DOI 10.4430/bgo00425

Spatial variability of non-ergodic GMM residuals related to source and path effects in Italy

G. Brunelli[1,2], G. Lanzano[1], S. Sgobba[1] and L. Luzi[1]

[1] *Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Milano, Milano, Italy*
[2] *Scuola di Scienze e Tecnologie-Geologia, Università di Camerino, Camerino, Italy*

(Received: 20 December 2022; accepted: 16 May 2023; published online: 27 July 2023)

ABSTRACT In this study, we exploit the advantages of non-ergodic modelling of the ground motion to map the regional characteristics of source and propagation effects in Italy. In particular, we focused on the study of source and propagation effects obtained from the decomposition of the total residuals, i.e. the logarithmic difference of ITACAext observations and the model predictions, for active crustal earthquakes in Italy. The spatial trends, obtained from interpolating the residuals, clearly showed areas where the motion was significantly different from that predicted by the reference model, and in particular was underestimated. This is the case, for example, for many events with epicentres in northern Italy and the southern Ionian Sea. In addition, the study shows that paths across the Po Valley and the Adriatic coast are characterised by slower attenuation compared to that observed in the central Apennines. In addition, a marked difference between attenuation in the volcanic domain of Etna and the Hyblaean Mountains is clearly observed.

Key words: ground motions, residual analysis, propagation effects, source effects.

1. Introduction

One of the most relevant topics in engineering seismology of recent years is the possibility of regionalising the ground motion models (GMMs), i.e. the equations used to predict the median amplitude (and the associated standard deviation) of the ground motion parameters, relevant for engineering applications, such as the assessment of seismic hazard (probabilistic or deterministic) and the generation of shaking scenarios.

In common practice, GMMs are calibrated over ground motion data sets of recordings and, generally, most of the data are related to one or more earthquake sequences, which sometimes occurred in the same small region. This is the case of Italy, where the available data sets, at the national scale (see Lanzano *et al*., 2019b; Brunelli *et al*., 2022), are predominantly comprised of the observations of central Italy related to the 2009 M_w 6.3 L'Aquila and 2016-2017 M_w 6.0 and 6.5 central Italy seismic sequences. These GMMs are, then, also applied at country scale under the ergodic assumption (Anderson and Brune, 1999).

As a consequence, GMM predictions are affected by considerable variability and are used with the same degree of confidence in areas less represented by the observations.

Given the increasing availability of data from the installation of new seismic networks throughout the world, the trend today is to relax the ergodic assumption in favour of regional models. This approach involves not only reducing the uncertainties associated with the estimates and, thus, improving the model accuracy, but also contributes to understanding seismogenic processes at a regional scale.

Fully non-ergodic models have been proposed in recent years in high seismic hazard countries, such as California and Italy, and include non-ergodic terms to simultaneously capture systematic effects related to source, path, and site; these types of models have up to 70% smaller aleatory variance than ergodic models (Landwehr *et al*., 2016; Abrahamson *et al*., 2019; Kuehn *et al*., 2019; Lavrentiadis *et al*., 2022).

From this perspective, non-ergodic models are also more physically-based. Examples of studies, using non-ergodic residual analyses to capture and investigate regional peculiarities of motion, were provided by Baltay *et al*. (2017), Sahakian *et al*. (2019), Sgobba *et al*. (2021), Parker and Baltay (2022), and Morasca *et al*. (2023).

The purpose of this work is to investigate the regional characteristics of source and propagation contributions to prepare the field for the development of a regionalised non-ergodic GMM for engineering purposes. The adopted methodology to estimate these contributions is based on the residual decomposition technique (Al Atik *et al*., 2010), aimed at identifying the systematic terms of event and path. All these random effects act as adjustment terms of the median prediction, while moving part of the aleatory variability into epistemic uncertainty (Anderson and Brune, 1999; Al Atik *et al*., 2010; Anderson and Uchiyama, 2011).

These systematic terms of uncertainty are spatially interpolated and correlated to physics-based parameters. The findings will serve to improve the model accuracy for probabilistic seismic hazard analysis (PSHA) purposes or site-specific hazard studies, and the state of knowledge on seismogenic processes in Italy with the goal of better reproducing empirical earthquake scenarios and ShakeMaps (Worden *et al*., 2018; Michelini *et al*., 2020).

2. Ground motion data set

For the analysis, we used the ITACAext data set (Brunelli *et al*., 2022), available on the web portal of the version 3.2 of the ITACA accelerometric database [ITalian ACcelerometric Archive: http://itaca.mi.ingv.it/ItacaNet_32/#/home; see Russo *et al*. (2022)]. ITACAext includes earthquakes of $M \geq 3.0$ that occurred during the 1972-2020 period. In case of magnitudes lower than 4.0 and areas with few events, the accelerometric records are integrated with velocimetric records, excluding those affected by instrument saturation. If accelerometers and velocimeters are co-located, the velocimetric record is selected, because of the better resolution of the weak motion instrument. Consistently with the accelerometric records, the velocimetric ones were manually processed by applying the standard ITACA scheme, described in Paolucci *et al*. (2011). The parametric table of the ITACAext records, collecting event and station metadata, along with ground motion intensity measures (IMs), is formatted consistently with the Engineering Strong-Motion (ESM) flat-file (Lanzano *et al*., 2019a) and made available at the URL http://itaca.mi.ingv.it/ItacaNet_32/#/products/itacaext_flatfile.

We further extract records of active shallow (focal depth lower than 35 km) crustal earthquakes by means of sensors installed at ground level and in free-field conditions. The maximum epicentral distance, used for the analysis, is set at 220 km. The final subset for the analyses consists of 37,098 records of 1,863 earthquakes, recorded by 1,922 recording stations. Fig. 1a shows the distribution of the events as a function of the event magnitude, highlighting, as expected, that the majority of the data refers to small-magnitude events, with a non-negligible amount (about 4.5%) related to large-magnitude events ($M > 5$) of engineering relevance. Fig. 1b shows the magnitude-distance scatter plot of the data set, also to confirm that the short distance ($R < 20$ km) records are relatively few (6,055 vs. 37,098 corresponding to 16.3%).

