

Source Modeling of an M_W 5.9 Earthquake in the
Nankai Trough, Southwest Japan, using Offshore and
Onshore Strong Motion Waveform Records

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Abstract

On 1 April 2016, an M_W 5.9 (M_{JMA} 6.5) plate-boundary earthquake occurred in the subduction zone of the Nankai Trough, offshore the Kii Peninsula, southwest Japan. This event is the largest plate-boundary earthquake in the source region after the 1944 Tonankai earthquake (M_W 8.0). In the last half century, moderate-to-large earthquakes of this focal type have become very rare in this region, and therefore, this event provides a good opportunity to investigate the source characteristics related to strong motion generation of subduction-zone plate-boundary earthquakes in the Nankai Trough. In this study, the source model of the earthquake was estimated on the basis of broadband strong motion waveform modeling using the empirical Green's function method. Source parameters of the strong motion generation area (SMGA) were optimized by waveform modeling in the frequency range 0.4–10 Hz. One SMGA is necessary to explain the observed waveforms at offshore and onshore strong motion stations. The best estimate of the size of the SMGA was 20.3 km², which does not follow the source scaling relationship for past plate-boundary earthquakes along the Japan Trench, northeast Japan. This result implies the possibility of differences between the source characteristics of plate-boundary events in the Nankai Trough and those along the Japan Trench. This

29 finding provides important information about regional variations of source
30 characteristics in ground motion prediction for hazard assessment of future
31 megathrust earthquakes.

32

Introduction

The Philippine Sea Plate subducts northwestward beneath southwest Japan along the Nankai Trough (e.g., Hashimoto and Jackson, 1993; Seno *et al.*, 1993), and the subduction of this oceanic plate has generated historical megathrust plate-boundary earthquakes (Ando, 1975). These earthquakes induced strong shaking and tsunamis across wide regions of the Japanese Islands. In order to estimate seismic hazards for such events, ground motion prediction on the basis of numerical simulations has been extensively studied for hypothetical megathrust earthquakes along the Nankai Trough (e.g., Miyake *et al.*, 2008; Sekiguchi *et al.*, 2008; Maeda *et al.*, 2016). Source heterogeneity is one of the key factors controlling the generation of strong ground motions (e.g., Miyake *et al.*, 2003). Thus, examining the regional characteristics of source parameters based on analysis of observed earthquakes is essential for improving ground motion prediction and seismic hazard assessment.

On 1 April 2016, an M_{JMA} 6.5 earthquake occurred offshore the Kii peninsula, southwest Japan at 11:39, Japan Standard Time (JST; 02:39, coordinated universal time [UTC]). This event was interpreted as a thrust-event on the plate boundary along the Nankai Trough (Wallace *et al.*, 2016). The centroid moment tensor (CMT)

solution by the Global CMT Project (Ekström *et al.*, 2012) also supports that this event was a low-angle thrust earthquake. The hypocenter of this event is located inside the source fault of the 1944 Tonankai earthquake (M_W 8.0) (e.g., Ichinose *et al.*, 2003; Kikuchi *et al.*, 2003) (Figure 1) and other historical megathrust earthquakes (e.g., Ando, 1975). The last megathrust earthquake in this subduction zone was the 1944 Tonankai earthquake, after which the M_{JMA} 6.5 earthquake is the largest plate-boundary earthquake in the source region.

The significance of this event regarding seismic observations is that this event occurred beneath an ocean-bottom seismic network called the Dense Oceanfloor Network system for Earthquake and Tsunamis (DONET), which is jointly operated by the National Research Institute for Earth Science and Disaster Resilience (NIED) and Japan Agency for Marine-Earth Science and Technology (JAMSTEC) (Kaneda *et al.*, 2015). DONET1 consists of 20 ocean-floor stations, and each station has three-component strong motion accelerometers along with three-component broadband velocity sensors, pressure gauges, differential pressure gauges, hydrophone, and thermometer (Kaneda *et al.*, 2015).

The source characteristics of such events can be determined through broadband strong motion waveform modeling using the empirical Green's function

69 method (Irikura, 1986; Miyake *et al.*, 2003). In this modeling, the source model is
70 characterized by a strong motion generation area (SMGA) (Miyake *et al.*, 2003),
71 which is defined as a rectangular area with high-stress drop or high slip-velocity.
72 As the empirical Green's function method uses the observed record of a small event
73 occurring close to the target event as a Green's function, the propagating-path and
74 site effects are included in the empirical Green's function itself. Therefore, the
75 SMGA source model based on the empirical Green's function method has high
76 potential to reproduce ground motion time history in a broad frequency range.
77 Strong motion modeling using the empirical Green's function method developed by
78 Irikura (1986) has successfully reproduced observed strong ground motions for
79 previous large subduction-zone plate-boundary earthquakes (e.g., Kamae and
80 Kawabe, 2004; Suzuki and Iwata, 2007; Ramírez-Gaytán *et al.*, 2010; Takiguchi *et*
81 *al.*, 2011; Asano and Iwata, 2012; Satoh, 2012; Kawabe and Kamae, 2013; Kurahashi
82 and Irikura, 2013) as well as inland crustal (e.g., Kamae and Irikura, 1998; Miyake
83 *et al.*, 2003; Suzuki and Iwata, 2006; Kurahashi *et al.*, 2008; Maeda *et al.*, 2008;
84 Maeda and Sasatani, 2009; Yamamoto and Takenaka, 2009; Kurahashi and Irikura,
85 2010; Poiata *et al.*, 2012; Wen *et al.*, 2014; Riahi *et al.*, 2015; Xia *et al.*, 2015; Wen
86 *et al.*, 2017) and intraslab earthquakes (e.g., Asano *et al.*, 2003; Morikawa and

Sasatani, 2004; Oth *et al.*, 2007; Poiata and Miyake, 2017).

The study of such earthquakes will drive improvements in ground motion prediction and seismic hazard assessment for hypothetical megathrust earthquakes expected along the Nankai Trough. However, moderate-to-large earthquakes of this focal type have become very rare in the source region in the last half century. Therefore, this event provides a unique opportunity to investigate the source characteristics related to strong motion generation of subduction-zone plate-boundary earthquakes along the Nankai Trough, southwest Japan.

In this study, the source model of the 2016 earthquake offshore the Kii peninsula was estimated through broadband strong motion waveform modeling using the empirical Green's function method to investigate the source characteristics related to strong ground motion generation during this event. The abovementioned previous works on subduction-zone plate-boundary earthquakes in Japan were implemented for events occurring along the Japan Trench in northeast Japan. We compared the source characteristics of this event with those from subduction-zone plate-boundary earthquakes in northeast Japan to illuminate and discuss the regional difference in source characteristics in terms of strong motion generation from plate-boundary earthquakes.

Source Modeling by Broadband Strong Ground Motion Simulation using the Empirical Green's Function Method

The source model of the 2016 earthquake offshore the Kii peninsula was estimated by the broadband strong motion waveform modeling using the empirical Green's function method based on the SMGA source model (Irikura, 1986; Miyake *et al.*, 2003). Detailed introduction of the concept of SMGA and the strong ground motion simulation technique using the empirical Green's function method of Irikura (1986) can be found in Miyake *et al.* (2003).

