The new release of the database of Earthquake Mechanisms of the Mediterranean Area (EMMA Version 2)

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We present here the second release of a database, running on MS-Access platform, of the earthquake focal mechanisms of the Mediterranean area, published in the literature. For all of the mechanisms (more than 6000) the published parameters, taken from about 193 papers, have been checked for consistency and if necessary corrected when possible. The MS-Access application also allows the major moment tensor catalogs available for the area to be imported (without checking) and used.

1. Introduction

The motivation of this work originates from the difficulties that any investigator interested in seismotectonics and seismic hazard analysis of Italy and surrounding regions encounters when collecting fault plane solutions from the literature. Italy is in fact a region with a relatively moderate seismicity, where earthquakes above the magnitude threshold of the Harvard CMT Catalog (about $M_w > 5.5$) have been only a few dozen since 1976. Therefore the contribution given by first pulse mechanisms published in the literature is also necessary to well characterize the tectonic styles of the various seismic source areas.The difficulties in using such data mainly come from the fact that they were very dispersed over a large number of papers and that, due to the hard copy format, they were not readily available for analyses by computer codes. Moreover, a number of mistakes are occasionally found in some of them, going from the incorrect use of terms (*i.e.* strike instead of dip-direction) to inconsistencies of the reported data (*i.e.* non-orthogonality of fault planes and deformation axes, inconsistency between plane and axes, etc.).

Therefore, taking advantage of a call for proposals, within the Framework Project 2000/2002 of the Italian Gruppo Nazionale Difesa dai Terremoti (GNDT), our group submitted a Coordinate Project («Revision of the theoretical and observational grounds of seismic hazard estimates at a national scale») where one of the tasks concerned the development of a reliable catalog of focal mechanisms to be used in new hazard estimates. We thus started to collect focal solution, from the national and international literature. Initially our interest was limited to Italy and the surrounding regions, but later the area was extended to include the whole Mediterranean Sea and surrounding regions, from the Atlantic Ocean to Iran. The first version of the database, published more than a year ago (Vannucci and Gasperini, 2003), contains 4995 mechanisms taken from 177 directly examined papers, some of which refer to 117 other works (mostly thesis or technical reports) which it was not possible to find. Such version was recently used to constrain the tectonic styles of the seismogenic source areas of the new seismic zonation ZS9 (ZS9 Working Group, 2004) which has been developed within the framework of the INGV initiative following the Italian Prime Minister's Ordinance of March 20, 2003 for the assessment of the new seismic hazard map of Italy.

The database is embedded in an MS-Access application allowing visual comparison between original and recomputed focal mechanisms data, the importing of the data from the on-line Global CMT Harvard Catalog and from two regional RCMT catalogs (Istituto Nazionale di Geofisica e Vulcanologia – INGV – of Rome and Eidgenössische Technische Hochschule – ETH – of Zurich), the selection of mechanisms on the basis of various criteria and exporting onto ASCII files of the data to be used in further computations.

An added value of the EMMA database is checking all the mechanism parameters for consistency and, in case of problems, correcting them so that the mechanisms are immediately usable for drawing maps or making further computations like the ones shown in the previous article of this issue. We checked that angles between planes and between axes did not differ from 90° by more than three degrees. Also, we checked the consistency between fault planes and axes and between moment tensor components and planes or axes. To make all of these checks and to homogeneously re-compute all relevant parameters (fault planes and deformation axes angles, moment tensor components) for each mechanism, we developed a structured package of Fortran 77 subroutines (FPSPACK, Gasperini and Vannucci, 2003) performing the most common computations and checks on focal mechanism data. This package is freely available from the ftp server of *Computers & Geosciences* journal: ftp://ftp.iamg.org/VOL29/v29-07-08.zip and includes, among others, routines to compute nodal planes from *P*- and *T*-axes and *vice versa* and to compute moment tensor components from planes or axes or best double couple parameters from moment tensor components. All definitions, conventions and formulas we have used are reported in Appendix A.