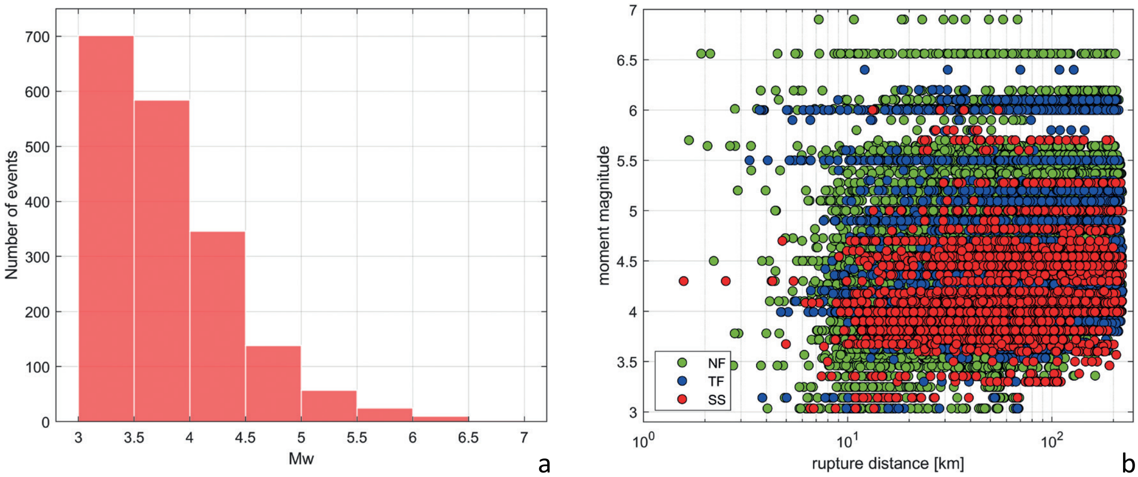

Fig. 1 - Number of events-magnitude distribution (a) and magnitude-distance distribution (b), coloured as a function of the type of faulting (NF: normal fault; TF: thrust fault; SS: strike-slip).

Since the aim of this work is to investigate the relationship between the residuals of a reference Italian GMM with physical source and propagation parameters, one aspect considered in the

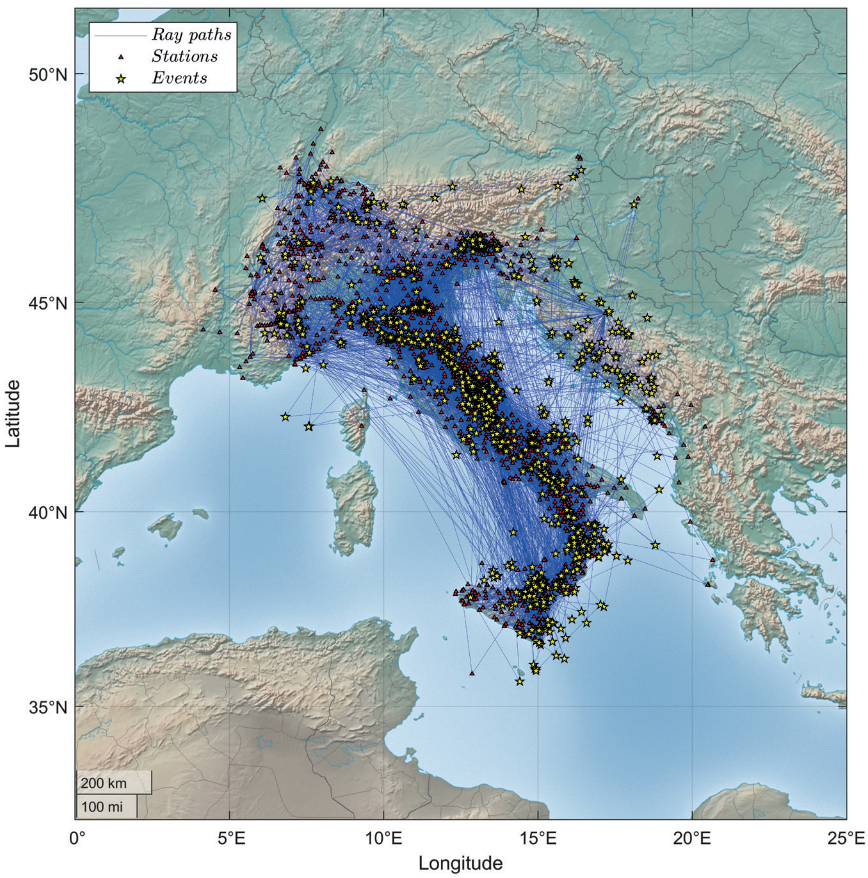

Fig. 2 - Source-to-station paths for the subset of ITACAext, used in this analysis.

choice of the data set is an adequate sampling of the source-to-site paths across the country. These paths are shown in the map in Fig. 2. The spatial coverage is dense and homogeneous over almost the entire national territory, except for eastern Apulia and Sardinia. Most of the seismic events occurred in the northern and central Apennines, while areas such as the northern Lombardy-Piedmont border, Salento, and western Sicily are less sampled.

3. Methods

The analysis is based on residual computation, i.e. the difference between the common logarithm of the observed ground motion parameter, $\log_{10}(Y_{obs})$, and the corresponding prediction, $\log_{10}(Y_{pred})$, from the GMM ITA18 (Lanzano *et al*., 2019b), in rupture-distance metric. Since ITA18 uses the moment magnitude provided by the RCMT [Regional Centroid Moment Tensor: Pondrelli *et al*. (2002)] method as explanatory variable, we harmonise the different estimates provided in ITACAext (moment magnitude by Time Domain Moment Tensor and local magnitude). To this purpose, we apply the empirical conversion equation proposed by Brunelli *et al*. (2023).

The method is based on a statistical decomposition of ITA18 residuals (*Res*), which are broken down into repeatable terms referring to event and station, following the notation of Al Atik *et al*. (2010), as:

$$Res = \delta B_e | event + \delta S2S_s | site + \delta W_{es} \tag{1}$$

where:

- δB_e (between-event residual) is the systematic deviation between prediction and observation for a specific event, *e*, i.e. the median of the residuals for single events;
- $\delta S2S_s$ (site-to-site residual) is the average station error that can be related to the systematic effect of the site response at the station, *s,* that is not captured by the model;
- δW_{es} (event- and site- corrected residual) is the leftover (aleatory) residual and should include all the effects not explained by the model fixed dependencies and random effects, such as regional propagation features.