We collected near-source strong motion data recorded by accelerometers at cabled sea-floor stations of DONET1. We also collected acceleration records from the Long-Term Borehole Monitoring System (LTBMS) installed within the accretionary prism underlying the Kumano sedimentary basin at a depth of 904 m below the sea floor at station KMDB1, which was installed by JAMSTEC. Some offshore stations close to the epicenter with high peak ground accelerations were excluded in this analysis to avoid any effect of soil nonlinearity during strong shaking. In addition to offshore stations, we collected strong motion data from velocity-type strong motion sensors (Tokyo-Sokushin VSE-355G3) at onshore

broadband stations in the Kii peninsula belonging to F-net of NIED (station KIS) and Disaster Prevention Research Institute (DPRI) of Kyoto University (station SMK).

The hypocenter locations of the mainshock and aftershocks were based on the hypocenter catalog of Wallace *et al.* (2016) (Figure 1). They located the mainshock and aftershocks within 48 h after the mainshock using DONET accelerometer data. The hypocenter of the mainshock in their catalog is 33.34999°N , 136.4010°E , and at a depth of 11.371 km. In addition to the M_{JMA} 6.5 mainshock, some $M3$ class aftershocks occurred on the same day. Because of their good quality, the records of an M_{JMA} 3.2 aftershock at 13:04 on 1 April 2016 (33.41679°N , 136.3475°E , at a depth of 14.186 km according to Wallace *et al.*, 2016) were selected to serve as the empirical Green's functions. The CMT solution of this aftershock is not available.

Firstly, the observed source spectral ratio between the mainshock and the aftershock, which was used as an empirical Green's function, was analyzed to objectively determine two scaling parameters N (integer) and C (real number). N gives the ratio of source dimensions between the target and EGF events. C corresponds to the ratio of stress drop between the target and EGF events. If we

assume that the source spectrum follows the ω^{-2} source model (Brune, 1970, 1971), these scaling parameters obey the following relationships (e.g., Miyake *et al.*, 2003),

$$\frac{U_0}{u_0} = \frac{M_0}{m_0} = CN^3, \quad (1)$$

$$\frac{A_0}{a_0} = \frac{M_0}{m_0} \cdot \left(\frac{f_{cm}}{f_{ca}} \right)^2 = CN. \quad (2)$$

U_0 and u_0 are the flat levels of displacement amplitude spectra for the target and EGF events, respectively. M_0/m_0 corresponds to the seismic moment ratio between the target and EGF events. A_0 and a_0 indicate the flat levels of the acceleration amplitude spectra for the target and EGF events. f_{cm} and f_{ca} are corner frequencies of the target and the EGF events, respectively.

The scaling parameters N and C were determined using strong motion data recorded at five DONET stations, one LTBMS ocean-bottom borehole station, and two onshore strong motion stations (Figure 1). The Fourier spectrum of the S-wave part was calculated for each station from a 40.96 s window of the three-component record beginning 1 s before the S-wave arrival. A Parzen window with a bandwidth of $\pm 5\%$ of each frequency point was applied to the original amplitude spectra in order to smooth the amplitude spectra. The propagation path effect was corrected by geometrical spreading for the S-wave and by a frequency-dependent attenuation

factor for the S-wave, $Q(f) = 182f^{0.68}$ (Shiba and Sato, 2007). The average S-wave velocity in and around the source region was assumed to be 3.45 km/s (Iwata *et al.*, 2008). The log average of the spectral ratios for all stations was employed as the observed source spectral ratio. The theoretical source spectral ratio function (SSRF) based on the ω^{-2} source model was fitted to the observed source spectral ratio by the source spectral ratio fitting method (Miyake *et al.*, 1999, 2003). SSRF was defined as

$$\text{SSRF}(f) = \frac{M_0}{m_0} \frac{1 + (f / f_{\text{ca}})^2}{1 + (f / f_{\text{cm}})^2}. \quad (3)$$

This method estimates the seismic moment ratio (M_0/m_0) and corner frequencies for the mainshock (f_{cm}) and the EGF event (f_{ca}). The observed source spectral ratio is compared with the best-fit theoretical source spectral ratio in Figure 2(a). The estimated seismic moment ratio was 2220, and the estimated corner frequencies for the mainshock and aftershock were 0.45 Hz and 3.4 Hz, respectively. From the seismic moment ratio and corner frequencies, the scaling parameters N and C were determined to be 8 and 5.1, respectively.

Finally, following the technique of Asano and Iwata (2012), we used a grid search approach and broadband ground motion simulations from the mainshock at

the relevant stations to estimate the model parameters of the SMGA. In their technique the waveform $U(t)$ for the target event is computed using records of the small event $u(t)$, considered as empirical Green's functions:

$$U(t) = \sum_{i=1}^N \sum_{j=1}^N \frac{R}{R_{ij}} \{F(t) * (C \cdot u(t))\} , \quad (4)$$

$$F(t) = \delta(t - t_{ij}) + \frac{1}{n'(1 - e^{-1})} \cdot \sum_{k=1}^{(N-1)n'} \left[e^{-\frac{k-1}{(N-1)n'}} \cdot \delta\left(t - t_{ij} - \frac{(k-1)\tau}{(N-1)n'}\right) \right] , \quad (5)$$

$$t_{ij} = T_{ij} - T_0 + \frac{\xi_{ij}}{V_r} . \quad (6)$$

Here, $F(t)$ is a filter function which corrects for the difference of slip-velocity functions between the target and EGF events (Irikura, 1986; Irikura *et al.*, 1997). R is the distance along the ray path of the S-wave for the EGF event, and R_{ij} is the distance along the ray path of the S-wave from the subfault (i, j) to the station. τ is the rise time of the SMGA, and T_{ij} and T_0 represent the travel times of the S-wave from the subfault (i, j) and the hypocenter, respectively. The velocity structure models used for calculating the ray path and travel time of the S-wave are one-dimensional velocity structure models derived from the crustal velocity structure model of Iwata *et al.* (2008). ξ_{ij} is the distance from the hypocenter to the subfault

(i, j) in the SMGA, and V_r is the rupture propagation velocity inside the SMGA.

The observed acceleration time histories were band-pass filtered between 0.4 Hz and 10 Hz with a Chebyshev-type recursive filter. The selection of the lower corner frequency of the bandpass filter was dictated by the relatively low signal-to-noise ratio of EGF records below 0.4 Hz. The strike and dip angles of the SMGA are 230° and 18° , respectively, following the Global CMT solution. As no clear initial phase existed in the initial part of the observed P-wave, we fixed the absolute location (latitude, longitude and depth) of the rupture starting point of the SMGA at the hypocenter located by Wallace *et al.* (2016). The model parameters of the SMGA estimated by the grid search were length L , rise time τ , rupture starting subfault (NSL , NSW) within the SMGA, and rupture propagation velocity V_r . The width W was assumed to be equal to L . The search range and its step size for each model parameter are summarized in Table 1. The time window used in estimating the waveforms goodness-of-fit starts 1 s before the S-wave arrival, and its length was fixed at 8 s for all stations, based on residuals of the acceleration envelopes and displacement waveforms (Miyake *et al.*, 1999, 2003).

