Supplementary Materials to "The Impact of Three-Dimensional Structure of Subduction Zone on Time-dependent Crustal Deformation Measured by HR-GNSS"

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S1. GMSH fault geometry

We use GMSH, a 3-D finite element mesh generator (Geuzaine and Remacle, 2009) to generate a triangular mesh for the Kuril region of the Japan trench with the Slab2.0 datasets (Fig. S1). The mesh contains 4409 subfaults with depths ranging from 10 to 80 km. The area of each subfault varies from 0.67 to 167.3 km^2 but averages 57.4 km^2. The smaller subfaults are to accommodate the curvature of the Japan trench. We output the mesh in two files needed by FakeQuakes ("Japan_trench.fault" and "Japan_trench.mshout"). The "Japan_trench.fault" file contains important parameters such as the latitude, longitude, depth, strike, dip, length, width, and area of each subfault. The "Japan_trench.mshout" file contains the coordinate of the centroid of each subfault including the coordinate of the nodes. The mesh files are available on Zenodo (https://doi.org/10.5281/zenodo.7765170).

S2. Creating rfile

The unified 3D velocity model of Japan is a rfile (about 34 Gb size) spanning lateral extent of latitude from 30° to 47° North (~2040 km) and longitude from 129° to 147° East (~1440 km). The model maintains the 23 layers in the original 3D Japan Integrated Velocity Structure Model (Koketsu et al., 2008, 2009), each with constant P- and S-wave velocities (Vp and Vs), density (ρ) and P- and S-wave quality factors (Qp and Qs) (Table S3). The rfile has 5 blocks with a constant horizontal spacing (hh) of 1 km, but the vertical grid spacing (hv) increases with depth. The rfile is available on Zenodo (https://doi.org/10.5281/zenodo.7765170).

The blocks information of the rfile are as follows:

1. Block 1: Topography/bathymetry (hv = no vertical spacing; hh = 1 km)
2. Block 2: -4 km to 30 km depth (hv = 200 m; hh= 1 km). The depth range of this block is large enough to contain the highest point in topography and the lowest point in bathymetry.
3. Block 3: 30 to 70 km (hv = 300 m; hh= 1 km)
4. Block 4: 70 to 100 km (hv = 400 m; hh= 1km)
5. Block 5: 100 to 200 km (hv = 500 m; hh= 1 km)

S3. Choosing the Grid spacing (h)

The choice of grid spacing is very important in SW4 as it determines the maximum frequency the model can resolve. It is related to the minimum shear wave velocity in the domain by $h=minVs/(PPW\times f_{max})$; where minVs is the minimum shear wave velocity, PPW is the Point Per Wavelength and f_{max} is the maximum frequency in the simulation. According to SW4 manual, the recommendation is that the PPW must be at least 8 for stable wave solutions. If we use a maximum frequency of 0.5 Hz while minimum Vs in the 3D velocity model is 350 m/s, h is 87.5m. Based on the size of the domain geometry, this grid spacing will make the computational cost very expensive.

We increase the minimum shear wave velocity to 1200 m/s based on the average Vs in the upper 400 km in the 3D structure to decrease the computational cost and memory usage. Using this minimum Vs gives h of 600 m and 300 m for 0.25 Hz and 0.50 Hz simulation, respectively. We use ‘refinement’ command in SW4 to increase the grid spacing with depth to reduce computational cost since the velocity increases with depth and the velocity model becomes more homogeneous with depth.

To maintain similar PPW for each block in the block boundary, we plot a profile of the Vs at different points in the 3D structure to determine optimal location of the block boundaries, usually where the minVs doubles (Fig. S5). The figure shows that the minVs increases to about 2800 m/s below 25 km and stays constant with depth to 200 km depth. This is due to the lower velocity value of the subducting slab compares with the surrounding higher velocity rocks with depth. We setup refinement level at 75 depth. For the 0.50 Hz simulations, for example, we use a curvilinear mesh of 300 m grid size in the upper 30 km depth, and Cartesian mesh below 30 km with a grid spacing of 300 m in the upper 30 – 75 km depth and 600 m from 75-200 km depth.