The random-effect method is applied to derive the systematic terms (Stafford, 2014; Bates *et al*., 2015), which became standard practice for the derivation of non-ergodic models.

In the following, we investigate the spatial trend of between-event residuals, δB_e, to study the characteristics of the seismic sources. Indeed, several authors (Bindi *et al*., 2018; Bindi and Kotha, 2020) showed that δB_e is correlated with source regional characteristics not captured by the standard magnitude scaling in GMMs, such as the stress drop.

In order to investigate the regional differences in terms of wave propagation, we start from the distance term proposed by the ITA18 model [Eq. 4 in Lanzano *et al.* (2019b)] to estimate an empirical term (δc_3) that represents the correction of the anelastic attenuation coefficient c_3, defined as follows:

$$\delta c_3 = \frac{\delta W_{es}}{\sqrt{R_{rup}^2 + h^2}} \tag{2}$$

where R_{rup} is the distance of each record from the fault, and h is the pseudo-depth of the ITA18 model for this distance metric. This approach is similar to the one adopted by Kotha *et al*. (2020)

to calibrate the regionalised European GMM, which explains the differences of the propagation media as variations in the anelastic attenuation coefficient of the model.

In the following, we analyse the regional variability of ground motion by mapping the spatial distribution of the residual terms in order to identify spatial patterns with the associated variability across different regions. The residuals are averaged over two period intervals, T = 0.07-0.4 s and T = 0.7-4.0 s, to examine spatial trends at short and long periods, respectively. These two period ranges were chosen as they are of engineering interest for different types of structural elements resonating at high (14-25 Hz) and low (1.4-0.25 Hz) frequencies, as also prescribed for seismic design in the latest proposal of European technical regulations (Paolucci *et al.*, 2021).

4. Analysis of regional features

4.1. Source effects

To empirically map the source effects, between-event residuals δB_e of ITA18 are spatially interpolated using the Empirical Bayesian Kriging [EBK: Gribov and Krivoruchko (2020)], which is one of the kriging algorithms implemented in ArcMap® (ESRI, 2016). EBK adopts an exponential type semivariogram, and the parameters are estimated using the REstricted Maximum Likelihood (REML). Fig. 3 shows maps of δB_e mean values in the two periods: the red-graded areas indicate positive residuals, i.e. where the observed value is higher than the predicted one, whereas the green-graded areas represent the zones where the opposite occurs.

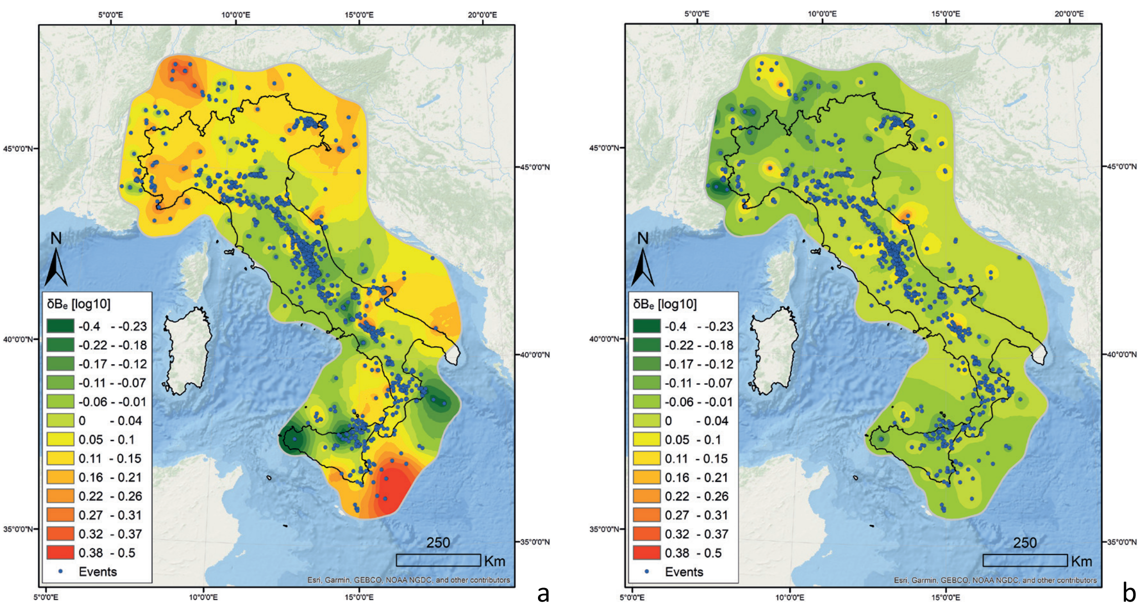

Fig. 3 - Interpolated maps of δB_e ($\log_{10}$) at: a) short periods (T = 0.07-0.4 s) and b) long periods (T = 0.7-4.0 s).

The highest values of δB_e are observed (see Fig. 4 for toponyms) in the Alpine arc (northern Italy), particularly in the western Alps and External Dinarides, as well as in southern Italy, in correspondence of the Apulian platform, the southern Ionian Sea and the Hyblaean plateau

