European-Mediterranean Regional Centroid Moment Tensor Catalog: solutions for 2005-2008

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E. Boschi

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Authors: S. Pondrelli, S. Salimbeni, A. Morelli, G. Ekström,
L. Postpischl, G. Vannucci, E. Boschi

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European-Mediterranean Regional Centroid Moment Tensor Catalog: solutions for 2005–2008

S. Pondrelli^a, S. Salimbeni^a, A. Morelli^a, G. Ekström^b, L. Postpischl^a, G. Vannucci^a, E. Boschi^c

^aIstituto Nazionale di Geofisica e Vulcanologia, Sezione di Bologna, 40128 Bologna, Italy

^bLamont-Doherty Earth Observatory, Columbia University, Palisades, NY, USA

^cIstituto Nazionale di Geofisica e Vulcanologia, Rome, Italy

Corresponding author: S. Pondrelli

Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Bologna

Via D. Creti 12

40128 Bologna, Italy

Fax: +39-051-4151499

E-mail: pondrelli@bo.ingv.it

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Abstract

Since 1997 we maintain and systematically update the European–Mediterranean Regional Centroid Moment Tensor (RCMT) Catalog, which contains seismic-moment tensors for earthquakes with moderate magnitude ($4.5 < M < 5.5$) in the Mediterranean and European regions. We present 354 new solutions for the period 2005–2008. The Catalog now spans 12 years and contains more than 1000 definitive RCMT solutions. In addition to definitive solutions, we maintain and update a dataset of recent ‘quick’ solutions that are computed soon after an earthquake occurs using the more limited set of data available in quasi-real time. We investigate the reliability of the moment tensor results in the RCMT catalog. Comparison with Global CMT results, which is possible for the larger events ($M > 5.0$) in the RCMT catalog, shows that for 75% of the events, the Kagan angle measure of the similarity of two moment tensors is smaller than 20° , reflecting good agreement of the results. We describe improvements and enhancements in the dissemination of the RCMT results through our web site.

Keywords: Seismic moment tensors, focal mechanisms, seismicity, European–Mediterranean region

1 Introduction

The centroid-moment-tensor (CMT) approach (Dziewonski et al., 1981; Dziewonski and Woodhouse, 1983) to the description and quantification of earthquake sources has become a well-established method for routine analysis of seismicity. On a global scale, the Global CMT Project (Ekström et al., 2005; www.globalcmt.org) systematically analyzes and publishes moment tensors for earthquakes larger than $M = 5.0$. Starting in 1997, we perform a similar comprehensive CMT analysis of earthquakes in Europe and the Mediterranean region. By considering intermediate-period surface waves recorded at regional distances, we are routinely able to analyze earthquakes as small as $M = 4.5$, thereby extending the capabilities of the CMT approach to a larger number of events than can be studied by using exclusively the global data set. Our Regional CMT (RCMT) effort has resulted in a comprehensive catalog of earthquakes which is systematically extended and updated (Pondrelli et al., 2002, 2004, 2007; www.bo.ingv.it/RCMT). Complementing the definitive moment-tensor results, preliminary ‘quick RCMT’ solutions are routinely calculated immediately following the occurrence of significant earthquakes in the region.

The availability of moment tensors for intermediate-magnitude events contributes to a better characterization of individual seismic sequences (e.g., Pondrelli and Morelli, 2008), and to investigations of the complex large-scale tectonics connected to the Africa-Eurasia collision (e.g., Vannucci et al., 2004). Seismicity is widespread in the Mediterranean region and, while strong earthquakes are rare, more frequent moderate-size events often cause significant damage. Systematic study of smaller events therefore also has the potential to contribute to the development of a better understanding of seismic hazard of this populated area.

In this paper, we describe RCMT results for the period 2005–2008. In the analyses described here, we have slightly modified our procedures compared to those employed in earlier reports (Pondrelli et al., 2002, 2004, 2007). Specifically, we now fit not only long-period surface waves in the inversion, but also include long-period body waves in the set of observations to be matched. We determined 354 moment-tensor solutions for the four-year period, and describe results for several noteworthy earthquake sequences. With the addition of the new solutions, the RCMT catalog now spans a time period of 12 years and contains results for more than 1000 earthquakes. We investigate the robustness of the solutions by comparing our results with those obtained in the GCMT Project using a global data set. Finally, we discuss new technical aspects of the maintenance and dissemination of the RCMT catalog.

