A selection of GMPEs for the United Kingdom based on instrumental and macroseismic datasets

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In countries with low-to-moderate seismicity the selection of appropriate ground motion prediction equations (GMPEs) to be used in a probabilistic seismic hazard analysis (PSHA) is a challenging step. Empirical observations of ground motion are limited and GMPEs, when available, are generally based on stochastic simulations or adjusted empirical GMPEs from elsewhere. This paper investigates the suitability of recent GMPEs to the United Kingdom (UK). To this end, the spectral accelerations obtained from available instrumental ground motion data in the UK, with magnitude lower than 4.5 are compared with the GMPEs' predictions through the analysis of residuals and the application of statistical tests. To compensate for the scarcity of data for the magnitude range of interest in the PSHA, a macroseismic dataset is also considered. Macroseismic intensities are converted to peak ground acceleration (PGA) and statistically compared with the PGA predicted by the GMPEs. The GMPEs are then compared in terms of median ground motion prediction through Sammon's maps to evaluate their similarities. The analyses from both datasets led to six suitable GMPEs, of which three are from the NGA West 2 project, one European, one is based mainly on a Japanese dataset, and one is a stochastic GMPE developed specifically for the UK. These GMPEs provide predictions that are consistent with the UK data and

22 can be used in the characterization of the ground motion attenuation in a PSHA in the
23 UK.

24 ## INTRODUCTION

25 The United Kingdom (UK) is a region of low to moderate seismicity for which a probabilistic
26 seismic hazard assessment (PSHA) is not always required. For ordinary constructions, seismic
27 hazard in the UK can be considered insignificant (Musson 2014). Booth et al. (2008) recommended
28 that that seismic actions should be explicitly considered for those structures where at least two out
29 of the three factors listed below apply:

30 1. Exceedance of regional seismic hazard at the site above a specified threshold. For the UK,
31 Booth et al. (2008) propose a threshold level based on the 2475 yr. return period peak
32 ground acceleration, PGA, on rock of at least 0.06 g.

33 2. The presence of soils overlaying rock at the site which might lead to a high amplification
34 of seismic actions.

35 3. The presence of unfavorable structural features.

36 Site specific PSHA in the UK is mandatory for strategic facilities such as nuclear power plants
37 (NPPs). The regulatory framework for nuclear facilities in the UK requires a formal and detailed
38 safety case to be submitted for NPP sites before permission to construct or operate can be granted.
39 As part of it, the seismic hazard should be estimated. Musson (2014) presented a history of seismic
40 hazard assessment for strategic facilities, highlighting that after a cessation of NPP construction in
41 Britain in 1995, in recent years steps have been taken towards a resumption of NPP building which
42 will see a need for new seismic hazard studies.

This study was developed as part of a seismic hazard assessment for a potential new nuclear site in the UK, Wylfa Newydd in North Wales. However, the findings and the data presented in this paper are not site specific and provide a suite of ground motion prediction equations (GMPEs) that can be used for any generic site in the country.

The epistemic uncertainty related to the ground motion characterization (GMC) is due to the uncertainty in the dynamic characteristics of the earthquake sources and of the wave propagation. Generally, in a PSHA this epistemic uncertainty is handled through a logic tree approach (Kulkarni et al., 1984). In a logic tree, each branch represents an alternative credible interpretation and all the branches are assumed to be mutually exclusive and collectively exhaustive. The weights on the branches represent the judgement about the credibility of the alternative models. These weights are often called probabilities, but they are better treated as evaluations of the relative merits of the alternative models (Abrahamson and Bommer, 2005). Scherbaum and Kuehn (2011) describe the weights as subjective estimates of the degree of certainty or degree of belief that the corresponding model is the one that should be used. In Musson (2012) they are described as the probability of each model to be the "best model available". In this context, same weight assigned to two different models may reflect the fact that we don't have a way to distinguish either of the models as superior (Bommer, 2012).

Although multiple GMPEs are traditionally used in a logic tree to characterize the GMC, different approaches have been used in recent seismic hazard assessments for NPPs to capture the epistemic uncertainty in the ground motion characterization. There are numerous examples of the use of use of a single or multiple GMPE as backbone and application of scaling factors to cover a broader range of uncertainty (as for instance uncertainty in the stress drop parameters).

Examples of a scaled backbone approach can be encountered in the development of ground motion models for PSHA applications in the Central and Eastern United States (CEUS), including Toro et al. (1997) and Electric Power Research Institute (EPRI 2004, 2013a); Atkinson and Adams (2013) used GMC logic trees for crustal earthquakes in active and stable regions, and also for subduction earthquakes, in which the upper and lower branches carried models that are scaled versions of a central "backbone" model. In the SSHAC (Senior Seismic Hazard Committee) Level 3 PSHA for the Thyspunt nuclear site in South Africa (Bommer et al., 2015), three GMPEs were selected and, after the application of the host-to-target Vs-κ adjustments, they were scaled by four scaling factors. In the Hanford project (Pacific Northwest National Laboratory, PNNL, 2014), a backbone GMPE was developed from a small number of equations, and additional branches were generated to capture the inherent epistemic uncertainty, including uncertainty in magnitude scaling and host-to-target adjustments.

In regions such as the United Kingdom (UK), the epistemic uncertainty associated with ground motion prediction is large and mainly due to the lack of strong motion data that can provide knowledge on the nature of expected ground motions. This is especially true for the magnitude range of primary interest for the seismic hazard (i.e. $M_w \geq 4.0$). Locally recorded ground motion data only cover events up to 4.5 M_w, which corresponds to the Market Rasen earthquake of 2008 according to the magnitude estimation by Ottemöler and Sargeant (2010). Due to the lack of strong motion data from the UK, there is a limited number of GMPEs derived specifically for the country. Among these, the PML (1982, 1985 and 1988) models, derived in terms of surface wave magnitude (M_s), have often been used for seismic hazard studies in the UK (e.g Arup, 1993; Goda et al., 2013;.Senior Hazard Working Party, SHWP, 2001). These models were not based on UK data, but developed from a suite of selected records with similar magnitude and duration characteristics as

typical British earthquakes. These GMPEs are not considered in this study because they were developed based on a limited datasets and the adopted regression methods are no longer considered best practice. Bommer et al. (2011) highlighted that "the shortcomings of the PML (1988) spectral prediction equations, when judged against the state-of-the-art in ground-motion prediction, are many and serious". Another UK specific GMPE was developed by Rietbrock et al. (2013) based on stochastic simulations and on the work of Edwards et al. (2008). During the development of the seismic hazard assessment for the Wylfa Newydd NPP, the original model of Rietbrock et al. (2013) was updated and is therefore included in this analysis. This model is hereafter called Rietbrock and Edwards (2017), RE17 and, since unpublished, is sumamrized in section "SUMMARY OF THE RIETBROCK AND EDWARDS (2017) MODEL". The methodology upon which the GMPE is built is the same as in the original work of 2013, however new data were implemented which led to a significant improvement in the ground motion predictions.

This study aims at evaluating the applicability of multiple GMPEs from worldwide and the Rietbrock and Edwards (2017) model to the UK conditions. Given the scarcity of data in the UK the use of multiple GMPEs is recommended since this allows to cover a wider range of spectral shapes, as shown later in the paper. The following steps were adopted:

- Two ground motion datasets were compiled: one for the instrumentally recorded ground motion which includes events with moment magnitude between 2.8 and 4.5 and one for macroseismic observations for moment magnitude between 3.0 and 5.8;
- A pre-selection of the GMPEs was performed based mainly on the rejection criteria of Cotton et al. (2006) and Bommer et al. (2010).
- The predictions from the GMPEs were compared with UK observations (instrumentally recorded ground motion data and macroseismic intensities) in terms of residuals. The

statistical tests of Scherbaum et al. (2009) and Kale and Akkar (2013) are used to rank the GMPEs and remove those that, although pass the rejection criteria, do not provide adequate estimates of the ground motion; and

- The median predictions of the suite of GMPEs from above were compared using Sammon's maps to evaluate similarities. The use of equations yielding similar ground motion predictions in fact could lead to an underestimation of the epistemic uncertainty (Bommer et al., 2015), undermining the benefits of using multiple GMPEs approach.

A suite of GMPEs is found to provide predictions that are consistent with the UK context and can be adopted in a logic tree approach. According to the specific conditions of the site under study, these GMPEs may then be adjusted through host-to-target adjustments and, if appropriate, scaled to cover a wider range of epistemic uncertainty.

SUMMARY OF THE RIETBROCK AND EDWARDS (2017) MODEL

The original work of Edwards et al. (2008), upon which Rietbrock et al. (2013) was based, was limited to single-component vertical short-period sensors. During the seismic hazard assessment of the Wylfa Newydd NPP, the GMPE by Rietbrock et al. (2013) was updated. Two models were developed: one for the UK and one site specific. In this paper, the model for the UK is summarized.

The upgraded digital broadband three component seismic network operated by the BGS since 2007 was adopted in the study. The data were processed in a consistent manner. Event location, arrival times for the S- and P-waves, station locations and instrument calibration files were provided by BGS. A signal to noise ratio analysis was performed to remove low quality signals. 187 signals were then processed (instrument corrected in velocity and band-pass filtered using an acausal 6-pole Butterworth filter with corner frequencies set at the lowest and highest frequencies

at which the signal to noise ratio exceeded 3) and the 5% damped acceleration response spectra were computed. As part of the study, the moment tensor solutions for recent UK events were determined as well as the high frequency attenuation parameter κ_0 for many recording stations in the UK using the approach of Anderson and Hough (1984) applied to larger magnitude UK events (M_L > 3.5). Figure 1 shows the κ_0 values of the RE17 study as a function of V_{S30} as well as the average values for each soil class: κ_0 was found to be approximately 0.03 s for soft soil ($V_{S30} \leq 360$m/s), stiff soil ($360 < V_{S30} \leq 760$m/s) and rock ($760 < V_{S30} \leq 1{,}100$m/s), while a value of 0.012s was found at hard rock stations ($V_{S30} > 1{,}100$m/s).

Using the results of the spectral analysis, the seismological model used by Rietbrock et al. (2013) for simulating strong ground-motion records in the UK was updated. In particular,

- Based on the average site amplification and H/V estimates determined during spectral analysis, the GMPE is developed for a hard-rock model (V_{S30} of 2600m/s). The shear-wave velocity profile for this model is based on the BGS's 1D UK model (Booth et al., 2001) and a κ_0 of 0.005 s was adopted.

- The duration of shaking used for the model was also investigated. Due to the small magnitude of recorded earthquakes, the measured duration is potentially affected by noise. Direct measurement of the D_{95}=5%-95% shaking duration using the new data and the method proposed by Boore and Thompson (2014) led to increased durations with respect to the model used by Rietbrock et al. (2013).

The seismological model was implemented in the simulation technique used by Rietbrock et al. (2013) which uses the stochastic ground-motion method in the random vibration theory framework (SMSIM, Boore, 2003), adjusted for moderate to large magnitude earthquakes for the

geometric effects related to the finite extent of rupture. Earthquakes of magnitude between 3 and 7 and distances between 1 and 300km were simulated over a depth distribution consistent with UK seismicity.

Finally, the UK GMPE was derived following the same functional form as in Rietbrock et al. (2013) and reported below for ease of reference:

$$log_{10}(Y) = c_1 + c_2 M_W + c_1 {M_W}^2 + (c_4 + c_5 M_W) F_0 + (c_4 + c_5 M_W) F_0 + (c_4 + c_5 M_W) F_0 + c_{10} R \quad (1)$$

Where

$$R = \sqrt{{R_{JB}}^2 + {c_{11}}^2} \quad (2)$$

$$F_0 = \begin{cases} log_{10}\left(\frac{10}{R}\right) & for\ R \leq 10km \\ 0 & for\ R > 10km \end{cases} \quad (3)$$

$$F_1 = \begin{cases} log_{10}(R) & for\ R \leq 50km \\ log_{10}(50) & for\ R > 50km \end{cases} \quad (4)$$

$$F_0 = \begin{cases} 0 & for\ R \leq 100\ km \\ log_{10}\left(\frac{R}{100}\right) & for\ R > 100\ km \end{cases} \quad (5)$$

In the above equations *Y* is the ground motion parameter (peak ground velocity, PGV, peak ground acceleration PGA or spectral acceleration at selected periods, T, between 0.03 and 5 s), R_{JB} is the Joyner and Boore distance, and c_i are the regression coefficients provided in Table 1, along with the associated total, between-event and within-event uncertainties. Comparisons of the two models are shown in Figure 2 in terms of attenuation curves for three magnitude values (M_W=4.5, 5.5 and 6.5) and two spectral periods (T=0 s, PGA, and T=1 s). The attenuation with distance follows a similar trend, however the new model leads to consistently higher predictions. Figure 2

shows the attenuation curves for PAG and spectral accelerations at T+1s for three magnitude values (M_W=4.5, 5.5 and 6.5): the new model provides spectral acceleration that are larger that Rietbrock et al. (2013) and, as we show later in the paper, are consistent with the UK ground motion data.

DESCRIPTION OF THE DATASETS ADOPTED FOR THE GMPES SELECTION

To enable quantitative and qualitative comparisons with the GMPEs predictions, we collated UK ground motion data. The number of strong motion recordings in the UK is limited, particularly for magnitudes greater than M_W =4.0 and therefore macroseismic intensity data were also included to assist with the evaluation of GMPEs. The two datasets are presented below. It is noted that these two datasets were collated and analyzed independently of the ground motion data used to derive the Rietbrock and Edwards (2017) model.

Data from nearby regions were excluded from this analysis. Sargeant and Ottomöller (2009) determined the regional average Q_{Lg} and performed tomographic inversions in the frequency range 1.0–10.0 Hz to map the lateral variations in Q_{Lg}. They adopted a dataset of 64 earthquakes with magnitude between 2.7 and 4.7 M_L recorded at 93 stations. The spatial coverage of the data is such that an estimate of regional average Q_{Lg} will be representative of most of onshore Britain. The results of the study indicated that attenuation in Britain is slightly higher than in France and significantly higher than in eastern North America and Scandinavia. A comparison of the Q_{Lg} attenuation for various regions is provided in Figure 3. A decision was therefore made to limit the dataset to UK events in order to avoid any bias due to differences in the attenuation characteristics.

UK INSTRUMENTAL DATASET

A dataset of instrumentally recorded ground motions was compiled for this study for earthquake with moment magnitude greater than or equal to 3.0 and epicentral distances shorter than 300 km. Overall, the dataset compiled for this study consists of 83 accelerograms (two horizontal and one vertical component) from 12 earthquakes recorded in the UK from 1996 to 2018 with moment magnitude between 3.2 and 4.5. A summary of these earthquakes is presented in Table 2. The location of these events and recording stations is shown in Figure 4 while Figure 5 shows their distribution in terms of magnitude versus (a) distance, (b) soil conditions and (c) peak ground acceleration (PGA). Four moderate size events in the UK have been recorded by the British Geological Survey, BGS, network since 2002. These are the 2002 Dudley earthquake with M_W=4.2 (Sargeant and Ottomöller, 2009, consistent with Baptie et al., 2005, who found previously M_W=4.1), the 2007 Folkestone earthquake with M_W=4.0 (Ottömoller et al., 2009; Ottömoller and Seargeant, 2010), the 2008 Market Rasen earthquake with M_W=4.5 (Ottömoller and Seargeant, 2010) and the 2018 Swansea earthquake with local magnitude according to the BGS website M_L=4.6 (converted to M_W=4.3 using the empirical correlation by Grünthal et al., 2009). The information (metadata) on the causative earthquakes, source to site distance metrics and local site conditions at the recording stations was compiled. The source parameters of the events were taken from Ottemöller and Sargeant (2010), Sargeant et al. (2008), Baptie et al. (2005) and Sargeant and Ottemöller (2009) for all the events up to 2008. The parameters for the 2014 Bristol Channel and 2015 Ramsgate events were calculated specifically for this study (Rietbrock and Edwards, 2017). The parameters for the Llyn peninsula and Swansea earthquakes are those provided on the BGS website and converted to moment magnitude as mentioned above.