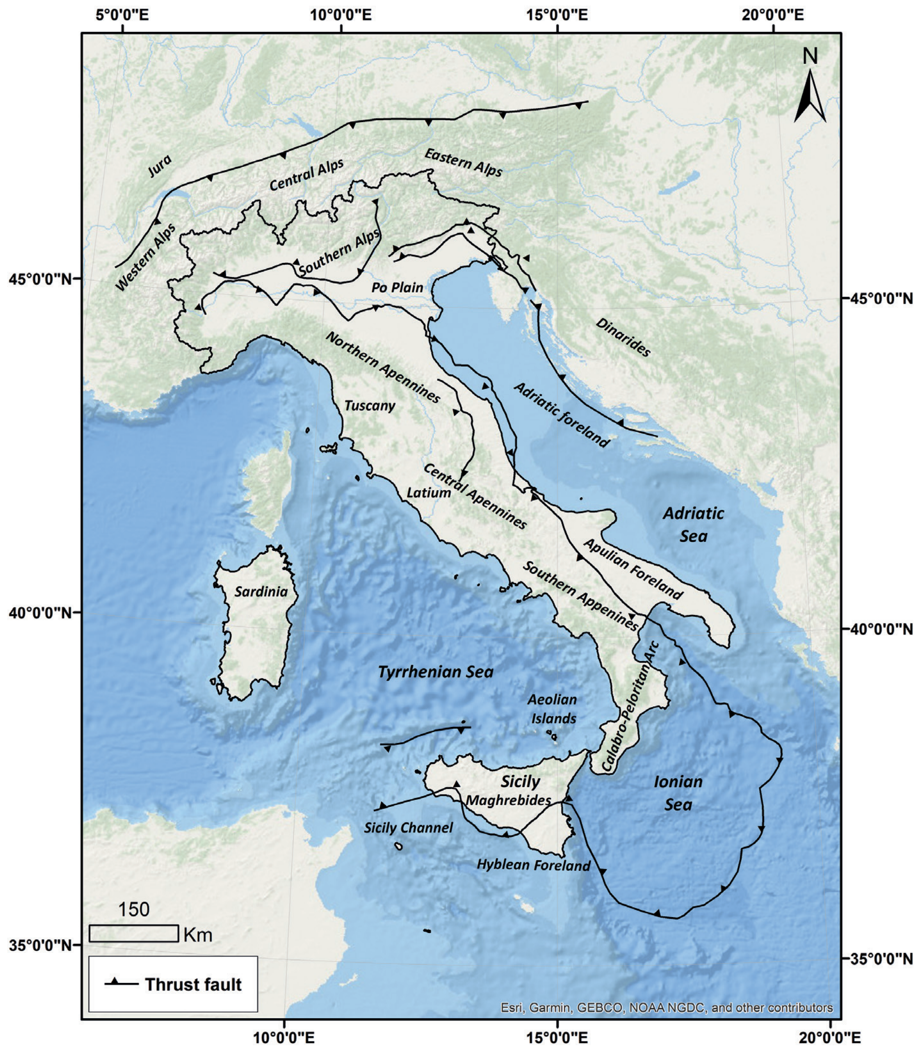

Fig. 4 - Main tectonic domains of Italy (modified after C.N.R. - P.F. Geodinamica, 1991; Palano, 2015).

(south-eastern Sicily). The lowest values are observed in northern Sicily and the northern Ionian Sea. Finally, along the Apennines, the between-event values are close to zero or slightly negative. When we observe long periods, all the considerations are significantly relaxed and the deviations from the reference model are much smaller, which means that the GMM describes the seismic motion quite well at the long periods over the whole Italian territory.

Such local anomalies of residuals δB_e across space are attributable to deviations of the seismic source characteristics from the median trend predicted by the GMM, which typically depend on stress drop variations (Bindi *et al*., 2017, 2018, 2019; Morasca *et al*., 2023). Hence, we compare our δB_e estimates with the Brune stress drop ($\Delta\sigma$) values provided by Morasca *et al*. (2022), for central Italy. The $\Delta\sigma$ estimates were derived from the modelling of the outcomes of a non-parametric inversion, obtained with the GIT [Generalised Inversion Technique: Oth *et al*. (2011)], for about 400 earthquakes in the 2008-2018 time interval and with local magnitude larger than 3.2 (Spallarossa *et al*., 2022; Morasca *et al*., 2023). The stress drop estimates are available for 269 earthquakes out of the 1,863 of the ITACAext data set, and are plotted in Fig. 5 against δB_e at short and long periods.

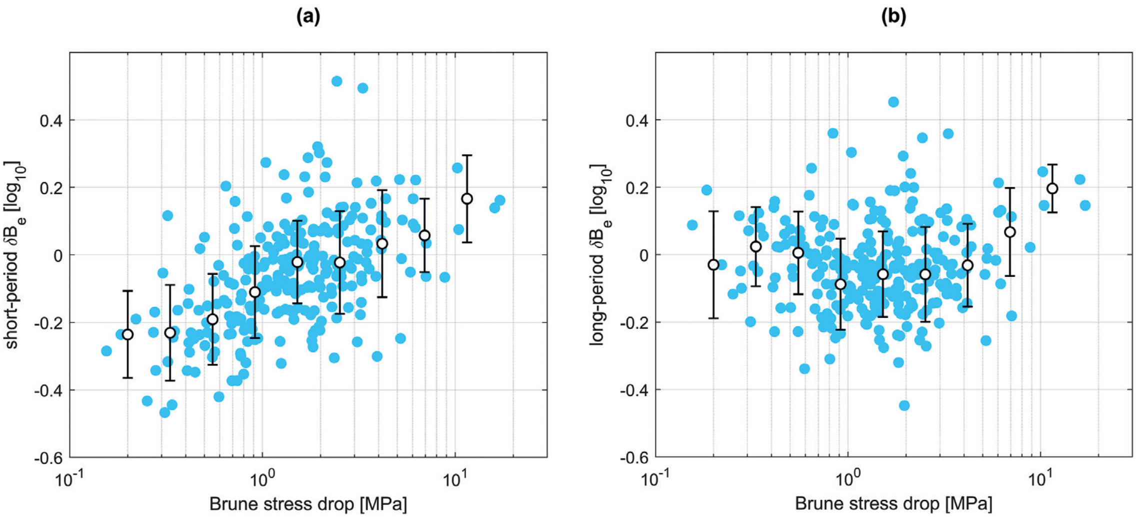

Fig. 5 - Brune stress drop values (Morasca *et al.*, 2022) vs. between-event residuals at: a) short and b) long periods.

As observed by several authors (Baltay *et al*., 2017; Bindi *et al*., 2017; Morasca *et al*., 2023; etc.), $\Delta\sigma$ is found to be closely correlated with event residuals at short periods: this finding is apparent since the GMM adopts moment magnitude as an explanatory variable, instead of local magnitude, which is stress-drop dependent (Bindi *et al*., 2019). At long periods, the correlation is weak, as expected and already observed (Bindi *et al*., 2019; Morasca *et al*., 2022). Assuming the Brune model for the source, the stress drop controls, for a given seismic moment, the amount of energy radiated by the source at high frequencies in the Fourier domain (see Anderson, 1997; Baltay *et al*., 2017). At low frequencies, most of the frequencies lie below the corner frequency for most events (small events with higher corner frequency), so the effect of a regional variation in the median stress drop is not visible.