Results

The best set of source parameters estimated by the grid search (Figure 2b) is summarized in Table 1. A schematic image of the obtained source model is shown in Figure 2(c). The size of SMGA was estimated to be $4.5 \text{ km} \times 4.5 \text{ km} = 20.3 \text{ km}^2$. The rupture of the SMGA primarily propagated northward or towards the down-dip direction. The rupture propagation in down-dip direction is typical of subduction-zone plate-boundary earthquakes in Japan (e.g. Kamae and Kawabe, 2004; Koketsu *et al.*, 2004; Suzuki and Iwata, 2007; Wu *et al.*, 2008). The seismic moment of the mainshock estimated by the Global CMT project is $9.18 \times 10^{17} \text{ Nm}$ (M_w 5.9). Thus, assuming that most of the seismic moment was released from the SMGA, the stress drop of the SMGA was estimated to be 25 MPa based on the circular crack model (Eshelby, 1957; Brune 1970, 1971). If the actual seismic moment of the SMGA is smaller than the total seismic moment, then the stress drop in the SMGA would be lower than the above estimation of 25 MPa. The seismic moment of the EGF event (m_0) was estimated to be $3.16 \times 10^{14} \text{ Nm}$ from the flat level of the displacement spectra at the onshore rock sites (KIS and SMK). Using the estimated seismic moment of the EGF event, the seismic moment released from the SMGA could be estimated to be $M_0^{\text{SMGA}} = C \cdot N^3 \cdot m_0 = 8.25 \times 10^{17} \text{ (Nm)}$. Thus, the stress drop in the

226 SMGA would be 22.1 MPa, which is slightly smaller than the above estimation of
227 25 MPa.

228 The comparison between the observed and the simulated acceleration,
229 velocity, and displacement waveforms in the frequency range between 0.4 and 10
230 Hz at the target stations are shown in Figure 3, and Fourier spectra for those
231 waveforms are plotted in Figure 4. The synthetic waveforms adequately explain the
232 observed waveforms in a broad frequency range. In order to check the validity of
233 the obtained source model, synthetic ground motions were also computed for six
234 stations that were not used in the grid-search source modeling. These stations are
235 indicated by * in Figure 3. Because stations KME17, KME19, and KME20 are
236 relatively close to the epicenter, and located on soft sediments within the oceanic
237 basin, the observed waveforms at these stations might be affected by soil nonlinear
238 response, which was not included in our simulations. This could explain the
239 difference between recorded and simulated waveforms at these stations.

240 Figure 2(b) shows the distribution of the residual in the model parameters
241 space in which the grid search was conducted. The grid search was performed on a
242 total of 1,915,200 models obtained by changing five rupture model parameters. The
243 star in this figure represents the best model summarized in Table 1. The residual

distribution is smooth and has only one global minimum. In particular, the direction of rupture propagation was well constrained by the data because of the good azimuthal coverage with the offshore and onshore stations.

Discussions

Asano *et al.* (2014) investigated the relationship between the seismic moment and the size of the SMGA for past subduction-zone plate-boundary earthquakes along the Japan Trench in northeast Japan (Figure 3.9d in their paper). They compiled a database of SMGA parameters in northeast Japan from previous results (e.g., Kamae and Kawabe, 2004; Miyahara and Sasatani, 2004; Suzuki and Iwata, 2005, 2007; Takiguchi *et al.*, 2011; Asano and Iwata, 2012). The resulting SMGA for the M_w 5.9 event in the Nankai Trough is plotted with past subduction-zone plate-boundary earthquakes in northeast Japan in Figure 5. Inland crustal earthquakes in Japan analyzed and compiled by Miyake *et al.* (2003) and Miyakoshi *et al.* (2015) are also plotted in the same figure for comparing source characteristics among subduction-zone plate-boundary earthquakes and inland crustal earthquakes. As reported by Miyake *et al.* (2003), the size of the SMGA obtained by broadband strong motion simulations for inland crustal earthquakes (gray circles in Figure 5)

are consistent with the empirical source scaling relationship for the combined area of asperities proposed by Somerville *et al.* (1999). However, SMGAs for subduction-zone plate-boundary earthquakes along the Japan Trench in northeast Japan (black circles in Figure 5) are systematically smaller than those for Japanese inland crustal earthquakes (Asano *et al.*, 2014). In addition, SMGAs for subduction-zone plate-boundary earthquakes in northeast Japan are smaller than those indicated by the empirical scaling relationship between the combined area of asperities and seismic moment for subduction-zone plate-boundary earthquakes by Murotani *et al.* (2008). The SMGA is smaller than asperity or large slip area for subduction-zone plate-boundary earthquakes in northeast Japan, which is a significant source characteristic differentiating subduction-zone plate-boundary earthquakes in northeast Japan from inland crustal earthquakes in Japan. Previous studies suggested that the stress drop of the SMGA for subduction-zone plate-boundary earthquakes along the Japan Trench is larger than that of inland crustal earthquakes in Japan. Such source characteristics would cause strong short-period seismic wave radiations from particular areas of the source fault.

The size of the SMGA of the M_w 5.9 earthquake in the Nankai Trough is almost similar to those for past inland crustal earthquakes in Japan with similar

magnitude. Thus, our broadband ground motion modeling of this earthquake revealed different source characteristics from those of previous subduction-zone plate-boundary earthquakes along the Japan Trench in terms of generation of strong motions. This can be explained by the difference in the average characteristics of stress drop for the SMGA between the Nankai Trough and Japan Trench. Another possible reason is the depth dependency of the source rupture behavior (e.g., Bilek and Lay, 1998; Lay *et al.*, 2012) because the focal depth of this event (11 km) was within the depth range of inland crustal earthquakes, being much shallower than that of past subduction-zone plate-boundary earthquakes along the Japan Trench. Notably, this study investigated only one M_w 5.9 earthquake and a single case in the Nankai Trough. Therefore, it is likely that the results of this study are not representative of the general characteristics of the target area. Nevertheless, this work contributes to future improvements of ground motion prediction by also taking into consideration change in rupture characteristics between different subduction-zone regions in Japan. Future analysis using such ocean-bottom ground motion data would be necessary to obtain more universally applicable source characteristics for this area.

Conclusions

The SMGA source model of the 2016 M_W 5.9 (M_{JMA} 6.5) thrust-type earthquake in the Nankai Trough, offshore the Kii peninsula, southwest Japan was estimated on the basis of broadband strong ground motion waveform modeling using the empirical Green's function method. The model parameters for the SMGA were constrained by modeling broadband ground motion waveforms in the frequency range from 0.4 Hz to 10 Hz observed at offshore and onshore strong motion stations. The best estimate of SMGA size was 20.3 km², and its stress drop was approximately 22 MPa, which differs from that of past plate-boundary earthquakes with similar magnitude along the Japan trench, northeast Japan. This implies the possibility that the average source characteristics of plate-boundary events in the Nankai Trough are different from those along the Japan Trench. Although the results of this study were obtained for only a single case in the Nankai trough, they may provide important information for consideration of regional variations in source rupture characteristics. This will contribute to improvements of ground motion prediction for seismic hazard assessment of future megathrust earthquakes in Japan. Future studies on this topic using offshore and onshore ground motion data would be helpful to obtain more universal characteristics of source rupture behavior in this

subduction zone.

