

Appendix D. Bayless and Somerville (2024) Update to the Somerville et al. (2009) GMM

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D.1 Introduction

Because considerable strong ground motion recordings have been collected and analysed in Australia in recent years, it was important to update the ground motion models (GMMs) which underpin the seismic hazard results and, ultimately, drive the design ground motions. The Somerville et al. (2009; Sea09) GMMs for Australia were due for improvement by taking advantage of these ground motions recorded in the past decade-plus. This appendix describes our update of the Sea09 GMM, which is also summarised in Bayless and Somerville (2024). The updated version of this appendix (dated April 22, 2026) includes an evaluation of the GMM with the 2019 earthquake off the Kimberley Coast, for which data became publicly available in early 2025; see Section D.8.3.

Comparisons with recently recorded ground motions in Australia have revealed that refinements to the distance and depth scaling components of the model provide a better fit to those data. This update also involves a large suite of earthquake ground motion simulations; these are validated using the recorded ground motion data and are used to extrapolate the model to larger earthquake magnitudes that typically control design ground motions but for which no Australian data are available.

The update of Sea09 involves the following five stages. Each stage is described in more detail in this appendix:

Stage 1: Data Collection and Processing. The database of recorded ground motions and earthquake metadata is used to constrain the empirical model and to validate the simulations.

Stage 2: Simulations of Recorded Earthquakes. Simulations were undertaken to validate the simulation methodology (and its key parameters) using well-recorded earthquakes.

Stage 3: Forward Simulations. We performed large suites of forward simulations using the Center for Advanced Research Computing (CARC) resources at the University of Southern California.

Stage 4: Base Ground Motion Model Regression. Using the databases of response spectra from recorded earthquakes and from the forward simulations, nonlinear mixed effects regressions were performed to determine updated model coefficients.

Stage 5: Model Refinement and Comparison. The model and its coefficients were refined based on iterative evaluations of model performance and data comparisons. Models for hanging wall effects, V_{S30} scaling, and the aleatory variability were adopted from others because they could not be reliably determined from the data. We tested the scaling of individual model components (distance attenuation, magnitude scaling, depth scaling) and compared with the Sea09 model and with other existing models.

D.2 Review of Sea09

The Sea09 ground motion models for Australia were developed under contract to Geoscience Australia (Somerville et al., 2009). Given the sparsity of recorded strong motion data in Australia, Sea09 used a broadband strong motion simulation procedure to account for the known earthquake source and crustal structure properties in Cratonic and Non-Cratonic Australia. The Sea09 ground motion model consists of separate Cratonic and Non-Cratonic models representing different shallow crustal structure and seismic wave propagation characteristics (Somerville and Ni, 2010). Sea09 developed and used seismic velocity models for the Perth Basin / Yilgarn Craton region and for the Sydney Basin / Lachlan Fold Belt region in the simulation of earthquake ground motions. Finite fault rupture models were derived for the 1968 Meckering and 1988 Tennant Creek earthquakes through the inversion of teleseismic waves and geodetic data. The rupture models of these earthquakes and other data were used to derive earthquake source models for the strong motion simulations. Finally, the ground motion models for response spectral acceleration were derived from these simulations.

The Somerville et al. (2009) model is based on broadband ground motion simulations for earthquake source and seismic wave propagation conditions that are specific to Australia, and are supported by very sparse recordings for small earthquakes in Australia. In particular, the Cratonic Australia model is based on earthquake source and seismic wave propagation conditions in the Yilgarn Craton. Sea09 compared their Cratonic model to others and found that it was more similar to the model developed using Yilgarn Craton data by Liang et al. (2008), and less similar to the models for stable regions of eastern North America by Toro et al. (1997) and Atkinson and Boore (2006). In Sea09, the very shallow earthquakes and the shallow low velocity layer in the crust in the Cratonic model give rise to large R_g waves that are observed both in the recordings and the simulations. These produce large peak velocities in the records and give rise to a peak in the ground motion response spectrum at a period of about 1.5 seconds

The Somerville et al. (2009) Non-Cratonic model is supported by very sparse recordings for small earthquakes in Non-Cratonic Australia, such as the Moss Vale earthquake. The Non-Cratonic model was found to provide an unbiased prediction of the recorded ground motion response spectra of the **M** 4.47 Thompson Reservoir earthquake of 1996.

D.2.1 Data Comparisons

We evaluated the performance of the Sea09 model by comparing it with the earthquake ground motion data. Figure D-4a shows an example of this observation for the Northern Territory **M**4.71 earthquake on May 30, 2019 (EQID 51 in Table D-1). In the top panel, the peak ground acceleration (PGA) versus distance predicted by the Sea09 Cratonic earthquake model is compared with the recordings, where the data are adjusted to the time-averaged shear-wave velocity (V_{S30}) condition of 865 m/s, for consistency with Sea09, using the Stewart et al. (2020) site amplification model for stable continental regions. Estimated values of V_{S30} for sites used in this study were compiled by Ghasemi and Allen (2021) and are from three independent sources, in order of preference: Kayen et al. (2015), McPherson (2017); Wald and Allen (2007).

Figure D-1a shows that the Sea09 median model overpredicts at close distances and underpredicts at large distances. The bottom panel of Figure D-1a shows ground motion residuals calculated from the Sea09 model, and the linear trend in these residuals also illustrates the difference in PGA attenuation for this event with that assumed in Sea09. Figure D-1b shows a map of the earthquake location and recording sites, along with the boundary between the Northern Australian Craton to the north, and the reactivated Proterozoic crust to the south. Sites within the Cratonic region boundary are filled circles in Figure D-1a, and sites outside the boundary are white squares. Similar behaviour is observed for the other Cratonic region events for which we have recorded data. Additionally, the fact that the Sea09 Cratonic ground motion model has a more rapid decay with distance than the non-Cratonic model (not shown), which is the opposite of what we would expect, is an indication that the Cratonic model needs adjustment. Stable continental regions are described by relatively lower effective anelastic attenuation (higher frequency-dependent quality factor) and so high-frequency ground motions have weaker decay with distance at regional distances than active regions (e.g. Baquer and Mitchell, 1998; Bayless, 2021).

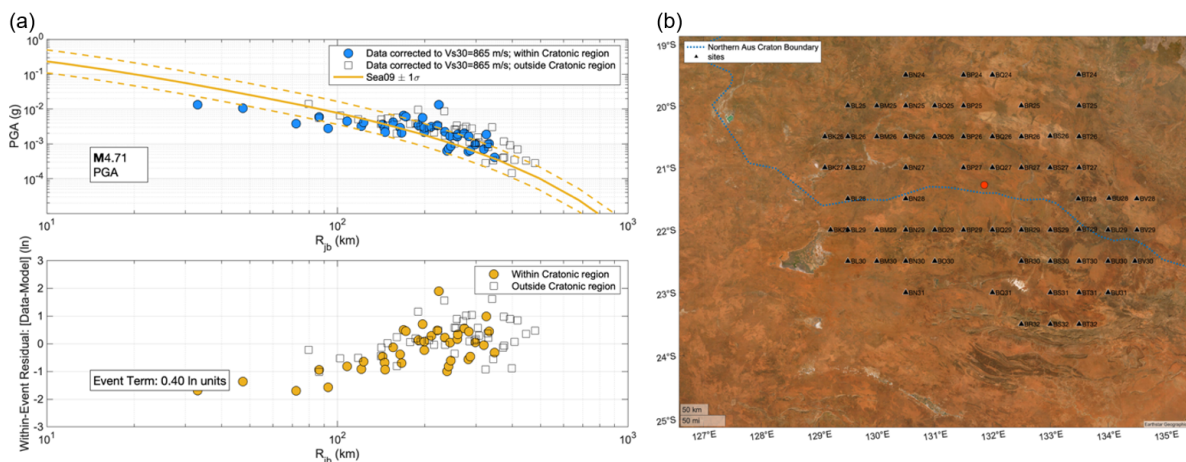


Figure D-1 (a) Evaluation of the Sea09 Cratonic model with ground motion recordings of the May 30, 2019 M4.71 earthquake. Top: PGA versus distance. Bottom: Within-event residuals versus distance. (b) A satellite image map of the May 30, 2019 M4.71 earthquake epicentre (red circle) and recording stations (triangles). The blue dashed line represents the boundary between the Northern Australian Craton to the north, and the reactivated Proterozoic crust to the south.

D.2.2 Model Components addressed in this update

Aside from the above distance-scaling issue, the Sea09 model has a few shortcomings which we aimed to address with this update. In Sea09 there is no dependence on the depth of the source, and the Cratonic model assumes a shallow depth, which may apply to the Yilgarn craton where earthquake sources are almost exclusively very shallow, but may not apply to the Gawler craton where earthquakes in the Cleve area of the Eyre Peninsula occur to depths of at least 30 km. The Sea09 model also does not explicitly model hanging wall effects and instead takes the simple approach of using the Joyner-Boore distance metric (R_{JB}) to account for these known effects, which impact high frequency ground motions. The Sea09 magnitude scaling and short-distance saturation were based on the simulations (M5.0 - M7.50) described in Sea09 and were due for re-evaluation using contemporary simulation methods. Finally, the Sea09 model is for a fixed V_{S30} condition of 865 m/s. All these shortcomings are addressed in this update.

D.3 Earthquake Ground Motion Data

We compiled a Cratonic earthquake ground motion database including waveform data from Geoscience Australia (Ghasemi and Allen, 2021), who provided instrument corrected recordings for events occurring within Cratonic regions, and from IRIS (<https://ds.iris.edu/wilber3/>). We removed events with M less than 3.0, recordings with distance greater than 600 km, and those identified as clipped, with poor signal to noise ratio, or other artifacts. Recordings without both orthogonal horizontal components were also removed. The resulting database contains 536, homogeneously processed, ground motion records from 84 events recorded by 155 unique stations.

The Cratonic ground motion database (Figures D-2 and D-3) includes three earthquakes with more than 80 records, these are the M3.91 event on 2019 May 30, the M4.71 event on 2019 May 30, and the M4.96 event on 2019 August 1. These three earthquakes were located within the Northern Australian Craton and were recorded by the temporary AusARRAY deployment (Gorbatov et al., 2020). The remaining 81 earthquakes in the database used in this study have fewer than 14 recordings within 600 km. There are 35 total events with $M \geq 4.0$ and 33 events with $3.5 \leq M < 4.0$. The 5%-damped, horizontal component pseudo-spectral accelerations (RotD50; Boore, 2010) are calculated from two-component band-passed acceleration time histories using the pyRotd python library (Kottke, 2018).

The cut-and-paste (CAP) method for retrieving earthquake source parameters (Zhao and Helmberger, 1994; Tan et al., 2010) breaks three-component data into regional P waves (P_{nl} , consisting of refractions along the crust–mantle interface, P_n , and the crustal P arrivals and P_{mP} along with various S segments at distances from 150 to 1400 km; Helmberger and Engen, 1980) and surface-wave segments, and models them separately, so imperfect 1-dimensional Green's functions can be effectively used to determine source parameters. We use the CAP method on nine of the 12 events listed in Table D-1 to improve our estimates of M , focal depth, focal mechanism, and location, resulting in some differences between our source parameter estimates and those from the GA and global catalogues. Figure D-4 shows the results of this method, using a six-station inversion, for the August 1, 2019 Northern Territory event. This inversion has a minimum waveform misfit error at 2 km depth (centre left panel), and a northeast p-axis orientation consistent with Hillis & Reynolds (2000) (top left). The event and recording station locations are shown in the bottom left panel, and the fits between the recorded (red) and synthetic (blue) waveforms are shown on the right.

The non-Cratonic ground motion database (Figure D-5) includes response spectra and metadata only and was provided by Geoscience Australia (Trevor Allen, personal communication) at our request. From the data provided by Geoscience Australia, we identified the 12 events listed in Table D-2 to be used for the GMM development. These include the 2021 M5.9 Woods Point and 2012 M5.1 Moe earthquakes in Victoria.

Table D-1 Cratonic region earthquakes used in the GMM development. Metadata for EQIDs 13, 49, and 55 are from Ghasemi and Allen (2021).

EQID	M	Date	Epicenter Longitude (deg)	Epicenter Latitude (deg)	Hypocenter Depth (km)	Strike, Rake, Dip (deg)	Region	No. of Usable 2-comp recs
61	4.96	2019-08-01	133.916	-19.7647	2	302, 47, 79	North. Aus. Craton	98
59	4.71	2019-05-30	131.85876	-21.28147	5	103, 59, 14	North. Aus. Craton	83

EQID	M	Date	Epicenter Longitude (deg)	Epicenter Latitude (deg)	Hypocenter Depth (km)	Strike, Rake, Dip (deg)	Region	No. of Usable 2-comp recs
60	3.91	2019-05-30	131.92337	-21.32752	4	101, 64, 3	North. Aus. Craton	85
58	5.34	2018-11-08	116.78733	-34.42316	9 [^]	151, 90, 52	Yilgarn Craton	13
53	4.90*	2018-09-16	116.78	-34.43	7 [^]	347, 53, 44	Yilgarn Craton	6
44	4.91	2016-07-08	122.511	-32.458	5	331, 37, 59	Yilgarn Craton	6
13	4.6	2002-03-30	117.049	-30.519	0.8	-, -, -	Yilgarn Craton	8
55	4.54	2018-10-12	116.79882	-34.39522	5.8	-, -, -	Yilgarn Craton	8
49	4.13	2017-01-03	118.455	-30.609	10	-, -, -	Yilgarn Craton	9
72	4.39	2010-06-05	136.796	-33.5949	23	0, 62, 51	Gawler Craton	5
82	3.53	2018-07-01	136.7729	-33.618	23	209, 38, 51	Gawler Craton	5
83	4.41	2018-11-21	136.923	-33.2585	33	319, 32, -83	Gawler Craton	5
84	5.32	2021-11-13	119.8416	-21.1301	34.9	-, -, -	Pilbara Craton	12
1006	6.6	2019-07-14	120.295	-18.262	20	-, -, -	Pilbara/Kimb-erley Cratons	1 ⁺

*The global CMT M and depth are 5.3 and 12 km

[^]More appropriate hypocentral depths may be in the range 2-4 km; Clark et al. (2020)

*Number of available ground motion data as of late 2024. Additional data available as of early 2025 were not used in model development but were used to evaluate the model performance; see Section D.8.

Table D-2 Non-Cratonic region earthquakes used in the GMM development.

EQID	M	Date	Epicenter Longitude (deg)	Epicenter Latitude (deg)	Hypocenter Depth (km)	No. of usable response spectra
1001	4.4	2007-12-26	138.383	-32.086	16.4	12
1002	4.5	2010-06-05	136.719	-33.589	22.4	6
1003	5.1	2012-06-19	146.29	-38.259	18.06	25
1004	3.6	2018-07-01	136.679	-33.606	10	10
1005	3.7	2018-11-21	136.846	-33.361	10	9
1007	4.2	2020-05-14	138.802	-33.711	10	8
1008	5.9	2021-09-21	146.348	-37.492	10	28
1009	4.7	2021-10-08	141.021	-35.408	1.7	13
1010	4.3	2023-03-22	139.592	-32.785	8.8	12
1011	4.4	2023-06-29	146.313	-37.502	7.4	29
1012	3.9	2023-09-08	150.733	-34.153	2.4	14
1013	4.8	2023-10-21	143.489	-38.651	7.2	17

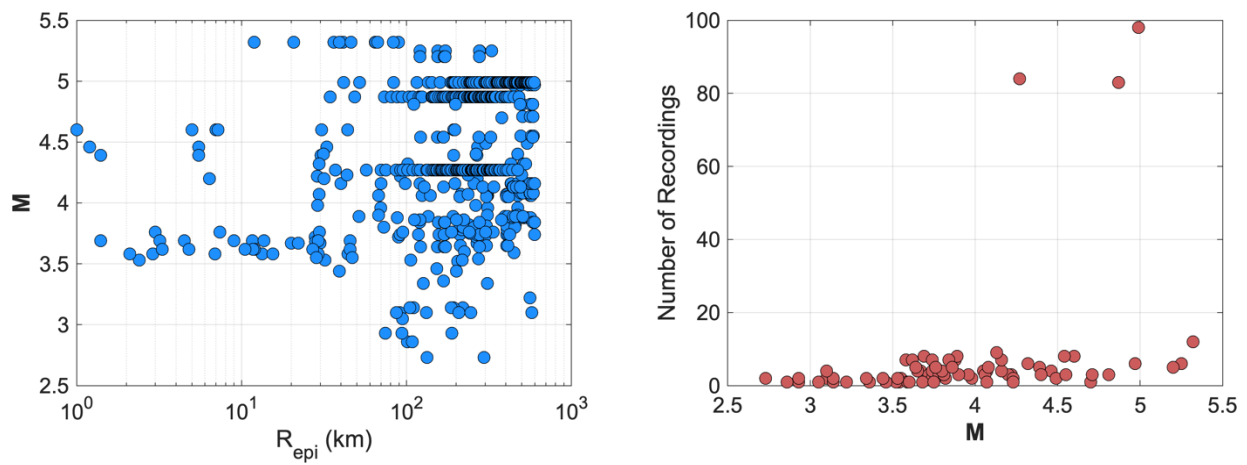


Figure D-2 Cratonic region ground motion recordings used in the GMM development. Left: magnitude and distance pairs. Right: Number of ground motion recordings versus earthquake magnitude.

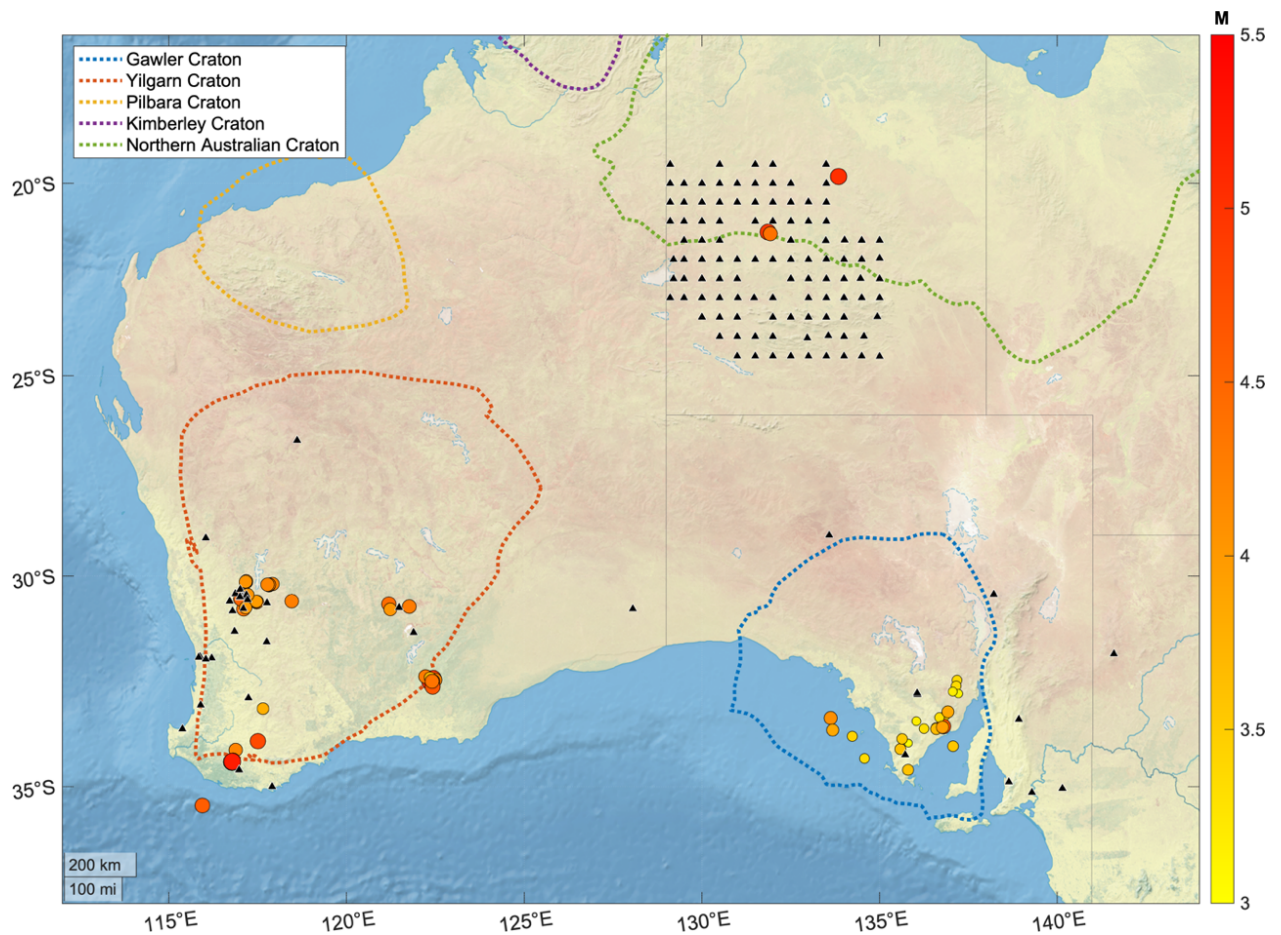


Figure D-3 A map of Cratonic domain earthquakes (circles) and recording stations (triangles) with Cratonic domain boundaries from NSHA18 (Clark et al., 2012).

