2167-24

Advanced School on Direct and Inverse Problems of Seismology

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GEOSCOPE procedure for centroid - moment tensor determination

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1 Introduction

The first quantitative information sought after an earthquake occurence is, beyond the geographical location of its epicenter, the characterization of the event: what is the magnitude and duration of the earthquake, its depth and its focal mechanism, *i.e.* the fault orientation and the direction of slip along that fault. A rapid estimation of these parameters is necessary before any further study. The seismic centroid moment tensor is an equivalent point source representation of these average characteristics.

Obtaining these information from seismograms is the mandatory first step of a seismic event analysis before further detailed investigations: ground deformation, kinematic of the rupture, seismicity analysis of a fault system, etc...

Also, sismological studies of the large scale structures of the Earth, from regional to global, are performed using a tomographic process in which thousands of synthetic seismograms are generated and compared to real data. Catalogues of seismic moment tensors are used as input to generate theses synthetic seismograms.

The centroid moment tensor is always determined for seismic event of scientific and/or social interest, but there are only two systematic catalogues at global scale, including a rapid determination of the earthquakes source mechanism: the Global CMT project[1] and the USGS centroid moment tensor[2] solution. A few regional initiative also exist (e.g. by the USGS or the regional moment tensor catalogue of the EMSC[3]).

In the framework of the French national worldwide seismological observatory GEOSCOPE, an application designed for the determination of the centroid seismic tensor for large earthquakes, *i.e.* producing long-period seismic signal (above 50s period) on a global scale has been implemented. As the method chosen is intrinsically distributed, deploying it on a Grid computing infrastructure that gathers several thousands of computers such as the EGEE[4] project was seen as a solution to reduce the time spent on this operation.

2 Contexte: the GEOSCOPE seismological observatory

GEOSCOPE is the French national worldwide seismological observatory. The GEOSCOPE network is composed by 32 wide band seismic stations covering the globe. GEOSCOPE is the French component of the networks of seismic monitoring know as "very broad band". It takes part in localizing of earthquakes on the whole planet, in determining the rupture mode of the faults

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[1] http://www.globalcmt.org/

[2] United States Geological Survey, http://www.earthquake.usgs.gov/

[3] European-Mediterranean Seismological Centre, http://www.emsc-csem.org/

[4] http://www.eu-egee.org/

causing them and in tomographies of the interior of our planet. GEOSCOPE is also associated to the development of international monitoring systems, in particular for tsunami related risks in the Indian Ocean and the Antilles.

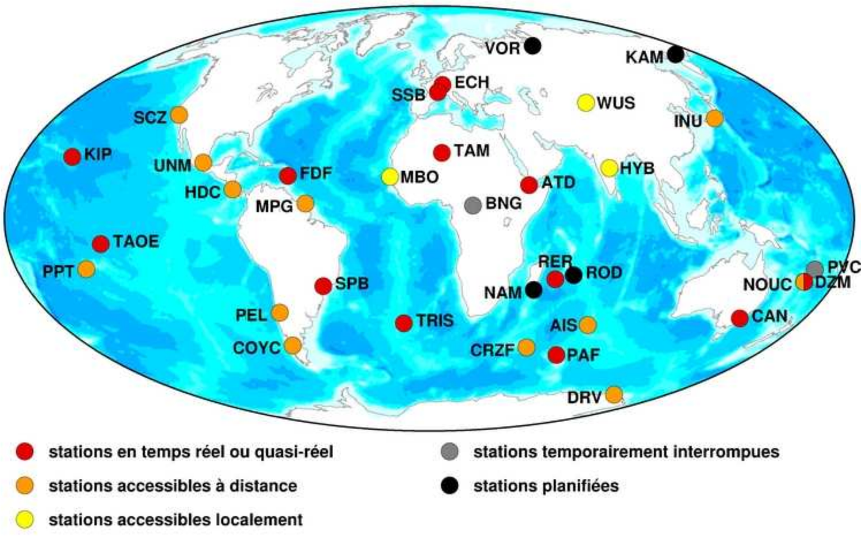

Figure 1: The GEOSCOPE network in 2007. Red: real (or quasi-real) time stations; Orange: remotely accessible stations; Yellow: locally accessible stations; Grey: temporarily interrupted stations; Black: planned stations.

3 Centroid Moment tensor computation using a linear inversion method

3.1 Seismic source representation

The moment tensor An efficient way to mathematically represent the average rupture process of a seismic event is the centroid moment tensor, which corresponds to a point source equivalent mechanism located at the barycenter of the seismic slip distribution, both in space and time [Backus and Mulcahy (1976a), Backus and Mulcahy (1976b), Dziewonski *et al.* (1981)]. The moment tensor $M_{ij}(i = 1, 3 j = 1, 3)$ is a system of forces described by a second-rank moment: The diagonal terms corresponds to linear dipoles, and the off-diagonal terms correspond to force couples. When assuming no net torque, the tensor is symmetric, reducing the number of independent components of the tensor to six. In the case of a source with no volume change, like a dislocation occurring along a fault, the trace of the moment tensor is zero, meaning no isotropic part, leading to five independent components. Isotropic part is however considered in the case of explosion or implosion, as, for example, in nuclear explosion, quarry blast or volcanic event.