Time history records were provided by the BGS who already performed the instrumental correction and the signal to noise evaluation. The records were then processed through a baseline correction and band-pass filtered using an acausal 4-pole Butterworth filter with corner frequencies at 0.01 and 50Hz and the 5% damped acceleration response spectra were computed. A visual check on the quality of the data and the associated response spectra was performed. It is highlighted that among all the data, one record from the Folkestone earthquake led to the maximum PGA recorded in the UK (PGA=0.1g) corresponding to the TFO station. However, the time history appears to be saturated. After discussion with BGS, the record was kept in the dataset with consideration that a maximum PGA of at least 0.1g is associated to that earthquake.

An understanding of site conditions at the stations locations is required to compare GMPEs predictions against the observed ground motion recordings. Since in-situ measurements of shear wave velocity (V_S) are not available for the majority of stations, the site conditions (Table 3) were estimated based on a joint evaluation of the following information:

- Geological descriptions from the BGS. The ranges of V_{S30} (the average shear wave velocity of the upper 30 m) associated with the description of geology are based on Borchedt (1994) for all stations except for the PGB1 station, which is based on Christensen et al. (1980);
- Horizontal-to-vertical (H/V) Fourier Amplitude spectral ratios from recorded ground motions computed in this study (Rietbrock and Edwards, 2017). Although based on response spectral ratios, the site class classification proposed by Di Alessandro et al. (2012) who considered earthquakes with M_W between 4.0 and 6.8 within 50 km of a seismometer was used as a guide. When not consistent with the known geological information, the latter was relied upon to assign a V_{S30} value; and

- Tallet-Williams and Fenton (2015) who carried out non-intrusive testing of three BGS stations. Only tests at two of them yielded V_{S30} values; these are CCA1 and SWN1 with values of 845 and 503 m/s respectively.

Table 3 presents a summary of the above information and the preferred V_{S30} value assigned to each station for this study.

UK MACROSEISMIC DATA

The macroseismic dataset for this study comprises an extract of the UK Historical Earthquake Database from the BGS website. All earthquakes with a magnitude greater than or equal to M_W =3.0 (based on the M_L to M_W correlation of Grünthal et al., 2009) and at least 50 macroseismic intensity data points (IDPs) were included. The online BGS database currently only extends to the year 2001. In addition to those events, five additional events were incorporated into the dataset for this study, including Folkestone (4.0 M_W) and Market Rasen (4.5 M_W) events. Data for these events were taken from the USGS "Did you feel it?" database. The database does not include the Dudley, Ramsgate and Caernarfon events. Table 4 presents the main features of the included earthquakes, while Figure 5 shows the geographical distribution of the epicentres.

An initial dataset of 15,3662 IDPs was compiled. Only IDPs from earthquakes with moment magnitude greater than or equal to 3, epicentral distance lower than 300 km and an intensity value greater than or equal to 3 were retained. The final dataset consists of a total of 11,412 IDPs. Since intensity is a categorical variable, "half-levels" of intensity do not exist. When these are found, generally displayed as for instance 3-4 or 5-6, the uncertainty in the intensity value is highlighted. These values are usually lumped with integer levels before proceeding any further. In this study, we randomly assigned each such IDP to the lower or higher level, with equal probability. The

initial and final datasets are presented in Figure 6 in terms of distributions of macroseismic intensity versus distance.

PRE-SELECTED GMPES FOR THE UK

As mentioned in the Introduction, the UK is a region of low seismicity for which strong motion data are rare. Moreover, the absence of reliable modern GMPEs specific for the UK makes the characterization of the ground motion attenuation for a seismic hazard assessment much more complicated. Equations from other regions need to be adopted and sometimes adapted to the regional conditions specific of the UK based on the limited available data.

Douglas (2018, Data and Resources) identifies a total of 450 published GMPEs which estimate PGA and 290 published GMPEs which estimate elastic response spectral ordinates. Criteria for the selection of GMPEs were first proposed by Cotton et al. (2006) and revisited by Bommer et al. (2010). These two sets of authors provide a total of 10 criteria which could assist with the selection of candidate GMPEs. Bommer et al. (2010) noted that only eight GMPEs met their criteria at the time of their publication. These consist of four NGA-West (Next Generation Attenuation Relationships for western US) GMPEs (Abrahamson and Silva, 2008; Boore and Atkinson, 2008; Campbell and Bozorgnia, 2008; Chiou and Youngs, 2008), Akkar and Bommer (2010), Atkinson and Boore (2006), Toro et al. (1997, modified as Toro, 2002) and Zhao et al. (2006). Since the criteria were published, many new GMPEs have been developed, as well as updates to the NGA West GMPEs.

Based on considerations of the UK characteristics, in addition to the criteria of Bommer et al. (2010) the following points were considered:

- Models developed for shield regions were excluded since the geological processes which led to the existence of the UK are significantly different to landmasses which exist today due to the formation of a shield. These differences will lead to different attenuation characteristics (Douglas, 2011);
- Only GMPE which incorporate an explicit V_{S30} term were included since κ_0 adjustments are required to make GMPEs from elsewhere applicable to the UK low kappa-site values shown in Figure 1 and to hard rock sites;
- Stochastic GMPEs based on Eastern North America (ENA) were excluded based on the difference in the attenuation of the seismic waves (Figure 3).

Based on these considerations, the GMPEs that were not rejected are the NGA West 2 GMPEs (Abrahamson et al., 2014, ASK14; Boore et al., 2014, BSSA14; Campbell and Bozorgnia, 2014, CB14; Chiou and Youngs, 2014, CY14; and Idriss 2014, I14), Bindi et al. (2014), BI14, Akkar et al. (2014a,b), ASB14, and Cauzzi et al., 2015, CA15. However, based on the limits of applicability of the Idriss (2014) model ($M_W \geq 5$, $R \leq 150$ km and $V_{S30} \geq 450$ m/s) and the inconsistencies with the available dataset for the UK earthquakes (Figure 5 and Figure 7), this GMPE was excluded from the following analysis.

In addition to the above GMPEs, the GMPE of Rietbrock and Edwards (2017), RE17, summarized in this paper is included. It is noted that although not yet published, the model is an update of an already published model and therefore fulfils the criteria described in Bommer et al. (2010). Moreover, although the model does not incorporate a V_{S30} term, it has been specifically developed for hard rock sites in the UK, therefore no adjustment will be necessary when applied to these conditions. In the following analysis, this GMPE is also compared against UK data that do not lie on hard rock, showing a very good performance.

V_S-κ_0 ADJUSTMENT FACTORS FOR THE UK

The high frequency attenuation parameters of the candidate GMPEs, κ_{host}, were computed to ensure these were consistent with the UK values (Figure 1) using the inverse random vibration theory, iRVT (Gasparini and Vanmarcke, 1976). To this end, response spectra for a set of magnitude and distance bins were computed, in particular M_W of 4.5, 5.5 and 6.5 and epicentral distances R_{epi} of 5, 10 and 20 km were used. Table 6 shows average κ_{host} values computed in this study for the selected empirical GMPEs. These values are larger than the average values for site class found by RE17.

Therefore, prior to any statistical analysis, adjustment factors for the UK were determined to modify the GMPEs for the average κ_0 values in the UK, following the methodology in PNNL (2014). The parameters needed for the adjustment factors are usually (1) the definition of V_S profiles and κ_0 values at the target site (i.e., a generic site in the UK) and (2) the definition of the V_S profiles and κ_0 at the host location, i.e. the average rock site for the selected GMPE.

For stations on stiff soil or rock, the V_{S30} values are within the range of applicability of the GMPEs, thus no adjustment for V_S was applied. The target high frequency parameter, κ_{target}, was assumed as 0.03 s, as per Figure 1. The κ_{host} values are those from Table 6.

For hard rock station, adjustments both for the V_S profile and the κ value were required where the target κ_0 value is taken as 0.012 s. The target Vs profile for the UK was defined according to Booth et al. (2001). The κ_{host} values are those from Table 6 corresponding to a V_{S30} of 760 m/s. The host V_S profiles for the empirical GMPEs were defined as follows:

- For all the NGA West GMPEs, the V_S profile defined by Boore (2015) was adopted.

- For the GMPEs of Akkar et al. (2014a,b) and Bindi et al. (2014), the V_S profile corresponding to an average V_{S30} of 760 m/s was derived using available V_S profiles on rock stations from Italy, Greece and Turkey (see Data and Resource), with a total of 13 stations.

- For the GMPE of Cauzzi et al. (2015), rock stations from the dataset with available V_S profiles were used, which consisted of 16 V_S profiles from Kik-net dataset and two from the Italian dataset (see Data and Resource).

The adjustment factors for the UK are shown in Figure 8 for three GMPEs. All the empirical GMPEs are corrected using the V_S-κ_0 adjustment factors for the UK. No adjustments are applied to the stochastic UK specific model.

The dependence of κ on magnitude, distance and V_{S30} was also explored. Results show a clear trend with κ decreasing as V_{S30} increases: for low V_{S30} values (250 or 400 m/s), kappa shows a stronger dependence on magnitude and distance compared with higher V_{S30} values. All the GMPEs showed similar trends.

COMPARISON OF GMPES WITH THE UK DATA

COMPARISON WITH THE UK INSTRUMENTAL GROUND MOTION DATA

Comparisons of the attenuation curves from the nine preselected GMPEs and the observations from the Dudley, Folkestone, Market Rasen and Swansea earthquakes are shown in Figure 9 and Figure 10. The attenuation curves are computed for sites with a V_{S30} of 760 m/s in the empirical GMPEs. The stations on rock, which are comparable with the curves, are shown as white squares. All other observations are shown, for completeness, as gray circles. In general, the predictions from the GMPEs slightly under-predict the observations from the Market Rasen earthquake which

has been formulated by several authors that could be a high stress drop event (e.g. Sargeant and Ottömoller, 2010). Good agreement is found for the other three earthquakes. For the GMPEs of RE17 the white squares represent data on hard rock sites consistent with the attenuation curves specific for hard rock sites. The agreement is very good for all four earthquakes.

There are numerous statistical methods to test the agreement between observed and predicted data (e.g. Chi-square test, Kolmogorov-Smirnov test, variance reduction and Pearson's correlation coefficient). These statistical methods can be used to understand the suitability of a given predictive model under a set of collected ground motions. A brief description of these methods can be found in Kale and Akkar (2013).

In this study, three methods are discussed to quantitatively evaluate the performance of the preselected GMPEs with respect to the UK dataset: the classical residual analysis, the method proposed by Scherbaum et al. (2009) and the method proposed by Kale and Akkar (2013).

The most common methodology for assessing predictive model performance is the residual analysis. This statistical method determines the existence of bias through the application of mean residuals, as well as the trend of the total residuals as function of estimator parameters such as magnitude and source to site distance.

The normalized residuals can be calculated as:

$$\text{residual(f)} = \frac{\log(\text{obs(f)}) - \log(\text{pre(f)})}{\sigma_{\text{GMPE}}(\text{f})} \qquad (6)$$

where residual is the total normalized residual at the spectral frequency, f, $obs(f)$ and $pre(f)$ are the observed and predicted spectral accelerations respectively and $\sigma_{GMPE}(f)$ is the total standard deviation of the model at a given spectral frequency. A positive value indicates that the observed ground motions are larger than those predicted by the GMPE while a negative value of the residual

indicates that the observed ground motions are lower than the predictions (i.e. the model over-predicts the data).

Residuals were computed for 10 spectral frequencies between 0 and 3 s. Figure 11 and Figure 12 show the residuals (gray circles) in terms of magnitude and distance for each of the preselected GMPEs for the PGA and the spectral acceleration at 1 s. The white squares in the figures show the average values for magnitude and distance intervals, in order to highlight if a clear trend exists. The comparisons show that most of the residuals fall within three standard deviations. Calculated residuals for some of the equations indicate under prediction of the observed ground motions (e.g. Boore et al., 2014; and Campbell and Bozorgnia, 2014).

Table 7 presents a qualitative summary of the general performance of the GMPEs. Overall, the GMPEs slightly under-predict the data. Considering only the data within 100 km of the earthquake sources, the mean residuals for the different frequencies tested are either side of zero or very close to zero, indicating reasonable performance for many of the GMPEs. Although the GMPE of for Cauzzi et al. (2015) GMPE is defined for a minimum magnitude M_W of 4.5, it performs well against the UK data.

To have a better understanding of the performance of the GMPEs against the UK recorded data, statistical tests were also investigated. The method proposed by Scherbaum et al. (2009) attempts to overcome the limitations found in the previous method by Scherbaum et al. (2004). Scherbaum et al. (2004) proposed a scheme based on exceedance probabilities (or likelihood, LH, values) to quantify the appropriateness of candidate models with respect to a set of response spectral reference data. One of the shortcomings of their method is that it still requires subjective decisions (e.g. definition of classes and thresholds for acceptability). Although the LH method was proven to be a robust approach for ranking the candidate GMPEs, its dependence on data size and

subjectivity in choosing the threshold LH value, led Scherbaum et al. (2009) to propose the log likelihood (LLH) method that overcomes these limits. The authors proposed an information theoretic approach that is more general and does not depend on ad hoc assumptions.

The method computes the log likelihood parameter which is defined as:

$$LLH\,(g,\underline{x}) = -\frac{1}{N}\sum_{i=1}^{N}\log_2\left(g(x_i)\right) \qquad (7)$$

where $x=\{x_i\}$, i = 1... N are the empirical data and $g(x_i)$ is the probability density function given by a GMPE to predict the observation x_i.

Since LLH is a divergence criterion to rank the candidate GMPEs, a small LLH indicates that the candidate model is close to representing the process that has generated the data while a large LLH corresponds to a model that is less likely of representing the observed data well.

Arroyo et al. (2014) highlight that the method may lead to incorrect weightings although correct ranking of models. In this study, we only use the LLH method for ranking the candidate GMPEs.

Kale and Akkar (2013) noted that the method proposed by Scherbaum et al. (2009) focuses on selecting a suite of GMPEs that can accurately represent the aleatory variability of the ground motion dataset used in testing. This objective may favor GMPEs with large sigma and selection of such GMPEs may result in conservative probabilistic seismic hazard for low annual probabilities of exceedance (Restrepo-Velez and Bommer, 2003). The authors propose a different metric (instead of likelihood) that tends to use greater weight for increased closeness to the mean value of the model and less weight for the impact of outliers. The method is based on the Euclidean distance which separately considers ground motion uncertainty (i.e. aleatory variability addressed

414 by the standard deviation) and the bias between the observed data and median estimations of
415 candidate GMPEs. Three indices are obtained from this method:

416 - The normalized distance based ranking (MDE), which evaluates the effect of sigma
417 while testing the performance of the GMPE under a given ground motion database;

418 - $k_{0.5}$, which provides the performance of the median prediction from the GMPE. The
419 parameter k is the ratio of the original and corrected Euclidean distances. Therefore, it
420 occurs when the estimates from the GMPEs are very close to the observations. The
421 optimum value is 1; and

422 - Euclidean distance based ranking (EDR), which provides an estimate of the overall
423 performance of the model.

424 Detailed equations for this method are provided in Kale and Akkar (2013).

425 Mak et al. (2014) criticized the method, in particular the index MDE, which according to the
426 authors, favors a smaller modeled uncertainty when two predictions give the same mean. However,
427 in their reply Kale and Akkar (2014) explains that MDE is tailored to assess the influence of GMPE
428 sigma on the estimated ground motions, while larger differences between the observed data and
429 estimated median will be penalized by $k_{0.5}$. Moreover, the authors highlight that EDR, as a two-
430 component score, would not prefer a model in which the median estimates entirely disagree with
431 the observed data.