Supplementary Figures

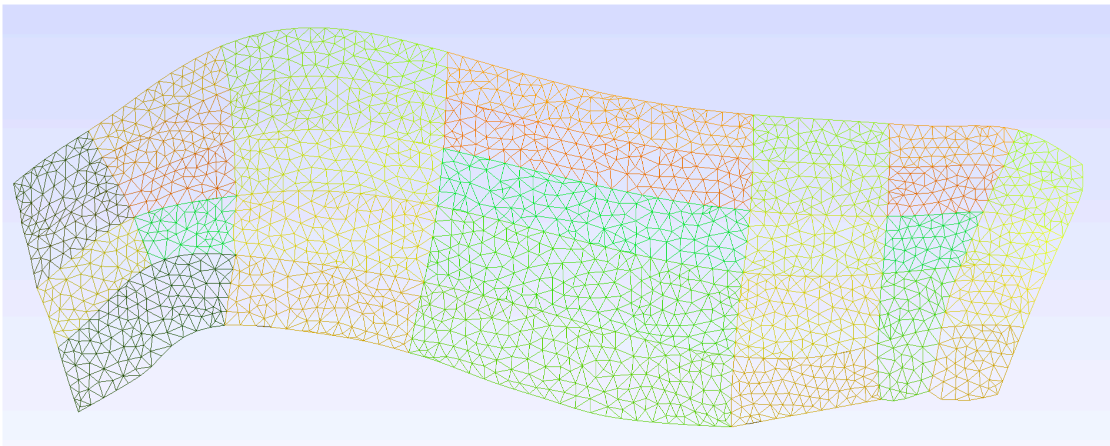

Fig. S1: Fault mesh of the Slab 2.0 model of Kuril region of the Japan Trench using GMSH. Each triangle shows the subfaults and the different colors show the partition of the Japan Trench for determining regular and undistorted mesh, but do not have any geological inference.

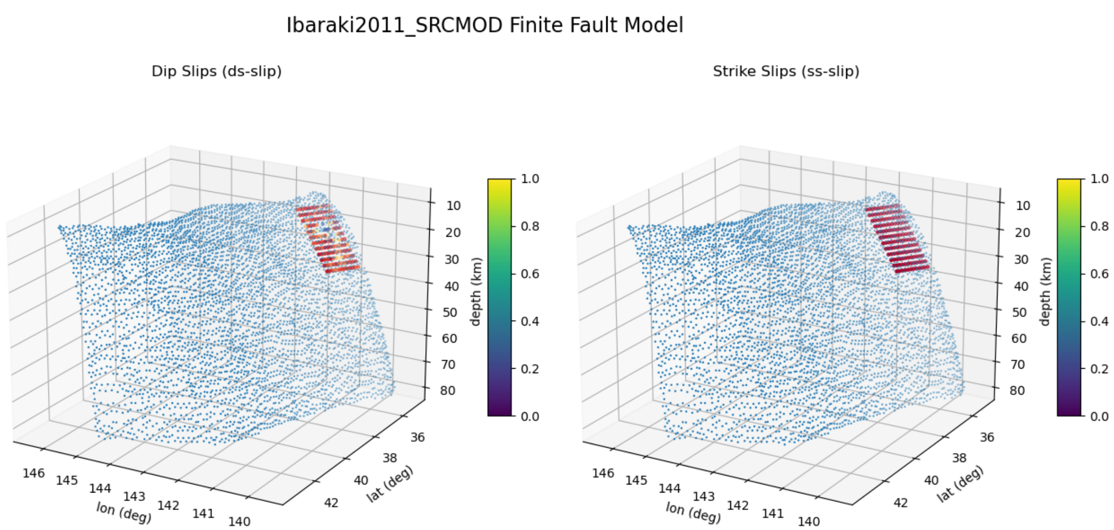

Fig. S2: Mapping of the planar Ibaraki 2011 SRCMOD rupture (Kubo et al., 2013) on the non-planar Japan trench geometry from Slab 2.0 model. Blue dots represent the location of the center of each subfault outlining the Japan Trench while the square pattern regions in the two subplots show the dip and strike slips of the Ibaraki 2011 SRCMOD rupture model, respectively.