Using this description, the computation of seismic wave excitation is a linear problem, making easier the determination of the source characteristics from the observations through an inverse problem. For a moment tensor with a_i components, a theoretical seismogram can be written as a sum of terms:

$$u(t) = [A_1(t) \cdots A_m(t)] * \begin{bmatrix} a_1 \\ a_2 \\ \cdots \\ a_m \end{bmatrix} \tag{1}$$

where each $A_j(t)$ elements is a Green's function giving the jth seismogram generated by a source with the jth moment tensor component is set to 1, and the other component are zero. For a set of n seismograms, the linear system of equation is:

$$\begin{bmatrix} u_1(t) \\ u_2(t) \\ \cdots \\ u_n(t) \end{bmatrix} = \begin{bmatrix} A_{11}(t) & \cdots & A_{1m}(t) \\ A_{21}(t) & \cdots & A_{2m}(t) \\ \vdots & \ddots & \vdots \\ A_{n1}(t) & \cdots & A_{nm}(t) \end{bmatrix} * \begin{bmatrix} a_1 \\ a_2 \\ \cdots \\ a_m \end{bmatrix} \tag{2}$$

Earthquake source mechanism interpretation

- Magnitude and duration:

  The size of an event is given by the seismic moment M_0 (expressed in $N.m$), which is directly obtained as it corresponds to the norm of the moment tensor, and its duration. The magnitude of a large event is commonly represented on the moment magnitude (M_w) scale (being an open scale) which is a function of M_0 only. M_0 (and thus M_w) is proportional to the area of the fault that ruptured and to the average amount of slip of this rupture.

- Source mechanism:

  There are different ways to interpret the moment tensor representation. In the case of earthquakes, the most common one is the decomposition into a best double-couple and a minimal compensated linear vector dipole (CLVD).

  The double-couple model is the preferred representation by equivalent body forces of a simple dislocation source. Its geometrical interpretation gives the fault plane orientation (strike and dip) and the direction of the slip vector (rake) on this plane. The double-couple gives actually two planes, one for each couple : the fault plane and the auxiliary plane, which can lead to ambiguity, but can be discriminated by the tectonic settings.

The CLVD component can be interpreted in different ways: complex rupture history, heterogeneity of the source medium, etc...
[Julian *et al.* (1998)].

Hence, the best double-couple and minimal CLVD representation assumes that the rupture process geometry is rather simple. In the seismic moment tensor determination procedure this representation is given as a by-product, but the seismic tensor itself allows different decompositions (as, for example, a composite rupture on different segment faults).

3.2 Seismic moment tensor determination procedure

The moment tensor is linearly related to the data when the centroid location in time and space is known. The centroid location, especially in space (depth and horizontal location), induces trade-off. Hence, in order to determine the centroid seismic tensor, we chose a mixed approach. The area around the first hypocentral determination is considered as a 3D parameter space to be explored, in terms of latitude, longitude and depth. The duration of the event is also explored as a 4th dimension of the parameter space. For each point of this exploration of the parameter space, a virtual source is determined by linear inversion, giving an associated moment tensor. In this way, the global problem is divided into several small linear problems.

The linear inversion is performed on the complex spectra domain using relevant temporal windows of data and frequency range. The seismic moment tensor solution is determined by the best fitting to the complex spectral data among all the moment tensors computed for each point of the exploration parameter space.

Note that this approach is similar to the methodology used for real-time monitoring of a specific zone, as the GRiD-MT[5] system in Japan, operating since 2003 [Tsuruoka *et al.* (2008)].

The current implementation of the procedure relies on the European Grid Infrastructure [6] that allows a secure access to a large amount of dedicated CPUs. The codes are wrapped in a home-made software that managed the computations.

Data selection and pre-processing

- Data: We use long-period three-component seismic data recorded worldwidely. Usually data are extracted from the LH record channel, corresponding to a sample rate of 1 Hz, over a time window of at least 5 hours

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[5] http://wwweic.eri.u-tokyo.ac.jp/GRiD_MT/

[6] http://www.eu-egee.org/

starting about 1 hour before the event orgin time. The data selection is first done on raw data to ensure that there is no instrumental problem (such as high level of noise, holes, glitches, signal saturation,...). And second selection is made after a coarse low-pass filtering, in order to avoid seismic traces with high long-period noise, and to obtain an azimuthal coverage as good as possible (the later strongly affected by the uneven distributions of large seismic events and permanent seismic stations over the Earth).

