

# Scaling and Depth Variability of Source Parameters in Central and Southern Italy Using Regional Attenuation Models

Dino Bindi<sup>1</sup>, Daniele Spallarossa<sup>2</sup>, Matteo Picozzi<sup>3</sup>, and Gabriele Tarchini<sup>2</sup>

## ABSTRACT

We study the scaling between seismic moment and corner frequency, and the spatial variability of the stress drop, in central and southern Italy. We analyze a data set generated by 28,943 earthquakes that occurred between 2005 and 2023 recorded by 1045 temporary or permanent stations. Considering the trade-off between source and propagation effects, we develop a spectral decomposition approach in which several attenuation models are derived for different subregions, and we perform an iterative decomposition to propagate the site amplification constraint to the whole data set. The use of multiple attenuation models has a significant impact on the source parameter estimation, resulting in stress-drop ratios on the order of a factor of 10 compared to values obtained without considering the attenuation differences. Once the attenuation variability is taken into account, the scaling between seismic moment and corner frequency shows different slopes for different subregions, with different degrees of self-similarity breakdown. Furthermore, we observe a clear trend in the slopes with depth for several subregions. Finally, the spatial variability of the stress-drop anomalies with respect to the average values expected for a given seismic moment shows a large lateral variability, which makes it difficult to detect increasing stress-drop trends with depth.

## KEY POINTS

- Correction for propagation effects is a critical step in determining source parameters.
- We develop an approach that uses multiple attenuation models to capture local source scaling characteristics.
- We compute the source parameters of 28,943 earthquakes in Italy and present the stress-drop spatial variability.

## Supplemental Material

## INTRODUCTION

Monitoring the mechanical properties of faults through the estimation of seismic source parameters such as seismic moment, corner frequency, and radiated energy, is fundamental to understand how and when faults slip and to improve our understanding of the physical processes that anticipates large earthquakes (e.g., Wang *et al.*, 2019; Durand *et al.*, 2020; Picozzi *et al.*, 2022, 2023). Furthermore, source parameters knowledge is crucial for seismic hazard assessment because the link between earthquake-specific ground-shaking variability at high frequency and stress drop is well established, for example, in central Italy (Bindi *et al.*, 2019), Japan (Oth *et al.*, 2017), northwestern (Bindi *et al.*, 2007) and eastern

(Bindi, Zaccarelli, *et al.*, 2023) Türkiye, southern California (Baltay *et al.*, 2017), and for a global data set (Baltay *et al.*, 2019). Over the years, several approaches have been proposed to retrieve the source time function or its amplitude spectrum, such as: deconvolution with an empirical Green's function in time (e.g., Mori and Frankel, 1990; Bertero *et al.*, 1997) or frequency (e.g., Abercrombie, 2021); coda-envelope decay modeling (e.g., Mayeda *et al.*, 2003; Morasca *et al.*, 2022); joint inversion of Fourier amplitude spectra (FAS) by generalized inversion technique (GIT; e.g., Andrews, 1986). Regardless of the method used, isolating the contribution of source properties of small and moderate earthquakes from far-field recordings is not straightforward, due to the difficulties in an adequate treatment of propagation and site effects (Abercrombie, 1995;

1. German Research Centre for Geoscience GFZ, Potsdam, Germany,  <https://orcid.org/0000-0002-8619-2220> (DB); 2. Department for Earth, Environment and Life Sciences DISTAV, University of Genova, Genova, Italy,  <https://orcid.org/0000-0002-8021-3908> (DS);  <https://orcid.org/0009-0004-7382-0189> (GT); 3. National Institute of Oceanography and Applied Geophysics OGS, Trieste, Italy,  <https://orcid.org/0000-0001-8078-9416> (MP)

\*Corresponding author: [bindi@gfz-potsdam.de](mailto:bindi@gfz-potsdam.de)

**Cite this article as** Bindi, D., D. Spallarossa, M. Picozzi, and G. Tarchini (2024). Scaling and Depth Variability of Source Parameters in Central and Southern Italy Using Regional Attenuation Models, *Bull. Seismol. Soc. Am.* **XX**, 1–17, doi: [10.1785/0120240144](https://doi.org/10.1785/0120240144)

© Seismological Society of America

Hough, 1997; Shearer *et al.*, 2019; Bindi *et al.*, 2020; Chen and Abercrombie, 2020). Moreover, the source parameter assessment is also hampered by the need to introduce a modeling framework for interpreting the source spectra (e.g., Brune, 1970), as the parameters of interest, such as the stress drop, are not directly observable. In the framework of the community stress-drop validation study initiative (Baltay *et al.*, 2024), the impact of different alternative choices for some processing and model assumptions in seismic moment and corner frequency estimation by the spectral decomposition approach have been investigated (Bindi *et al.*, 2023a,b). The results of these studies have highlighted that: (1) modern dense networks allow the source parameters of small and moderate events to be calculated with small statistical uncertainties (high precision); (2) the impact of processing- and model-related assumptions introduces large epistemic uncertainties, generating systematic biases in both the seismic moment (i.e., the parameter that provides information about source dimension) and the source corner frequency (the parameter on which the stress drop depends) that affect the interpretation of the final results. As a consequence of the trade-off between source and propagation effects, inaccurate path corrections can affect source parameters and our ability to capture their spatial variability (Shearer *et al.*, 2022), such as the detection of the depth dependence of the stress drop (Abercrombie *et al.*, 2021).

In this study, we estimate the source parameters of earthquakes that have occurred over the Apennine belt in Italy since 2005. Previous source studies have focused either on specific seismic sequences (Kemna *et al.*, 2021; Calderoni and Abercrombie, 2023; Calderoni *et al.*, 2023; De Gori *et al.*, 2023), to mention only a few recent studies or on specific segments of the Apennines (e.g., Bindi *et al.*, 2020; Picozzi *et al.*, 2021). Here, we consider a wider region including both the northern, central and southern Apennines, to describe the source parameters and their spatial variability within a harmonized methodological framework. Because the active tectonics in the Italian peninsula is heterogeneous (Faccenna *et al.*, 2014; Latorre *et al.*, 2023), we apply the spectral decomposition approach (Andrews, 1986), calibrating separate attenuation models for different subregions and developing a strategy to consistently constrain the decomposition over the entire region. With regard to the trade-off between source and propagation effects, we show that the use of different local attenuation models allows us to capture the differences in source scaling for different areas and to investigate the spatial distribution of stress-drop anomalies both laterally and with hypocentral depth.

In the following, we first introduce the data set considered and describe the spectral decomposition approach developed. Then, we show the effect of using the local attenuation models on the source parameter distributions and finally we present the spatial variability of the source scaling properties and the stress-drop parameter.

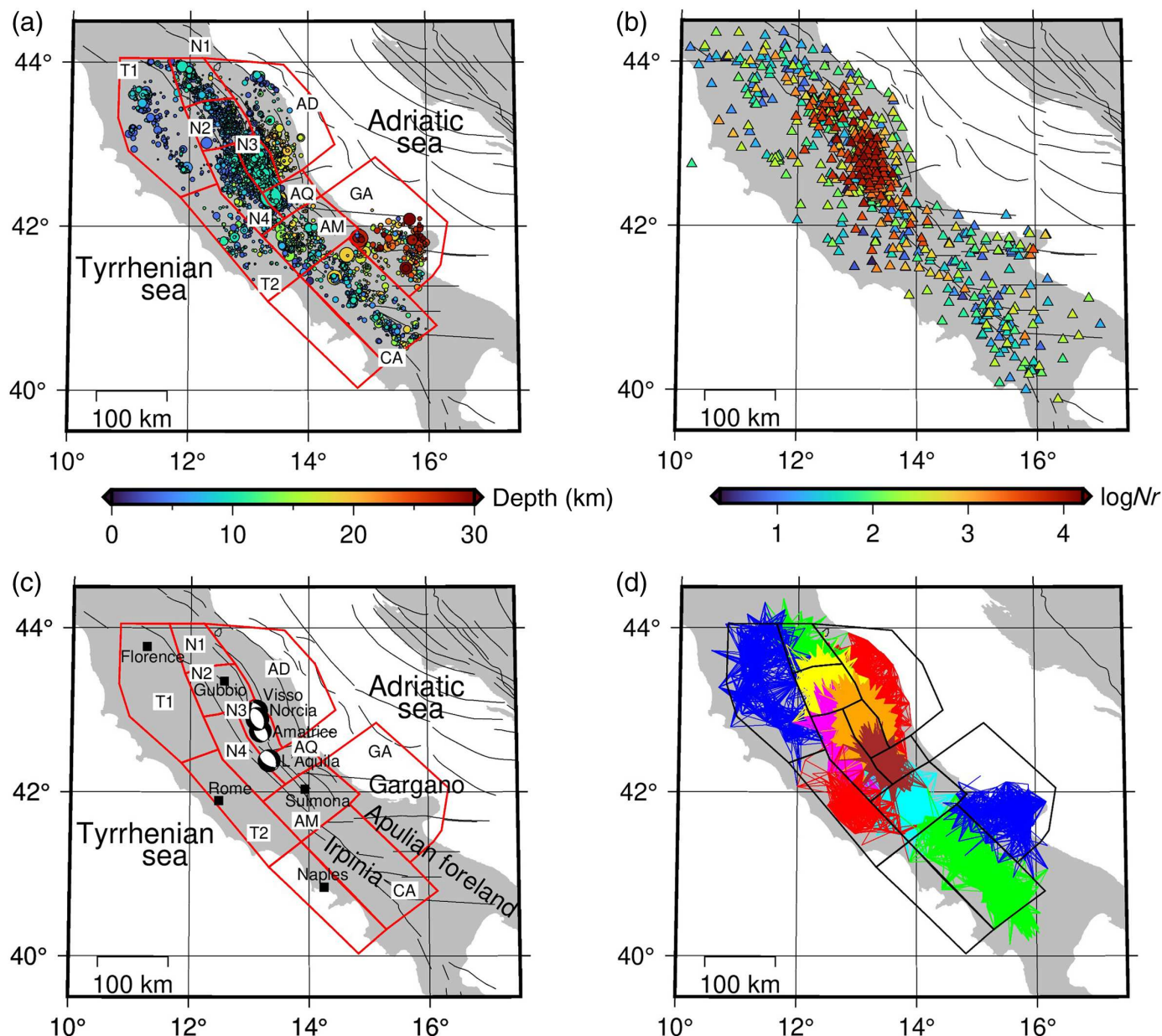
## DATA SET

The procedure for compiling the data set is described in Spallarossa *et al.* (2021). In particular, the download of waveforms is guided by the National Institute of Geophysics and Volcanology (INGV) catalog (see Data and Resources) and the Complete Automatic Seismic Processor (CASP; Scafidi *et al.*, 2019) is applied to automatically pick *P* and *S* onset, to perform the phase association, and to relocate the events with NLLoc software (Lomax *et al.*, 2000). We computed the local magnitude by applying the Di Bona (2016) attenuation model to the maximum Wood–Anderson amplitudes extracted from the analyzed data set. We applied the procedure to about 220,000 earthquakes that occurred in the study area between May 2005 and November 2023. CASP identified about 15 million *P* and *S* phases, used to relocate the events with NLLoc starting from the INGV locations.

For the spectral decomposition, we select 28,943 earthquakes (Fig. 1a) with magnitude greater than 1 and with well-constrained locations. Figures S1–S4, available in the supplemental material to this article, provide information on the quality of location in terms of horizontal and vertical errors, number of phases used, and maximum azimuthal gap. We consider both permanent and temporary networks (see Data and Resources) for a total of 1045 stations (Fig. 1b) counted as unique sensors (i.e., if a site is equipped with both a broadband and accelerometer sensors, they are considered as two different stations). All recordings are converted to acceleration after the correction for the instrumental response.

The FAS are computed for *S* waves considering windows extracted from the horizontal components starting 0.1 s before the onset of the *S* wave. The window ends when different distance-dependent percentages of the cumulative squared velocity are reached: 90% for distances  $R \leq 25$  km, 80% for  $25 \text{ km} < R \leq 50$  km; 70% for  $R > 50$  km (Pacor *et al.*, 2015), computing the percentages with respect to the values obtained for a duration of 40 s and setting the minimum and maximum duration of the selected windows to 5 and 20 s, respectively. Spectra are smoothed using the algorithm of Konno and Ohmachi (1998), with a smoothing parameter of 40. The frequency-dependent signal-to-noise ratio (SNR) is computed with respect to the pre-event noise window and we set the threshold to 3. Finally, we compute the square root of the sum of the two horizontal components squared. The number of records processed varies with frequency as a consequence of the SNR criteria applied and the number of FAS selected for the spectral decomposition at 3 Hz is 901,228. The magnitude–distance scatter plot for each polygon is shown in Figure S5. The variations of the number of events, stations, and FAS in the 0.3–30 Hz frequency range considered for the spectral decomposition are shown in Figure S6.

To account for possible regional variations in spectral attenuation with distance, and to avoid the attenuation in the most sampled areas masking possible regional variations,



we introduce a spatial zoning scheme. Considering the trade-off between the source and attenuation contributions to ground shaking, the segmentation avoids that differences in attenuation for different regions are accommodated by the source term. The segmentation is driven by general tectonic considerations and takes into account the seismicity distribution to define polygons that are still suitable for performing spectral decomposition over reduced data sets. We start by considering the Tyrrhenian tectonic domain, the Apennine chain, and the Adriatic tectonic domain (Fig. 1c). Then, considering the seismicity distribution and the  $V_P/V_S$  maps for the upper crust (Menichelli *et al.*, 2023), the Tyrrhenian tectonic domain is divided into two polygons T1 and T2, in which T1 is characterized by high heat flow, shallow Tyrrhenian Moho depth, and geothermal activity (Latorre *et al.*, 2023). The northern Apennines are divided into polygons N1 and N2;

**Figure 1.** (a) Event distribution, with color encoding the hypocentral depth. (b) Station distribution, with color encoding the logarithm of the number of available records. (c) Polygonal segmentation of the study area (red) was introduced for the spectral attenuation model. The focal mechanism plots indicate the focal mechanism of the 2016 Amatrice, Visso and Norcia mainshocks, and the 2009 L'Aquila mainshock. (d) Path coverage for each polygon. The color version of this figure is available only in the electronic edition.

the central Apennines are split in polygons N3, N4, and AQ, in which polygon N3 contains the 2016–2017 Amatrice–Visso–Norcia sequence, and AQ contains the 2009 L'Aquila sequence. The transition zone between the central and southern Apennines is represented by polygon AM, which includes the Sulmona and Fucino basin faults where the 1915  $M_w$  6.7 Avezzano earthquake occurred. The southern Apennines



corresponds to polygon CA, including the seismicity of the Irpinia region, where the 1980  $M_w$  6.9 Irpinia earthquake occurred. The Adriatic area consists of two polygons, AD in the north and GA in the south. These polygons are characterized by seismicity at greater depths associated with the subduction of the Adria plate beneath the Apennines; the GA polygon includes the Gargano promontory and part of the Apulian foreland. The GA is therefore characterized by a heterogeneous tectonics, including also strike-slip and thrust faults (Lucente *et al.*, 2023).