To make reliable selections on the basis of the earthquake size and to compute the seismic moment tensor, we uniformly computed the scalar seismic moment, using empirical regressions with available magnitude estimates for all of the mechanisms for which this parameter is not reported in the original paper.

Another feature of the EMMA database is the choice of the best mechanism among the available duplicates. We weighted each solution on the basis of a series of objective criteria based on: i) the correctness of the solution (presence or absence of errors in the published FPS parameters); ii) the originality of the source (original sources are preferred with respect to indirect ones); iii) the «authoritativeness» of the source (chosen roughly proportional to the impact factor of the journal where the mechanism is published); iv) the recentness of the publication (most recent papers override previous ones). We did not consider any kind of quality estimators (solution quality factor, number of stations, etc.) as these are only given by a minority of the published solutions. The «best solution» is the one with the highest weight and is marked in the database by a specific flag that can be included in selection.

2. Database contents and functionalities

This second version of the database is released about one year after the first one, taking advantage of this Special Issue of *Annals of Geophysics* to distribute it among the scientific community. All files required to run the MS-Access application are included in a CD-ROM attached to the journal (see EMMA_tutorial.pdf file inside the CD-ROM the instructions to install and use the MS-Access application). The spatial coverage is similar to previous version (see fig. 1) but the consistency of the data was only improved of about 20% (see table I). The present one is the first release available to a wide community of potential users as the initial release only had a circulation among a restricted ambit. The origin time year ranges from 1905 to 2003 while the moment magnitude M_w from 4 to 8.7.

The MS-Access application we have written allows users to access mechanism data through a series of menus and masks (figs. 2 to 5). The user can display the mechanisms of the entire database or make selections on the basis of earthquake source parameters (date, location, magnitude, etc.) and/or

