

1 A methodological workflow for the identification of earthquake 2 sources from macroseismic data

3 Veronica Gironelli¹, Lucia Luzi¹, Andrea Antonucci¹, Andrea Rovida¹

4 ¹ Istituto Nazionale di Geofisica e Vulcanologia (INGV), Milano, Italy

5 Correspondence to: Veronica Gironelli (veronica.gironelli@ingv.it)

6 **Abstract.** Macroseismic intensity data are a fundamental source of information for characterising historical earthquakes.
7 This study presents a methodology to constrain the sources of large earthquakes through the analysis and modelling of
8 macroseismic intensity data. The proposed workflow consists of three main stages: (1) the identification and removal of
9 outlier intensity data points; (2) the revision of macroseismic earthquake parameters (epicentral location and magnitude);
10 and (3) the construction of three-dimensional (3D) seismogenic sources, simulation of ground shaking including site
11 effects, and a subsequent residual analysis. The key novelty lies in the detection of intensity outliers through residual
12 analysis between observed and predicted macroseismic intensities using an intensity prediction equation (IPE). The
13 application of this workflow to a set of case studies from the parametric catalogue of Italian earthquakes demonstrates
14 that the implemented approach allows the identification of seismogenic sources for large to moderate magnitude events,
15 which are consistent with macroseismic data, geological structures and ground motion data, when available. The results
16 of this study can have direct implications for seismic hazard assessment and shaking scenario modelling. The proposed
17 workflow can be systematically applied to reconstruct the seismogenic sources of the strongest Italian historical
18 earthquakes ($M_w \geq 5.5$).

19 1 Introduction

20 Macroseismic intensity is used to classify the level of shaking caused by earthquakes based on
21 qualitative observations of its effects on people, buildings, and the environment, using standardised
22 intensity scales (e.g., MCS, Sieberg, 1932; MSK, Medvedev et al., 1964; EMS-98, Grünthal, 1998).
23 Among these, the Mercalli–Cancani–Sieberg (MCS) scale and the European Macroseismic Scale
24 1998 (EMS-98) are the most widely adopted in Italy. These scales consist of twelve intensity degrees,
25 each representing increasing severity of ground shaking based on observed effects. Macroseismic
26 intensity is associated with a specific earthquake and site through geographic coordinates and
27 constitutes a macroseismic Intensity Data Point (IDP).

28 Macroseismic observations are widely used in earthquake engineering applications for vulnerability
29 modelling and for the calibration of Intensity Prediction Equations (hereafter, IPEs, e.g., Pasolini et
30 al., 2008; Sørensen et al., 2009; Bindi et al., 2011; Rotondi et al., 2016; Gomez-Capera et al., 2024;
31 Lolli et al., 2024), which estimate the expected macroseismic intensity at any site based on parameters
32 such as epicentral distance and magnitude. Similarly, these data are used as input to develop Ground
33 Motion to Intensity Conversion Equations for a specific region (GMICEs, e.g., Gomez-Capera et al.,
34 2020; Oliveti et al., 2022), which relate ground motion Intensity Measures (IMs) to macroseismic
35 intensities or vice versa. In this framework, macroseismic data are also used as a reference for
36 reconstructing the ground shaking distribution of pre-instrumental events (e.g., Allen et al., 2008;
37 Faenza et al., 2013; Oliveti et al., 2024; Gironelli et al., 2023; Munafò et al., 2024; Volatili et al.,
38 2025). Moreover, the spatial distribution of IDPs (i.e., the macroseismic field) enables the estimation
39 of key earthquake parameters such as epicentral location, magnitude, and depth (e.g., Gasperini and
40 Ferrari, 1995, 2000; Bakun and Wentworth, 1997; Pettenati et al., 1999; Gasperini et al., 1999, 2010;
41 Provost and Scotti, 2020; Sbarra et al., 2019; 2023).

42 The physical dimensions and orientation of seismogenic sources associated with large historical
43 events can also be inferred from the spatial distribution of IDPs. For Italy, apart from the quantitative
44 approach proposed by Gasperini et al. (1999), which estimates source orientation and dimensions
45 from the spatial distribution of intensity data points (IDPs), the association between historical
46 earthquakes and their seismogenic sources is generally based on qualitative interpretations (e.g.,
47 Albini and Rovida, 2010; Galli et al., 2010; Galli and Pallone, 2019). The Database of Italian
48 Seismogenic Sources (DISS; Basili et al., 2008; DISS Working Group, 2025) provides hypotheses
49 on the association between potential seismogenic sources and historical earthquakes reconstructed
50 from geological and macroseismological data.

