD component.

1. *Introduction*

To help constrain stress conditions and tectonic features in the Italian region it is necessary to supplement the information provided by global seismology (e.g. CMT-Harvard solutions, USGS) with regional and local broad-band studies. In fact the Italian region is seismically very active but most of the relevant seismicity is

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concentrated in the magnitude range 5-6, with a little number of events with Mw>6.0. The study of earthquakes with Mw<6.0 is necessary to obtain information about the tectonic structures and it is important in the framework of seismic risk assessment, because even moderate magnitude events can contribute to the seismic risk due to the uniqueness of the cultural heritage of Italy.

The Centroid Moment Tensor (CMT) project [11, 12] has provided one of the most robust, rapid and reliable methodologies for focal mechanisms determination. CMT solutions are produced on a routine basis for events with moment magnitude (Mw) greater than about 5.0-5.5. The methodology uses body waves filtered with periods larger than 45 sec and, for large events, long-period (T>135 sec) mantle waves, for the inversion of the seismic moment tensor. Small or moderate earthquakes cannot be analysed using teleseismic data and the standard CMT methodology cannot be routinely applied to study small and intermediate magnitude earthquakes. For that reason, the CMT catalogue contains only a small number of events with Mw as low as 5.0. Very recently, Harvard started using regional surface waves in order to extend the analysis to magnitude 4.8 events.

For earthquakes with low magnitude, it is necessary to analyse local and regional waveforms. The determination of focal mechanisms at a regional scale is now possible because of the increasing amount of high-quality broad-band data available in Europe and surrounding areas. Several moment tensor inversion schemes for moderate magnitude events have recently been developed: the RCMT (Regional Centroid Moment Tensor) algorithm [2] is an extension of the standard CMT algorithm, based on the inversion of surface waves recorded at regional distance. The methodology has already been applied in a number of studies of Italian moderate magnitude earthquakes [13, 24, 30, 31]. A full waveform inversion scheme is also used by the Swiss Seismological Service to routinely determine earthquake source parameters for moderate to strong events in the European-Mediterranean area [4, 5].

In this paper we analyse a set of earthquakes, with magnitude between 4.8 and 6.0 that occurred in the Italian region during the period 1997-2005. We selected those earthquakes according to the CMT database for the same period. To determine the source parameters, we apply the methodology called INPAR [36, 38] that performs a full waveform inversion to obtain the source moment tensor. The INPAR method has been successfully applied within a wide variety of tectonic [7, 9, 15, 16, 33, 39], volcanic, and geothermal environments [6, 8, 17, 18, 19, 22, 35] and it has been shown that it can handle earthquakes in a wide range of magnitudes, from Mw=1.5-2.0 for events in volcanic environments [18], up to Mw=6.0 in tectonic settings [15, 39]. A significant feature of the INPAR method is the possibility of retrieving useful information about the seismic source even in case of a limited number of records available [39]. Therefore the INPAR method is particularly useful for regional and local studies, especially when few stations are available because of logistic problems or sparse seismometric networks. It follows that such

methodology can be complementary to global scale methodologies (e.g. CMT), mainly when it permits a reliable estimation of focal depth, fixed a priori in CMT inversion, and can confidentially be extended to the analysis of smaller events.

2. *Methodology and data*

INPAR method [36, 38] uses the point source approximation and consists of two main steps. The first step is a linear inversion and the six moment tensor rate functions (MTRF) are retrieved. They are obtained extracting from the data, with a damped least squares algorithm, the Green functions, in this case with a time dependence given by a Heaviside function, computed by the modal summation method [14, 25, 27]. Therefore the procedure does not require the a priori assumption of an initial source model.

The broad-band modelling of local and regional seismic waveforms needs a quite precise location of the hypocentre: any mislocation affects the confidence of the source mechanism determination. For this reason, the INPAR method performs, whenever necessary, dynamic relocation of the hypocentre simultaneously with the determination of the mechanism [38]. The base functions are thus computed for a set of values of the hypocentral coordinates lying between two extremes, defined on the basis of hypocentral estimates. We indicate the different values of the source coordinates with the variables (X_1,X_2,X_3). In the course of the inversion intermediate values of the parameters (X_1,X_2,X_3) are computed, incrementing the initial values with steps chosen a priori. The base functions corresponding to intermediate values of the source coordinate are computed with a linear interpolation of the base functions evaluated at the grid defined by the assumed set of coordinates. The difference between the observed records and the synthetic seismograms, corresponding to a given source coordinate set is computed using a L_2-norm. The norm can be considered as a function of the parameters (X_1,X_2,X_3) and its minimum is searched. The second step is non-linear, and the six MTRF, obtained after the first step of the inversion, are reduced to a constant moment tensor and the corresponding source time function taking only the correlated part from each MTRF. This is a basic feature of the INPAR method since, when taking only the coherent part at different stations, the influence on the solution of non-modelled structural details and of scattering by non-modelled heterogeneities is reduced [23]. The problem is non-linear and it is solved iteratively by imposing constraints such as positivity of the source time function and, when clear readings of first arrivals are available, consistency with polarities. A genetic algorithm is used in the search of solutions and in the estimate of the error areas for the different source parameters [36].