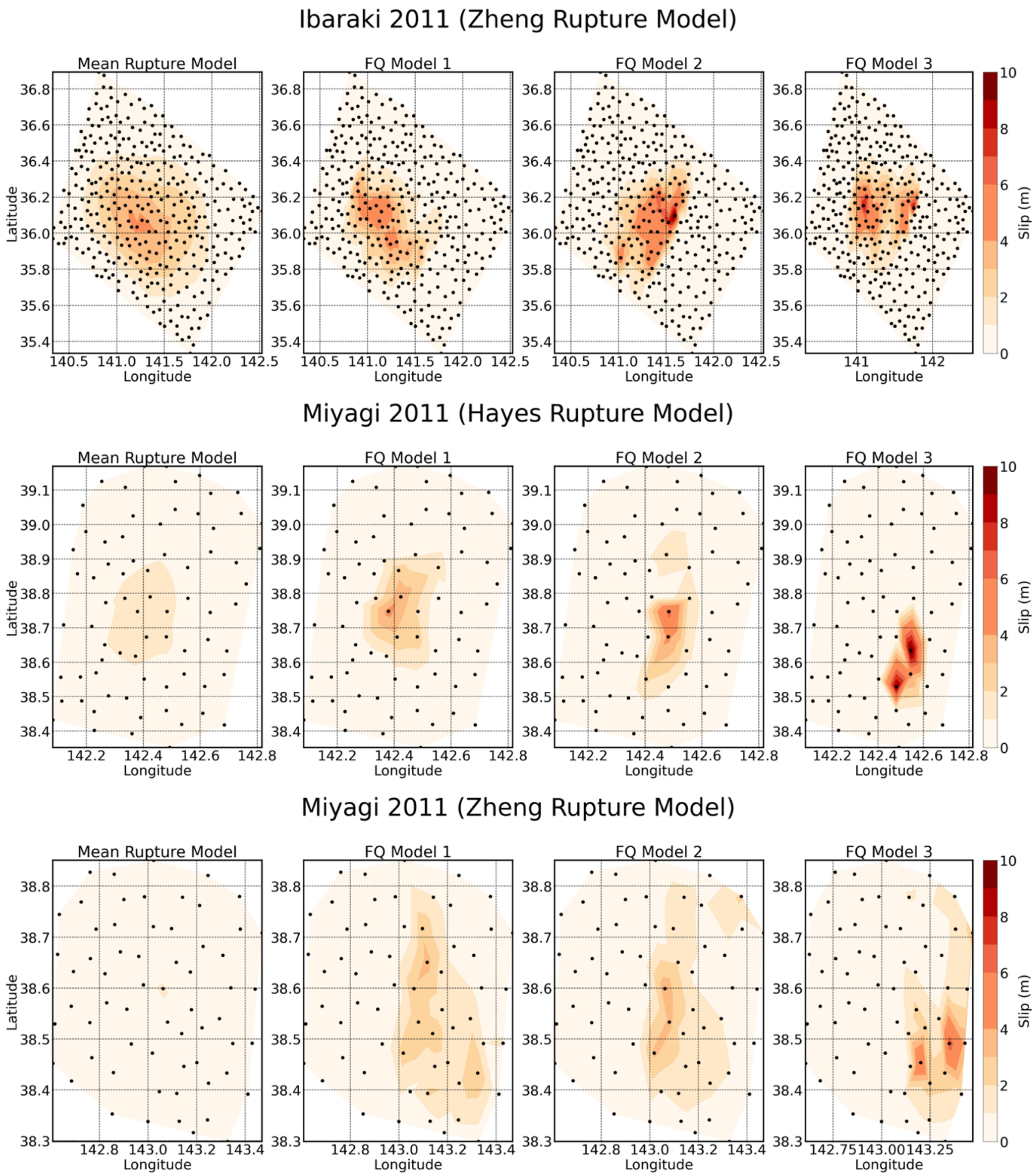

Fig. S3: Mean rupture model for Ibaraki 2011 (Zheng model), Miyagi 2011 (Hayes and Zheng models), and three examples of the 100 FakeQuake random realization of the mean models. The color indicates the amount of slip per subfault, and the black dots signify the center of each subfault. The slip is bigger overall in the FakeQuake models compared to the mean slip model in the top left to conserve the moment release in response to the change in rigidity at the subfault locations compared to the one used to generate the mean slip model.

