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Determination of the isotropic component of the 1994 Bolivia deep earthquake

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Abstract. We determine the isotropic component of the moment tensor of the 1994 Bolivia deep earthquake using various seismic waves, including body waves, surface waves, and normal mode data, in the period band between 20 s and 1000 s. We carefully investigate whether the isotropic component can be obtained independently from the other components by checking the correlation matrices. We show that it is possible to obtain a precise estimate of the isotropic component by using normal mode data in the period band between 550 and 1000 s. We find that the Bolivia earthquake did not have a significant isotropic component in this period band.

Introduction

Whether deep earthquakes have significant isotropic components has been the subject of much discussion, since this is important for understanding their physical mechanism. Although many studies have attempted to observe a significant isotropic component, none has ever been convincingly identified [e.g., *Dziewonski and Gilbert*, 1974; *Okal and Geller*, 1979]. *Kawakatsu* [1991] showed that no significant isotropic component of the moment tensor was observed for a dataset of deep earthquakes. Since the period band where the possible existence of an isotropic component was intensively investigated by *Kawakatsu* [1991] was only between 50 s and 100 s, further investigation of the isotropic component in different period bands is desirable.

In the present study, using various seismic waves in the period band between 20 s and 1000 s, we determine the isotropic component of the moment tensor of the Bolivia deep earthquake of June 9, 1994 [origin time: 00:33:13.2UT; location: 13.737°S, 67.414°W; depth: 641km; Mw: 8.2, after USGS], the largest deep earthquake ever recorded. Its very large size and the availability of many high quality broadband seismograms make it possible for the first time to intensively investigate the possible existence of an isotropic component of a deep earthquake at long periods up to 1000 s.

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Analyses

We perform four different analyses using IRIS broadband seismograms. In the first analysis, also using GEOSCOPE seismograms, we employ the first portion of the observed seismograms including 26 P wavetrains (P, pP, PP, sP), whose duration is 300 s, and 24 SH waves, whose duration is 60 s, to determine the moment tensor and the source time function. The inversion scheme follows that of *Kuge and Kawakatsu* [1993]. The observed seismograms are bandpass-filtered between 20 s and 250 s.

The second analysis is a CMT inversion of long period body waves, containing P, PP, SP, SS, and other phases, in the period band between 50 s and 100 s. As shown by *Kawakatsu* [1991], this dataset has good coverage of the focal sphere, and is suitable for determining the isotropic component independently from the other components.

The third analysis is a CMT inversion of long period surface waves in the period band between 250 s and 500 s. The earth model used for the second and the third analyses is Model 1066A [*Gilbert and Dziewonski*, 1975].

In the fourth analysis, we employ the observed seismograms in the period band between 550 s and 1000 s, which can be analyzed owing to the very large size of the Bolivia event. The duration of the seismograms is 10 hours. We call this dataset the normal mode data; however, we analyze relatively short time series (compared to the usual normal mode analyses) in order to reduce the effect of 3-D earth structure on observed waveform data. We use the Direct Solution Method (DSM) [e.g., *Hara et al.*, 1991] to compute the Green's functions for 1066A. The DSM expands the displacement in terms of trial functions. As trial functions, we choose the eigenfunctions of the degenerate singlets of all the multiplets of 1066A whose eigenperiods are larger than 350 s. We consider the coupling between multiplets due to the earth's rotation and its elliptical figure. We use

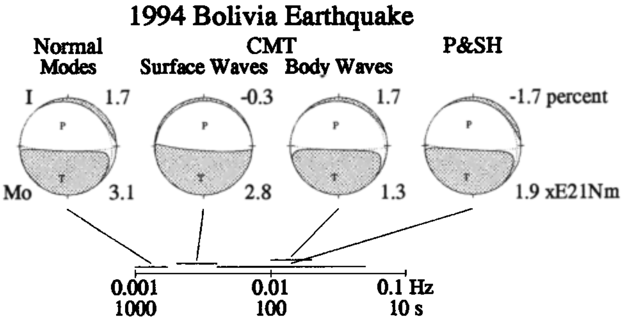

Figure 1. The equal-area projections (lower hemisphere) of the moment tensor solutions obtained by our analyses. The numbers at the upper-right show the isotropic components as a percentage of the deviatoric seismic moments. The numbers at the lower-right show the deviatoric seismic moments ($\times$ 10^{21}Nm).