We report here the results of the inversion for all the damaging events recorded within the Italian Peninsula in the period 1997-2005 with magnitude Mw≥4.8: we include also two events recorded in Slovenia, near the border with

Italy, due to their relevance for the Italian tectonic setting. The moment magnitude threshold has been selected because it corresponds to the minimum magnitude of events reported by the Centroid Moment Tensor (CMT) Catalogue [11, 12]: therefore it is possible to compare the fault plane solutions obtained using INPAR method with those reported by the CMT Catalogue. We used waveform data from IRIS consortium, ORFEUS, and MedNet network recorded at local and regional distance. The structural models used for the inversion are taken from the EUR-ID data set [10] updated with recent surface wave tomographic studies [26, 32, 34]. For each event, we choose the appropriate model according to the region where the source receiver path propagates.

3. *Inversion of source mechanisms*

We have inverted a set of 22 events and the results of the inversions are reported in Table 1 and Table 2, while the fault plane solutions are plotted in Fig. 1. We have performed the inversions using a maximum of 18 signals (vertical, NS and EW components). An example of the waveform fit is shown in Fig.2. To retrieve information about the error of the solution we use the posterior probability density function to mark confidence zones of the model parameters [36]. From the size and shape of the confidence areas we can decide about the reliability level of the solution. The MTRFs retrieved from the waveform inversion, and then the average mechanism and source time function, are considered to be affected by three types of errors, generated respectively by: (1) the noise present in the data; (2) the horizontal mislocation of the hypocenter adopted to compute the base functions in the depth grid used in the inversion; (3) the improper structural models used to compute the base functions [37]. The variance is turned into confidence regions of the eigenvalues and eigenvectors of the moment tensor. From the confidence areas for each mechanism, shown in Fig. 3, we can see that most of the fault mechanisms are well resolved.

Table 2 lists the nodal planes and the percentages of the moment tensor components, Double Couple (DC) and Compensated Linear Vector Dipole (CLVD), corresponding to each event. We observe in several cases a departure from a pure double couple mechanism and the presence of a significant CLVD component.

In 1997 a major seismic sequence started in Central Italy, with the 26 September Mw=5.6 event. We have inverted seven of the events in the sequence (event n°1-7), and all of them have a normal faulting mechanism, (event 6 shows a strike slip component), that defines a fault system extending along a NW-SE trend. The hypocentral depth for events 1,2,4,5,7 varies within the uppermost 10 km of the crust, while it is about 20 km for event 3. For event 6 the hypocentral depth is about 50 km, thus we are probably dealing with an event occurred in the mantle lid. The normal faulting character for the events in Central Italy and the presence of mantle lid seismicity agree with the results proposed by [9]. The extensional

N°	Date	Time	Lat	Lon	Depth	Mw
1	26.9.1997	0:33:12.25	42.90±0.19	12.88±0.19	3±3	5.6
2	26.9.1997	9:40:26.90	43.10±0.07	12.78±0.19	6±2	6.0
3	3.10.1997	8:55:21.50	43.10±0.10	12.90±0.20	20±1	5.2
4	6.10.1997	23:24:52.50	42.90±0.15	13.00±0.02	6±3	5.5
5	12.10.1997	11:8:36.30	42.81±0.06	12.93±0.08	5±2	5.2
6	26.3.1998	16:26:11.50	43.07±0.05	12.80±0.14	50±20	5.5
7	3.4.1998	7:26:36.60	43.18±0.01	12.79±0.02	10±1	5.2
8	12.4.1998	10:55:32.50	46.27±0.01	13.55±0.01	10±4	5.7
9	18.5.1998	17:19:4.80	39.27±0.04	15.30±0.19	278±1	5.3
10	9.9.1998	11:27:59.30	39.65±0.01	15.71±0.19	20±10	5.6
11	10.5.2000	15:09:0.81	44.33±0.03	11.90±0.16	8±7	4.9
12	21.8.2000	17:14:31.10	44.90±0.01	8.25±0.04	7±1	5.0
13	17.4.2002	6:42:54.30	39.60±0.16	16.90±0.29	10±3	5.2
14	6.9.2002	1:21:28:60	38.50±0.01	13.68±0.06	40±1	6.0
15	27.9.2002	6:10:44:90	38.10±0.13	13.64±0.16	21±6	5.0
16	31.10.2002	10:32:58.77	41.59±0.02	14.80±0.17	7±1	5.8
17	1.11.2002	16:52:9:81	41.72±0.04	14.99±0.17	15±10	5.6
18	14.9.2003	21:42:51.86	44.20±0.17	11.55±0.02	32±1	5.4
19	5.5.2004	13:39:43:86	38.47±0.13	14.67±0.14	230±20	5.2
20	12.7.2004	13:04:07.16	46.27±0.01	13.64±0.01	7±1	5.3
21	24.11.2004	22:59:40.05	45.70±0.18	10.72±0.07	10±3	5.2
22	22.8.2005	12:2:8.60	41.30±0.40	12.53±0.08	12±4	4.8

Table 1 – Source parameters for the events analysed in this study. The values for latitude, longitude and depth are those retrieved after the inversion with dynamic relocation of the hypocentre, as provided by the INPAR method. Mw is the magnitude from scalar seismic moment [21].

character of the Central Apennine area is reported also by the ZS9 new seismic zonation of the Italian region [42] as well.