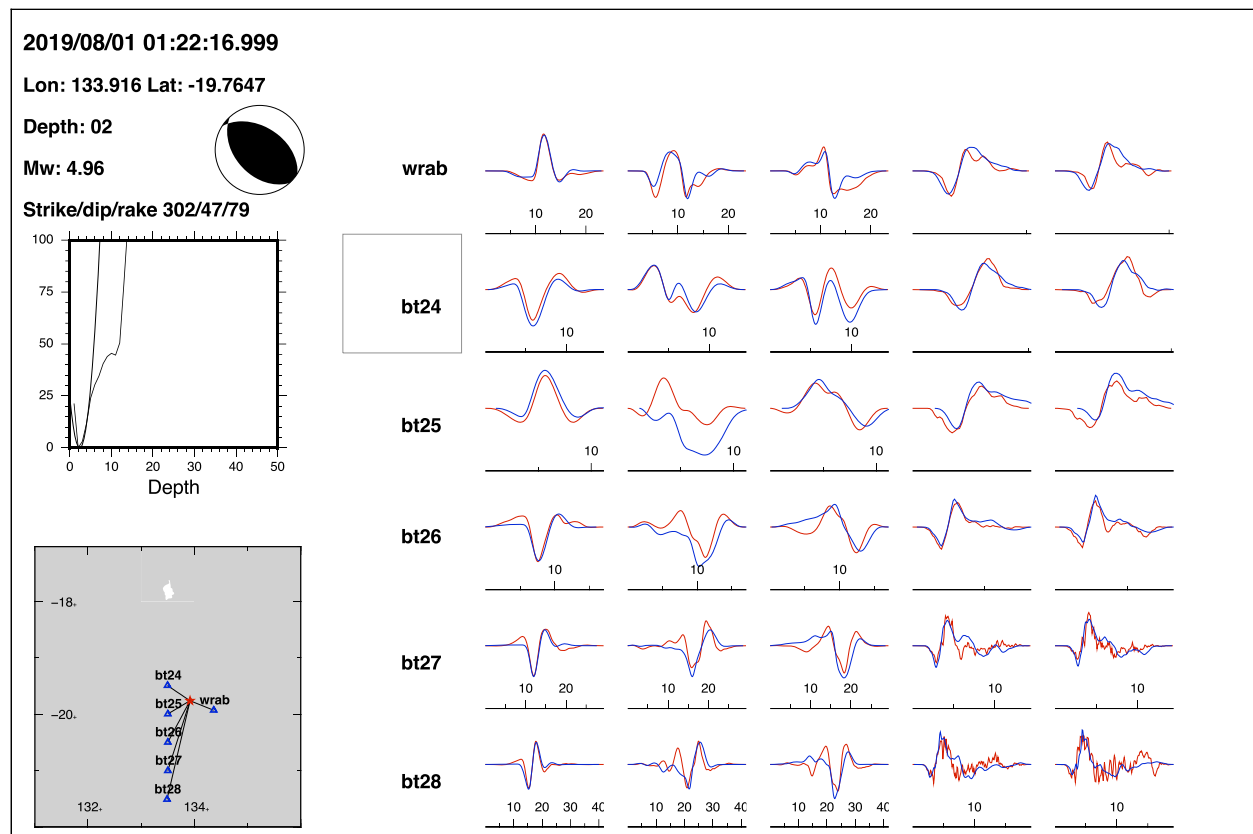


Figure D-4 CAP method results for the 2019/08/01 earthquake in the NT.

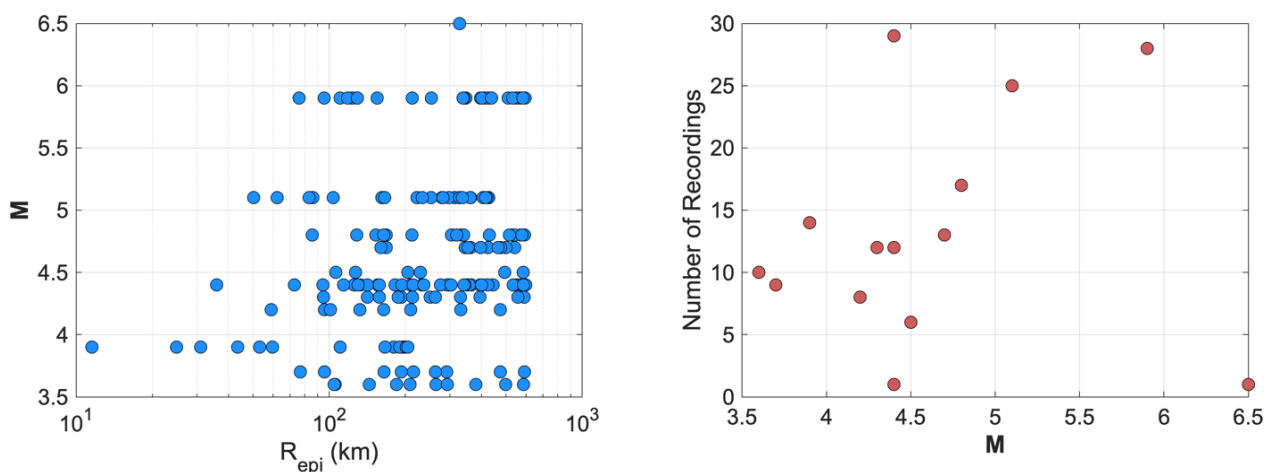


Figure D-5 Non-Cratonic region ground motion recordings used in the GMM development. Left: magnitude and distance pairs. Right: Number of ground motion recordings versus earthquake magnitude.

D.4 Ground Motion Simulation Framework

Ground motion simulations were used to extrapolate the model to larger earthquake magnitudes that typically control design ground motions but for which no Australian data are available. The earthquake ground motion simulations were validated using the recorded ground motion data.

D.4.1 Simulation Method Overview

We used the hybrid broadband ground motion simulation methodology of Graves and Pitarka (2015; 2014; 2010; 2004; GP15) as implemented on the Southern California Earthquake Center Broadband Platform, version 22.4 (SCEC BBP; Maechling et al., 2015). The GP15 method combines a deterministic approach at low frequencies ($f < 1$ Hz) with a semistochastic approach at high frequencies ($f > 1$ Hz), where the broadband (0-10 Hz) response is obtained by summing the separate

responses in the time domain using matched filters centred at 1 Hz. In GP15 the fault rupture is represented kinematically and incorporates spatial heterogeneity in slip, rupture speed, and rise time by discretising an extended finite-fault into a number of smaller subfaults. The GP15 prescribed slip distribution is constrained to follow an inverse wavenumber-squared fall-off and the average rupture speed is set at a fraction of the local shear-wave velocity, which is then adjusted such that the rupture propagates faster in regions of high slip and slower in regions of low slip. At low frequencies ($f < 1$ Hz), the GP15 methodology contains a theoretically rigorous representation of fault rupture and wave propagation effects and attempts to reproduce recorded ground motion waveforms and amplitudes by summing the response for many point sources distributed across each subfault. At high frequencies ($f > 1$ Hz), GP15 uses a stochastic representation of source radiation, which is combined with a simplified theoretical representation of wave propagation and scattering effects for each subfault.

D.4.2 Simulation Input Parameters

Graves and Pitarka (2015) extended their broadband simulation method from active region crustal earthquakes to earthquakes in stable continental regions based on findings from Somerville et al. (2009), Leonard (2010; 2014), Beresnev and Atkinson (2002), and with calibration using three eastern North America earthquakes. The modifications included: increasing the average rise time, reducing the average corner frequency, increasing the high frequency stress parameter, using the Leonard (2010; 2014) magnitude-area scaling relations, changing the high frequency attenuation (through kappa and Q models), changing the background rupture speed, and removing the shallow and deep weak zones from the rupture characterisation (Graves and Pitarka, 2015).

For Cratonic region earthquakes, we used the parameter recommendations from Graves and Pitarka (2015) as a starting point and took a trial-and-error approach to refine the parameters based on the simulation and validation of earthquakes in Table D-1. Additional requirements to perform a simulation are the seismic velocity model and 1D Green's functions, the kinematic source description, and the station information and site response. These are described in the following sections.

D.4.3 Seismic Velocity Models

The Australian Seismological Reference Model (AuSREM; Salmon et al., 2013) was used to develop the 1D velocity models to represent Cratonic and Non-Cratonic regions. AuSREM is a 3D grid based crustal structure model (P wave speed, S wave speed, density and depths of major boundaries) with a 0.5-degree sampling in latitude and longitude, so that properties can be extracted and interpolated at any point in the country. We extracted profiles within the Yilgarn and Gawler Cratons at 2-degree intervals in latitude and longitude, and outside of these Cratons in southeast Australia. These profiles are very similar at depths below about 5 km. In the 1-5 km depth range, we found significant differences between the Cratonic and Non-Cratonic profiles. Based on these findings, we developed a representative AuSREM Cratonic seismic velocity model based on the average of the profiles within the Yilgarn and Gawler cratons, and a representative Non-Cratonic model based on the average of the extracted profiles in southeast Australia. Below 5 km depth these profiles are identical. Above 1 km depth, the models are tapered to yield reference V_{S30} values of 760 m/s. The reference V_{S30} value of 760 m/s is a standard velocity for representing firm rock site conditions and is used by the NSHA18, NSHA23, the U.S. Geological Survey, and others (Allen et al., 2018; Allen et al., 2024; Petersen et al., 2020). This reference V_{S30} value represents the site condition for the ground motion model, and to the condition which site amplification factors are to be applied.

The velocity models developed in Sea09 are similar to the AuSREM models at depth, with slightly lower velocities at all depths in Sea09. To develop the final seismic velocity models, the mean of the AuSREM representative models and the Sea09 models was taken, and this mean model is down-sampled to a serviceable number of layers (17 layers for Cratonic and 23 for Non-Cratonic). The final models are shown in Figure D-6.

The seismic velocity models were used to calculate theoretical Green's functions (GFs) including anelastic attenuation, computed using the Zhu and Rivera (2002) frequency-wavenumber technique. The GFs contain the full theoretical waveform response from zero to several Hz. The GFs are computed for three fundamental fault orientations (SS, DS, DD), from which any arbitrary faulting mechanism can be computed using a linear combination of the fundamental fault response. We computed a database of GFs for both velocity models and for source depths ranging from 0-30 km and source-site distances ranging from 0-600 km.

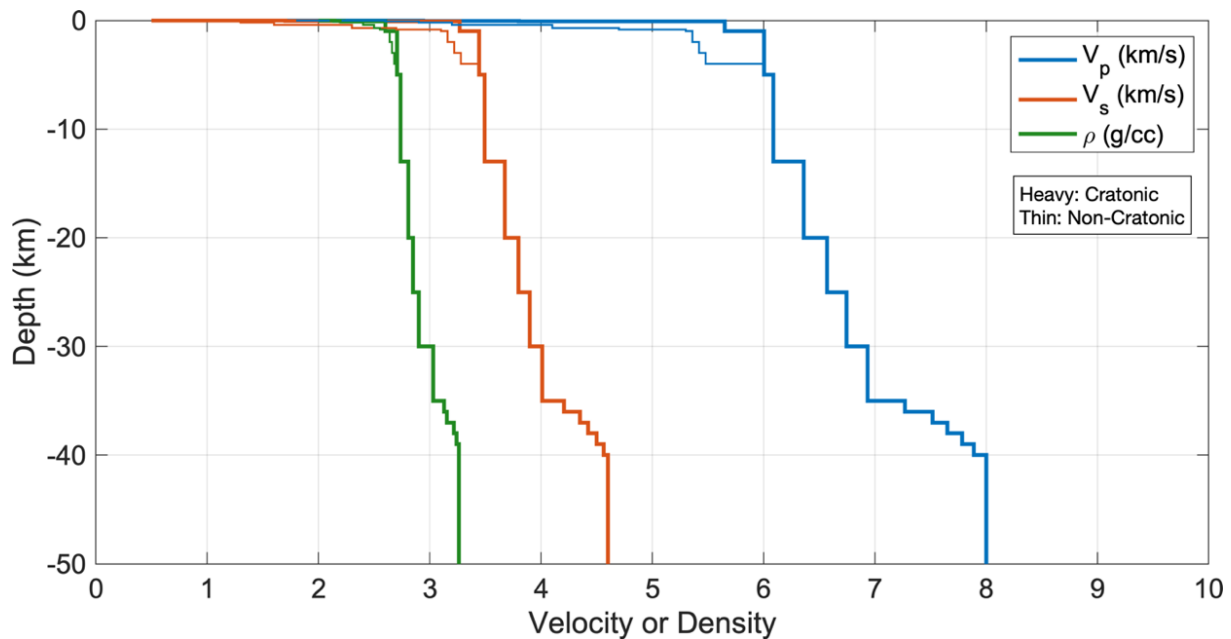


Figure D-6 The 1D seismic velocity models used to represent Cratonic (heavy lines) and Non-Cratonic (thin lines) Australia.

D.5 Validation Simulations

The first phase of using the earthquake ground motion simulations was validation against the available data from Section D.3. The validation phase establishes confidence in the simulations and their input parameters, such as the seismic velocity models used to develop Green's Functions. The validation efforts involved simulating the well-recorded earthquakes in the region and comparing the simulated waveforms, response spectra (including attenuation with distance and spectral shape), and finally with a goodness-of-fit calculation to determine if there is any period-dependence in the mean bias of the simulations with respect to the data.

The simulations were performed for the events and recording stations listed in Table D-1, using the GP15 method and with the Green's functions described above. The simulation results for the first event in Table D-1 (EQID 61) are presented in this appendix. The AusARRAY sites which recorded the EQID 61 earthquake, shown in Figure D-7, are located near or within the Northern Australian Craton region defined in NSHA18, and their site conditions are poorly known. We adjusted each site's recorded response spectrum to the $V_{S30}=760$ m/s condition using the Stewart et al. (2020) site amplification model for stable continental regions. The uncertainties in V_{S30} values and in the site response adjustments are significant and could be reduced in the future with additional data collection or improved models; these sources of uncertainty were similarly identified and accepted in NGA-East (Goulet et al., 2021).

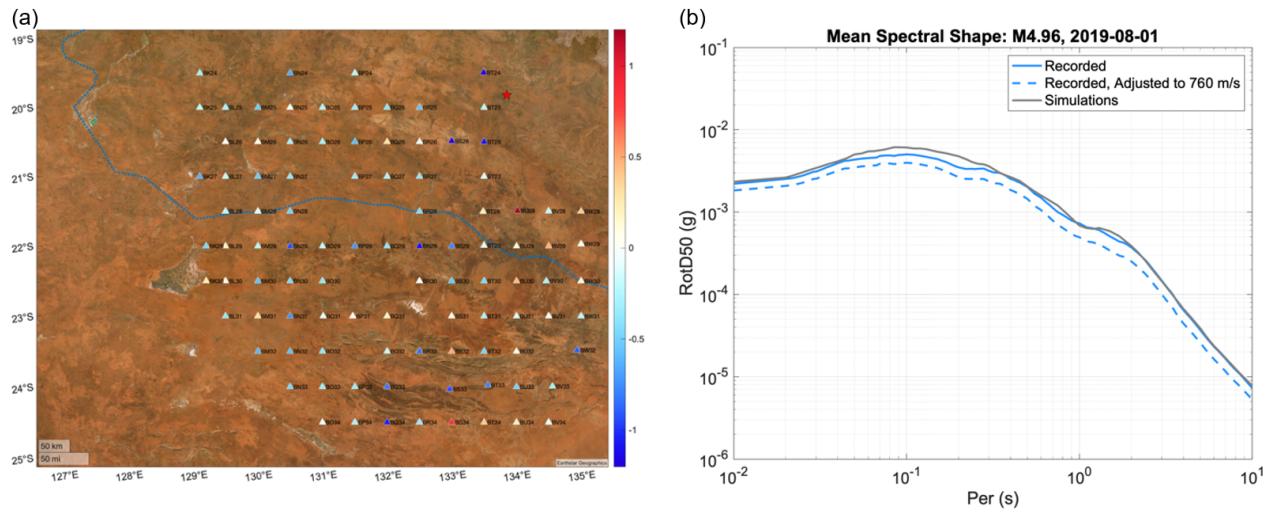


Figure D-7 (a) A satellite image map showing color-coded within-event residuals (EQID 61, M 4.96) at the recording sites with less than 600 km hypocentral distance. (b) Mean spectral shapes of all sites within 300 km, showing simulated, recorded, and recorded with adjustment to the $V_{S30}=760$ m/s site condition.

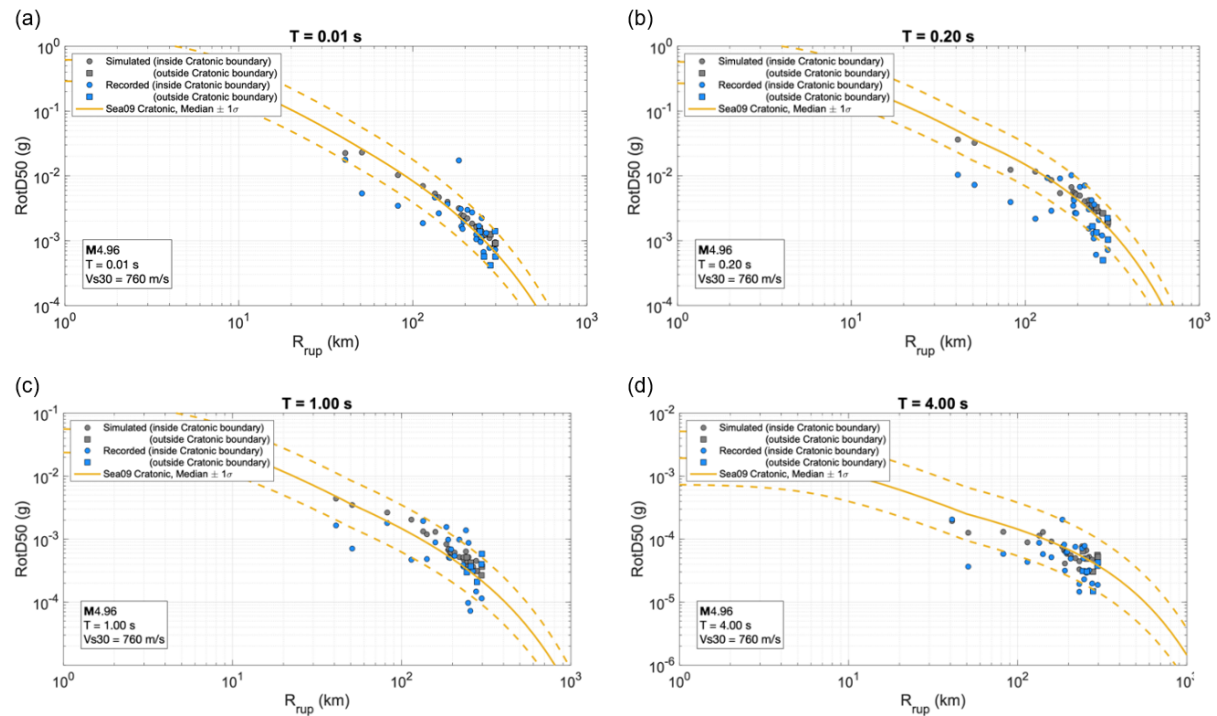


Figure D-8 For EQID 61, distance attenuation of recorded (blue) and simulated (grey) RotD50 spectral acceleration at all sites with less than 300 km rupture distance, for four periods: (a) 0.01 sec (PGA), (b) 0.2 sec, (c) 1 sec, and (d) 4 sec.

For a given spectral period and recording station, the residual is defined as the difference between the natural logarithm of the recorded spectral acceleration (data) and the simulated spectral acceleration, after correcting for site conditions. Figure D-7a shows a map of the within-event PGA residuals for this simulation, where negative residuals (cool colours) correspond to simulation over-prediction. Figure D-7b shows the mean of spectral acceleration over all sites at each period; this compares the mean spectral shape of the simulations with the data. The dashed blue line in Figure D-7b is the mean spectral shape after adjusting each site's recorded response spectrum to the $V_{S30}=760$ m/s condition using the Stewart et al. (2020) site amplification model for stable continental regions (recommended model with weights for large impedance contrast and gradual velocity gradient models determined as a function of V_{S30}). The small bump at about 1.5-2 seconds in the response spectra of both the simulations and the recordings is due to the R_g wave, which is caused by a shallow low velocity layer in the crust, and which produces large peak ground velocities. Sea09 observed and modelled this ground motion feature.

Figure D-8 shows the distance attenuation of RotD50 spectral acceleration at all sites with less than 300 km rupture distance, for four periods: 0.01 sec (PGA), 0.2 sec, 1 sec, and 4 sec. The Sea09 Cratonic median plus and minus one standard deviation model predictions are shown, and the circles represent stations inside the Cratonic region boundary, while squares represent stations outside of this boundary. Figure D-8 illustrates good agreement in the distance scaling of the simulations with the data from this event.

Figure D-9a shows the goodness-of-fit (GOF) summary for this earthquake simulation. The GOF is computed for each spectral period. The mean bias (black line) is the mean residual calculated from all recording stations, using the same definition of residual as defined previously. The red shaded area represents the 90% confidence interval in the mean bias and the green shaded area represents ± 1 standard deviation among the residuals. The simulation of this event over-predicts the data slightly across all periods without strong period dependence in the mean GOF; the lack of period dependence is encouraging, and a mean bias is generally acceptable if some other events are systematically low, because each event is expected to have an event term.

Figure D-9b shows displacement time series with rupture distance (vertical axis) for the simulations (left) and recordings (right) with less than 300 km rupture distance. Overall, there are strong similarities in the amplitudes, phasing, and durations of the waveforms between the simulations and the recordings. Postcritical reflections from the lower crust generate the second arrival seen in the simulations at distances of 50 km and less.