2 Seismic moment tensors for the years 2005–2008

The routine RCMT analysis relies on the fitting of surface waves in the period band 35–150 seconds, recorded at regional distance and modeled using global phase-velocity maps (Arvidsson and Ekström, 1998; Ekström et al., 1998). Recently, we have started including body waves in the analysis, modeled in the same manner as in the Global CMT Project by summation of the normal modes of the Earth corrected for large-scale three-dimensional mantle structure (Woodhouse and Dziewonski, 1984). Body waves are now included in the RCMT inversion when the epicentral distance is large enough to separate their arrivals from the surface wave packet, and when the signal-to-noise ratio is sufficiently high. Figure 1 shows the body-wave and surface-wave windows included in the inversion for one example seismogram recorded at a distance of 31.89° from a $M_W = 5.5$ earthquake. We find that the use of the two different wave types has a stabilizing effect on the centroid location. This is particularly useful for events occurring near the border of our study region since for these events the azimuthal station coverage is often poor.

Figure 2 shows a regional map with the 354 new seismic moment-tensor solutions that we determined for the period 2005–2008. The earthquake source parameters are listed in Tables 1–12 (added as Supplementary Material), including the reported magnitude M and the computed moment magnitude M_W . Centroid shifts δlat_0 , δlon_0 and δdep_0 are given with respect to the initial hypocentral coordinates, which we obtain from the European–Mediterranean Seismological Center (EMSC/CSEM, www.emsc-csem.org). Our criteria for selecting earthquakes for analysis are based on the reported magnitude M and the earthquake location. Generally we do not select for analysis earthquakes with $M > 5.5$ since these events will be analyzed as part of the Global CMT Project. However, we occasionally choose to analyze earthquakes of particular interest or significance with $M > 5.5$, and also include the results in the RCMT catalog. At the low-magnitude end, we use $M \geq 4.5$ as the general selection criterion, but often attempt analysis for smaller earthquakes, especially for those located in Italy and nearby areas where the station distribution is favorable for the RCMT analysis. For earthquakes with a reported magnitude $M < 4.5$, a successful analysis is contingent on a favorable station distribution and a high signal-to-noise ratio at close-in stations.

For approximately 30% of the events presented here we were able to augment the surface-wave data set with body-wave data. Solutions determined using both types of data are identified in Tables 1, 4, 7 and 10 (see Supplementary Material) by event codes that start with a ‘C’ (for ‘combined’) rather than an ‘S’ (for ‘surface waves’).

Following the method developed to describe the relative reliability of RCMT results for earthquakes in Italy (Pondrelli et al., 2006), we now provide a quality flag for each event (A/B/C/D, see Tables 3, 6, 9, and

12 in Supplementary Material) that we believe reflects the robustness of the RCMT solution. The ‘A’ flag (assigned to 80% of the earthquakes) indicates the best-quality solution. For these events the distance of the centroid epicenter from the reported epicenter is smaller than 0.3° , the residual normalized misfit between seismograms and synthetics is lower than 0.4, and the resulting non-double couple component is smaller than 0.33. The ‘B’ flag (9% of the earthquakes) is assigned to solutions with a centroid–epicenter shift between 0.3° and 0.5° . Such shifts generally occur when the station distribution is not very homogenous azimuthally. We assign the ‘C’ flag (11%) to earthquakes for which we fixed the epicentral location, usually because of a very limited number of recording stations. The ‘D’ flag is assigned to earthquakes with a large non-double couple component (larger than 0.33), but none of the new solutions presented here fall in this category.