Data and Resources

The strong motion data used in this study were collected from the Dense Oceanfloor Network system for Earthquake and Tsunamis (DONET) jointly operated by the National Research Institute for Earth Science and Disaster Resilience (NIED) and Japan Agency for Marine-Earth Science and Technology (JAMSTEC), the Long-Term Borehole Monitoring System of JAMSTEC, the Full Range Seismograph Network (F-net) of NIED, and Disaster Prevention Research Institute (DPRI), Kyoto University. Data of DONET and F-net are available from the NIED Hi-net website at www.whinet.bosai.go.jp (last accessed on 14 January 2017). Data of LTBMS can be obtained from the JAMSTEC Ocean-bottom Seismology Database at join-web.jamstec.go.jp/join-portal/ (last accessed on 6 June 2016). The source models of the 1944 Tonankai earthquake were retrieved from SRCMOD website (Mai and Thingbaijam, 2014) at equake-rc.info/SRCMOD/ (last accessed on 10 May 2017). The Global Centroid Moment Tensor Project database was searched using www.globalcmt.org/CMTsearch.html (last accessed on 28 November 2017). The data source of topography and bathymetry data is JTOPO30v2, which is available

from the Japan Hydrographic Association. All figures were made using the Generic Mapping Tools version 5.4.1 (www.soest.hawaii.edu/gmt; Wessel *et al.*, 2013).

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References

- Ando, M. (1975). Source mechanism and tectonic significance of historical earthquakes along the Nankai trough, Japan, *Tectonophysics* **27**, 119–140, doi:10.1016/0040-1951(75)90102-X.
- Asano, K., and T. Iwata (2012). Source model for strong ground motion in 0.1–10

352 Hz during the 2011 Tohoku earthquake, *Earth Planets Space* **64**, 1111–1123,
 353 doi:10.5047/eps.2012.05.003.

354 Asano, K., T. Iwata, and K. Irikura (2003). Source characteristics of shallow
 355 intraslab earthquakes derived from strong-motion simulations, *Earth Planets*
 356 *Space* **55**, e5–e8, doi:10.1186/BF03351744.

357 Asano, K., H. Sekiguchi, T. Iwata, W. Suzuki, S. Aoi, and T. Kunugi (2014),
 358 Source process of the 2011 off the Pacific coast of Tohoku earthquake, in
 359 *Studies on the 2011 Off the Pacific Coast of Tohoku Earthquake* Hiroshi Kawase
 360 (Editor), Springer Japan, Tokyo, 17–36, doi:10.1007/978-4-431-54418-0_3.

361 Bilek, S. L., and T. Lay (1998). Variation of interplate fault zone properties with
 362 depth in the Japan subduction zone, *Science* **281**, 1175–1178,
 363 doi:10.1126/science.281.5380.1175.

364 Brune, J. N. (1970). Tectonic stress and the spectra of seismic shear waves from
 365 earthquakes, *J. Geophys. Res.* **75** 4997–5009, 1970,
 366 doi:10.1029/JB075i026p04997.

367 Brune, J. N. (1971). Correction, *J. Geophys. Res.* **76**, 5002, 1971,
 368 doi:10.1029/JB076i020p05002.

369 Ekström, G., M. Nettles, and A. M. Dziewonski (2012). The global CMT project

370 2004-2010: Centroid-moment tensors for 13,017 earthquakes, *Phys. Earth*
 371 *Planet. Inter.* **200–201**, 1–9, doi:10.1016/j.pepi.2012.04.002.
 372 Eshelby, J. D. (1957). The determination of the elastic field of an elliptical
 373 inclusion, and related problems, *Proc. Roy. Soc.* **A241**, 376–396,
 374 doi:10.1098/rspa.1957.0133.
 375 Hashimoto, M. and D. D. Jackson (1993). Plate tectonics and crustal deformation
 376 around the Japanese Islands, *J. Geophys. Res.* **98**, 16149–16166,
 377 doi:10.1029/93JB00444
 378 Ichinose, G. A., H. K. Thio, P. G. Somerville, T. Sato, and T. Ishii (2003).
 379 Rupture process of the 1944 Tonankai earthquake (M_S 8.1) from the inversion
 380 of teleseismic and regional seismograms, *J. Geophys. Res.* **108**, B10, 2497,
 381 doi:10.1029/2003JB002393.
 382 Irikura, K. (1986). Prediction of strong acceleration motions using empirical
 383 Green’s function, *Proc. 7th Japan Earthq. Eng. Symp.*, Tokyo, Japan, 151–156.
 384 Irikura, K., T. Kagawa, and H. Sekiguchi (1997). Revision of the empirical
 385 Green’s function method by Irikura (1986), *Prog. Abst. Seism. Soc. Japan*, **2**,
 386 B25 (in Japanese).
 387 Iwata, T., T. Kagawa, A. Petukhin, and Y. Onishi (2008). Basin and crustal

388 velocity structure models for the simulation of strong ground motions in the
 389 Kinki area, Japan, *J. Seism.* **12**, 223-234, doi:10.1007/s10950-007-9086-7.
 390 Kamae, K., and K. Irikura (1998). Source model of the 1995 Hyogo-ken Nanbu
 391 earthquake and simulation of near-source ground motion, *Bull. Seism. Soc. Am.*
 392 **88**, 400–412:
 393 Kamae, K., and H. Kawabe (2004). Source model composed of asperities for the
 394 2003 Tokachi-oki, Japan, earthquake ($M_{JMA} = 8.0$) estimated by the empirical
 395 Green's function method, *Earth Planets Space* **56**, 323–327,
 396 doi:10.1186/BF03353059.
 397 Kaneda Y., K. Kawaguchi, E. Araki, H. Matsumoto, T. Nakamura, S. Kamiya, K.
 398 Ariyoshi, T. Hori, T. Baba, and N. Takahashi (2015). Development and
 399 application of an advanced ocean floor network system for megathrust
 400 earthquakes and tsunamis, in *Seafloor Observatories: A New Vision of the*
 401 *Earth from Abyss* Paolo Favali, Laura Beranzoli, and Angelo De Santis
 402 (Editors), Springer-Verlag, Berlin Heidelberg, 643–662, doi:10.1007/978-3-
 403 642-11374-1_25.
 404 Kawabe, H., and K. Kamae (2013). Source modeling of the 2011 off the Pacific
 405 coast of Tohoku earthquake, *J. Jpn Assoc. Earthq. Eng.* **13**(2), 75–87,

doi:10.5610/jaee.13.2_75 (in Japanese with English abstract).

Kikuchi, M., M. Nakamura, and K. Yoshikawa (2003). Source rupture process of the 1944 Tonankai earthquake and the 1945 Mikawa earthquake derived from low-gain seismograms, *Earth Planets Space* **55**, 159–172, doi:10.1186/BF03351745.

Koketsu, K., K. Hikima, and S. Miyazaki (2004). Joint inversion of strong motion and geodetic data for the source process of the 2003 Tokachi-oki, Hokkaido, earthquake, *Earth Planets Space* **56**, 329–334, doi:10.1186/BF03353060.

Kurahashi, S., K. Masaki, and K. Irikura (2008). Source model of the 2007 Noto-Hanto earthquake (M_w 6.7) for estimating broad-band strong ground motion, *Earth Planets Space* **60**, 89–94, doi:10.1186/BF03352766.

Kurahashi, S., and K. Irikura (2010). Characterized source model for simulating strong ground motions during the 2008 Wenchuan earthquake, *Bull. Seism. Soc. Am.* **100**, 2450–2475, doi:10.1785/0120090308.

Kurahashi, S., and K. Irikura (2013). Short-period source model of the 2011 M_w 9.0 off the Pacific coast of Tohoku earthquake, *Bull. Seism. Soc. Am.* **103**, 1317–1393, doi:10.1785/0120120157.

