Comparisons of ground motions from the **M** 9 Tohoku earthquake with ground-motion prediction equations for subduction interface earthquakes

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I used data from Shakemap (http://earthquake.usgs.gov/earthquakes/shakemap/global/shake/c0001xgp/download/stationlist.txt). According to D. Wald (written commun., 17 March 2011), the distance in the stationlist file is distance to the rupture surface. The data are from the K-NET network of strong-motion instruments. The shear-wave velocities at most of the stations are available to maximum depths varying from 5 to 20 m. As many recent ground-motion prediction equations (GMPEs) use the average velocity to 30 m (V_{S30}) as the site response predictor variable, it is necessary to extrapolate the shear-wave velocities at the K-NET stations in order to estimate V_{S30}. In this note I do not correct the observations to a reference value of V_{S30}. Instead, I show ground motions from GMPEs for a range of V_{S30}. In order to chose the range, I make use of a recently submitted paper (Boore *et al.*, 2011). The e-supplement to that paper (available from the online publications page on www.daveboore.com) contains estimates of V_{S30} at K-NET stations. Figure 1 shows histograms of the estimated values (estimated using correlations of average velocity to various depths and V_{S30} from velocity models from Japanese KiK-net stations and from borehole measurements in California). Log values of V_{S30} are shown because the distribution of V_{S30} is closer to log-normal than normal, as shown in Boore *et al.* (2011). The V_{S30} estimates for the 10 and 90 percentiles are 186 m/s and 586 m/s, respectively, and the GMPEs are evaluated for these values (for some of the GMPEs, V_{S30} is used only to specify a site class rather than as a continuous variable).