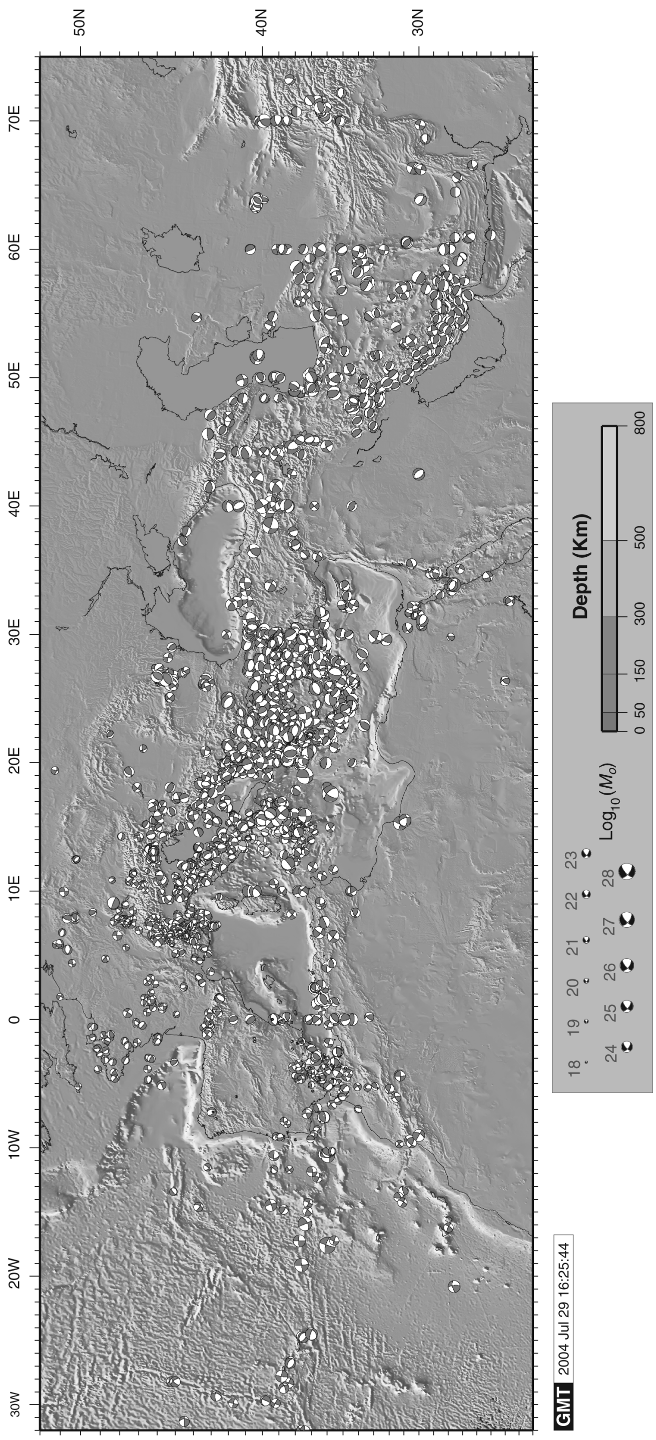

Fig. 1. Spatial distribution of fault plane solutions taken from the literature (on-line CMT catalogs excluded).

Table I. Summary of the results of the checks performed on the focal mechanisms found in hard copy literature.

Type of data	Number	%
All examined	**6156**	**100.0**
Correct FPS parameters	3761	61.1
FPS parameters with some defects	2395	38.9
Recoverable	**2090**	**34.0**
Wrong axes, correct planes and rakes	126	2.0
Wrong planes or rakes, correct axes	1459	23.7
Only strike and dip of two planes (polarity determined from figures)	505	8.2
Unrecoverable	**305**	**4.9**
Axes and/or planes not perpendicular	205	3.3
Undetermined	100	1.6
Correct+recovered	**5851**	**95.1**
Lacking of earthquake identification parameters (date, location, magnitude)	300	4.9
Usable solutions	5551	90.2
Duplicate solutions	2316	
Distinct earthquakes	**3840**	**100.0**
Earthquakes with only one mechanism	2906	75.7
Earthquakes with more than one mechanism	934	24.3

of bibliographic references (authors, journal, etc.). In addition, the mechanism data can be exported to ASCII files to be plotted by GMT (Wessel and Smith, 1991), or processed by external codes. Another feature of the MS-Access application is the compilation and export of the list of bibliographic references of all of the data or a selection of them. This simplifies the correct citation of all of the contributing papers to investigations making use of the EMMA database. We will give here only an overview of the main features of the MS-Access application while a more complete description can be found in the EMMA_tutorial.pdf file inside the CD-ROM.

At the startup, the MS-Access application shows the Main menu with four choices (fig. 2): the first (EVENT SELECTION) allows users to access an Event Selection Mask (fig. 5), the second (COMPLETE DATABASE) accesses a further menu allowing to display (fig. 3), view and export the complete reference list, export onto ASCII files the focal mechanism data, the third (IMPORT CATALOGS) accesses a menu allowing users to import in the database the focal solutions data of three on-line catalogs:

– The global CMT Catalog continuously updated by the Harvard Seismology team (Dziewonski *et al.*, 1981 and subsequent papers appeared quarterly in *Physics of the Earth and Planetary Interiors*) is available at: http://www.seismology.harvard.edu/projects/CMT/.

– The Regional CMT (RCMT) Catalog of the Mediterranean Region, published by the Istituto Nazionale di Geofisica e Vulcanologia (INGV) of Rome (Pondrelli *et al.*, 2002, 2004), is available at: http://www.ingv.it/seismoglo/RCMT/.

– The Regional CMT (RCMT) Catalog of the *Eidgenössische Technische Hochschule* (ETH) of Zürich (Braunmiller *et al.*, 2002), mainly covering the Mediterranean region, is available at: http://seismo.ethz.ch/info/mt.html.

The last choice of the Main menu (EXIT) exits the database application.