In addition, we investigate the δB_e dependencies on the event parameter, not explicitly introduced as explanatory variables in the ground motion modelling, such as the event depth. In Fig. 6, we provide the comparison between short-period δB_e estimates and focal depths, mainly

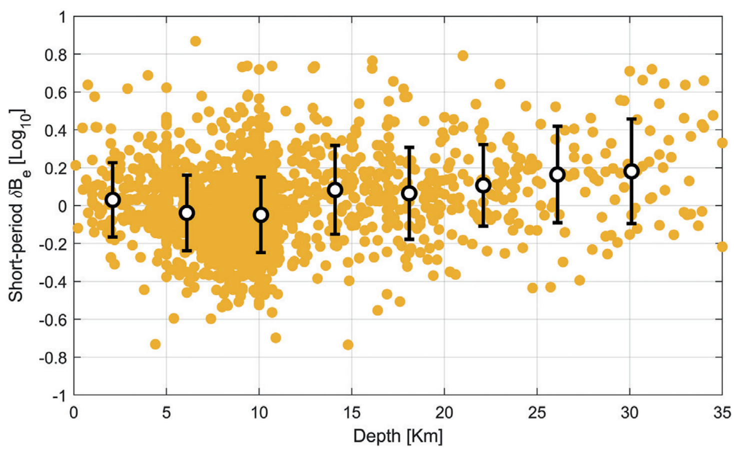

Fig. 6 - Short-period δB_e vs. focal depth.

provided by the INGV bulletin: a weak positive correlation is observed at short periods, as also expected, since stress drop and focal depth are not independent parameters (Abercrombie *et al.*, 2021). However, the trend is characterised by a large scatter, mainly because the estimation of earthquake depth could be affected by a large uncertainty especially if a few or no stations in the epicentral area are used for event localisation.

However, we assume that the non-ergodic source terms reflect the regional changes in the median stress drop, but it is mainly relative to small-magnitude events that dominate the data set. Considering the regional scaling laws between magnitude and stress drop, the question is: do higher, or lower than the median, between-events, for small-magnitude events, imply a similar regional change for large-magnitude events? In order to address this issue, we evaluate how short-period δB_e is representative of a magnitude range that includes both small and large earthquakes. To this end, we selected 4 zones on the basis of the source zonation proposed by Brunelli *et al.* (2023), in which major earthquake sequences had occurred, so that the observations covered a sufficiently wide range of magnitude. The selected zones are (Fig. 7):

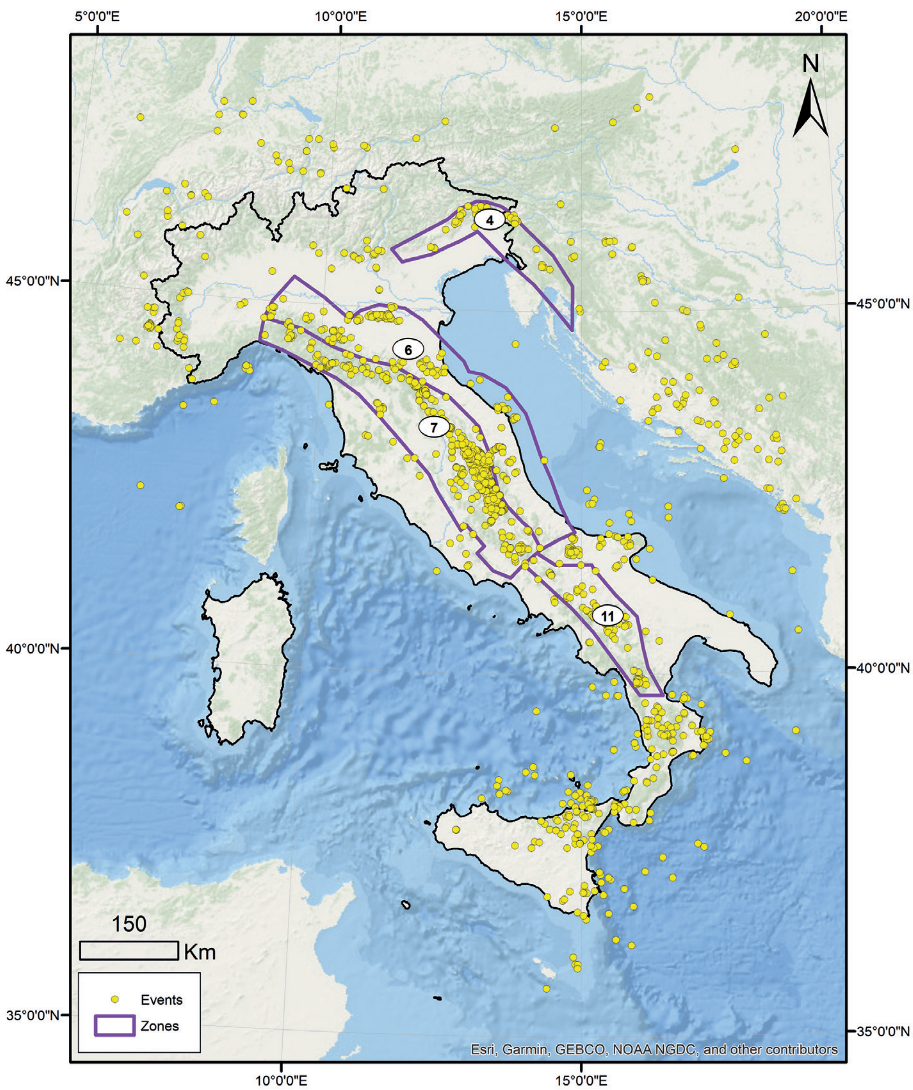

Fig. 7 - Zones selected from the source zonation by Brunelli *et al.* (2023) to analyse the values of δB_e for the seismic sequences.

zone #4 enclosing the Friuli sequence (1976-1977 M_w 6.4 reverse fault mechanism), zone #6 with the Po Valley sequence (2012 M_w 6.0 and 6.1 reverse fault mechanism), zone #7 corresponding to the central Apennines in which at least 3 significant sequences occurred (1997-1998 Umbria-Marche, 2009 L'Aquila, and 2016-2017 Amatrice-Norcia, all normal faulting events), and finally zone #11 enclosing the Irpinia sequence (1980 M_w 6.9, normal fault mechanism).