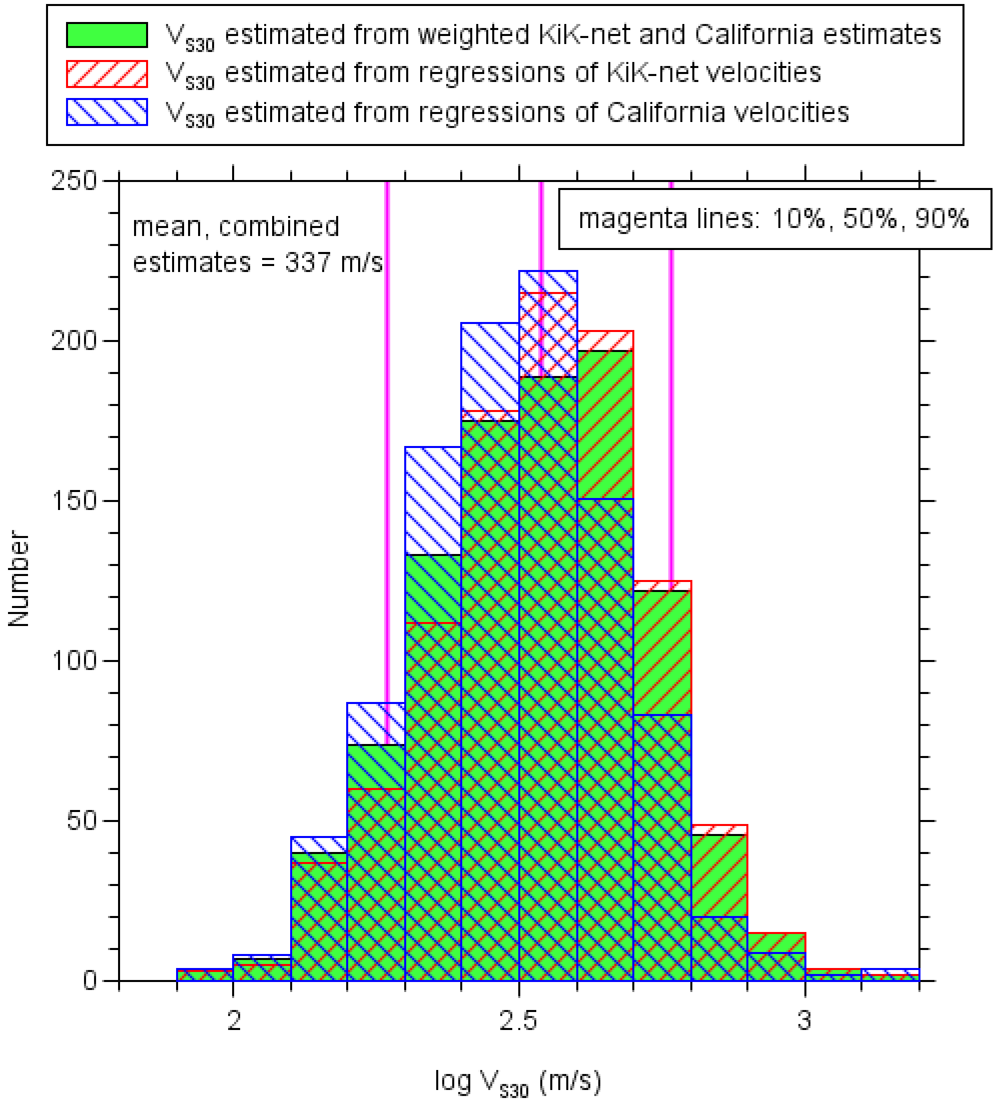

Figure 1. Histograms of V_{S30} estimates using correlations from KiK-net and California velocity models, as well as a combination of the estimates from those two sets of velocity models. The vertical magenta lines show the 10, 50, and 90 percentiles for the combined estimates.

For the ground-motion prediction equations (GMPEs), I included the equations used in the 2008 National Seismic Hazard Maps (Petersen et al., 2008). These equations are Youngs et al. (1997: Yea97), Atkinson and Boore (2003: AB03), and Zhao et al. (2006: Zea06). In addition, I included GMPEs from Gregor et al. (2002: Gea02) and Kanno et al. (2006: Kea06). The Zea06 and Kea06 equations are based in regressions using data from Japan; the AB03 equations contain adjustment factors for Japan.

Various site-response predictor variables are used in the equations, ranging from “rock” and “soil” to continuous V_{S30}. I evaluated the GMPEs for site response corresponding to the 10 and 90 percentile estimates of V_{S30} at K-NET stations (186 m/s and 586 m/s, respectively). I did not correct the observations to a common value of V_{S30}.

Figure 2 shows the comparisons. The observed motions are the geometric mean of the two horizontal components. (See also Figure 4 for additional GMPEs).