The Mechanism display window (fig. 3) is accessed from the Main menu as well as from the Event Selection Mask described below. It scrolls the mechanisms by the arrow buttons located close to the bottom-left corner of the window. The two large buttons located close to the arrows activate the Summary and plot window (fig. 4) including a beach-ball plot of the mechanism in the lower hemisphere standard representation and in the upper hemisphere alternative representation

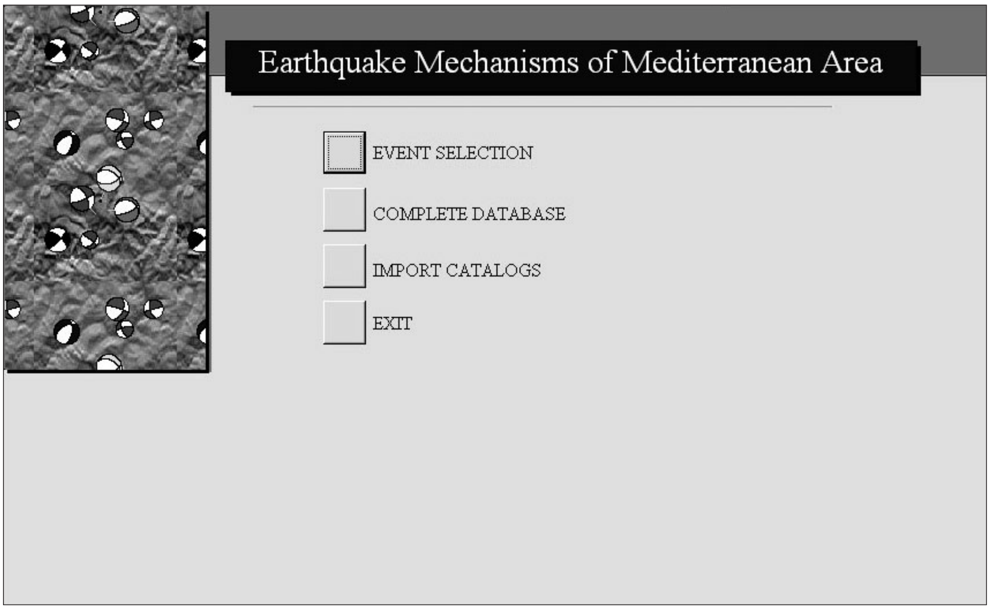

Fig. 2. Main menu of EMMA database.

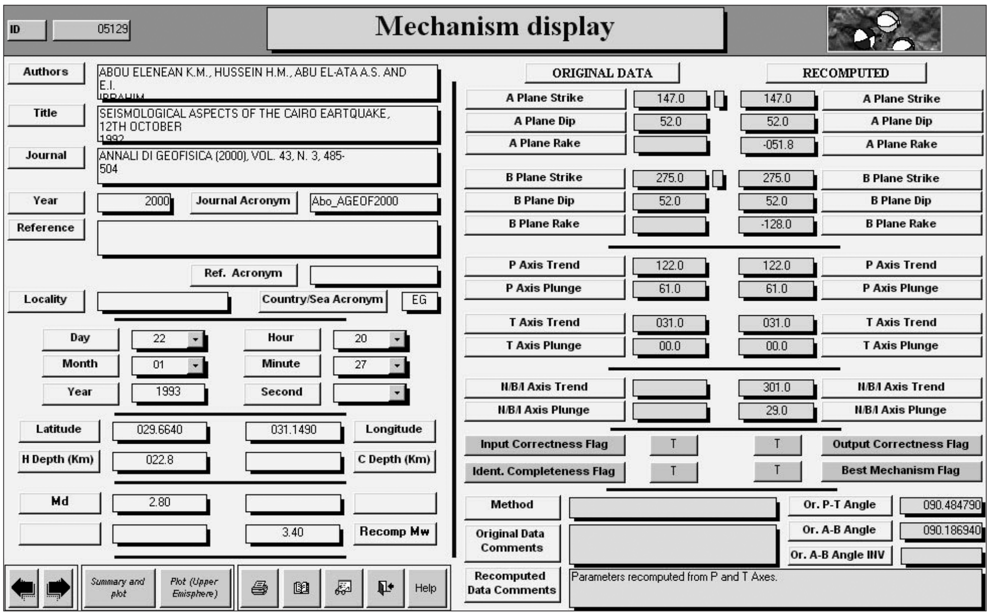

Fig. 3. Mechanism display window.