The spatial zoning is used to derive an attenuation model for each subregion and avoiding that propagation effects are transferred to the sources. Because a given recording is associated with the polygon containing the event location, there is a limited spatial overlap between the data sets used for different polygons, as the stations recording the events can also be located outside the polygon (Fig. 1d), particularly for the longer (and therefore deeper) paths. The overlap between the data sets considered for different polygons (Figs. S7, S8) introduces a buffer zone that avoids sharp discontinuities in the attenuation obtained for adjacent polygons.

## SPECTRAL DECOMPOSITION

We apply a nonparametric spectral decomposition approach known as GIT (Castro *et al.*, 1990; Oth *et al.*, 2011). The spectral decomposition is based on the assumption that the FAS can be expressed as a product of three terms representing source, propagation, and site effects. Taking the logarithm of the FAS, the GIT approach is based on the following model:

$$\text{Log}(\text{FAS}_{ij})(f) = \text{Log}(S_i)(f) + \text{Log}[P^k(R_{ij}, f)] + \text{Log}(Z_j)(f). \quad (1)$$

The nonparametric GIT splits the FAS into three terms, which are not described in terms of a seismological model but by generic vectors representing the source spectrum  $S_i(f)$  for each event  $i$  and the site amplification  $Z_j(f)$  at each station  $j$ . For each polygon  $k = 1, \dots, 11$ , with  $k$  depending on the event index  $i$ , the propagation effects are described by a matrix of values  $P^k(R_{ij}, f)$  capturing the variation with hypocentral distance  $R_{ij}$  of the spectral amplitudes at different frequencies  $f$ . An additional decomposition is performed without introducing the polygonal segmentation, that is, considering a unique attenuation model  $P(R_{ij}, f)$  for the whole area. When the indices  $i$  and  $j$  are iterated over all available recordings, equation (1) generates an overdetermined linear system which we solved in a least-squares sense (Koenker and Ng, 2021). A known characteristic of the linear system generated by equation (1) is that the solution is not unique because there are two unresolved degrees of freedom that generate trade-offs between the three terms. Therefore, constraints are needed to select solutions that satisfy a priori conditions (Bindi *et al.*, 2023a). We constrain

the attenuation to 1 at a reference distance of 8 km and we apply a reference amplification condition to selected sites. The selected reference distance is a compromise between using the shortest distance possible to minimize the shift of the attenuation characteristics to the source, and selecting a distance that is constrained by the data.

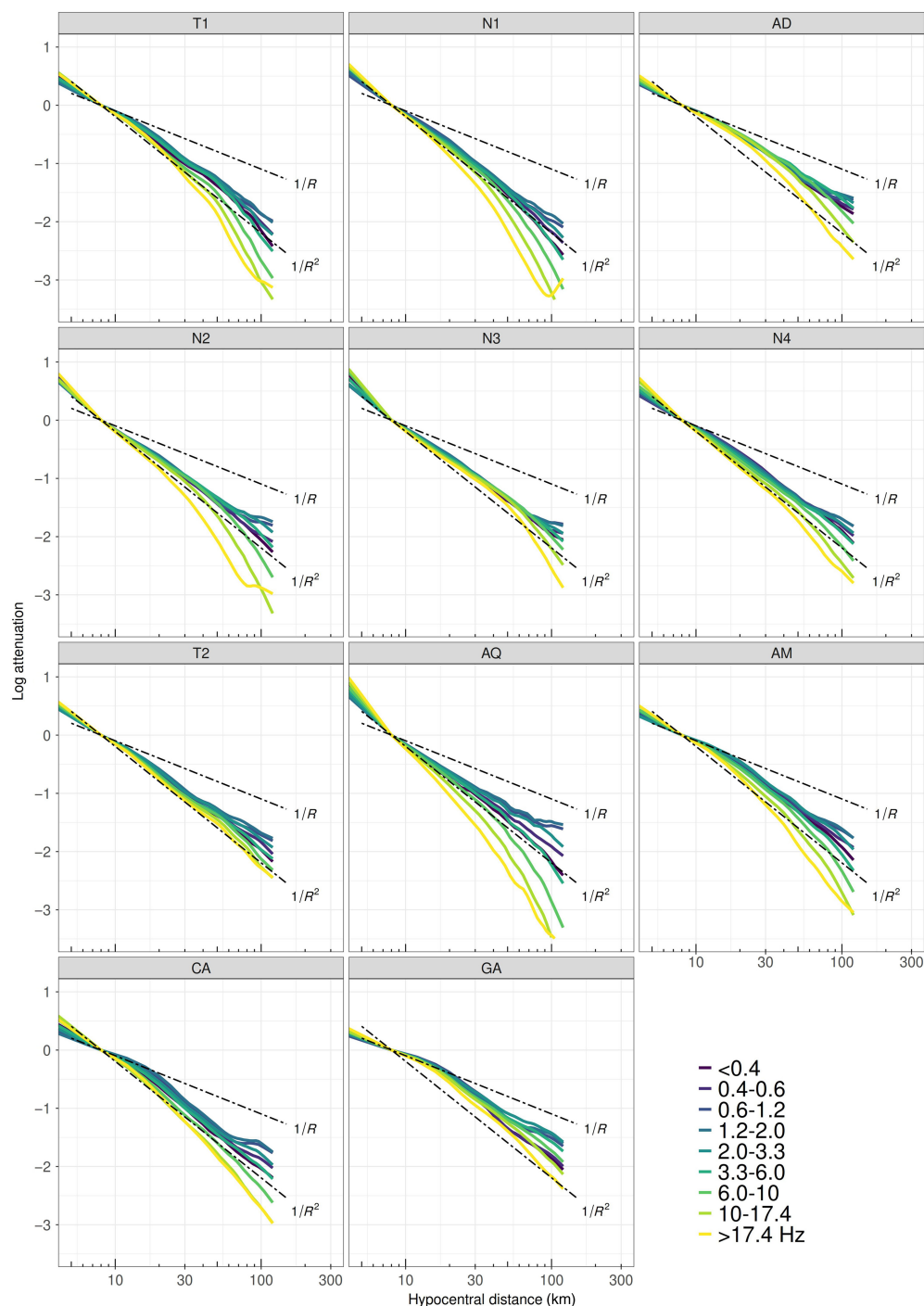
We implement the following strategy to perform the spectral decomposition.

- We perform the spectral decomposition (equation 1) for each polygon separately; as this first set of decompositions focuses on the attenuation term, we consider events with magnitude greater than 2 and hypocentral distances up to 120 km. The magnitude threshold is introduced to provide a more balanced distribution of data with distance, as the SNR selection allows very small magnitudes to contribute mainly at short distances. In addition, as for well-sampled data sets the attenuation term is almost independent of the reference site condition, we set the average site amplification computed for the considered stations to 1. The distance range is discretized into the following bins : 0, 8, 12, 16, 20, 24, 28, 32, 36, 40, 44, 48, 52, 56, 60, 64, 68, 72, 76, 80, 84, 88, 92, 96, 100, 105, and 120 km, and a linear interpolation is applied between two consecutive nodes. The spectral attenuation curves are smoothed by requiring that their second derivative with distance is small (Castro *et al.*, 1990).
- The FAS corrected for the propagation effects are then used to separate the source and site terms. For this decomposition, we consider all events with magnitude greater than 1.5, hypocentral distances up to 60 km to limit the effect of propagation complexities and regional variability (Fig. S8), and we perform an iterative procedure that allows the site amplification constraint to be propagated to the entire data set.
- The iterative decomposition starts with polygon N3, that is, the most populated polygon containing the 2016 Amatrice–Visso–Norcia seismic sequence; to guarantee the same reference amplification model used in a previous study, we constrain the site amplification of three stations in common with Morasca *et al.* (2022) to their results (i.e., stations IV.T1221.\_EH, IT.LSS.\_HN and IT.NCR.\_HN).
- After N3, we carried out the decomposition of other polygons or combinations of polygons, by constraining the site amplifications at all stations already processed in previous steps to the solutions obtained. The sequence of decomposition is N3, AQ, N4, N1 + N2 + N4, T1 + T2 + N4, AD + N2, AM + AQ, AM + AQ + CA, AM + AQ + CA + GA.

## REGIONAL SPECTRAL ATTENUATION

Figure 2 shows the spectral attenuation  $P^k(R, f)$  for all polygons, averaging the results over different frequency intervals. At a first glance, the attenuation varies considerably for the different polygons, both in terms of absolute values and in





**Figure 2.** Spectral attenuation for the different subregions. Different colors represent the average attenuation over frequency ranges as indicated in the legend. The color version of this figure is available only in the electronic edition.

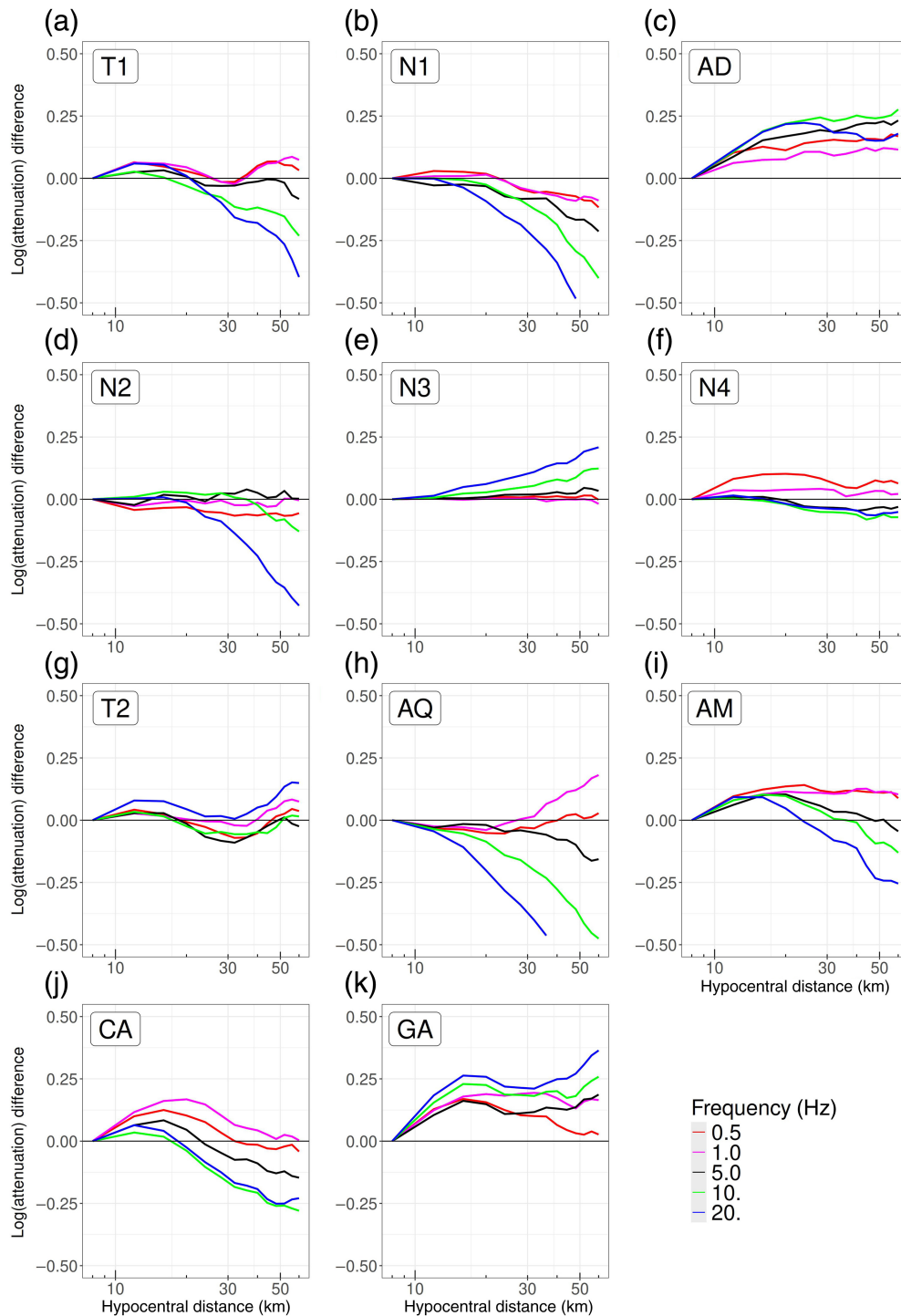
terms of its dependence on frequency. The attenuation for the polygons along the Tyrrhenian Sea, in particular for T1, and along the Apennines (e.g., polygons N1, N2, and AQ) is faster than for the polygons along the Adriatic Sea (i.e., AD and GA); regarding the frequency dependence, the spread of the attenuation values is larger for T1, N1, N2, and AQ. Figure 3 quantifies the difference in spectral attenuation between each polygon and

the model obtained considering all polygons together (without regionalization) for five frequencies (i.e., 0.5, 1, 5, 10, and 20 Hz). Considering the large sampling that characterizes N3 (which includes the 2016–2017 Amatrice, Visso, and Norcia sequence), a decomposition without regionalization would be driven by N3, especially below 5 Hz, biasing the results in other polygons. At higher frequencies, N3 shows a slower attenuation than the model without regionalization, suggesting that the anelastic attenuation for N3 is lower than for the whole area. Along the Apennines, the high-frequency attenuation (results for 10 and 20 Hz in Fig. 3) is strongest for AQ (including the L'Aquila mainshock), N1 and CA (Irrpinia region), and for T1 on the Tyrrhenian side: for these polygons, the 10 Hz attenuation at 50 km is more than 25% stronger than without regionalization. On the other hand, the attenuation at all frequencies is lowest for AD and GA, especially at high frequencies, with ratios between 10% and 25% for distances greater than 20 km. According to these results, a strong influence of the regionalization on the source parameters can be expected.

## SITE EFFECTS AND SOURCE PARAMETERS ESTIMATION

The FAS corrected for propagation effects are used to isolate the source spectra from the site

amplifications using the iterative decomposition approach described in the [Spectral decomposition](#) section. Figure 4 shows the obtained site amplifications at all stations (Fig. 4a) and the source spectra of all events (Fig. 4b). The site amplifications at a few stations are highlighted in color: LSS (black) and NRCA (blue) are two of the stations constrained by the results of [Morasca et al. \(2022\)](#); CLF (green) is installed



**Figure 3.** Difference for four selected frequencies between the logarithm of the attenuation obtained for each subregion of Figure 1, shown in the upper left corner of the panels from (a) to (k), and the attenuation obtained without introducing a spatial zoning. The color version of this figure is available only in the electronic edition.

inside the Colfiorito basin; the amplifications at 1 Hz observed for CLF have been extensively studied (Di Giulio *et al.*, 2003) and related to basin-induced Love waves. The result obtained for these stations, together with the results for some other stations not discussed here, confirms the reliability of the source-site decomposition.