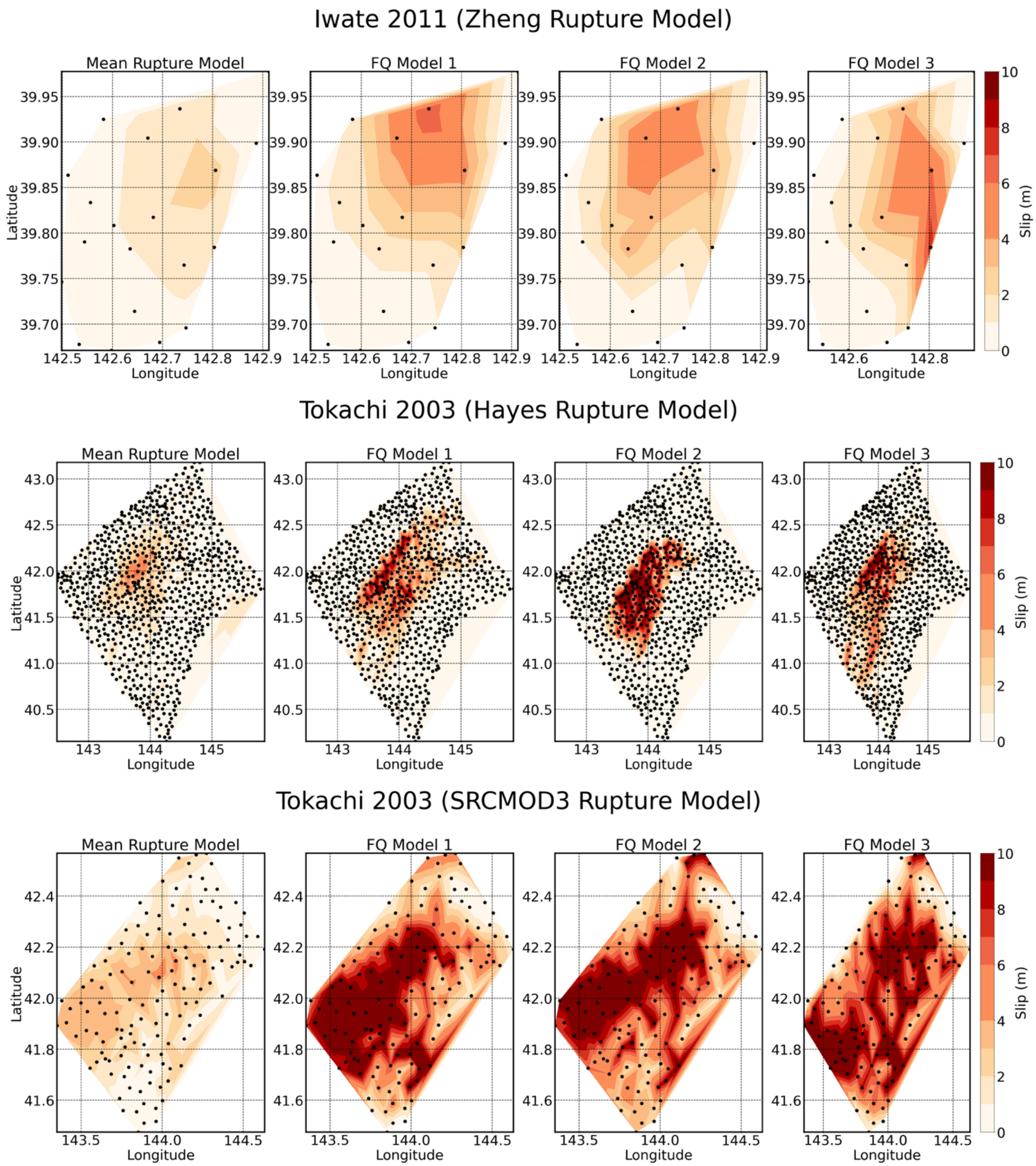

Fig. S4: Same as Figure S3, but for Iwate 2011 (Zheng model), Tokachi 2003 (Hayes and SRCMOD models).