For the largest earthquakes of those we have analyzed (marked by a star in Tables 1-12 in the Supplementary Material), both a global GCMT and a regional RCMT are available. We compared the scalar moments and the moment tensors, and found a very close similarity (Figure 3). For each pair of solutions we computed the Kagan angle (Kagan, 1991, 2007) between their double-couple representations. This angle can vary from 0° , reflecting complete agreement, to a maximum of 120° , for complete disagreement. For 75% of the events, the Kagan angle is smaller than 20° , considered to correspond to very good qualitative geometrical agreement (Kagan, 1991, 2007). Figure 3 shows that for nearly all events the Kagan angle is less than 60° , an empirical threshold indicating general agreement. The rotations of the P, T and N axes needed to overlap each pair of moment tensors is also reported in Figure 3. The largest Kagan angles occur for those events for which a relatively large non-double-couple component exists in at least one of the two moment tensors, as for the examples shown in Figure 4. In such cases, the double-couple representation is not appropriate, and the actual radiation patterns may show substantial similarity in spite of the large Kagan angle.

3 Significant earthquakes in 2005 – 2008

Most of the earthquakes in the study region occur in the eastern Mediterranean (Figure 2), in particular in Greece, along the Hellenic Trench, in the Aegean Sea and in Turkey. Each year more than one earthquake with magnitude greater than 5.5 has occurred in this area. Figure 5 shows an enlarged view of part of this region, with structural features indicated and individual earthquake sequences identified in panels A, B, and C.

Panel A is centered on the Ionian Islands, an area in which different tectonic styles of deformation are

active, as reflected by the diversity of RCMT and GCMT focal mechanisms. A seismic sequence, with the larger events occurring in October 2005 and in April 2006 (Tables 1 and 4 of the Supplementary Material), occurred immediately south of Zakynthos, the southernmost island of the Ionian archipelago. All moment tensors in the sequence reflect thrust motion, in agreement with the tectonics expected along a subduction trench. Four strike-slip events, mapped in panel A of Figure 5, occurred north of this sequence, close to Kefhalonia, on the strike-slip Kefhalinia fault, in March 2007. A third sequence of earthquakes in this area occurred north of the Gulf of Patras in April 2007 (Table 7 of Supplementary Material) for which all moment tensor show normal faulting.

Panel B shows RCMT and GCMT solutions for events in the seismic sequence associated with the M_W 6.6 and 6.2 earthquakes of February 2008 located along the Hellenic Trench (Roumelioti et al., 2009; Sokos et al., 2009). This sequence lasted for more than four months and we determined source parameters for 25 earthquakes with $M \geq 4.5$ (Table 10 of Supplementary Material). Most of the events have a thrust mechanism, with a smaller number of strike-slip earthquakes located in the northernmost part of the area hit by the sequence.

Panel C shows RCMT and GCMT solutions for the earthquakes that occurred in October 2005 in the northernmost part of the Aegean Sea, in eastern Turkey (Table 1 in the Supplementary Material). The focal mechanisms reflect the strike-slip motion expected in this area, related to the propagation of faults associated with the Northern Anatolian fault in the Aegean Sea.

Outside of the regions where most of seismicity occurs, we note several earthquakes on the Iberian peninsula. Two events occurred in 2005, January 29 and February 3 (Table 1 of Supplementary Material, events 4-05 and 7-05; Figure 6), both mostly strike-slip, similar to previous solution for the Murcia region. Our RCMT solutions are similar to moment tensors determined for the same events at IAG (Stich et al., 2003; www.ugr.es/iag/tensor/mtc.html). Other earthquakes located on the Iberian peninsula are two events of 2006, April 23 and June 10 (Table 4 of Supplementary Material, events 35-06 and 47-06) located in northern Spain, the 2006, March 10, M_W 4.8 extensional earthquake located between Valencia and Madrid, and the two thrust earthquakes with M_W 4.5 and 4.8, that occurred in 2007, June 30 and 2008, October 2 (Tables 7 and 10 of Supplementary Material) north of Gibraltar.