We determined that the simulations are acceptably calibrated to the recorded data using validation metrics such as those shown in Figures D-7 through D-9 for all events listed in Table D-1.

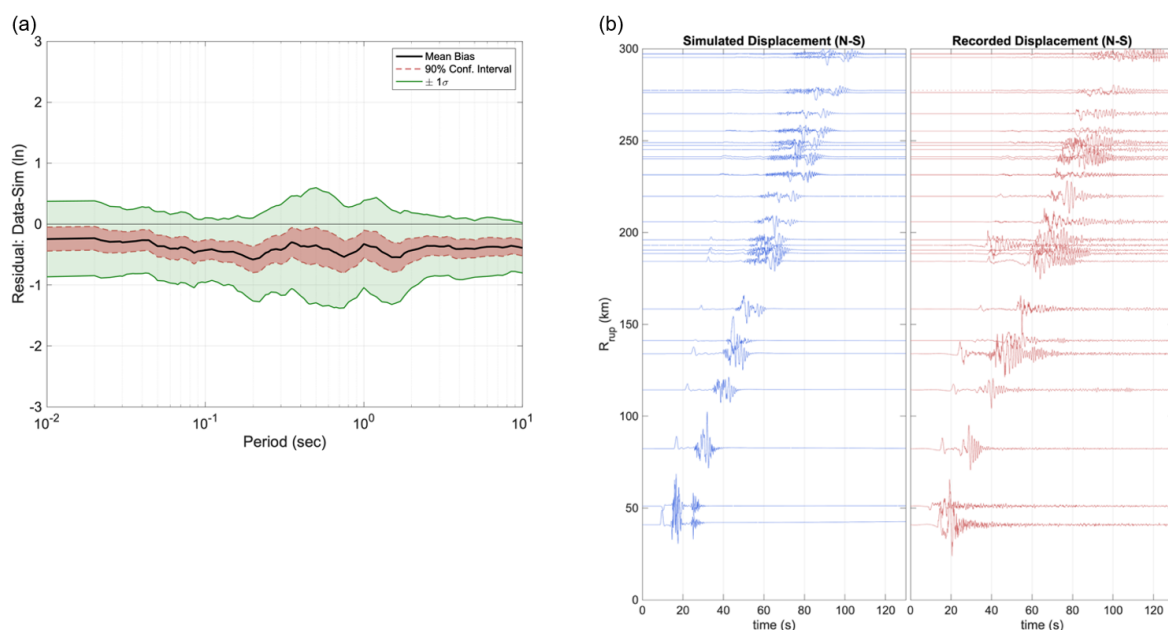


Figure D-9 (a) The response spectral goodness-of-fit (GOF) summary for the EQID 61 earthquake simulation. (b) simulated and recorded displacement time series as a function of rupture distance; the vertical scale for displacement amplitudes is the same between both panels of (b).

D.6 Forward Simulations

The second simulation phase involved performing simulations for suites of scenario events with a range of magnitudes, source depths, and kinematic source realizations to develop a simulated ground motion database. The suites of simulations were used in constraining the magnitude scaling, depth scaling, near-source saturation, and distance scaling components of the GMM.

D.6.1 Organisation

The forward simulations were performed using the Center for Advanced Research Computing (CARC) resources at the University of Southern California. Tables D-3 and D-4 list the parameters used to define the earthquake scenarios for the Cratonic and non-Cratonic simulations, respectively. The scenarios are all reverse-faulting earthquakes with **M** ranging from 5.0 to 7.75 with rupture dimensions from the Leonard (2010) magnitude-area scaling relations for SRC (Cratonic) and DS (dip-slip non-

Cratonic) earthquakes, which have different dimensions, as indicated in Tables D-3 and D-4. For each magnitude, we specified one scenario which breaks the ground surface, even though small earthquakes do not usually break the surface in tectonically active regions (Wells and Coppersmith, 1994), and at least one scenario nucleating deeper in the crust. As indicated in Table D-1 and described by King et al. (2019) and Yang et al. (2021), earthquakes in Cratonic regions of Australia tend to have shallow hypocentres and rupture the ground surface, even for magnitudes 5.0 and smaller (Dawson et al., 2008). The 2021 Marble Bar earthquake in the Pilbara Craton and earthquakes near Cleve, Eyre Peninsula in the Gawler Craton are exceptions, occurring at depths of 30 km or more. Accordingly, for the Cratonic scenarios, two depths were used per magnitude: a surface rupturing earthquake, and one with depth to bottom of rupture at 30km. For non-Cratonic simulations, we used a range of earthquake depths for each magnitude. Ten realisations of the finite-fault source model with randomly located hypocentres are used for each scenario.

Simulation stations (locations where the ground shaking time histories are saved) were oriented in rupture distance (R_{rup}) bands surrounding the finite faults, with 20 stations per band surrounding the rupture at the following rupture distances: 0.1, 0.2, 0.3, 0.5, 1, 2, 3, 5, 7, 10, 20, 30, 50, 70, 100, 200, 300, 500, and 600 km (Figure D-10). In cases where the earthquake depth is greater than any of these R_{rup} distances, the subset of possible distance bands was used. Using the same R_{rup} bands for each scenario, regardless of the depth, allows for isolation of depth effects, as described further below. Figure D-11 shows examples of the dense coverage of magnitudes and distances in two Non-Cratonic simulations and the large quantity of simulation stations per scenario. The simulations use the Green's functions described above and are for a reference V_{S30} condition of 760 m/s with no site response.

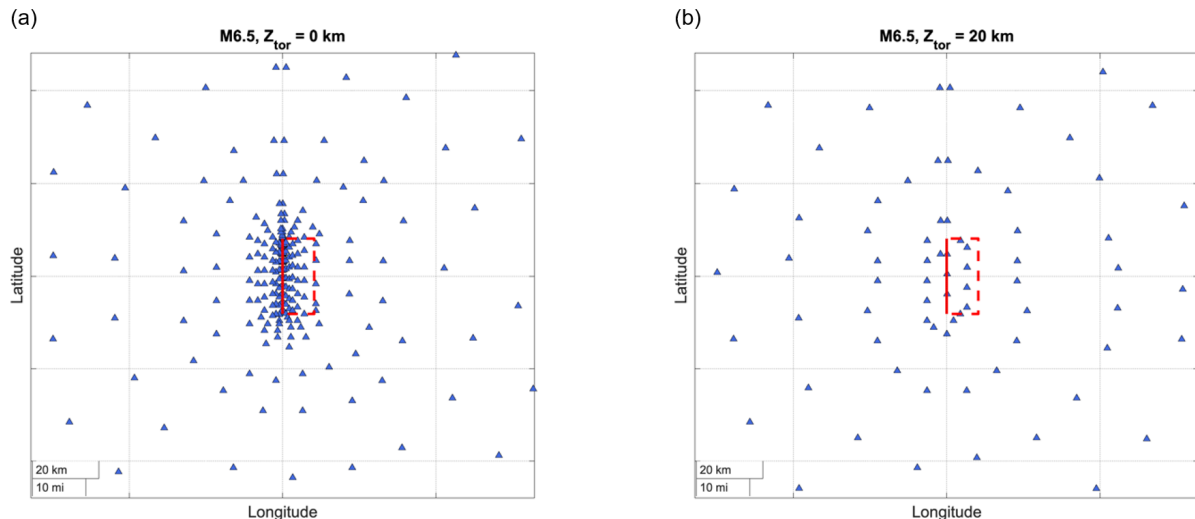


Figure D-10 Maps of ground motion simulation station locations (triangles) and the surface projection of the rupture planes (red lines) for M6.5 scenarios with depths to the top of rupture of (a) 0 km and (b) 20 km. For visibility, only simulation stations within about 50km of the surface trace are shown.

Table D-3 Simulation parameters of the Cratonic region earthquake scenarios used in the GMM development

M	Rupture Length, L (km) from Leonard (2010)	Down-Dip Rupture Width, W (km) from Leonard (2010)	Dip (deg)	Depth to top of rupture, Z_{tor} (km)	Depth to Bottom of Rupture (km)
5.0	2.6	2.5	45	0.0	1.8
				28.2	30.0
5.5	5.1	4.0	45	0.0	2.8
				27.2	30.0
6.0	10.2	6.3	45	0.0	4.5
				25.5	30.0
6.5	20.3	10.0	45	0.0	7.1
				22.9	30.0
7.0	40.6	15.9	45	0.0	11.2

M	Rupture Length, L (km) from Leonard (2010)	Down-Dip Rupture Width, W (km) from Leonard (2010)	Dip (deg)	Depth to top of rupture, Z_{tor} (km)	Depth to Bottom of Rupture (km)
				18.8	30.0
7.5	80.9	25.2	45	0.0	17.8
				12.2	30.0
7.75	114.3	31.7	45	0.0	22.4

Table 0-1 Simulation parameters of the Non-Cratonic region earthquake scenarios used in the GMM development.

M	Rupture Length, L (km) from Leonard (2010)	Down-Dip Rupture Width, W (km) from Leonard (2010)	Dip (deg)	Depth to top of rupture, Z_{tor} (km)	Depth to Bottom of Rupture (km)
5.0	2.8	3.5	45	0.0	2.5
				5.0	7.5
				10.0	12.5
				15.0	17.5
				20.0	22.5
				25.0	27.5
5.5	5.7	5.6	45	0.0	3.9
				2.5	6.4
				5.0	8.9
				7.5	11.4
				10.0	13.9
				15.0	18.9
				20.0	23.9
				25.0	28.9
6.0	11.3	8.8	45	0.0	6.2
				5.0	11.2
				10.0	16.2
				15.0	21.2
				20.0	26.2
6.5	22.6	14.0	45	0.0	9.9
				5.0	14.9
				10.0	19.9
				15.0	24.9
				20.0	29.9
7.0	45.1	22.2	45	0.0	15.7
				5.0	20.7
				10.0	25.7
				15.0	30.7
7.5	90.0	35.1	45	0.0	24.8
				5.0	29.8

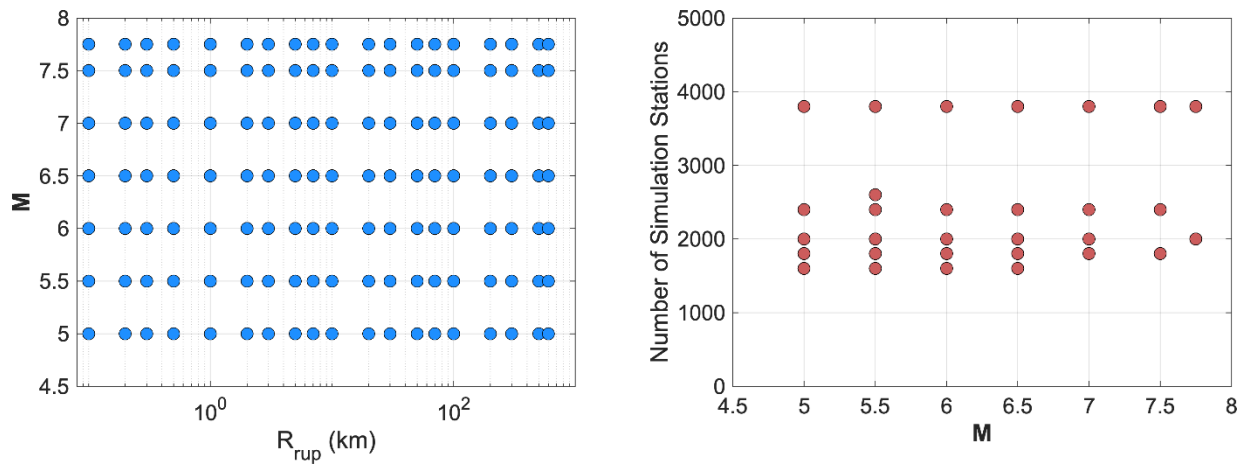


Figure D-11 Ground motion simulations used in the GMM development. Left: magnitude and distance pairs. Right: The number of ground motion simulations stations versus earthquake magnitude for the scenarios listed in Tables D-3 and D-4.

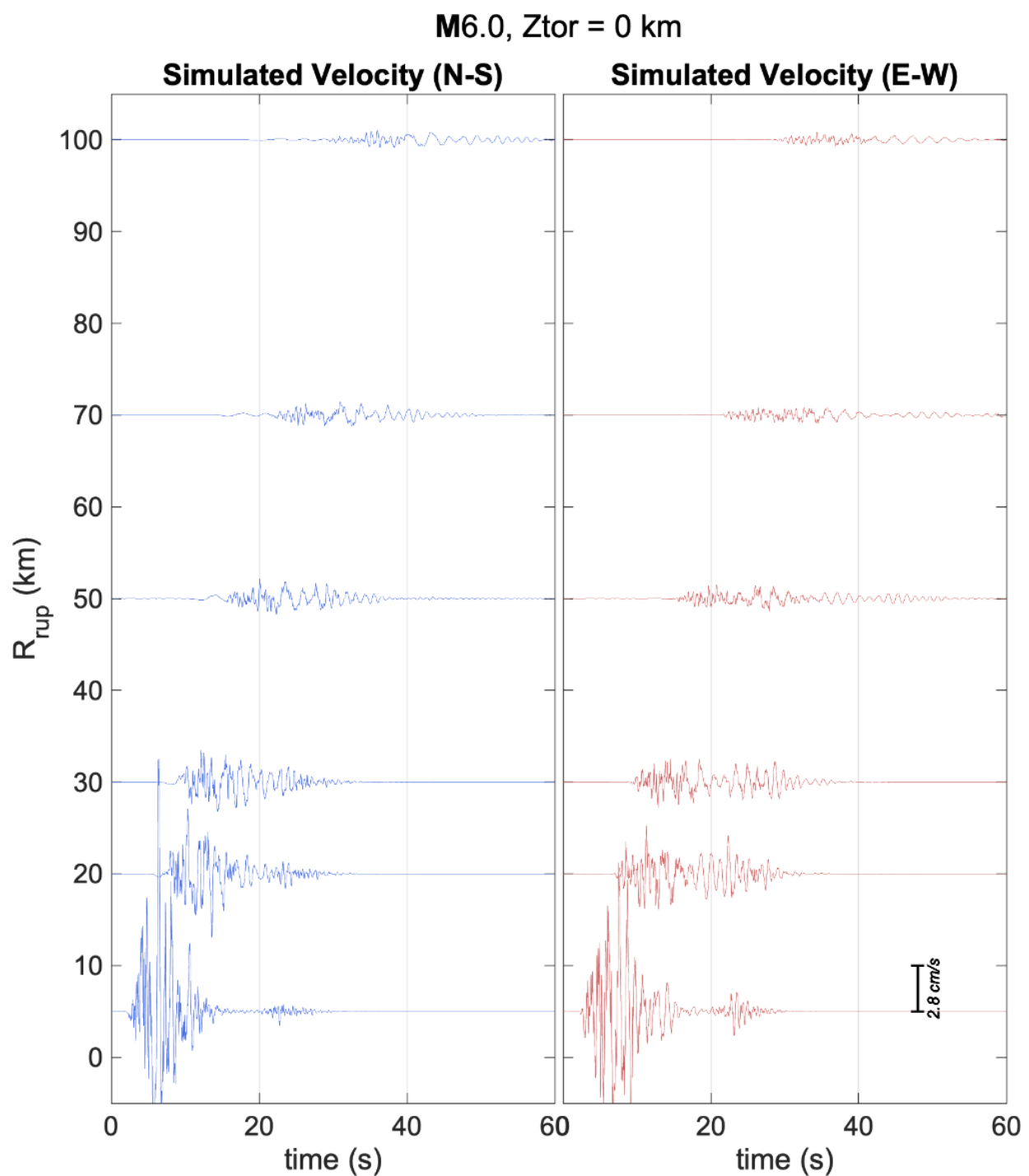


Figure D-12 Example velocity waveforms from a ground motion simulation. In this example, the Non-Cratonic earthquake source is M6.0 with $Z_{\text{tor}} = 0$ km depth (surface rupture) and simulated waveforms are shown at six simulation stations at distances ranging from 5-100 km and for both horizontal components.

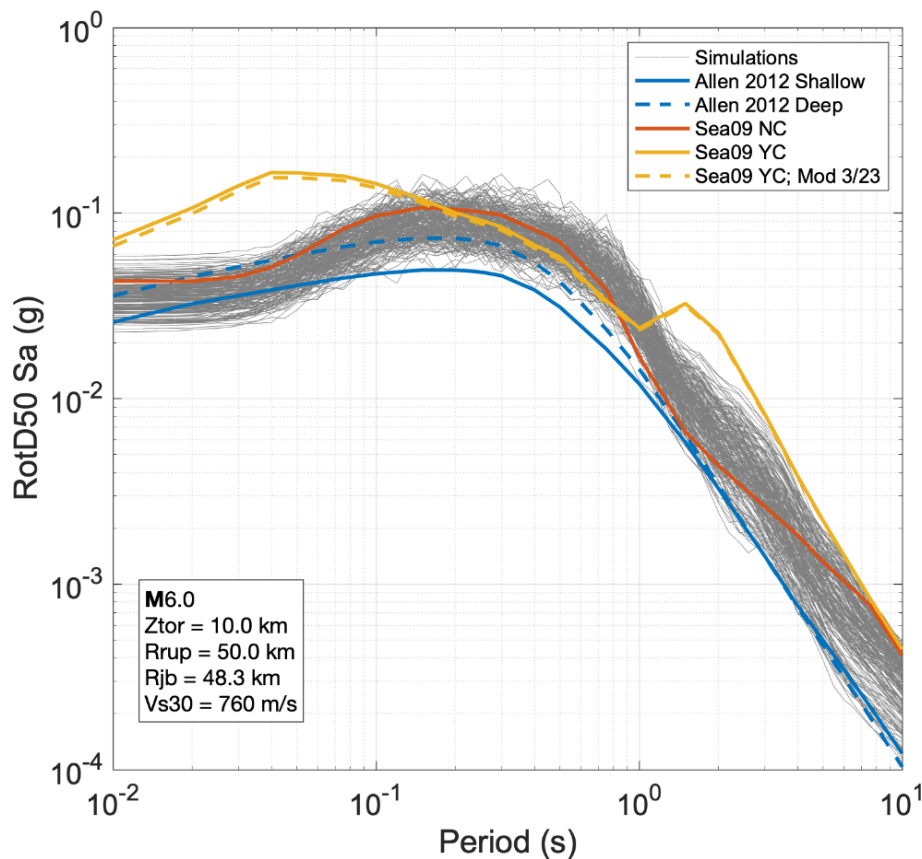


Figure D-13 Example response spectra from a ground motion simulation (Non-Cratonic M6.0 earthquake with $Z_{\text{tor}} = 10$ km, simulation stations at $R_{\text{rup}} = 50$ km). For comparison, the Allen (2012) and Sea09 median GMMs are shown for the same scenario.

D.6.2 Products

The principal products of the simulations are the ground motion time histories and response spectra. In total, there are 104,000 simulated three-component ground motion time histories from 410 simulated earthquakes. The ground motion time histories (acceleration, velocity, and displacement) were saved and plotted, e.g. Figure D-12. The simulated response spectra were also plotted and compared with The Sea09 and Allen (2012) GMMs, e.g. Figure D-13. The simulated response spectra and metadata were compiled into spreadsheets for use in the ground motion model update described in the next section.

D.7 Updated Ground Motion Model

D.7.1. Development Approach

The random-effects model was used for the regression analysis following the procedure described by Abrahamson and Youngs (1992). This procedure leads to the separation of total residuals into between-event residuals (δB) and within-event residuals (δW) following the notation of Al Atik et al. (2010).

The median GMM has components for magnitude scaling, distance scaling, and earthquake depth scaling which were developed from regression analyses on the simulations and checked against the data. The mixed effects regressions were performed in a series of steps to prevent trade-off of correlated model coefficients and to constrain different components of the model using the simulations or data relevant to each component. These steps are listed in Table D-5. At each regression step the model components determined in previous steps were fixed unless noted otherwise. In step 1, the earthquake depth scaling was determined using all of the Cratonic and Non-Cratonic simulations. The simulations were designed to isolate the depth scaling from distance scaling; see D.7.5. In steps 2 and 3, the magnitude scaling and near-source saturation of the magnitude scaling (the finite-fault effect) were determined from the simulations. In steps 4a and 4b, the distance scaling components were determined from the Cratonic and Non-Cratonic simulations, respectively. In steps 5a and 5b, the lead coefficient was determined for the Cratonic and Non-

Cratonic models respectively. In step 6 (which is not a regression but is included in Table D-5) we adopted the following model components from others: V_{S30} scaling, basin depth scaling, and hanging wall scaling for the median model, and a model for the aleatory variability. Finally, in steps 7a and 7b, we fixed all model coefficients except the lead coefficient and performed the regressions using the Cratonic and Non-Cratonic data with our Cratonic and Non-Cratonic models, respectively.

Table D-5 GMM regression steps.