The active tectonic region localized at the border between Italy and Slovenia was affected by two earthquakes, recorded in 1998 and 2004, with moment magnitude 5.7 and 5.3 (events n°8 and n°20) respectively. The mechanism for the event of 1998 is a strike slip and seems to correlate with the NW-SE trend of the Dinaric structures [3]; the fault plane solution of the 2004 event shows a dominant thrust component, that matches the mean focal mechanism for the area (ZS9 seismic zonation, [42]) that is characterized by the convergence of the Adriatic and Euro-

N°	Nodal planes	DC(%)	CLVD(%)	N° of waveforms
1	333 42 -57/112 56 -116	56	44	14
2	299 42 -123/160 56 -64	13	87	13
3	353 51 -56/126 50 -124	87	13	13
4	349 61 -100/189 31 -73	25	75	10
5	342 70 -78/131 23 -119	74	26	10
6	120 89 127/211 37 1	76	24	11
7	320 65 -86/130 25 -99	25	75	13
8	216 67 -20/314 72 -156	31	69	14
9	50 20 77/244 71 95	87	13	12
10	233 44 -1/324 89 -134	73	27	12
11	106 82 75/350 17 153	36	64	13
12	343 50 -105/187 42 -73	68	32	8
13	54 39 101/219 52 81	38	62	6
14	85 62 65/310 37 129	77	23	8
15	68 75 73/298 23 138	52	48	9
16	261 85 173/352 83 5	71	29	7
17	262 54 -171/167 82 -37	96	4	18
18	227 56 89/49 34 91	44	56	8
19	182 15 -128/41 78 -81	44	56	11
20	101 36 122/243 60 69	89	11	8
21	231 47 64/87 49 115	82	18	6
22	6 76 137/109 48 19	65	35	12

Table 2 – Nodal planes and moment tensor component percentages for the studied events in the Italian Peninsula; DC(%): percentage of the double couple component; CLVD(%) percentage of the CLVD component. In the last column is reported the number of records used in the inversion for each event.

pean plates. Both of the events are shallow, with a considerable CLVD component in case of event 8. Quite large confidence regions characterize the mechanism of event 20; nevertheless the dominant thrust component is confirmed.

Two of the analysed earthquakes are located in north western Italy. Event n° 12, in the Monferrato area, is characterized by a normal source mechanism, but large confidence areas indicate uncertainty in the solution. Event n° 21 occurred near the city of Brescia and the Garda Lake with a dominantly thrust mechanism.

Event n° 11 and event n° 18 are located in the region around the city of Bologna. Event n°18 presents a thrust mechanism while event n° 11 a thrust mech-