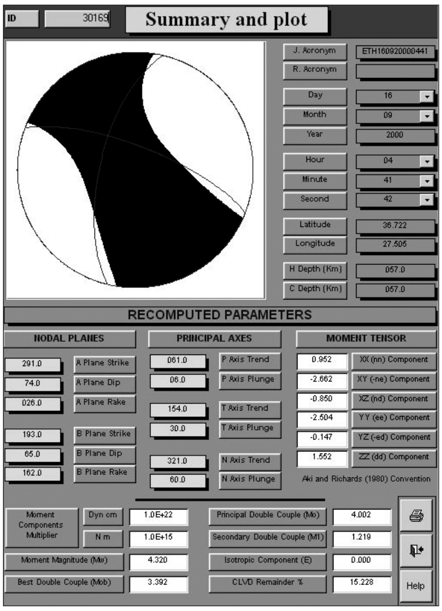

Fig. 4. Summary and plot window (lines indicate best double couple nodal planes).

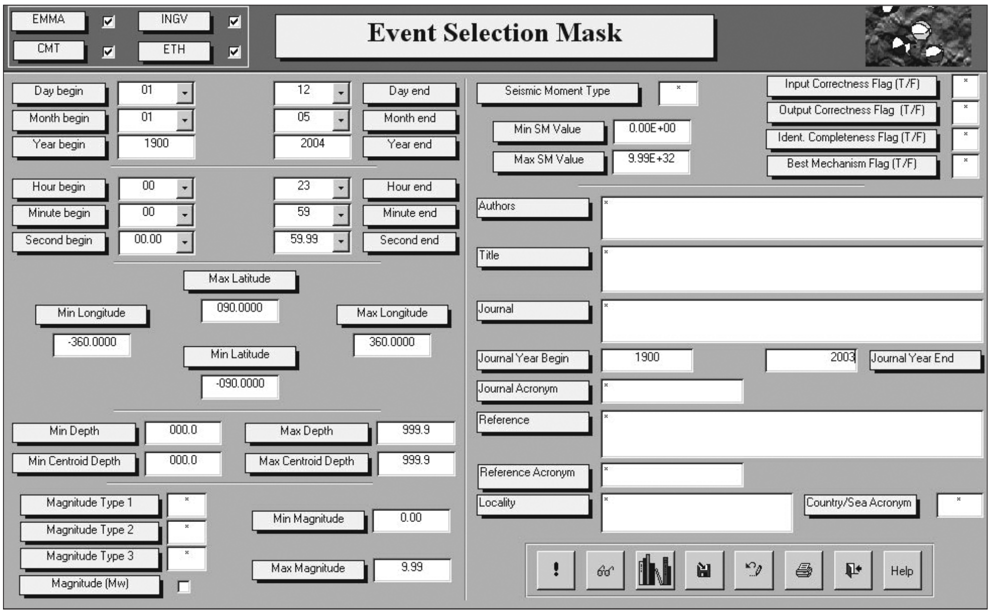

Fig. 5. Mechanism Selection Mask.

respectively. The remaining buttons, allow users to: print the layout of the window for the current record as well as for all the selected records, activate a window showing the values of additional parameters like moment tensor components and moment tensor decomposition parameters, exit the window and return to the calling menu or mask, display a help window with a brief explanation of each button.

The left-hand side of the mask displays, for each fault plane solution, a comprehensive report of the earthquake parameters and of the bibliography of the work from which the data are actually taken as well as of the original reference, when the latter is not directly available and the data were taken from a paper referring it. All earthquake parameters shown in this section exactly match those reported in the examined source works, excluding the «Recomp. M_w» moment magnitude. This value is uniformly revaluated from the scalar seismic moment or the magnitudes given by the source, to make uniform magnitude selections and determine the seismic moment tensor. It is the result of different possible choices, depending on the parameters available from the source paper. The highest priority is given to direct M_w estimates or ones derived from the reported scalar seismic moment, while in the absence of them, M_w is recomputed from other types of magnitude (for details see: Vannucci and Gasperini, 2003). Correspondingly, the scalar seismic moment is recomputed, when not available from the paper, from M_w or other types of magnitude.