Step	Data or Simulations Used	GMM Components Determined after the Regression Step
1	All Cratonic and Non-Cratonic Simulations	Earthquake Depth Scaling (f_{Ztor})
2	All Cratonic and Non-Cratonic Simulations	Magnitude Scaling (f_M)
3	All Cratonic and Non-Cratonic Simulations	Near-source saturation of magnitude scaling (additive distance c_{4M})
4a	Cratonic Simulations with $R_x < 0$ km (Footwall)	Distance Scaling (f_P) – magnitude dependent geometric spreading and Q for Cratonic GMM
4b	Non-Cratonic Simulations with $R_x < 0$ km (Footwall)	Distance Scaling (f_P) – magnitude dependent geometric spreading and Q for Non-Cratonic GMM
5a	Cratonic Simulations	Mean spectral shape (source spectrum coefficient a_1) – Cratonic GMM
5b	Non-Cratonic Simulations	Mean spectral shape (source spectrum coefficient a_1) – Non-Cratonic GMM
6	(Adopted from other Models; see text)	V_{S30} scaling, basin depth scaling, hanging wall scaling, and the aleatory variability
7a	Cratonic Data	Mean spectral shape (source spectrum coefficient a_1) – Cratonic GMM
7b	Non-Cratonic Data	Mean spectral shape (source spectrum coefficient a_1) – Non-Cratonic GMM

This staged model-building approach allowed us to iteratively compare the model and its components with the available data (Tables D-1 and D-2). That comparison was formalised in stages 7a and 7b using a mixed effects regression, in which we evaluated trends in residuals versus the predictive parameters, and we found that short period ground motions in non-Cratonic regions were being systematically under-estimated. We modified the leading coefficient (representing the mean spectral shape due to the energy radiated at the source) to account for this difference, so the GMMs are based on the combination of the scenario simulations and the data residual analyses.

The Cratonic and non-Cratonic versions of our GMM share a functional form and differ only in their coefficient values. The magnitude scaling and geometric spreading coefficients are the same for both models. The Cratonic and non-Cratonic GMMs differ in their high frequency source spectra and differ in their anelastic attenuation components; these represent the differences in source and crustal structure between regions.

Each of the model components from Table D-5 are described in the following sections.

D.7.2 Model Form

Because the Sea09 model works well for earthquake ground motions in Australia (e.g. Hoult et al., 2021; Allen et al., 2023, Tables 7.5 and 7.6), our initial preference was to make minor modifications to the model in this GMM update. However, the simulations indicated significant differences in magnitude scaling that we determined would be difficult to incorporate with minor modifications to Sea09. Additionally, we wanted to adopt an existing model for hanging wall effects and identified the Donahue and Abrahamson (2014) model as the best option. The Donahue and Abrahamson (2014) model is designed to adjust a model based on the rupture distance metric (R_{rup}) and is not compatible with a Joyner-Boore distance (R_{JB}) based model, which Sea09 uses. Because of these factors, we chose to develop a completely new model rather than a modification to Sea09, by adopting the formulation of the magnitude and distance scaling from Abrahamson et al. (2014; ASK14 hereafter).

The model for the RotD50 component of 5% damped spectral acceleration (units g) is:

$$\ln(RotD50) = \ln(RotD50)_{med} + \epsilon\sigma \quad (D-1)$$

in which σ is the total aleatory variability and the standard normal random variable ϵ is the number of logarithmic standard deviations above or below the median. The median model is:

$$\ln(RotD50)_{med} = f_M + f_P + f_S + f_{Z1.0} + f_{Ztor} + f_{HW} \quad (D-2)$$

in which each of the model components in Eq. D-2 is described in the following sections. The values for all model coefficients are provided in Section D.10.

D.7.3 Magnitude Scaling

To represent the effects of energy radiated at the source, the polynomial formulation for the magnitude scaling is adopted from ASK14:

$$\begin{aligned} f_M &= a_1 + a_5(\mathbf{M}-M_1) + a_8(8.5-M)^2 & \text{for } \mathbf{M} \geq M_1 \\ f_M &= a_1 + a_4(\mathbf{M}-M_1) + a_8(8.5-M)^2 & \text{for } M_2 \leq \mathbf{M} < M_1 \\ f_M &= f_M(\mathbf{M}=M_2) + a_6(\mathbf{M}-M_2) + a_7(M-M_2)^2 & \text{for } \mathbf{M} < M_2 \end{aligned} \quad (D-3)$$

where $\mathbf{M}$ is the moment magnitude and the magnitude scaling breaks are $M_2 = 5.0$ and period-dependent M_1 ranging between 6.75 and 7.25. The magnitude scaling term coefficients a_1 , a_4 , a_5 , and a_8 , were determined in the regression from simulations (Table D-5). The coefficients a_6 and a_7 are for $\mathbf{M}$ 4.0-5.0 which is outside the range of the simulations. We adopted the ASK14 values of a_6 and a_7 after verifying that the model scaled well with the data for these magnitudes. The leading coefficient a_1 (representing the mean spectral shape due to the energy radiated at the source) is different for the Cratonic and Non-Cratonic GMMs to account for the differences source and crustal structure between regions.

D.7.4 Distance Scaling

The path scaling formulation of ASK14 is used:

$$f_P = [a_2 + a_3(\mathbf{M}-M_1)] \ln(R) + a_{17}R_{rup} \quad (D-4)$$

where $R = (R_{rup}^2 + c_{4M}^2)^{1/2}$ with R_{rup} in km and c_{4M} is the additive distance term to represent the near-source amplitude saturation effects of the finite-fault rupture dimension as described in Abrahamson et al. (2014). The $\ln(R)$ term models the magnitude-dependent geometric spreading and the term $a_{17}R_{rup}$ models anelastic attenuation and scattering effects (Q). The Q term models deviations from the attenuation due to geometric spreading, and the Cratonic and Non-Cratonic GMMs have different Q models to account for the differences crustal structure between regions.

D.7.5 Earthquake Depth Scaling

For source effects related to earthquake depth we have developed a new model which represents the effects of R_g waves from shallow events, impacting longer periods, and the effects of energetic buried ruptures, impacting short periods. This depth model is a polynomial of the form:

$$f_{Ztor} = d_1 Z^3 + d_2 Z^2 + d_3 Z + d_4 \quad (D-5)$$

where $Z = \min(Z_{tor} - 10, 5)$ and d_1 through d_4 are period-dependent coefficients and Z_{tor} is the depth to the top of the rupture plane in km. Figure D-14 shows the depth scaling model for a set of spectral periods.

Somerville (2003) found that the short-period ground motions generated by earthquakes that do not have large shallow asperities are stronger than those of earthquakes that do. The simulations we performed, and the Z_{tor} scaling model derived from them, is consistent with this observation: the short periods (dotted lines) have lower ground motions for shallow sources and higher ground motions for deeper sources. Allen (2012) empirically developed analogous shallow and deep models based on data from southeastern Australian earthquakes.

Somerville et al. (2009) found that a shallow low velocity layer overlying crystalline basement explained very dispersive R_g waves observed in recordings of shallow Australian earthquakes, noting that R_g is typically excited by events shallower than 3km (Saikia et al., 1998). As a result, the Sea09 Cratonic model includes a localised peak (or bump) in the predicted response spectra for periods of approximately 2-3 seconds due to the shallow earthquake source located in the high near-surface velocity structure. Our simulations are also consistent with this as shown in Figure 1; for shallow earthquakes the periods between about 1.5-3 sec (dashed lines) have stronger ground motions. For periods longer than about 3 sec (solid lines) the simulations demonstrated decreasing ground motions with depth (down to about 20 km) at a given R_{rup} .

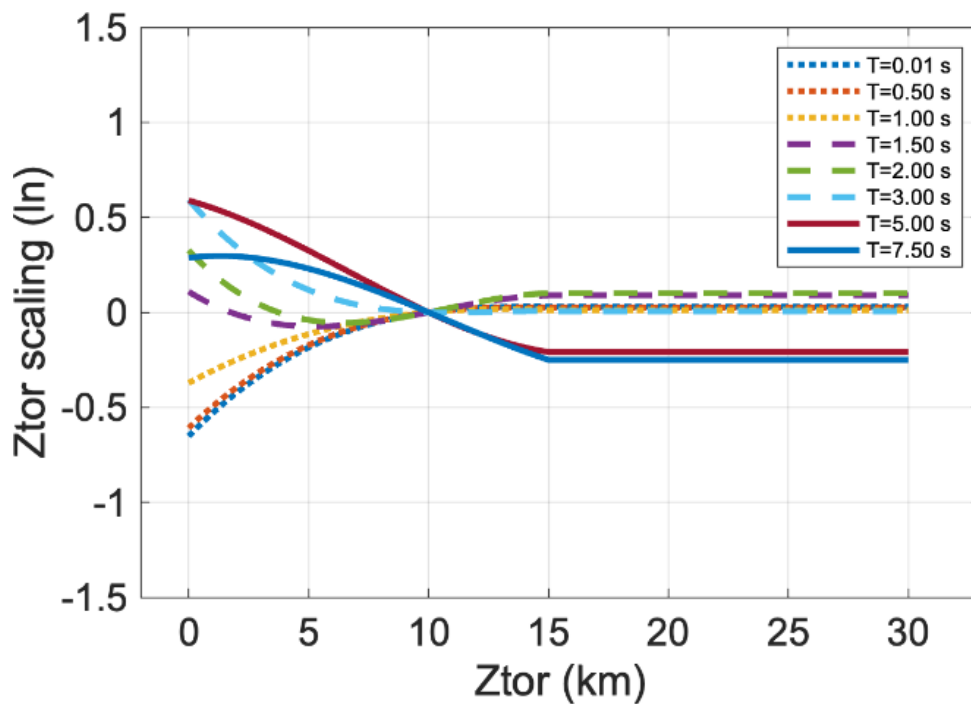


Figure D-14 The earthquake depth (Z_{tor}) scaling model.

The model shown in Figure D-14 was developed from the simulations using the following approach. For each scenario earthquake (with a fixed magnitude) the ground motions at a given rupture distance were averaged over all simulation stations with the same rupture distance. The mean RotD50 spectral acceleration at this distance was then examined versus the earthquake depth (e.g., Figure D-15a). The simulations were intentionally assembled this way to isolate the effect of the earthquake depth at a given magnitude and distance. The trends of mean RotD50 (at a given magnitude and distance) versus depth were evaluated for the full range of scenario magnitudes, distances, and spectral periods. We found a consistent and clear pattern of reduced short period ground motions for shallow earthquakes, and of larger long period ground motions for shallow earthquakes, with minimal scaling beyond 10 km depth (e.g., Figure D-15a). Using the simulation data from all scenario earthquakes, we took the natural log of the mean RotD50 at a given magnitude and distance normalized by the mean RotD50 at $Z_{tor} = 10$ km (e.g., Figure D-15b), and fit the four coefficients of Eq. D-5. These natural log values represent the target behavior of the depth scaling in the GMM

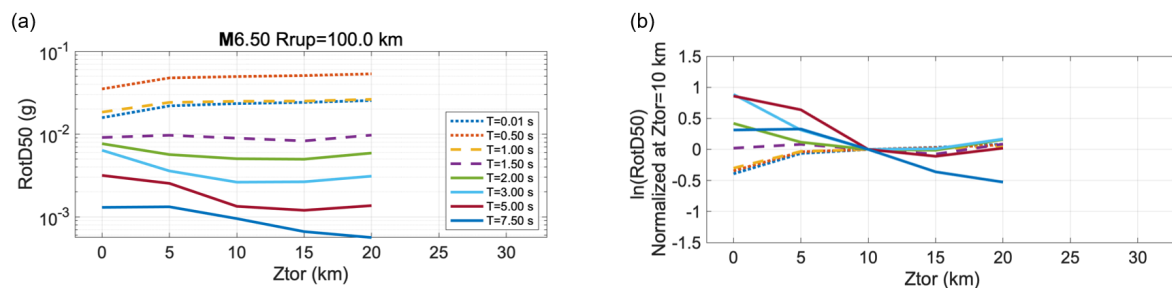


Figure D-15 Example evaluation of the effect of earthquake depth, (a) in this example for a M6.5 simulation, showing mean RotD50 for all stations with R_{rup} of 100 km. (b) Showing the natural log of the mean RotD50 data from (a) normalized by the value at $Z_{tor} = 10$ km.

These results were evaluated for all combinations of magnitude, distance, and spectral period. At short periods, there is a clear reduction in the GMs for shallow events at all distances. For longer spectral periods (longer than about 3 sec), there is some distance dependence, with stronger Z_{tor} scaling for the larger distances. At intermediate spectral periods (approximately 1 sec), there is relatively moderate depth scaling of the GMs across all distances and magnitudes. For model simplicity, we chose not to model any magnitude or distance dependence of the depth scaling. We fit the depth scaling polynomial of D-5, with the coefficient d_4 fixed to zero, at each period independently. By fixing d_4 to be zero, Equation D-5 is a third order polynomial without a constant coefficient, and the scaling model is forced to be zero (no scaling) at $Z_{tor} = 10$ km. We selected this depth for centering the model based on the observation that there is minimal scaling in the ground motions beyond this

depth, especially for the short spectral periods. With this modeling decision, $Z_{tor} = 10$ km is the reference depth for adjusting the ground motions.

The model is a better fit to the simulation data at short spectral periods compared with longer spectral periods. The cap for Z_{tor} scaling at 15 km was set based on the observation that the functional form we selected is an oversimplification of the depth scaling of the simulated ground motions for long periods. At these periods, the depth scaling varies with distance, most significantly for Z_{tor} values larger than about 15 km. The uncertainty is large enough that we chose to cap the scaling at 15 km. To support this decision, we calculated the log-likelihood values for the fit of Equation D-5 at each spectral period. The log-likelihood value of a regression model is a way to measure the goodness of fit for a model. The higher the value of the log-likelihood, the better a model fits a dataset. The log-likelihood value for a given model can range from negative infinity to positive infinity. The actual log-likelihood value for a given model is mostly meaningless but is useful for comparing models. We use the log-likelihood to measure the fit of the depth scaling model between spectral periods, and to compare the depth scaling model when applied to all depths and only applied to depths of 15 km and less. Using log-likelihoods supports the observation that the depth scaling model fits the simulation data better at short periods (shorter than about 1 sec). There is a modest improvement in the fit when capping the Z_{tor} scaling to 15 km and less, which also supports our decision to use this cap.

D.7.6 Adopted Median Model Components

We adopted the hanging wall effects model from Donahue and Abrahamson (2014) as implemented in ASK14, including the functional form and coefficients. This model is designed to modify a GMM based on R_{rup} and was calibrated based on simulations similar to those used in this paper and validated against the available data. The hanging wall model increases the short period ground motions for near-fault sites on the hanging wall side of the rupture using distance tapers to define the hanging wall region.

Models for V_{S30} scaling and $Z_{1.0}$ scaling are adopted from Boore et al. (2014), including the functional form and coefficients. The Boore et al. (2014) V_{S30} scaling model is described in Seyhan and Stewart (2014) and includes linear and non-linear components; this model has a reference V_{S30} (velocity at which the amplification is unity) of 760 m/s which is directly compatible with our simulation-based GMM. The $Z_{1.0}$ scaling is an adjustment to the base model to consider the effects of basin depth; it is based on the variation in $Z_{1.0}$ at a given site relative to the average $Z_{1.0}$ derived from V_{S30} . Until further data V_{S30} and $Z_{1.0}$ data are collected in Australia, we recommend using the default Boore et al. (2014) $Z_{1.0}$ value derived from V_{S30} , which turns off the $Z_{1.0}$ scaling component of the GMM.

D.7.7 Aleatory Variability Model

Models for the aleatory variability are adopted from Al Atik (2015), including models for the between-event standard deviation (τ), and total within-event standard deviation (ϕ). The total standard deviation in natural log units is calculated from these components using Eq. D-6:

$$\sigma = \sqrt{\tau^2 + \phi^2} \quad (D-6)$$

where the Al-Atik (2015) model for τ has the form of Eq. D-7:

$$\tau = \begin{cases} \tau_1 & \text{for } M \leq 4.5 \\ \tau_1 + (\tau_2 - \tau_1) * \frac{M-4.5}{0.5} & \text{for } M \leq 5.0 \\ \tau_2 + (\tau_3 - \tau_2) * \frac{M-5.0}{0.5} & \text{for } M \leq 5.5 \\ \tau_3 + (\tau_4 - \tau_3) * \frac{M-5.5}{1.0} & \text{for } M \leq 6.5 \\ \tau_4 & \text{for } M > 6.5 \end{cases} \quad (D-7)$$

and where the Al-Atik (2015) model for ϕ has the form of Eq. D-8:

$$\phi = \begin{cases} \phi_a & \text{for } M \leq 5.0 \\ \phi_a + (M - 5.0) * \frac{\phi_b - \phi_a}{1.5} & \text{for } M \leq 6.5 \\ \phi_b & \text{for } M > 6.5 \end{cases} \quad (D-8)$$

The values for coefficients τ_1 , τ_2 , τ_3 , τ_4 , ϕ_a and ϕ_b are provided in Section D.10.

D.7.8 Model Range of Applicability

The Cratonic and non-Cratonic GMMs are applicable for M 4.0-8.0, rupture distances from 0-300 km, and spectral periods 0.01-10 sec. The Boore et al. (2014) V_{S30} and $Z_{1.0}$ models are applicable for V_{S30} between 150-1,500 m/s and $Z_{1.0}$ between 0-3 km, and although we recommend using the same ranges, care should be taken to use these models until more V_{S30} and $Z_{1.0}$ data are collected in Australia. The upper limit of M 8.0 is beyond the largest simulation (M 7.75) and is based on extrapolation which we have checked and assumed to be reasonable. The GMM lower limit of M 4.0 is lower than the smallest magnitude of the forward simulations (M 5.0; Tables 3 and 4) and this is appropriate because the validation of the simulation methodology was performed using the data listed in Tables D-1 and D-2, which mostly ranges from M 4-5, and because the GMM verifications described below were performed using the same data.

D.8 Model Performance

D.8.1 Median Scaling and Comparisons with Other Models

Figure D-16 shows median response spectra from the models for the reference V_{S30} condition of 760 m/s, without $Z_{1.0}$ scaling, and for $Z_{tor} = 0$ km. In Figure D-16, the solid lines are the non-Cratonic model, and the dotted lines are the Cratonic model. The different line colours are for different earthquake M as indicated in the figure legend. The left and right panels of Figure D-16 show response spectra for $R_{rup} = 15$ km and 150 km, respectively.

In Figure D-16, the saturation in magnitude scaling at large M , especially at short periods and close distances, is apparent in the large spread in median spectra for small magnitudes, and very little sensitivity at larger M . The M -dependence of the predominant period is visible, with longer predominant period for increasing M . This figure also illustrates the differences between Cratonic and non-Cratonic models; for a given M and R_{rup} , the Cratonic model has higher short period (less than 0.2 sec) median response spectra, and the two models are more similar at longer spectral periods.

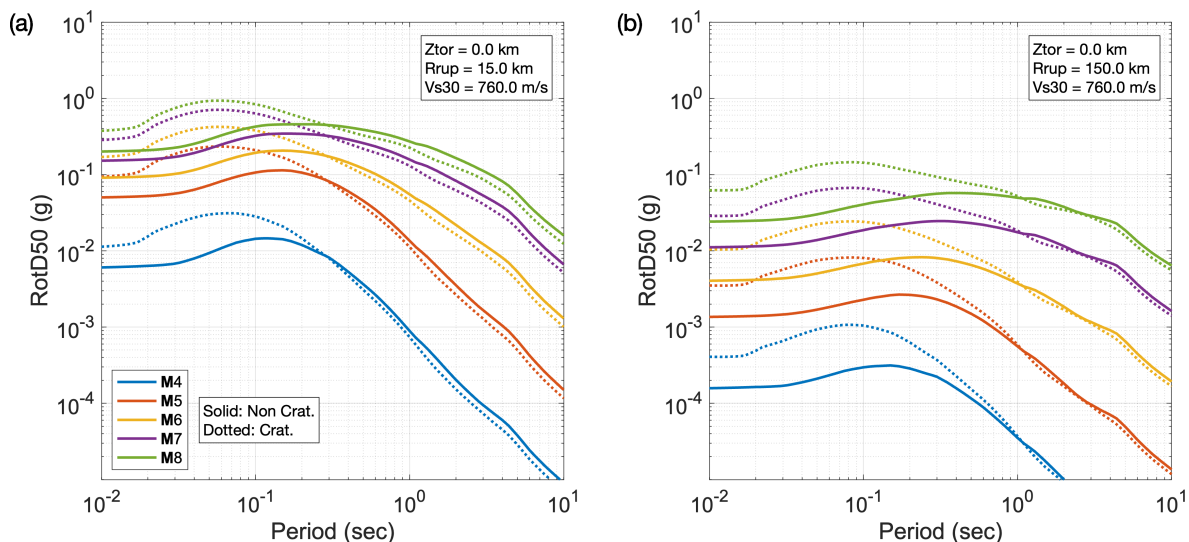


Figure D-16 Median GMM response spectra for scenarios with $Z_{tor}=0$ km and the reference V_{S30} condition and without $Z_{1.0}$ scaling, for range of magnitudes (colours), for the Cratonic (dotted lines) and non-Cratonic (solid lines) models, at (a) R_{rup} of 15 km and (b) 150 km.

Figure D-17 compares the short-period median response spectra versus R_{rup} with the Australian GMMs Allen (2012) and Sea09. This comparison uses $Z_{tor} = 5$ km and assumes sites are located on the footwall of the fault so there are no hanging wall effects. Sea09 is an R_{JB} model and in Figure D-17 we use $R_{JB} = (R_{rup}^2 - Z_{tor}^2)^{1/2}$; this assumption is exact for sites on the footwall side of the rupture. We note that the Allen (2012) deep GMM is not strictly comparable to our models for 5 km depth but is still informative.