51 A few recent studies focus on individual earthquakes, comparing shaking scenarios generated by
52 known fault ruptures with the macroseismic evidence of major historical events (e.g., Visini et al.,
53 2009; Sgobba and Pacor, 2023; Munafò et al., 2024). The limitation of the existing studies is the lack
54 of a validation with both macroseismic observations and geological constraints, and the analysis is
55 restricted to individual earthquakes without proposing a standardised approach that can be
56 systematically applied to an entire catalogue of historical events. In contrast, we propose a
57 methodological workflow that can be systematically applied to investigate all the Italian past events,
58 independently of their size.

59 In Italy, IDPs are collected and organised in the Italian Macroseismic Database (Database
60 Macrosismico Italiano - DBMI15; Locati et al., 2022), to provide a homogeneous dataset for assessing
61 earthquake parameters and compiling the Italian Parametric Earthquake Catalogue (Catalogo
62 Parametrico dei Terremoti Italiani - CPTI15; Rovida et al., 2020, 2022). In the CPTI15 catalogue, the
63 parameterization of historical events is based on the intensity dataset selected among those archived
64 in the Italian Archive of Historical Earthquake Data (ASMI; Rovida et al., 2017, 2025) according to
65 quality criteria such as: (i) the completeness and spatial distribution of IDPs; (ii) the methodological
66 robustness of the original study; and (iii) the reliability of the event interpretation (Locati et al., 2022).
67 Given the extensive availability of high-quality macroseismic data in Italy, this study leverages these
68 records to implement a comprehensive workflow for historical seismic source identification. This
69 workflow includes a pre-processing step followed by three stages: (i) reconstruction of seismogenic
70 sources; (ii) ground shaking simulations; and (iii) validation through residual analysis. The pre-
71 processing step detects possible outliers in macroseismic intensity distributions to better constrain the
72 reconstruction of earthquake seismogenic sources.

73 The complete workflow is tested on three instrumental earthquakes with different characteristics to
74 explore the overall applicability of the method. These events are the 1984 Monti della Meta (Mw
75 5.8), the 1989 Prealpi Vicentine (Mw 4.85), and the 2008 Parmense (Mw 5.36) earthquakes.
76 Subsequently, the approach is applied to a historical earthquake, the 3 June 1781 Cagli earthquake
77 (Central Apennines). For this event, seismogenic sources are reconstructed from two alternative, but
78 plausible and reliable, macroseismic fields: the intensity distribution in DBMI15 (Monachesi, 1987)
79 and the dataset from Guidoboni et al. (2018). This allows a quantitative evaluation of the impact of
80 different datasets in terms of earthquake parameterisation and source geometries.

81 The results of this study emphasise that the proposed workflow, including the initial pre-processing
82 of macroseismic fields, can be a useful tool for reconstructing seismogenic sources consistent with
83 macroseismic data and for generating realistic shaking scenarios, especially for past events.

2 Data selection and pre-processing

In the CPTI15 catalogue, the parametrisation of historical earthquakes is performed using the Boxer code (Gasperini et al., 1999, 2010), which is applied to the macroseismic field, hereinafter referred to as the preferred dataset, provided in DBMI15. Specifically, macroseismic epicentres and magnitudes are estimated using the “Method 0” implemented in Boxer. This approach determines the epicentral location as the barycentre of the sites experiencing the highest intensities, and the magnitude is inferred as the average of the magnitude estimates, for each intensity class, computed from the area of the circular isoseismal with radius equivalent to the average epicentre-to-site distance for that intensity level. These magnitude values are calculated with the IPE by Sibol et al. (1987), which also considers epicentral intensity. The final magnitude is then obtained as a weighted trimmed mean of the independent estimates derived from all intensity classes (see Gasperini et al., 2010, for further details). This parametrisation strongly depends on the quantity and spatial distribution of the input macroseismic data. In this work, a set of 191 earthquakes was selected from CPTI15 as a test dataset, with moment magnitudes (M_w) ranging between 5.5 and 7.0, occurring in the period 1117–2017 (Fig. 1a). This magnitude threshold was chosen to focus on events associated with seismogenic sources capable of generating substantial ground shaking. The events selection was based on the following criteria: (i) at least three associated IDPs, to exclude poorly constrained macroseismic fields; (ii) inland epicentres, as offshore events typically produce asymmetric intensity distributions; and (iii) events occurred in areas where the seismogenic layer is shallower than 35 km, consistent with the applicability range of the adopted IPE (Gomez-Capera et al., 2024), which is calibrated for shallow crustal earthquakes. Overall, the final dataset comprises 31,656 macroseismic observations, forming the basis for the subsequent analysis.