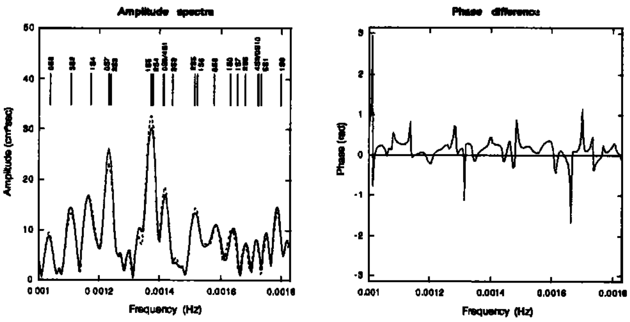

Figure 2. An example of observed and synthetic spectra. The station is CAN. The left panel shows the amplitude spectra, and the right panel shows the phase difference between the observed and synthetic spectrum. The vertical bars in the left panel indicate the eigenfrequencies of the normal modes computed for 1066A.

the centroid time and location determined by Harvard [origin time: 00:33:44.4; location: 13.81°S, 67.20°W; depth: 657.4km].

We calculate the correlation matrix in each analysis to carefully investigate whether the isotropic component is obtained independently from the other components [*Kawakatsu*, 1991]. In order to clearly show the correlation between the isotropic component and the other components, the diagonal components of the moment tensors are re-defined as $\mathbf{I} = (M_{rr} + M_{\theta\theta} + M_{\phi\phi})/3$, $\mathbf{C} = (-2M_{rr}+M_{\theta\theta}+M_{\phi\phi})/3$, and $\mathbf{D} = (M_{\theta\theta}-M_{\phi\phi})/3$, where **I** is the isotropic component, and **C** is a vertical compensated linear vector dipole (CLVD) [*Randall and Knopoff*, 1970].

Results

Figure 1 and Table 1 show the moment tensor solutions determined by the above four analyses. The focal mechanisms are consistent with one another, while the seismic moments estimated using surface wave and normal mode data are larger than those estimated using body wave data. This is probably because long period surface wave and normal mode data are less sensitive to 3-D earth structure and the details of the rupture process, and thus provide a better constraint for estimation of the seismic moment. The fit between the normal mode data and the synthetics computed using the solution presented in Table 1(d) is very good. We show an example of the observed and synthetic spectra in Fig. 2. This excellent fit and the small correlation between the isotropic component and the other components, which we show below, allow us to precisely estimate the isotropic component based on the normal mode analysis.

Figures 3 show the correlation matrices calculated for each of the four analyses. Fig. 3(a) shows that the correlation between the isotropic component and the vertical CLVD component is large in the first analysis due to the poor coverage of the focal sphere. Thus, although, as shown in Table 1, the isotropic component obtained by the first analysis is larger than one standard deviation, the actual uncertainty is likely to be larger than one standard deviation due to contamination of the CLVD component. This implies that the 10% implosive component recently obtained by *Kikuchi and Kanamori* [1994] using a similar dataset is subject to the same kind of contamination. Considering the effect of the 3-D earth structure, which is not taken into account in the first analysis, the uncertainty seems to become still larger. Thus, the analysis of the first portion of P and SH waves does not give a good constraint for estimation of the isotropic component.

As shown by *Kawakatsu* [1991], the correlation between the isotropic component and other components is small for the CMT solution using the long period body wave data (Fig. 3b). However, as in Table 1, the variance reduction obtained by this analysis is small, since the 3-D earth structure is not considered. This causes the relatively large standard error for estimation of the isotropic component, although it is determined inde-

Table 1. The moment tensor solutions (the unit is 10^{21} N·m).