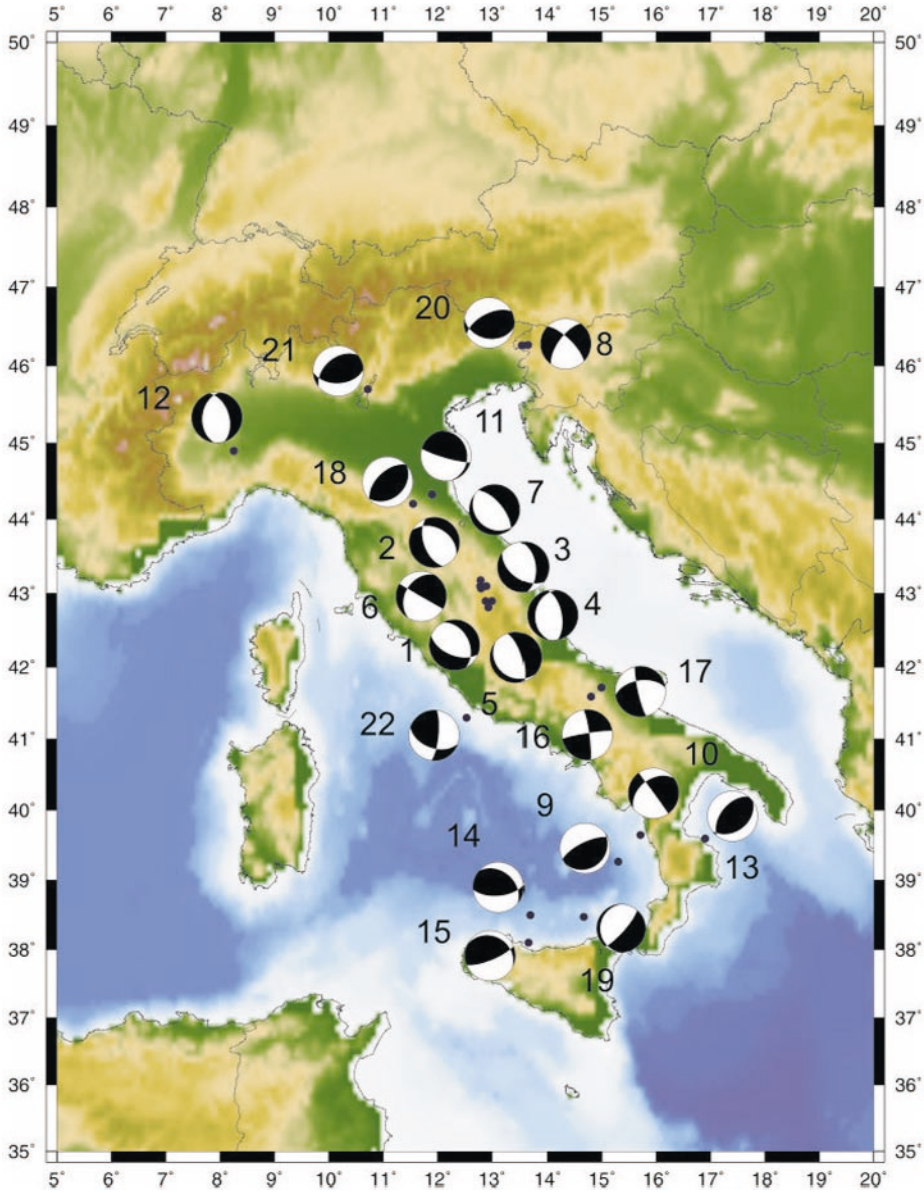

Figure 1 – Map with fault plane solutions determined for the events analysed in this study.

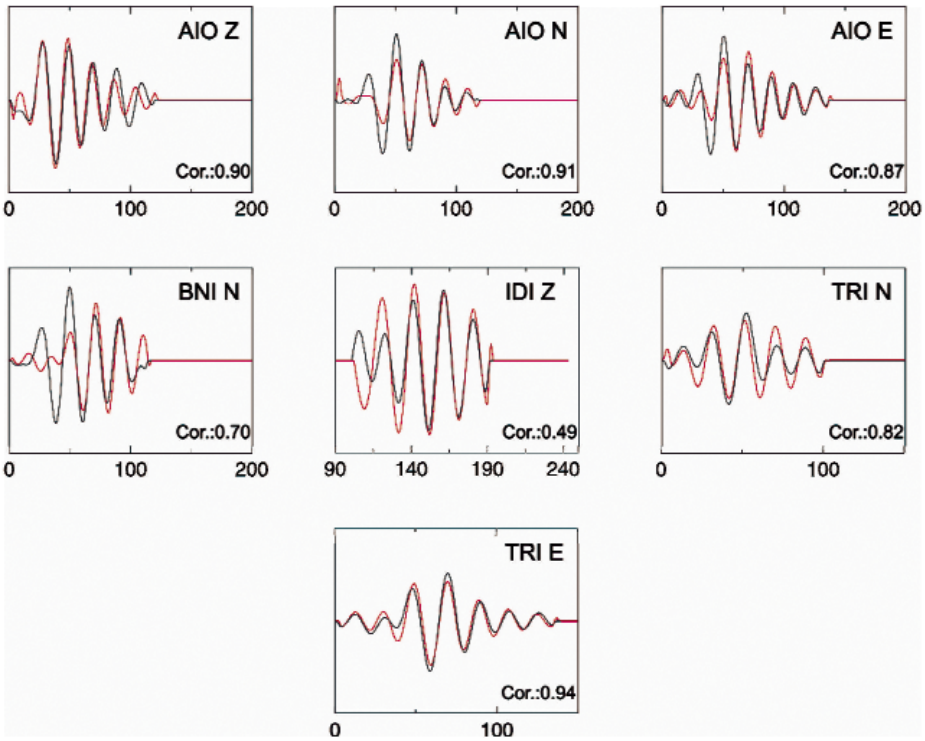

Figure 2 – Waveform fit for the moment tensor inversion of event n° 8. Cor. is the correlation value between the real data and the synthetic seismogram.

anism with a small strike slip component. They evidence the compressional environment of the Northern Apenninic chain that can originate thrust faulting earthquakes, in agreement with the indications contained in ZS9 seismic zonation [42].

Two earthquakes were recorded in the Calabria region: the first one in 1998 (event n°10) shows a normal mechanism with a strike slip component; even if the average mechanism is affected by large uncertainties it is in agreement with the prevalent faulting mechanism defined by the ZS9 zonation [42]. For the other event (n° 13) we have obtained a thrust mechanism that may indicate a compressional environment.

A significant seismic sequence occurred in the late 2002 in Southern Italy (Molise). The first event took place on 31st October 2002 (event n°16) with a magnitude Mw=5.8. Another event occurred the following day, 1st November 2002, with magnitude Mw=5.6 (event n°17). Both of the events are associated with a dominantly strike slip mechanism, very close to a pure double couple, originated in a faulting system with an E-W trend. The most recent event (22) is located offshore Central Italy and it is characterized by a thrust with strike-slip component mechanism.