The source spectra are fit in a least-squares sense (Elzhov *et al.*, 2023) to a  $\omega^2$  model to estimate the seismic moment  $M_0$  and the corner frequency  $f_c$ ,

$$S(f) = \frac{\Omega^0}{[1 + (f/f_c)^2]}, \quad (2)$$

$$\Omega^0 = \frac{R^{\theta\phi} F V M_0}{4\pi\rho\beta^3 r_{\text{ref}}}, \quad (3)$$

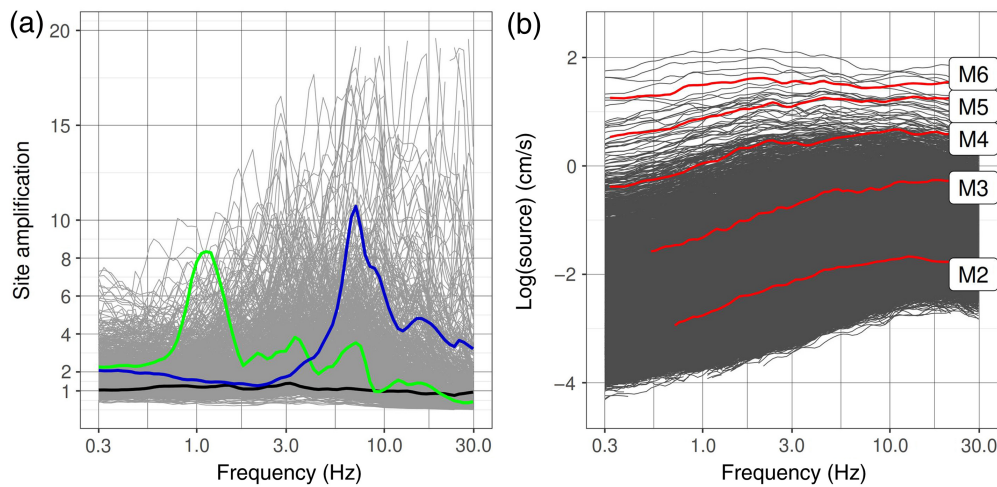
$$r = \frac{k\beta}{f_c}, \quad (4)$$

$$\Delta\sigma = \frac{7}{16} \frac{M_0}{r^3}, \quad (5)$$

in which we use, an average radiation pattern  $R^{\theta\phi} = 0.55$ , a free-surface amplification factor  $F = 2$ , an equipartition energy factor  $V = 1$ , an average density  $\rho = 2700 \text{ kg/m}^3$ , and the reference distance  $r_{\text{ref}} = 8000 \text{ m}$ . In equation (4), we use  $k = 0.37$  (Brune, 1970), and the stress drop  $\Delta\sigma$  in equation (5) is computed for a circular rupture with uniform stress drop (Eshelby, 1957). For the shear-wave velocity  $\beta$ , we used the values from the tomographic model of Menichelli *et al.* (2023) by applying a trilinear interpolation to estimate the velocities at the hypocentral locations.

Two additional constraints are applied to compute the source parameters. First, we anchor the seismic moments to the INGV moment tensor catalog (see Data and Resources) by requiring that  $M_w$  on average

matches the INGV catalog in the magnitude range 3–5. By anchoring  $M_w$  to the INGV catalog, we remove possible biases introduced either by the average reference site amplification due to the trade-off between source and site terms, and by the values assumed for different constants in equation (3). The second constraint is to fix individual  $M_w$  above 5 to the INGV values. This



**Figure 4.** (a) Nonparametric site and (b) source spectra obtained with the spectral decomposition. The site amplifications for CLF, NRCA, and LSS stations are shown in green, blue, and black, respectively. The color version of this figure is available only in the electronic edition.

constraint is necessary because the bandwidth available for the spectral fitting (i.e., 0.3–30 Hz) does not allow  $M_0$  and  $f_c$  to be resolved for large events (i.e., the correlation between  $M_0$  and  $f_c$  as computed from the covariance matrix approaches  $-1$ ).

## SOURCE PARAMETER RESULTS

### Impact of regional attenuation

We first assess the impact of the regional attenuation models on the source parameters. Figure 5 shows the ratios of the seismic moment (Fig. 5a), the corner frequency (Fig. 5b), and the stress-drop (Fig. 5c) values computed for the 11 polygons (Fig. 1c) with respect to the values obtained without introducing the regional models. We recall that the segmentation is introduced to allow the attenuation to capture regional variability but it is not applied to the sources. The reason why the parameters shown in Figure 5 are divided per polygon is to highlight the impact of considering or not different attenuation models (trade-off between source and attenuation terms). There is a clear influence of the regional models on all the source parameters, especially for polygon GA, for which the  $f_c$  ratio is above 2 and the stress-drop ratio is above 10. For some polygons, the  $\Delta\sigma$  ratio decreases with increasing  $\Delta\sigma$ , such as for example in AQ (L'Aquila) and N1 (Gubbio and Alto Tiberina area). Figure 5d shows that the trend of the  $\Delta\sigma$  ratio for AQ is controlled by the hypocentral depth because events with larger  $\Delta\sigma$  are located at greater depths. The source scaling obtained is discussed subsequently, taking into account the regional attenuation models to correct for propagation effects.

### Regional $M_0 - f_c$ scaling and depth dependency

Figure 6 shows the  $M_0$  versus  $f_c$  scaling for all polygons. The comparison with the equal stress-drop lines indicates that the

scaling in the different polygons differs both in terms of stress-drop values and terms of slope.

To quantify the differences in the scaling of Figure 6, we first fit a linear model between the logarithm of  $M_0$  and of  $f_c$ , that is,

$$\log(M_0) = a_1 + b_1 \log(f_c), \quad (6)$$

in which values of the slope  $b_1$  other than  $-3$  indicate deviations from self-similarity. Considering the whole data set, the coefficients of the best-fitting least-squares model are  $a_1 = 13.73 \pm 0.01$  and  $b_1 = -2.32 \pm 0.01$ . The standard deviation of the residuals is 0.43 and the Akaike information criterion (AIC) is  $AIC = 33122$ . The value of  $b_1$  indicates that the average behavior of the whole population deviates from a self-similar scaling, but Figure 6 shows that the stress-drop values are spread over four decades.

Therefore, to account for the differences in scaling between polygons, we perform mixed-effects regressions (Bates *et al.*, 2015) using the polygons as grouping factors, indicated in the following as region of interest (ROI), for both the intercept and slope of the model, that is,

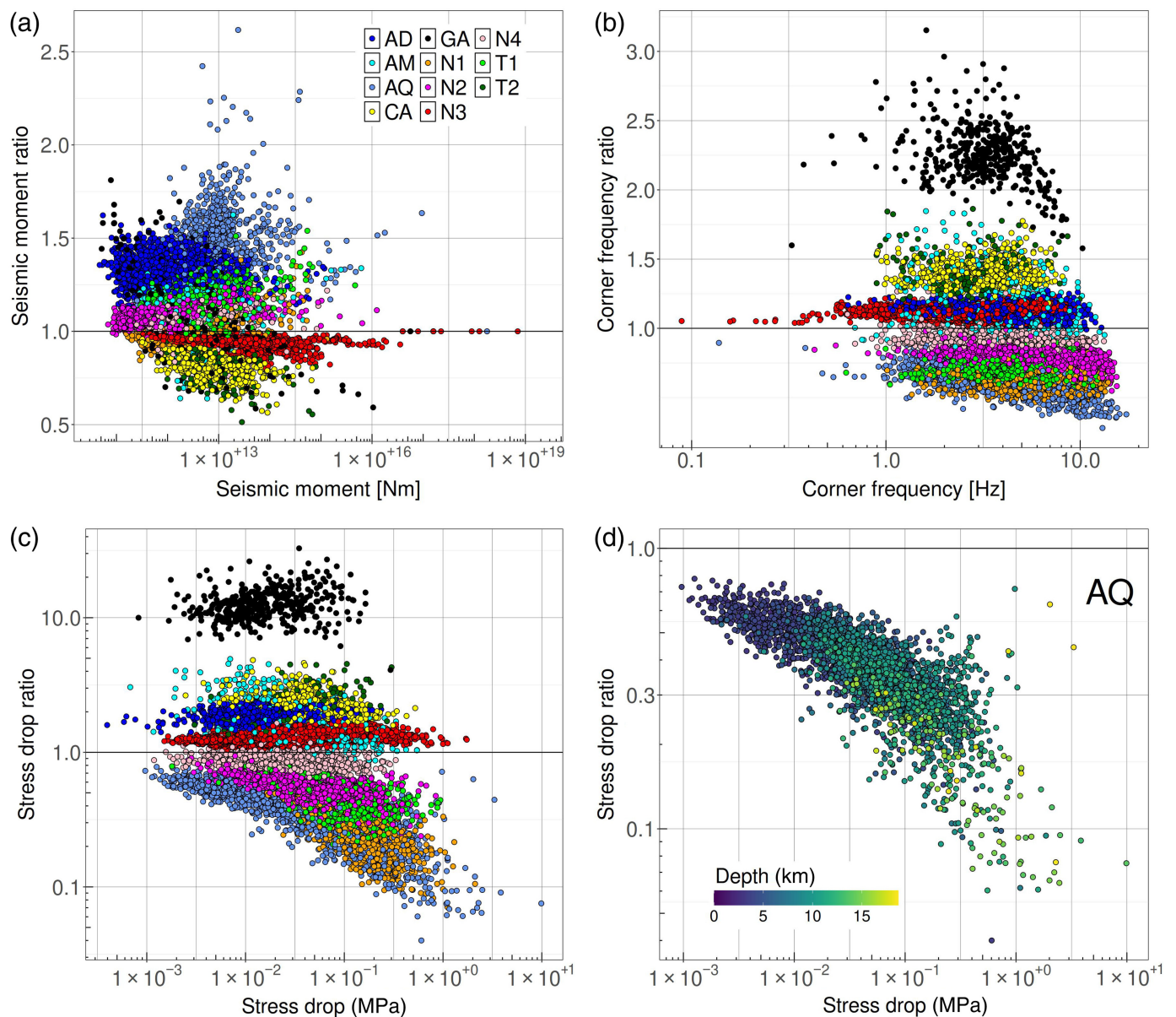
$$\log(M_0) = a_2 + b_2 \log(f_c) + \delta a_2^{\text{ROI}} + \delta b_2^{\text{ROI}}, \quad (7)$$

in which  $\delta a_2^{\text{ROI}}$  and  $\delta b_2^{\text{ROI}}$  are the polygon-dependent random intercepts and slopes, respectively. The fixed effects of the models are  $a_2 = 13.92 \pm 0.13$  and  $b_2 = -2.50 \pm 0.14$ . The AIC value is 29,359, indicating an improvement over the model (equation 6). The random effects are shown in Figure 7. The random slopes vary between ROIs with almost all absolute values less than the self-similarity value: the values for ROIs N1 and T1 (obtained by adding the random effects  $\delta b_2^{\text{ROI}}$  to the slope  $b_2 = -2.50$ ) are the closest to self-similarity; GA is the only one lower than  $-3$ ; the slopes of ROIs T2, N4, AM, AQ are close to  $-2$ .

To assess the role played by the depth, we perform another mixed-effects regression for which the depth random effects are nested in the ROI. The depth range is discretized in the following intervals: [0,5], [5,10], [10,15], [15,20], [20,30], > 30 km; then, we consider the following mixed-effects model:

$$\log(M_0) = a_3 + b_3 \log(f_c) + \delta a_3^{\text{ROI/DEPTH}} + \delta b_3^{\text{ROI/DEPTH}}, \quad (8)$$





in which  $\delta a_3^{\text{ROI/DEPTH}}$  and  $\delta b_3^{\text{ROI/DEPTH}}$  represent the random effects for the DEPTH grouping factor nested in the ROI factor, taking into account the intercept and slope, respectively. The obtained fixed effects are  $a_3 = 14.11 \pm 0.11$  and  $b_3 = -2.74 \pm 0.12$ , and the Akaike value of 21,390 indicates an improvement over the model in equation (7). The random effects are shown in Figure 8a,b for the ROI grouping factor, and Figure 8c,d for the DEPTH nested within the ROI grouping factor. For most of the ROIs, the depth-dependent random slope adjustments (Fig. 8c) show a trend with depth, as highlighted in Figure 9 for six selected ROIs. In most cases, the ROI-specific slope adjustment decreases with increasing depth, with some ROIs showing large variations (e.g., GA, CA, and AQ) whereas in other areas the increase with depth is less pronounced (e.g., for AM and AD).

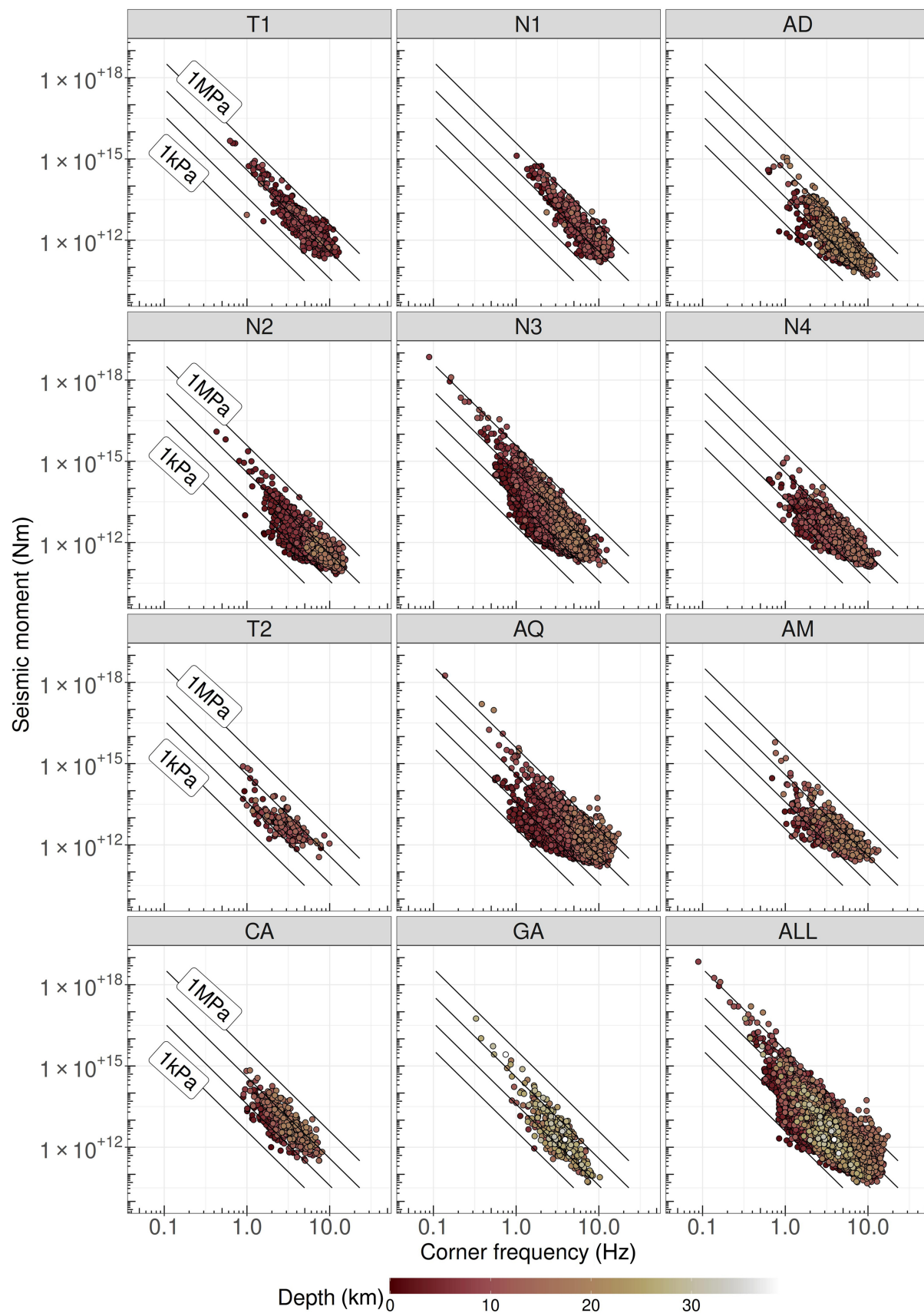
Figure 10 shows the scaling of  $\Delta\sigma$  with depth for the different polygons. Each frame also shows the 10th, 50th, and 90th percentiles of quantile regression (Koenker, 2023).