Figure D-17 shows that the non-Cratonic model attenuates short-period ground motions more rapidly with increasing distance than the Cratonic model, due to differences in crustal Q (the $a_{17}R_{rup}$ term). The most significant differences in Figure D-17 are due to how the attenuation with distance is modelled. Allen (2012) used a tri-linear geometrical attenuation featuring a transition zone between approximately 80-150 km in which the ground motions increase with distance, designed to account for direct waves joined by postcritical reflections from the Moho as originally proposed by Burger et al. (1987) and modelled by Allen (2012) and Allen et al. (2007). Sea09 represented the arrival of critical

reflections from the lower crust with a decreased attenuation at 50 km but did not model an increase in ground motions with distance. Our analyses of the available data support a change in attenuation in this distance range as shown in Section D.8.2, but our simulations support an attenuation model without a transition zone, such as the adopted ASK14 distance scaling model. Because of the limited quantity of recorded data, and particularly our uncertainty in the site response adjustments, we elected to base the distance scaling component of our model primarily on the simulations.

Figure D-18 compares median ground motions versus distance for the hanging wall (solid lines) and footwall (dashed lines) sides of the fault. In Figure D-18, R_x is the horizontal distance from the top edge of the rupture to the site measured perpendicular to the fault strike and W is the rupture down-dip width; all scenarios assume a dip of 45 degrees.

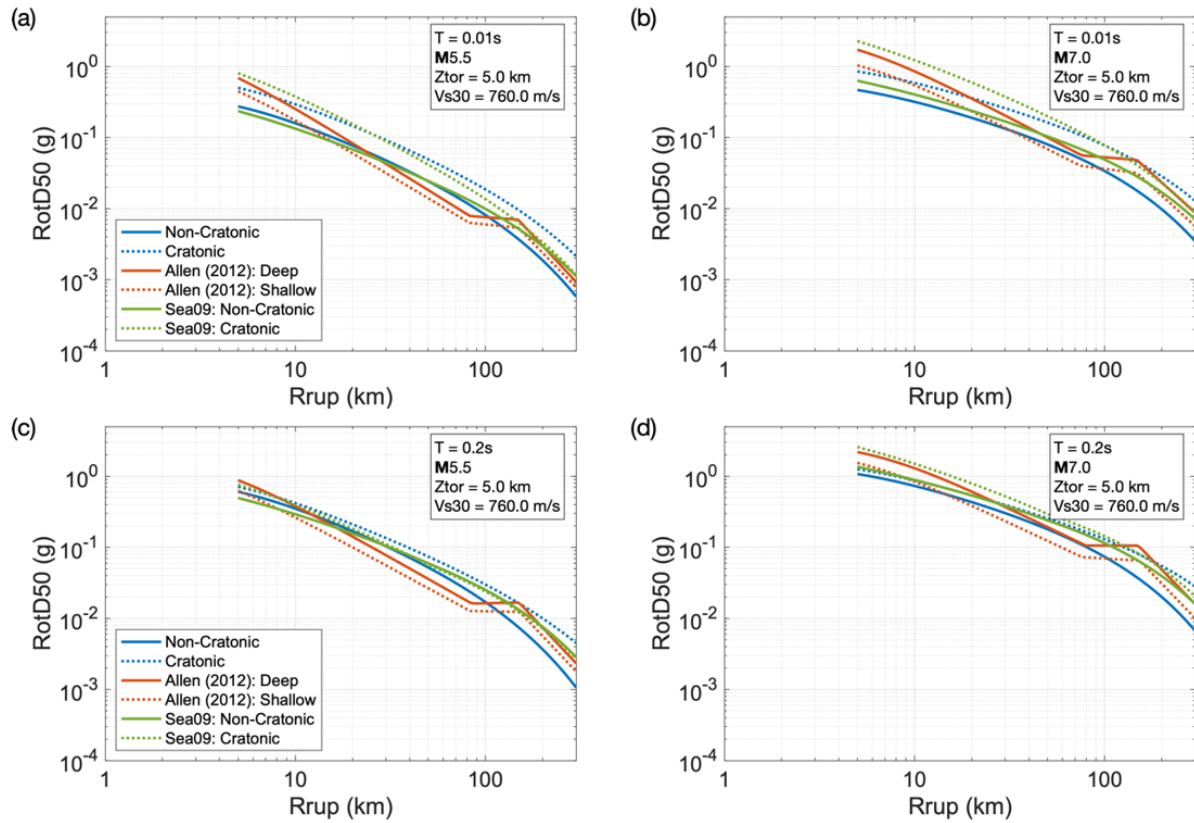


Figure D-17 A comparison of short-period median GMM response spectra for sites on the footwall side of the rupture and the reference V_{s30} condition, scenarios with $Z_{tor} = 5$ km: (a) $T = 0.01$ sec and $M5.5$, (b) $T = 0.01$ sec and $M7.0$, (c) $T = 0.2$ sec and $M5.5$, (d) $T = 0.2$ sec and $M7.0$.

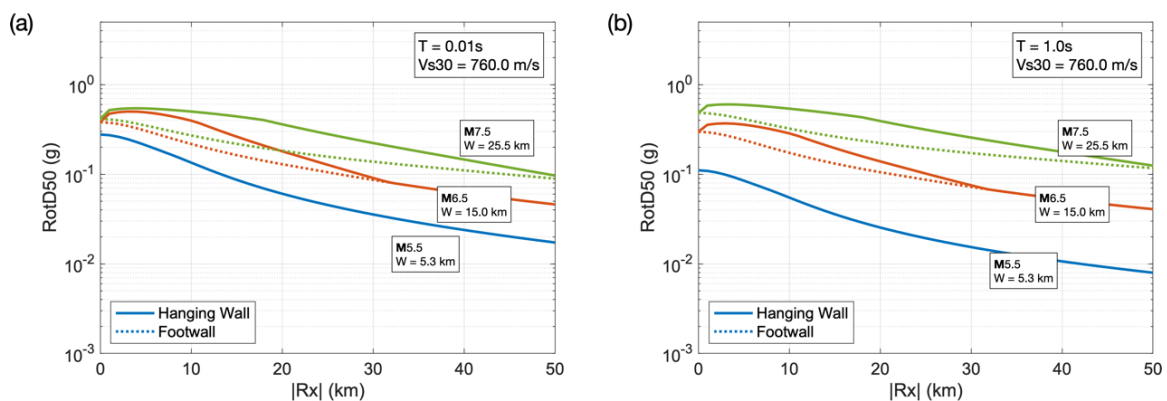


Figure D-18 A comparison of hanging wall and footwall ground motions at: (a) $T = 0.01$ sec and (b) $T = 1$ sec. All sites use the reference V_{s30} condition, and all scenarios use $Z_{tor} = 0$ km.

Sea09 observed and modelled a localised peak around 1.5-2.0 seconds in the response spectra due to the R_g waves caused by a shallow low velocity layer in the Yilgarn Craton crust; this feature is present in the Sea09 Cratic model for all earthquake depths (Figure D-19). In our new model, the effects of R_g waves are represented in the depth scaling term which amplifies the long period ground

motions for shallow earthquakes (Figure D-19a) and de-amplifies them for deep earthquakes (Figure D-19b). Relative to the Sea09 model, this long-period amplification is over a broader period range and so the spectral shape does not have a localised peak around 1.5-2.0 seconds. Figure D-19 also shows that the revised Cratonic model has significantly different magnitude scaling from Sea09, especially at short spectral periods.

Figure D-20 shows the magnitude scaling of the median GMMs for short ($T=0.2$ sec) and long ($T=3.0$ sec) spectral periods, and for rupture distances 1, 30, and 200 km. This figure illustrates the near-source saturation of the magnitude scaling (the finite-fault effect) which strongly impacts the model predictions at short periods.

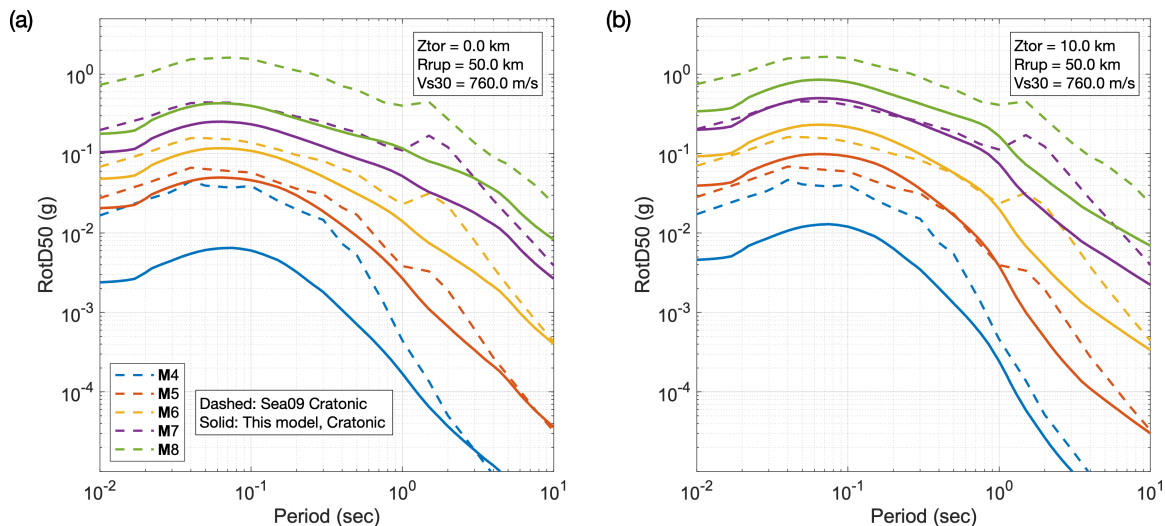


Figure D-19 A comparison of footwall median GMM response spectra between Sea09 Cratonic (dashed lines) and the new Cratonic model (solid lines) at $R_{rup} = 50$ km, for (a) $Z_{tor} = 0$ km and (b) $Z_{tor} = 10$ km.

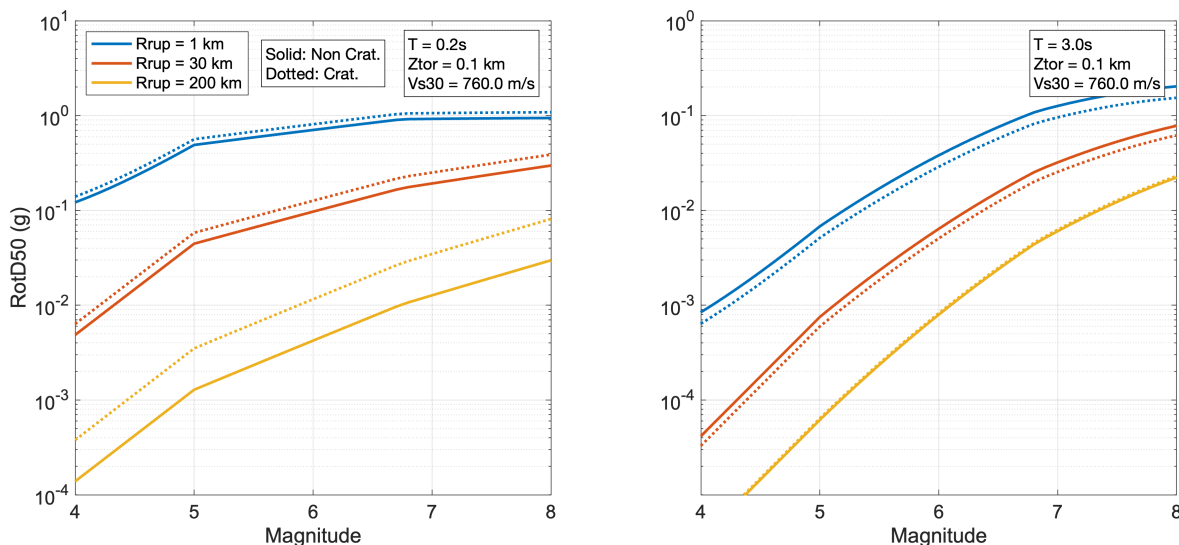


Figure D-20 Magnitude scaling of the median GMM at: (a) $T = 0.2$ sec and (b) $T = 3.0$ sec. All sites use the reference V_{s30} condition, and all scenarios use $Z_{tor} = 0.1$ km.

D.8.2 Comparisons with Recorded Data

In regression stages 7a and 7b (Table D-5) we used the data described in Section D.3 to check that the median GMM developed from the simulations is compatible with the Australian data. The total residual, defined as the difference between the natural logarithm of the recorded spectral acceleration (data) and the natural logarithm of the median GMM, is partitioned into between-event residuals (δB) and within-event residuals (δW) in the mixed-effects regression. Figure D-21 compares the 2012 Moe earthquake response spectra with the median GMM and within-event residuals at $T=0.2$ sec and $T=1$ sec. This figure shows that the overall ground motion levels are well-predicted for this event, and that the distance scaling in the model is compatible with the data, as evident in the lower panels of Figure D-21, where the within-event residuals do not show trends with distance.

Figure D-22 shows the between-event residuals for all Cratonic and Non-Cratonic earthquakes from section D.3 at $T=0.2$ and $T=1$ sec, which we believe to have acceptably small biases and trends. Figure D-23 shows within-event residuals versus the model predictive parameters at $T=0.2$ sec and $T=1$ sec. This figure shows that the model is not strongly biased with respect to magnitude, depth, or distance in comparison with the Australian data. There is a visible trend in the V_{S30} scaling at $T=1$ sec, although it is highly uncertain due to the shortage of data, especially for V_{S30} values lower than 400 m/s. The uncertainties in V_{S30} values and in the site response adjustments are significant and could be reduced in the future with additional data collection or improved models; these sources of uncertainty were similarly identified and accepted in NGA-East (Goulet et al., 2021).

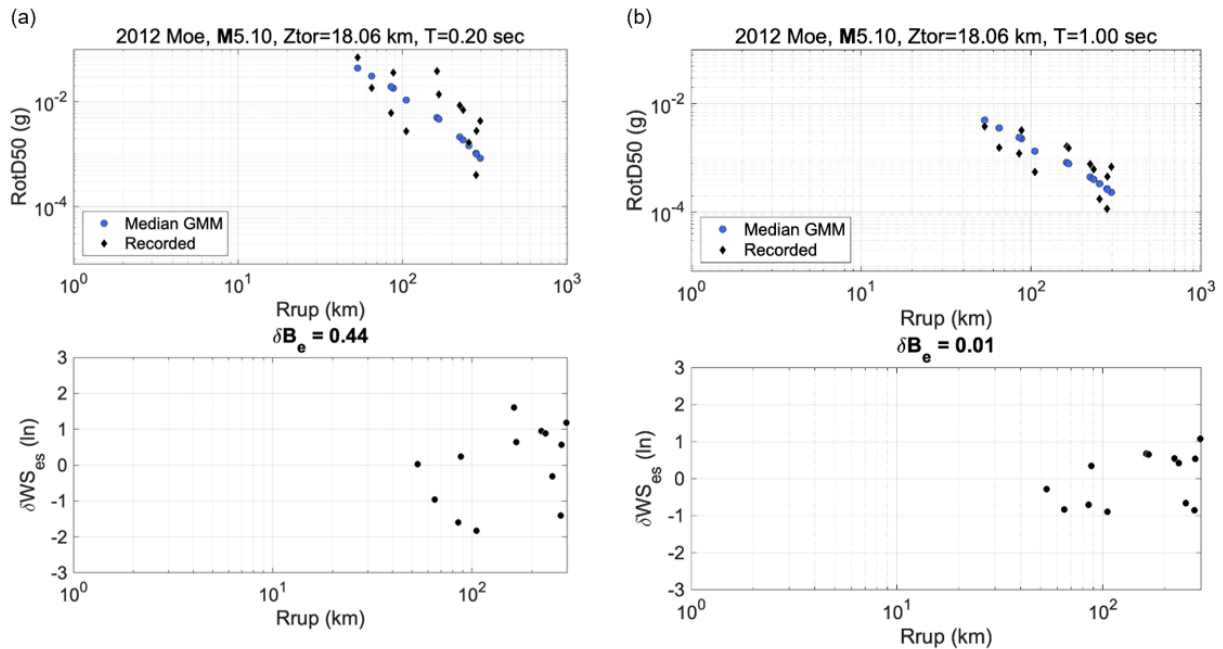


Figure D-21 Comparison between the model and data recorded in the 2012 Moe earthquake.

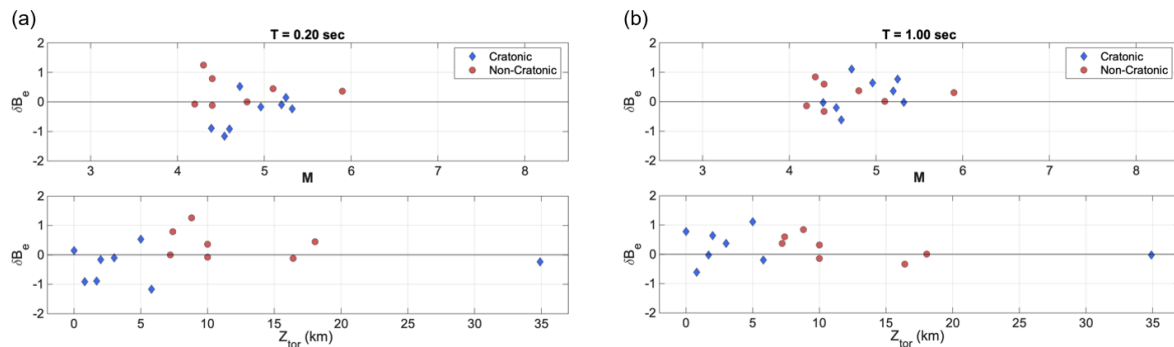


Figure D-22 Between-event residuals for the complete dataset versus magnitude and depth (a) $T=0.2$ sec, (b) $T=1$ sec.

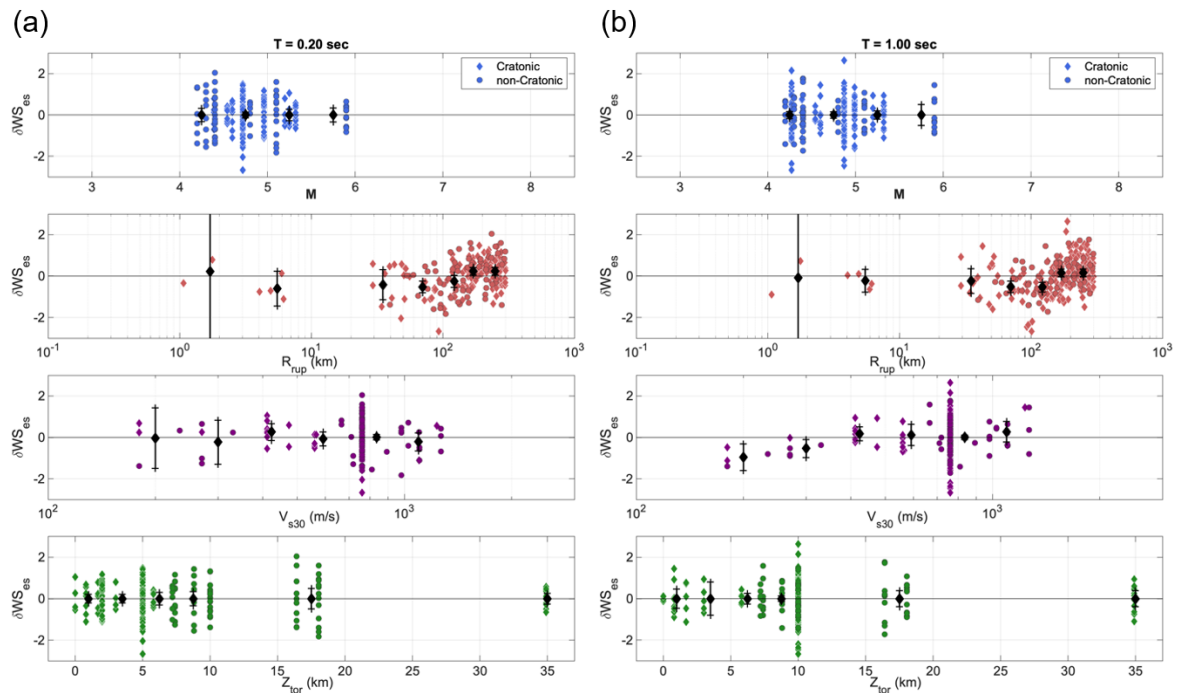


Figure D-23 Within-event residuals versus magnitude, R_{rup} , V_{s30} , and Z_{tor} at (a) $T=0.2$ sec, (b) $T=1$ sec. Black diamonds with whiskers represent the binned residual means with 95% confidence intervals.

D.8.3 Model Evaluation using the 2019 M6.6 Kimberley Coast Earthquake

As of early 2025, the 2019 earthquake off the Kimberley Coast has publicly available ground motion data that were not available at the time this model was developed (late 2024). These data are particularly useful because this earthquake is the largest magnitude earthquake in the dataset used to develop the GMM, and we previously had only one usable recording of this earthquake. Because we applied a lower limit of 5 recordings per earthquake in the GMM regression, the single recording from this event was not used in developing or evaluating the GMM described in this appendix. With significantly more ground motion data for this earthquake we can do two things: (1) evaluate the previously developed GMM with the newly acquired ground motion recordings and (2) repeat the GMM regression using these recordings to evaluate which changes, if any, to the GMM would better fit these data.