- Input parameters:
  1. Time windows (from a few hundreds to a few thousands seconds) are selected for each single trace, corresponding to the maximum signal. Several time windows can be used for each traces.
  2. A frequency range is determined for the spectral domain inversion, depending on the first estimation of the magnitude. Typically, for a large event of magnitude Mw 6.8 to 7.8 the frequency window is 4-8 mHz. These numbers may be modified for re-iteration of the inversion process if necessary.

Centroid moment tensor determination procedure

Latitude, longitude, depth and duration of the point source centroid being fixed,

1. 6 synthetic traces (seismograms) are computed for each data trace corresponding to a given component (horizontal North-South or horizontal East-West or vertical trace) for a given station and the given source location. These 6 synthetic seismograms are computed using a virtual source consisting of one of the independent component of the tensor being equal to one, the others being equal to zero. The set of these synthetic seismograms are our so-called Green functions (Note that even if 5 components of the moment tensor are actually inverted if we consider the non-isotropic case, the 6 Green functions are necessary in order to reconstruct synthetic seismograms to compare with data).

   The inverse problem solved is then: For a set of n seismograms,

$$\begin{bmatrix} u_1(\omega) \\ u_2(\omega) \\ \cdots \\ u_n(\omega) \end{bmatrix} = \begin{bmatrix} A_{11}(\omega) & \cdots & A_{16}(\omega) \\ A_{21}(\omega) & \cdots & A_{26}(\omega) \\ \vdots & \ddots & \vdots \\ A_{n1}(\omega) & \cdots & A_{n6}(\omega) \end{bmatrix} \cdot \begin{bmatrix} a_1 \\ a_2 \\ \cdots \\ a_m \end{bmatrix} \tag{3}$$

2. A first linear inversion, using the complex spectra of the selected time windows, is performed to obtain a preliminary solution.

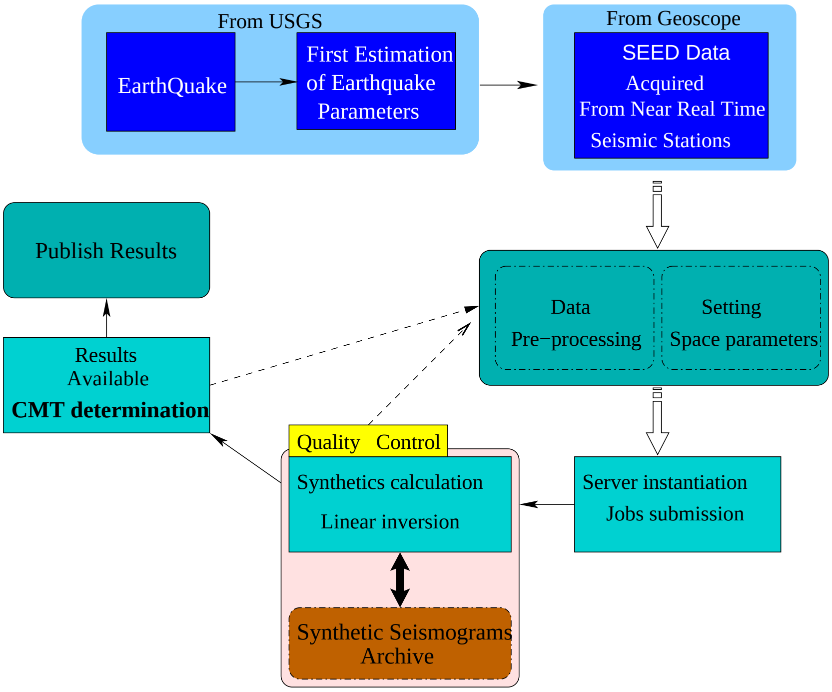

Figure 2: Workflow used for the determination of the seismic moment tensor at the centroïd of an earthquake

3. Using the preliminary moment tensor solution, a synthetic seismogram is computed for each seismogram. A cross-correlation with the real trace is performed in order to determine a time centroid for each station.
4. Taking into account the local shift in time at each station, a final linear inversion is performed, giving a moment tensor solution for the fixed location.
5. The synthetic seismograms are constructed using the moment tensor solution and the value of the cost function for this point of the parameter space estimated.