	M_{rr}	$M_{\theta\theta}$	$M_{\phi\phi}$	$M_{r\theta}$	$M_{r\phi}$	$M_{\theta\phi}$	I	V. R.
(a)	-0.48±0.04	0.48±0.04	-0.10±0.04	-1.80±0.02	0.06±0.01	-0.32±0.02	-1.7±1.0%	87.2%
(b)	-0.26±0.05	0.39±0.06	-0.07±0.05	-1.22±0.04	0.02±0.02	-0.11±0.03	1.7±3.8%	31.6%
(c)	-0.70±0.06	0.70±0.08	-0.02±0.07	-2.73±0.03	0.19±0.02	0.04±0.03	-0.3±2.3%	80.0%
(d)	-0.74±0.04	0.97±0.04	-0.06±0.05	-2.95±0.02	0.01±0.03	-0.53±0.03	1.7±0.7%	94.4%

(a) P and SH waveform analysis; (b) CMT inversion of long period body waves; (c) CMT inversion of long period surface waves; (d) Normal mode analysis. I is the isotropic component specified as a percentage of the deviatoric seismic moment. V. R. is the variance reduction obtained by each solution

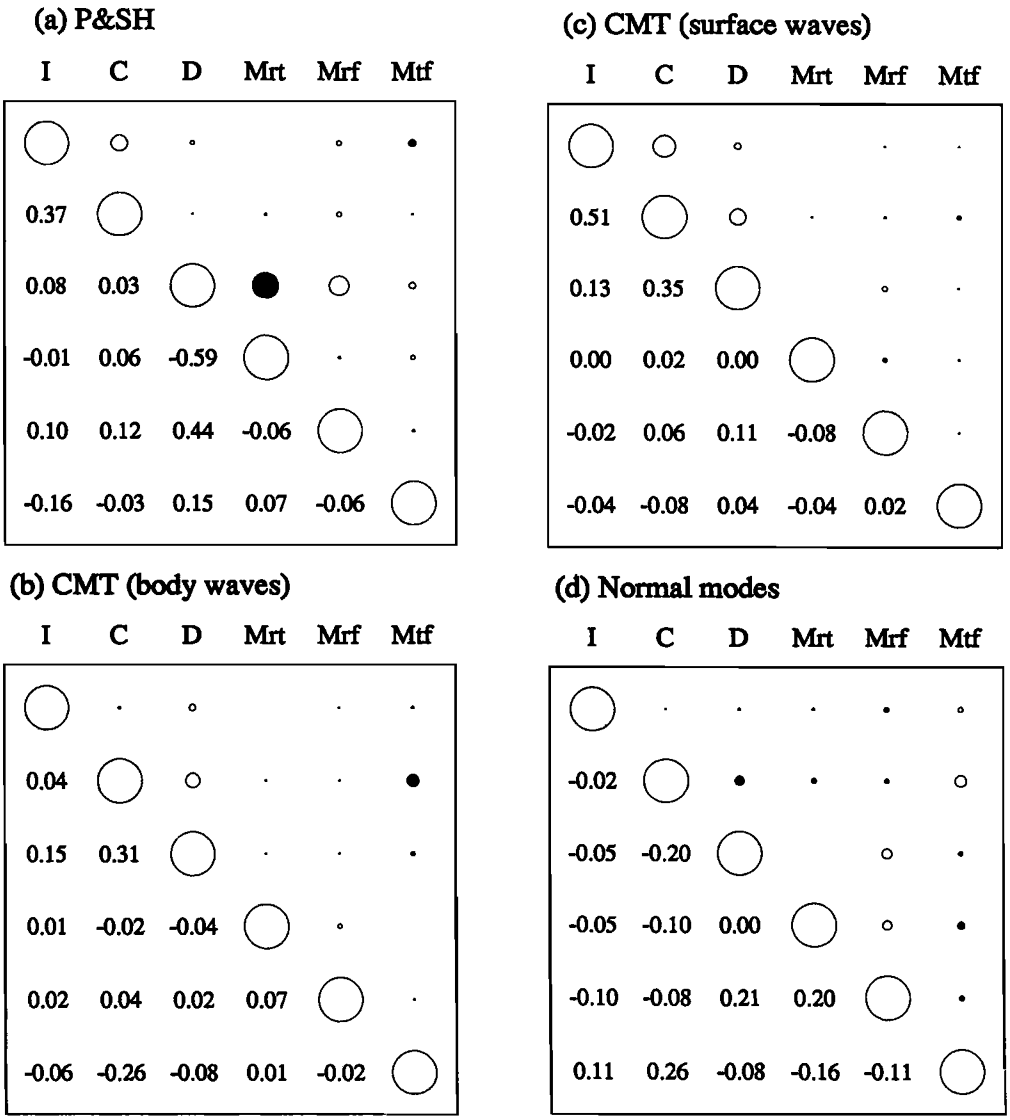

Figure 3. The correlation matrices corresponding to the solutions shown in Figs. 1 and Table 1. The diameters of the circles are proportional to the magnitudes of the correlation coefficients. The solid and open circles indicate negative and positive values, respectively.

pendently from other components. Also, the smaller seismic moment estimated by this analysis is partially due to this small variance reduction [*Dziewonski et al.*, 1984].