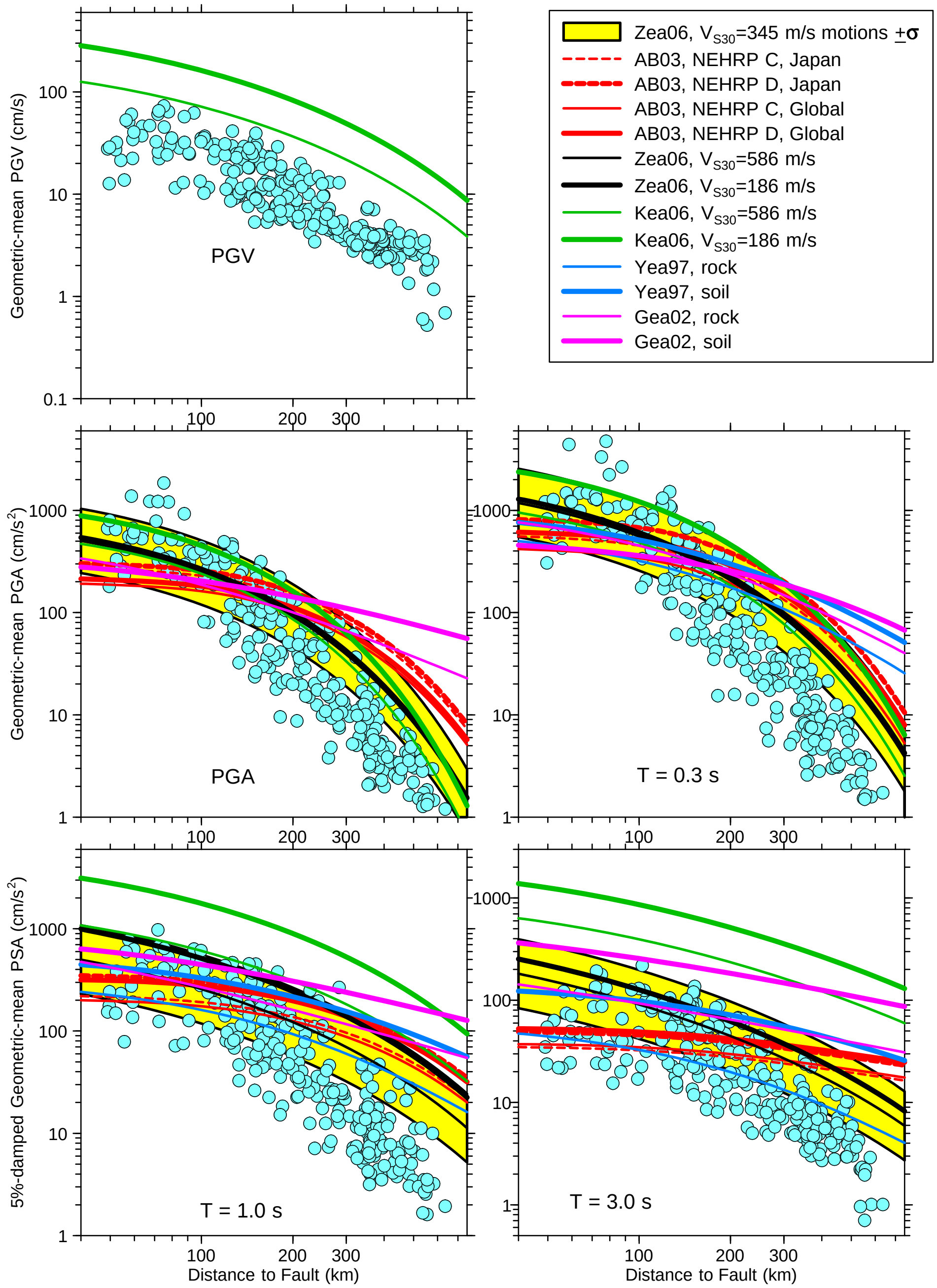

Figure 2. Observed and predicted ground motions (see text for definitions of the GMPE abbreviations). The yellow band corresponds to minus and plus one standard deviation in predicted values for the Zea06 GMPEs for V_{S30} of 345 m/s (because Zea06 uses discrete site classes, the motions are the same as for V_{S30} of 586 m/s, because their site class 2 ranges from 300 to 600 m/s).

Only Kea06 give GMPEs for peak ground velocity (PGV). The observed PGVs seem low for an event of this size. In order to give some idea of how those motions compare to those from non-subduction events, the next figure is the same as Figure 2, with the addition of the predictions from the Abrahamson and Silva (2008: AS08) and Boore and Atkinson (2008: BA08) GMPEs. I hesitate to show these, because they were NOT developed for subduction events and are not intended to be used for magnitudes as large as 9. But someone would probably ask how they compare, so here is the comparison. Note that no effort has been made to use published finite-fault models of the earthquake in defining the distance measures needed in the GMPEs, other than to roughly estimate the dip (14 degrees), width (100 km), and depth (20 km) using the model of Gavin Hayes on the USGS web site (http://earthquake.usgs.gov/earthquakes/eqinthenews/2011/usc0001xgp/finite_fault.php). The AS08 GMPEs require several distance measures and information regarding whether stations are on the hanging or footwall. I assumed that $R_{JB} = \sqrt{R_{RUP}{}^2 - H^2}$, with $H = 20\text{ km}$. I assumed that the stations are formally on the hanging wall side of the fault. I used the Fortran program described in Kaklamanos et al. (2010) to evaluate the GMPEs; the control file for the program is available from me by request.