Lay, T., H. Kanamori, C. J. Ammon, K. D. Koper, A. R. Hutko, L. Ye, H. Yue, and

424 T. M. Rushing (2012). Depth-varying rupture properties of subduction zone
 425 megathrust faults, *J. Geophys. Res.* **117**, B04311, doi:10.1029/2011JB009133.
 426 Maeda, T., M. Ichiyanagi, H. Takahashi, R. Honda, T. Yamaguchi, M. Kasahara,
 427 and T. Sasatani (2008). Source parameters of the 2007 Noto Hanto earthquake
 428 sequence derived from strong motion records at temporary and permanent
 429 stations, *Earth Planets Space* **60**, 1011–1016, doi:10.1186/BF03352861.
 430 Maeda, T., and T. Sasatani (2009). Strong ground motions from an M_j 6.1 inland
 431 crustal earthquake in Hokkaido, Japan: the 2004 Rumoi earthquake, *Earth*
 432 *Planets Space* **61**, 689–701, doi:10.1186/BF03353177.
 433 Maeda, T., A. Iwaki, N. Morikawa, S. Aoi, and H. Fujiwara (2016). Seismic-hazard
 434 analysis of long-period ground motion of megathrust earthquakes in the Nankai
 435 trough based on 3D finite-difference simulation, *Seism. Res. Lett.* **87**, 1265–
 436 1273, doi:10.1785/0220160093.
 437 Mai, P. M., and K. K. S. Thingbaijam (2014). SRCMOD: An online database of
 438 finite-fault rupture models, *Seism. Res. Lett.* **85**, 1348–1357,
 439 doi:10.1785/0220140077.
 440 Miyahara, S., and T. Sasatani (2004). Estimation of source process of the 1994
 441 Sanriku Haruka-oki earthquake using empirical Green’s function method,

442 *Geophys. Bull. Hokkaido Univ.* **67**, 197–212. (in Japanese with English abstract)
 443 Miyake, H., T. Iwata, and K. Irikura (1999). Strong ground motion simulation and
 444 source modeling of the Kagoshima-ken Hokuseibu earthquakes of March 26
 445 (M_{JMA} 6.5) and May 13 (M_{JMA} 6.3), 1997, using empirical Green's function
 446 method, *Zisin 2 (J. Seism. Soc. Jpn.)* **51**, 431–442,
 447 doi:10.4294/zisin1948.51.4_431. (in Japanese with English abstract)
 448 Miyake, H., T. Iwata, and K. Irikura (2003). Source characterization for broadband
 449 ground-motion simulation: Kinematic heterogeneous source model and strong
 450 motion generation area, *Bull. Seism. Soc. Am.* **93**, 2531–2545,
 451 doi:10.1785/0120020183.
 452 Miyake, H., K. Koketsu, and T. Furumura (2008). Source modeling of subduction-
 453 zone earthquakes and long-period ground motion validation in the Tokyo
 454 metropolitan area, *Proc. Fourteenth World Conf. Earthq. Eng.*, Beijing, China,
 455 paper no. S10-012.
 456 Miyakoshi, K., K. Irikura, and K. Kamae (2015). Re-examination of scaling
 457 relationships of source parameters of the inland crustal earthquakes in Japan
 458 based on the waveform inversion of strong motion data, *J. Jpn. Assoc. Earthq.*
 459 *Eng.* **15**(7), 141–156, doi:10.5610/jaee.15.7_141. (in Japanese with English

460 abstract)

461 Murotani, S., H. Miyake, and K. Koketsu (2008). Scaling of characterized slip
462 models for plate-boundary earthquakes, *Earth Planets Space* **60**, 987–991,
463 doi:10.1186/BF03352855.

464 Oth, A., F. Wenzel, and M. Radulian (2007). Source parameters of intermediate-
465 depth Vrancea (Romania) earthquakes from empirical Green's functions
466 modeling, *Tectonophysics* **438**, 33–56, doi:10.1016/j.tecto.2007.02.016.

467 Poiata, N., and H. Miyake (2017). Broadband ground motion simulation of the
468 2004 and 1977 Vrancea, Romania, earthquakes using the empirical Green's
469 function method, *Pure Appl. Geophys.* **174**, 3503–3519, doi:10.1007/s00024-
470 017-1605-z.

471 Poiata, N., K. Koketsu, A. Vuan, and H. Miyake (2012). Low-frequency and
472 broad-band source models of the 2009 L'Aquila, Italy, earthquake, *Geophys. J.*
473 *Int.* **191**, 224–242, doi:10.1111/j.1365-246X.2012.05602.x.

474 Ramírez-Gaytán, A., J. Aguirre, C. I. Huerta-López, and R. Vazquez-Rosas (2010).
475 Simulation of accelerograms, peak ground accelerations, and MMI for the
476 Tecomán earthquake of 21 January 2003, *Bull. Seism. Soc. Am.* **100**, 2163–2173,
477 doi:10.1785/0120090053.

478 Riahi, A., H. Sadeghi, and S. K. Hosseini (2015). Simulation of 2003 Bam (Iran)
 479 earthquake using empirical Green's function method via very small and near-
 480 fault events, *Geophys. J. Int.* **201**, 1264–1286, doi:10.1093/gji/ggv074.

481 Satoh, T. (2012). Source modeling of the 2011 off the Pacific coast of Tohoku
 482 earthquake using empirical Green's function method –From the viewpoint of
 483 the short period spectral level of interplate earthquakes–, *J. Struct. Constr.*
 484 *Eng., AIJ* **77**, 695–704, doi:10.3130/aijs.77.695. (in Japanese with English
 485 abstract)

486 Sekiguchi, H., M. Yoshimi, H. Horikawa, K. Yoshida, S. Kunitatsu, and K.
 487 Satake (2008). Prediction of ground motion in the Osaka sedimentary basin
 488 associated with the hypothetical Nankai earthquake, *J. Seism.* **12**, 185–195,
 489 doi:10.1007/s10950-007-9077-8.

490 Seno, T., S. Stein, and A. E. Gripp (1993). A model for the motion of the
 491 Philippine Sea Plate consistent with NUVEL-1 and geological data, *J. Geophys.*
 492 *Res.* **98**, 17941–17948, doi:10.1029/93JB00782.

493 Shiba, Y., and H. Sato (2007). Source and path characteristics of earthquakes
 494 occurring off the Kii peninsula, *CRIEPI Research Report*, N07007, 22pp.

495 Suzuki, W. and T. Iwata (2005). Source characteristics of interplate earthquakes in

496 northeast Japan inferred from the analysis of broadband strong-motion records,
 497 *Eos Trans. Am. Geophys. Union* **86**(52), Fall Meet. Suppl., Abstract S43A-1040.
 498 Suzuki, W. and T. Iwata (2006). Source model of the 2005 west off Fukuoka
 499 prefecture earthquake estimated from the empirical Green's function simulation
 500 of broadband strong motions, *Earth Planets Space* **58**, 99–104,
 501 doi:10.1186/BF03351921.
 502 Suzuki, W., and T. Iwata (2007). Source model of the 2005 Miyagi-oki, Japan,
 503 earthquake estimated from broadband strong motions, *Earth Planets Space* **59**,
 504 1155–1171, doi:10.1186/BF03352063.
 505 Takiguchi, M., K. Asano, and T. Iwata (2011). The comparison of source models of
 506 repeating subduction zone earthquakes estimated using broadband strong
 507 motion records –1982 and 2008 Ibarakiken-oki M7 earthquakes–, *Zisin 2* (J.
 508 Seismol. Soc. Japan) **63**, 223–242, doi:10.4294/zisin.63.223. (in Japanese with
 509 English abstract)
 510 Wallace, L. M., E. Araki, D. Saffer, X. Wang, A. Roesner, A. Kopf, A. Nakanishi,
 511 W. Power, R. Kobayashi, C. Kinoshita, S. Toczko, T. Kimura, Y. Machida, and
 512 S. Carr (2016). Near-field observations of an offshore Mw 6.0 earthquake from
 513 an integrated seafloor and subseafloor monitoring network at the Nankai

514 Trough, southwest Japan, *J. Geophys. Res.* **121**, 8338–8351,
515 doi:10.1002/2016JB013417.

516 Wen, Y.-Y., H. Miyake, Y.-T. Yen, K. Irikura, and K.-E. Ching (2014). Rupture
517 directivity effect and stress heterogeneity of the 2013 Nantou blind-thrust
518 earthquakes, Taiwan, *Bull. Seism. Soc. Am.* **104**, 2933–2942,
519 doi:10.1785/0120140109.