The right-hand side of the display window reports fault planes and/or deformation axes parameters found on the examined source (ORIGINAL DATA) as well as those (RECOMPUTED) resulting from the validation and correction procedure described by Vannucci and Gasperini (2003). The other information displayed in this side of the window gives details on the mechanism estimate method, on the «correctness» of the original data and, in case of problems, on the procedure followed to correct them. In particular, four logical flags (with only two possible values: true and false) indicate the following focal mechanism properties:

– Input correctness flag: if true, the original nodal planes and/or *P*- and *T*-axes were found to be consistent among each other and thus no corrections were made to the original data. In this case only the parameters not given by the source are recomputed. If false, some kind of inconsistency was found and then, if possible, all the parameters were recomputed consistently.

– Ident. completeness flag: if true all information needed for an univocal identification of the earthquake (epicentral location, origin-time and magnitude or scalar moment) are available from the source. If false, the data reported by the source do not permit the correct identification and thus the mechanism is not «usable» for further analyses.

– Output correctness flag: if true, the original or the recomputed nodal planes and *P*- and *T*-axes parameters are correct and usable. If false, the data reported by the source are not consistent and/or do not allow to re-compute reliable parameters. Even in this case the mechanism is not «usable» for further analyses.

– Best mechanism flag: if true, this mechanism is the «best» (in the sense described by Vannucci and Gasperini, 2003) among duplicates for the same earthquake. If false, the mechanism is an alternative solution among duplicates for the same earthquake but not the preferred one.

The boxes located in the lower-right portion of the window report further details on the methods employed to compute the mechanism (First motion, CMT, *P*- and *S*-waves, velocity models etc.), evident misprints or terms misused in the original data, inconsistencies in the input data (the angles between *P*- and *T*-axes, and between nodal planes (A and B), and, for defective solutions, a synthetic description of problems encountered with the original mechanism data and the procedure followed to solve them and to re-compute consistent parameters.

The Mechanism selection mask (fig. 5), accessed by the Main menu shows at the top-left corner, the catalog (or catalogs) to be processed. These can be included or not by selecting the tick box corresponding to the different catalogs: EMMA for the revised mechanisms taken from the literature, CMT for the Harvard CMT Project Catalog, ETH and INGV for the Regional MT catalogs of the ETH and INGV respectively.

The Event Selection Mask generates a database query that always checks only the earthquake date, location and depths and the Journal Year. The remaining parameters are considered for selections only if explicitly selected. The initial limits are set so that to select all the events of the chosen catalogs. The various buttons located in the bottom-right side of the mask allow users to (from left to right): execute the selection, enter the Mechanism display window (see above, fig. 3) allowing to display the selected mechanisms, view or export a list of references, view and export the selected mechanisms data for various purposes, restore the initial settings of the mask, print the layout of mask, exit the mask and return to previous menu, display a help window containing a brief description of the function of each button.

3. Concluding remarks

Although we did our best, we can easily predict that at least some defects are still present in our work. In addition, we certainly missed some published papers (see the complete list of contributing papers in Appendixes I and II). So we explicitly request the collaboration of all investigators interested in improving this database to point out any mistakes and malfunctioning of the procedure they find or the omission of interesting papers they know have been published.

We also want to state clearly that our contribution only represents an added value to the work done by the authors of original papers and thus the database must not be cited as the source of data alone but only as a tool to access them easily. We thus strongly recommend that users insert in their references the complete list of original works that actually computed the focal plane solutions they use. As noted above, a specific option is available to simplify this task in our MS-Access application.

Appendix A. Definitions, conventions and formulas used to check and re-compute mechanism parameters.