**Figure 5.** The ratio of source parameters obtained without regionalization to those obtained with regionalization plotted against the values obtained with regionalization (i.e., no-region/region vs. region): (a) seismic moment, (b) corner frequency, and (c) stress drop. Panel (d) shows the stress-drop results for region AQ with symbols filled according to depth. The color version of this figure is available only in the electronic edition.

Polygons showing an increasing trend with depth are mostly in central Italy, in particular, N3 (a factor of 10 increase for the median from the surface to 20 km depth) and AQ (about a factor of 20); the trend is almost flat for AD and GA on the Adriatic side, for T1 and T2 on the Tyrrhenian side, and for N1 and N2 in the northern Apennines.

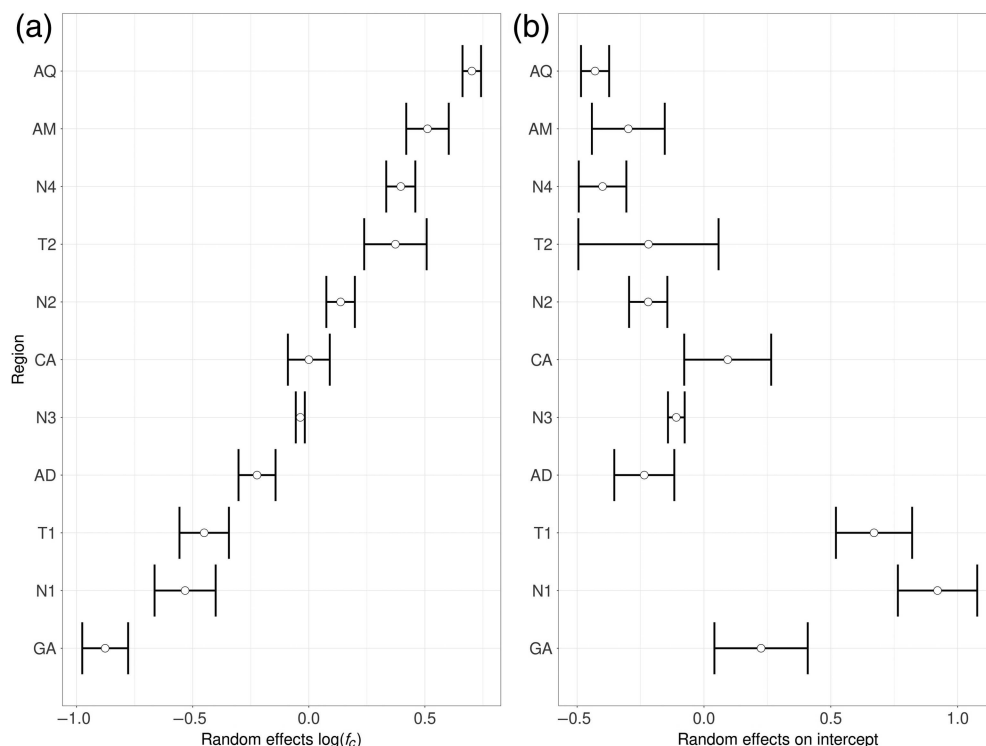
To study the lateral variability and with depth of  $\Delta\sigma$ , we first calibrate a model describing the scaling of  $\Delta\sigma$  with  $M_0$ , that is,

$$\log(\Delta\sigma) = c_1 + c_2 \text{Log}(M_0). \quad (9)$$



**Figure 6.** Seismic moment versus corner frequency scaling for different sub-regions (i.e., the polygons in Fig. 1). Colors encode the hypocentral depth.

The color version of this figure is available only in the electronic edition.



**Figure 7.** Random effects for the model in equation (7) for different polygons (ROI). (a) Random effects on the slope ( $\delta b_2^{\text{ROI}}$  in equation 7). (b) Random effects on the intercept ( $\delta a_2^{\text{ROI}}$  in equation 7, which has a slope of  $b_2 = -2.50 \pm 0.14$ ).

The best-fitting least-squares model is described by  $c_1 = -4.46 \pm 0.04$  and  $c_2 = 0.242 \pm 0.004$ . The event-specific residuals, denoted by  $\epsilon$ , from the median predictions of the model (equation 9) are used to map the spatial distribution of the stress-drop anomalies  $\epsilon$ , using an interpolation based on ordinary kriging (Hiemstra *et al.*, 2008). For the interpolation, we considered events in the magnitude range 1.8–5 and we masked unconstrained areas in the vertical sections. The resulting vertical sections are shown in Figures 11 and 12.

## DISCUSSION

In this study, we investigate the impact of considering different attenuation models when performing the spectral decomposition to isolate the source spectra of earthquakes in central and southern Italy. Previous studies have shown that the complex tectonics characterizing this region results in a significant spatial variability of attenuation both at regional (Castro *et al.*, 1999; Nardoni *et al.*, 2021) and local (e.g., Lucente *et al.*, 2023) for polygon GA; (Talone *et al.*, 2023) for AM and CA; (Akinci *et al.*, 2020) and (Gabrielli *et al.*, 2023) for N3; (Pisconti *et al.*, 2015) for N2 and N3; (Piccinini *et al.*, 2010) for T1, N1, N2, AD spatial scales. Concerning the spatial variability of the attenuation from the point of view of ground-motion modeling, both Kotha *et al.* (2020) and Brunelli *et al.* (2023) confirmed that, at the regional scale, the seismic

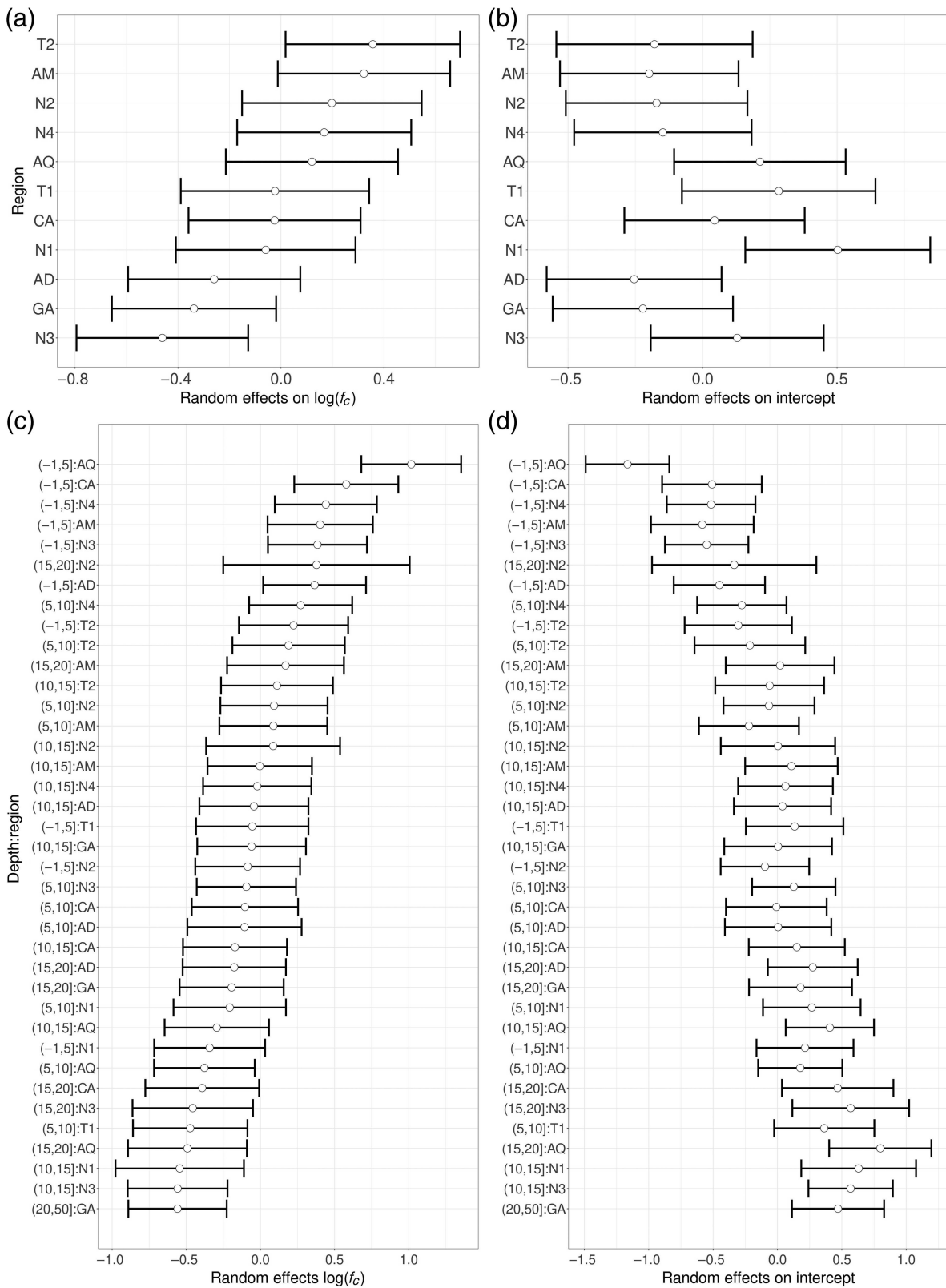
attenuation is faster on the Tyrrhenian side and slower on the Adriatic side at high frequencies.

The spectral decomposition (Figs. 2, 3) captures well the spatial variability of the attenuation in the study area. We observe fast attenuation at high frequencies in polygons such as T1 and N1 for which the heat flow is high, and slow attenuation along the Adriatic side. In particular, the attenuation is slow in the GA polygon which includes the outcrop of a continental lithospheric block belonging to Adria plate (i.e., the Gargano promontory), where the seismicity occurs in areas of high-intrinsic quality factor  $Q_i$  (Lucente *et al.*, 2023).

Considering the trade-off between source and propagation contributions to ground shaking, the introduction of different spectral attenuation

models for the different polygons has a strong influence on the source parameters. Figure 5 shows that the introduction of different attenuation models reduces the corner frequencies for GA by an average factor of about 2.5 and the stress drop by a factor of about 10 with respect to the values obtained without differentiating the attenuation between the polygons. Large differences are also observed for some polygons in central Italy, such as AQ and N1, for which the ratios for the largest  $\Delta\sigma$  values fall below 0.3.

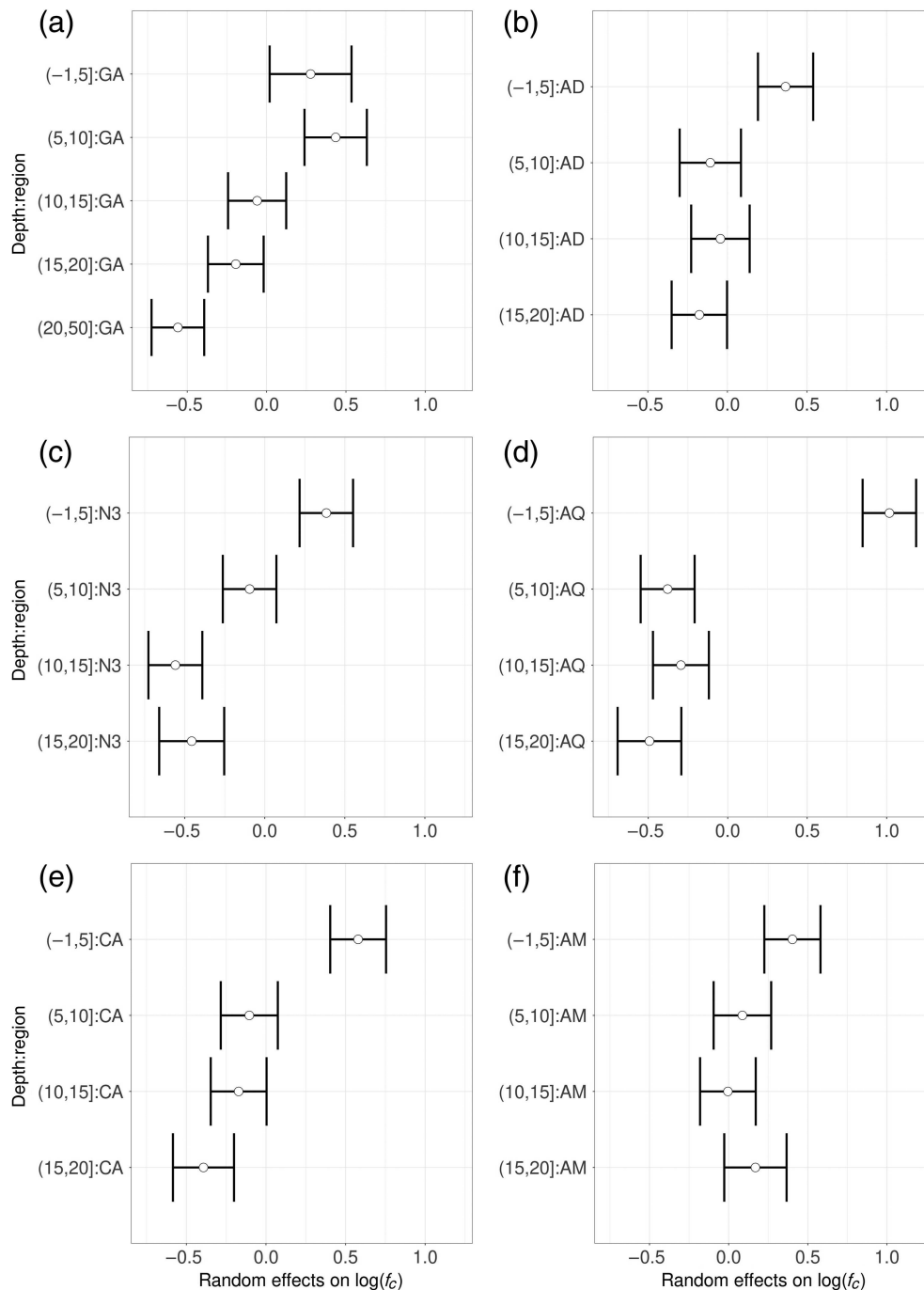
By correcting for attenuation to account for regional differences, source scaling can be examined for each polygon. Previous studies in Japan and California (Oth, 2013; Trugman and Shearer, 2017) have shown that the scaling between  $M_0$  and  $f_c$  can vary within a region or between seismic sequences. For the dataset we have analyzed, we observe significant differences in the scaling in the different polygons. For example, the slope of the  $\text{Log}(M_0)$  versus  $\text{Log}(f_c)$  scaling shifts from  $-2.3$  when all events are analyzed without considering differences in the scaling between the polygons (but using different attenuation corrections) to  $-2.5$  when polygon-specific adjustments are introduced as random effects on the intercept and slope through a mixed-effects regression. When depth-dependent adjustments are further introduced within each polygon, the slope of the average model becomes  $-2.7$ . Thus, accounting for local differences in the source characteristics



has an effect on the median scaling. In our case, capturing the variability between polygons and between different depths within each polygon makes the median scaling between  $\log(M_0)$  and  $\log(f_c)$  steeper approaching the self-similarity value of  $-3$ . Furthermore, for almost all polygons, the

**Figure 8.** Random effects (a,c)  $\delta b_3^{\text{ROI/DEPTH}}$  and (b,d)  $\delta a_3^{\text{ROI/DEPTH}}$  for the model in equation (8). Panels (a,b) show the random effects for the ROI grouping factor; whereas panels (c,d) show the random effects for the depth interval grouping factor nested within the ROI grouping.



