DETERMINATION OF FOCAL MECHANISM OF THE TONGA-FIJI EARTHQUAKES WITH A SPARSE REGIONAL SEISMIC NETWORK

Mafoa Latu Penisoni[1]
MEE20703

Supervisor: Daisuke SUETSUGU[2], Tatsuhiko HARA[3*]
Toshiaki YOKOI[3], Bunichiro SHIBAZAKI[3**],**
Naohiko HIBINO[4]**

ABSTRACT

We performed moment tensor inversion of waveform data from the temporary seismic network Southwest Pacific Seismic Experiment (SPASE) from 1994 to 1995 for focal mechanism, focal depth and moment magnitude of shallow earthquakes in the Tonga-Fiji region. We focused the shallow earthquakes, since they are more important than deep earthquakes in the viewpoint of disaster mitigation such as tsunami warning. We classified the quality of our solutions mainly on the basis of similarity to those in the Global Centroid Moment Tensor (GCMT) catalog as 'good', 'moderate' and 'poor'. We also used P-wave polarity data and proportion of double-couple component for the classification. We could obtain 'good' solutions for all of earthquakes with Mw > 6. A proportion of 'good' solutions is a little greater than half for earthquakes with Mw < 5.9. Geographical dependency of the quality shows that the quality of our solutions is much better in the region covered by the SPASE network, while worse in the northern end or south of Tonga. Comparing to Mw by GCMT and depths from the United States Geological Survey (USGS), Mw of this study is underestimated by about 0.1. Differences of Focal depths of this study and the USGS depth are within 15 km. The result based on data from the SPASE network suggests that it is feasible for quick and reliable determination of earthquake parameters for shallow Tongan earthquakes of Mw > 6 off Ha'apai, Vava'u, and Tongatapu, using data only from a regional sparse network. To improve a reliability in the earthquake parameters in the northern Tonga arc, where seismicity is very high, a few stations should be deployed there.

Keywords: Focal mechanism, Tonga-Fiji region, Moment tensor inversion

1. INTRODUCTION

Tonga and Fiji groups of islands are sitting and floating on the northern rim of the Indo-Australia plate, moving northeastward while the Pacific plate is moving in the northwest direction. A convergence boundary between these two plates corresponds to the seismically active Tonga-Kermadec subduction zone. The Pacific plate is subducted beneath the Indo-Australian plate from the Tonga-Kermadec arc. The Lau basin has active spreading ridges characterized by normal faults. The northern Tonga arc has a complicated region comprising of strike-slip and normal faults. The Tonga-Fiji region is characterized by high activity of both shallow and deep earthquakes. The Tonga-Fiji region has the highest activity of deep earthquakes in the world. Shallow earthquakes (focal depth < 50 km) are also active along the Tonga-Kermadec arc, which has high tsunami potential. Precise locations and focal mechanisms of earthquakes along the arc are essential to study the dynamics of the subduction zone and to prepare for earthquake and tsunami hazards in the future.

[1] Ministry of Land and Natural Resources, Tonga.
[2] Japan Agency for Marine-Earth Science and Technology (JAMSTEC).
[3] International Institute of Seismology and Earthquake Engineering, Building Research Institute.
[4] National Graduate Institute for Policy Studies.
* Chief examiner, ** Examiner

The Tonga Seismic Network, the first permanent seismic network, was established with five stations in 2011 by JICA and owned and operated by the Ministry of Land, and Natural Resources (MLNR) Tonga Government. The same JICA project also constructed the Fiji Seismic Network. Seismic data were exchanged between Tonga and Fiji on a real-time basis via satellite commutations. Unfortunately, all the Tongan stations have been down since 2017 due to some technical and funding problems. Recently a recovery plan of the Tonga Seismic Network has been emerged by the Tonga Government and international institutions. The recovery and cooperation with neighboring countries such as Fiji should enable a close watch of the Tongan earthquake activity. Note that cooperative observation between Tonga and Fiji remains essential to monitor earthquakes in Tonga because only a combined Tonga-Fiji network can cover earthquake locations in this region.

The present study aims to assess the feasibility of focal mechanism determination by moment tensor inversion with the Tonga and Fiji Seismic Network, which is substantially sparse compared with a regional seismic network such as Japanese and a global seismic network. Although a determination of focal mechanism has been routinely performed with dense seismic networks in international and regional scales, it is necessary to examine whether it is feasible with a sparse network in Tonga and Fiji.