Fig. 8 shows the δB_e values for each individual event in the zone (grey circles), the median values (and associated uncertainty) calculated per magnitude bin (black line), and the median calculated over all data (red line).

For zones #4 and #6, although a weak positive correlation with magnitude is observed, median δB_e at the short periods computed over all data represents the entire data population fairly well, and the fluctuations in the binned values are all within the range of the standard deviation.

In the case of zone #7, there is a clear dependence on magnitude and a positive correlation with δB_e. This trend, also thanks to the large amount of data available, has already been observed

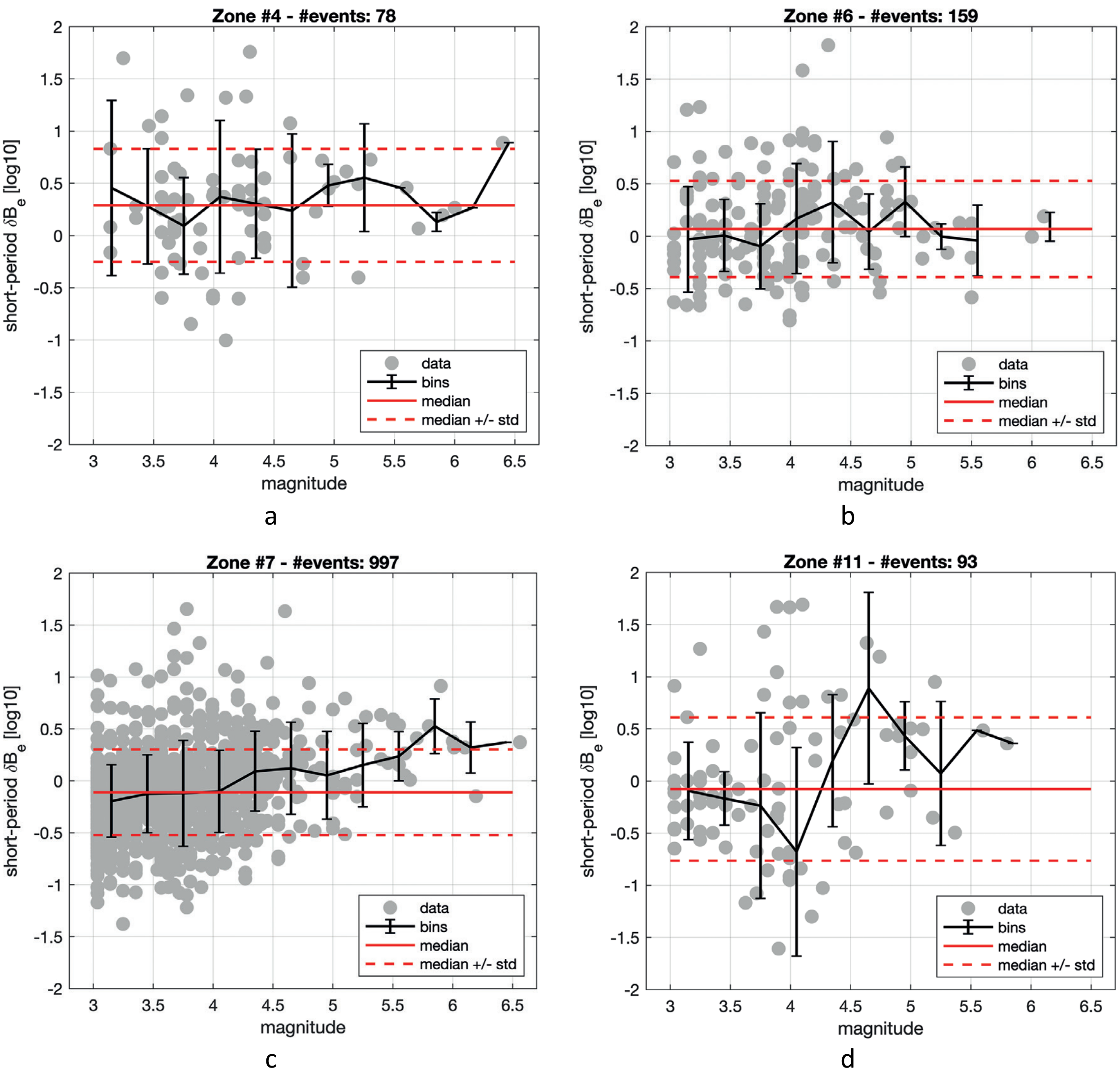

Fig. 8 - Short-period δB_e vs. moment magnitude for different source zones: a) zone #4, b) zone #5, c) zone #7, d) zone #11.

in literature, such as in the work of Bindi *et al*. (2018) or Morasca *et al*. (2023). In this case, median δB_e, calculated over all data, is representative mainly of small magnitude events (between 3.5 and 4). In the case of zone #11, the trend is considerably scattered, due to the poor quality of the few recordings of the Irpinia sequence, yet shows a trend more similar to zone #7.

4.2. Propagation effects

In order to investigate the spatial distribution of δc_3, we must keep in mind that the characteristics of seismic wave propagation are a function of the mutual position of event and station. In this study (see also Brunelli *et al*., 2023), we assign δc_3 to the midpoint along the event-to-station path, as representative of the area affected by the wave propagation. In particular, the origin of the event corresponds to the nucleation point, if the source geometry is known, and to the hypocentre coordinates, otherwise. In order to explore the regional variability of δc_3, we only consider the recordings with source-to-site distances above 80 km, because the effects of the anelastic attenuations become relevant for long event-station distances (Sedaghati and Pezeshk, 2017). The δc_3 values are spatially interpolated with the same approach of δB_e, and the results, for short and long period ranges, respectively, are shown in Fig. 9.