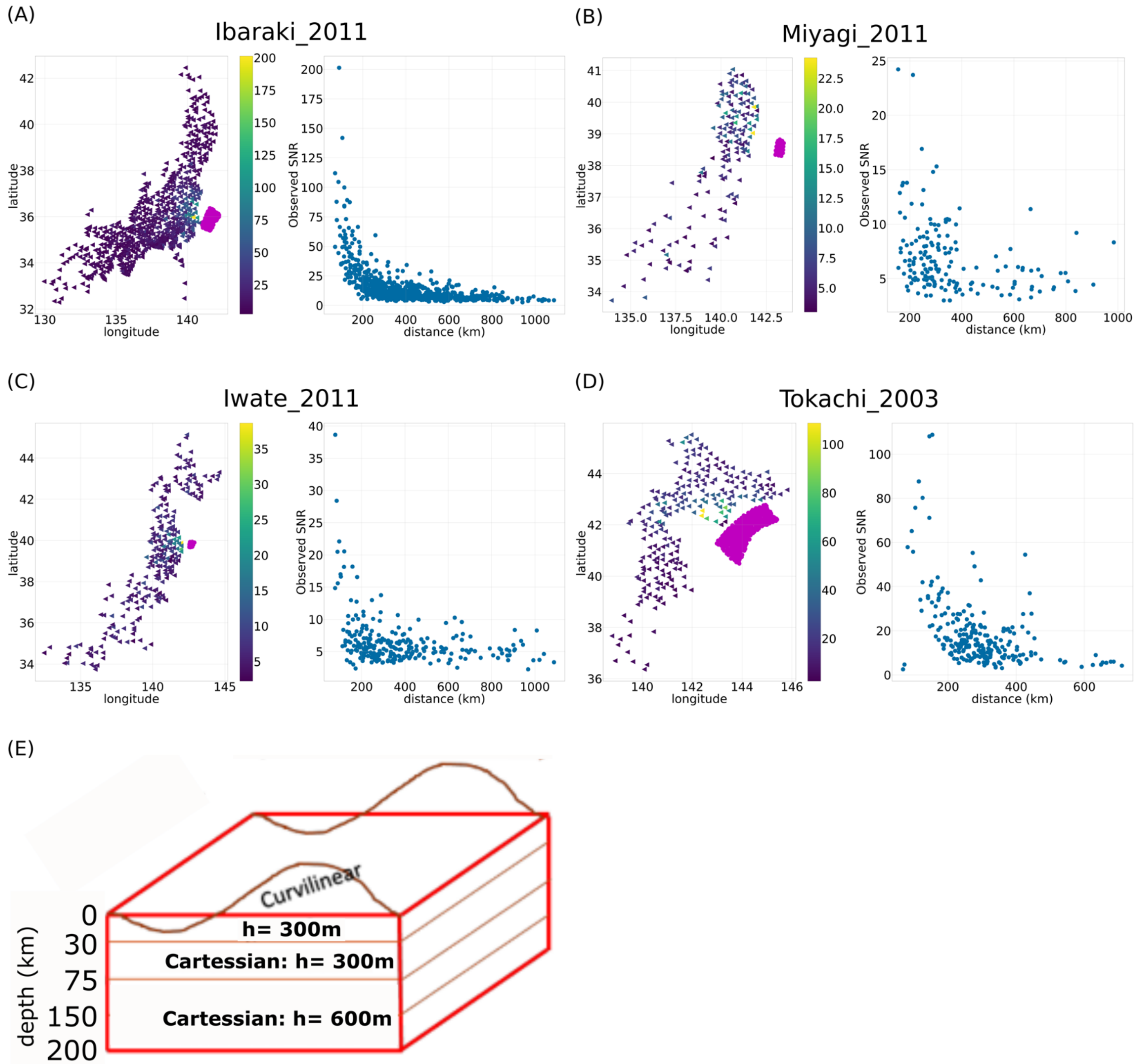

Fig. S5: SW4 domain for the 0.50 Hz simulations showing the (A-D) selected GNSS stations (colored by the observed signal-to-noise ratio) and surface-projection of the FakeQuake ruptures for each earthquake, and the observed Signal-to-Noise ratio (SNR) with distance. Figure S5E shows the domain geometry showing the grid spacing, the refinement layer and types of mesh used in the simulations. We used a curvilinear mesh for the topography/ bathymetry to a depth of 30 km, and cartesian mesh below 30 km with 300 m grid spacing from 30-75 km depth, and 600 m from 75 – 200 km depth.

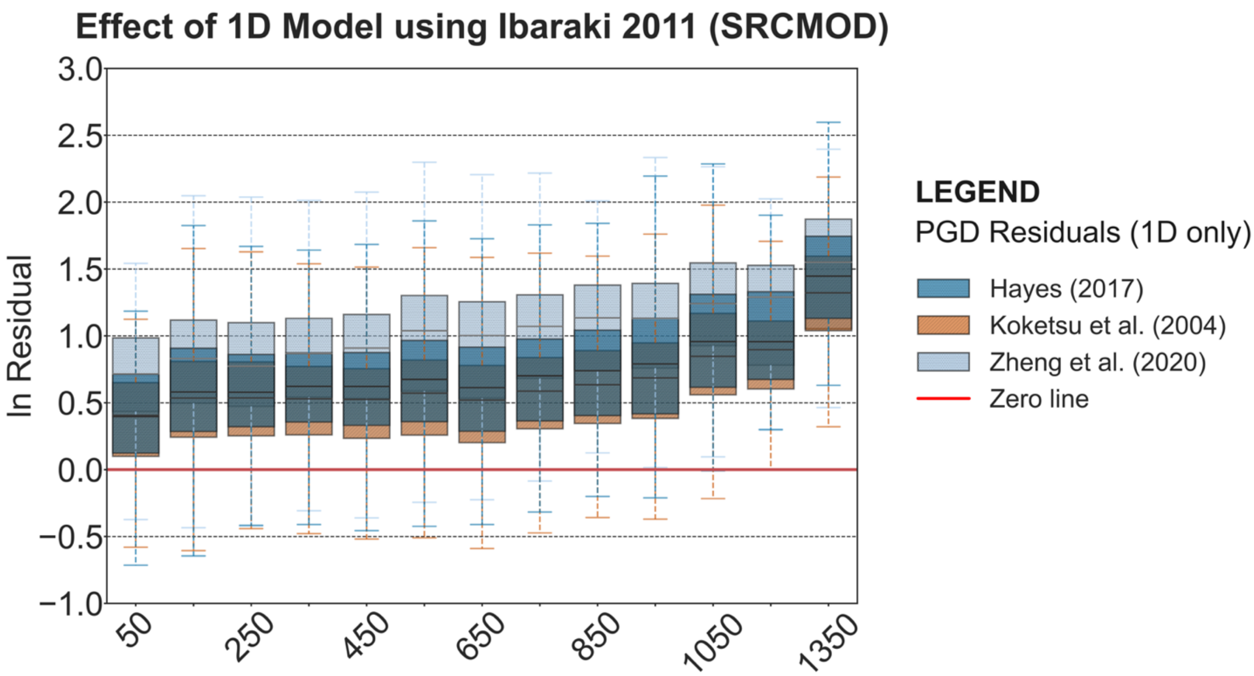

Figure S6: Effect of the choice of 1D velocity model used for the 1D simulations on PGD residuals using three 1D velocity models used by two other researchers: Zheng et al. (2020) and Koketsu et al. (2004). On each boxplot, residuals for each model are shown as patterned box and whisker plots. The blue, orange and light blue boxplots represent the PGD residuals for Hayes (20017), Koketsu et al. (2014) and Zheng et al. (2020) studies, respectively. The red horizontal line represents the zero residual line.