432 Figure 13 shows the results of the eight preselected GMPEs in terms of LLH values with
433 frequency while Figure 14 provides the results of the method by Kale and Akkar (2013).

434 Table 8 summarized the results providing the average score over the range of periods
435 considered in the Scherbaum et al. (2009) and Kale and Akkar(2013) statistical tests. To assist the

reader, the three GMPEs that performed the best are underlined: Abrahamson et al. (2014), Cauzzi et al. (2015) and Rietbrock and Edwards (2017).

COMPARISON WITH THE UK MACROSEISMIC DATA

Due to a lack of strong motion data at short distances and larger magnitudes, a macroseismic dataset for the UK was also used to test the nine preselected GMPEs. This allows inclusion of earthquakes with magnitude greater than 4.0M_W and greatly increases the number of data close to the epicentre of an earthquake. The idea of using macroseismic data to evaluate the performance of GMPEs was proposed by Scherbaum et al. (2009) who demonstrated it to be a useful way of assessing GMPEs using Californian data from Delavaud et al. (2009).

The methodology is similar to that used for UK instrumental data. However, an additional step is required, involving conversion of the PGA ground motion into a macroseismic intensity. Therefore, an assessment of a correlation between ground motion and intensity needs to be undertaken. A total of six relationships were considered and are presented in Table 9.

To test their applicability, the correlations were compared for seven earthquakes in the UK for which both recorded PGA and macroseismic intensities were available: Penzance, Arran, Sennybridge, Warwick, Dudley, Folkestone and Market Rasen. For all events intensity observations at the recording stations were assigned based on the intensity maps or an interpolation of the closest intensity measurements. For each relationship, the median and its 5-95% band of variability are compared with the data in Figure 15. Although the uncertainty of the relationship between ground motion and intensity is large, the two correlations that best capture the UK data are: (1) Faccioli and Cauzzi (2006), FC06, based on a dataset with distances lower than 100 km and PGA values between 0.2 and 6 m/s^2 and (2) Atkinson and Kaka (2007), AK07, which also

458 includes earthquakes at very large distances; up to about 500 km. Both equations are of the form:
459 $I_{EMS} = a + b log PGA$ with an associated uncertainty σ_{GMICE}.

460 For the computation of the residuals equation (1) was modified as below:

461 $$\text{residual} = \frac{I_{obs} - I_{pre}}{\sigma_I} \quad (8)$$

462 where I_{obs} is the observed macroseismic intensity, I_{pre} is the predicted value derived from the
463 conversion of the predicted PGA from the GMPE and σ_I is the standard error associated with the
464 prediction. Since the PGA comes from a GMPE and therefore has an associated standard error, the
465 total standard error was computed as shown below:

466 $$\sigma_I = \sqrt{\left(b\ \sigma_{log10(PGA)}\right)^2 + {\sigma_{GMICE}}^2} \quad (9)$$

467 where $\sigma_{log10(PGA)}$ is the standard error of the logarithm of PGA in base 10.

468 To allow the comparison of GMPEs with the macroseismic data, an estimate of V_{S30} at each
469 macroseismic location is required. An estimate of V_{S30} was obtained using the global V_{S30} maps
470 provided by the USGS (Wald and Allen 2007), based on correlations between topography and
471 V_{S30}. Although the method has recognized limitations, it has been used for this study only to assess
472 the V_{S30} at the macroseismic locations due to the large amount of data to be processed and the
473 scarcity of information on the V_{S30} parameter over the whole of the UK. Linear interpolation from
474 the Wald and Allen (2007) map was adopted.

475 Examples of the results in terms of residuals is presented in Figure 15 for the GMPE of
476 BSSA14, BI14 and CA15 using the correlation of Faccioli and Cauzzi (2006). Similar trends in
477 the residuals are found using Atkinson and Kaka (2007).

In general, the trend of the residuals does not differ from that found for the ground motion data at short period. The residuals with respect to magnitude are close to zero for $Mw \geq 4$ in the case of Abrahamson et al. (2014) and Chiou and Youngs (2014). A slight under prediction is found in the case of Bindi et al. (2014), Campbell and Bozorgnia (2014), Cauzzi et al. (2015) and Rietbrock and Edwards (2017), while Akkar et al. (2014) display strong linear trends.

The results in terms of the two methods of Scherbaum et al. (2009) and Kale and Akkar (2013) are presented in Table 10 where the three best results for each test are underlined. Overall, Abrahamson et al. (2014), Boore et al. (2014), Chiou and Youngs (2014), Cauzzi et al. (2015) and the stochastic UK specific model, Rietbrock and Edwards (2017) show good performance.

COMPARISON OF GMPES' MEDIAN PREDICTION

The approach used to evaluate similarities in the GMPEs involved the graphical comparison of the attenuation curves (e.g. PGA versus distance) for a particular magnitude value and spectral ordinate. Figure 17 shows comparisons among the response spectra computed with eight GMPEs adopted in this study for hard rock sites, for two moment magnitude (5 and 6) and two epicentral distances (15 and 50 km). For the conversion among the different distance metrics a strike slip fault mechanism (typical for UK earthquakes) has been assumed in all cases. The figure highlights the differences among the GMPEs in terms of predicted amplitude and spectral shape. The Rietbrock and Edwards (2017) appears as the most dissimilar. The level of amplitudes predicted is overall comparable, however the peak of the spectrum occurs at 0.1 s while for the empirical adjusted GMPEs it is found at 0.05 s. Moreover, the spectral accelerations are lower than the other GMPEs at very short period, and much larger at periods longer than 0.1 s especially for a distance of 50 km. Among the empirical adjusted GMPEs, ASK14 provides the larger acceleration at magnitude 5.

An exhaustive comparison of all the GMPEs for many spectral periods and magnitudes is not practical and would be difficult to evaluate in an objective manner. To overcome this issue, Scherbaum et al. (2010) suggest the use of the Sammon's maps (Sammon, 1969). Sammon's maps are a statistical technique which enables the projection of high dimensional vectors onto 2D maps in such a way that the distances between the vectors can be preserved. More than one 2D configuration can exist for a given set of GMPEs. The absolute numbers on the axes do not have a physical meaning. Only the distances and relative positions are of importance.

Given the spectral acceleration, SA, for a certain magnitude distance combination k, the Euclidean distance $\Delta\mathrm{GMPE}_{ij}$ between two GMPEs, i and j is computed as:

$$\Delta GMPE_{ij} = \sqrt{\sum_k \left(logSA_{k,i} - logSA_{k,j}\right)^2} \qquad (10)$$

and projected in 2D maps. In this study, the Euclidean distances were computed based on magnitudes between 4.0 to 7.0 M_W at 0.2 M_W intervals for 12 R_{epi} distances (1, 5, 10, 20, 30… 100 km). For each combination of magnitude and distance, the ground motion has been computed at periods between 0 and 3 s. Examples of the results are shown in Figure 18 for rock (where RE17 is not included) and in Figure 19 for hard rock (where all the GMPEs are corrected for a κ_0 of 0.012s, except RE17 which is directly applicable on hard rock). Maps of the Euclidean distances for each spectral ordinate are also presented and shown on the left panels of the figures. Dark colours highlight the GMPEs that are most dissimilar. Of the four NGA West 2 GMPEs, Abrahamson et al. (2014) and Chiou and Youngs (2014) are relatively close, indicating that the two provide similar predictions, while Boore et al. (2014) and Campbell and Bozorgnia are more distant from the others. Also, Akkar et al. (2014) and Bindi et al. (2014) are relatively

close at all spectral periods. Large distances are found between the Rietbrock and Edwards (2017) and all adjusted empirical GMPEs when the predictions are used for hard rock sites.

DISCUSSION AND CONCLUSIONS

In region of high seismicity, the definition of the ground motion attenuation can often benefit from the availability of a large number of instrumentally recorded ground motion data that cover the magnitude and distance ranges of interest of a seismic hazard assessment and, as a consequence, of published ground motion prediction equations developed specifically for the same region. This becomes more complicated when the site under study is in a region of low-to-moderate seismicity. Generally, available time histories are scarce and many times they are related to low or moderate magnitude earthquakes. This is the case of the UK, where the maximum magnitude of the instrumentally recorded ground motion data is M_W= 4.5 (related to the Market Rasen earthquake occurred in 2008). This study attempts to select GMPEs through a methodic approach that compares the predictions from GMPEs available from elsewhere against available UK data. A UK instrumental dataset was firstly collated and used for comparison against the GMPEs prediction. It is highlighted that the dataset in statistical terms has sufficient data to perform statistical tests and the data are consistent with the datasets of the GMPEs. However, the extrapolation of the results for magnitude lower than 4.5 to larger magnitude can be difficult. Therefore, given the scarcity of instrumental data especially for magnitude greater than 4.5, the study proposes to make use also of macroseismic observations. The uncertainty related to the conversion from intensity and ground motion (in this case PGA) was carried through the calculations and combined with the uncertainty in the estimation of PGA from the GMPEs.

The empirical GMPEs selected based on Bommer et al. (2010) from other parts of the world required adjustments in order to account for specific characteristics of the attenuation of the ground

motion in the UK. In this study, a correction between the kappa-site from the GMPE (κ_{host}) and kappa-site values specifically computed for the UK stations was applied prior to any comparison. Therefore, all the comparisons and analyses were performed with adjusted empirical GMPEs. A correction for the quality factor attenuation was not considered, although this could be a possible improvement. However, the comparison between the $Q_{Lg\text{-}1}$ attenuation between the UK and West US presented in Figure 3 showed that differences are small. In addition to empirical GMPEs, an update of the stochastic model of Rietbrock et al. (2013) was developed within the study and herein referred to as Rietbrock and Edwards (2017). The GMPE is for hard rock sites in the UK. A total of eight GMPEs were used in the analyses.

Based on the residuals analysis, the statistical results computed with Scherbaum et al. (2009) and Kale and Akkar (2013) and the Sammon's maps, the following observations are made:

- The Rietbrock and Edwards (2017) GMPE performs very weel against instrumental and macroseismic data also for sites that are not classified as hard rock. It behaves differently from all the other GMPEs in terms of median prediction at all periods;
- The four NGA West2 GMPEs are based on the same, or similar, dataset and were developed within the same project. Comparisons against UK data showed that the GMPE developed by Campbell and Bozorgnia (2014) is the one that worse fits the data, while the GMPE by Abrahamson et al. (2014) and Chiou and Youngs (2014) displayed a better fit with the UK data. The Sammon's maps showed that Abrahamson et al. (2014) and Chiou and Youngs (2014) are expected to perform similarly, while among these four GMPEs, Boore et al. (2014) shows larger distances.

- Bindi et al. (2014) and Akkar et al. (2014a, b) are both based on European data and in the Sammon's maps they appear to perform in a similar way at short period. Among the two GMPEs, Bindi et al. (2014) performed better against the UK data.
- The predictions from Cauzzi et al. (2015) are in agreement with the UK data and they are distant on the Sammon's maps with respect to the other GMPEs. However, for some spectral periods, they are close in the Sammon's maps to Chiou and Youngs (2014). However, their datasets are completely independent and based mainly on two different regions: California and Japan.

This study shows that five empirical GMPEs adjusted for the UK kappa-site values provide predictions that are consistent with the UK data: Abrahamson et al. (2014), Chiou and Youngs (2014), Boore et al. (2014), Bindi et al. (2014) and Cauzzi et al. (2015).

Given the lack of instrumental recorded data for magnitude greater than 4.5, and therefore the uncertainty on the spectral shape of future earthquakes, the use of multiple GMPEs is recommended. Based on the results and the GMPEs similarities in terms of database, it is recommended that in the definition of the ground motion characterization for a PSHA in the UK, at least one NGA West 2 GMPE among the above three is selected together with the GMPEs of Bindi et al. (2014) and Cauzzi et al. (2015). For PSHA on hard rock sites, in addition to the above GMPEs adjusted for the appropriate V_S-κ_0, Rietbrock and Edwards (2017) is recommended as, this analysis shows a very good agreement well with the UK ground motion data.

DATA AND RESOURCES

- Ground motion data were made available to the authors directly by the British Geological Survey (BGS).
- Macroseismic data were downloaded from the Historical Earthquake Database from the BGS website: http://quakes.bgs.ac.uk/historical/. Last accessed February 2016
- V_{S30} data for the UK were downloaded from: Global VS30 Map Server, retrieved from earthquake.usgs.gov/hazards/apps/vs30/, Last accessed December 2015.
- List of available GMPEs until 2015 were consulted from Douglas, J. (2015). Ground motion prediction equations 1964 – 2015, http://www.gmpe.org.uk, Last accessed February 2016
- V_S profiles for stations in Italy were retrieved from the ITACA (Italian Accelerometric Archive) Project (available at http://itaca.mi.ingv.it), Last accessed February 2016
- V_S profiles for stations in Greece were retrieved from the database monitored by ITSAK (Institute of Engineering Seismology and Earthquake Engineering) http://monographs.itsak.gr/. Last accessed February 2016.
- V_S profiles for stations in Turkey were retrieved from the database of the Disaster and Emergency Management Presidency of Turkey (http://kyh.deprem.gov.tr/en/home). Last accessed February 2016.
- V_S profiles for stations in Japan were retrieved from the Kik-Net website (http://www.kyoshin.bosai.go.jp/). Last accessed February 2016.

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TABLES

Table 1 – Coefficients of the Rietbrock and edwards (2017) GMPE for the UK.

T (s)	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	σ_T	σ_B	σ_W
PGV	-4.596	1.699	-0.108	-1.609	0.198	-1.626	0.154	-2.317	0.067	-0.001	2.389	0.274	0.224	0.157
0.00	-2.334	1.695	-0.130	-1.848	0.215	-1.830	0.162	-1.970	0.068	-0.002	2.076	0.337	0.292	0.169
0.03	-1.518	1.610	-0.127	-2.198	0.240	-2.114	0.181	-1.712	0.089	-0.003	1.498	0.369	0.301	0.213
0.05	-1.830	1.649	-0.124	-1.744	0.174	-1.683	0.127	-1.530	0.070	-0.003	1.425	0.356	0.304	0.185
0.10	-2.481	1.777	-0.131	-1.437	0.142	-1.404	0.098	-1.786	0.039	-0.002	1.719	0.330	0.294	0.150
0.20	-3.575	2.040	-0.149	-1.283	0.130	-1.251	0.084	-2.028	0.027	-0.001	1.938	0.305	0.269	0.143
0.25	-4.049	2.155	-0.157	-1.241	0.125	-1.208	0.080	-2.081	0.024	-0.001	1.921	0.297	0.259	0.146
0.50	-5.643	2.502	-0.178	-1.112	0.106	-1.088	0.067	-2.173	0.017	-0.001	1.674	0.278	0.226	0.161
1.00	-6.845	2.624	-0.175	-1.030	0.096	-1.049	0.066	-2.205	0.012	0.000	1.579	0.265	0.197	0.177
2.00	-6.993	2.357	-0.139	-1.150	0.122	-1.230	0.099	-2.239	0.017	0.000	1.809	0.256	0.173	0.190
4.00	-6.514	1.913	-0.094	-1.441	0.171	-1.525	0.147	-2.355	0.050	0.000	2.037	0.245	0.145	0.198
5.00	-6.412	1.795	-0.082	-1.512	0.182	-1.588	0.157	-2.426	0.067	0.000	2.046	0.242	0.136	0.200

Table 2 – Main features of the recorded earthquakes in the UK.