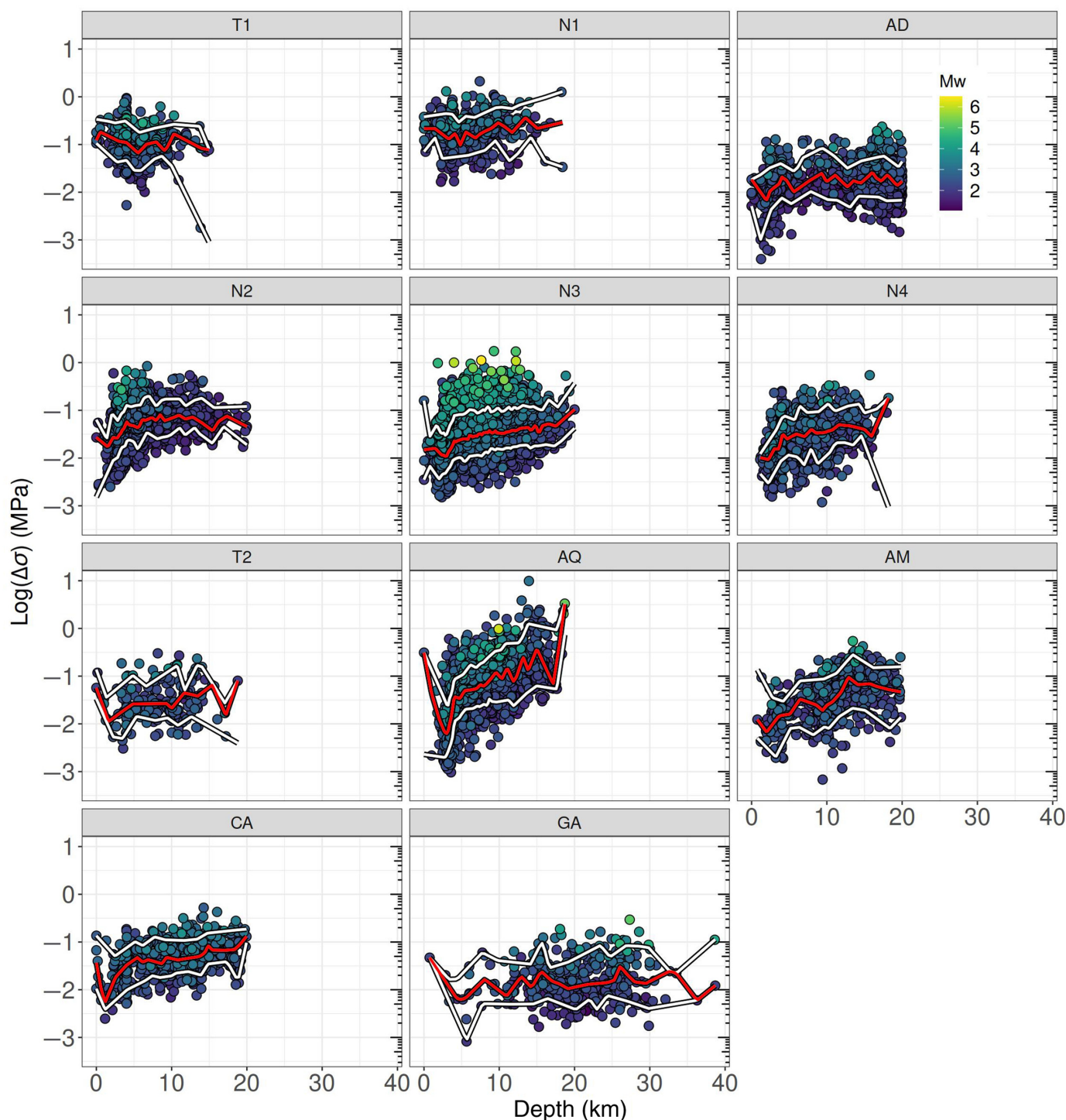


**Figure 9.** Random effects for the depth-interval grouping factor nested in the ROI factors (see Fig. 8) considering six different polygons of Figure 1 (i.e., results for GA, AD, N3, AQ, CA and AM are shown in panels from (a) to (f), respectively). Depth interval and ROI are indicated on the vertical axis.

depth-dependent adjustments to the polygon-specific slope show a systematic tendency to increase with depth, suggesting that depth plays an important role in controlling the scaling between  $M_0$  and  $f_c$ .

Regarding the stress drop  $\Delta\sigma$ , there is an ongoing debate as to whether we are able to capture its increase with depth or whether the trade-off with the depth-dependent attenuation is the

motivation behind the apparent trends found in some studies (Goertz-Allmann and Edwards, 2013; Abercrombie *et al.*, 2021). Looking at the  $\Delta\sigma$  variability with depth, we observe clear trends in the median and in the 10th and 90th percentiles for only a few polygons (e.g., N3, AQ, Fig. 10), whereas other polygons show a less pronounced or flat trend (e.g., AD, N1, GA, and T2). However, even for those polygons with a clear trend, the values of  $\Delta\sigma$  for the same depth span several decades. The broad  $\Delta\sigma$  distributions suggest that the lateral variability may be large and make it difficult to identify trends with depth, as has been also suggested for California (Shearer *et al.*, 2022). Because  $\Delta\sigma$  depends on  $M_0$ , to avoid that the spatial and depth trend of  $M_0$  introducing biases in the spatial distribution of  $\Delta\sigma$ , we first fit a linear model to the relationship between  $\text{Log}(\Delta\sigma)$  and  $\text{Log}(M_0)$ , and then we examine the spatial distribution of stress drop anomalies  $\epsilon$  with respect the median model. Figures 11 and 12 show that the highly variable lateral distribution of  $\epsilon$  dominates over the trend with depth. As shown in Figure 10, there are only a few areas where there is a clear contrast between low shallow and high deep  $\epsilon$  values, such as under point 7 of the B–B' profile in the lower panel of Figure 11 (AQ polygon, where the 2009  $M_w$  6.1 L'Aquila earthquake occurred). The increase with depth is also evident for polygon N3, which hosts the 2016 Amatrice–Visso–Norcia sequence, as shown in the middle panel of Figure 12 (vertical A–A' section), between points 4 and 5. The vertical A–A' section in Figure 11 shows a clear lateral contrast between T1 (positive  $\epsilon$ ) and T2 (small or negative  $\epsilon$ ) along the Tyrrhenian side, whereas the vertical B–B' section in Figure 12 shows the contrast between CA (Irpina region,



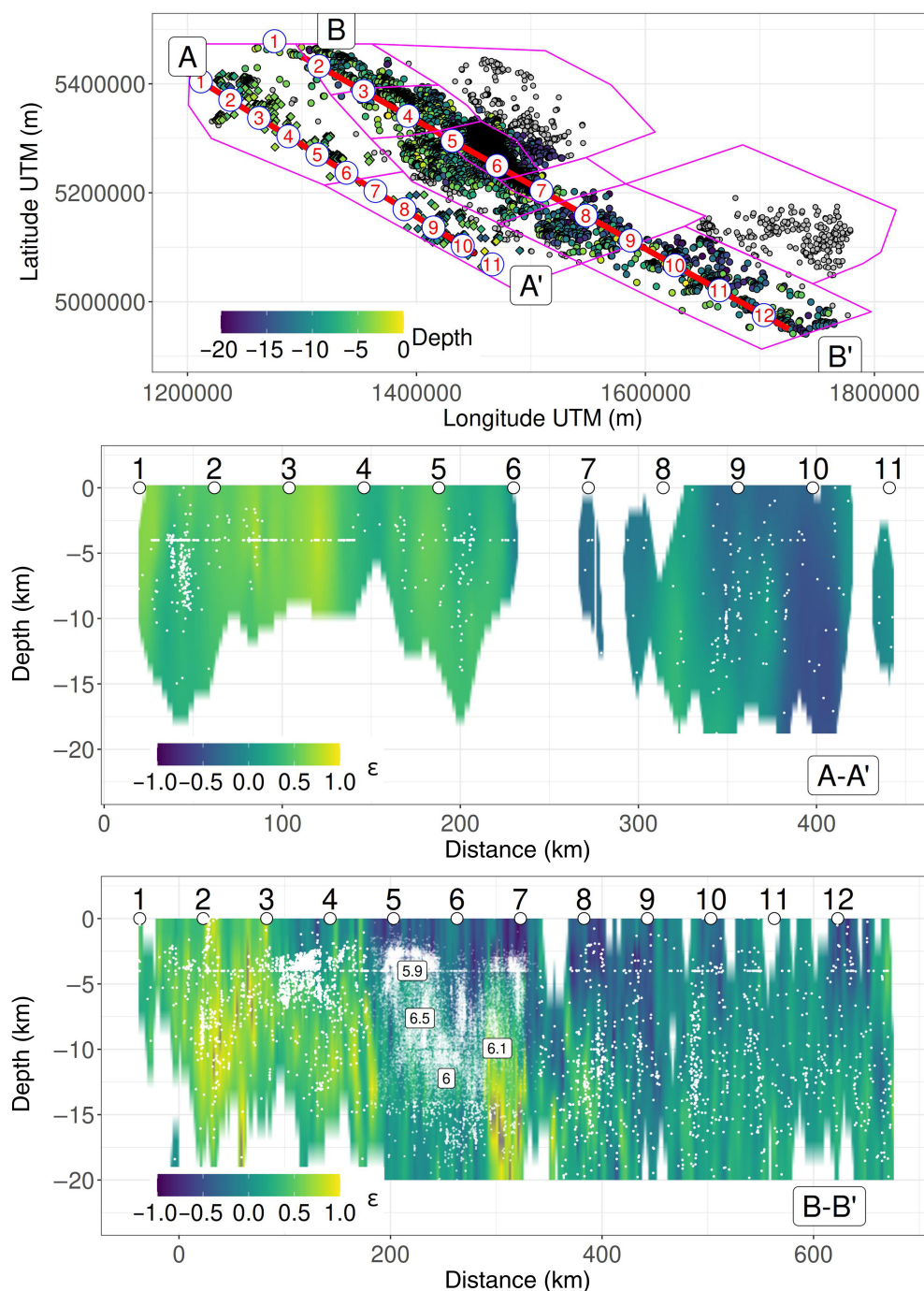
points between 1 and 3) and GA (Gargano and Apulian foreland region, points 4–6).

## CONCLUSIONS

The determination of the source parameters is affected by large epistemic uncertainties related to the strategies adopted to remove the propagation effects and to model the source spectra. In particular, the trade-off between source and propagation effects makes the interpretation of the source scaling dependent on the strategy adopted to correct for the attenuation effects. We

**Figure 10.** Stress-drop scaling versus depth for the different polygons of Figure 1. The continuous lines represent the result of a quantile regression (Koenker, 2023) performed for the 10th, 50th, and 90th percentiles. The color version of this figure is available only in the electronic edition.

develop a spectral decomposition approach to isolate the source spectra of earthquakes occurring in central and southern Italy considering several local attenuation models to correct for propagation effects. Taking into account the differences in



**Figure 11.** Vertical sections of stress-drop anomalies  $\epsilon$ , computed as residuals with respect to the values predicted by equation (9). Maps are generated using ordinary kriging (Hiemstra *et al.*, 2008), and event locations are shown as white dots, coordinates are given in UTM, zone 33, datum WGS84 (Pebesma and Bivand, 2005). In the lower panel, the locations of the  $M_w$  6.1 2009 L'Aquila,  $M_w$  6 2016 Amatrice,  $M_w$  6.5 Norcia, and  $M_w$  5.9 Visso earthquakes are indicated by labels. The color version of this figure is available only in the electronic edition.

the attenuation between different areas allows us to study the local characteristics of the scaling between seismic moment and corner frequency, highlighting the role of depth in controlling the slope of the scaling. The spatial distribution of the stress-drop anomalies, computed with respect to the values expected for a given seismic moment, shows a large lateral variability,

consistent with the heterogeneity of the active tectonics of Italy. Depth dependencies of the stress drop are observed only in a few areas, such as those interested by the 2009 L'Aquila and 2016 Amatrice-Visso-Norcia sequences and we conclude that the large lateral variability makes it difficult to isolate stress-drop trends with depth when large areas are considered.