520 Wen, Y.-Y., S.-Y. Chao, Y.-T. Yen, and S. Wen (2017). Source characteristics of
521 moderate-to-strong earthquakes in the Nantou area, Taiwan: insight from strong
522 ground motion simulations, *Earth Planets Space* **69**:132, doi:10.1186/s40623-
523 017-0720-5.

524 Wessel, P., W. H. F. Smith, R. Scharroo, J. F. Luis, and F. Wobbe (2013). Generic
525 Mapping Tools: Improved version released, *Eos Trans. Am. Geophys. Union*
526 **94**(45), 409–413, doi: 10.1002/2013EO450001.

527 Wu, C., K. Koketsu, and H. Miyake (2008). Source processes of the 1978 and 2005
528 Miyagi-oki, Japan earthquakes: Repeated rupture of asperities over successive
529 large earthquakes, *J. Geophys. Res.* **113**, B08316, doi:10.1029/2007JB005189.

530 Xia, C., B. Zhao, M. Horike, and T. Kagawa (2015). Strong ground simulations of
531 the M_w 7.9 Wenchuan earthquake using the empirical Green’s function method,

532 *Bull. Seism. Soc. Am.* **105**, 1383–1397, doi:10.1785/0120140001.

533 Yamamoto, Y., and H. Takenaka (2009). Source modeling of the 2007 Niigataken

534 Chuetsu-oki earthquake using the empirical Green’s function method, *Zisin 2*

535 (J. Seismol. Soc. Japan) **62**, 47–59, doi:10.4294/zisin.62.137. (in Japanese with

536 English abstract)

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545 **Table 1** Search range, grid interval, and estimated value of model parameters in
546 the grid search

	Search range	Interval	Estimated value
Length L (km)	0.8–14.0	0.1	4.5
Rise time τ (s)	0.08–1.2	0.08	0.32
Rupture starting subfault in strike direction NSL	1–8	1	6
Rupture starting subfault in dip direction NSW	1–8	1	3
Rupture velocity V_r (km/s)	2.2–3.6	0.1	3.3

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List of Figure Captions

Figure 1. Map showing the studied area. The rectangle indicated by dotted lines in the left panel corresponds to the geographical area drawn in the right panel. The stars represent the epicenters of the mainshock of the 2016 offshore the Kii peninsula earthquake (open star) and the EGF event (solid star) located by Wallace *et al.* (2016). The moment tensor solution by the Global CMT Project (lower hemisphere projection) is shown inside the left panel. Brown and magenta contours represent the slip distributions of the 1944 Tonankai earthquake estimated by Kikuchi *et al.* (2003) and Ichinose *et al.* (2003), respectively. The blue, red, and black triangles indicate seafloor (DONET), ocean-bottom borehole (LTBMS), and inland broadband seismic stations, respectively.

Figure 2. (a) Observed source spectral ratios between the target and EGF events at each strong motion station (thin gray lines) and average observed source spectral ratio (thick line). The red curve represents the theoretical source spectral ratio based on the ω^{-2} source model for the best estimate. The solid and open triangles indicate the corner frequency of the target and EGF events, respectively. (b) Distribution of

residual values obtained by the grid search method. The star indicates the best estimate. (c) Schematic illustration of the obtained SMGA source model. The solid star indicates the rupture starting point.

Figure 3. Comparison between observed (gray) and synthetic (black) acceleration, velocity, and displacement waveforms in the frequency range 0.4–10 Hz. Two horizontal components are shown. The stations with asterisk were not used in source modeling by the grid search.

Figure 4. Comparison between the Fourier amplitude spectra of the observed (gray) and simulated acceleration waveforms (black).

Figure 5. Scaling relationship between the SMGA and total seismic moment. The star represents the M_W 5.9 event in the Nankai Trough analyzed in this study. The black and gray circles indicate past subduction-zone plate-boundary earthquakes and inland crustal earthquakes in Japan, respectively. The solid lines show the empirical scaling relationship of the combined area of asperity by Murotani *et al.* (2008) for subduction-zone plate-boundary earthquakes and Somerville *et al.* (1999)

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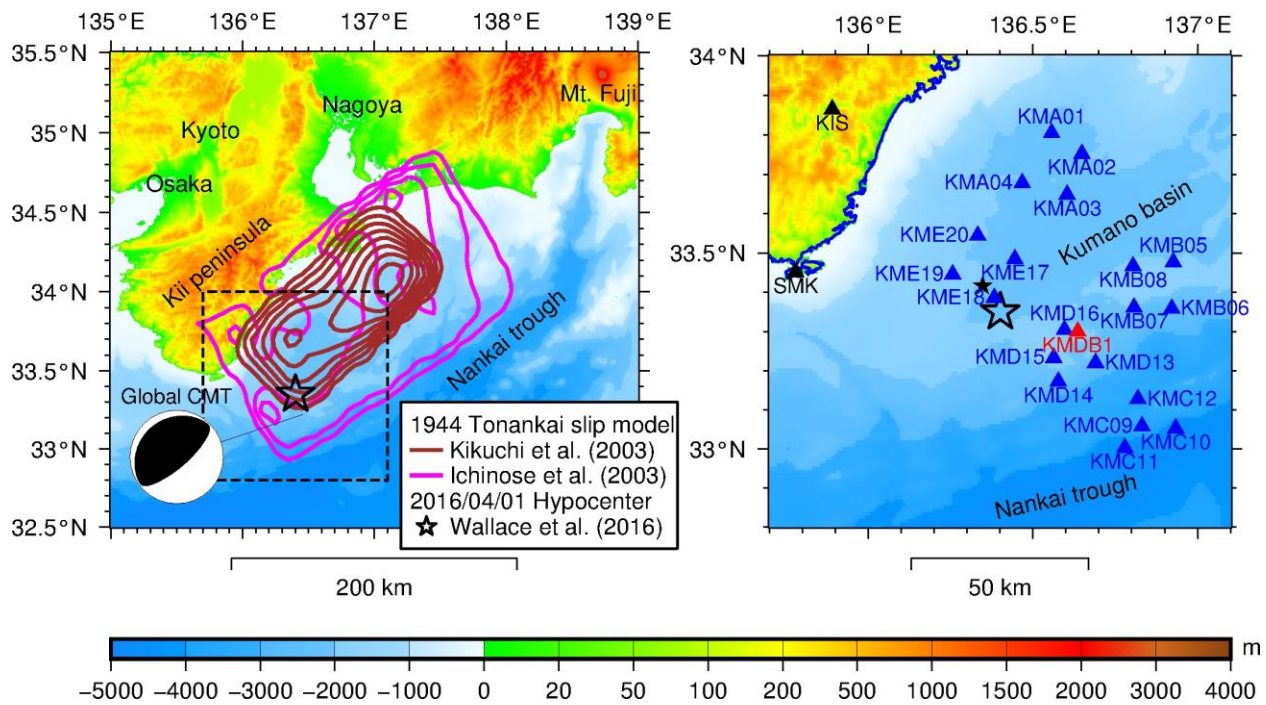