While the correlation is large for the CMT inversion of long period surface wave data (Fig. 3c), the correlation between the isotropic component and the vertical CLVD component is small for the analysis of the normal mode data (Fig. 3d). We briefly explain the reason below.

The excitation of the $m = 0$ component of spheroidal normal modes due to the diagonal components of the moment tensor (for a laterally homogeneous earth model and a point source on the z-axis) is proportional to

$$M_{rr}\frac{dU}{dr} + (M_{\theta\theta} + M_{\phi\phi})\left(\frac{U}{r} - l(l+1)\frac{V}{2r}\right),$$

where U and V are the radial eigenfunctions, and l is the angular order number. *Mendiguren and Aki* [1978] showed that it is difficult to independently determine M_{rr} and $(M_{\theta\theta} + M_{\phi\phi})$ in the period band employed in the CMT inversion of long period surface wave data. The reason is that the ratio of $[U/r - l(l+1)V/(2r)]$ to dU/dr for fundamental modes depends only weakly on frequency in this period band. This causes the large correlation between the isotropic component and the vertical CLVD component.

On the other hand, the ratio of $[U/r - l(l+1)V/(2r)]$ to dU/dr varies significantly in the period band between 550 s and 1000 s, which makes it possible to distinguish M_{rr} from $(M_{\theta\theta} + M_{\phi\phi})$. This is the reason that we can reduce the correlation between the isotropic component and the vertical CLVD component. Recently, *Kikuchi and Kanamori* [1994] suggested that the isotropic component is less than 2% using the excitation of ${}_0S_0$. However, although ${}_0S_0$ is sensitive to the isotropic component, the isotropic and vertical CLVD components of the moment tensor cannot be determined independently using only ${}_0S_0$, since we have only one equation, but two unknowns, I and C.

In order to evaluate the uncertainty of the isotropic component estimated by the normal mode analysis, we vary the duration of the seismograms from 3 to 20 hours, and change the centroid location by 10 km in all three directions (vertical, east - west, and north - south). We also determine the moment tensor using the Green's functions computed for model S12_WM13 [*Su et al.*, 1994] using the spherically symmetric part of 1066A to investigate the effect of the laterally heterogeneous earth structure. We scale the lateral heterogeneity of P-wave velocity, S-wave velocity, and density according to $d\ln v_p/d\ln v_s = 0.8$ and $d\ln\rho/d\ln v_s = 0.4$. We fully consider the coupling between multiplets due to the laterally heterogeneous structure.

In all cases, the standard deviation of the isotropic component and the correlation between the isotropic component and the other components do not change drastically compared to the analysis presented in Fig. 1 and Table 1, although the variance reduction is larger for shorter time series, and S12_WM13 gives a larger variance reduction than 1066A. We find that the uncertainty of the isotropic component is about 2% of the deviatoric seismic moment. Therefore, the 1.7% isotropic component estimated by the normal mode analysis is not significant, although it is larger than two standard deviation.

Based on our analyses, we conclude that the moment tensor of the Bolivia earthquake is primarily deviatoric in the period band between 550 and 1000 s, and that the magnitude of the isotropic component is on the order of 4% of the deviatoric seismic moment or less.

Conclusion

We have analyzed the IRIS and GEOSCOPE broadband seismograms to investigate whether the Bolivia earthquake has an isotropic component. No significant isotropic component is observed in the period band between 20 s and 1000 s. We show that we can precisely estimate the isotropic component using normal mode data in the period band between 550 and 1000 s, and that the Bolivia earthquake had no significant isotropic component in this period band. Our results are consistent with the results presented by *Kawakatsu* [1991], and extend the longest period where no significant isotropic component is observed from 100 s to 1000 s.

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