2019 Earthquake Ground Motion Data

We collected the waveform data from the the Australian Passive Seismic Server (AusPass) hosted by the International Federation of Digital Seismograph Networks (Huaiyu Yuan, 2017). The temporary broadband seismic array on the China-Western Australia Seismic Array (CWAS) (4N) network was operated by Macquarie University, Geological Survey of Western Australia, and the Institute of Geology and Geophysics, Chinese Academy of Sciences (Zhao et al., 2022; Li et al., 2024). The stations for which we collected ground motion waveforms are shown in Figure D-24. This array was in operation between the years 2017-2022, although the ground motion data were not publicly available until early 2025. We downloaded and processed the waveforms following the processing procedures described in Section D.3. In total there were 60 sites in the temporary array, and we downloaded 30 based on an initial screening of the data for source-to-site distances, data quality, and excluding ocean-bottom seismometers. Of this dataset, 13 recordings have distances less than 300 km and are therefore candidates to be compared with the GMM (Table D-6). The 5%-damped, horizontal component pseudo-spectral accelerations (RotD50; Boore, 2010) were calculated from the two-component band-passed acceleration time histories using the pyRotd python library (Kottke, 2018).

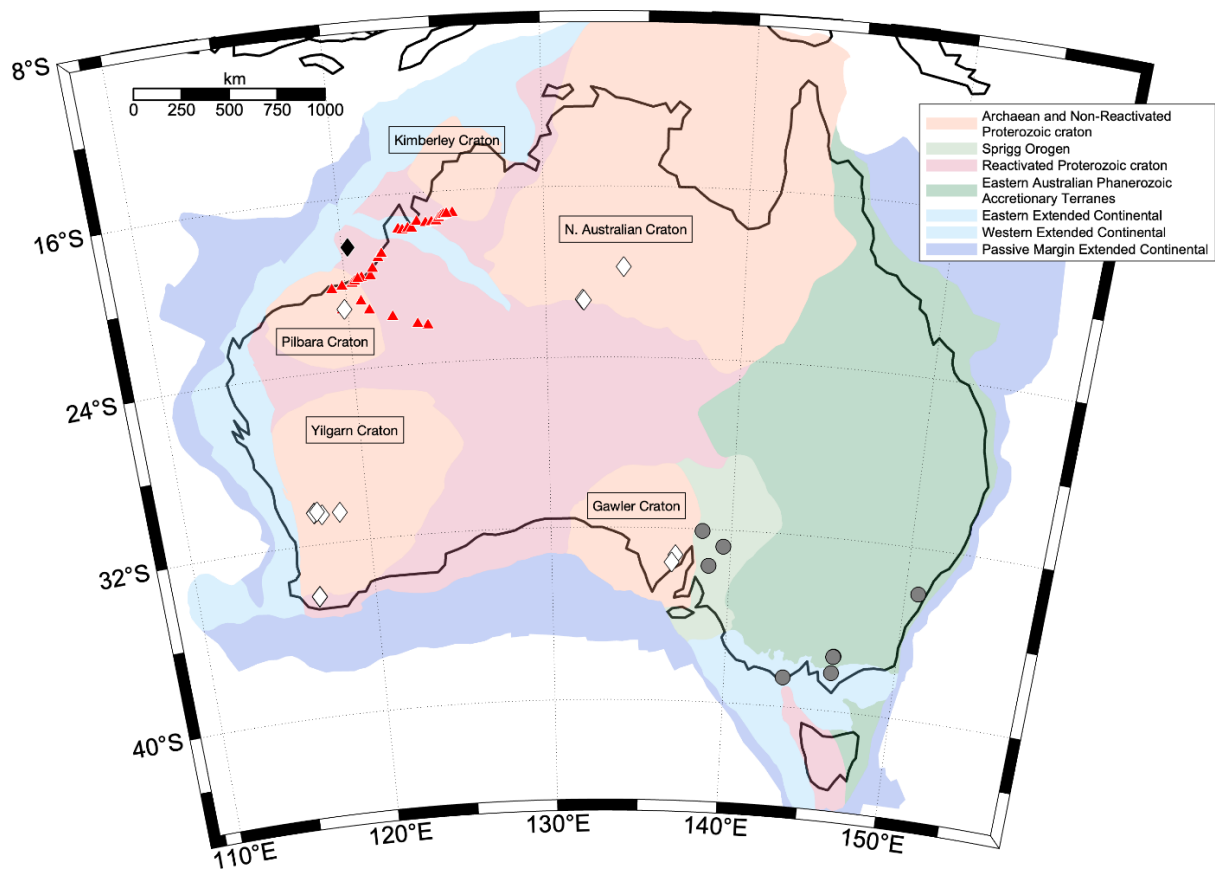


Figure D-24 A map of the events in the ground motion dataset used to develop the GMM. Diamonds represent events in NSHA23 Precambrian regions (including the Archaean and Non-Reactivated Proterozoic craton and Reactivated Proterozoic craton) and circles represent events in the NSHA23 Phanerozoic regions. Shaded areas are the regions from NSHA23. The 2019 M6.6 Kimberley Coast earthquake is the black diamond and the recordings of this earthquake collected for the evaluation of the GMM are red triangles.

Table D-6 Kimberley Coast earthquake stations used for comparison with the GMM.

Station Name	Longitude (deg)	Latitude (deg)	R_{epi} (km)	V_{s30} (m/s)
CA06	120.7001	-20.8408	291.9	253
CA08	119.3030	-20.1677	242.1	249
CA10	119.8280	-20.0561	210.3	310
CA11	120.3445	-19.9648	192.7	719
CA12	120.4994	-19.8878	184.8	309
CA13	120.8352	-19.7403	175.2	197
CA14	121.2872	-19.6941	189.9	366
CA16	121.4398	-19.3693	170.6	295
CA19	121.7516	-18.8995	165.1	343
CA20	121.9289	-18.7097	174.5	337
CA26	122.8531	-17.6314	272.4	329
CA27	123.0403	-17.6853	290.4	305
CAWA	120.6413	-19.7782	174.6	268

Earthquake and Ground Motion Metadata

For this analysis, we used moment magnitude (**M**) 6.6 and a hypocentral depth of 20 km. Both the magnitude and depth are from the GA ground-motion database (AGMD; Ghasemi et al., 2026). We used a point source for calculating source-to-site distances (R_{rup}) and the depth to top of rupture (Z_{tor}) because no finite fault information is available for this earthquake. The site V_{s30} values are from the AGMD with all sites V_{s30} 's labelled as “proxy”, so these are assumed to have considerable uncertainty.

Response Spectra and GMM Residuals

Figure D-25 shows the response spectra of the 2019 Kimberley Coast earthquake compared with the response spectra used in developing the GMM. All response spectra are plotted using their usable period range determined as $T_{min} = 1.25/f_{Nyq}$ and $T_{max} = 0.8/l_c$ where f_{Nyq} is the Nyquist frequency in Hertz and l_c is the higher of the two high-pass corner filter frequencies from the two horizontal component waveforms. Figure D-25 shows that the 2019 Kimberley Coast earthquake ground motions are some of the highest ground motions in the dataset, particularly at longer spectral periods. Figures D-26 and D-27 show response spectra for 12 of the recordings, indicating good agreement between the recorded response spectra and the Cratonic GMM both in terms of amplitudes and spectral shapes.

Figures D-28 and D-29 compare distance scaling of the recorded data with the median Cratonic GMM, for periods of $T=0.05$, $T=0.2$, $T=1$, and $T=5$ sec. The lower panels of these figures show within-event residuals versus rupture distance with event-terms indicated in the figure titles. Any bias in the distance scaling of the median GMM with respect to the recorded data (with distances between 165-292 km) would show as a slope in the residuals. Overall, there are not strong trends in the residuals, suggesting that the distance scaling of the data do not disagree with the model for this distance range. The absolute value of event-terms shown in Figures D-28 and D-29 are relatively small at 0.23 ln units and lower, indicating that the ground motion amplitudes from this earthquake are also in relative agreement with the median GMM on average.

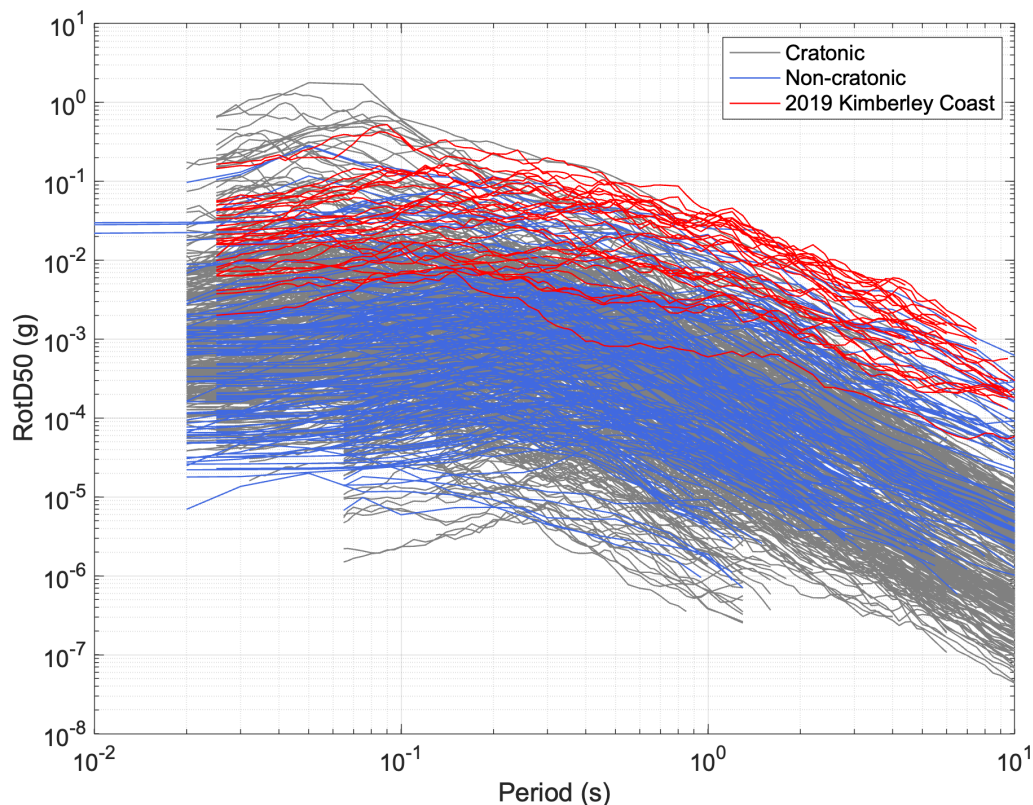


Figure D-25 RotD50 response spectra of the ground motion database used to develop the GMM, with data from Precambrian regions in grey, Phanerozoic regions in blue, and the 2019 Kimberley Coast earthquake data in red.

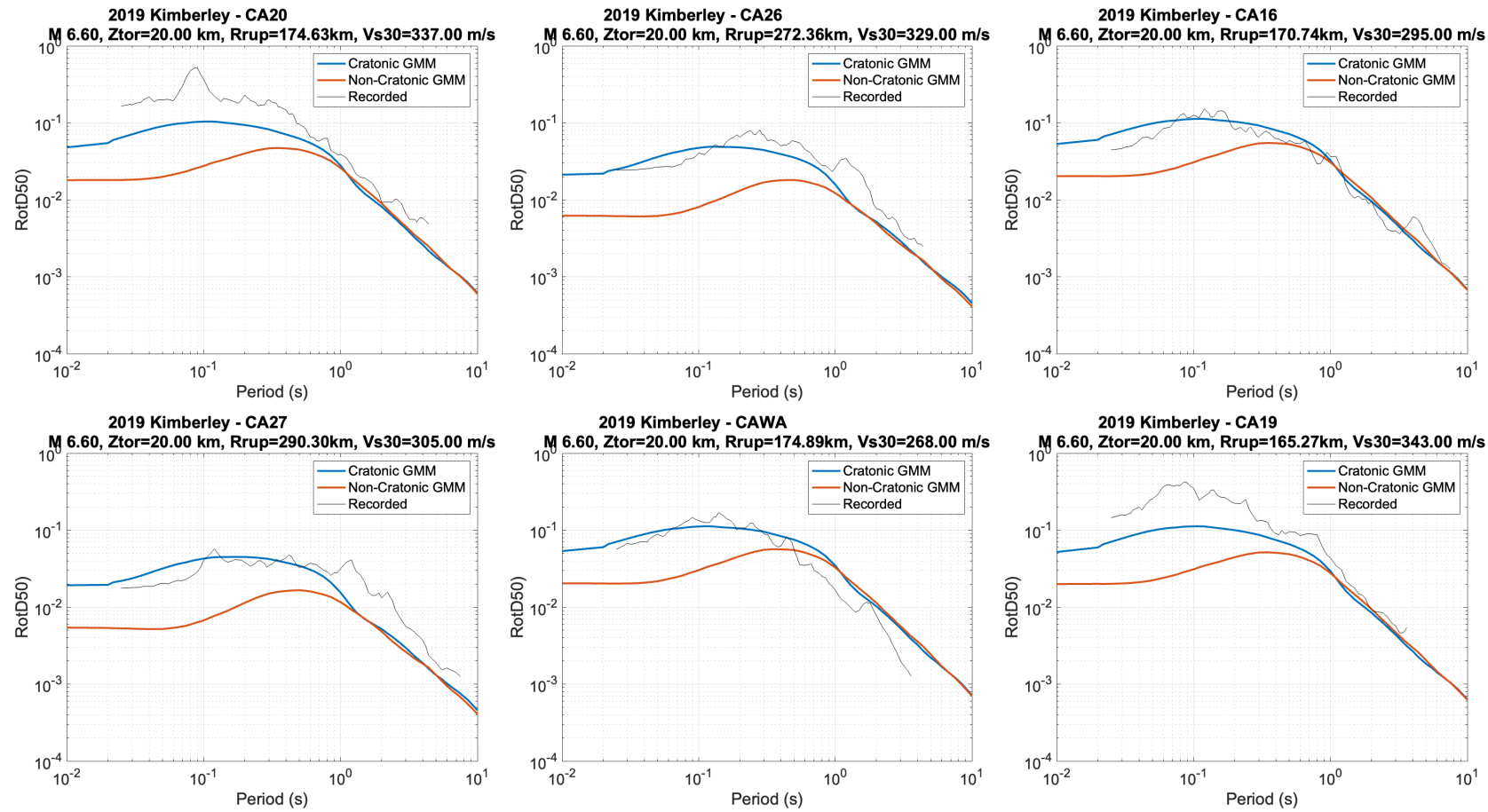


Figure D-26 RotD50 response spectra from the 2019 Kimberley Coast earthquake compared with the GMM. Each panel identifies the site name, distance, and Vs30.

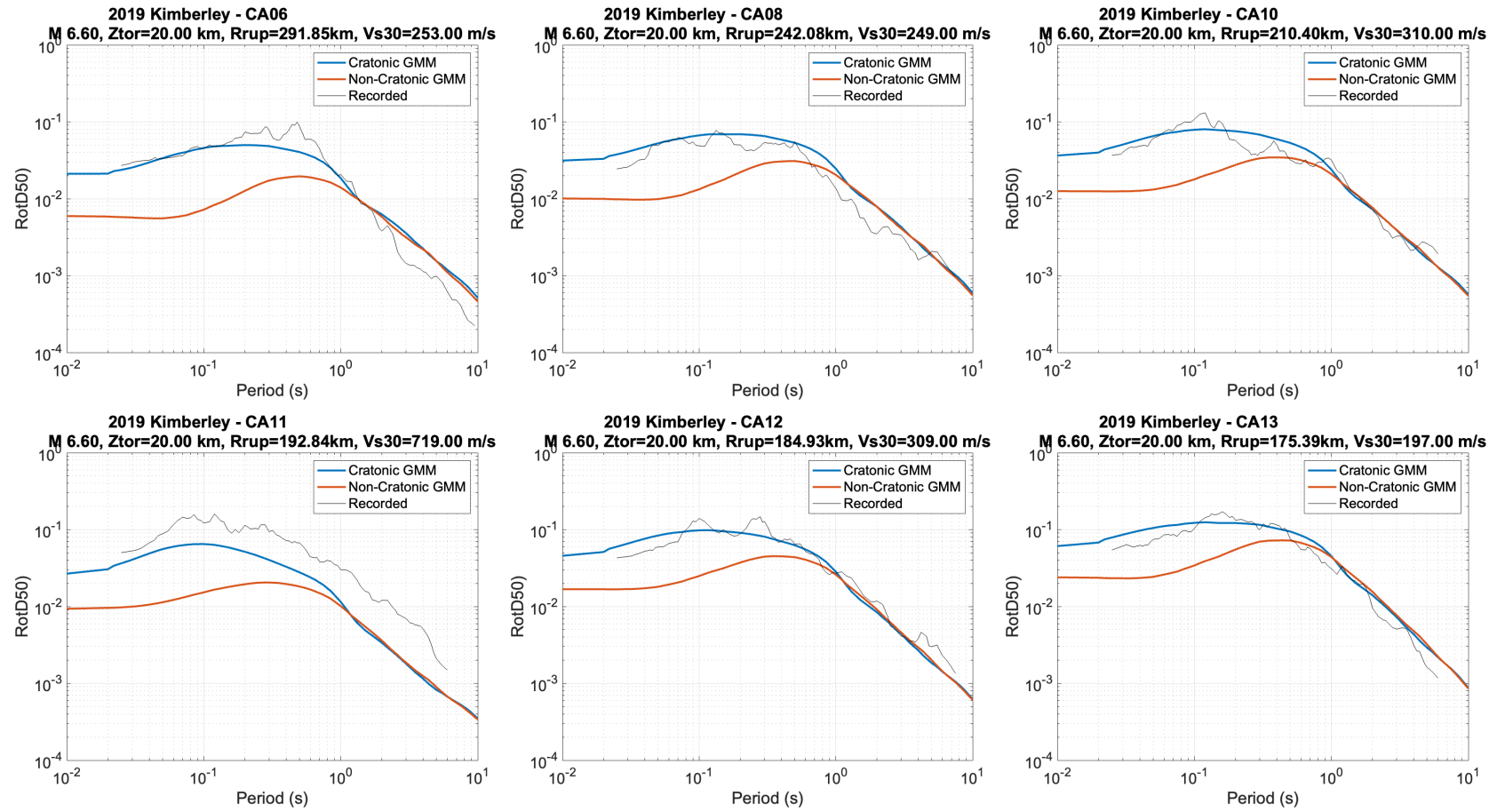


Figure D-27 RotD50 response spectra from the 2019 Kimberley Coast earthquake compared with the GMM. Each panel identifies the site name, distance, and Vs30.

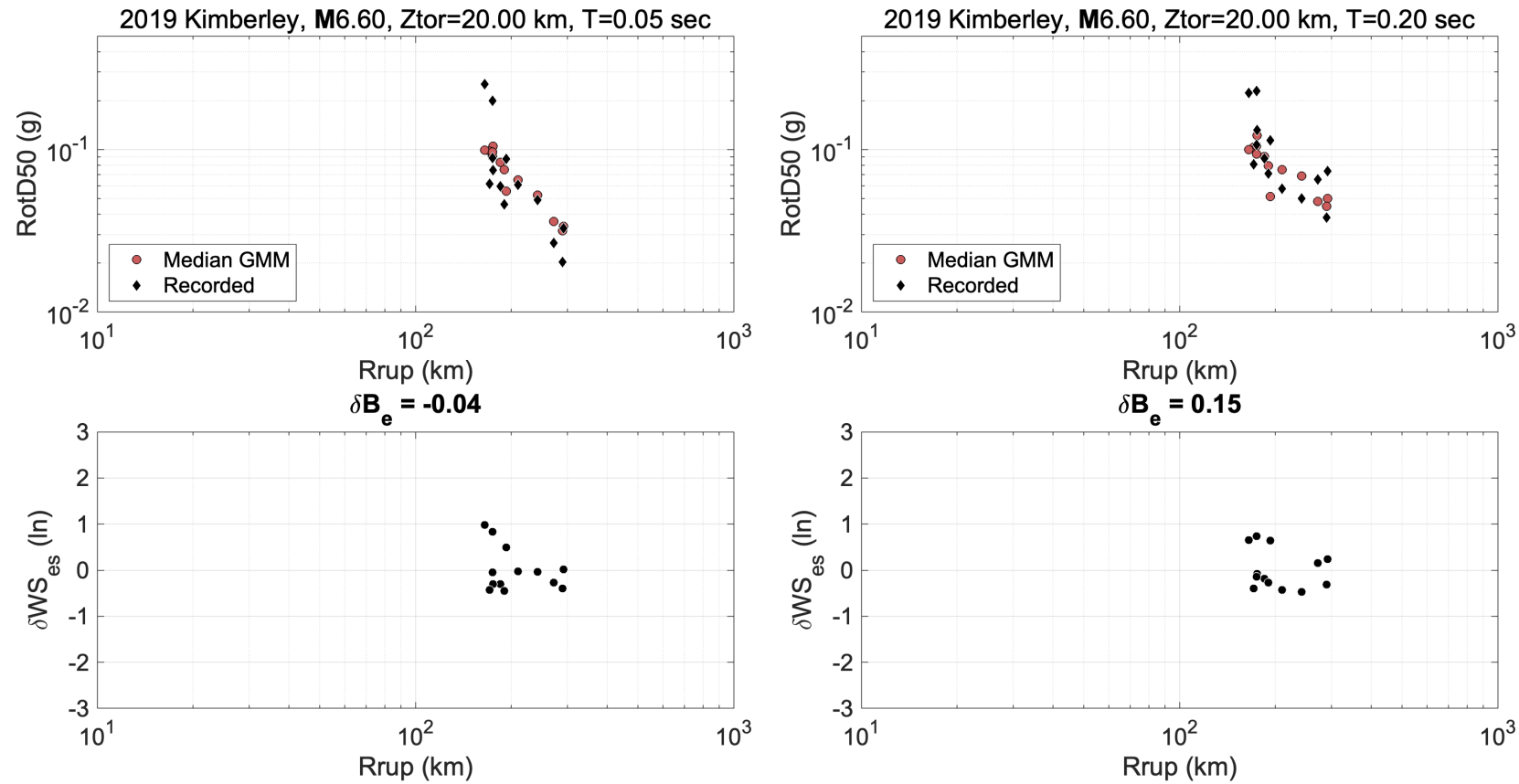


Figure D-28 Comparison of the distance scaling of the 2019 Kimberley Coast earthquake data compared with the GMM, for T=0.05 sec spectral acceleration (left) and T=0.2 sec spectral acceleration (right). The lower panel of each figure shows the within-event residuals plotted versus distance.