3.2.1 CMT determination Typical Workflow

A typical workflow is shown Figure 2 : the user receives an alert from the USGS (or from another organization devoted to the same task) when an earthquake occurs. He/She can then look for the seismic stations available depending on the distance to the earthquake location and the time scale phenomenon relevant to the algorithm. The user gets the data related to the earthquake on the GEOSCOPE center website under the form of a SEED[7]

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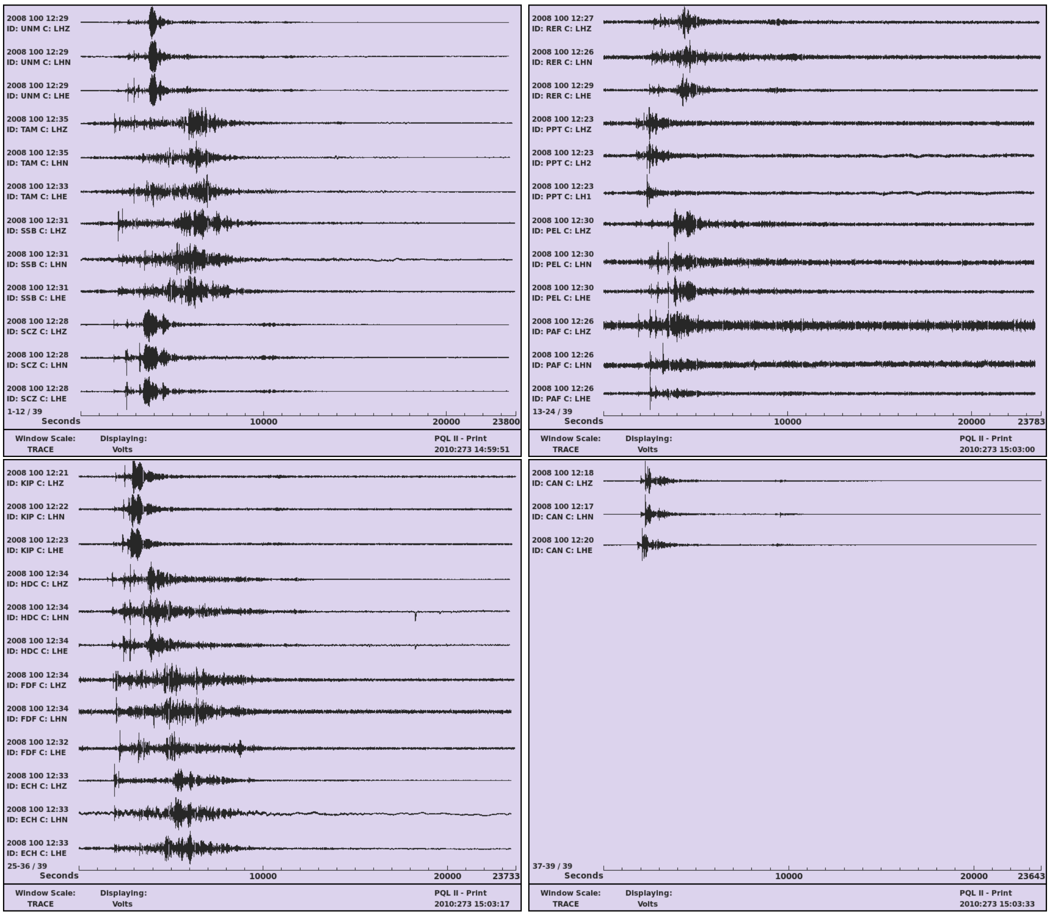
[7] The Standard for the Exchange of Earthquake Data (SEED) is an international standard format for the exchange of digital seismological data developed by the International Federation of Digital Seismograph Networks (FDSN)

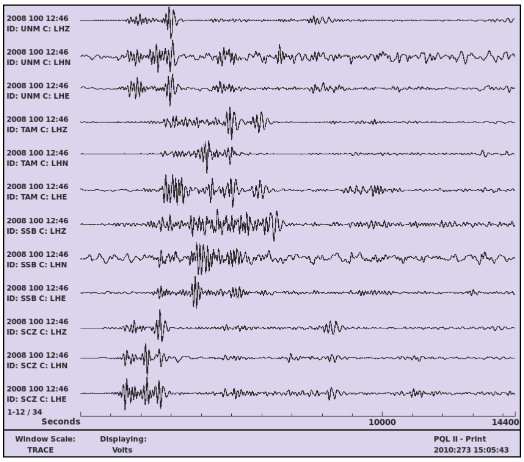
volume. Those data usually come from the GEOSCOPE seismic stations, however data from other networks could be included. Once the data are acquired, some pre-processing of the SEED files is needed to ensure their quality and to convert them to a suitable format for the program (cutting in time, rotating the data to local polar coordinates, etc... which demand some (minor) user interaction) so that the data matches the application needs. The user then transfers an data archive to one of the grid access points (*i.e.* any machine equipped with the compulsory software to submit jobs) he/she has access to. Finally, after instantiation of the server the user submits the created jobs to the grid. The synthetic Green functions are calculated if needed for each parameter space cell. They are automatically stored in order to avoid re-computation in case of results improvement triggered by unsatisfying outcome –dash arrows on Fig 2– or for a probable aftershock (more about this in next section). Early and final quality control are assisted by a color 3D moveable representation of the variance between simulated and recorded data. Finally, solved problems are published on the GEOSCOPE website.