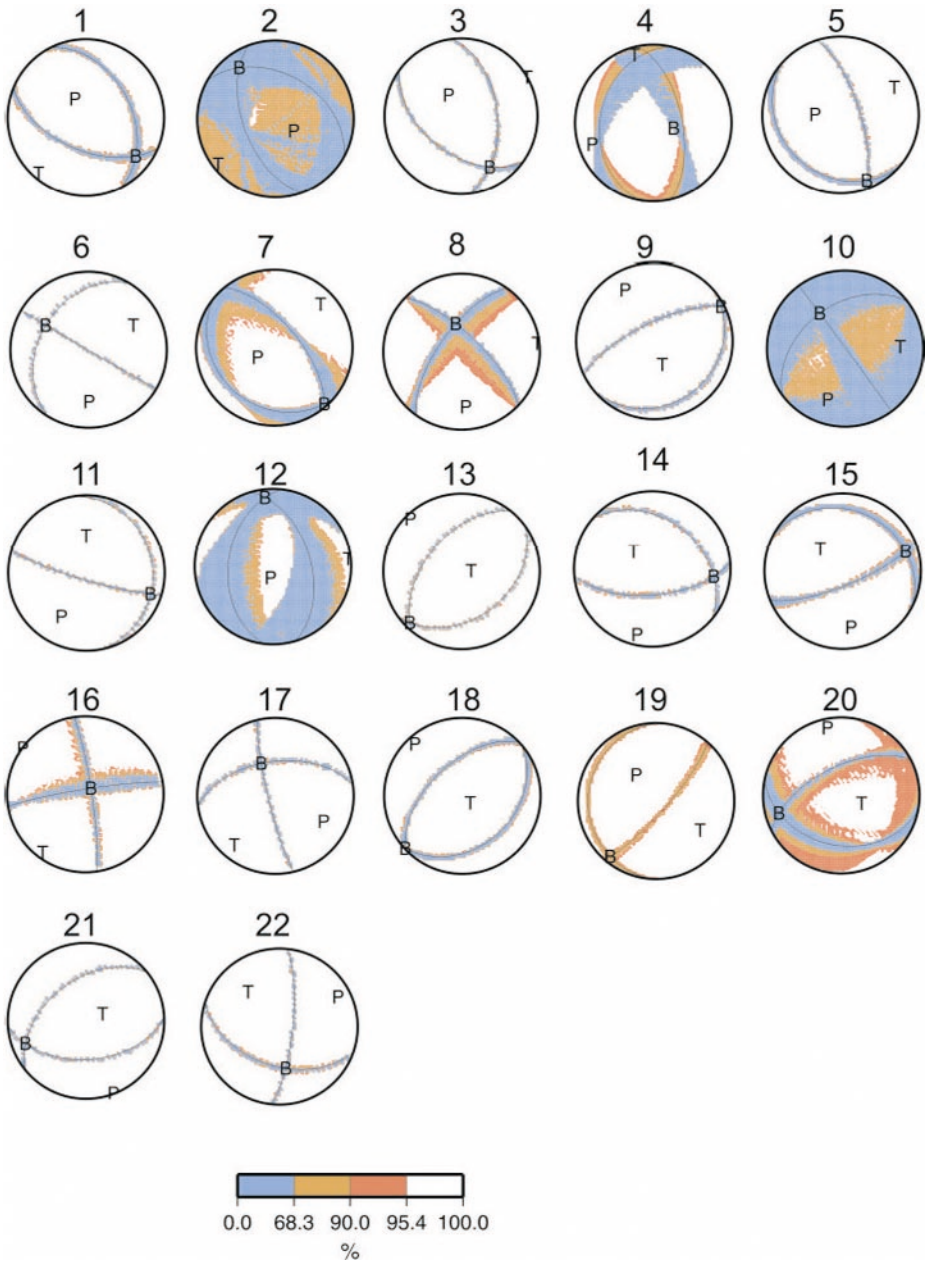

Figure 3 – Fault plane solutions of the studied earthquakes with their confidence error areas.

Date	Time	Lat.	Lon.	Depth	Mw	Nodal Planes	DC(%)	CLVD(%)	N° of waveforms
17.7.2001	15:6:15.24	46.67±0.04	11.10±0.04	14±8	5.0	207 64 -5/299 85 -154	74	26	11
14.2.2002	3:18:1.39	46.38±0.08	13.11±0.12	3±3	4.8	50 62 74/ 262 32 118	71	29	15

Table 3 – Table with the source parameters for the 17 July 2001 and the 14 February 2002 events. The values for latitude, longitude and depth are those retrieved after the inversion with dynamic relocation of the hypocentre, as provided by the INPAR method; Mw is the magnitude from scalar seismic moment [21]; DC(%): percentage of the double couple component; CLVD(%) percentage of the CLVD component; in the last column is reported the number of records used in the inversion for each event.

Four events located at the border between the Southern Tyrrhenian Sea and Northern Sicily have been analysed (ev. 9, 14, 15, 19). Events 14 and 15 have a very similar thrust mechanism that indicates a compressional environment. Events 9 and 19 are intermediate-depth events (278 and 230 km) both occurring on an almost vertical fault plane.