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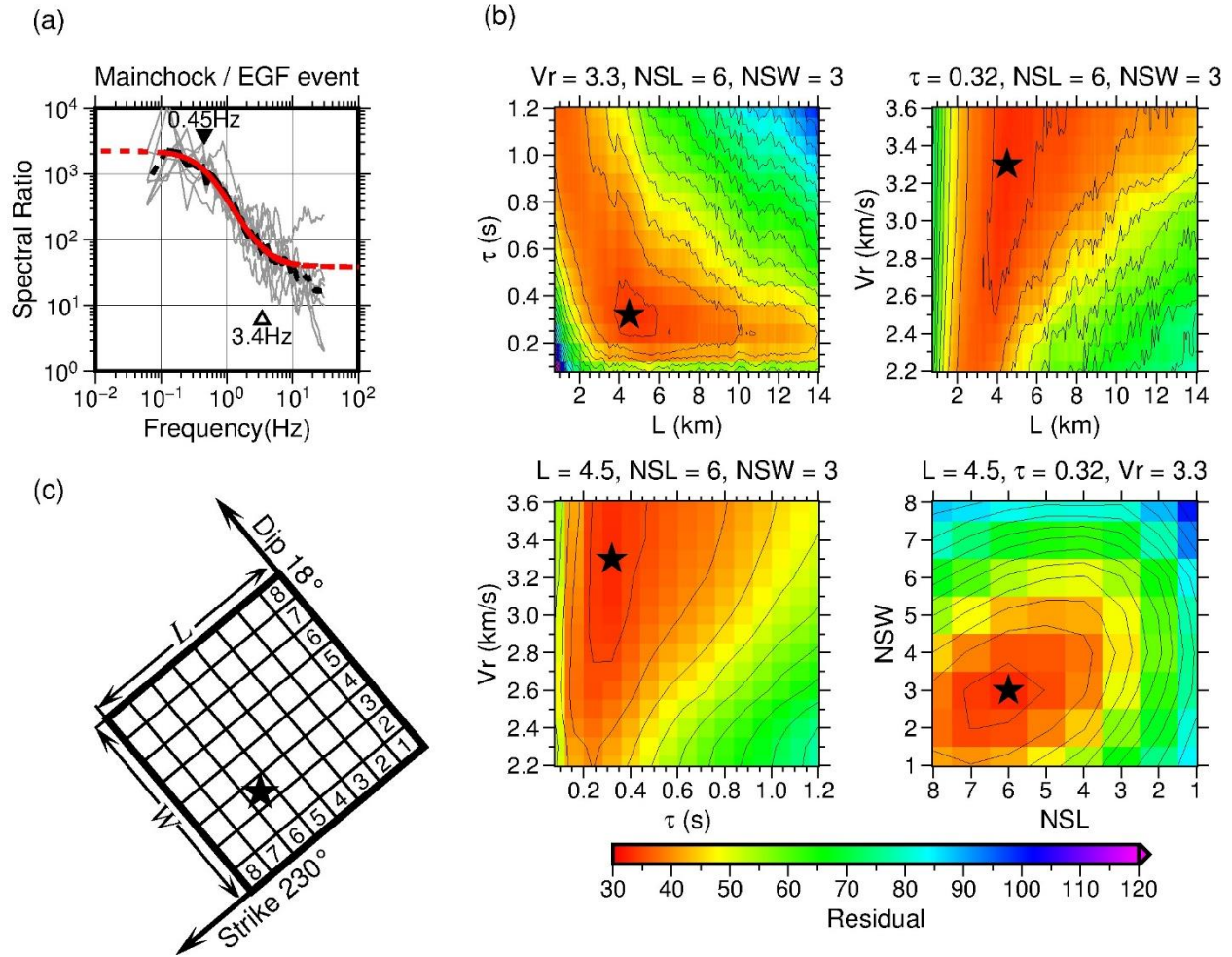
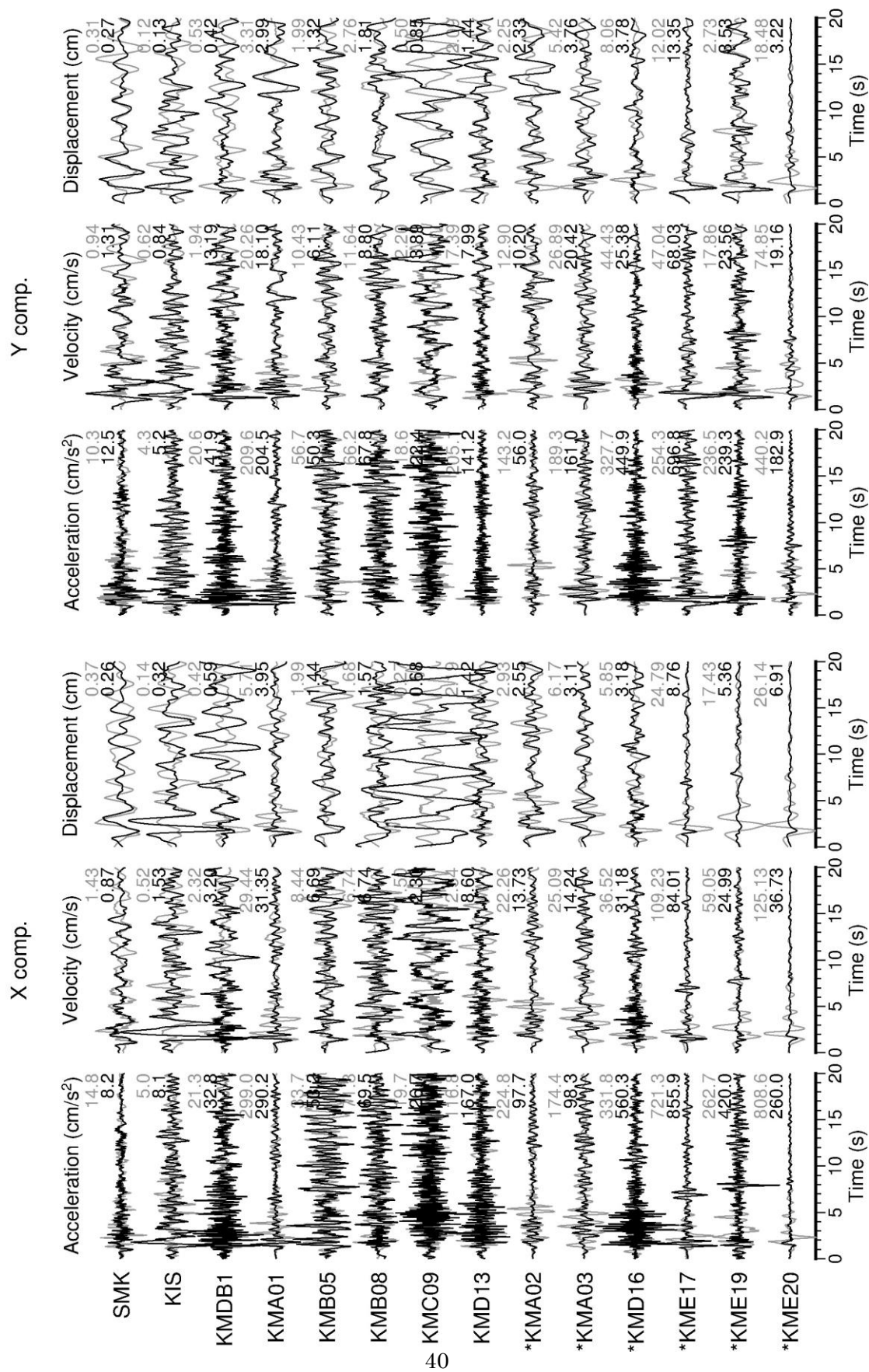
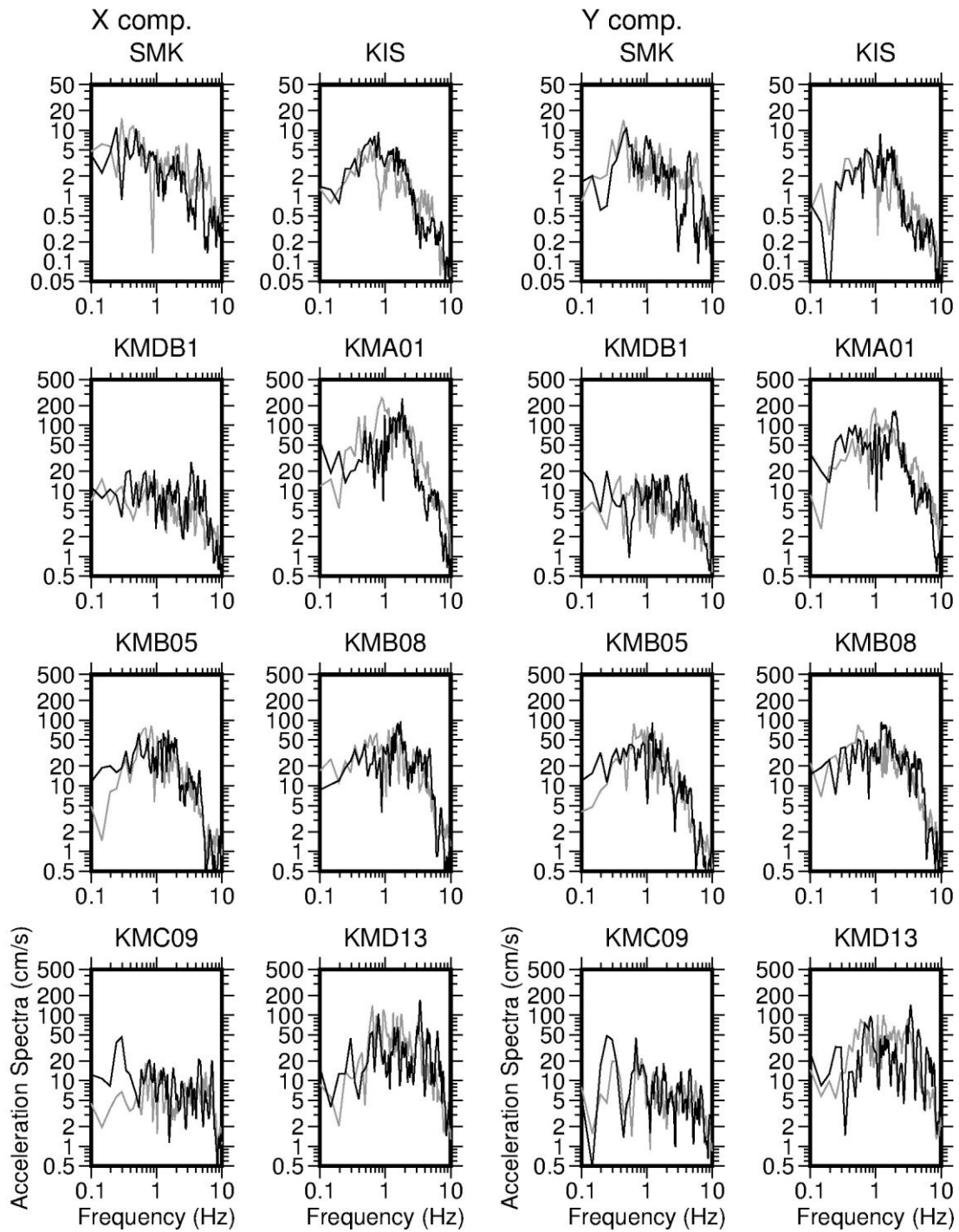