Only a subset of 24 recent events has instrumental estimates of epicentre and magnitude, available in the CPTI15 or in ASMI; these events therefore provide a benchmark for testing the methodology (Fig. 1a).

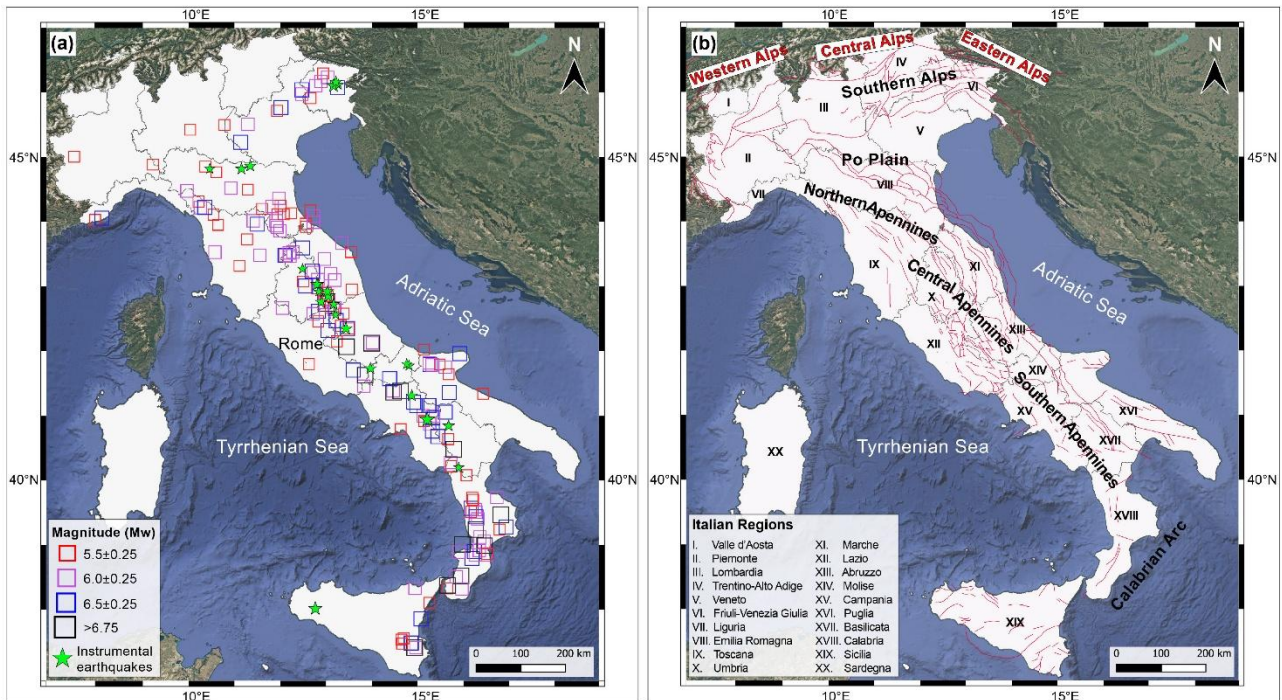


Figure 1 (a) Selected dataset of 191 earthquakes with $M_w \geq 5.5$ from the CPTI15 catalogue (Rovida et al., 2022). Square colours and sizes are proportional to the earthquake magnitude. Green stars indicate the subset of 24 earthquakes for which instrumental solutions are available. (b) Map of the main physiographic structures and tectonic lineaments of Italy (Bigi et al., 1989) cited in the text. Roman numerals (I to XX) refer to the Italian administrative regions with the names detailed in the legend. Basemap source: Google Satellite imagery. Map data ©2015 Google.