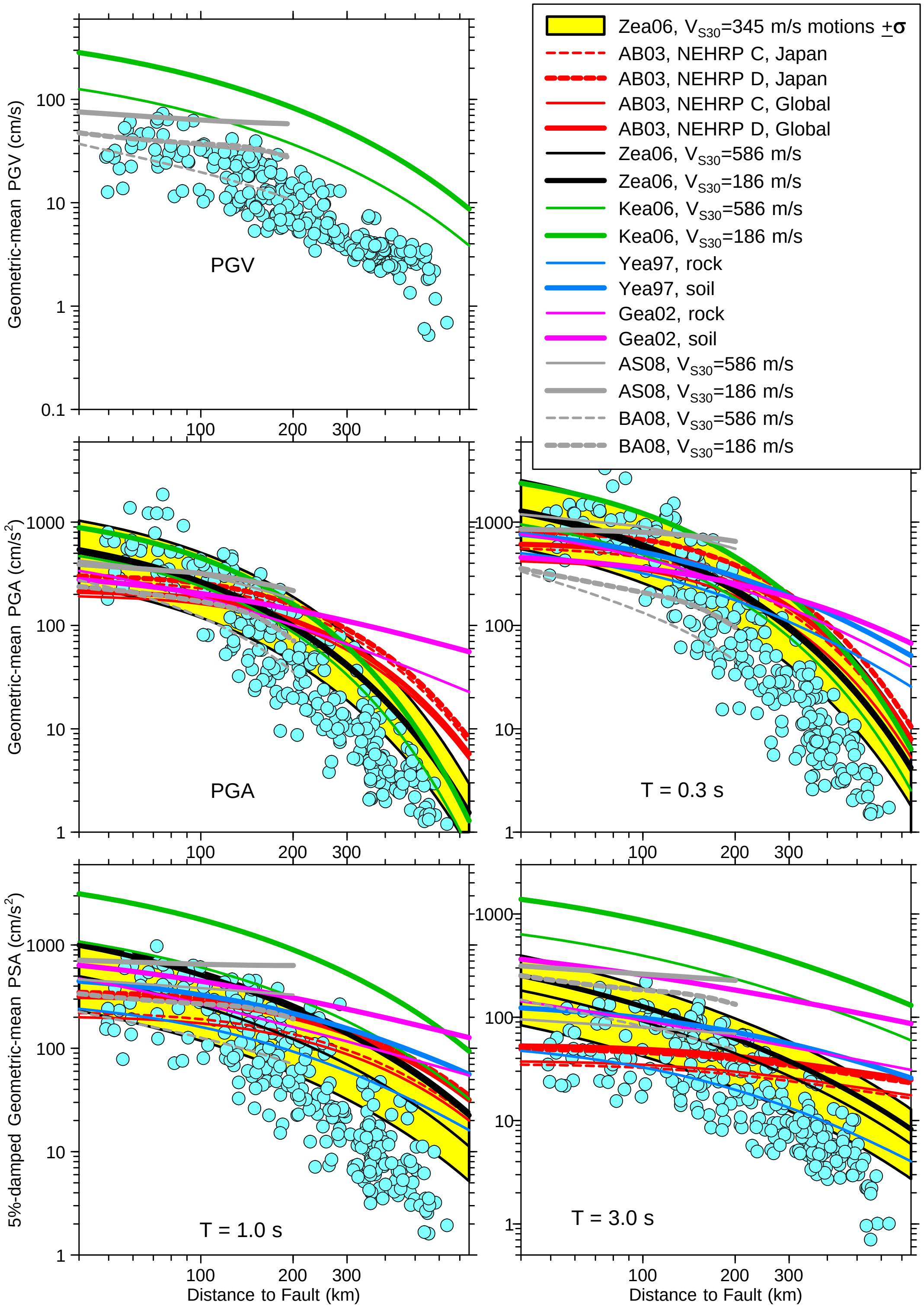

Figure 3. The same as Figure 2, with the addition of AS08 and BA08.