4. *A comparison with CMT and RCMT database solutions*

For all the events inverted a Harvard CMT solution is available, therefore it is possible to compare the results. Fig. 4 shows the fault plane solutions obtained in this study and the Harvard CMT solutions, together with the Mediterranean-European RCMT solutions, when available. There is good agreement between the three sets of solutions, both as source mechanisms (best double couple) and moment magnitude. A strike orientation different with respect to the CMT solutions is found for events 14, 15 and 18, but the thrust character of the mechanisms is confirmed. A difference in strike orientation is also found for event 4: our solution is not in agreement with the trend found for the Central Italy sequence (events 1-7), but the solution for event 4 has large confidence areas. This particular case shows that the use of the posterior probability density function to mark confidence zones of the model parameters is very valuable in the validation of the focal mechanisms solution. In a similar way, large confidence regions characterize event 10 and event 12, which show mechanisms different with respect to the CMT solutions.

The main differences among the solutions are related to the hypocentral depths. The value reported in the CMT catalogue is often fixed for shallow earthquakes in order to minimize the instabilities in the moment tensor components that usually increase at shallow depths [2]. In fact, in the CMT inversion algorithm the partial derivatives of the synthetic spectra with respect to the moment tensor com-

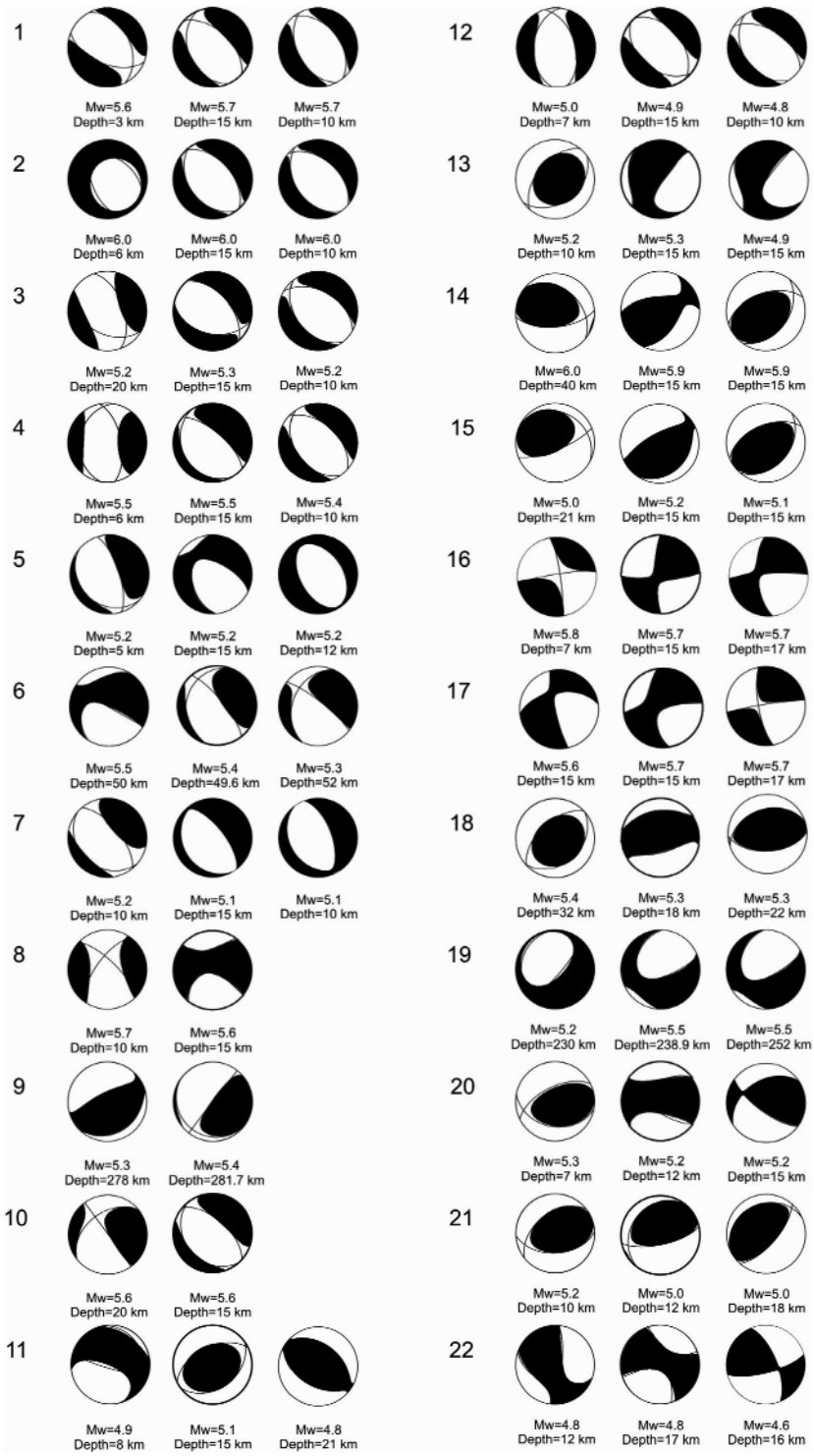

Figure 4 – Comparison between the fault plane solutions obtained in this study (first column), the Harvard CMT solutions (second column) and the Mediterranean-European RCMT catalogue (third column). The moment magnitude Mw and the depth are reported for each solution.

ponents and hypocentral coordinates are calculated, and by an iterative procedure convergence is achieved to the best fitting parameters [11]. In the INPAR algorithm, no partial derivative of the synthetic seismograms is computed, but we search for the best depth which minimizes the L2 distance between observed and corresponding computed seismograms [38]. The first step in the INPAR methodology is a linear inverse problem and the solution is obtained solving a system of normal equations.

