Moment tensor inversion for deep earthquakes at the Tonga-Kermadec subduction zone using 3-D Green's functions

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Abstract

Seismic moment tensors from the Global CMT catalog have been widely used to infer source mechanisms and physical properties around local regions where earthquakes occur. However, the zero-trace constraint used in the source inversion algorithm may be not suitable for earthquakes occurred at depths greater than 300 km, considering that mechanisms for deep earthquakes are different from shallow events. In addition, the velocity model in use is quite simple, without considering complicated and rapidly varying velocity structure at subduction zones, which may introduce errors in the moment tensor solutions of deep earthquakes. In this study, we perform moment tensor inversion for deep earthquakes at the Tonga-Kermadec subduction zones using 3-D Green's functions. Our results show reductions in the scalar moment for most of the selected deep earthquakes, and a large portion of selected events has non-double-couple components, which is consistent with the input catalog as well as seismic observations over decades. Meanwhile, about two-thirds of these moment tensors contain negative trace while the rest one-third present positive trace. We further perform control experiments using a subset of 70 events to illustrate that the usage of a 3-D velocity model is more essential to cause data misfit reduction compared with dropping the zero-trace regularization.

Data and Methodology

We select 269 deep earthquakes occurred at the Tonga-Kermadec subduction from 2005 to 2020 with moment magnitudes ranging from 5.5 to 7.0, and acquire their moment tensor solutions from the Global CMT (GCMT) catalog, as well as the corresponding seismic data from the IRIS Data Management Center.

The Green's functions are computed using SPECFEM3D_GLOBE with a recently constructed 3−D tomographic model AU32, including fine−scale velocity structures as well as seismic anisotropy beneath the Australasian region and the Tonga−Kermadec subduction zone. We apply bandpass filters to both observed and synthetic data in order to separate body waves (20−60 s) and surface waves (50−150 s), and use FLEXWIN to automatically pick time−windows based on the similarity of observed and synthetic seismograms.

We use the classical Hessian−based inversion scheme (Liu et al, 2004) to invert for the moment tensor solutions. The misfit function $\boldsymbol{\phi}$ is defined as the L2 difference betweenobserved data $\boldsymbol{d}$ and synthetics $\boldsymbol{s}$ computed using given parameters $\boldsymbol{m}$={m_j, j=1,…,9}:

$$\phi(\boldsymbol{m}) = \frac{1}{2}\int (\boldsymbol{s}(\boldsymbol{m}) - \boldsymbol{d})^2\, dt$$

Taking the first and second order derivatives of the misfit function with respect to $\boldsymbol{m}$, we have

$$\frac{\partial\phi(\boldsymbol{m})}{\partial m_j} = \int (\boldsymbol{s}(\boldsymbol{m}) - \boldsymbol{d})\frac{\partial \boldsymbol{s}(\boldsymbol{m})}{\partial m_j} dt$$

$$\frac{\partial\phi(\boldsymbol{m})}{\partial m_j}\frac{\partial\phi(\boldsymbol{m})}{\partial m_k} = \int \frac{\partial \boldsymbol{s}(\boldsymbol{m})}{\partial m_j}\frac{\partial \boldsymbol{s}(\boldsymbol{m})}{\partial m_k} dt$$

By assuming that the first derivatives equal to zero for optimal model parameters, we have

$$\frac{\partial\phi(\boldsymbol{m})}{\partial m_j} + \frac{\partial \boldsymbol{s}(\boldsymbol{m})}{\partial m_j}\frac{\partial \boldsymbol{s}(\boldsymbol{m})}{\partial m_k}\left(m_k^{final} - m_k^{initial}\right) = 0$$

Therefore, we only need the derivatives of synthetic seismograms with respect to each model parameter, which can be numerically computed using our 3-D tomography model AU32.