Here is an updated and somewhat simplified version of Figure 2, in which I've shown the GMPEs for soil sites (when available) and have added GMPEs for Lin and Lee (2008: LL08), Arroyo et al. (2010: Aea10), Megawati and Pan (2010: MP10), and the GMPEs developed by N. Abrahamson (and N. Gregor? Others?) for British Columbia Hydo (BCHydro10; I have no formal reference for the report containing these GMPEs, but I was provided a file named bchydro_GMPE-062010k.doc that contains a description of the equations; the Fortran program I wrote to evaluate the BCHydro equations was based on bcHydro_subduction.f, provided by N. Gregor on 29 March 2011). Also shown in the figure below are the motions from Zea06 for **M** 8. I show this because the event seems to have been a double event, and the response spectra from two smaller events separated by a time interval significantly greater than the period of oscillation will be the same as if the response spectrum was computed for a single subevent—thus it could be argued that it is more appropriate to use **M** 8 rather than **M** 9 in evaluating the GMPEs.

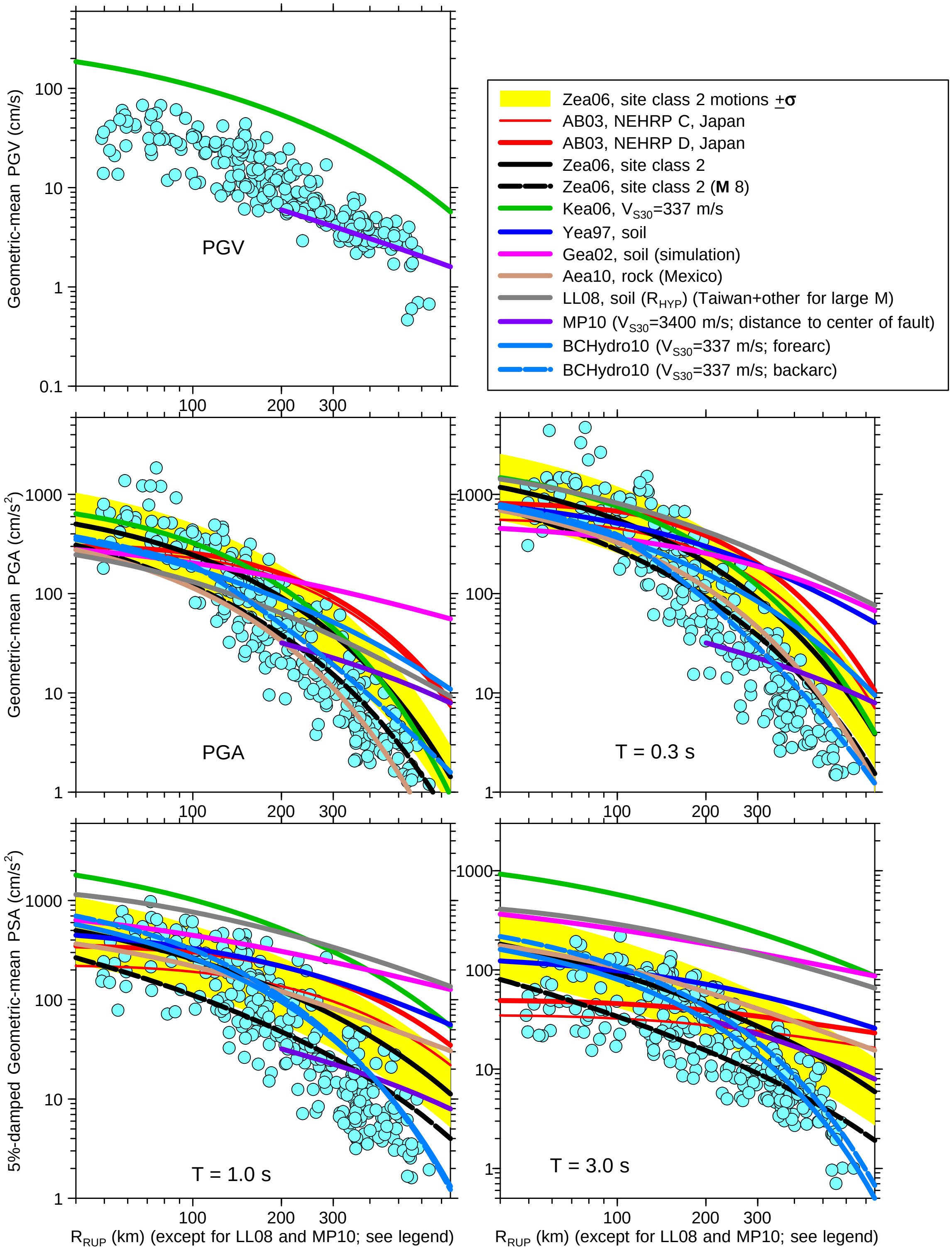

Figure 4. Similar to Figure 2, adding LL08, Aea10, MP10 GMPEs, and BCHydro10, and showing soil sites only for GMPEs (except for Aea10 and MP10, which are only for rock).