The focal mechanism of an earthquake can be completely represented by the seismic moment (symmetric) tensor M_{ij}. For a pure double couple it can be defined, in the Aki and Richards System (AR System), as a function of the outward normal and slip vectors of one of the nodal planes as

$$M_{ij}^{AR} = M_0 \begin{Vmatrix} 2n_x d_x & n_x d_y + n_y d_x & n_x d_z + n_z d_x \\ n_y d_x + n_x d_y & 2n_y d_y & n_y d_z + n_z d_y \\ n_z d_x + n_x d_z & n_z d_y + n_y d_z & 2n_z d_z \end{Vmatrix}. \tag{A.1}$$

In this case only four components are independent, while for a general composite mechanism there are six independent components of the moment tensor.

Most of CMT solutions available in the on-line catalogs are given in the Harvard CMT coordinate system. The tensor can be expressed as a function of the six independent components reported on the CMT Catalog (M_{SS}, M_{EE}, M_{RR}, M_{SE}, M_{RS}, M_{RE}) as

$$M_{ij}^{Harvard} = M_0 \begin{Vmatrix} M_{SS} & M_{SE} & M_{RS} \\ M_{SE} & M_{EE} & M_{RE} \\ M_{RS} & M_{RE} & M_{RR} \end{Vmatrix} \tag{A.2}$$

As the direction of two coordinate axes (1 and 3) are reversed with respect to the AR System, the signs of the components 1-2 and 2-3 must be exchanged when passing from one to the other of the two systems

$$M_{12}^{AR} = M_{21}^{AR} = -M_{12}^{Harvard} = -M_{21}^{Harvard}$$
$$M_{23}^{AR} = M_{32}^{AR} = -M_{23}^{Harvard} = -M_{32}^{Harvard}. \tag{A.3}$$

The eigenvectors of the moment tensor corresponding to the most negative, most positive and intermediate eigenvalues coincide with the directions of the *P*-, *T*- and *B*-axes. Hence these can be used to compute the nodal planes of the double couple best representing the mechanism. The latter however well represents the entire mechanism only when the most compressive and most tensional eigenvalues are close in modulus and the intermediate one is negligible with respect to them. Otherwise the mechanism is complex and can be decomposed making some assumptions on the causative mechanics (see *i.e.* Lay and Wallace, 1995; and Julian *et al.*, 1998, for a comprehensive discussion of different cases).

All decomposition methods require the removal of the isotropic tensor component. The result of this operation (preliminarily done in most CMT catalogs) is the deviatoric moment tensor that in the major axis coordinate system is given by

$$\begin{Vmatrix} \lambda'_1 & 0 & 0 \\ 0 & \lambda'_2 & 0 \\ 0 & 0 & \lambda'_3 \end{Vmatrix} = \begin{Vmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{Vmatrix} - \begin{Vmatrix} E & 0 & 0 \\ 0 & E & 0 \\ 0 & 0 & E \end{Vmatrix} \tag{A.4}$$

where $E = (\lambda_1 + \lambda_2 + \lambda_3)/3$. The most popular decomposition method subdivides the deviatoric moment tensor into the sum of two double couples. Assuming a decreasing ordering in modulus of deviatoric eigenvalues $(|\lambda'_1| > |\lambda'_2| > |\lambda'_3|)$ we can write

$$\begin{Vmatrix} \lambda'_1 & 0 & 0 \\ 0 & \lambda'_2 & 0 \\ 0 & 0 & \lambda'_3 \end{Vmatrix} = \begin{Vmatrix} M_0 & 0 & 0 \\ 0 & -M_0 & 0 \\ 0 & 0 & 0 \end{Vmatrix} + \begin{Vmatrix} 0 & 0 & 0 \\ 0 & M_1 & 0 \\ 0 & 0 & -M_1 \end{Vmatrix} \tag{A.5}$$

where $|M_0|$ and $|M_1|$ are the scalar seismic moment of major and minor double couples respectively.