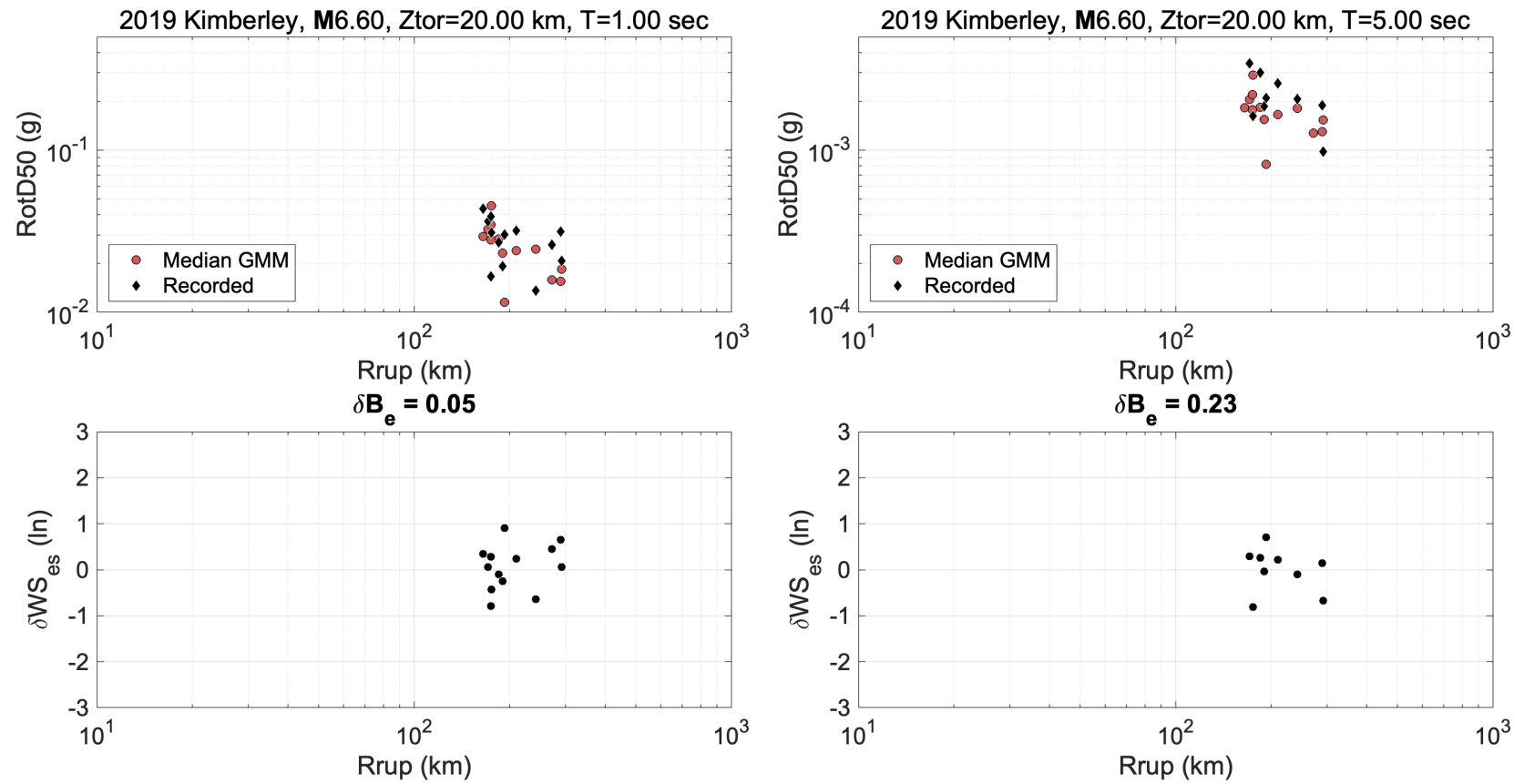


Figure D-29 Comparison of the distance scaling of the 2019 Kimberley Coast earthquake data compared with the GMM, for T=1 sec spectral acceleration (left) and T=5 sec spectral acceleration (right). The lower panel of each figure shows the within-event residuals plotted versus distance.

Figure D-30 shows the goodness-of-fit (GOF) analysis. The GOF shows the period dependence of the mean bias of the 2019 Kimberley Coast earthquake data with respect to the median Cratonic GMM. The mean bias is the mean residual over all stations at a given spectral period. The green filled area corresponds to the mean bias plus and minus one standard deviation and the red filled area corresponds to the 90% confidence interval of the mean bias. Increased width of the 90% confidence interval at specific periods indicates that the mean is constrained by less data (records).

Figure D-30 shows that the overall bias of the recorded ground motions with respect to the Cratonic GMM is very small. The 90% confidence interval in the mean bias contains the value 0 (no mean bias) for all spectral periods except for the small period range of about 0.1 – 0.2 sec, where the mean bias is slightly higher, representing model under-prediction on average for this range. The absence of strong non-zero slopes or trends in the mean bias also indicates strong match to the spectral shapes of the recorded ground motions on average. Based on Figure D-30, the performance of the median Cratonic GMM is very strong for this event.

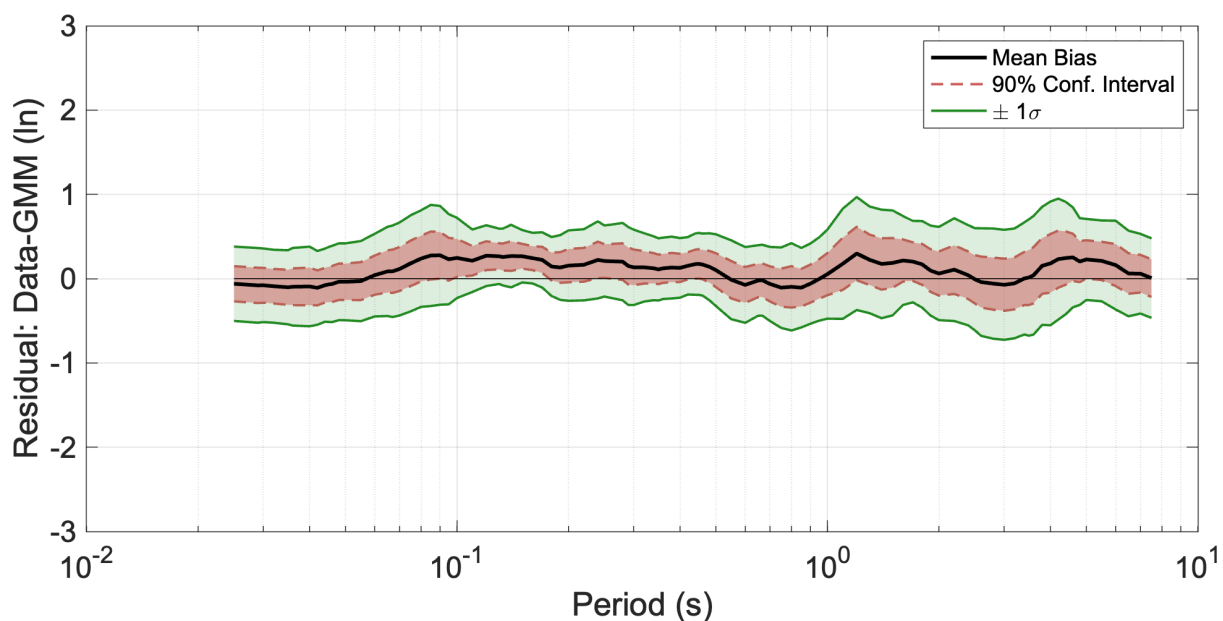


Figure D-30 Goodness-of-fit residual plot showing the mean bias of the 2019 Kimberley Coast earthquake data with respect to the GMM. The red and green bands are the 90% confidence interval in the mean bias and the mean bias plus and minus one standard deviation, respectively.

Impact of Including the 2019 Kimberley Coast Event in the GMM Regression

We repeated the regression stages 7a and 7b (Table D-5; see Sections D.7.1 and D.8.2) including the 2019 Kimberley Coast earthquake data.

Figure D-31 shows the between-event residuals for all Cratonic and Non-Cratonic earthquakes from Section D.3, plus the **M**6.6 Kimberley Coast earthquake, at $T=0.2$ and $T=1$ sec. The small biases and trends in the event terms discussed in Section D.8.2 are not impacted by the inclusion of this earthquake in the dataset because of the strong match between the Cratonic GMM and the data for this event.

Similarly, Figure D-32 shows within-event residuals versus the model predictive parameters at $T=0.2$ sec and $T=1$ sec with the Kimberley Coast earthquake data included. As before, this figure shows that the model is not strongly biased with respect to magnitude, depth, or distance in comparison with the Australian data.

Because of the strong agreement between the ground motions recorded in the 2019 Kimberley Coast earthquake and the median Cratonic GMM predictions for this event, we did not make any modifications to the GMM.

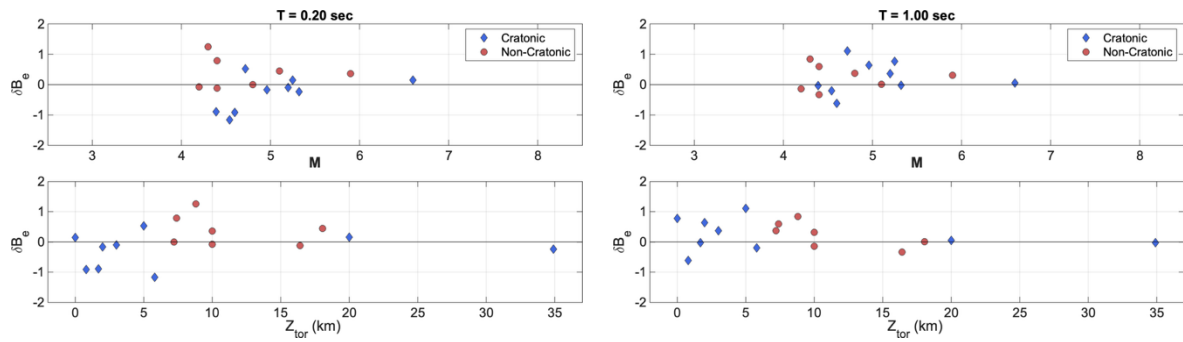


Figure D-31 Between-event residuals for the complete dataset, including the 2019 M6.6 Kimberley Coast earthquake ($Z_{\text{tor}}=20$ km), versus magnitude and depth (left) $T=0.2$ sec, (right) $T=1$ sec.

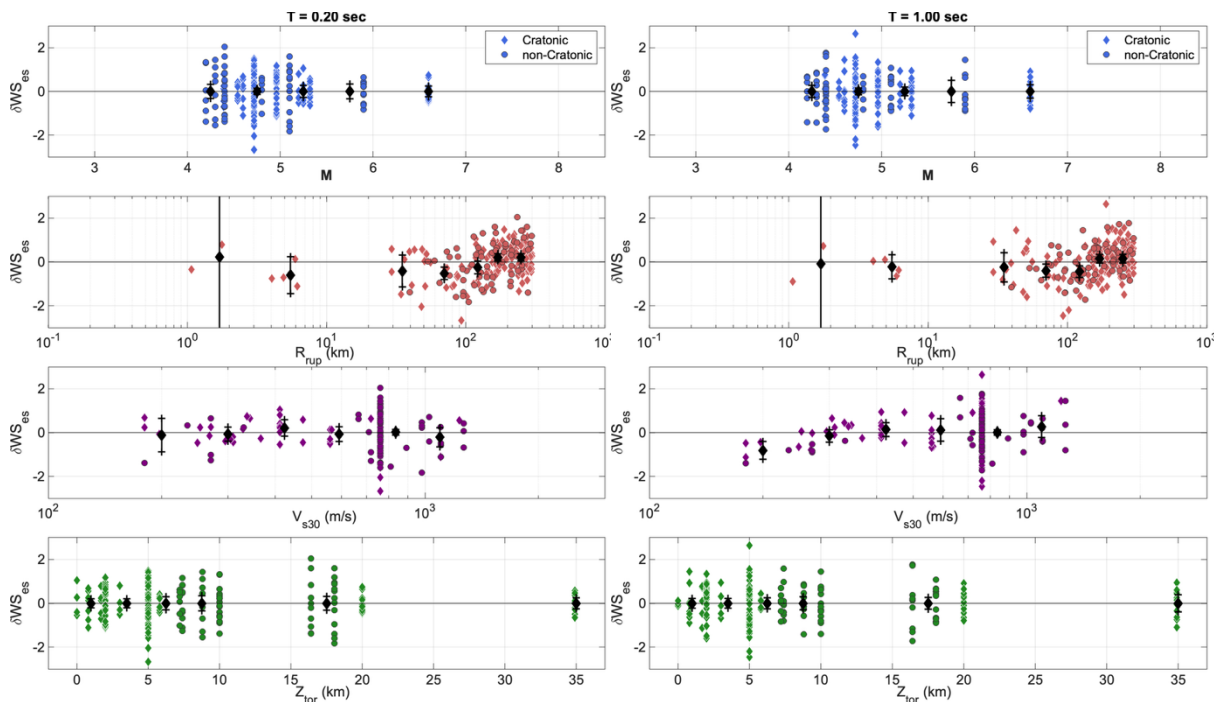


Figure D-32 Within-event residuals for the complete dataset, including the 2019 M6.6 Kimberley Coast earthquake, versus magnitude, R_{rup} , V_{s30} , and Z_{tor} at (left) $T=0.2$ sec and (right) $T=1$ sec. Black diamonds with whiskers represent the binned residual means with 95% confidence intervals.

Conclusions

New ground motion data recorded in the 2019 M6.6 Kimberley Coast earthquake are useful for evaluating the GMM because (1) this earthquake is the largest magnitude earthquake in our dataset, and (2) this event was not used in developing or evaluating the GMM. This event was not used previously because we had only one usable recording of this earthquake and required at least 5 recordings per earthquake during the GMM development.

We collected and processed the 2019 M6.6 Kimberley Coast earthquake waveform data from AusPass using the same ground motion processing procedures as in Section D.3. We identified 13 recordings which are of high quality and are within the distance range of applicability of the GMM. The response spectral data compare favourably with the cratonic GMM, with low event terms (mean bias) that do not show a trend with spectral period. The distance scaling of the GMs is also comparable to the model. Had this earthquake been classified as non-cratonic, the non-cratonic GMM would have strongly under-estimated the short period GMs. Because the nearest station is ~ 170 km, we could not test the magnitude or distance saturation features of the model. The depth scaling component of the model seems to work well for this earthquake. Because of the strong agreement between the recorded GMs and the median GMM, the residual analysis repeated including the new data did not suggest any modifications to the GMM are required.

To refine this analysis, it would be beneficial to get improved source metadata for this event (finite fault dimensions/orientation and a better resolved depth), as well as more reliable site V_{s30} data. These limitations notwithstanding, the median Cratonic GMM developed in this appendix performs exceptionally well for this event, which supports use of the model for forward application

D.9 Summary of Updated Model

This appendix describes an updated GMM for the median and standard deviation of the horizontal (RotD50) component of response spectral acceleration for Cratonic and non-Cratonic regions of Australia. This update uses broadband strong motion simulations to account for the effects of earthquake source and crustal structure properties of Australia; these are validated using the available recorded ground motion data and are used to extrapolate the model to larger earthquake magnitudes that typically control design ground motions but for which no Australian data are available. We use the simulations to constrain the magnitude scaling, depth scaling, near-source saturation, and distance scaling components of the GMM. Two source effects related to earthquake depth are modelled: the effects of short period surface (Rg) waves from shallow events, impacting longer periods, and the effects of energetic buried ruptures, impacting short periods. We adopted the ASK14 model for hanging wall effects, the Boore et al. (2014) model for V_{s30} scaling, and the Al Atik (2015) global aleatory variability model.

The magnitude scaling and geometric spreading terms are the same for the Cratonic and non-Cratonic GMMs. The models differ in their anelastic attenuation components, which model deviations from the attenuation due to geometric spreading, and also differ in their high frequency source spectra derived from the simulations and validated by the data; these account for the differences in source and crustal structure between regions. The models provide adequate representations of the data and embody the differences in ground motions observed between Cratonic and non-Cratonic regions of Australia.

Because the updated GMM is based on a considerably larger database of Australian source and ground motion data, the updated model supersedes the Somerville et al. (2009) model.

D.10 Model Coefficients

Table D-7 GMM coefficients determined as part of this study.

T (sec)	a1, Cratonic	a17, Cratonic	a1, Non-Cratonic	a17, Non-Cratonic	M1	c4	a2	a3	a4	a5	a8	d1	d2	d3	d4
0	1.484000	-0.005124	0.894300	-0.007517	6.75	4.5	-0.7627	0.22	-0.0209	-0.3309	-0.0017	0.0001680	-0.0031086	0.0173023	0
0.01	1.504200	-0.005124	0.914500	-0.007517	6.75	4.5	-0.7627	0.22	-0.0209	-0.3309	-0.0017	0.0001680	-0.0031086	0.0173023	0
0.011	1.517100	-0.005224	0.918700	-0.007525	6.75	4.5	-0.7627	0.22	-0.0209	-0.3309	-0.0017	0.0001680	-0.0031089	0.0173060	0
0.012	1.531000	-0.005322	0.922500	-0.007533	6.75	4.5	-0.7627	0.22	-0.0209	-0.3309	-0.0017	0.0001681	-0.0031093	0.0173094	0
0.013	1.546300	-0.005418	0.926500	-0.00754	6.75	4.5	-0.7627	0.22	-0.0209	-0.3309	-0.0017	0.0001681	-0.0031096	0.0173139	0
0.015	1.582800	-0.005601	0.934300	-0.007555	6.75	4.5	-0.7627	0.22	-0.0209	-0.3309	-0.0017	0.0001682	-0.0031104	0.0173239	0
0.017	1.633400	-0.00577	0.942700	-0.007568	6.75	4.5	-0.7627	0.22	-0.0209	-0.3309	-0.0017	0.0001683	-0.0031113	0.0173342	0
0.02	1.823000	-0.006087	0.957800	-0.007603	6.75	4.5	-0.7627	0.22	-0.0209	-0.3309	-0.0017	0.0001685	-0.0031130	0.0173562	0
0.022	1.959400	-0.006259	0.969400	-0.00764	6.75	4.5	-0.7627	0.22	-0.0209	-0.3309	-0.0017	0.0001685	-0.0031147	0.0173823	0
0.025	2.075500	-0.006479	0.992000	-0.0077	6.75	4.5	-0.7627	0.22	-0.0209	-0.3309	-0.0017	0.0001686	-0.0031176	0.0174450	0
0.029	2.194900	-0.006646	1.029700	-0.007802	6.75	4.5	-0.7627	0.22	-0.0209	-0.3309	-0.0017	0.0001690	-0.0031225	0.0175368	0
0.032	2.262100	-0.006667	1.061000	-0.007898	6.75	4.5	-0.7627	0.22	-0.0209	-0.3309	-0.0017	0.0001695	-0.0031273	0.0176121	0
0.035	2.315800	-0.006638	1.100600	-0.008007	6.75	4.5	-0.7627	0.22	-0.0209	-0.3309	-0.0017	0.0001700	-0.0031348	0.0177065	0
0.04	2.379500	-0.006528	1.171100	-0.008203	6.75	4.5	-0.7627	0.22	-0.0209	-0.3309	-0.0017	0.0001709	-0.0031531	0.0178841	0
0.045	2.421700	-0.006364	1.246200	-0.008412	6.75	4.5	-0.7627	0.22	-0.0209	-0.3309	-0.0017	0.0001718	-0.0031741	0.0180691	0
0.05	2.446500	-0.006199	1.319300	-0.008607	6.75	4.5	-0.7627	0.22	-0.0209	-0.3309	-0.0017	0.0001729	-0.0031884	0.0182319	0
0.055	2.454300	-0.006032	1.387900	-0.008781	6.75	4.5	-0.7627	0.22	-0.0209	-0.3309	-0.0017	0.0001736	-0.0031937	0.0183842	0
0.06	2.453900	-0.00587	1.451200	-0.008931	6.75	4.5	-0.7627	0.22	-0.0209	-0.3309	-0.0017	0.0001728	-0.0032041	0.0186484	0
0.065	2.450400	-0.005716	1.506700	-0.009053	6.75	4.5	-0.7627	0.22	-0.0209	-0.3309	-0.0017	0.0001726	-0.0032129	0.0188733	0
0.075	2.428200	-0.005441	1.597900	-0.009201	6.75	4.5	-0.7627	0.22	-0.0209	-0.3309	-0.0017	0.0001729	-0.0032293	0.0191311	0
0.085	2.400000	-0.005206	1.666000	-0.009252	6.75	4.5	-0.7627	0.22	-0.0209	-0.3309	-0.0017	0.0001744	-0.0032372	0.0191675	0
0.1	2.342400	-0.004904	1.733000	-0.009259	6.75	4.5	-0.7627	0.22	-0.0209	-0.3309	-0.0017	0.0001759	-0.0032447	0.0191090	0
0.11	2.298000	-0.004734	1.762900	-0.009177	6.75	4.5	-0.7627	0.22	-0.0209	-0.3309	-0.0017	0.0001761	-0.0032483	0.0191474	0