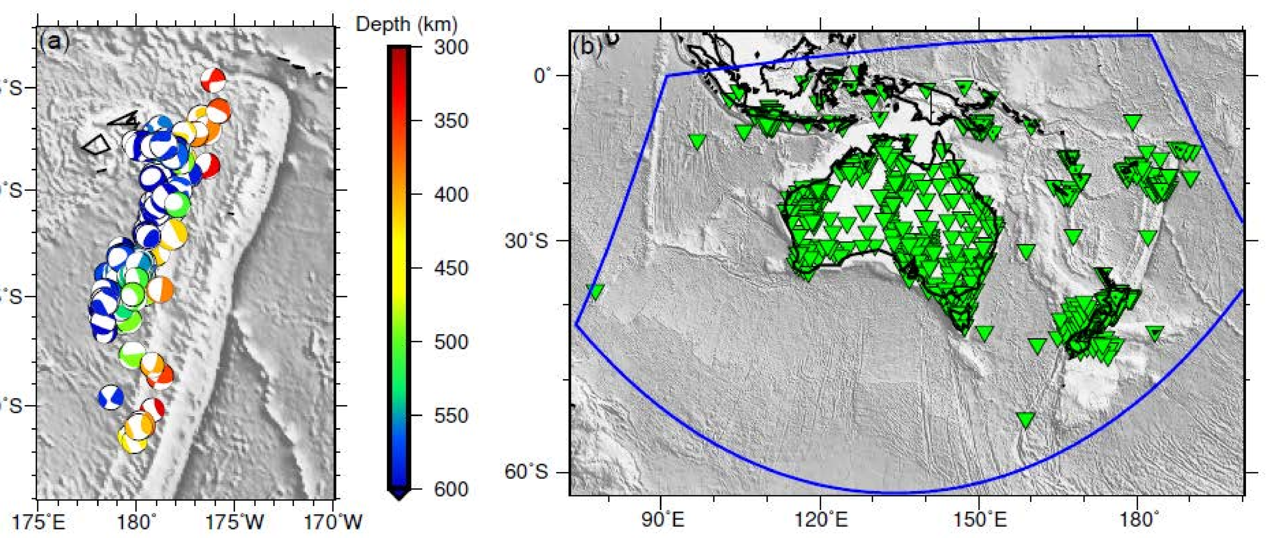

Figure 1: Distributions of deep earthquakes (a) and stations (b) used in this study. Blue lines denote the simulation domain in SPECFEM3D_GLOBE.

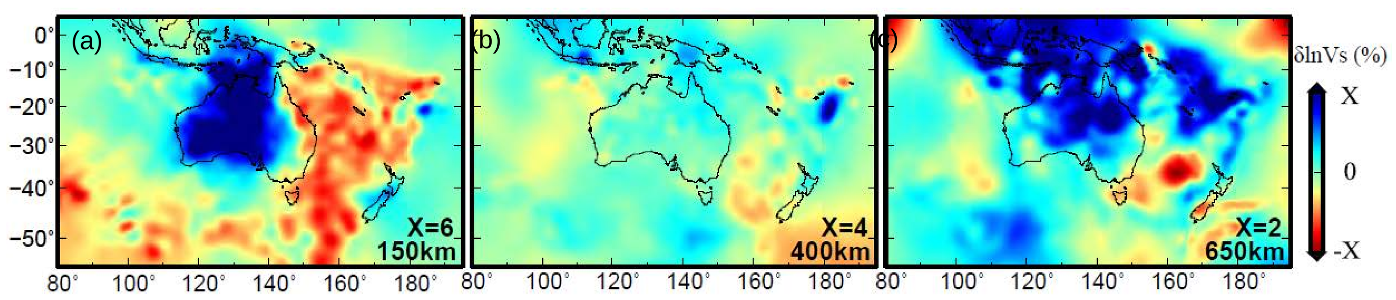

Figure 2: Horizontal slices of the shear wavespeed perturbation of model AU32 with respect to the 1-D reference model STW105 at 150, 400, and 650 km depths.

Results

We first show some statistics of the inverted moment tensor solution results, including the distribution of variance reduction (1-$\boldsymbol{\phi new}/\boldsymbol{\phi old}$), and the correction in the moment magnitude, depth, and horizontal location. We do not see significant update for most events from these histograms, suggesting the earthquake location and moment magnitude from the GCMT catalog is quite reliable

We decompose the inverted moment tensors to double couple (DC), compensated linear vector dipole (CLVD), and isotropic (ISO) components, and then compute their percentage magnitudes for each event. The mean and standard deviation values are DC (65.9% ± 20.6%), CLVD (24.1% ± 18.3%), ISO (10.0% ± 9.5%). These results are quite similar to the general estimation by Vavryčuk (2005), with CLVD up to 30% and ISO up to 15% at subduction zones. Due to the zero-trace regularization, GCMT results do not contain any isotropic components. However, our results indicate that 85 events have notable positive trace (>+3%), accounting for about 1/3 of the whole dataset.