Earthquake Name	Date	Lat. (°)	Long. (°)	Depth (km)	M_L	M_W	Number of Records	R_{epi} Range (km)	PGA Range Geometric Mean (cm/s^2)
Penzance	10/11/1996	50.00	-5.58	8.3	3.8	3.2[1]	1	34	3.59
Arran	04/03/1999	55.40	-5.24	19	4.0	3.2[1]	1	135	0.43
Sennybridge	25/10/1999	51.97	-3.57	14.1	3.6	3.3[1]	1	38	2.57
Warwick	23/09/2000	52.28	-1.61	14.4	4.2	3.3[1]	3	76 to 101	0.51 to 1.94

Melton Mowbray	28/10/2001	52.84	-0.85	14.4	4.1	3.4[1]	2	16 to 143	0.99 to 18.26
Dudley	22/09/2002	52.53	-2.16	14	4.7	4.2[1]	9	80 to 383	0.05 to 9.79
Folkestone	28/04/2007	51.10	1.17	5.3	4.3	4.0[2,3]	11	2 to 396	0.02 to 100
Market Rasen	27/02/2008	53.40	-0.33	17.8	5.2	4.5[3,7]	18	93 to 412	0.11 to 9.99
Lleyn Peninsula	29/05/2013	52.88	-4.72	10.5	3.8	3.7	7	50 to 175	0.17 to 2.29
Bristol Channel	20/02/2014	51.36	-4.16	3.5	4.1	3.7[4,7]	12	47 to 281	0.04 to 0.54
Ramsgate	22/05/2015	51.30	1.44	12.1	4.2	3.8[7]	6	27 to 280	0.11 to 1.63
Swansea	17/02/2018	51.77	-3.83	7.0	4.6	4.3[8]	12	63 to 187	0.24 to 8.23

1: Sargeant and Ottermöller (2009); 2: Ottermöller et al. (2009); 3: Ottermöller and Sargeant (2010); 4: Hicks (2014a); 5: Hicks(2014b); 6: Hicks (2015); 7: Rietbrock and Edwards (2017); 8: From correlation between M_L and M_W from Akkar et al. (2009)

Table 3 – Site Classification of the recording stations.

Station ID	**Lat (°)**	**Long (°)**	**Site Description (Provided by the BGS or Based on Geological Maps)**		**V_{S30} Based on Geological Description (#) (m/s)**	**Site Classification Based on H/V Ratio (°)**	**Assumed V_{S30} (m/s)**
			Rock Outcrop / Underlying Rock Type	Seismometer Foundation			
AEU	52.620	1.235	Cretaceous Chalk	Sand/gravel drift deposits and topsoil (< 15m thick)	375 to 700	Very hard rock	500(*)

APA	52.300	1.478	Crag Group	Lowestoft Formation – Chalky Till with outwash Sands and Gravels, Silts and Clays	200 to 375	Soft stiff soil	300 (+)
BCC	55.015	-3.220	Sherwood Sandstone	Shallow soil	540 to 1,050	N/A	760 (*)
CCA1	50.186	-5.228	Saprolite (Weathered Granite)	Bedrock	700 to 1,400	Hard rock	845 (Tallet-Williams and Fenton, 2015)
CRQ	50.167	-5.173	Carnmenellis Intrusion – Granite	Bedrock	700 to 1,400	N/A	760 (*)
CWF	52.738	-1.307	Neoproterozoic Volcaniclastic Breccia	Topsoil (1-2m)	700 to 1,400	Hard rock	1,050 (+)
DYA	50.435	-3.931	Granite Batholith	Saprolite (in-situ rock weathering products, <1m thick)	700 to 1,400	Hard rock	1,050 (+)
EDI	55.923	-3.186	Andesite	Isolated Concrete Pier on Bedrock	700 to 1,400	Hard rock	1,500 (-)
ELSH	51.148	1.137	Middle Cretaceous Chalk	Weathered Chalk	375 to 700	Soft soil	200 (-)
ESK	55.317	-3.205	Silurian Greywacke	Isolated Concrete Pier on Bedrock	1,050 to 1,400	Very hard rock	2,000 (-)
FOEL	52.890	-3.201	Llangynog Formation – Sandstone and Mudstone	Bedrock	540 to 1,050	Rock	760 (+)
GAL1	54.866	-4.711	Silurian Greywacke	Bedrock	700 to 1,400	Very hard rock	2,000 (-)
HBL2	52.051	-3.038	Saltwick Formation – Sandstone, Siltstone and Mudstone	Shallow soil	540 to 1,050	N/A	760 (*)
HLM1	52.518	-2.881	St Maughans Formation - Argillaceous Rocks and Sandstone	Head (rock fragments/soil creep deposit, 1 to 2m thick)	540 to 1,050	Hard rock	1,000 (+)

HPK	53.955	-1.624	Neoproterozoic Sandstone	Glacial Till drift deposit (> 3m thick)	540 to 1,050	Rock	760 (+)
HTL	50.994	-4.485	Carboniferous Sandstone	Weathered bedrock	540 to 1,050	Hard rock	1,000 (+)
JSA	49.188	-2.171	Carboniferous Sandstone	Unknown	N/A	Hard rock	1500 (-)
KEY2	52.877	-1.075	Unknown	Lias	375 to 700	N/A	550(*)
LBWR	53.402	-1.725	Blue Anchor Formation – Mudstone	Shale Grit	540 to 1,050	Rock	760 (+)
LDU	53.803	-1.555	Carboniferous Sandstones/Shales	Bedrock	540 to 1,050	Hard rock	1,000 (+)
LDU2	53.803	-1.555	Pennine Lower Coal Measures Formation – Sandstone, Siltstone and Mudstone	Bedrock	540 to 1,050	Hard rock	1,000 (+)
LMK	53.457	-0.327	Pennine Lower Coal Measures Formation – Sandstone, Siltstone and Mudstone	Bedrock	540 to 1,050	Stiff soil	550 (+)
MCH	51.998	-2.998	Carstone Formation – Sandstone	Bedrock	540 to 1,050	Rock	760 (+)
MCH1	51.998	-2.998	Devonian-Silurian, interbedded Sandstones/Siltstones	Bedrock	540 to 1,050	Rock	760 (+)
MONM	51.839	-2.804	Old Red Sandstone	Devonian sandstones/siltstones (interbedded)	540 to 1,050	N/A	760 (*)
OLDB	51.661	-2.551	Mercia Mudstone	Tidal Flats	100 to 375	Soft soil	180 (+)
PGB1	55.810	-4.478	Vesicular Basalt	Heavily weathered porous bedrock	> 760	Rock	760 (-)
RSBS	51.953	-4.745		Mudstone shale formation/igneous intrusion	1,500 to 2,300(**)	N/A	2000 (*)
SPK1	54.434	-3.488	Chalk	Bedrock	375 to 700	N/A	500 (*)
STNC	53.091	-2.206	Carboniferous Sandstone/Siltstone/Mudstone	Glacial Till/Topsoil (> 3m thick)	540 to 1,050	Rock	760 (*)

STRD	51.776	-2.164	Birdlip Limestone Formation	Bedrock	540 to 1,050	Stiff soil / Rock	600 (*)
SWN	51.513	-1.801	Cretaceous Chalk	Topsoil (< 1m thick)	375 to 700	Stiff soil	503 (+)
SWN1	51.513	-1.800	Cretaceous Chalk	Bedrock	375 to 700	Stiff soil	503 (Tallet-Williams and Fenton, 2015)
TFO1	51.114	1.141	Cretaceous Chalk	Sandy Clay with Flints	375 to 700	Stiff soil	480 (+)
WACR	52.725	0.627	Chalk	Lowestoft Formation – Chalky Till with outwash sands and gravels, silts and clays. (2-18m thick)	100 to 300	Soft soil	200 (+)
WLF1	53.289	-4.397	Hornfel Lens in Granite Terrane	Bedrock	700 to 1,400	Very hard rock	2500 (-)
WOL	51.313	-1.223	Chalk	Bedrock	375 to 700	Unclear	500 (*)
WPS	53.400	-4.499	New Harbour Group	Glacial Till (very thin)	2,300 to 3,000	Very hard rock	2,000 (+)

Note:

(*) Geology preferred, (-) = H/V preferred, (+) = Geology and H/V ratio broadly correlate

(#) Ranges based on Borchedt (1994) for all stations except PGB1 station which is based on Christensen et al. (1980), see Section 2.1.

(°) Based on Di Alessandro et al. (2012).

(**) Based on Press (1966).

(+) Estimated surface V_{s30} from data at adjacent Wylfa Development Area

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833 Table 4 – Main features of the UK earthquakes in the macroseismic database.

Event	**Date**	**Lat (°)**	**Long (°)**	**M_L**	**M_W**	**Max Intensity**	**Number of IDPs**
Dover Straits	06/04/1580	51.06	1.60	5.8	5.5	7-8	91
Swansea	08/09/1775	51.73	-3.81	5.1	4.8	7	74
Whitehaven	11/08/1786	54.53	-3.68	5.0	4.7	6-7	57
Inverness	13/08/1816	57.43	-4.33	5.1	4.8	7-8	72
Lancaster	20/08/1835	54.02	-2.69	4.4	4.1	5-6	70
Lancashire	17/03/1843	54.00	-3.60	5.1	4.8	5	117

Event	Date	Lat (°)	Long (°)	M_L	M_W	Max Intensity	Number of IDPs
Caernarvon	09/11/1852	53.05	-4.43	5.3	5.0	7	222
Newquay	13/01/1860	50.46	-5.31	4.0	3.7	5-6	71
Hereford	06/10/1863	52.00	-2.80	5.2	4.9	6	298
Neath	30/10/1868	51.73	-3.67	4.9	4.6	5-6	186
Appleby	17/03/1871	54.71	-2.47	4.9	4.6	6	334
Colchester	22/04/1884	51.82	0.90	4.6	4.3	8	414
Invergarry	02/02/1888	57.10	-5.14	4.8	4.5	5-6	133
Edinburgh	18/01/1889	55.87	-3.36	3.2	3.0	5	64
Inverness	15/11/1890	57.46	-4.35	4.5	4.2	6	141
Pembroke	18/08/1892	51.70	-5.04	5.1	4.8	7	179
Leicester	04/08/1893	52.72	-1.22	3.7	3.4	7	130
Carmarthen	02/11/1893	51.81	-4.41	5.0	4.7	7	131
Hereford	17/12/1896	52.02	-2.55	5.3	5.0	7	735
Carlisle	09/07/1901	54.80	-3.04	4.1	3.8	6	64
Inverness	18/09/1901	57.43	-4.32	5.0	4.7	7	172
Derby	24/03/1903	53.05	-1.70	4.6	4.3	7	176
Caernarvon	19/06/1903	53.03	-4.28	4.9	4.6	6	80
Derby	03/07/1904	53.05	-1.75	4.2	3.9	6	220
Doncaster	23/04/1905	53.40	-0.99	4.3	4.0	5-6	203
Swansea	27/06/1906	51.62	-3.81	5.2	4.9	7	310
Derby	27/08/1906	53.09	-1.51	3.5	3.3	5	52
Stafford	14/01/1916	52.85	-2.19	4.6	4.3	7	143
South Brent	25/12/1923	50.47	-3.86	3.3	3.1	5	82
Ludlow	15/08/1926	52.31	-2.66	4.8	4.5	7	300
Dogger Bank	07/06/1931	54.08	1.50	6.1	5.8	7	887
Wensleydale	14/01/1933	54.30	-2.15	4.4	4.1	6-7	109
Torridon	16/08/1934	57.54	-5.34	4.1	3.8	6	71
Caernarvon	12/12/1940	53.03	-4.18	4.7	4.4	5	100
Skipton	30/12/1944	53.86	-2.02	4.8	4.5	7	115
Ashby	10/01/1956	52.72	-1.27	3.6	3.3	6	64
Derby	12/02/1957	52.82	-1.33	4.2	3.9	6	96
Chichester	25/10/1963	50.77	-0.97	4.7	4.4	5-6	53
Kirkby Stephen	09/08/1970	54.50	-2.47	4.1	3.8	5	69
Todmorden	07/03/1972	53.70	-2.03	4.0	3.7	6	84

Event	Date	Lat (°)	Long (°)	M_L	M_W	Max Intensity	Number of IDPs
Bala	23/01/1974	52.98	-3.49	3.5	3.3	5	111
Newport	25/02/1974	51.64	-3.05	3.9	3.6	5	192
Carlisle	26/12/1979	55.03	-2.82	4.7	4.4	6	652
Carlisle	01/01/1980	55.03	-2.79	3.8	3.5	5	61
Felindre	15/04/1984	52.41	-3.25	3.3	3.1	4	63
Lleyn Peninsula	19/07/1984	52.96	-4.38	5.4	5.1	7	342
Oban	29/09/1986	56.45	-5.65	4.1	3.8	5	76
Bishop's Castle	02/04/1990	52.43	-3.03	5.1	4.8	6	2,350
Peterborough	17/02/1992	52.49	-0.20	3.4	3.2	5	144
Caernarvon	29/07/1992	53.13	-4.39	3.5	3.3	5	115
Norwich	15/02/1994	52.56	0.91	4.0	3.7	5	302
Shrewsbury	07/03/1996	52.80	-2.74	3.4	3.2	5	63
Penzance	10/11/1996	50.00	-5.58	3.8	3.2	5	96
Arran	04/03/1999	55.40	-5.24	4.0	3.2	5	228
Caernarvon	01/09/1999	53.19	-4.34	3.2	3.0	4	37
Sennybridge	25/10/1999	51.96	-3.57	3.6	3.3	5	112
Warwick	23/09/2000	52.28	-1.61	4.2	3.3	5	282
Bude	31/05/2001	51.01	-4.63	3.6	3.3	5	118
Folkestone	28/04/2007	51.10	1.17	4.3	4.0	6	50
Market Rasen	27/02/2008	53.40	-0.33	5.2	4.5	6	641
Masham	03/01/2011	54.17	-1.70	3.6	3.3	4	166
Ashwell	28/01/2015	52.73	-0.72	3.8	3.5	5	106
Broadstairs	22/05/2015	51.30	1.44	4.2	3.9	5	109

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839 Table 5 – Summary of GMPE Database and Range of Applicability

GMPE	Magnitude Range (MW)	Distance Range (km)	Period Range (s)	Distance Metric	Definition of Ground Motion	VS30 range (m/s)	Max PGA(g) in Database
Abrahamson et al. (2014), ASK14	3.0 to 8.5	0 to300	PGA, 0.01-10 s	Rrup	RotD050	180 to 1,000	1.77
Boore et al. (2014), BSSA14	3.0 to 8.5	0 to 400	PGA, 0.01-10 s	Rjb	RotD050	150 to 1,500	1.77

Campbell and Bozorgnia (2014), CB14	3.3 to 8.5	0 to 300	PGA, 0.01-10 s	Rrup	RotD050	150 to 1,500	1.77
Chiou and Youngs (2014), CY14	3.5 to 8.5	0 to 300	PGA, 0.01-10 s	Rrup	RotD050	150 to 1,500	1.77
Akkar et al. (2014), ASB14	4.0 to 7.6	0 to 200	PGA, 0.01-4 s	Repi, Rhyp or Rjb	GM	150 to 1,200	0.99
Bindi et al. (2014), BI14	4.0 to 7.6	0 to 300	PGA, 0.01-3 s	Rhyp or Rjb	GM	150 to 1,000	0.98
Cauzzi et al. (2015) CA15	4.5 to 7.9	0 to 150	0.01-10 s	Rrup	GM	150 to 1,500	1.6
Rietbrock and Edwards (2017), RE17	3.0 to 7.0	1 to 300	PGA, 0.033-5 s	Rjb	GM	Very hard Rock	Based on simulations
GM = Geometric mean of two horizontal and orthogonal components RotD050 = The 50th percentile of the response spectra over all non-redundant rotation angles (Boore, 2010)							

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841 Table 6 – Average κ_{host} values computed for the eight preselected GMPEs.