Before applying the methodology, we note that the input dataset may include outliers, i.e., intensity observations that are anomalously high or low with respect to the expected attenuation pattern. To address this issue, a pre-processing step was implemented to identify and remove such outliers using the IPE proposed by Gomez-Capera et al. (2024). Intensity data exceeding three standard deviations of the model ($3\sigma \approx 2.25$ intensity units) are classified as outliers and discarded, and the resulting macroseismic dataset is considered (hereinafter referred to as the *revised* dataset). We adopted a 3σ criterion to ensure a conservative filtering of macroseismic observations, aimed at identifying only the largest discrepancies between observed and those predicted by the model, while minimising the exclusion of potentially reliable intensity data. This choice also considers the inherent uncertainty associated with macroseismic intensity, i.e. one intensity degree, and related to its ordinal nature. The outlier removal is necessary since the best-fitting fault is identified through the analysis of residuals between observed and predicted intensity values (based on the median predictions of the adopted model). In this context, the presence of outliers in the macroseismic dataset may systematically bias the residual distribution and, consequently, the inferred fault geometry.

To ensure the overall consistency of our procedure, we recompute earthquake parameters of the analysed earthquake with the Boxer code, with the same settings as in CPTI15 (described in Rovida et al., 2020), starting from the revised dataset. First, we tested the results of this pre-processing by computing the earthquake parameters both including and excluding the identified outliers. For the subset of 24 events with instrumental parameters, the difference between macroseismic and instrumental magnitudes is -0.12 for the preferred dataset and -0.13 for the revised dataset. Differences between macroseismic and instrumental epicentral locations are, on average, negligible.

The same analysis, performed on the full dataset of 191 earthquakes, shows that the two epicentral estimates are generally consistent, with an average difference of approximately 3 km. The comparison between magnitudes from the preferred and revised macroseismic fields shows a mean decrease of 0.15 magnitude units, within the uncertainty range of the Boxer estimates (e.g., 0.26 for pre-1900 events). These results align with Antonucci et al. (2025), who demonstrated that randomly varying intensities in the macroseismic fields of DBMI15 by ± 1 intensity degree, Boxer locations remain very stable with locations within 10 km in 83% of cases and magnitude differences within ± 0.3 units in 87% of the cases. However, significant variations in earthquake location and magnitude estimates (e.g., > 20 km and > 0.3 magnitude units) may lead to markedly different constraints on both the spatial position and the extent of the causative rupture. With this perspective, the pre-processing proves particularly effective in identifying macroseismic fields that require closer scrutiny or, in some cases, exclusion from the analysis. For completeness, Table S1 in the Supplement summarises the comprehensive details for each selected event and the results of the comparisons between solutions for the entire dataset.

The earthquakes that occurred on 25 December 1222, 4 September 1293, and 5 May 1990 show the largest epicentral shifts of approximately 20, 30, and 43 km, respectively. The 1222 and 1293 events are characterised by very few and uncertain macroseismic effects distributed over wide areas, maximum intensities documented at considerable distances from the inferred source, and large azimuthal gaps.

156 We consider the 1990 Potenza earthquake as a clear example of how IDPs identified as outliers can
 157 lead to a large epicentral shift (43 km). Similarly, we consider the well-documented 24 August 2016
 158 Amatrice earthquake, characterised by well-constrained instrumental parameters and a documented
 159 seismogenic source (Tinti et al., 2016; DISS Working Group, 2025).