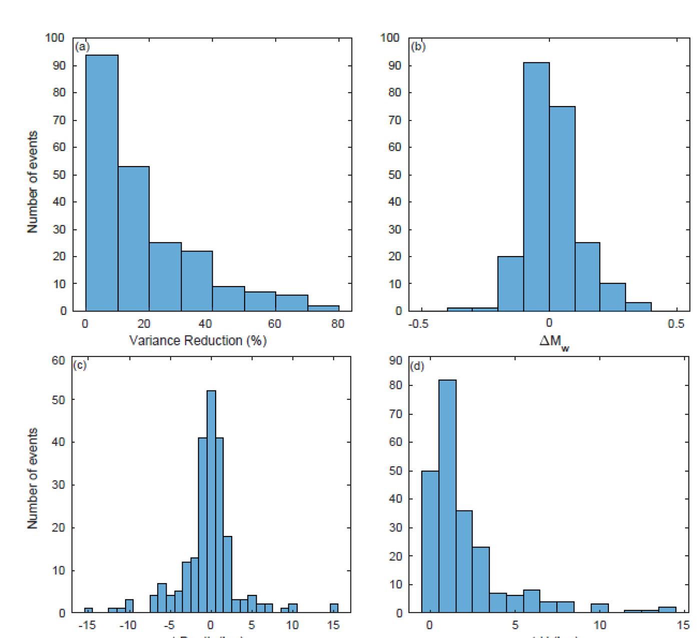

Figure 3: Histograms of the variance reduction (a), and updated values for the moment magnitude (b), depth (c), and horizontal location (d).

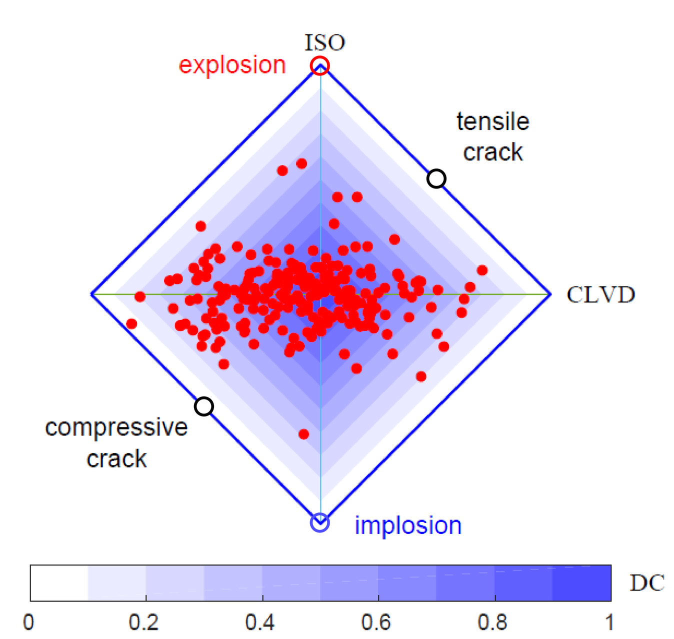

Figure 4: The diamond CLVD-ISO-DC plot with colormap denotes the DC component. Red dots represent deep earthquakes used in this study.

We select one event (CMT201706290703A) to visualize the difference between the GCMT catalog and our new results, and compare synthetics using two moment tensors with observed data.

	Latitude	Longitude	Depth	DC	CLVD	ISO
GCMT	30.930° S	179.920° W	409.5 km	97.6%	2.4%	0%
Inverted	30.936° S	179.921° W	410.9 km	95.6%	2.7%	1.7%