GMPE	**κ_{host} (s) with V_{S30}=550m/s**	**κ_{host} (s) with V_{S30}=760m/s**
ASK14	0.059	0.051
BSSA14	0.048	0.046
CB14	0.046	0.037
CY14	0.047	0.042
ASB14	0.044	0.041
BI14	0.043	0.042
CA15	0.041	0.038

842 Table 7 – Summary of the Performance of the GMPEs with Respect to the Residuals

GMPE	**Magnitude Trends**	**Distance Trends**	**Residual Range**	**Mean Residuals for Distance < 100 km**
ASK14	No trend	No strong trend	-2.7 to 3.4	0 to 1
BSSA14	No trend	No strong trend	-2.5 to 3.5	0.3 to 1.7
CB14	No strong Trend	Linear trend	-2.1 to 3.2	0.3 to 1.3
CY14	No trend	Linear trend	-2.6 to 3.3	0.1 to 1.7
ASB14	Linear trend	No strong trend	-2.7 to 3.2	-0.5 to 1.6
BI14	No trend	No trend	-0.9 to 3.6	0.5 to 1.6
CA15	No strong trend	No strong trend	-2.5 to 3.2	-0.5 to 1.4
RE17	No trend	No trend	-3.6 to 3.5	-0.3 to 1.4

843 Table 8 –Performance results with respect to the UK ground motion dataset.

GMPE	Scherbaum et al. (2009)	Kale and Akkar (2013)		
	LLH	MDE	$k_{0.5}$	EDR
ASK14	2.67	1.30	1.22	1.59
BSSA14	3.16	1.49	1.31	1.97
CB14	3.49	1.56	1.31	2.06
CY14	3.40	1.50	1.30	1.96
BI14	3.02	1.44	1.35	1.95
CA15	2.78	1.38	1.25	1.73
RE17	2.42	1.09	1.12	1.21
Note: Underlined values represent best three values for each of the GMPEs assessed.				

844 Table 9 – Intensity Correlations Considered Against the UK Data

Intensity Correlation	Data from	Intensity range
Atkinson and Kaka (2007)	California and Central US	I – IX
Faenza and Michelini (2009)	Italy	II – VIII
Tselentis and Danciu (2008)	Greece	IV – VIII
Wald et al. (1999)	California	V – VIII
Faccioli and Cauzzi (2006)	Italy	V – IX
Worden et al. (2012)	California	II – IX

845 Table 10 – Performance of Preselected GMPEs Against the UK Macroseismic Data

GMPE	Faccioli and Cauzzi (2006)				Atkinson and Kaka (2007)			
	Scherbaum et al. (2009)	Kale and Akkar (2013)			Scherbaum et al. (2009)	Kale and Akkar (2013)		
	LLH	EDR	$k_{0.5}$	MDE	LLH	EDR	$k_{0.5}$	MDE
ASB14	2.39	1.42	1.11	1.57	2.33	1.39	1.28	1.79
ASK14	2.13	1.31	1.00	1.31	2.00	1.26	1.06	1.34
BI14	2.44	1.33	1.16	1.55	2.37	1.37	1.38	1.88
BSSA14	2.30	1.39	1.08	1.50	2.25	1.37	1.21	1.66
CA15	2.19	1.23	1.07	1.32	2.15	1.26	1.27	1.60
CY14	2.16	1.31	1.01	1.32	2.06	1.27	1.10	1.40
CB14	2.56	1.53	1.17	1.80	2.50	1.49	1.37	2.04
RE17	2.15	1.22	1.12	1.36	2.19	1.29	1.34	1.73

Note: Underlined values represent best three values for each of the method adopted.

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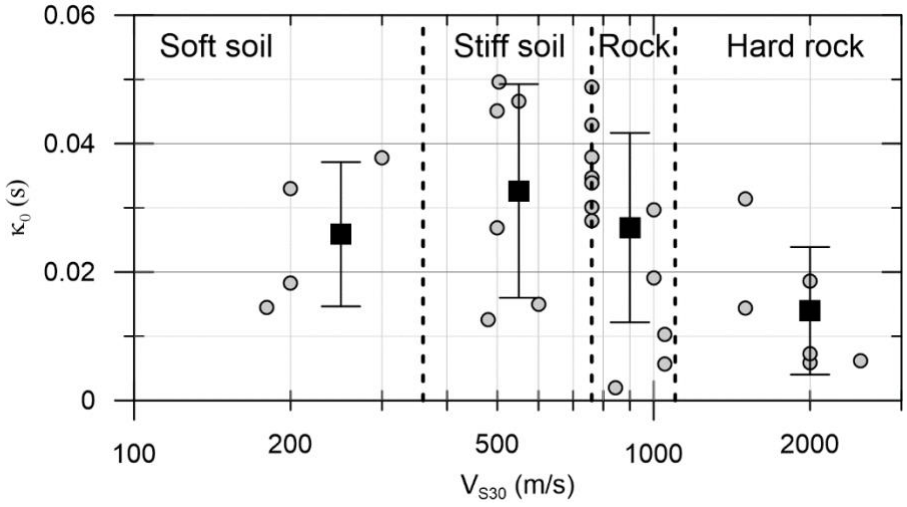

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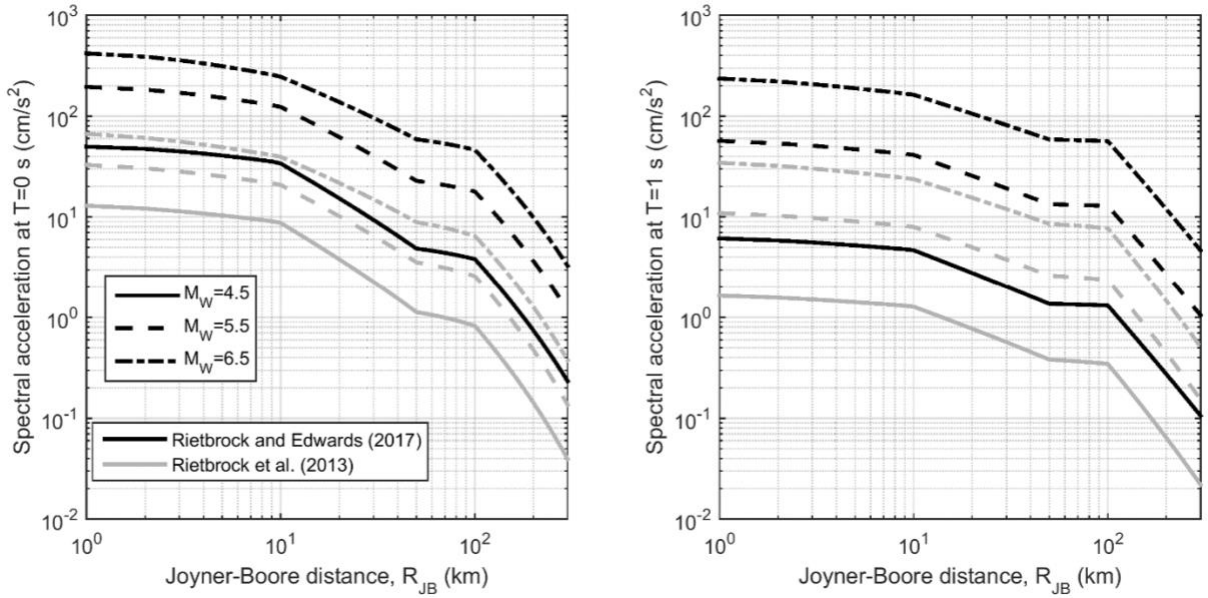

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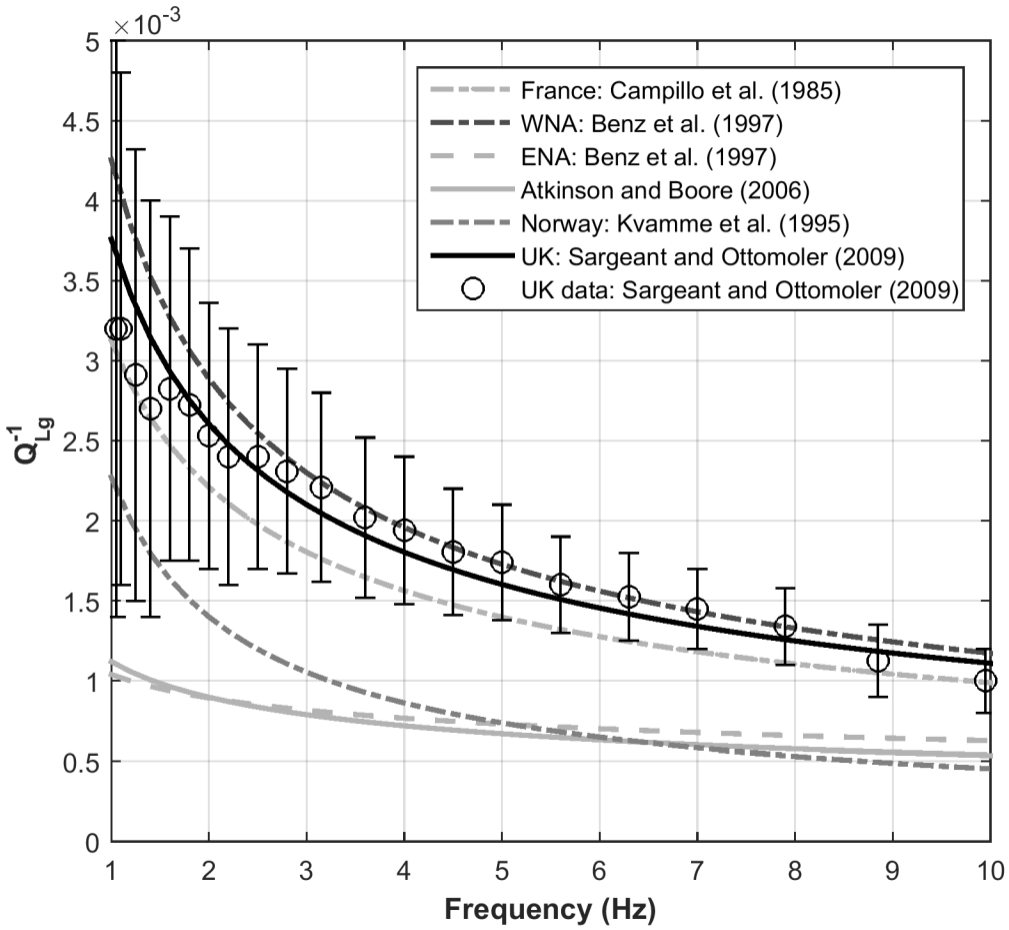

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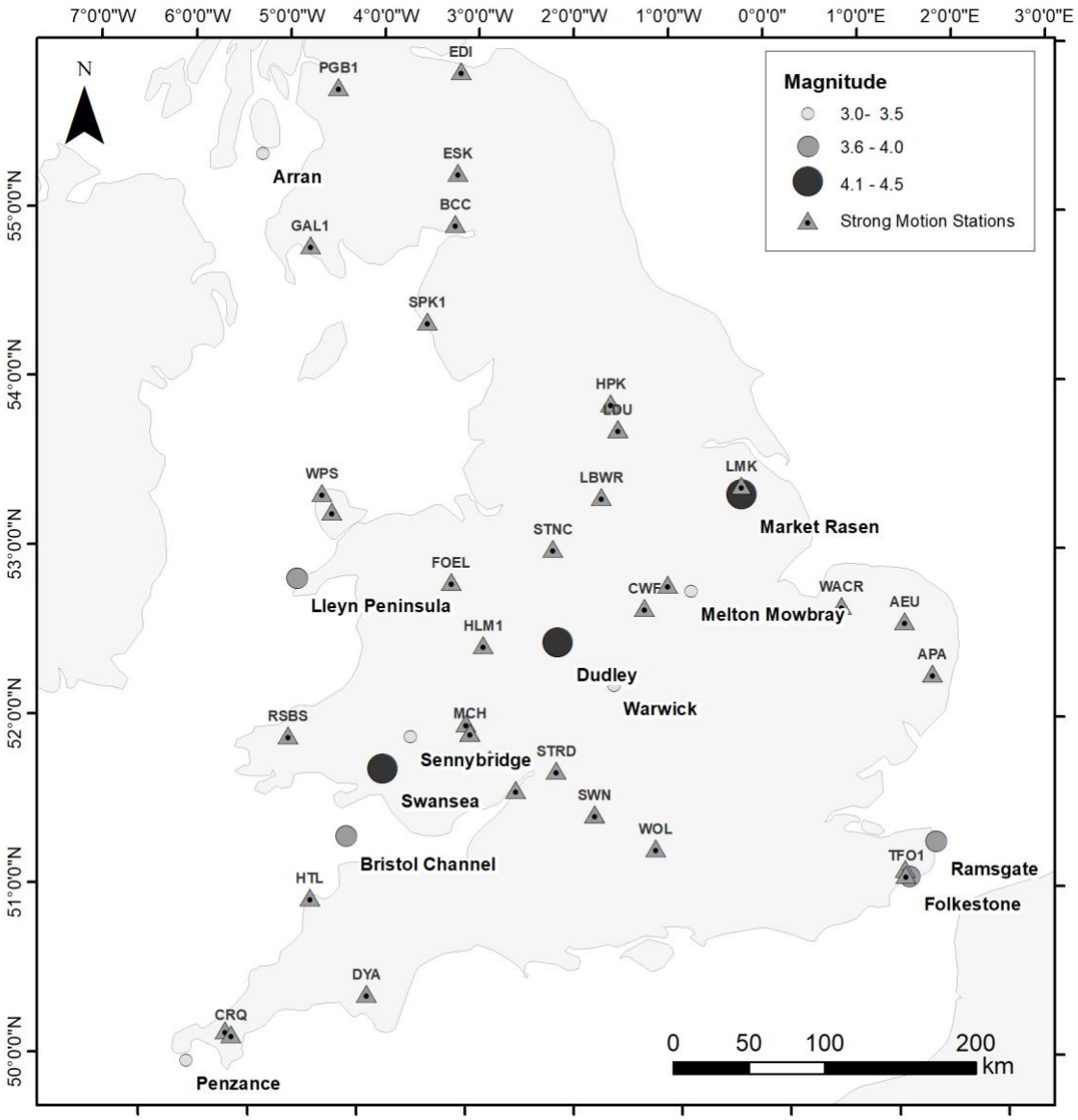

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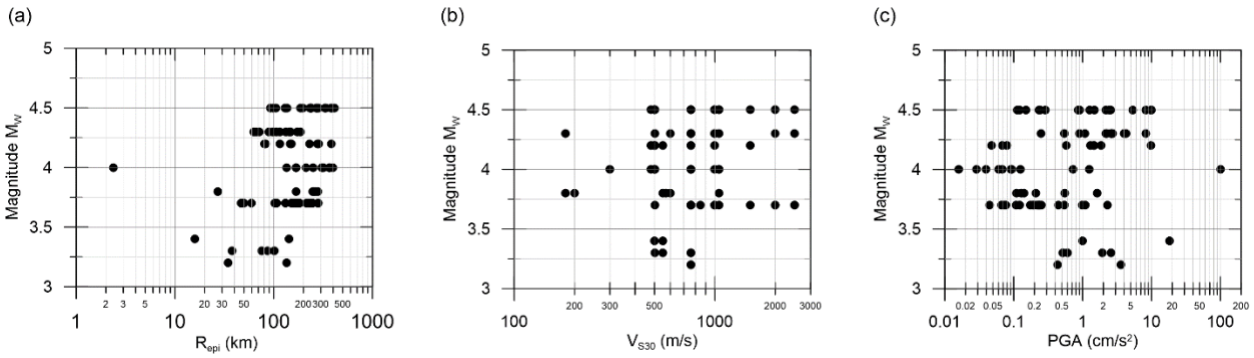
910 