## DATA AND RESOURCES

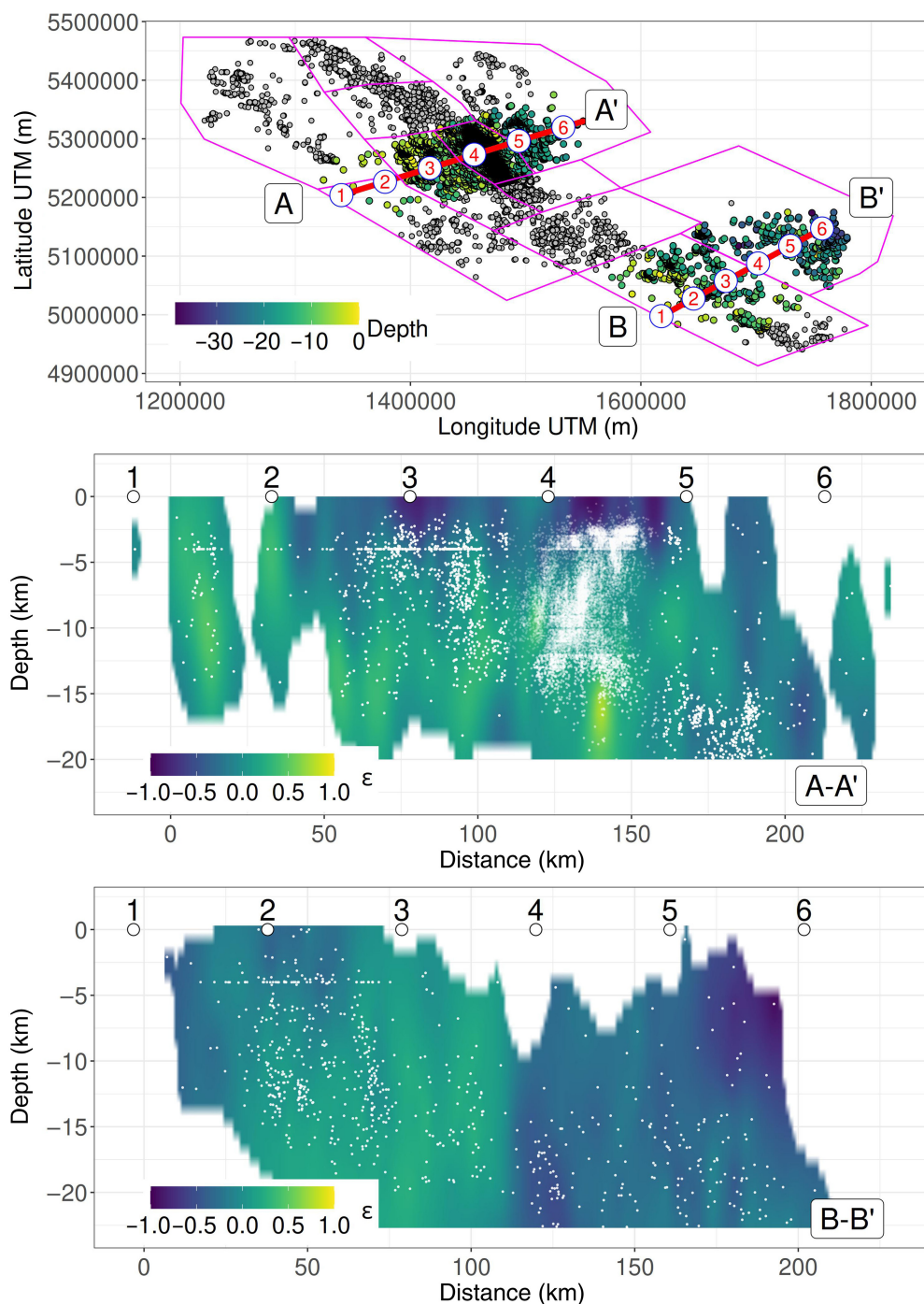
Analyses were performed using R software (R Core Team, 2020) and the Generic Mapping Tools (GMT; Wessel *et al.*, 2019). We used data from the following networks: IV, MN, TV, IT, RR, MZ, GE, BA, IX, VD, OT, GU, ZH\_2022, YR\_2016, 3A\_2016, 4A\_2012, 7F\_2021, 3H\_2009, XJ\_2009, YD\_2018, Y1\_2022, and XO\_2016, with full citations available in Bindi *et al.* (2024). The National Institute for Geophysics and Volcanology (INGV) bulletin is used to guide the data download and retrieve the moment magnitudes (<https://webservices.ingv.it/fdsnws/event/1>). We used data and information retrieved from the European Integrated Data Archive (EIDA; <https://www.orfeus-eu.org/data/eida/>), the Incorporated Research Institutions for Seismology (IRIS; <https://www.iris.edu/hq/>), and the Italian Civil Protection Department (<http://ran.protezionecivile.it/EN/index.php>). All websites were last accessed in May 2024. The supplemental material includes eight figures, Figures S1–S4 are about quality of locations, Figures S5 and S6 are about data distributions, and Figures S6 and S7 are about path coverage for the spectral decomposition.

The results of this study (e.g., source parameters, random effects for the different models, etc.) are available in Bindi *et al.* (2024).

## DECLARATION OF COMPETING INTERESTS

The authors acknowledge that there are no conflicts of interest recorded.





**Figure 12.** Same as Figure 11 but for two different sections perpendicular to the Apennines, with the locations shown in the top panel. In the upper panel, events for which  $\epsilon$  values are projected onto the vertical planes are colored according to their depth. The color version of this figure is available only in the electronic edition.

## ACKNOWLEDGMENTS

The authors thank two anonymous reviewers and Associate Editor Silvia Castellaro for providing several suggestions that helped them improve an earlier version of the article. The authors thank Irene Menichelli, Pasquale De Gori, and coauthors for sharing the electronic version of their tomographic model. The authors also acknowledge several discussions with colleagues from the National Institute of Geophysics and Volcanology (INGV) in the context of the SECURE

project (Regional-scale earthquake ground-motion prediction through physics-based and empirical approaches: a case study central Italy). This research was supported by the Piani di Rilevante Interesse Nazionale (PRIN) 2022 project “2022ZHXWC9”—Intercepting the PREparatory Phase of IARge earthquakes from seismic information and gEodetic Displacement (PREPARED).

## REFERENCES

- Abercrombie, R. E. (1995). Earthquake source scaling relationships from -1 to 5 ML using seismograms recorded at 2.5 km depth, *J. Geophys. Res.* **100**, no. B12, 24,015–24,036.
- Abercrombie, R. E. (2021). Resolution and uncertainties in estimates of earthquake stress drop and energy release, *Phil. Trans. Roy. Soc. Lond. A* **379**, no. 2196, doi: [10.1098/rsta.2020.0131](https://doi.org/10.1098/rsta.2020.0131).
- Abercrombie, R. E., D. T. Trugman, P. M. Shearer, X. Chen, J. Zhang, C. N. Pennington, J. L. Hardebeck, T. H. W. Goebel, and C. J. Ruhl (2021). Does earthquake stress drop increase with depth in the crust? *J. Geophys. Res.* **126**, no. 10, e2021JB022314, doi: [10.1029/2021JB022314](https://doi.org/10.1029/2021JB022314).
- Akinci, A., E. D. Pezzo, and L. Malagnini (2020). Intrinsic and scattering seismic wave attenuation in the Central Apennines (Italy), *Phys. Earth Planet. In.* **303**, 106,498.
- Andrews, D. J. (1986). Objective determination of source parameters and similarity of earthquakes of different size, *American Geophysical Union (AGU)*, 259–267.
- Baltay, A., R. Abercrombie, S. Chu, and T. Taira (2024). The SCEC/USGS community stress drop validation study using the 2019 Ridgecrest earthquake sequence, *Seismica* **3**, no. 1, doi: [10.26443/seismica.v3i1.1009](https://doi.org/10.26443/seismica.v3i1.1009).
- Baltay, A. S., T. C. Hanks, and N. A. Abrahamson (2017). Uncertainty, variability, and earthquake physics in ground-motion prediction equations, *Bull. Seismol. Soc. Am.* **107**, no. 4, 1754–1772.



- Baltay, A. S., T. C. Hanks, and N. A. Abrahamson (2019). Earthquake stress drop and arias intensity, *J. Geophys. Res.* **124**, no. 4, 3838–3852.
- Bates, D., M. Mächler, B. Bolker, and S. Walker (2015). Fitting linear mixed-effects models using lme4, *J. Stat. Softw.* **67**, no. 1, 1–48.
- Bertero, M., D. Bindi, P. Boccacci, M. Cattaneo, C. Eva, and V. Lanza (1997). Application of the projected Landweber method to the estimation of the source time function in seismology, *Inverse Prob.* **13**, no. 2, 465–486.
- Bindi, D., S. Parolai, H. Grosser, C. Milkereit, and E. Durukal (2007). Empirical ground-motion prediction equations for northwestern Turkey using the aftershocks of the 1999 Kocaeli earthquake, *Geophys. Res. Lett.* **34**, no. 8, doi: [10.1029/2007GL029222](https://doi.org/10.1029/2007GL029222).
- Bindi, D., M. Picozzi, D. Spallarossa, F. Cotton, and S. R. Kotha (2019). Impact of magnitude selection on aleatory variability associated with ground-motion prediction equations: Part II—analysis of the between-event distribution in Central Italy, *Bull. Seismol. Soc. Am.* **109**, no. 1, 251–262.
- Bindi, D., D. Spallarossa, M. Picozzi, and P. Morasca (2020). Reliability of source parameters for small events in Central Italy: Insights from spectral decomposition analysis applied to both synthetic and real data, *Bull. Seismol. Soc. Am.* **110**, no. 6, 3139–3157.
- Bindi, D., D. Spallarossa, M. Picozzi, A. Oth, P. Morasca, and K. Mayeda (2023a). The community stress-drop validation study—part I: Source, propagation, and site decomposition of Fourier spectra, *Seismol. Res. Lett.* **94**, no. 4, 1980–1991.
- Bindi, D., D. Spallarossa, M. Picozzi, A. Oth, P. Morasca, and K. Mayeda (2023b). The community stress-drop validation study—part II: Uncertainties of the source parameters and stress drop analysis, *Seismol. Res. Lett.* **94**, no. 4, 1992–2002.
- Bindi, D., D. Spallarossa, M. Picozzi, and G. Tarchini (2024). Supplements to “Scaling and depth variability of source parameters in central and southern Italy using regional attenuation models”, *Zenodo*, doi: [10.5281/zenodo.13313095](https://doi.org/10.5281/zenodo.13313095).
- Bindi, D., R. Zaccarelli, F. Cotton, G. Weatherill, and S. R. Kotha (2023). Source scaling and ground-motion variability along the East Anatolian Fault, *Seism. Record* **3**, no. 4, 311–321.
- Brune, J. N. (1970). Tectonic stress and the spectra of seismic shear waves from earthquakes, *J. Geophys. Res.* **75**, no. 26, 4997–5009.
- Brunelli, G., G. Lanzano, L. Luzi, and S. Sgobba (2023). Data-driven zonations for modelling the regional source and propagation effects into a Ground Motion Models in Italy, *Soil Dynam. Earthq. Eng.* **166**, 107775.
- Calderoni, G., and R. E. Abercrombie (2023). Investigating spectral estimates of stress drop for small to moderate earthquakes with heterogeneous slip distribution: Examples from the 2016–2017 Amatrice earthquake sequence, *J. Geophys. Res.* **128**, no. 6, e2022JB025022, doi: [10.1029/2022JB025022](https://doi.org/10.1029/2022JB025022).
- Calderoni, G., L. Improta, and R. GiovambattistaDi (2023). Investigating the role of fluids in the source parameters of the 2013–2014 Mw 5 Matese seismic sequence, Southern Italy, *Seismol. Res. Lett.* **95**, no. 1, 299–319.
- Castro, R. R., J. G. Anderson, and S. K. Singh (1990). Site response, attenuation and source spectra of S waves along the Guerrero, Mexico, subduction zone, *Bull. Seismol. Soc. Am.* **80**, no. 6A, 1481–1503.
- Castro, R. R., M. Mucciarelli, G. Monachesi, F. Pacor, and R. Berardi (1999). A review of nonparametric attenuation functions computed for different regions of Italy, *Ann. Geophys.* **42**, no. 4, doi: [10.4401/ag-3753](https://doi.org/10.4401/ag-3753).
- Chen, X., and R. E. Abercrombie (2020). Improved approach for stress drop estimation and its application to an induced earthquake sequence in Oklahoma, *Geophys. J. Int.* **223**, no. 1, 233–253.
- De Gori, P., F. Pio Lucente, and C. Chiarabba (2023). Source-parameter estimation after attenuation correction through the use of Q tomography, *Bull. Seismol. Soc. Am.* **113**, no. 4, 1739–1758.
- Di Bona, M. (2016). A local magnitude scale for crustal earthquakes in Italy, *Bull. Seismol. Soc. Am.* **106**, no. 1, 242–258.
- Di Giulio, G., A. Rovelli, F. Cara, R. M. Azzara, F. Marra, R. Basili, and A. Caserta (2003). Long-duration asynchronous ground motions in the Colfiorito plain, central Italy, observed on a two-dimensional dense array, *J. Geophys. Res.* **108**, no. B10, doi: [10.1029/2002JB002367](https://doi.org/10.1029/2002JB002367).
- Durand, V., S. Bentz, G. Kwiatek, G. Dresen, C. Wollin, O. Heidbach, P. Martinez-Garzón, F. Cotton, M. Nurlu, and M. Bohnhoff (2020). A two-scale preparation phase preceded an Mw 5.8 earthquake in the Sea of Marmara Offshore Istanbul, Turkey, *Seismol. Res. Lett.* **91**, no. 6, 3139–3147.
- Elzhov, T. V., K. M. Mullen, A.-N. Spiess, and B. Bolker (2023). minpack.lm: R interface to the Levenberg-Marquardt nonlinear least-squares algorithm found in MINPACK, plus support for bounds, *R package version 1.2-4*.
- Eshelby, J. D. (1957). The determination of the elastic field of an ellipsoidal inclusion, and related problems, *Proc. Math. Phys. Sci.* **241**, no. 1226, 376–396.
- Faccenna, C., T. W. Becker, L. Auer, A. Billi, L. Boschi, J. P. Brun, F. A. Capitanio, F. Funiciello, F. Horvath, L. Jolivet, et al. (2014). Mantle dynamics in the Mediterranean, *Rev. Geophys.* **52**, no. 3, 283–332.
- Gabrielli, S., A. Akinci, L. De Siena, E. PezzoDel, M. Buttinelli, F. E. Maesano, and R. Maffucci (2023). Scattering attenuation images of the control of thrusts and fluid overpressure on the 2016–2017 Central Italy seismic sequence, *Geophys. Res. Lett.* **50**, no. 8, e2023GL103132, doi: [10.1029/2023GL103132](https://doi.org/10.1029/2023GL103132).
- Goertz-Allmann, B. P., and B. Edwards (2013). Constraints on crustal attenuation and three-dimensional spatial distribution of stress drop in Switzerland, *Geophys. J. Int.* **196**, no. 1, 493–509.
- Hiemstra, P., E. Pebesma, C. Twenhöfel, and G. Heuvelink (2008). Real-time automatic interpolation of ambient gamma dose rates from the Dutch radioactivity monitoring network, *Comput. Geosci.* doi: [10.1016/j.cageo.2008.10.011](https://doi.org/10.1016/j.cageo.2008.10.011).
- Hough, S. E. (1997). Empirical Green’s function analysis: Taking the next step, *J. Geophys. Res.* **102**, no. B3, 5369–5384.
- Kemna, K. B., A. Verdecchia, and R. M. Harrington (2021). Spatio-temporal evolution of earthquake static stress drop values in the 2016–2017 Central Italy seismic sequence, *J. Geophys. Res.* **126**, no. 11, e2021JB022566, doi: [10.1029/2021JB022566](https://doi.org/10.1029/2021JB022566).
- Koenker, R. (2023). quantreg: Quantile regression, *R package version 5.97*.
- Koenker, R., and P. Ng (2021). SparseM: Sparse linear algebra, *R package version 1.81*.
- Konno, K., and T. Ohmachi (1998). Ground-motion characteristics estimated from spectral ratio between horizontal and vertical components of microtremor, *Bull. Seismol. Soc. Am.* **88**, no. 1, 228–241.
- Kotha, S. R., G. Weatherill, D. Bindi, and F. Cotton (2020). A regionally-adaptable ground-motion model for shallow crustal earthquakes in Europe, *Bull. Earthq. Eng.* **18**, 4091–4125.