Within the set of events analysed in this study, in 18 cases the depth reported by CMT is fixed a priori. For the remaining events, the results are comparable. Our analysis gives a quite uniform distribution of hypocentral depths and the values retrieved are in most of the cases in agreement with the mean depth at which most of the earthquakes have origin, according to the results reported by the ZS9 Working Group (2004). Depth values retrieved in this study reveal that events with magnitude Mw>5.5 are located in the depth range 0-20 km; therefore they are confined within the upper crust. There are two exceptions: for event 6 the hypocentral depth is about 50 km and for event 14 it is about 40 km, thus we are very likely dealing with events occurred in the mantle lid. No earthquakes with depth larger that 50 km are found in the Italian peninsula and the two events (9 and 19) occurred in the Tyrrhenian Sea.

In several of the solutions obtained in this study we observe the presence of a significant CLVD component. The CLVD component is in most cases higher in our solutions than in CMT and RCMT solutions. Excluding events with large confidence areas, six events have CLVD components between 44% and 75%, all but one with hypocentral depth ≤32 km. Unambiguous interpretations of the CLVD components resulting from moment tensor inversion are still matter of debate. [28] showed that the CLVD components may be artefacts of the inversion process, caused by sparse station distribution and the use of inaccurate Earth models for inversion while, [20] explain CLVD components also as the effect of poor resolution for two moment tensor components for shallow earthquakes. If the CLVD components represent real source effects, they can be explained by the occurrence of sub events with different pure double-couple mechanisms very close in time (within a few seconds). Therefore, we have analysed the events with relevant CLVD components and repeated the inversion dividing the source time function into two subintervals, following the procedure described by [37] and [8]. As a general result, we have obtained for each earthquake analysed two sub-events with very small CLVD (less than 20%) and different mechanisms (best double couple) both not too far from the best double couple retrieved in the inversion with a single source time function and reported in Fig.1. Inversions at lower periods (down to 10 s), as it is possible using the INPAR method, allow to better retrieve the details of the source mechanisms. We show in Fig.5, as example, the results of the inversion for event 1 for which we split the source time function into almost equal parts of about 1.7 s each.

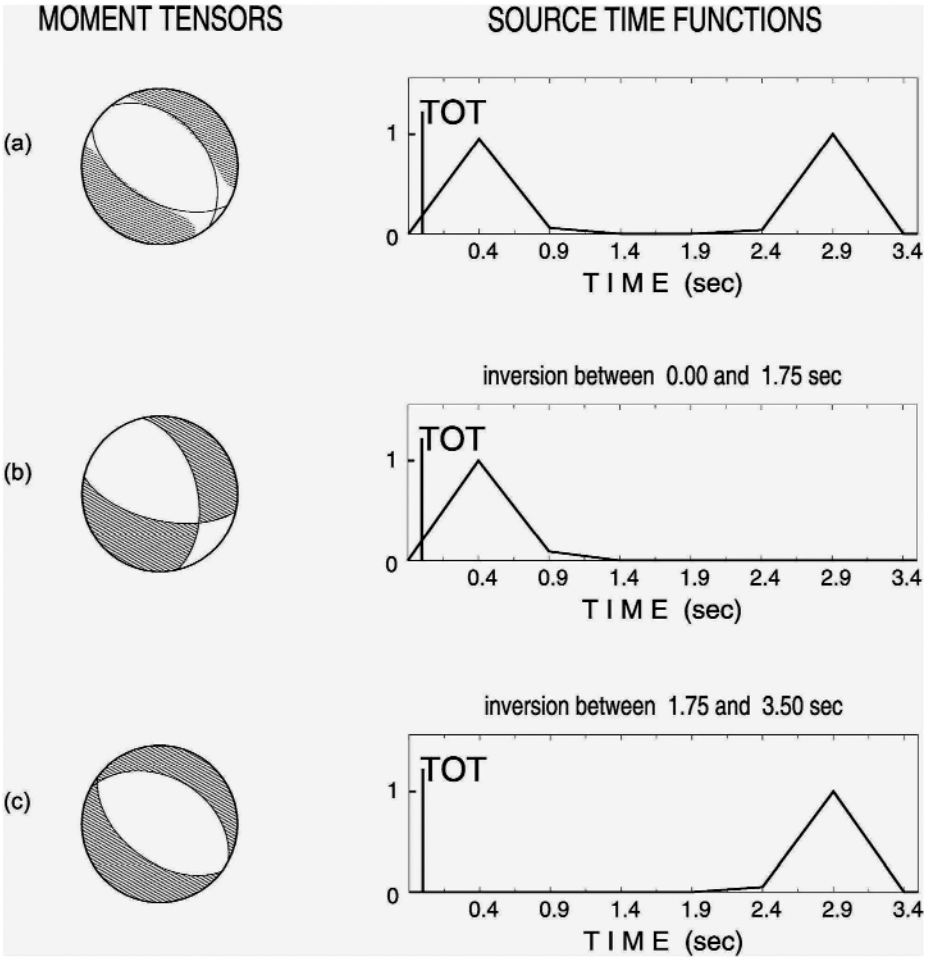

Figure 5 – Results of the inversion for event 1 with the source time function divided into two subintervals. (a) Source mechanism and source time function for the first inversion, (b) for the interval 0-1.75 s, (c) for the interval 1.75-3.4 s.