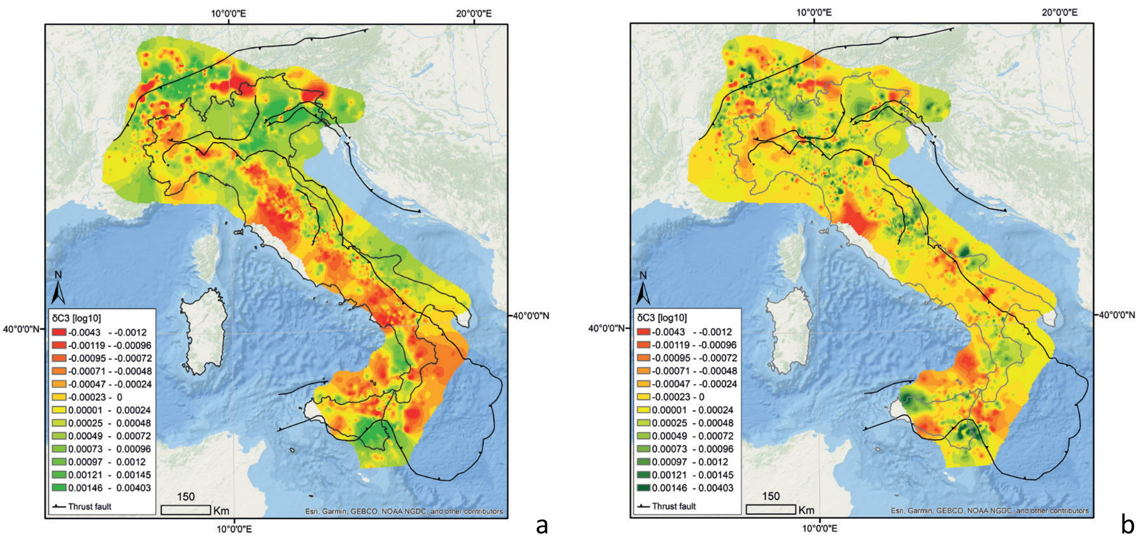

Fig. 9 - δc_3 of Eq. 2 with R_{rup} > 80 km: a) short and b) long period intervals.

Positive values, marked with green areas, indicate a slower attenuation compared to the reference model, while areas in red indicate faster attenuation. At short periods, the most relevant feature is the clear distinction of attenuation between the Adriatic (slow) and Tyrrhenian (fast) sides along the entire Apennine arc, also clearly observed by Kotha *et al*. (2020) in the ground motion model of Europe. Concerning the Alps, we observe a variation in attenuation between the east (slow) and west (fast) sides of the arc. In Sicily, the Hyblaean foreland (south-western Sicily) is clearly characterised by a slower attenuation with respect to the rest of the island. Positive values of δc_3, also observed in the Po Valley, are probably related to refraction on the Moho surface, and cause the enhancement of high-frequency spectral amplitude at distances larger than 80 km (Bragato *et al*., 2011; Lanzano *et al*., 2016). At long periods, the contribution of the anelastic attenuation to the distance scaling becomes almost negligible, also due to the fact that, in the reference GMM, the value of c_3 is null for a $T > 0.7$ s period.

In order to physically interpret our findings, we took under consideration the geothermal properties of Italy, such as the heat flow map at national scale, modified after Della Vedova *et al*. (1991) (see Fig. 10a). The crustal temperature was also considered: the one by Weatherill and Cotton (2020) at a larger European scale, to regionalise the stable cratonic regions, and the one by Kotha *et al*. (2022) to explain the regional differences of δc_3 obtained from a European-