- Latorre, D., R. Di Stefano, B. Castello, M. Michele, and L. Chiaraluce (2023). An updated view of the Italian seismicity from probabilistic location in 3D velocity models: The 1981–2018 Italian catalog of absolute earthquake locations (CLASS), *Tectonophysics* **846**, 229664.
- Lomax, A., J. Virieux, P. Volant, and C. Berge-Thierry (2000). *Probabilistic Earthquake Location in 3D and Layered Models*, C. H. Thurber and N. Rabinowitz (Editors), Springer Netherlands, Dordrecht, The Netherlands, 101–134.
- Lucente, S., T. Ninivaggi, S. de Lorenzo, E. Del Pezzo, M. Filippucci, G. Prosser, and A. Tallarico (2023). Q, Qc, Qi, Qs of the Gargano Promontory (Southern Italy), *J. Seismol.* **27**, 827–846.
- Mayeda, K., A. Hofstetter, J. L. O'Boyle, and W. R. Walter (2003). Stable and transportable regional magnitudes based on coda-derived moment-rate spectra, *Bull. Seismol. Soc. Am.* **93**, no. 1, 224–239.
- Menichelli, I., P. De Gori, F. P. Lucente, L. Improta, and C. Chiarabba (2023). Lithosphere structure, processes, and physical state of the Alpine-Apennine System, *J. Geophys. Res.* **128**, no. 4, e2023JB026411, doi: [10.1029/2023JB026411](https://doi.org/10.1029/2023JB026411).
- Morasca, P., D. Bindi, K. Mayeda, J. Roman-Nieves, J. Barno, W. R. Walter, and D. Spallarossa (2022). Source scaling comparison and validation in central Italy: Data intensive direct s waves versus the sparse data coda envelope methodology, *Geophys. J. Int.* **231**, 1573–1590.
- Mori, J., and A. Frankel (1990). Source parameters for small events associated with the 1986 North Palm Springs, California, earthquake determined using empirical Green functions, *Bull. Seismol. Soc. Am.* **80**, no. 2, 278–295.
- Nardoni, C., L. D. Siena, F. Cammarano, F. Magrini, and E. Mattei (2021). Modelling regional-scale attenuation across Italy and the Tyrrhenian Sea, *Phys. Earth Planet. In.* **318**, 106,764.
- Oth, A. (2013). On the characteristics of earthquake stress release variations in Japan, *Earth Planet. Sci. Lett.* **377**, 132–141.
- Oth, A., D. Bindi, S. Parolai, and D. Di Giacomo (2011). Spectral analysis of K-NET and KiK-net Data in Japan, Part II: On attenuation characteristics, source spectra, and site response of borehole and surface stations, *Bull. Seismol. Soc. Am.* **101**, no. 2, 667–687.
- Oth, A., H. Miyake, and D. Bindi (2017). On the relation of earthquake stress drop and ground motion variability, *J. Geophys. Res.* **122**, no. 7, 5474–5492.
- Pacor, F., D. Spallarossa, A. Oth, L. Luzi, R. Puglia, L. Cantore, A. Mercuri, M. D'Amico, and D. Bindi (2015). Spectral models for ground motion prediction in the L'Aquila region (central Italy): evidence for stress-drop dependence on magnitude and depth, *Geophys. J. Int.* **204**, no. 2, 697–718.
- Pebesma, E. J., and R. Bivand (2005). Classes and methods for spatial data in R, *R News* **5**, no. 2, 9–13.
- Piccinini, D., M. Di Bona, F. P. Lucente, V. Levin, and J. Park (2010). Seismic attenuation and mantle wedge temperature in the northern Apennines subduction zone (Italy) from teleseismic body wave spectra, *J. Geophys. Res.* **115**, no. B9, doi: [10.1029/2009JB007180](https://doi.org/10.1029/2009JB007180).
- Picozzi, M., D. Bindi, G. Festa, F. Cotton, A. Scala, and N. D'Agostino (2021). Spatiotemporal evolution of microseismicity seismic source properties at the Irpinia near-fault observatory, Southern Italy, *Bull. Seismol. Soc. Am.* **112**, no. 1, 226–242.
- Picozzi, M., A. G. Iaccarino, D. Spallarossa, and D. Bindi (2023). On catching the preparatory phase of damaging earthquakes: An example from central Italy, *Sci. Rep.* **13**, doi: [10.1038/s41598-023-41625-0](https://doi.org/10.1038/s41598-023-41625-0).
- Picozzi, M., D. Spallarossa, A. G. Iaccarino, and D. Bindi (2022). Temporal evolution of radiated energy to seismic moment scaling during the preparatory phase of the Mw 6.1, 2009 L'Aquila Earthquake (Italy), *Geophys. Res. Lett.* **49**, no. 8, e2021GL097382, doi: [10.1029/2021GL097382](https://doi.org/10.1029/2021GL097382).
- Pisconti, A., E. Del Pezzo, F. Bianco, and S. de Lorenzo (2015). Seismic Q estimates in Umbria Marche (Central Italy): Hints for the retrieval of a new attenuation law for seismic risk, *Geophys. J. Int.* **201**, no. 3, 1370–1382.
- R Core Team (2020). *R: A Language and Environment for Statistical Computing*, R Foundation for Statistical Computing, Vienna, Austria.
- Scafidi, D., D. Spallarossa, G. Ferretti, S. Barani, B. Castello, and L. Margheriti (2019). A complete automatic procedure to compile reliable seismic catalogs and travel-time and strong-motion parameters datasets, *Seismol. Res. Lett.* **90**, no. 3, 1308–1317.
- Shearer, P. M., R. E. Abercrombie, and D. T. Trugman (2022). Improved stress drop estimates for m 1.5 to 4 earthquakes in Southern California from 1996 to 2019, *J. Geophys. Res.* **127**, no. 7, e2022JB024243, doi: [10.1029/2022JB024243](https://doi.org/10.1029/2022JB024243).
- Shearer, P. M., R. E. Abercrombie, D. T. Trugman, and W. Wang (2019). Comparing EGF methods for estimating corner frequency and stress drop from P wave spectra, *J. Geophys. Res.* **124**, no. 4, 3966–3986.
- Spallarossa, D., M. Picozzi, D. Scafidi, P. Morasca, C. Turino, and D. Bindi (2021). The RAMONES service for rapid assessment of seismic moment and radiated energy in Central Italy: Concepts, capabilities, and future perspectives, *Seismol. Res. Lett.* **92**, no. 3, 1759–1772.
- Talone, D., L. De Siena, G. Lavecchia, and R. de Nardis (2023). The attenuation and scattering signature of fluid reservoirs and tectonic interactions in the Central-Southern Apennines (Italy), *Geophys. Res. Lett.* **50**, no. 22, e2023GL106074, doi: [10.1029/2023GL106074](https://doi.org/10.1029/2023GL106074).
- Trugman, D. T., and P. M. Shearer (2017). Application of an improved spectral decomposition method to examine earthquake source scaling in Southern California, *J. Geophys. Res.* **122**, no. 4, 2890–2910.
- Wang, H., Y. Ren, R. Wen, and P. Xu (2019). Breakdown of earthquake self-similar scaling and source rupture directivity in the 2016–2017 Central Italy seismic sequence, *J. Geophys. Res.* **124**, no. 4, 3898–3917.
- Wessel, P., J. F. Luis, L. Uieda, R. Scharroo, F. Wobbe, W. H. F. Smith, and D. Tian (2019). The generic mapping tools version 6, *Geochem. Geophys. Geosys.* **20**, no. 11, 5556–5564.

Manuscript received 17 June 2024

Published online 29 October 2024

# Scaling and depth variability of source parameters in central and southern Italy using regional attenuation models

Dino Bindi<sup>1</sup>, Daniele Spallarossa<sup>2</sup>, Matteo Picozzi<sup>3</sup>, and  
Gabriele Tarchini<sup>2</sup>

<sup>1</sup>German Research Centre for Geoscience GFZ, Potsdam,  
Germany

<sup>2</sup>University of Genova, Department for Earth, Environment  
and Life Sciences DISTAV, Genova, Italy

<sup>3</sup>National Institute of Oceanography and Applied Geophysics  
OGS, Trieste, Italy

August 14, 2024

The supplemental material includes 8 Figures:

- Figure S1: Empirical Cumulative Density Functions (ECDF) of the horizontal (red) and vertical (black) statistical location errors (Erh and Erz, respectively) as estimated by the NLLoc software (Lomax et. al, 2000).
- Figure S2: ECDF of the total number of phases used for the locations with NLLoc.
- Figure S3 ECDF of the source to station primary azimuthal gap for each polygon.
- Figure S4 ECDF of the root mean square of the phase residuals (RMS) associated with NLLoc locations.



- Figure S5 shows the magnitude versus distance scatterplot for 2.5 Hz, representing the data distribution available for each polygon of Figure 1;
- Figure S6 shows the variability of the number of stations, events and records considered for the spectral decomposition at different frequencies normalized to the 3.0 Hz values.
- Figure S7 shows the source to station path coverage for each polygon of Figure 1, used to calibrate the spectral attenuation models for each sub-region (the maximum hypocentral distance is 120 km).
- Figure S8 shows the source to station path coverage for each polygon of Figure 1, used to separate the source and site terms (the maximum hypocentral distance is limited to 60 km).

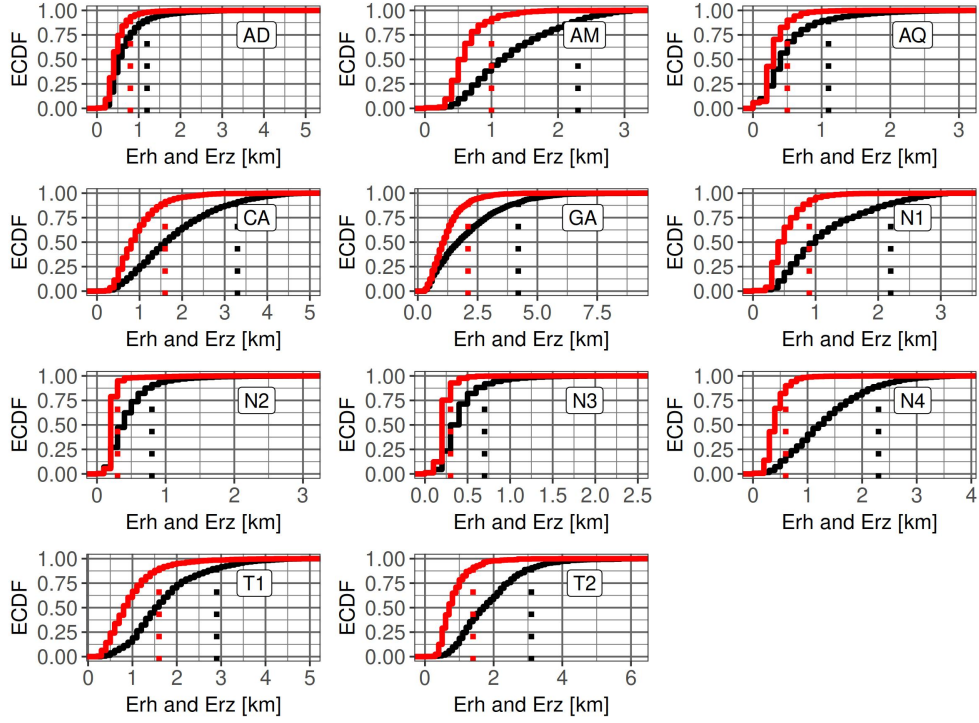


Figure S1: Empirical Cumulative Density Functions (ECDF) of the horizontal (red) and vertical (black) statistical location errors (Erh and Erz, respectively) as estimated by the NLLoc software (Lomax et. al, 2000). The red and black dotted lines indicate the 90th percentiles of the distribution. Each panel shows the ECDF for one polygon of the segmentation in Figure 1.

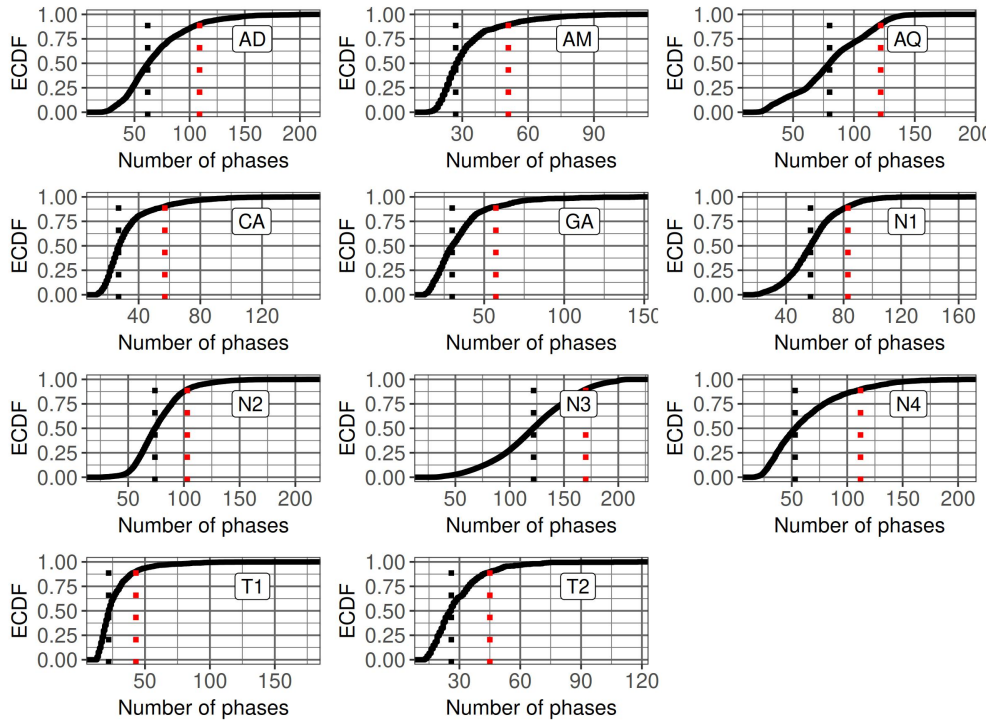


Figure S2: ECDF of the total number of phases used for the locations with NLLoc. Black and red dotted lines indicate the 50th and the 90th percentiles of the distribution, respectively.

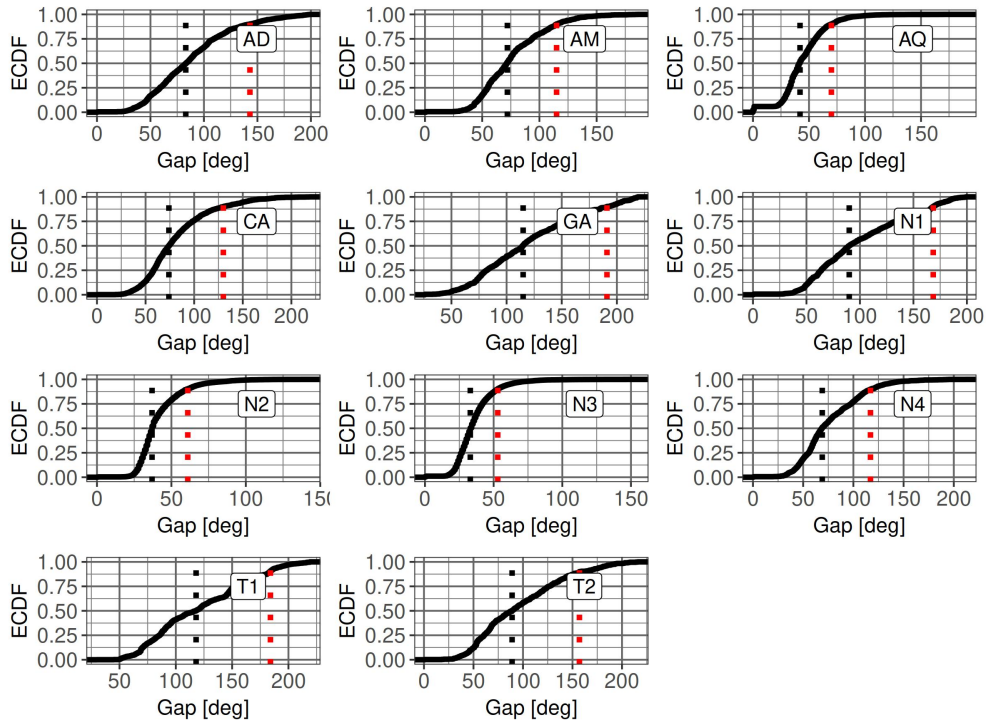


Figure S3: ECDF of the source to station primary azimuthal gap for each polygon. Black and red dotted lines indicate the 50th and the 90th percentiles of the distribution, respectively.