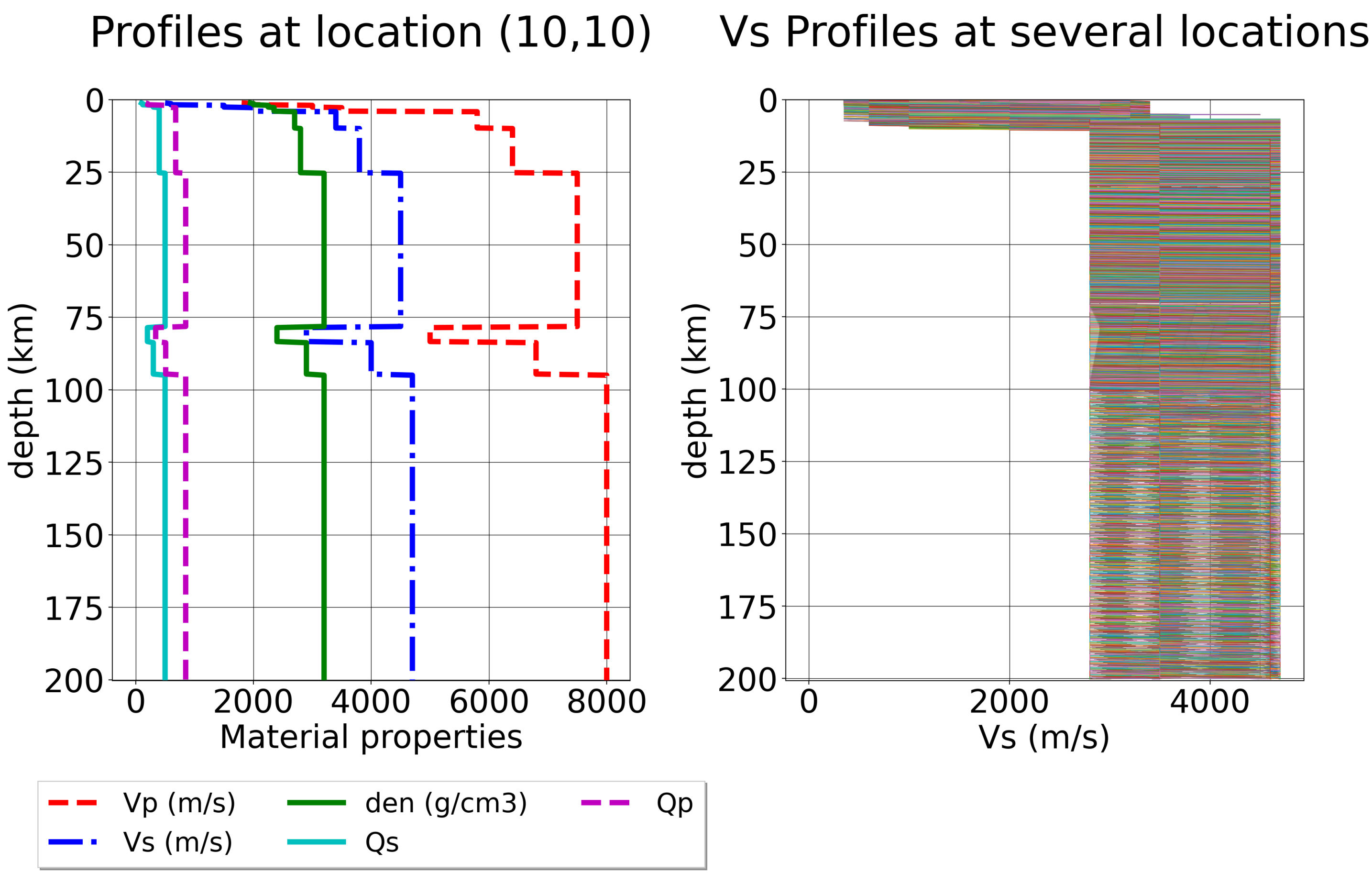

Fig. S7: (left) Profiles of the material properties at location x=10 km and y= 10 km in the 3D Japan Integrated Velocity Structure Model (Koketsu et al., 2008, 2009), while (right) shows all the Vs profiles at different locations within the 3D structure showing the variation of minimum shear wave velocity with depth.