T (sec)	a1, Cratonic	a17, Cratonic	a1, Non-Cratonic	a17, Non-Cratonic	M1	c4	a2	a3	a4	a5	a8	d1	d2	d3	d4
0.12	2.252707	-0.004582	1.781300	-0.009085	6.75	4.5	-0.7627	0.22	-0.0209	-0.3309	-0.0017	0.0001753	-0.0032509	0.0192582	0
0.13	2.202329	-0.004444	1.788000	-0.008987	6.75	4.5	-0.7627	0.22	-0.0209	-0.3309	-0.0017	0.0001760	-0.0032528	0.0191215	0
0.15	2.110043	-0.004214	1.789500	-0.008729	6.75	4.5	-0.7627	0.22	-0.0209	-0.3309	-0.0017	0.0001761	-0.0032471	0.0188873	0
0.17	2.019826	-0.004018	1.784900	-0.008484	6.75	4.5	-0.7627	0.22	-0.0209	-0.3309	-0.0031	0.0001746	-0.0032363	0.0187695	0
0.2	1.910226	-0.003783	1.775111	-0.008129	6.75	4.5	-0.7627	0.22	-0.0209	-0.3309	-0.008	0.0001710	-0.0031949	0.0187646	0
0.22	1.845815	-0.003654	1.767936	-0.007908	6.75	4.5	-0.7627	0.22	-0.0209	-0.3309	-0.012	0.0001699	-0.0031728	0.0186389	0
0.24	1.789125	-0.003539	1.759307	-0.007703	6.75	4.5	-0.7627	0.22	-0.0209	-0.3309	-0.0159	0.0001692	-0.0031572	0.0184102	0
0.26	1.735130	-0.003438	1.747363	-0.007512	6.75	4.5	-0.7627	0.22	-0.0209	-0.3309	-0.0198	0.0001679	-0.0031621	0.0181260	0
0.28	1.686263	-0.003346	1.733176	-0.007335	6.75	4.5	-0.7627	0.22	-0.0209	-0.3309	-0.0238	0.0001679	-0.0031587	0.0177491	0
0.3	1.639132	-0.003262	1.717391	-0.007174	6.75	4.5	-0.7627	0.22	-0.0209	-0.3309	-0.0279	0.0001686	-0.0031411	0.0173395	0
0.35	1.532470	-0.003079	1.673622	-0.006823	6.75	4.5	-0.7627	0.22	-0.0209	-0.3309	-0.0379	0.0001723	-0.0030860	0.0162942	0
0.4	1.446727	-0.002933	1.623189	-0.006533	6.75	4.5	-0.7627	0.22	-0.0209	-0.3309	-0.0475	0.0001712	-0.0030473	0.0156504	0
0.45	1.370238	-0.002813	1.572967	-0.00628	6.75	4.5	-0.7627	0.22	-0.0209	-0.3309	-0.0565	0.0001655	-0.0030111	0.0154703	0
0.5	1.301333	-0.002713	1.522867	-0.006059	6.75	4.5	-0.7627	0.22	-0.0209	-0.3309	-0.065	0.0001550	-0.0029635	0.0156587	0
0.55	1.242784	-0.002635	1.472803	-0.005863	6.75	4.5	-0.7627	0.22	-0.0209	-0.3309	-0.0733	0.0001477	-0.0029095	0.0155313	0
0.6	1.189783	-0.002567	1.426091	-0.005685	6.75	4.5	-0.7627	0.22	-0.0209	-0.3309	-0.0814	0.0001454	-0.0028753	0.0147774	0
0.65	1.144214	-0.002524	1.375845	-0.005522	6.75	4.5	-0.7627	0.22	-0.0209	-0.3309	-0.0895	0.0001409	-0.0028403	0.0141591	0
0.75	1.044763	-0.002523	1.272261	-0.005212	6.75	4.5	-0.7627	0.22	-0.0209	-0.3309	-0.1044	0.0001275	-0.0027274	0.0131897	0
0.85	0.927476	-0.002584	1.144038	-0.004891	6.75	4.5	-0.7627	0.22	-0.0209	-0.3309	-0.118	0.0001026	-0.0025134	0.0124530	0
1	0.692772	-0.002658	0.907520	-0.004428	6.75	4.5	-0.7627	0.22	-0.0209	-0.3309	-0.136	0.0000342	-0.0019648	0.0122706	0
1.1	0.499532	-0.00263	0.735429	-0.004103	6.75	4.5	-0.7627	0.22	-0.0209	-0.3309	-0.1465	-0.0000304	-0.0014934	0.0133770	0
1.2	0.300181	-0.002568	0.585796	-0.003822	6.75	4.5	-0.7627	0.22	-0.0209	-0.3309	-0.1559	-0.0001122	-0.0009342	0.0159051	0
1.3	0.128555	-0.002495	0.448148	-0.003562	6.75	4.5	-0.7627	0.22	-0.0209	-0.3309	-0.1644	-0.0001897	-0.0004667	0.0189489	0
1.5	-0.142325	-0.00216	0.202059	-0.003244	6.75	4.5	-0.7626	0.22	-0.0209	-0.3309	-0.1792	-0.0003026	0.0001986	0.0230155	0
1.7	-0.334603	-0.001818	-0.013183	-0.003	6.75	4.5	-0.7622	0.22	-0.0209	-0.3309	-0.1914	-0.0003802	0.0006619	0.0249428	0

T (sec)	a1, Cratonic	a17, Cratonic	a1, Non-Cratonic	a17, Non-Cratonic	M1	c4	a2	a3	a4	a5	a8	d1	d2	d3	d4
2	-0.601027	-0.001338	-0.292665	-0.002803	6.75	4.5	-0.7595	0.22	-0.0209	-0.3309	-0.2062	-0.0004649	0.0012127	0.0258630	0
2.2	-0.759501	-0.001087	-0.456569	-0.002712	6.7665	4.5	-0.7567	0.22	-0.0209	-0.3309	-0.2143	-0.0005032	0.0015487	0.0253306	0
2.4	-0.895100	-0.000881	-0.606202	-0.002615	6.7815	4.5	-0.7535	0.22	-0.0209	-0.3309	-0.2211	-0.0005111	0.0018446	0.0226896	0
2.6	-1.029900	-0.00073	-0.743851	-0.002463	6.7953	4.5	-0.7472	0.22	-0.0209	-0.3309	-0.2268	-0.0004640	0.0020792	0.0156308	0
2.8	-1.147600	-0.000611	-0.871293	-0.002292	6.8081	4.5	-0.7422	0.22	-0.0209	-0.3309	-0.2314	-0.0003883	0.0022830	0.0061093	0
3	-1.269500	-0.000529	-0.989940	-0.002111	6.82	4.5	-0.7346	0.22	-0.0209	-0.3309	-0.235	-0.0003127	0.0024804	-0.0027589	0
3.5	-1.556400	-0.000372	-1.255031	-0.001697	6.8736	4.5	-0.7134	0.22	-0.0209	-0.3309	-0.2413	-0.0001302	0.0028429	-0.0228845	0
4	-1.787900	-0.000309	-1.484664	-0.001348	6.92	4.5	-0.6882	0.22	-0.0209	-0.3309	-0.2451	0.0000418	0.0029391	-0.0404482	0
4.4	-1.947806	-0.000294	-1.648568	-0.001106	6.9542	4.5	-0.6698	0.22	-0.0209	-0.3309	-0.2472	0.0001500	0.0028224	-0.0511861	0
5	-2.162276	-0.000294	-1.868402	-0.001106	7	4.5	-0.6449	0.22	-0.0209	-0.3309	-0.2498	0.0002338	0.0021320	-0.0593148	0
5.5	-2.322182	-0.000294	-2.032306	-0.001106	7.0314	4.5	-0.6261	0.22	-0.0209	-0.3309	-0.2517	0.0002670	0.0013660	-0.0624146	0
6	-2.468164	-0.000294	-2.181938	-0.001106	7.06	4.5	-0.6088	0.22	-0.0209	-0.3309	-0.2534	0.0002800	0.0006464	-0.0633128	0
6.5	-2.602455	-0.000294	-2.319587	-0.001106	7.0905	4.5	-0.5926	0.22	-0.0209	-0.3309	-0.2549	0.0002597	0.0002179	-0.0604585	0
7.5	-2.842541	-0.000294	-2.565676	-0.001106	7.145	4.5	-0.5633	0.22	-0.0209	-0.3309	-0.2575	0.0001959	-0.0004168	-0.0523823	0
8.5	-3.052532	-0.000294	-2.780918	-0.001106	7.1907	4.5	-0.5371	0.22	-0.0209	-0.3309	-0.2595	0.0001410	-0.0006883	-0.0446089	0
10	-3.325196	-0.000294	-3.060400	-0.001106	7.25	4.5	-0.5025	0.22	-0.0209	-0.3309	-0.2621	0.0000745	-0.0009020	-0.0345404	0

Table D-8 GMM coefficients adopted from others.

	Abrahamson et al. (2014)			Boore et al. (2014)						Al Atik (2015)					
T (sec)	a13	a6	a7	c	vc	b4	b5	b6	b7	tau1	tau2	tau3	tau4	PhiA	PhiB
0	0.6	2.1541	0	-0.6037	1500	-0.1483	-0.007	-9.9	-9.9	0.4518	0.427	0.3863	0.3508	0.7131	0.577
0.01	0.6	2.1541	0	-0.6037	1500	-0.1483	-0.007	-9.9	-9.9	0.4518	0.427	0.3863	0.3508	0.7131	0.577
0.011	0.6	2.153	0	-0.5996	1500	-0.1481	-0.007	-9.9	-9.9	0.4518	0.427	0.3863	0.3508	0.713	0.5771
0.012	0.6	2.152	0	-0.5959	1500	-0.148	-0.0071	-9.9	-9.9	0.4518	0.427	0.3863	0.3508	0.713	0.5772
0.013	0.6	2.1511	0	-0.5924	1500	-0.1478	-0.0071	-9.9	-9.9	0.4518	0.427	0.3863	0.3508	0.7129	0.5773
0.015	0.6	2.1494	0	-0.5863	1500	-0.1476	-0.0072	-9.9	-9.9	0.4518	0.427	0.3863	0.3508	0.7128	0.5774
0.017	0.6	2.148	0	-0.5809	1500	-0.1474	-0.0072	-9.9	-9.9	0.4518	0.427	0.3863	0.3508	0.7127	0.5775
0.02	0.6	2.1461	0	-0.5739	1500	-0.1471	-0.0073	-9.9	-9.9	0.4518	0.427	0.3863	0.3508	0.7126	0.5777
0.022	0.6	2.1486	0	-0.5645	1501	-0.1489	-0.0073	-9.9	-9.9	0.4518	0.427	0.3863	0.3508	0.7137	0.5793
0.025	0.6	2.1519	0	-0.552	1502	-0.1514	-0.0073	-9.9	-9.9	0.4518	0.427	0.3863	0.3508	0.7151	0.5814
0.029	0.6	2.1557	0	-0.5374	1503	-0.1542	-0.0073	-9.9	-9.9	0.4518	0.427	0.3863	0.3508	0.7167	0.5838
0.032	0.6	2.1475	0	-0.5245	1503	-0.1596	-0.0072	-9.9	-9.9	0.4518	0.427	0.3863	0.3508	0.7194	0.5875
0.035	0.6	2.1348	0	-0.5111	1502	-0.1661	-0.0071	-9.9	-9.9	0.4518	0.427	0.3863	0.3508	0.7226	0.5918
0.04	0.6	2.116	0	-0.4912	1502	-0.1758	-0.0069	-9.9	-9.9	0.4518	0.427	0.3863	0.3508	0.7274	0.5982
0.045	0.6	2.0994	0	-0.4737	1502	-0.1843	-0.0067	-9.9	-9.9	0.4518	0.427	0.3863	0.3508	0.7407	0.6147
0.05	0.6	2.0845	0	-0.458	1501	-0.192	-0.0065	-9.9	-9.9	0.4518	0.427	0.3863	0.3508	0.7526	0.6295
0.055	0.6	2.0713	0	-0.4547	1500	-0.2021	-0.0063	-9.9	-9.9	0.4518	0.427	0.3863	0.3508	0.7614	0.6405
0.06	0.6	2.0593	0	-0.4517	1498	-0.2113	-0.0061	-9.9	-9.9	0.4518	0.427	0.3863	0.3508	0.7694	0.6505
0.065	0.6	2.0483	0	-0.449	1497	-0.2198	-0.006	-9.9	-9.9	0.4518	0.427	0.3863	0.3508	0.7767	0.6597
0.075	0.6	2.0285	0	-0.4441	1494	-0.235	-0.0057	-9.9	-9.9	0.4518	0.427	0.3863	0.3508	0.7899	0.6761
0.085	0.6	2.0339	0	-0.4629	1488	-0.2412	-0.0057	-9.9	-9.9	0.4518	0.427	0.3863	0.3508	0.7932	0.6809
0.1	0.6	2.0408	0	-0.4872	1479	-0.2492	-0.0056	-9.9	-9.9	0.4518	0.427	0.3863	0.3508	0.7974	0.6872

	Abrahamson et al. (2014)			Boore et al. (2014)						Al Atik (2015)					
T (sec)	a13	a6	a7	c	vc	b4	b5	b6	b7	tau1	tau2	tau3	tau4	PhiA	PhiB
0.11	0.6	2.0596	0	-0.5089	1471	-0.2511	-0.0057	-9.9	-9.9	0.4518	0.427	0.3863	0.3508	0.7927	0.6833
0.12	0.6	2.0768	0	-0.5287	1463	-0.2528	-0.0057	-9.9	-9.9	0.4518	0.427	0.3863	0.3508	0.7884	0.6797
0.13	0.6	2.0926	0	-0.547	1456	-0.2543	-0.0058	-9.9	-9.9	0.4518	0.427	0.3863	0.3508	0.7844	0.6765
0.15	0.6	2.1208	0	-0.5796	1443	-0.2571	-0.0059	-9.9	-9.9	0.4518	0.427	0.3863	0.3508	0.7773	0.6706
0.17	0.6	2.1657	0	-0.6266	1421	-0.2525	-0.006	-9.9	-9.9	0.4518	0.427	0.3863	0.3508	0.7646	0.6607
0.2	0.6	2.2241	0	-0.6876	1393	-0.2466	-0.0061	-9.9	-9.9	0.4518	0.427	0.3863	0.3508	0.7481	0.6478
0.22	0.6	2.2618	0	-0.7236	1377	-0.2419	-0.0063	-9.9	-9.9	0.4518	0.427	0.3863	0.3508	0.737	0.6396
0.24	0.6	2.2962	0	-0.7564	1363	-0.2377	-0.0064	-9.9	-9.9	0.4518	0.427	0.3863	0.3508	0.7268	0.6321
0.26	0.6	2.318	0	-0.7868	1346	-0.2321	-0.0065	-9.9	-9.9	0.4518	0.427	0.3863	0.3508	0.7174	0.6257
0.28	0.6	2.3285	0	-0.8152	1327	-0.2254	-0.0066	-9.9	-9.9	0.4518	0.427	0.3863	0.3508	0.7086	0.6203
0.3	0.6	2.3383	0	-0.8417	1308	-0.2191	-0.0067	-9.9	-9.9	0.4518	0.427	0.3863	0.3508	0.7005	0.6152
0.35	0.5893	2.4082	0	-0.8788	1279	-0.2066	-0.0069	-9.9	-9.9	0.4518	0.427	0.3863	0.3508	0.6831	0.6069
0.4	0.58	2.4688	0	-0.9109	1253	-0.1958	-0.0071	-9.9	-9.9	0.4518	0.427	0.3863	0.3508	0.668	0.5998
0.45	0.5694	2.5162	0	-0.9417	1227	-0.1848	-0.0073	-9.9	-9.9	0.4518	0.427	0.3863	0.3508	0.6556	0.5943
0.5	0.56	2.5586	0	-0.9693	1204	-0.175	-0.0074	-9.9	-9.9	0.4518	0.427	0.3863	0.3508	0.6446	0.5893
0.55	0.5529	2.5876	0	-0.9801	1191	-0.1665	-0.0076	-7.5512	-7.559	0.4518	0.427	0.3863	0.3508	0.6354	0.5854
0.6	0.5465	2.6141	0	-0.99	1179	-0.1587	-0.0077	-5.407	-5.4218	0.4518	0.427	0.3863	0.3508	0.627	0.5819
0.65	0.5406	2.6385	0	-0.9991	1167	-0.1515	-0.0079	-3.4345	-3.4558	0.4518	0.427	0.3863	0.3508	0.6193	0.5786
0.75	0.53	2.6821	0	-1.0154	1148	-0.1387	-0.0081	0.092	0.059	0.4518	0.427	0.3863	0.3508	0.6055	0.5728
0.85	0.5169	2.7173	0	-1.0305	1131	-0.1241	-0.0083	0.2116	0.1238	0.4518	0.427	0.3863	0.3508	0.5943	0.5669
1	0.5	2.763	0	-1.05	1110	-0.1052	-0.0084	0.367	0.208	0.4518	0.427	0.3863	0.3508	0.5797	0.5593
1.1	0.4812	2.78	0	-1.0489	1101	-0.095	-0.0083	0.4307	0.2317	0.4518	0.427	0.3863	0.3508	0.5717	0.5545
1.2	0.464	2.7956	0	-1.0479	1093	-0.0858	-0.0081	0.4889	0.2534	0.4518	0.427	0.3863	0.3508	0.5644	0.5501
1.3	0.4482	2.8099	0	-1.047	1086	-0.0772	-0.008	0.5424	0.2734	0.4518	0.427	0.3863	0.3508	0.5577	0.546

	Abrahamson et al. (2014)			Boore et al. (2014)						Al Atik (2015)					
T (sec)	a13	a6	a7	c	vc	b4	b5	b6	b7	tau1	tau2	tau3	tau4	PhiA	PhiB
1.5	0.42	2.8355	0	-1.0454	1072	-0.062	-0.0077	0.638	0.309	0.4518	0.427	0.3863	0.3508	0.5457	0.5388
1.7	0.3895	2.8624	0	-1.0427	1045	-0.0507	-0.0064	0.7394	0.3408	0.4518	0.427	0.3863	0.3508	0.5362	0.5324
2	0.35	2.8973	0	-1.0392	1009	-0.0361	-0.0048	0.871	0.382	0.4518	0.427	0.3863	0.3508	0.5239	0.524
2.2	0.3147	2.8994	0	-1.0326	989	-0.0308	-0.0041	0.9331	0.4135	0.4518	0.427	0.3863	0.3508	0.518	0.518
2.4	0.2826	2.9013	0	-1.0266	970	-0.026	-0.0035	0.9897	0.4423	0.4518	0.427	0.3863	0.3508	0.5125	0.5126
2.6	0.2529	2.903	0	-1.0211	953	-0.0215	-0.0029	1.0418	0.4687	0.4518	0.427	0.3863	0.3508	0.5075	0.5076
2.8	0.2255	2.9046	0	-1.016	937	-0.0174	-0.0023	1.0901	0.4932	0.4518	0.427	0.3863	0.3508	0.5029	0.5029
3	0.2	2.9061	0	-1.0112	922	-0.0136	-0.0018	1.135	0.516	0.4518	0.427	0.3863	0.3508	0.4986	0.4986
3.5	0.0928	2.8968	0	-0.9888	881	-0.008	-0.0017	1.2079	0.5765	0.4518	0.427	0.3863	0.3508	0.4917	0.4917
4	0	2.8888	0	-0.9694	844	-0.0032	-0.0015	1.271	0.629	0.4518	0.427	0.3863	0.3508	0.4857	0.4857
4.4	0	2.8929	0	-0.9481	823	-0.002	-0.0015	1.2958	0.6756	0.4518	0.427	0.3863	0.3508	0.4828	0.4828
5	0	2.8984	0	-0.9195	793	-0.0003	-0.0014	1.329	0.738	0.4518	0.427	0.3863	0.3508	0.4789	0.4789
5.5	0	2.8969	0	-0.8859	788	-0.0003	-0.0014	1.329	0.7547	0.4518	0.427	0.3863	0.3508	0.4773	0.4773
6	0	2.8955	0	-0.8552	783	-0.0002	-0.0014	1.329	0.7699	0.4518	0.427	0.3863	0.3508	0.4758	0.4758
6.5	0	2.8864	0	-0.827	779	-0.0002	-0.0014	1.329	0.7839	0.4518	0.427	0.3863	0.3508	0.4745	0.4744
7.5	0	2.87	0	-0.7766	771	-0.0001	-0.0014	1.329	0.809	0.4518	0.427	0.3863	0.3508	0.4721	0.472
8.5	0	2.8583	0	-0.724	773	-0.0001	-0.0014	1.2655	0.7629	0.4518	0.427	0.3863	0.3508	0.4712	0.4711
10	0	2.8431	0	-0.6558	775	0	-0.0014	1.183	0.703	0.4518	0.427	0.3863	0.3508	0.47	0.47

D.11 References

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