160 The May 5, 1990 Potenza earthquake struck the Southern Apennines with a Mw 5.8 from the Global
 161 Centroid Moment Tensor (GCMT, Dziewonski, 1981; <http://www.globalcmt.org/CMTsearch.html>).
 162 The Revised Bulletin of the International Seismological Centre (ISC 2025, www.isc.ac.uk) locates
 163 the epicentre slightly north of Potenza at [40.756°N, 15.843°E] and the Italian Seismic Bulletin
 164 (Bollettino Sismico Italiano, BSI; <http://bollettinosismico.rm.ingv.it/>) at [40.682°N, 15.848°E], while
 165 the CPTI15 adopts the location at [40.738°N, 15.741°E] of the previous version of the ISC Bulletin
 166 (Fig. 2c). These differences in instrumental locations, compared with more recent events, are likely
 167 due to the limited density and heterogeneous configuration of the Italian National Seismic Network
 168 at the time of the 1990 event, which was still under development and only partially digitalised. The
 169 Boxer method, applied to the macroseismic field from DBMI15 (Gasparini et al., 1991b; Fig. 2a),
 170 estimates the epicentral location and magnitude as [40.710°N, 15.299°E] and Mw 5.37, respectively.
 171 These solutions do not match any of the available instrumental locations, and for this reason it is not
 172 included in CPTI15. The pre-processing identified 116 intensity outliers within the macroseismic
 173 field (Fig. 2b). Specifically, positive residuals exceeding 3 standard deviations were concentrated in
 174 the Neapolitan area, very far from the instrumental locations, in correspondence with the highest
 175 intensity values ($I = 6-7$ and 7). According to Antonucci et al. (2026), these IDPs were overestimated
 176 due to the cumulative damage caused by the 23 November 1980 earthquake
 177 (https://emidius.mi.ingv.it/CPTI15-DBMI15/eq/19801123_1834_000). Negative residuals were
 178 identified at large distances from the epicentre, particularly in southern Abruzzo, Molise, and Calabria
 179 regions (Fig. 1b). After removing these outliers, the recalculated macroseismic epicentre [40.591°N,
 180 15.785°E] shows a significant improvement, reducing the misfit with the CPTI15-ISC2016
 181 instrumental location from 37.3 km to only 16.7 km, relocating the epicentre near the city of Potenza
 182 (Fig. 2c). The recalculated macroseismic magnitude (Mw 5.4) is significantly lower than the
 183 instrumental one but higher than the Mw 5.19 estimated by Antonucci et al. (2026).