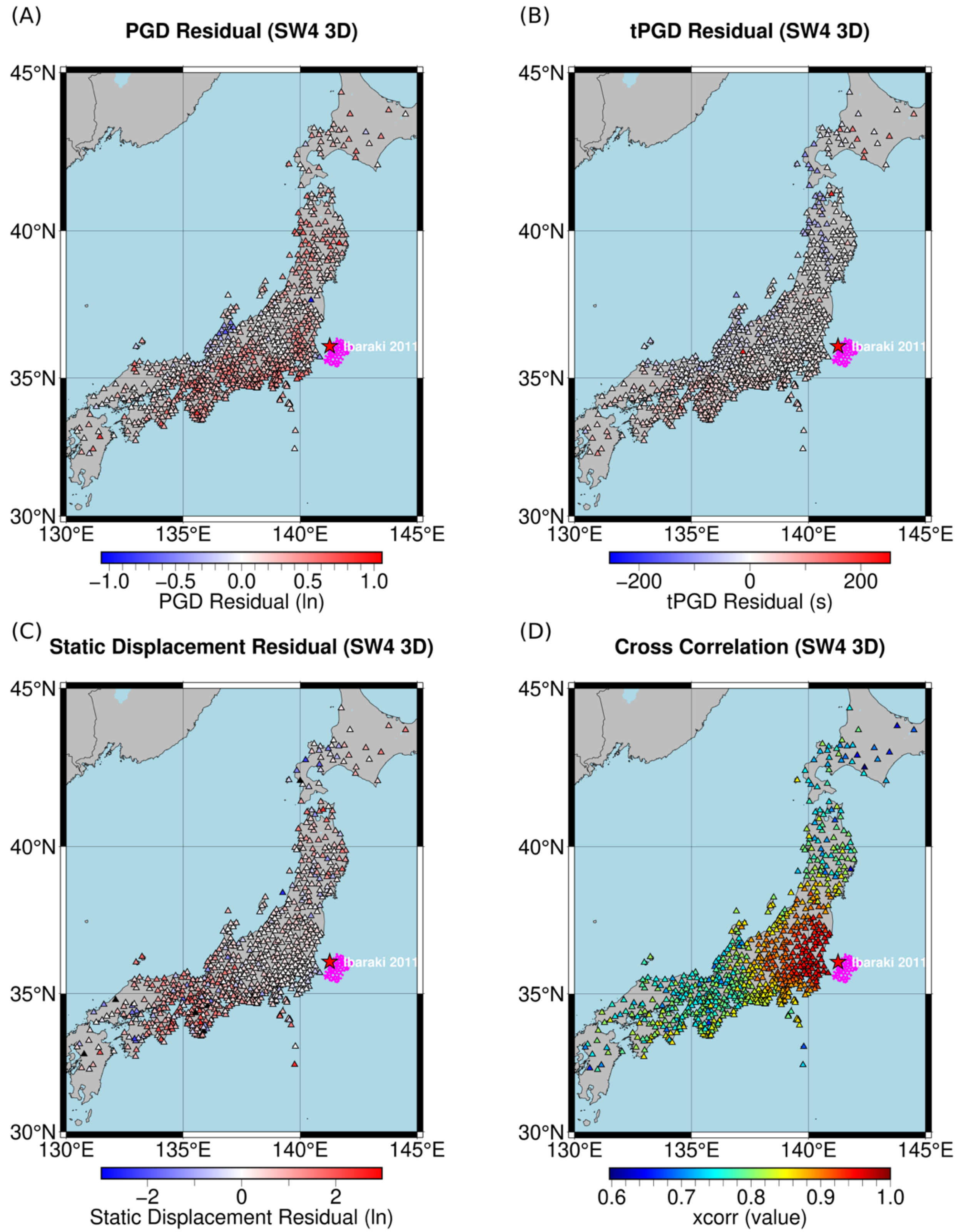

Fig. S8: The PGD, t_{PGD}, SD residuals and cross correlation map showing the spatial variation of the 3D residuals for the Ibaraki 2011 earthquake for Rupture 5 of the 100 FakeQuake ruptures using the SRCMOD mean rupture model (Kubo et al., 2013).