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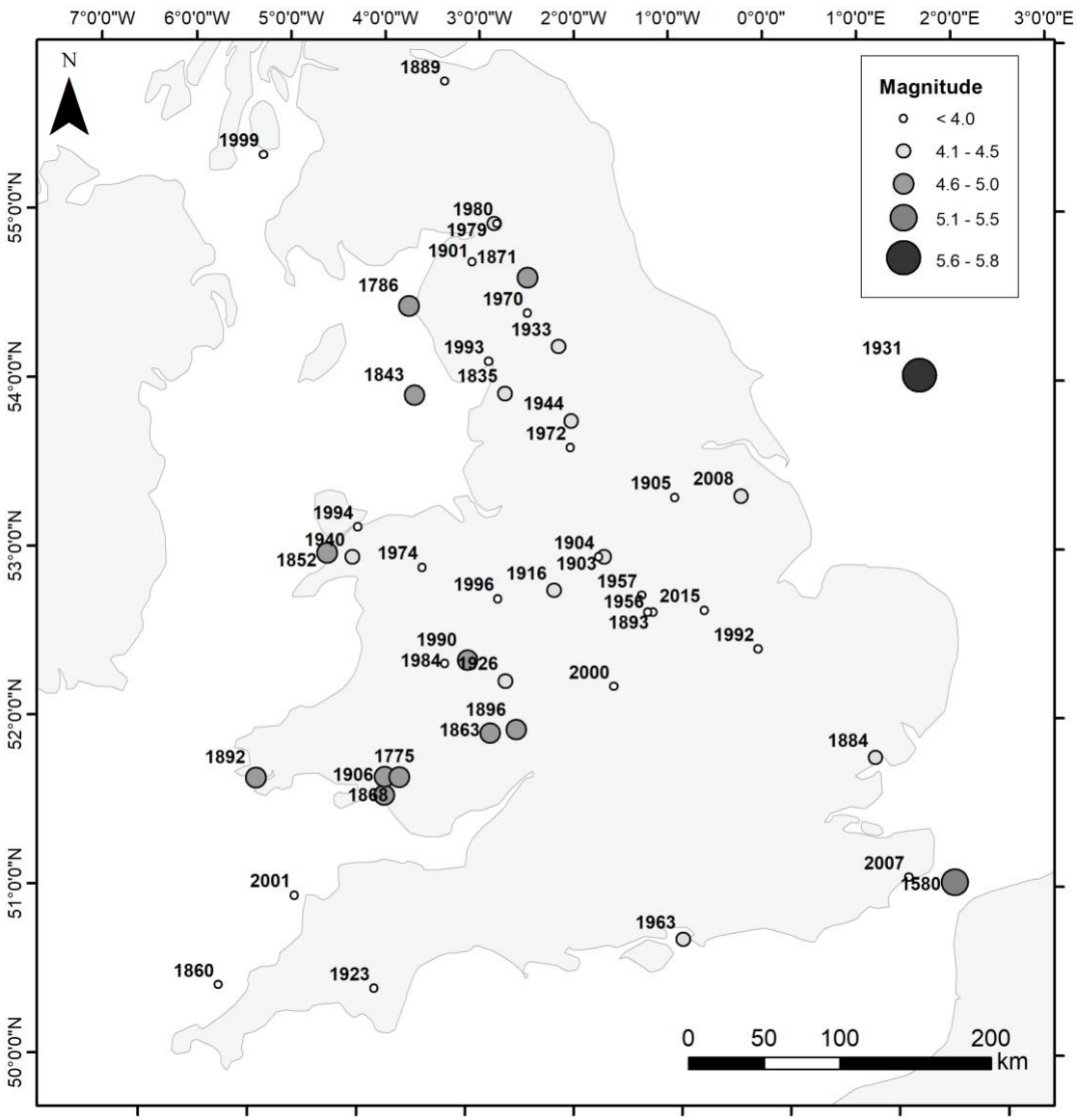

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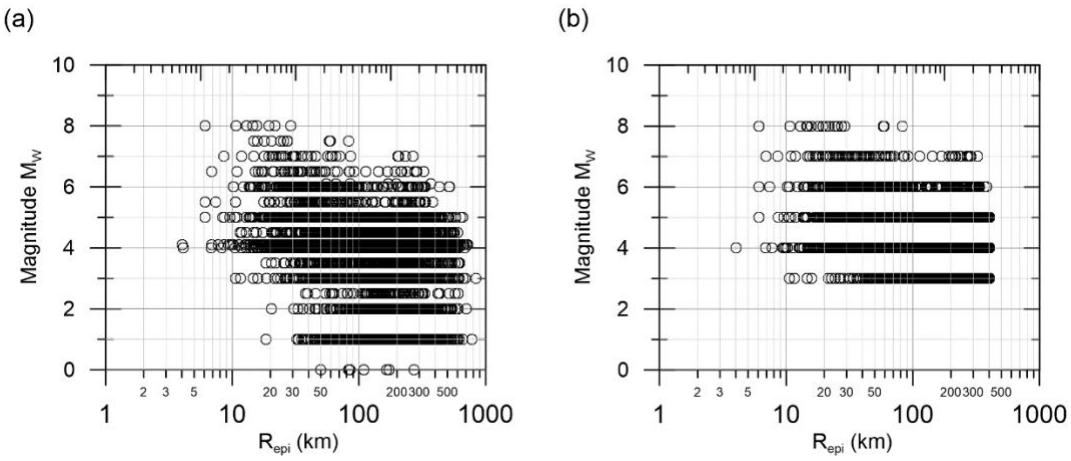

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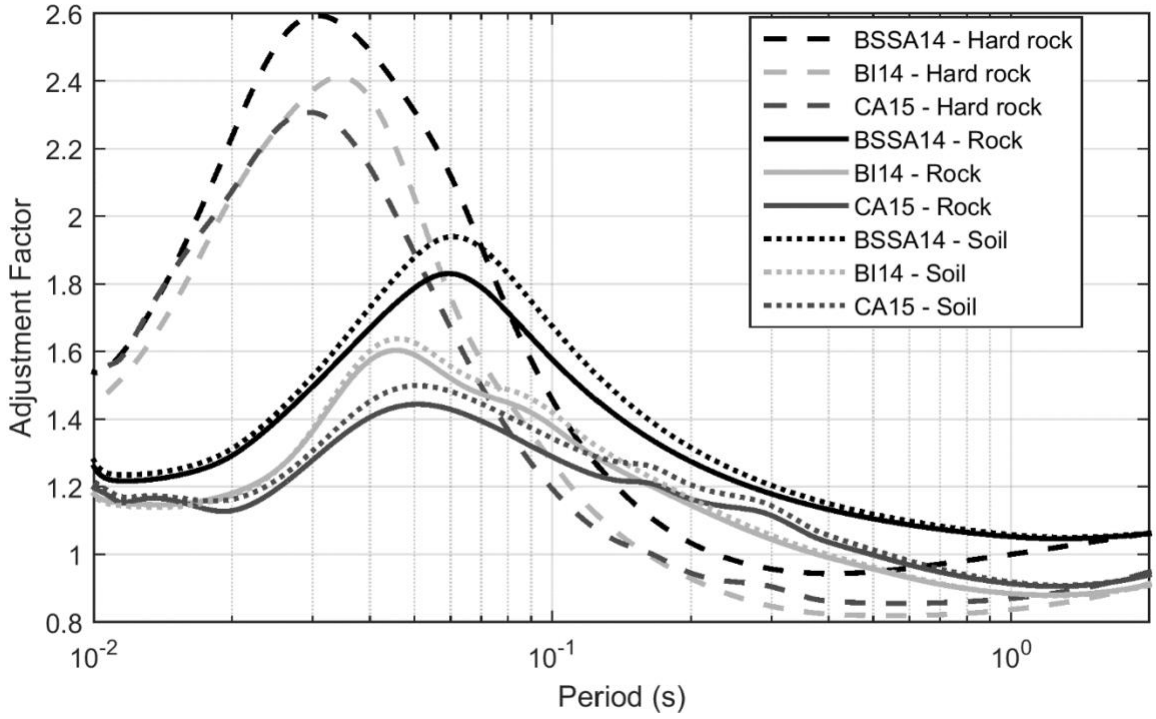

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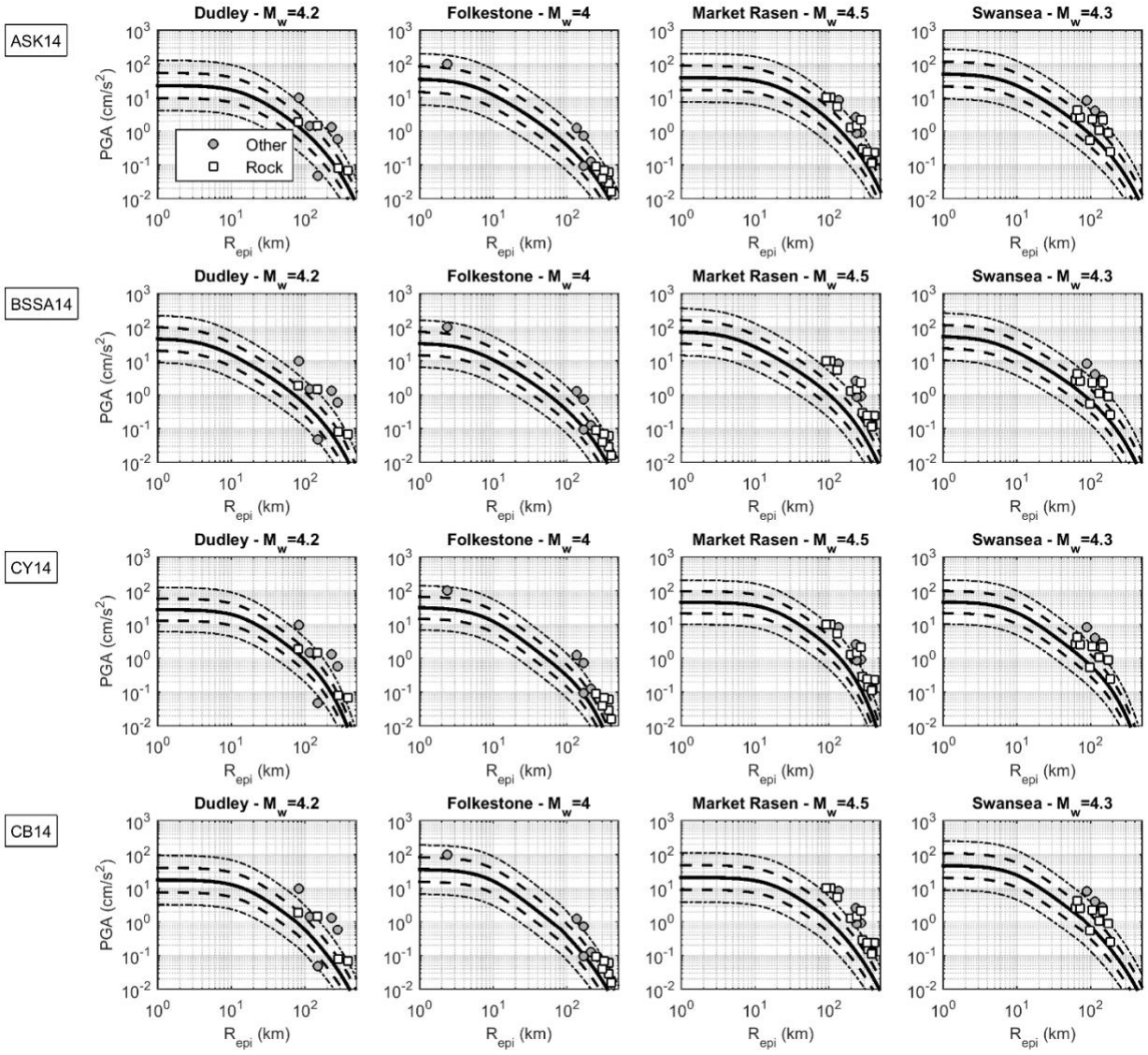

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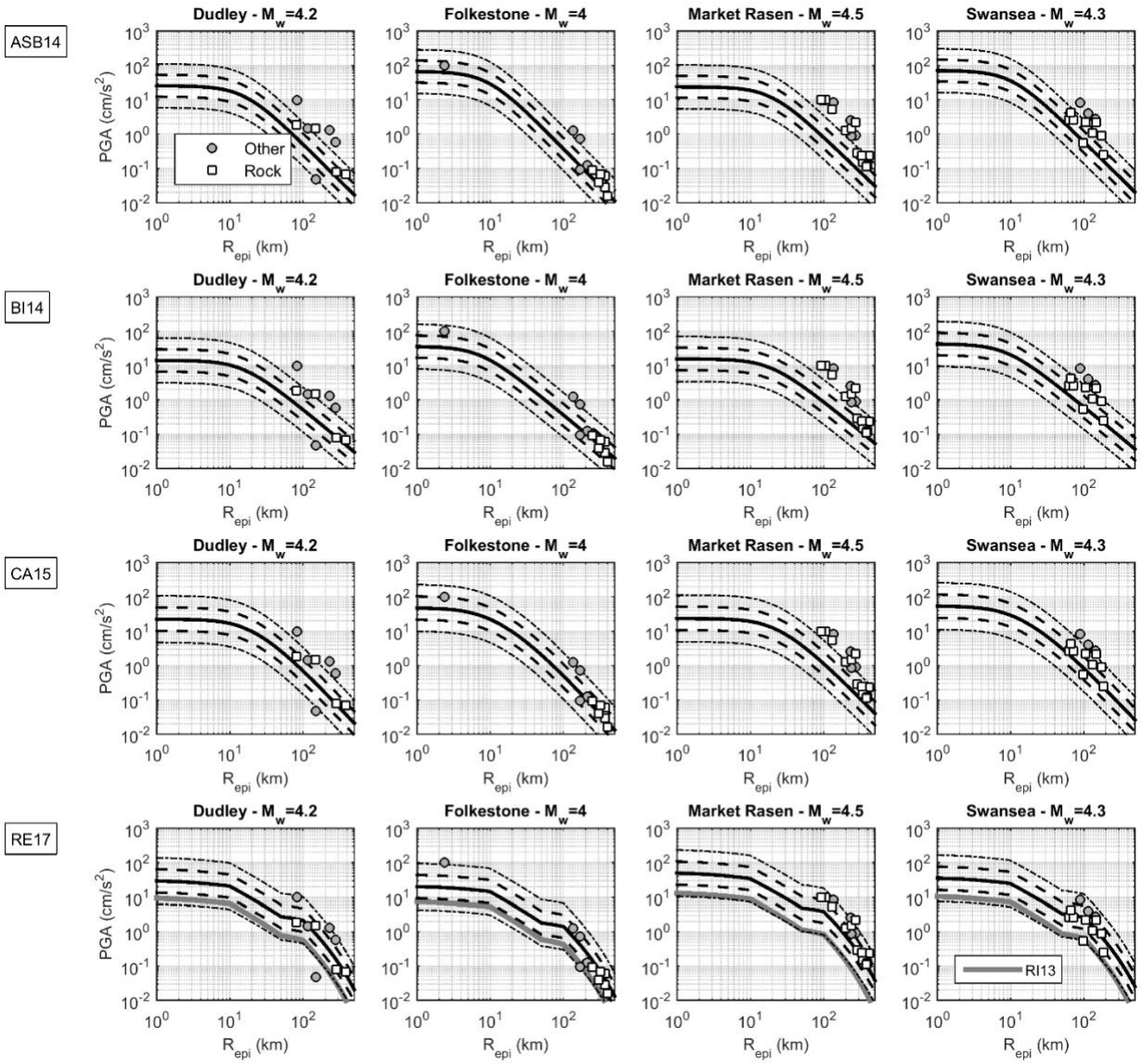