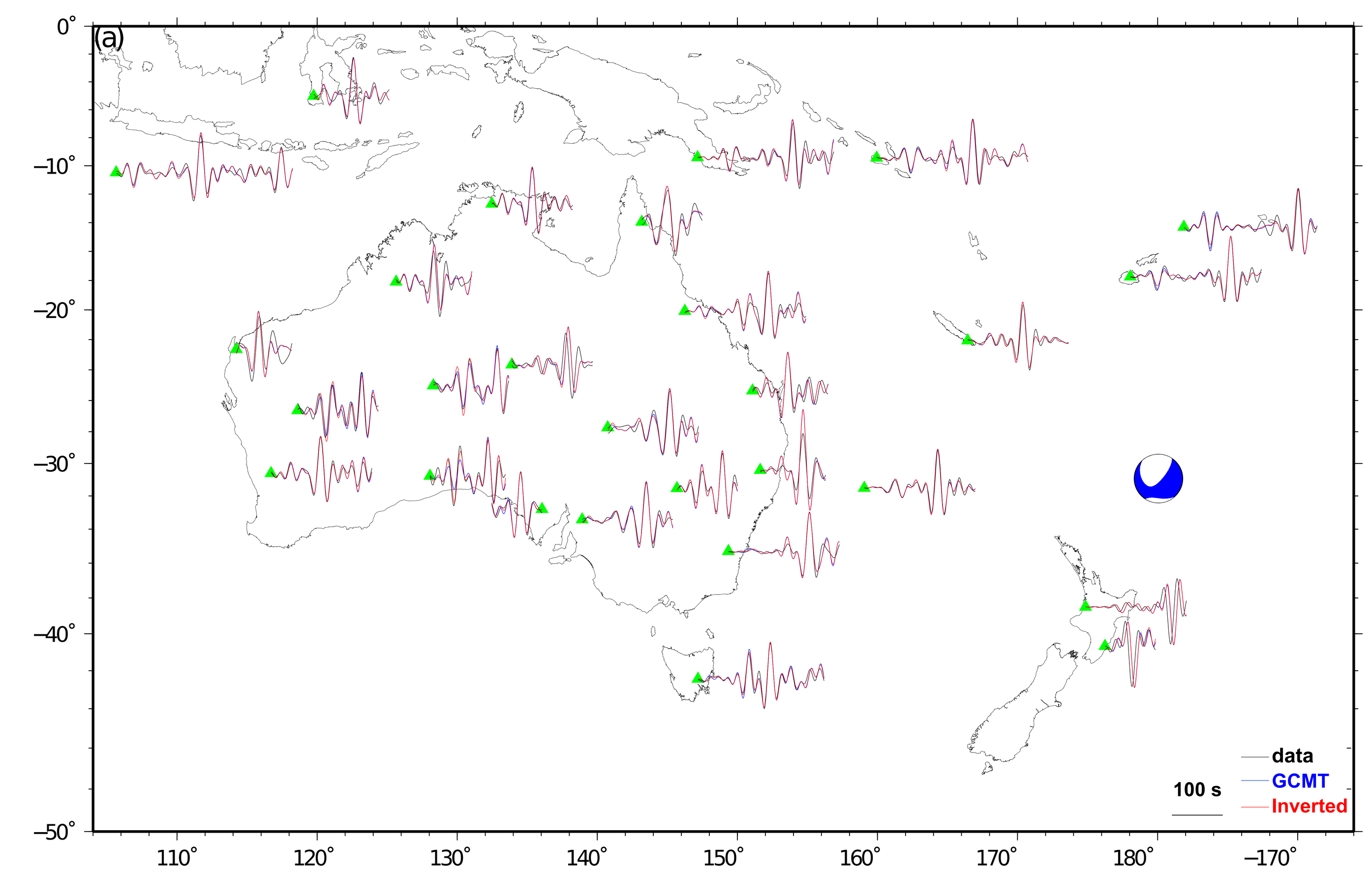

Figure 5: Comparisons of short-period (20-60 s) vertical component observed (black) and synthetics using the GCMT catalog result (blue) and the inverted moment tensor (red).

In comparison with the GCMT catalog, our results are constructed using 3-D Green's functions, and the zero-trace regularization is not applied. To investigate which factor is more influential, we design a two-by-two control test on a subset of 70 events. For each event, we perform moment tensor inversions under following four different settings.

	1-D velocity model STW105	3-D velocity model AU32
With zero-trace regularization	Control group	Experiment 2
Without zero-trace regularization	Experiment 1	Experiment 3

For each event, we normalize the four misfit values by the value from the control group. The histogram suggests that the usage of 3-D Green's functions is more influential and it will prominently reduce the data misfit.

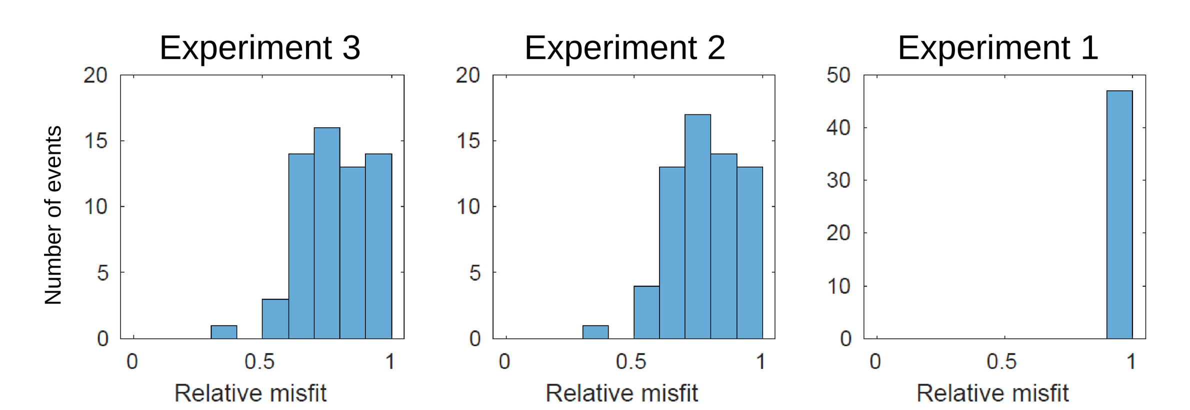

Figure 6: Histograms of relative misfits for the three experiments. Misfits in the control group are equal to one thus it is not shown here.

Summary

- Isotropic components in the moment tensors of deep earthquake at the Tonga-Kermadec subduction zone may be underestimated by current results from the GCMT catalog.
- 3-D Green's functions are important for moment tensor inversion.
- We may relax the zero-trace regularization when computing moment tensors for deep earthquakes.