We conduct the present study:

(i) To evaluate the reliability of focal mechanism determination by a sparse seismic network in Tonga and Fiji and also,

(ii) To evaluate a lower limit of the Tonga-Fiji earthquakes for which focal mechanism can be determined (> Mw5.5 by Global CMT at present). An increase of focal mechanisms could be helpful to improve our understanding of regional tectonics. A quick determination of the focal mechanism could be beneficial for urgent action of disaster mitigation such as tsunami warning.

2. DATA

It is more important to study shallow earthquakes than deep earthquakes from the viewpoint of earthquake and tsunami disasters. We selected shallow earthquakes (focal depth < 50 km) with moment magnitude Mw > 5.3 in 1994 and 1995 within the Tonga-Fiji region with latitude of 13°S to 28°S South and longitude of 177°E to 171°W. The number of the selected earthquakes is 35 (Figure 1a). We used the hypocentral coordinates determined by USGS**.**

We analyzed seismograms recorded at the SPASE network (Wiens et al., 1995). Twelve temporary stations were deployed by Washington University, St Luis from the US, from 1993 to 1995, under the IRIS/PASSCAL program (Figure 1b). We also used two Global Seismic Network (GSN) stations in the studied region. All the data from these stations is stored in Data Management Center of

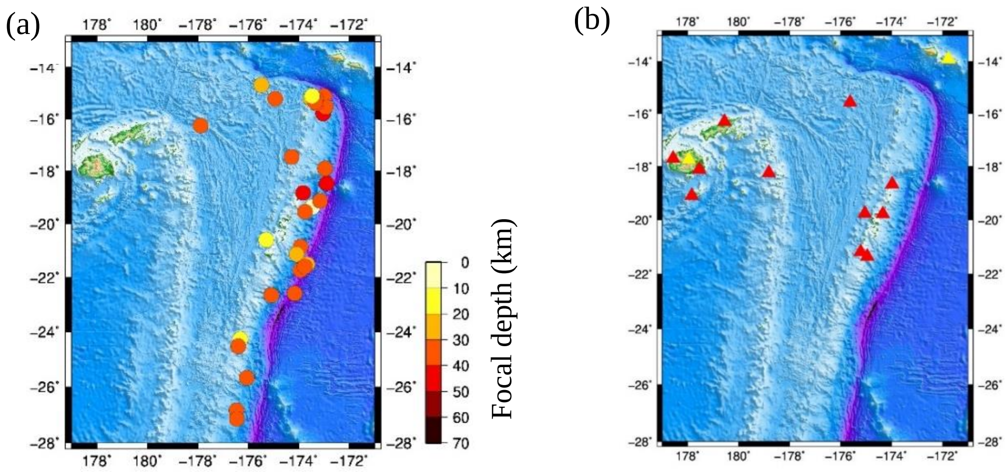

Figure 1. (a) Shallow earthquakes (h < 50 km) in 1994 and 1995 analyzed in this study (solid circle). A color of the circles represents focal depth. (b) Seismic stations used in the present study. Red triangles are SPASE stations, and yellow ones are GSN stations.

Incorporated Research Institutions for Seismology (IRIS/DMC). Distances between earthquakes and stations are less than about 1000 kilometers. We chose the SPASE network for the present study, mainly because the station number and spatial distribution are similar to those of the planned Tonga Seismic Network and networks in the neighboring countries. We can assess a capability of the planned network for focal mechanism determination through the present study using the SPASE data.

3. METHODOLOGY

3.1. Basic Theory

We can consider spatial and temporal point-source in simplifying seismic sources. To solve for seismic moment tensor, the following equation is solved using least square for a given source depth**.**

$$U_n(x,t) = M_{ij} * G_{ni,j}(x,z,t) \tag{1}$$

where U_n = Observed *n*th component of displacement, $G_{ni,j}$ = nth component Green's function, and M_{ij} = scalar seismic moment tensor, *i*, *j* = Geographical direction.
To find the best focal depth, we should vary the depth and find the solution for the largest variance reduction using this equation

$$VR = \left[1 - \sum_i \sqrt{(data_i - synth_i)^2} \,/\, \sqrt{data_i{}^2}\right] * 100 \tag{2}$$

where *data* and *synth* are observed and synthetic seismograms. The synthetic seismograms are calculated by a multiplication of moment tensors and Green's function. The summation is applied for all stations and components.