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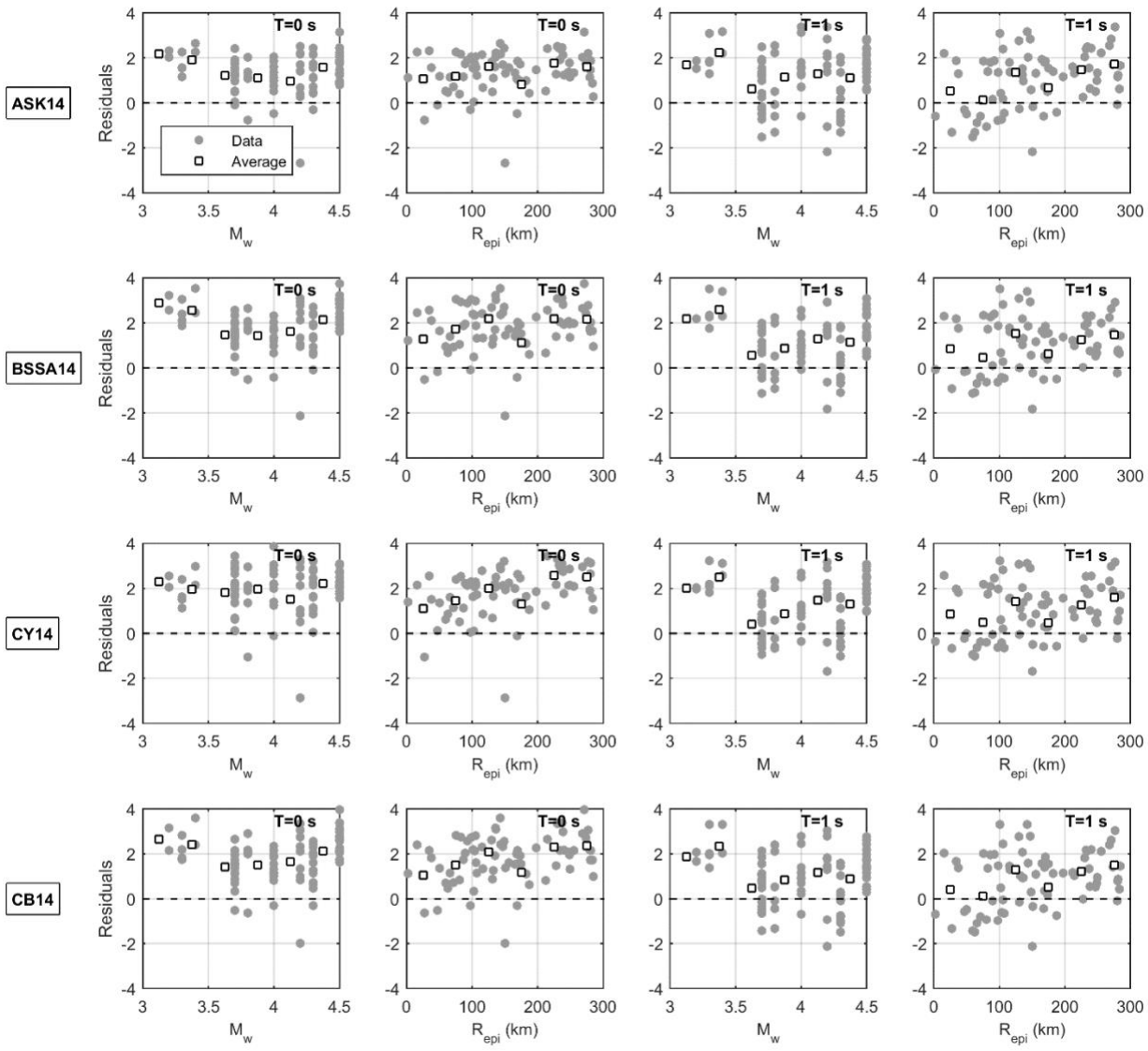

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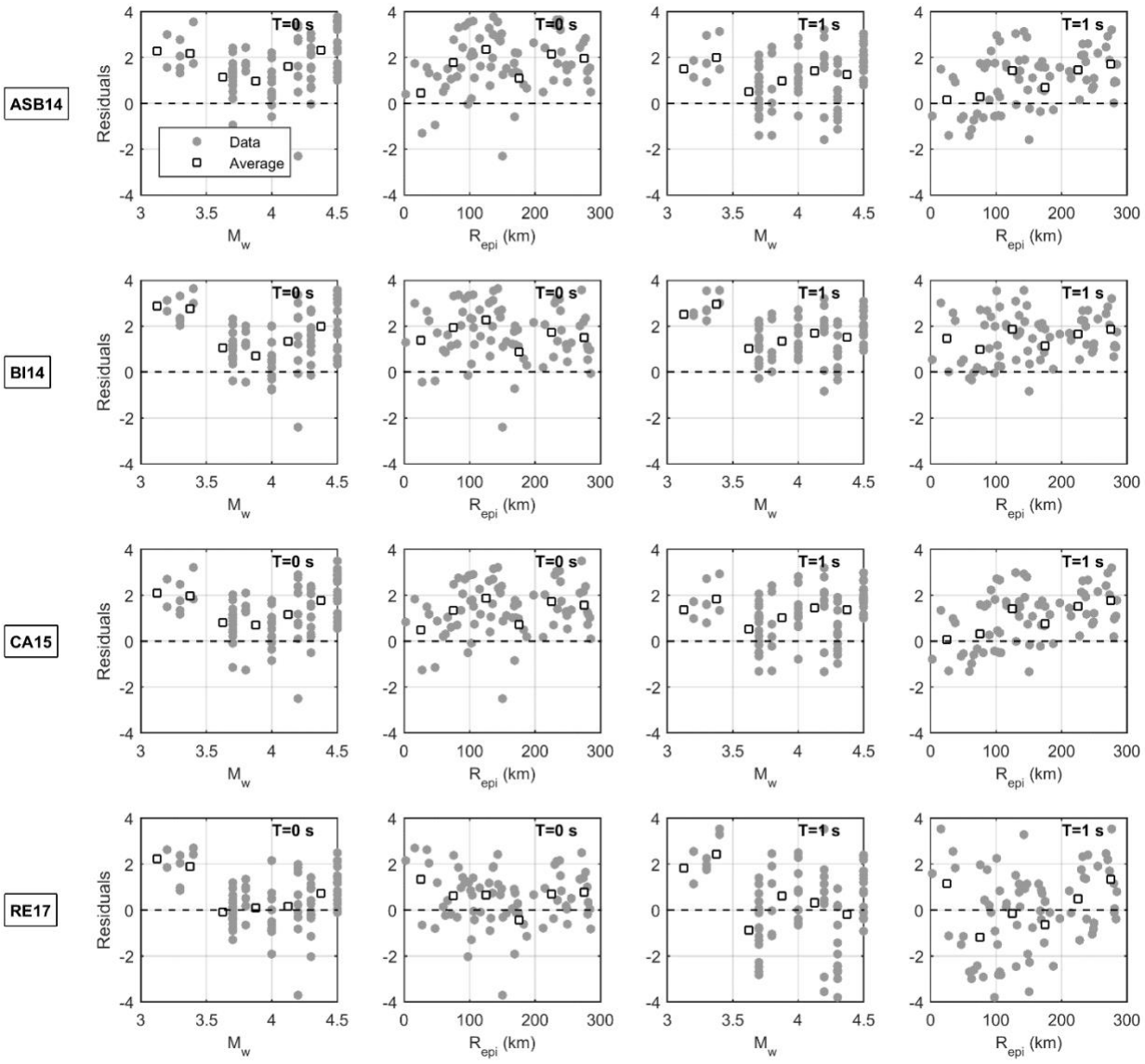

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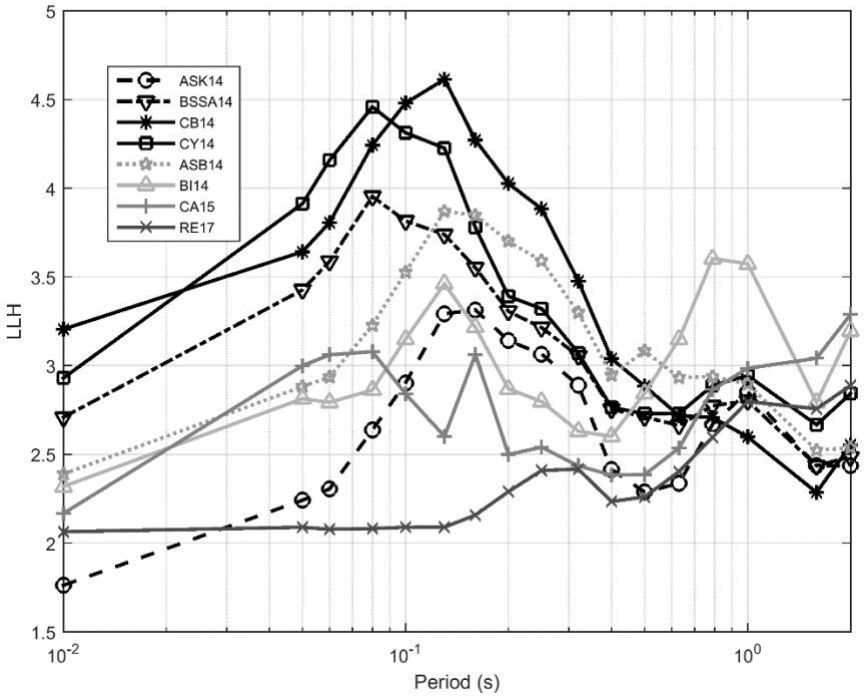

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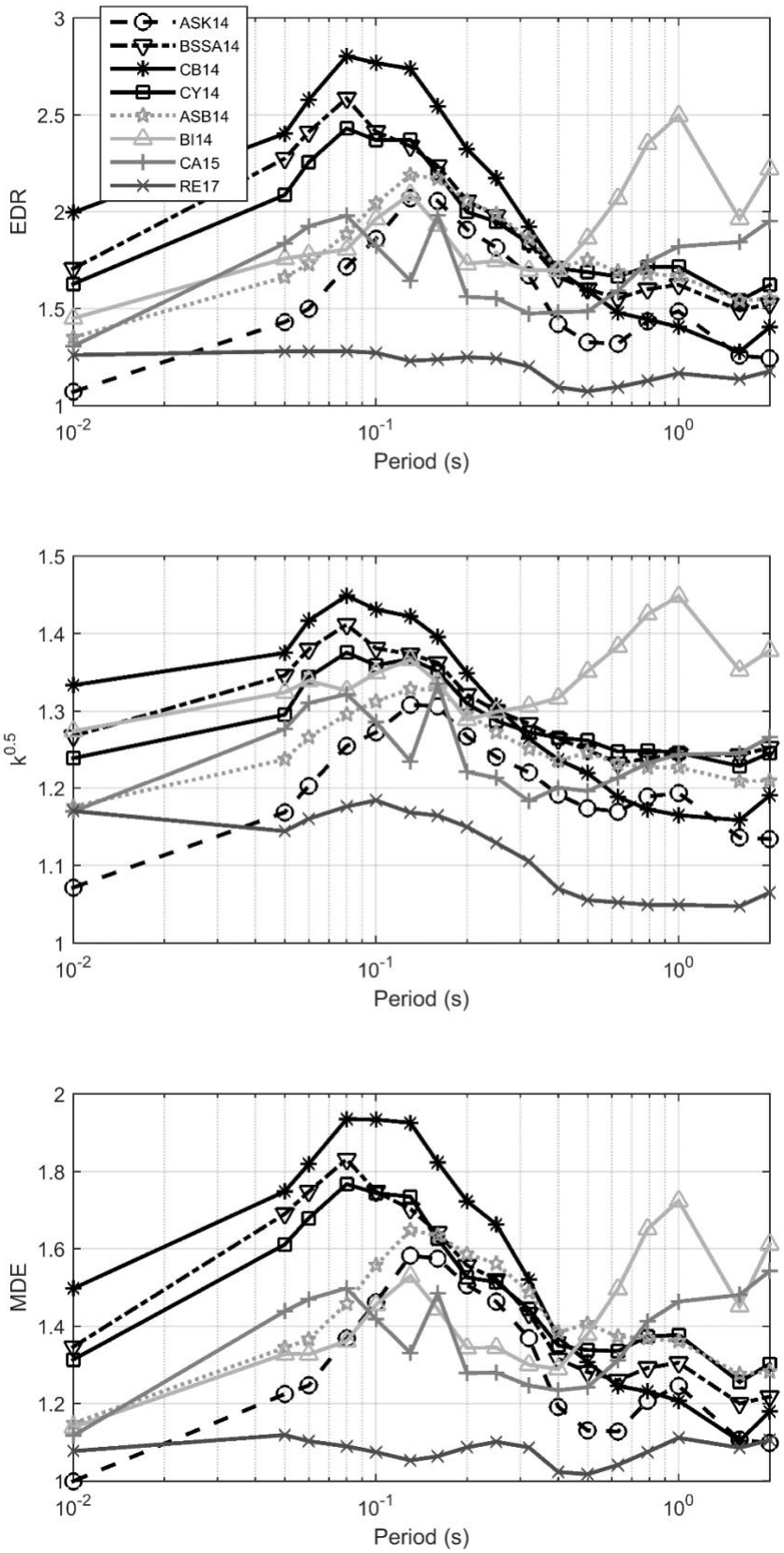

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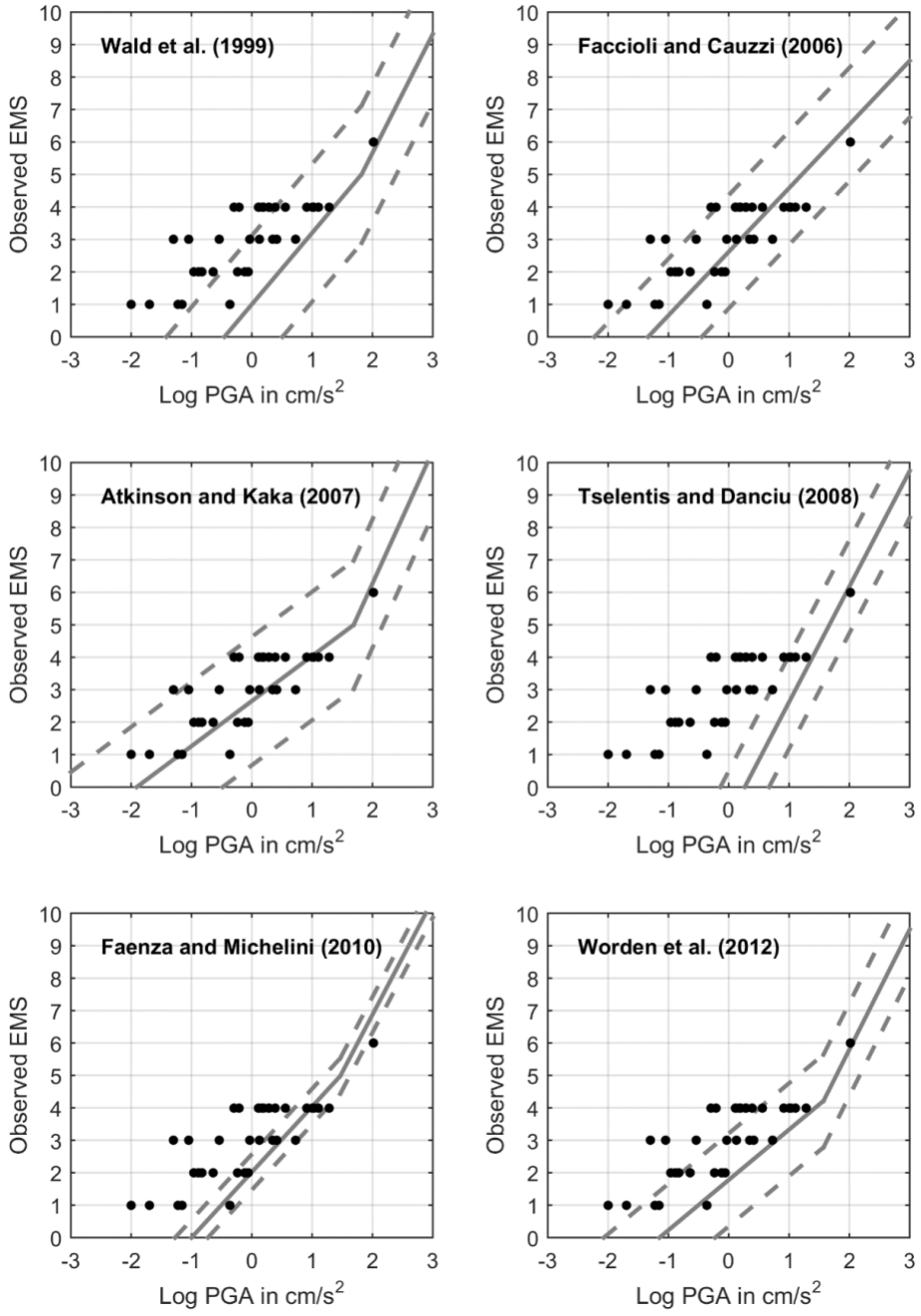