An alternative method, originally proposed by Knopoff and Randall (1970), decomposes the deviatoric moment tensor into the sum of a double couple and a Compensated Linear Vector Dipole (CLVD), with same *P*- and *T*-axes. Assuming again a decreasing ordering in modulus for the deviatoric moment tensor eigenvalues, this is given by

$$\begin{Vmatrix} \lambda'_1 & 0 & 0 \\ 0 & \lambda'_2 & 0 \\ 0 & 0 & \lambda'_3 \end{Vmatrix} = (1-\eta) \begin{Vmatrix} \lambda'_1 & 0 & 0 \\ 0 & -\lambda'_1 & 0 \\ 0 & 0 & 0 \end{Vmatrix} + \eta \begin{Vmatrix} \lambda'_1 & 0 & 0 \\ 0 & -\lambda'_1/2 & 0 \\ 0 & 0 & -\lambda'_1/2 \end{Vmatrix} \tag{A.6}$$

where $\eta = -2\lambda'_3/\lambda'_1$ is a measure of the size of the CLVD component with respect to the total deviatoric moment tensor. It may range from 0 for a pure double couple to 1 for a pure CLVD. The scalar seismic moment of the double couple is given by $M_0 = (1-\eta)|\lambda'_1| = |\lambda'_2 - \lambda'_3| = |\lambda'_1 - 2\lambda'_3|$.

A slightly different procedure is followed by the Harvard CMT and other routine catalogs. They compute the scalar moment M_{0b} of largest possible (best) double couple that has a CLVD remainder (Dzievonski *et al.*, 1987) as the average of the two largest eigenvalues in modulus

$$M_{0b} = \frac{|\lambda'_1| + |\lambda'_2|}{2} = \frac{|\lambda'_1 - \lambda'_2|}{2} \tag{A.7}$$

where the last passage is correct because the largest eigenvalue has an opposed sign with respect to the other two due to the zero tensor trace and the assumed eigenvalues ordering. In this representation the isotropic moment tensor decomposes as

$$\begin{Vmatrix} \lambda'_1 & 0 & 0 \\ 0 & \lambda'_2 & 0 \\ 0 & 0 & \lambda'_3 \end{Vmatrix} = \begin{Vmatrix} (\lambda'_1 - \lambda'_2)/2 & 0 & 0 \\ 0 & (\lambda'_2 - \lambda'_1)/2 & 0 \\ 0 & 0 & 0 \end{Vmatrix} + \begin{Vmatrix} -\lambda'_3/2 & 0 & 0 \\ 0 & -\lambda'_3/2 & 0 \\ 0 & 0 & \lambda'_3 \end{Vmatrix}. \tag{A.8}$$

The ratio between the sizes of CLVD remainder and total deviatoric moment tensor is now given by $\eta' = -\lambda'_3/(2\lambda'_1)$ that is exactly one fourth of the previous definition. Thus equation (A.8) can be written as

$$\begin{Vmatrix} \lambda'_1 & 0 & 0 \\ 0 & \lambda'_2 & 0 \\ 0 & 0 & \lambda'_3 \end{Vmatrix} = (1-\eta') \begin{Vmatrix} \lambda'_1 & 0 & 0 \\ 0 & -\lambda'_1 & 0 \\ 0 & 0 & 0 \end{Vmatrix} + \eta' \begin{Vmatrix} \lambda'_1 & 0 & 0 \\ 0 & \lambda'_1 & 0 \\ 0 & 0 & -2\lambda'_1 \end{Vmatrix}. \tag{A.9}$$

The lower limit of the ratio $\eta' = 0$ still corresponds to a pure double couple, while the upper one $\eta' = 0.25$ corresponds to a moment tensor apparently showing a pure CLVD mechanism. However, this decomposition scheme assumes that the double couple component dominates (75% of the size of total deviatoric moment tensor).

The latter scheme would be preferable if the CLVD remainder is the result of inversion errors while the previous one (A.6) would be more appropriate if the CLVD component has a physical origin.

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APPENDIX I. List of directly examined papers (direct references).

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APPENDIX II. List of original papers referred by others (indirect references). As they were not directly examined, some of the mechanisms reported by them may not be included in the database.

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