Expressing Eq. (1) in vector and matrix form, we have

$$\boldsymbol{U} = \boldsymbol{GM} \tag{3}$$

where $\boldsymbol{U}$ is observed ground motion, $\boldsymbol{G}$ is a Green’s function, and $\boldsymbol{M}$ moment tensors. The only $\boldsymbol{M}$ is unknown. The Green’s function is calculated from seismic structure model for a given focal depth, azimuth, and distance between event and station using the wavenumber integration method (Saikia, 1994, GJI). We used a regional velocity model in Tonga and Fiji region (Conder and Wiens, 2006). Moment tensor $\boldsymbol{M}$ is determined by a linear least square method as

$$\boldsymbol{M} = (\boldsymbol{G}^{\mathrm{T}}\boldsymbol{G})^{-1}\, \boldsymbol{G}^{\mathrm{T}}\boldsymbol{U} \tag{4}$$

3.2. Computer codes

3.2.1. SEISAN

We used SEISAN, one of the systems to analyze earthquake, developed by Havskov et al. (2020) and Havskov and Ottemoller, (1999) (http://seisan.info/), for data processing of local, regional, and global earthquakes. This system can determine hypocenter location, fault plane solutions, and spectral parameters and is able to plot hypocenters. It contains integrated research-type programs like moment tensor inversion.

3.2.2. Time Domain Moment Tensor INVerse Code (TDMT_INVC)

We performed moment tensor inversion with the code TDMT_INVC, which has been used at the University of California, Berkeley Seismological Laboratory (BSL) since 1993 to automatically investigate all ML > 3.5 in Northern California. It was developed by Dreger (2003) and is implemented in SEISAN.

4. RESULTS

We determined focal mechanism, moment magnitude, and focal depth of 35 shallow earthquakes in Tonga-Fiji region, of which the magnitude range from 5.3 to 7.3. We classified a quality of the 35 solutions to ‘good’, ‘moderate’, and ‘poor’ on the basis of mainly similarity to the corresponding solutions from the Global Centroid Moment Tensor (GCMT) catalog (https://www.globalcmt.org/; Dziewonski, et al., 1981; Ekström, et al., 2012).

The similarity is measured by a rotation angle between a focal mechanism by this study and GCMT using a method by Kagan (2007). Events of the rotation angle less than 50°, those from 50° to 70°, and those greater than 70° were classified as good, moderate, and poor solutions, respectively. A fitness of P-wave polarity picked by the present study and a proportion of double-couple component in moment tensors (a moment tensor solution is decomposed into a double-couple moment tensor and a compensated linear vector dipole moment tensor (Dreger, 2003)) were also taken into consideration. Three events do not have a GCMT solution and are classified as moderate because of relatively good fitness of the P-wave polarity to focal mechanisms. The 35 solutions comprise 19 good, 4 moderate, and 12 poor solutions.