Several events with moderate magnitude took place in northern Africa, including two earthquakes with M_W 4.8 and 5.1 located along the coast of Tunisia in February 2005 (Table 1 of Supplementary Material, events 8-05 and 9-05), and the M_W 5.2 earthquake on March 20, 2006; the M_W 5.1 earthquake on April 4, 2006; the M_W 4.8 earthquake on August 7, 2006 (Table 4 of Supplementary Material, events 13-06, 16-06

and 56-06); and the M_W 5.5 earthquake on June 6, 2008, in Algeria (Table 10 of Supplementary Material; Figure 6, event 55-08). These events show different styles of deformation, primarily thrust faulting, but also strike-slip faulting, mainly in eastern Algeria toward Tunisia. This heterogeneity can be attributed to the effects on the present-day kinematics of the complex evolution of the Alboran Sea-Gibraltar arc (Facenna et al., 2004; Serpelloni et al., 2007).

In the easternmost part of the Mediterranean, two small earthquakes in the Dead Sea region in 2007 (Table 7 of Supplementary Material, events 10-07 and 78-07; Figure 2) appear consistent with the left-lateral strike-slip motion of the Dead Sea fault. In Italy, a seismic sequence hit the Italian northern Apennines, with two main events on December 23, 2008 (Table 10 of Supplementary Material, events 95-08 with M_W 5.5 and 96-08 with M_W 4.9; Figure 7; Ercolani et al., 2009). Several deep earthquakes occurred along the southern Tyrrhenian slab (Figure 7, gray background focal mechanisms) and a shallow earthquake, on February 27, 2006, M_W 4.4, in the Messina Straits, occurred near the location of the strongest Italian earthquake of modern times, on December 28, 1908, I_{max} XI, M_W 7.1 (Pino et al., 2000).

Two noteworthy earthquakes are the $M_W = 4.6$, United Kingdom event on February 27, 2008 (Table 10 of Supplementary Material, event 21-08 and Figure 2), and the earthquake on the French Atlantic coast on April 18, 2005 ($M_W = 3.9$, event 16-05 in Table 1 of Supplementary Material; Figure 2). These two events occurred in areas where seismic activity reaching these magnitudes is rare. The first, the Market Rasen (UK) earthquake, has been the subject of a detailed study (Heyburn and Fox, 2010) to determine source parameters using body and regional surface waves at higher frequencies than those employed in our analysis. The source parameters determined in the two studies are very similar for the location, depth, magnitude and the focal mechanism (Heyburn and Fox, 2010). The second event is located along the Atlantic coast. It is isolated and provides an additional example of a moderate event with a preliminary reported magnitude 5.2 m_b (Table 1 of Supplementary Material), significantly greater than the M_W 3.9 obtained here.

4 1997-2008: 12 years of RCMT solutions

Efforts leading to the European–Mediterranean RCMT Catalog were initiated following the study of the 1997-1998 Umbria-Marche earthquake sequence (Ekström et al., 1998; Amato and Cocco, 2000; Morelli et al., 2000). In that investigation (Ekström et al., 1998), we were able, for the first time, to compute reliable seismic moment tensors immediately following a significant earthquake sequence in Italy. The analysis provided important data for the assessment of the ongoing sequence, and for further tectonic studies (e.g., Pondrelli and Morelli, 2008). We then applied the same methods to analyze routinely moderate-

magnitude seismicity in Europe and the Mediterranean, and to building and updating a regional moment-tensor catalog (Pondrelli et al., 2002, 2004, 2007). In addition, we established a routine procedure for determining quick RCMT solutions immediately following the occurrence of an earthquake (see med-net.rm.ingv.it/quick_rcmt.php; earthquake.rm.ingv.it/qrcmt.php or the individual event pages at www.emsc-csem.org). In the real-time analyses we rely mainly on data from the MEDNET (Mazza et al., 2008) and GEOFON (Hanka and Kind, 1994) networks.

Systematic moment-tensor investigations similar to the RCMT effort are conducted, or have recently been conducted, by other research groups in Europe. The ETHZ moment tensor catalog (Braunmiller et al., 2002; www.seismo.ethz.chprod/tensors/index_EN) is not maintained beyond 2006, but automated solutions for recent earthquakes are still provided. The IAG catalog (Stich et al. 2003; www.ugr.es/iag/tensor/mtc.html) is updated through the end of 2005, and the IGN (Rueda and Mezcua, 2005; www.ign.es/ign/en/IGN/SisCalculo.jsp) real-time catalog is up to date, but both of these catalogs are limited to the Spanish region and parts of northern Africa. These independent studies, some of which have a more limited regional scope than the RCMT effort, but also a lower magnitude threshold, offer opportunities for comparisons of results for the few events that are in common.