5. *Inversion of earthquakes not reported in the CMT database*

We extend the analysis to two earthquakes not contained in the CMT catalogue: the 17 July 2001 event and the 14 February 2002 event, located in the North eastern regions of Italy. The results of the inversions and the confidence areas for the mechanisms retrieved are reported in Fig. 6 and Fig.7, together with the solutions of the Mediterranean-European RCMT catalogue as comparison. The 17 July 2001 fault plane solution is a well resolved strike-slip mechanism, in perfect agreement with the RCMT solution. For the 14 February 2002 event the thrust charac-

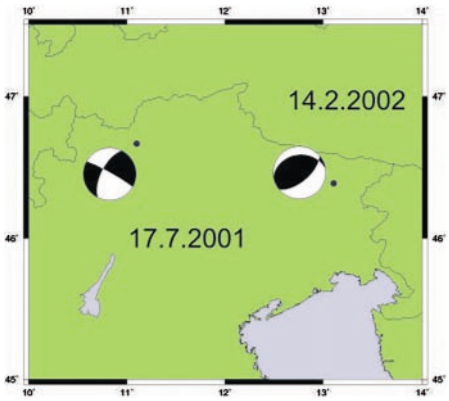

Figure 6 – Map with the location of the 17 July 2001 event and the 14 February 2002 event, located in the North eastern regions of Italy.

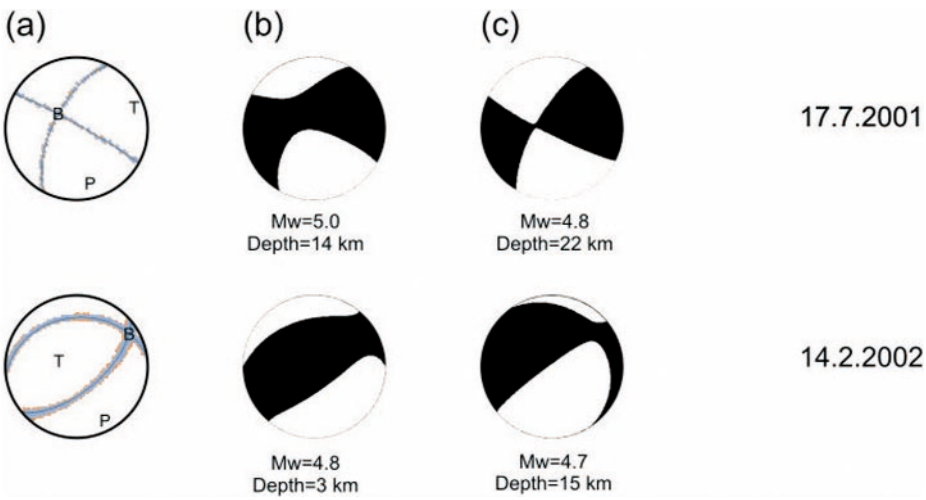

Figure 7 – Results of the inversion for the 17 July 2001 event and the 14 February 2002 event: (a) fault plane solution obtained in this study with the confidence error area; (b) fault plane solution obtained in this study; (c) fault plane solution from the Mediterranean-European RCMT catalogue.

ter is more pronounced than in the RCMT mechanism, and it is in better agreement with the thrust mechanisms obtained for the 1976-1977 Northern Italy seismic sequence [1, 29] and the average focal mechanism proposed by the ZS9 seismogenetic zonation [42].

The previous results confirm the results reported in the foregoing sections. Our systematic comparison of the solutions obtained using the INPAR methodology with those contained in the Harvard-CMT catalogue and the Mediterranean-European RCMT catalogue for regional distance earthquakes, justify the intensive application of the INPAR to regional and local events. We have used for these events less waveforms with respect to those used by RCMT. Therefore methodology can be applied in Italy but also in regions where logistical problems make it difficult the simultaneous operation of many instruments and the relevant seismicity is characterized by low-to-medium magnitude events, i.e. in all those cases when the global scale methodologies does not ensure reliable high quality results.

6. *Conclusions*

We have analysed a set of events recorded in the Italian peninsula in the period between 1997 and 2005. The aim of our study was to compare the results of the inversion using the INPAR method and the solutions reported in the CMT Catalogue in order to assess the reliability of the methodology. The fault plane solutions reported in this paper are in agreement with the CMT solutions. We found that our results compare well to the results of the Mediterranean-European RCMT algorithm, the extension of the standard CMT algorithm to regional studies. As the INPAR method proved to be particularly useful for regional and local analysis, especially when a limited number of stations is available, it follows that such methodology can be complementary to global scale methodologies (e.g. CMT), since it permits a refinement of focal depth, mainly when depth values are fixed a priori as in CMT and RCMT inversions, and it can confidentially be extended to the analysis of smaller events down to magnitude 1.5-2.0, including an exploratory analysis of the significance of CLVD components.

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