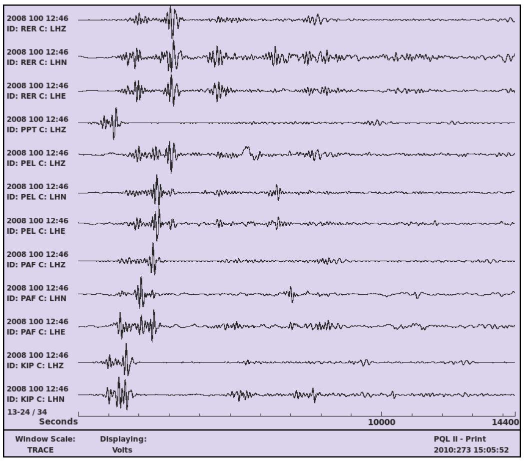
4 An example: The Loyalty Islands 2008/04/09 event

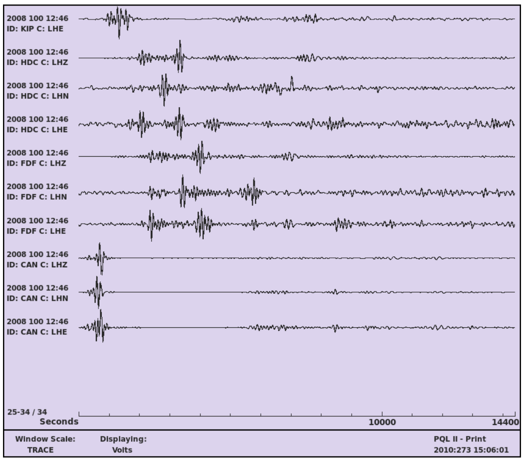
The Loyalty Islands 2008/04/09 event was reported by the USGS as having magnitude $m_b = 6.3$ and $M_s = 7.3$. The PDE location is: latitudei= $-20.07°$, longitud$e = 168.89°$, with a depth=33.0km.
LH (sample rate= 1s) 3-component data from 13 stations of the GEOSCOPE network are obtained:



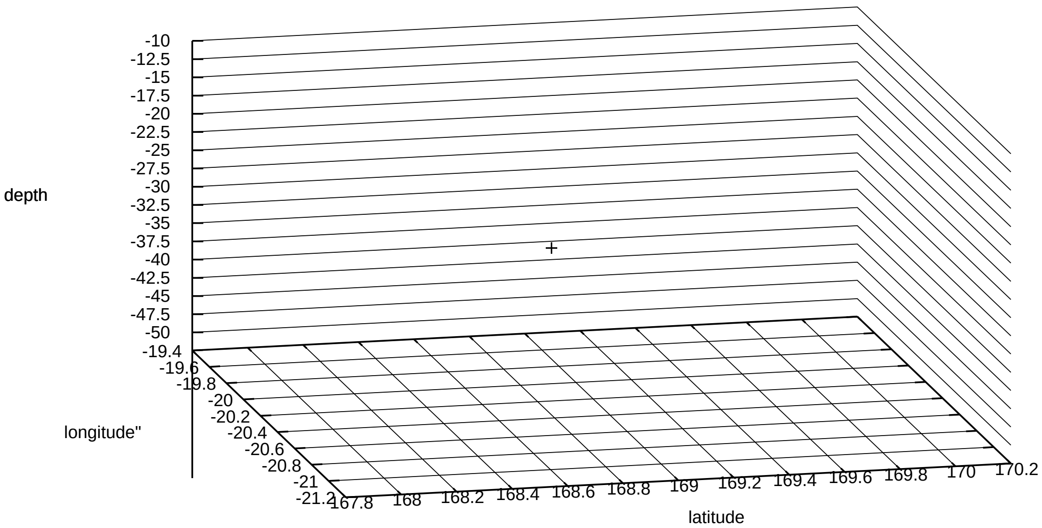
After a first visual selection of the raw data, the traces are band-pass filtered between 1 and 12.5mHz (80 to 1000s) in order to select time windows for the inversion:



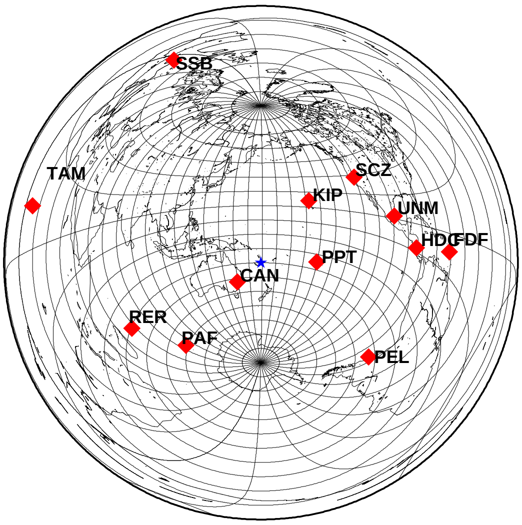




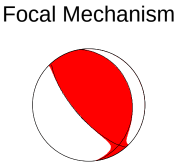
A grid in space (latitude, longitude, depth) is designed. In this case, the grid is 2° by 2° with a 0.2° in latitude and longitude, and from 10 to $50km$ with a step of $2.5km$ in depth. Each point of this grid is considered as a centroid location, and data are inverted to retrieve a moment tensor for this virtual centroid.