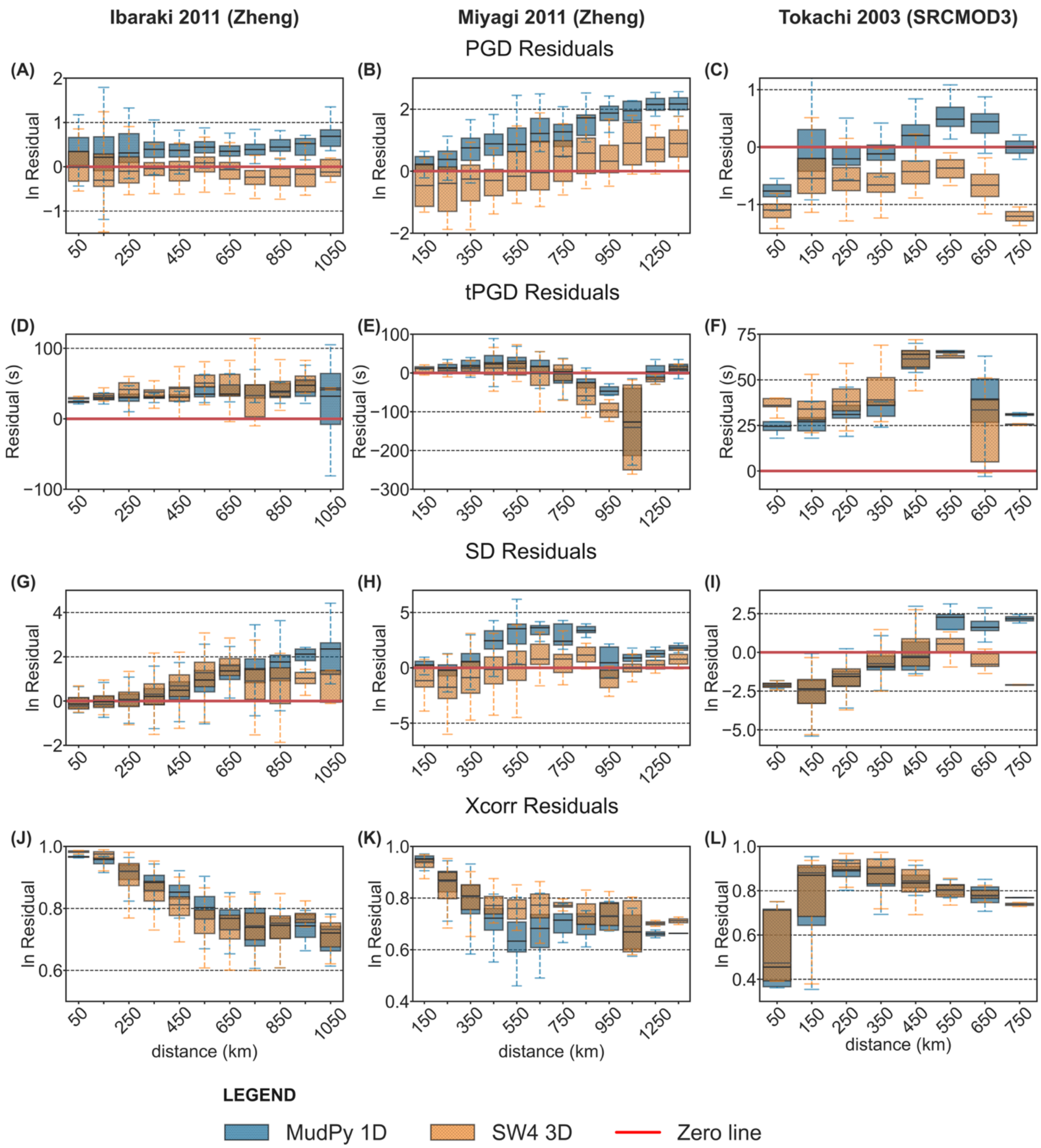

Fig. S9: Comparing MudPy 1D vs SW4 3D residuals between the synthetic to observed GNSS waveforms for Ibaraki 2011 (Zheng), Miyagi 2011 (Zheng) and Tokachi 2003 (SRCMOD3). Figure (A-C) PGD residuals, (D-F) t_{PGD} (s) residuals, (G-I) static displacement residuals and (J-L) cross correlation values. We compare only the residuals of two corresponding rupture models in the MudPy and SW4 synthetic simulations. The blue boxplots with circle hatched style represents the MudPy 1D residuals while the orange boxplot (diamond hatch style) represents the SW4 3D simulation. The red horizontal line represents the zero residual line.

Table S1: P- and S-wave velocities (Vp and Vs), density (ρ) and P- and S-wave quality factors (Qp and Qs) for the 23 layers in the 3D Japan Integrated Velocity Structure Model (Koketsu et al., 2008, 2009).

Layer number	P-wave velocity (m/s)	S-wave velocity (m/s)	Density (kg/m^3)	P-wave quality factor (Qp)	P-wave quality factor (Qs)
1	1700	350	1800	119	70
2	1800	500	1950	170	100
3	2000	600	2000	204	120
4	2100	700	2050	238	140
5	2200	800	2070	272	160
6	2300	900	2100	306	180
7	2400	1000	2150	340	200
8	2700	1300	2200	442	260
9	3000	1500	2250	510	300
10	3200	1700	2300	578	340
11	3500	2000	2350	680	400
12	4200	2400	2450	680	400
13	5000	2900	2600	680	400
14	5500	3200	2650	680	400
15	5800	3400	2700	680	400
16	6400	3800	2800	680	400
17	7500	4500	3200	850	500
18	5000	2900	2400	340	200
19	6800	4000	2900	510	300
20	8000	4700	3200	850	500
21	5400	2800	2600	340	200
22	6500	3500	2800	510	300
23	8100	4600	3400	850	500