The RCMT catalog now contains more than 1000 solutions. Figure 8 shows the growth with time of the number of solutions available for the whole Mediterranean area in the RCMT catalog (in green), compared to the global GCMT, and ETHZ (red) catalogs. The RCMT solutions for the period 1977-1996 are exclusively for the Italian region (Pondrelli et al., 2006), and the European-Mediterranean scope of the catalog starts in 1997. For Europe and the Mediterranean, the RCMT catalog roughly doubles the number of seismic moment tensors available.

Figure 9 shows a frequency-magnitude distribution for the RCMT catalog and the appropriate Gutenberg-Richter line (Gutenberg and Richter, 1944). The b -value has been determined on the basis of the distribution of the events with a M_W greater than the completeness magnitude M_c , using the Maximum Likelihood method (Aki, 1965; Bender 1983; for the uncertainties, see Shi and Bolt, 1982). The M_c , that corresponds to 4.7, has been computed using the maximum curvature method (Wiemer and Wyss, 2000). The completeness falls off rapidly for magnitude smaller than 4.5 earthquakes, reflecting the lack of close-in stations with high signal-to-noise ratio seismograms for most small earthquakes, and the practical limits of the RCMT method of analysis.

Each year we add nearly one hundred new RCMT solutions to the catalog (Figure 10). The number of successful analyses, with respect to those attempted, has grown from approximately 60% in 1997 to

86% in 2008 (Figure 10). There are several possible reasons for failure to compute a reliable solution. The most frequent is a high preliminary magnitude for a too-small event. As an example, event 16-05 was initially reported with $m_b = 5.2$ but turned out to have a much smaller moment magnitude, $M_W = 3.9$. In other instances, such situations do not lead to a stable RCMT solution, such as for the November 17, 2006, earthquake in France, which was initially reported with $M_L = 5.0$, but later described with $M_W = 4.4$ (Sylvander et al., 2008). A second significant cause for failure is the overlap of seismic signals from two earthquakes that occur close in time. This situation is not uncommon, since in many cases we analyze events belonging to the same seismic sequence. The gradual improvement in the success rate seen in Figure 10 is likely due to more consistent preliminary magnitudes and the expansion of seismographic networks in the Mediterranean region.

Figure 11 shows epicentral locations for all earthquakes (1997–2008) for which we have attempted analysis. Yellow symbols correspond to successful analyses and red symbols show locations of events for which we did not obtain a robust result. In some regions, for example in Poland, we have so far been unable to obtain a single acceptable moment-tensor result even though the reported magnitudes for several events have suggested that successful RCMT analysis would be possible. A potential explanation is that some of the events in Poland are associated with mining activity, and thus may have unusual frequency characteristics with low excitation of the long-period surface waves used in the RCMT analysis.

Figure 12 shows the geographical distribution of the recently added quality parameter (A, B, C, D) described above. The inset diagram, displaying the number of events of A, B, or C quality at different magnitudes, shows that there is no clear correlation between quality and magnitude. There also does not appear to be a geographical correlation once the relative level of seismicity of different regions is taken into account.

In addition to providing standard earthquake parameters for individual events of interest, the comprehensive character of the RCMT catalog makes it a valuable source of information for investigations of the character of seismic deformation in Europe and the Mediterranean region. The data set has been used, for example, for the compilation of stress maps (e.g., Montone et al., 2004; Sperner et al., 2003) and strain maps (e.g., Kreemer et al., 2003; Serpelloni et al., 2007; Vannucci et al., 2004; Hollenstein et al., 2008), for seismotectonic studies (e.g., Stich et al., 2007; Mauffret, 2007), and for the assessment of seismicity and seismic sequences (e.g., Grunthal et al., 2009; Pondrelli et al., 2010).