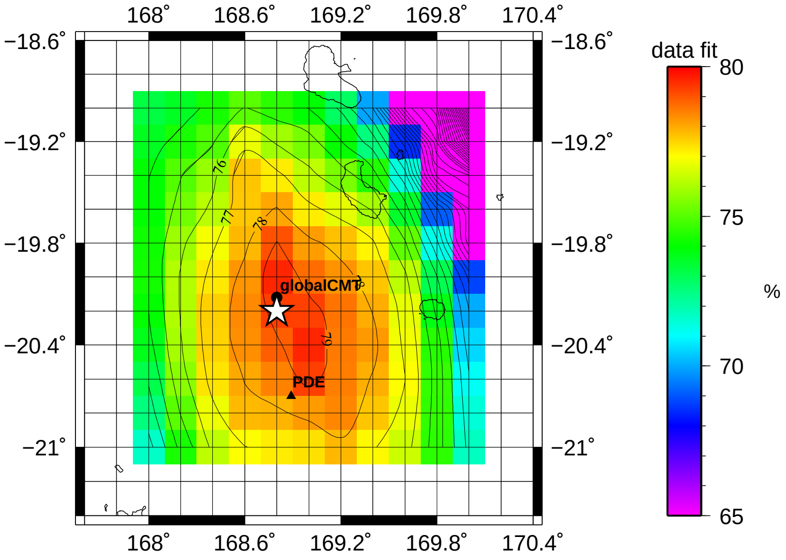


Finally, the centroid moment tensor giving the best fit to the data is:
Mrr0.687 Mtt=-0.064 Mpp=-0.623 Mrt=0.618 Mrp=-0.593 Mtp=0.345 $(10^{20} N.m)$

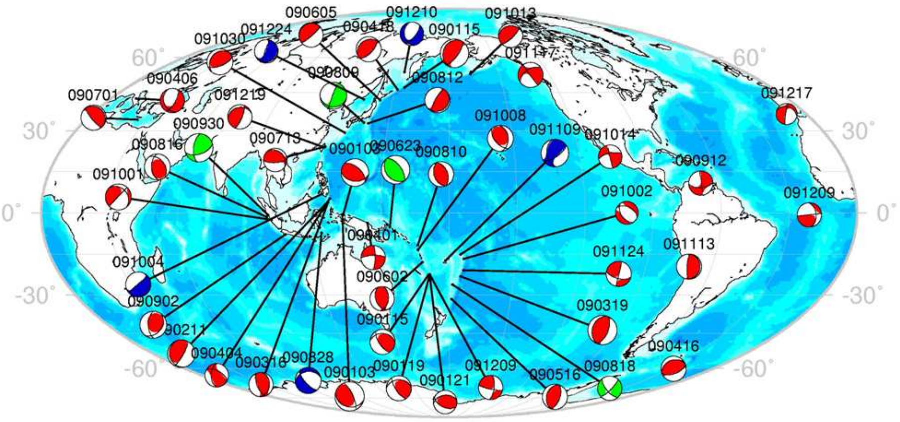


Centroid location: depth=25 km
latitude=−20.2° longitude=168.8°
Magnitude M_w=7.3 half−duration=10 s
Plane 1: strike=349° dip=17° rake=114°
Plane 2: strike=144° dip=74° rake=83°

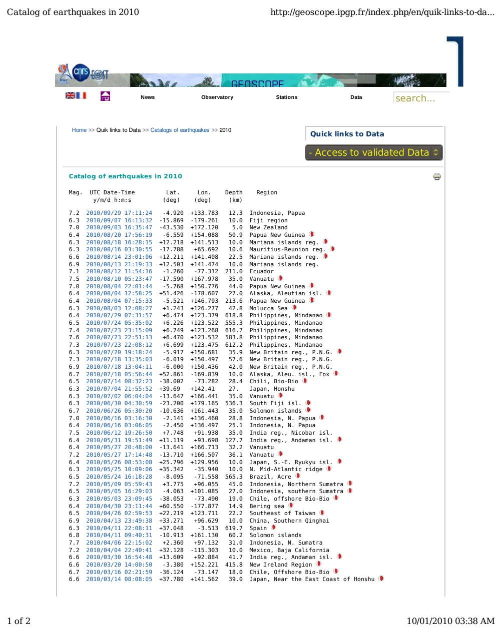




Events processed in 2009...



... And the GEOSCOPE catalogue for 2010 up to now – the little beachballs indicate when a CMT has been determined – :



Catalog of earthquakes in 2010 http://geoscope.ipgp.fr/index.php/en/quik-links-to-da...