What do I see in the figures?   Here are a few observations, based on a quick inspection of the figures. The recorded ground motions decay more rapidly than predicted from many of the GMPEs (except the decay at shorter periods and greater distances is in agreement with the Aea10 and Zea06 curves).   This may be due to propagation to back-arc stations, through the low-Q material beneath the volcanic arc (Ghofrani and Atkinson,2011). Considering only distances within about 150 km, the short-period motions are better predicted than the longer period motions, with the Zea06 and Kea06 GMPEs (both developed using data from Japan) giving the best comparisons with the observations, and there seems to be a trend for the observed motions to be smaller than the predicted motions as period increases. Using a smaller magnitude in the GMPEs will bring the predictions and observations into better agreement, at the expense of the shorter period motions at closer distances. According to Frankel (written commun., 18 March 2011), some of the very high observed motions may be a result of site response due to a thin layer of low-velocity sediments over hard material. Here is the velocity model for one of those sites (MYG004):

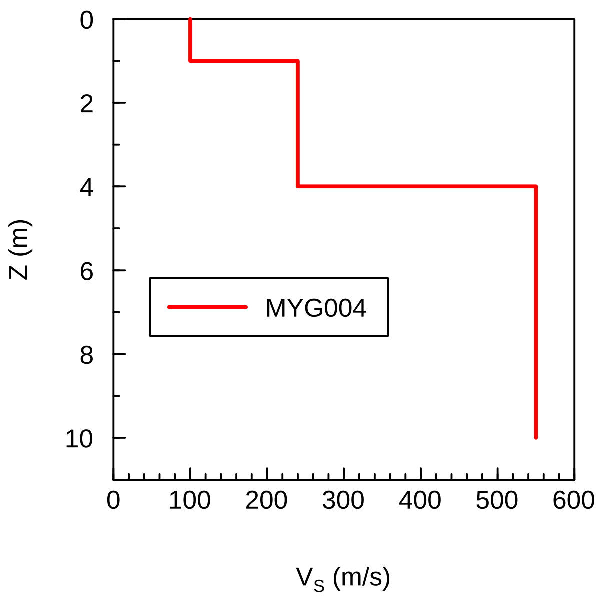

Figure 5. Velocity model for K-NET station MYG004. I assume that the depths in the model file correspond to the bottom of the layer (e.g., the first and second entries have depths of 1 m and 2 m, and velocities of 100 m/s and 240 m/s; I assume that this corresponds to a 100 m/s layer from 0 to 1 m and a 240 m/s layer from 1 m to 2m, etc.).

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