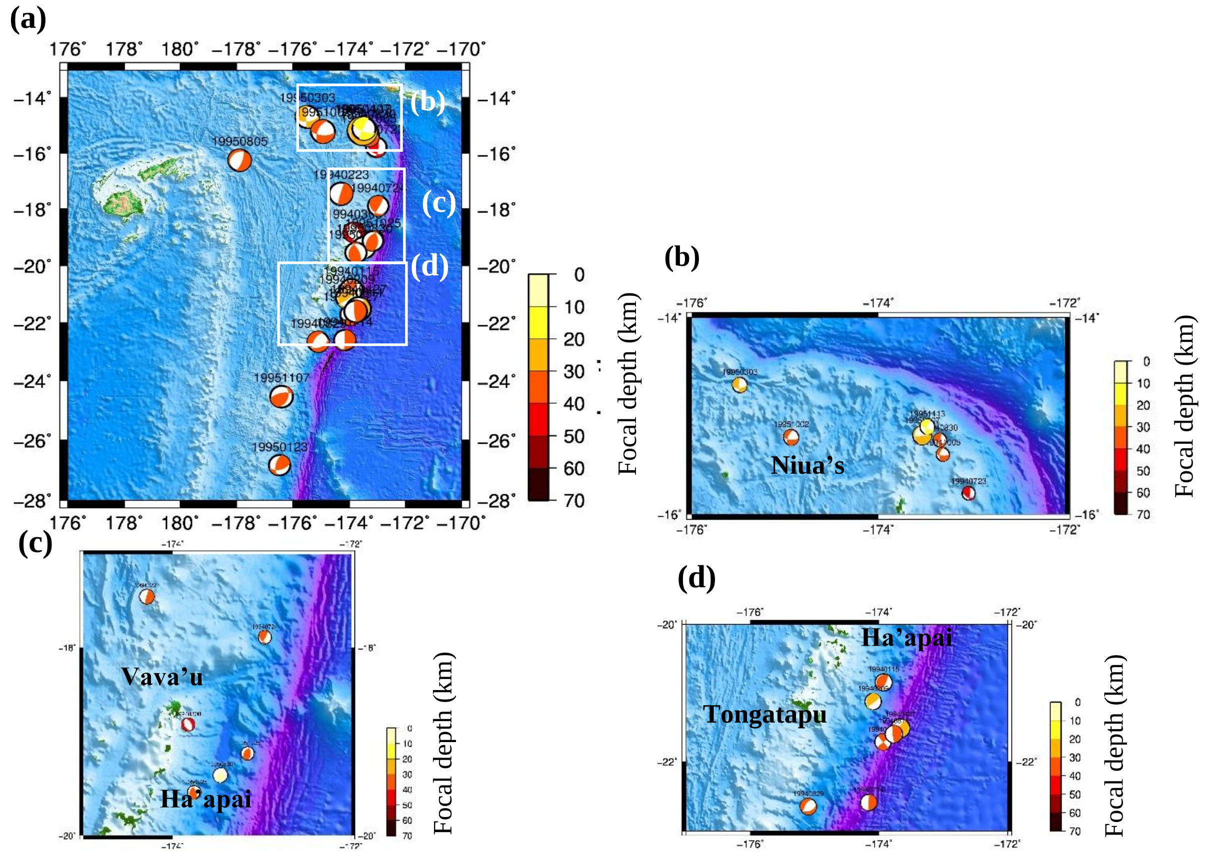

Figure 2. Distribution of focal mechanisms determined by the present study. (a) All the good and moderate solutions. (b) Northern Tonga arc; (c) Off Vava’u and Ha’apai; (d) Off Tongatapu. A color of mechanism diagram represents focal depth. Locations of (b), (c), (d) are shown in (a).

Figure 2 shows a distribution of 23 good and moderate focal mechanism solutions. A focal mechanism was less determined in the south of 24°S, mainly because it is far away from the SPASE network. A reverse fault mechanism with strike subparallel to the trench dominates shallow earthquakes in the south of a latitude of 17°S (Figures 2a, c and d) near the Tonga-Kermadec trench, which represents subduction of the Pacific plate. There is a minor normal faulting activity away from the trench. At the region north of 16°S, where the trench is distorted, a focal mechanism is mainly strike slip faulting with WNW-ESE T axes (Figure 2b). It may be related to a spreading ridge-transform fault system developed in the region (Peltier et al., 1998).

5. DISCUSSION

We examine geographical dependence (latitude dependence) of quality of the focal mechanism solution in Table 1. A proportion of good/moderate solutions is largest (13 of total 16) from 23°S to 17°S, where is in the SPASE network. This is probably due to a good station coverage. The solutions in the northern Tonga arc are worse (the proportion is 8 of total 14), since it is located at the northern end of the network where the station coverage is worse than that from 23°S to 17°S. To improve a reliability of focal mechanism solution in the northern Tonga arc, it is important to have stations in the northern Tonga islands. The Kermadec arc is outside the SPASE network, resulting in worst proportion (2 of total 5). It may be difficult to improve it, because of sparse inhabited islands there.

We look into a magnitude dependence of the quality as in Table 2. A proportion of good/moderate solutions is 10 of total 17 for events of Mw 5.5~5.9 and 9 of total 14 for events of Mw < 5.4. All the solution is good for events of Mw > 6, which is encouraging in the viewpoint of disaster mitigation such as tsunami warning.

Table 1. Geographical dependence of quality of focal mechanism solution

	North of 16°S (Northern Tonga arc)	23°S ~ 17°S (Off Ha'apai, Vava'u, Tongatapu)	South of 24°S (Kermadec arc)
Good	7	11	1
Moderate	1	2	1
Poor	6	3	3

Table 2. Magnitude dependence of quality of focal mechanism solution

	Mw or mb from 5.3 to 5.4	5.5 < Mw < 5.9	Mw > 6
Good	6	9	4
Moderate	3	1	0
Poor	5	7	0
Total	14	17	4

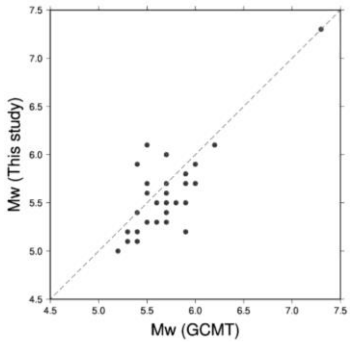

Figure 3. Comparison of Mw determined by this study and GCMT.