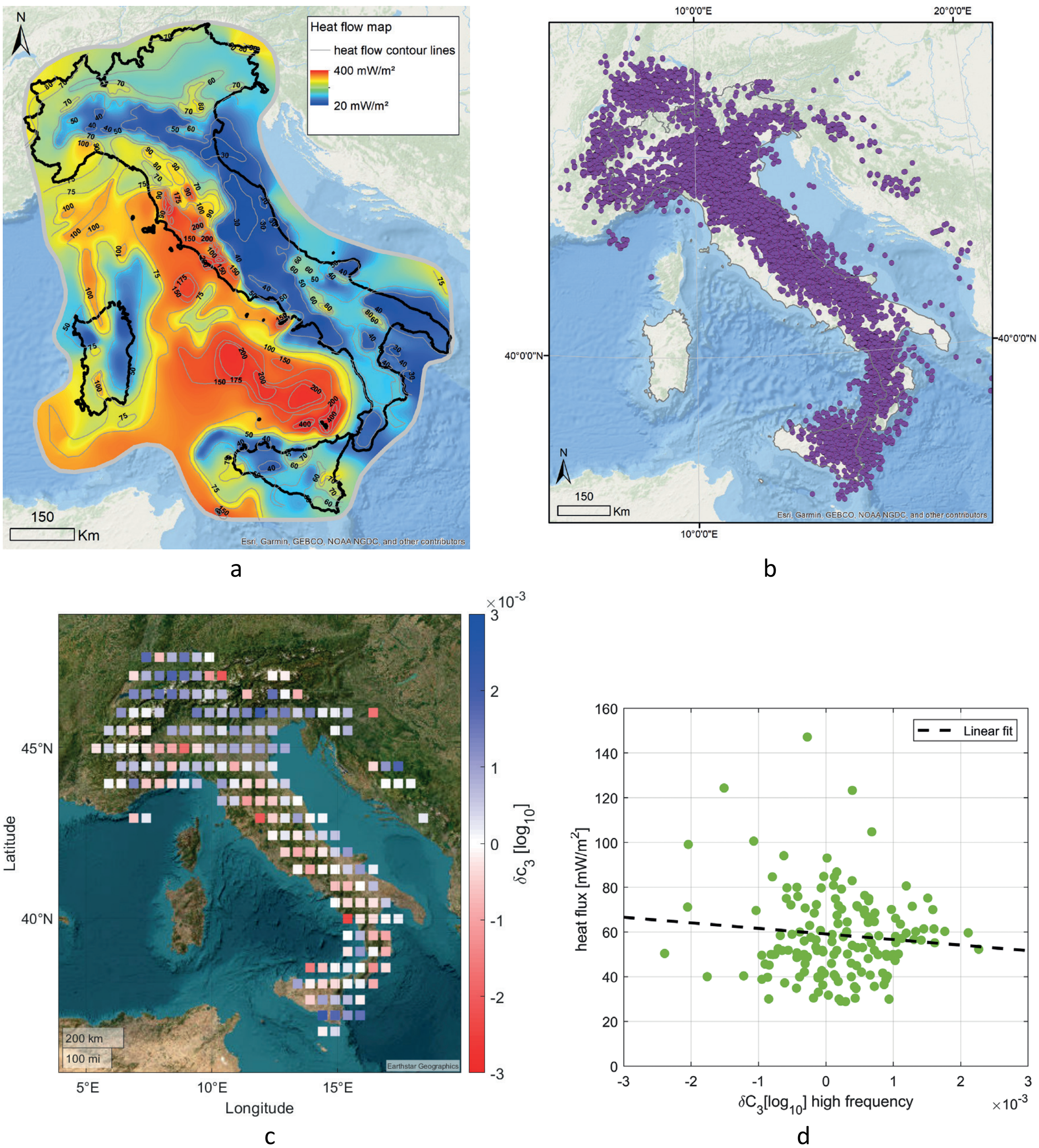

Fig. 10 - Map of heat flux (a) interpolated after Della Vedova *et al*. (1991), spatial distribution of δc_3 estimates (b), map of high frequency δc_3 values, averaged for 50×50 km² cells (c), and δc_3 estimates vs. heat flux values (d).

scale GMM for the ordinates of the Fourier Amplitude Spectrum. Carletti and Gasperini (2003) also used the results of Della Vedova *et al*. (1991) to compare them with the attenuation anomalies highlighted by using the macroseismic data. As observed by Brunelli *et al*. (2023), the heat flow variation qualitatively matches the spatial pattern observed in Fig. 7a for the Apennine arc, where negative δc_3 (faster attenuation) corresponds to areas with higher values of heat flow (volcanic districts, especially in the Tuscany and Latium). On the contrary, positive values of δc_3 (slower attenuation) are found in the Po Plain and Adriatic coast, where heat flow is lower.

We set up a quantitative comparison by dividing the study area into 50×50 km^2 square cells. Then the high-frequency δc_3 values (see spatial distribution in Fig. 10b) are averaged within each cell (Fig. 10c), and plotted against the heat flux estimates averaged within the same cell. In order to make the comparison as robust as possible, we consider only the cells with more than 4 observations. The results of this comparison are shown in Fig. 10d, where a weak negative trend can be observed. The poor correlation can be ascribed to: i) poor spatial resolution of the original map of Della Vedova *et al.* (1991), which is the only spatial representation of this parameter available for Italy over the past thirty years; ii) a low sampling level of δc_3 in an area where greater lateral thermal anisotropy is expected, such as the coastal areas of Tuscany and Latium, and southern Tyrrhenian Sea, as shown in Fig. 10b.

6. Conclusions

The objective of this analysis is to quantify the regional characteristics of source and propagation effects, and the impact on seismic shaking. The method adopted is the residual decomposition method, consisting in the difference between observed data parameters and the prediction of a reference model for Italy. The residuals are separated into a repeatable event term, site, and remaining random residual.

The event term is spatially analysed, and correlated to regional source characteristics and fault maturity-related parameters, such as stress drop (Radiguet *et al*., 2009; Perrin *et al*., 2016; Manighetti *et al*., 2021). The spatial variability of the spectral ordinates, at the short periods, shows significant differences in the event term in some areas of Italy, such as the Alpine Arc and the Ionian Sea, where the model tends to underestimate seismic motion.

The residual term, cleaned of site and source effects, is used to identify spatial patterns related to wave propagation. In fact, a δc_3 term is estimated to investigate how much the individual observation shows different anelastic attenuations compared to those obtained from the calibration of the reference model. The result is a δc_3 map showing areas of differential attenuation throughout the country. In particular, the Adriatic coast, Po Valley and Hyblaean Plain, show slower attenuation with respect to the reference model, and a general underestimation of the prediction.

These empirical observations represent the fundamental basis for building a new generation of predictive GMMs in Italy. Moreover, the results demonstrate that the non-ergodic GMM residuals can also be used to contribute to our understanding of seismogenic processes in Italy. In particular, some suggestions for subsequent model building could be:

1. the introduction of focal depth as an explicit explanatory variable, by modulating the pseudo-depth parameter, as already proposed by Kotha *et al*. (2020). This strategy allows modifying the extension of the area, affected by the largest shaking around the epicentre, as a function of focal depth; however, the introduction of this parameter should be done

with extreme caution, since it requires the use of precise hypocentral depth estimates (e.g. Chiaraluce *et al*., 2022);

2. the definition of homogeneous zones in Italy for the regionalisation of source effects, based on the spatial trend of δB_e, as already carried out by Brunelli *et al*. (2023). In the calibration of the final model, where possible, the scaling laws and difference in variability, observed between small and large earthquakes, should be appropriately taken into account. For example, a magnitude-dependent correction and/or intra-zone heteroscedastic variability may be introduced. In cases where there are insufficient observations for strong earthquakes, the user should be aware that these correctives (and associated variability) may only be valid for small earthquakes;
3. the introduction of a spatially distributed correction for propagation effect (see map in Fig. 8a) by defining the attenuation coefficient correctives on the points of a fixed grid, with a sufficient number of observations. This approach also proves very advantageous for generating shaking scenarios, and overcoming limitations of standard prediction models;
4. the exploration of the regionalisation of site effects, not discussed in this paper but which deserves further specific analysis in a future work. As a matter of fact, worth noting is that a significant portion of the variability is attributable to these effects (see Lanzano *et al*., 2019b), and, thus, it is crucial to introduce regional site effects into the next-generation predictive models.

Acknowledgments. This research is supported by INGV Pianeta Dinamico - Working Earth project - Geosciences For The Understanding The Dynamics Of The Earth And The Consequent Natural Risks (CUP code D53J19000170001), funded by MIUR (the Italian Ministry of University and Research, fund aimed at relaunching investments in the central administrations of the State and the development of the country, law 145/2018) - Task S3 - Seismic attenuation and variability of seismic motion.

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Corresponding author: Giulio Brunelli
Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Milano
Via Alfonso Corti 12, Milano, Italy
Phone: +393402407968; e-mail: giulio.brunelli@ingv.it