Distribution of moment-tensor information occurs mainly through the worldwide web. In response to the increasing size of the RCMT data base, as well the variety of user requirements, we have added

new functionalities to the RCMT web site. Earthquake data are available in yearly files and in several possible formats, such as those required to plot seismic moment tensors with the GMT map tool (Wessel and Smith, 1998) and in Google Earth. An advanced web interface (Postpischl et al., 2010) provides full search capabilities of the entire dataset by location, time, magnitude and quality parameters (www.bo.ingv.it/RCMT/searchRCMT.html). The searchable database includes all reviewed solutions for the period 1997-2008 and all quick solutions up to the present. Solutions can be further filtered to distinguish between quick and definitive results.

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Figure captions

Figure 1: Recorded (blue) and synthetic seismograms (red) used to compute the RCMT solutions for an event that occurred in the Mediterranean Sea, on February 3, 2007, with $M_W = 5.5$. Epicentral distance is 31.89° . In this case, body (a) and surface (b) waves were simultaneously used in the inversion.

Figure 2: Map of RCMT solutions for the time span of 2005-2008 (in red). The focal mechanisms with gray extensional quadrants are for earthquakes with hypocentral depth greater than 50 km. Small black mechanisms shown in the background correspond to earlier RCMT solutions from the catalog.

Figure 3: Upper left: Frequency plot of Kagan angles for the 2005-2008 RCMT and GCMT compared solutions. Upper right: Frequency plot of P, T and N axes rotations. Lower: Plot of the logarithm of the scalar moment for compared RCMT and GCMT solutions.

Figure 4: Examples of pairs of RCMT (grey) and GCMT (black) solutions for earthquakes that show Kagan angles greater than 60° . Each pair is coded by the ID number used in the Tables of Supplementary Material.

Figure 5: Map of significant events and seismic sequences in the eastern Mediterranean region. In the principal image are reported in red all RCMT solutions determined in the present study. The focal mechanisms with gray extensional quadrants correspond to earthquakes with hypocentral depth greater than 50 km. Small black focal mechanisms show earlier RCMT solutions. Insets A, B and C show the main seismic sequences of 2005-2008 respectively in Southern Greece (close to the Kephallinia fault), along the Hellenic trench and in the eastern Aegean Sea and Turkey. Black focal mechanisms show GCMT solutions for the main shocks.

Figure 6: Map of significant events in the westernmost part of our study region, for which RCMT solutions are determined in the present study. Small black focal mechanisms show earlier RCMT solutions. For larger events, the date of occurrence is given.

Figure 7: Map of significant events in Italy and surrounding regions, for which RCMT solutions are determined in the present study. The focal mechanisms with gray extensional quadrants refer to earthquakes with hypocentral depth greater than 50 km. In the background — small black focal mechanisms — all previous RCMT solutions are also shown. The two main events of the sequence that hit the northern Apennines in December 2008 are highlighted.

Figure 8: Growth with time of the number of centroid-moment tensors for the Euro-Mediterranean region in different catalogs: Global CMT (blue); ETHZ data (red); our RCMT data (green).

Figure 9: Frequency-magnitude distribution of the RCMT catalog earthquakes (squares, cumulative; triangles, not-cumulative) and relative Gutenberg Richter line (red line) for the events of magnitude M_W larger than the completeness magnitude (M_c).

Figure 10: Number of events attempted (white columns) and number of obtained RCMT solutions (black columns) for each year from 1997 to 2008.

Figure 11: Map of attempted (red circles) and successful solutions (yellow squares) for RCMT solutions in the 12-year period of the catalog.

Figure 12: Map of whole catalog solutions, distinguished by quality flag, represented by different colors: flag A (best quality), red; flag B, orange; flag C, yellow; flag D, white. Upper right: histogram of the number of events with respect to M_W and quality flags: flag A, white; flag B, dark gray; flag C, light gray.

2007/02/03 13:43:23.1, $\vartheta = 35.81$, $\varphi = 22.43$, $h = 59.0$
KURK-II $\Delta = 42.51$, $\alpha = 51.42$, $\beta = 271.80$

Figure 1

Figure 2

Figure 3

43-06 **60-05** **04-07** **22-07**

Figure 4

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

Figure 12