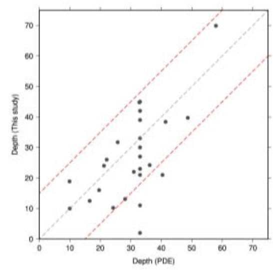

Figure 4. Comparison of focal depth by this study and PDE published by USGS. The red dashed lines represent the range between +15km and -15km from the focal depths from PDE

Next, we examine whether a systematic bias exists for estimated magnitude and focal depth. An accurate determination of magnitude and focal mechanism is crucial for appropriate estimate of tsunami, since it is directly related to seafloor deformation and tsunami generation. Figure 3 shows that Mw estimated by the present study is smaller than that of GCMT by 0.1 in average. It is especially evident for events of Mw < 5.9. Focal depths by the present study are relatively shallower than those of

Preliminary Determination of Epicenters (PDE) by USGS, while the difference is within 15 km except for events of the PDE depth of 33 km (Figure 4). The large scatter at the PDE depth of 33 km is probably attributed to less accurate PDE depth, since the USGS assigns 33 km in the case of ill-constrained focal depth.

This study demonstrates that we could determine the focal mechanisms, focal depths, and Mw by analyzing seismic waves arriving 7-8 minutes after the earthquake occurrence recorded at less than ten regional sparse stations, while GCMT requires seismic waves arriving 40-50 minutes after earthquake occurrence recorded at 40-50 stations over the world. It is encouraging for us that we could obtain reliable earthquake parameters of relatively large earthquakes (Mw > 6.0) near most populated islands using seismograms with short durations (~ 500 second) from regional sparse network SPASE.

6. CONCLUSIONS

We performed moment tensor inversion of seismograms from temporary seismic network SPASE in 1994 and 1995 for focal mechanism, focal depth, and moment magnitude of 35 shallow earthquakes (h < 50km) in the Tonga-Fiji region.

We classified quality of our solutions mainly on the basis of similarity to GCMT as ‘good’, ‘moderate’ and ‘poor’. Our solutions are classified into 19 good, 4 moderate and 12 poor solutions. We could obtain ‘good’ solutions for all of earthquakes with Mw > 6. A proportion of ‘good’ solutions is a little greater than half for earthquakes with Mw < 5.9. The main part of Tonga arc has a greater proportion of good solutions as compared to the Kermadec and northern Tonga arcs, owing to better station coverage. Comparing to Mw by GCMT and PDE depth, Mw of this study is underestimated by about 0.1. Differences in Focal depths of this study and the PDE depth are mostly within 15 km.

The result based on data from the regional sparse SPASE network is encouraging to quick and reliable determination of earthquake parameters of shallow Tongan earthquakes of Mw > 6 near the most populated area in Tonga. To improve the reliability in earthquake parameters in the northern Tonga arc, where seismicity is very high, more stations should be deployed there.

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to the supervisors Drs. Daisuke Suetsugu and Tatsuhiko Hara for their instructions during my study. I would like to thank Drs. Toshiaki Yokoi and Bunichiro Shibazaki for their comments. I am grateful to Drs. Doug Wiens and James Conder for kindly sending their velocity model by digitizing a figure in Conder and Wiens (2006). We used data from SPASE data taken from IRIS/DMC. We used CMT solutions from the Global CMT project. We used SEISAN, TDMT_INV, and Generic Mapping Tools (Wessel and Smith, 1998) in this study. The land topography and ocean bathymetry are from GEBCO Compilation Group (2020).

REFERENCES

Conder, J.A., and Wiens, D.A., 2006, Geochem. Geophys. Geosyst, 7, doi:10.1029/2005GC001113.
Dreger, D.S., 2003, International Handbook of Earthquake and Engineering Seismology, Vol. 81B, p 1627.
Dziewonski, A.M., Chou, T.-A., and Woodhouse, J. H., 1981, J. Geophys. Res., 86, 2825-2852.
Ekström, G., Nettles, M., and Dziewonski, A.M., 2012, Phys. Earth Planet. Inter., 200-201, 1-9.
GEBCO Bathymetric Compilation Group 2020, doi:10.5285/a29c5465-b138-234d-e053-6c86abc040b9.
Havskov, J., and Ottemoller, L., 1999, Seis. Res. Lett., 70, 532-534.
Havskov, J., Voss, P.H., and Ottemoller, L., 2020, Seis. Res. Lett, 91, 1846-1852.
Kagan, Y.Y., 2007, Geophys. J. Int, 171, 411–418.
Pelletier, B., Calmant, S., and Pillet, R., 1998, Sci. Lett., 164, 263-276.
Saikia, C., 1994. Geophys. J. Int., 118, 142–158.
Wessel, P., and Smith, W.H.F., 1998, Eos, Trans. Am. geophys. Un., 79, 579.
Wiens, D.A., Shore, J.P., Mcguire, J.J., and Roth, E., 1995, IRIS Newsletter, 14, No. 1.