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Quick links to Data

Catalog of earthquakes in 2010

Mag.	UTC Date-Time y/m/d h:m:s	Lat. (deg)	Lon. (deg)	Depth (km)	Region	
7.2	2010/09/29 17:11:24	-4.920	+133.783	12.3	Indonesia, Papua	
6.3	2010/09/07 16:13:32	-15.869	-179.261	10.0	Fiji region	
7.0	2010/09/03 16:35:47	-43.530	+172.120	5.0	New Zealand	
6.4	2010/08/20 17:56:19	-6.559	+154.088	50.9	Papua New Guinea	●
6.3	2010/08/18 16:28:15	+12.218	+141.513	10.0	Mariana islands reg.	●
6.3	2010/08/16 03:30:55	-17.788	+65.692	10.6	Mauritius-Reunion reg.	●
6.6	2010/08/14 23:01:06	+12.211	+141.408	22.5	Mariana islands reg.	●
6.9	2010/08/13 21:19:33	+12.503	+141.474	10.0	Mariana islands reg.	
7.1	2010/08/12 11:54:16	-1.260	-77.312	211.0	Ecuador	
7.5	2010/08/10 05:23:47	-17.590	+167.978	35.0	Vanuatu	●
7.0	2010/08/04 22:01:44	-5.768	+150.776	44.0	Papua New Guinea	●
6.4	2010/08/04 12:58:25	+51.426	-178.607	27.0	Alaska, Aleutian isl.	●
6.4	2010/08/04 07:15:33	-5.521	+146.793	213.6	Papua New Guinea	●
6.3	2010/08/03 12:08:27	+1.243	+126.277	42.8	Molucca Sea	●
6.4	2010/07/29 07:31:57	+6.474	+123.379	618.8	Philippines, Mindanao	●
6.5	2010/07/24 05:35:02	+6.226	+123.522	555.3	Philippines, Mindanao	
7.4	2010/07/23 23:15:09	+6.749	+123.268	616.7	Philippines, Mindanao	
7.6	2010/07/23 22:51:13	+6.470	+123.532	583.8	Philippines, Mindanao	
7.3	2010/07/23 22:08:12	+6.699	+123.475	612.2	Philippines, Mindanao	
6.3	2010/07/20 19:18:24	-5.917	+150.681	35.9	New Britain reg., P.N.G.	●
7.3	2010/07/18 13:35:03	-6.019	+150.497	57.6	New Britain reg., P.N.G.	
6.9	2010/07/18 13:04:11	-6.000	+150.436	42.0	New Britain reg., P.N.G.	
6.7	2010/07/18 05:56:44	+52.861	-169.839	10.0	Alaska, Aleu. isl., Fox	●
6.5	2010/07/14 08:32:23	-38.002	-73.282	28.4	Chili, Bio-Bio	●
6.3	2010/07/04 21:55:52	+39.69	+142.41	27.	Japan, Honshu	
6.3	2010/07/02 06:04:04	-13.647	+166.441	35.0	Vanuatu	●
6.3	2010/06/30 04:30:59	-23.200	+179.165	536.3	South Fiji isl.	●
6.7	2010/06/26 05:30:20	-10.636	+161.443	35.0	Solomon islands	●
7.0	2010/06/16 03:16:30	-2.141	+136.460	28.8	Indonesia, N. Papua	●
6.4	2010/06/16 03:06:05	-2.450	+136.497	25.1	Indonesia, N. Papua	
7.5	2010/06/12 19:26:50	+7.748	+91.938	35.0	India reg., Nicobar isl.	
6.4	2010/05/31 19:51:49	+11.119	+93.698	127.7	India reg., Andaman isl.	●
6.4	2010/05/27 20:48:00	-13.641	+166.713	32.2	Vanuatu	
7.2	2010/05/27 17:14:48	-13.710	+166.507	36.1	Vanuatu	●
6.4	2010/05/26 08:53:08	+25.796	+129.956	10.0	Japan, S.-E. Ryukyu isl.	●
6.3	2010/05/25 10:09:06	+35.342	-35.940	10.0	N. Mid-Atlantic ridge	●
6.5	2010/05/24 16:18:28	-8.095	-71.558	565.3	Brazil, Acre	●
7.2	2010/05/09 05:59:43	+3.775	+96.055	45.0	Indonesia, Northern Sumatra	●
6.5	2010/05/05 16:29:03	-4.063	+101.085	27.0	Indonesia, southern Sumatra	●
6.3	2010/05/03 23:09:45	-38.053	-73.490	19.0	Chile, offshore Bio-Bio	●
6.4	2010/04/30 23:11:44	+60.550	-177.877	14.9	Bering sea	●
6.5	2010/04/26 02:59:53	+22.219	+123.711	22.2	Southeast of Taiwan	●
6.9	2010/04/13 23:49:38	+33.271	+96.629	10.0	China, Southern Qinghai	
6.3	2010/04/11 22:08:11	+37.048	-3.513	619.7	Spain	●
6.8	2010/04/11 09:40:31	-10.913	+161.130	60.2	Solomon islands	
7.7	2010/04/06 22:15:02	+2.360	+97.132	31.0	Indonesia, N. Sumatra	
7.2	2010/04/04 22:40:41	+32.128	-115.303	10.0	Mexico, Baja California	
6.6	2010/03/30 16:54:48	+13.609	+92.884	41.7	India reg., Andaman isl.	●
6.6	2010/03/20 14:00:50	-3.380	+152.221	415.8	New Ireland Region	●
6.7	2010/03/16 02:21:59	-36.124	-73.147	18.0	Chile, Offshore Bio-Bio	●
6.6	2010/03/14 08:08:05	+37.780	+141.562	39.0	Japan, Near the East Coast of Honshu	●