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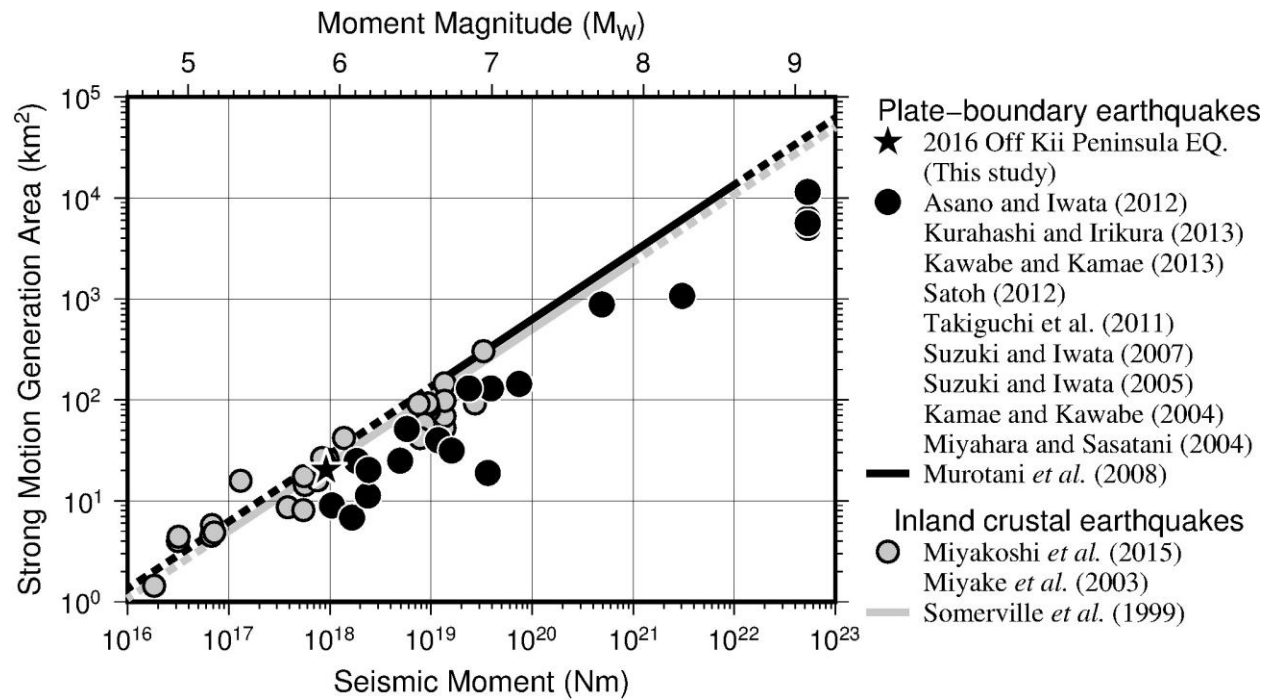


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