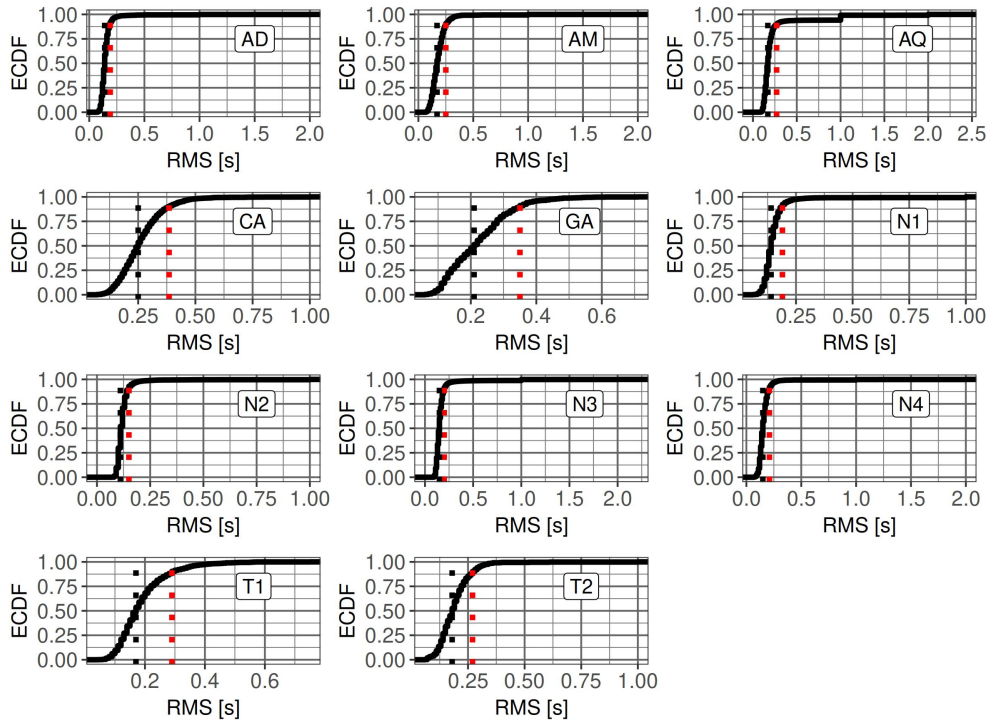


Figure S4: ECDF of the root mean square of the phase residuals associated with NLLoc locations. Black and red dotted lines indicate the 50th and the 90th percentiles of the distribution, respectively.

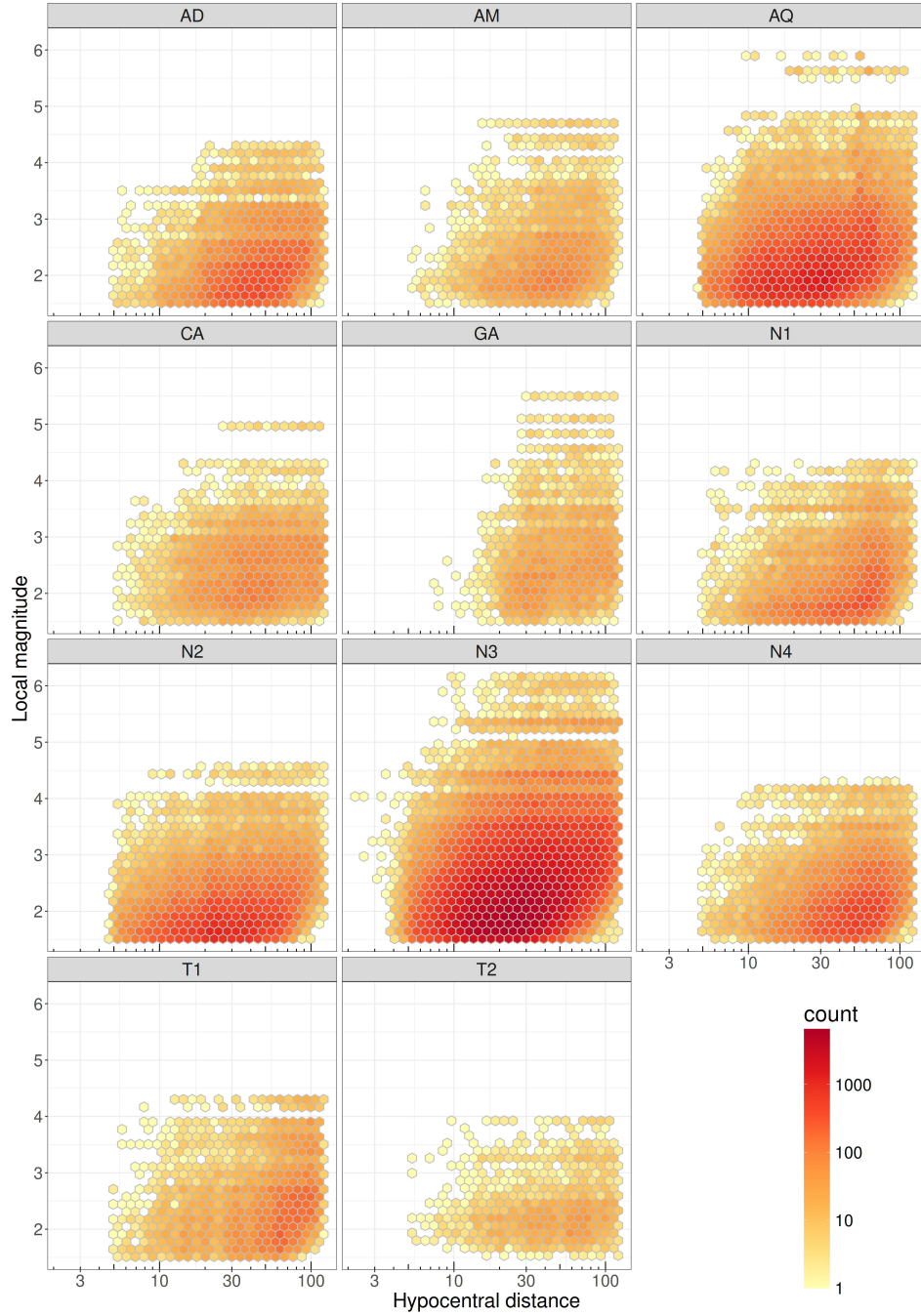


Figure S5: Number of spectral amplitudes as a function of local magnitude and hypocentral distance, representing the data distribution available to perform the spectral decomposition at 3.0 Hz for each polygon in Figure 1.

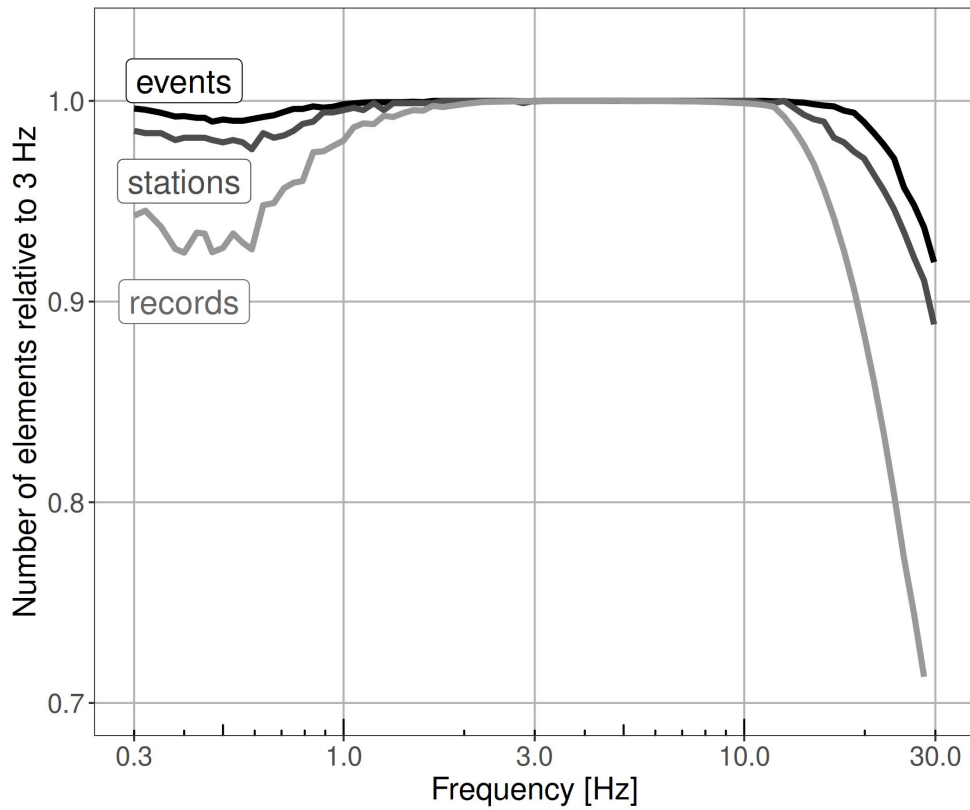


Figure S6: Variability of the number of stations, events and records considered for the spectral decomposition at different frequencies normalized to the 3.0 Hz values. At 3.0 Hz, the numbers are: 27817 earthquakes, 901 stations, 901228 spectral amplitudes.

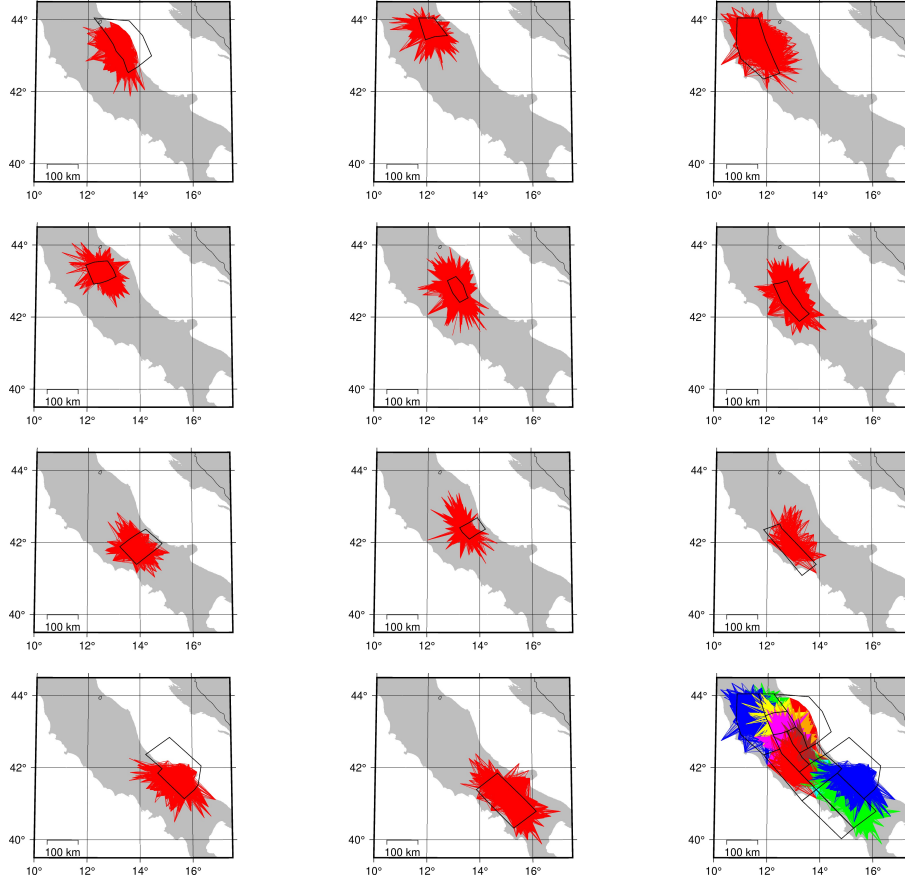


Figure S7: Source to station path coverage for each polygon of Figure 1, used to calibrate the spectral attenuation models for each sub-region (the maximum hypocentral distance is 120 km).



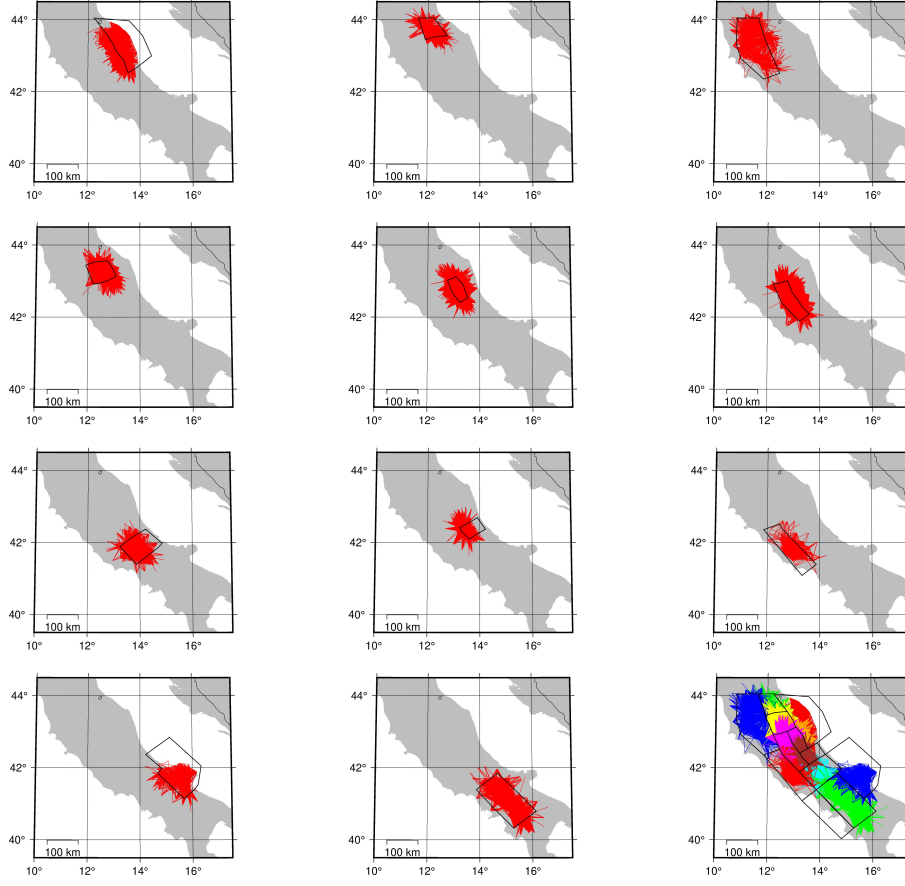


Figure S8: Source to station path coverage for each polygon of Figure 1, used to separate the source and site terms (the maximum hypocentral distance is limited to 60 km).