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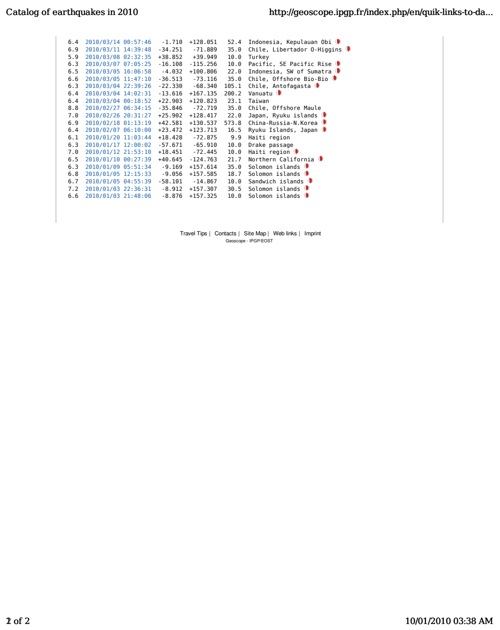

Catalog of earthquakes in 2010 http://geoscope.ipgp.fr/index.php/en/quik-links-to-da...

Mag.	UTC Date-Time y/m/d h:m:s	Lat. (deg)	Lon. (deg)	Depth (km)	Region	
6.4	2010/03/14 00:57:46	-1.710	+128.051	52.4	Indonesia, Kepulauan Obi	●
6.9	2010/03/11 14:39:48	-34.251	-71.889	35.0	Chile, Libertador O-Higgins	●
5.9	2010/03/08 02:32:35	+38.852	+39.949	10.0	Turkey	
6.3	2010/03/07 07:05:25	-16.108	-115.256	10.0	Pacific, SE Pacific Rise	●
6.5	2010/03/05 16:06:58	-4.032	+100.806	22.0	Indonesia, SW of Sumatra	●
6.6	2010/03/05 11:47:10	-36.513	-73.116	35.0	Chile, Offshore Bio-Bio	●
6.3	2010/03/04 22:39:26	-22.330	-68.340	105.1	Chile, Antofagasta	●
6.4	2010/03/04 14:02:31	-13.616	+167.135	200.2	Vanuatu	●
6.4	2010/03/04 00:18:52	+22.903	+120.823	23.1	Taiwan	
8.8	2010/02/27 06:34:15	-35.846	-72.719	35.0	Chile, Offshore Maule	
7.0	2010/02/26 20:31:27	+25.902	+128.417	22.0	Japan, Ryuku islands	●
6.9	2010/02/18 01:13:19	+42.581	+130.537	573.8	China-Russia-N.Korea	●
6.4	2010/02/07 06:10:00	+23.472	+123.713	16.5	Ryuku Islands, Japan	●
6.1	2010/01/20 11:03:44	+18.428	-72.875	9.9	Haiti region	
6.3	2010/01/17 12:00:02	-57.671	-65.910	10.0	Drake passage	
7.0	2010/01/12 21:53:10	+18.451	-72.445	10.0	Haiti region	●
6.5	2010/01/10 00:27:39	+40.645	-124.763	21.7	Northern California	●
6.3	2010/01/09 05:51:34	-9.169	+157.614	35.0	Solomon islands	●
6.8	2010/01/05 12:15:33	-9.056	+157.585	18.7	Solomon islands	●
6.7	2010/01/05 04:55:39	-58.101	-14.867	10.0	Sandwich islands	●
7.2	2010/01/03 22:36:31	-8.912	+157.307	30.5	Solomon islands	●
6.6	2010/01/03 21:48:06	-8.876	+157.325	10.0	Solomon islands	●

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A detailed description of the technical aspects of the procedure can be found in:
Distributed jobs on EGEE Grid infrastructure for an Earth science application: moment in tesnosr computation at the centroid of an earthquake, *Earth Science Informatics*, 2:97-106, 2009.

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