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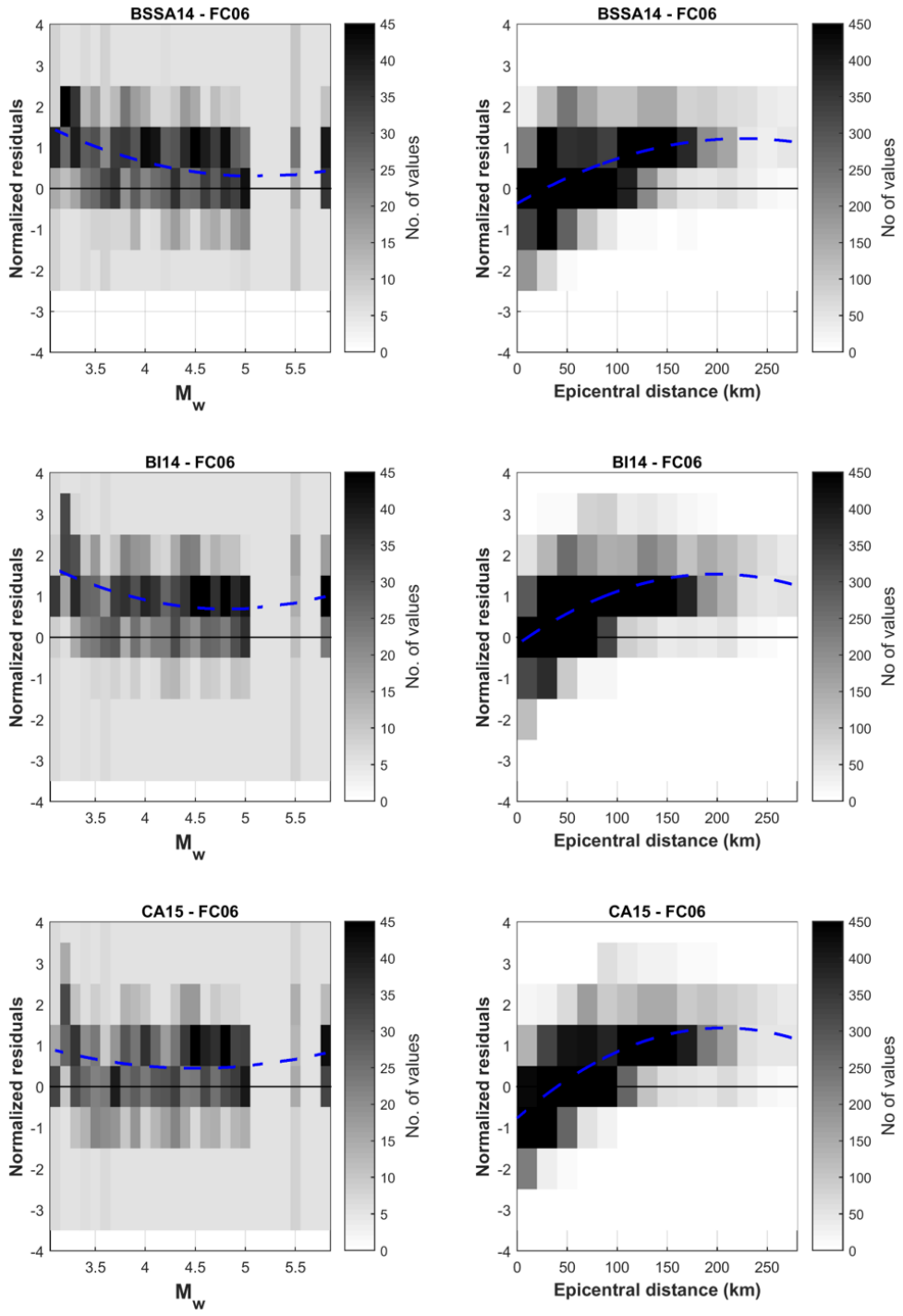

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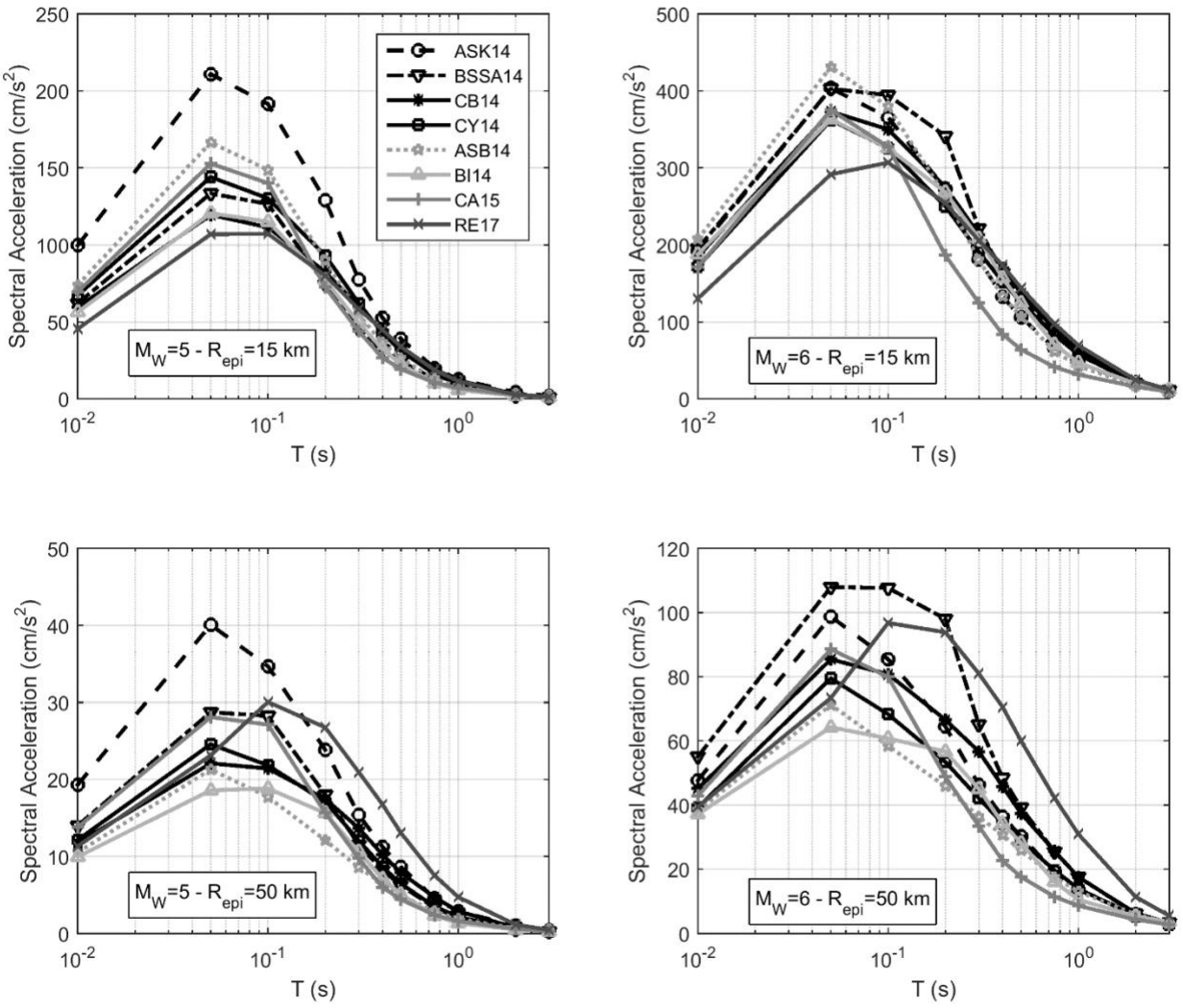

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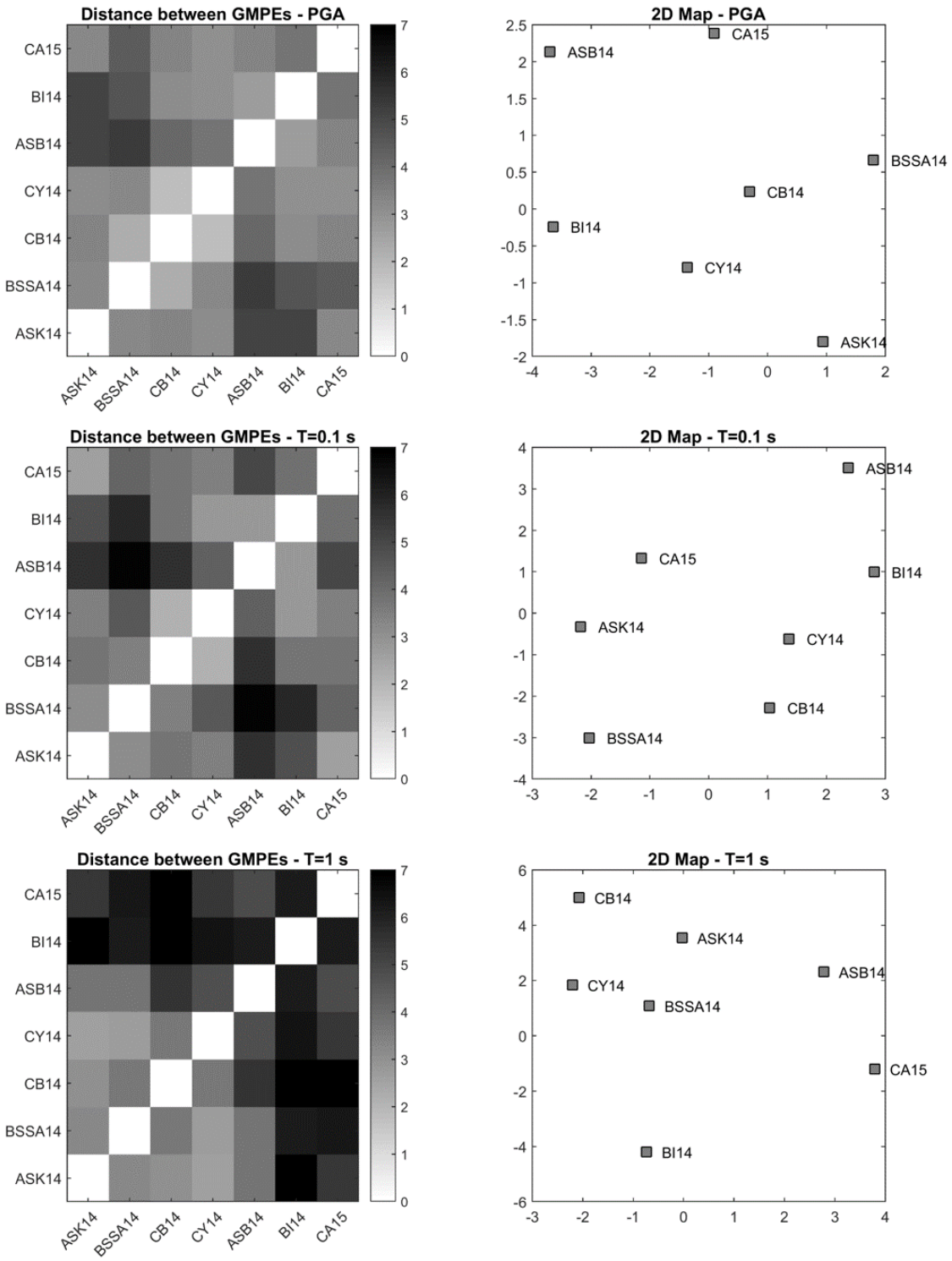

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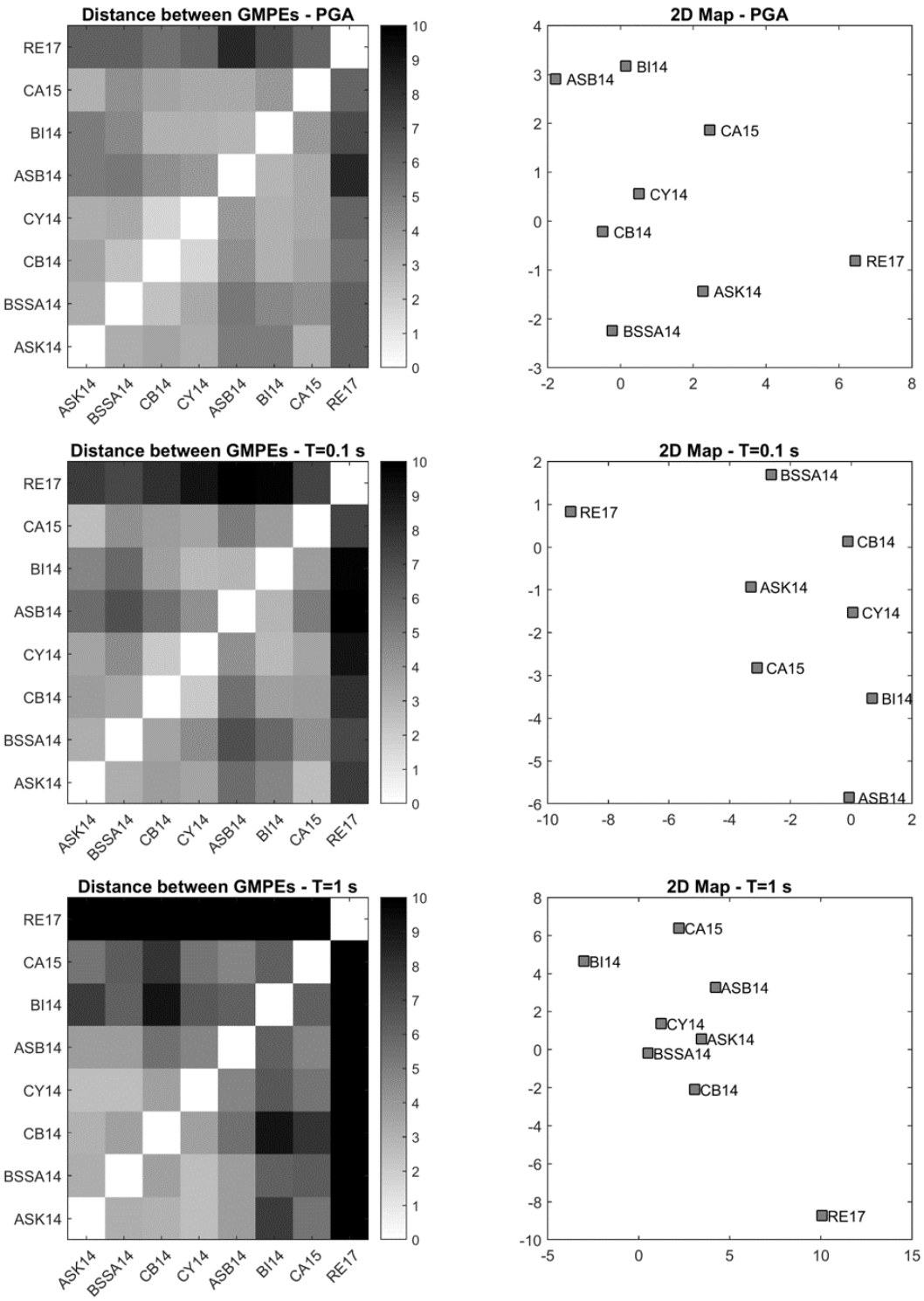

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