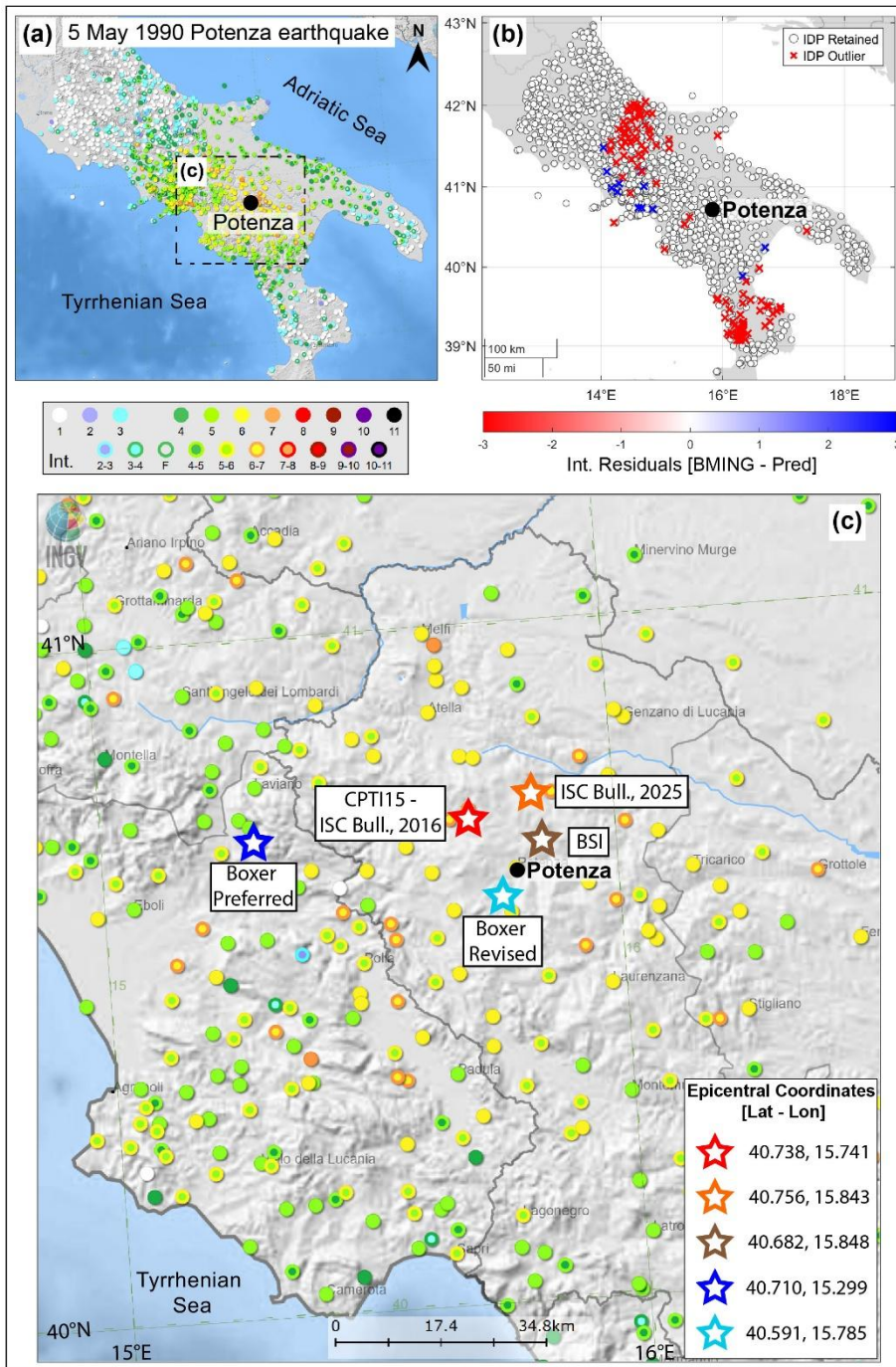


Figure 2 The May 5, 1990 (M_w 5.8) Potenza earthquake. (a) Macroseismic intensity distribution of the BMING dataset (Bollettino Macrosismico ING) from Gasparini et al. (1991b). (b) Intensity residuals (blue = positive; red = negative) between BMING observations and predictions from the IPE of Gomez-Capera et al. (2024), where crosses indicate the 116 identified outliers. (c) Comparison of epicentral locations: red, orange, and brown stars represent the instrumental epicentral solutions from CPTI15 (ISC Bulletin, 2016), ISC Bulletin (2025), and BSI, respectively. Blue and light blue stars indicate the macroseismic epicentres derived with Boxer from the preferred (BMING) and revised macroseismic fields. Maps in panels (a) and (c) are derived from the CPTI15-DBMI15 catalogue, which uses the TINITALY Digital Elevation Model as background.

A second example is the August 24, 2016 Amatrice earthquake, the triggering event of the Central Italy seismic sequence. The event was located by the BSI at $[42.698^\circ\text{N}, 13.233^\circ\text{E}]$. Different moment magnitude estimates are available: M_w 6.2 from the Regional Centroid Moment Tensor (RCMT, Pondrelli, 2002) and GCMT, and M_w 6.0 from the Time Domain Moment Tensor (TDMT INGV, Scognamiglio et al., 2006, <http://terremoti.ingv.it/>). The adopted macroseismic field in DBMI15, derived from the field survey described in Rossi et al. (2019; ROSAL019), consists of 221 IDPs with intensities ranging from $I = 2-3$ up to $I \geq 9$ in the EMS-98 scale (Fig. 3a). From this macroseismic

field the Boxer epicentral location and magnitude estimates are $[42.683^{\circ}\text{N}, 13.277^{\circ}\text{E}]$ and M_w 6.46, as reported in CPTI15. The pre-processing identified 8 intensity outliers: two with positive residuals and six with negative ones (Fig. 3b). After removing these outliers, the recalculated macroseismic epicentre is $[42.658^{\circ}\text{N}, 13.288^{\circ}\text{E}]$. Both macroseismic epicentres are consistent with the BSI instrumental location, differing by just 3.9 km and 6 km, respectively. This slight shift is related to the removal of the IDP at Pescara del Tronto ($I = 10$), where the observed damage was amplified due to the location on pre-existing landslide deposits. Conversely, an improvement is observed in the magnitude estimate: the recalculated value (M_w 6.26) is notably lower and more consistent with the instrumental ones. This difference in magnitude has significant implications for the reconstruction of the seismic source, since a magnitude of M_w 6.46 would imply a rupture area of approximately 270 km^2 , which is inconsistent with the portion of the fault system activated during the mainshock, and with structural-geological data and DInSAR modelling ($\sim 180 \text{ km}^2$; Lavecchia et al., 2016), as well as with the observed rupture length of 20–25 km (Chiaraluce et al., 2017).

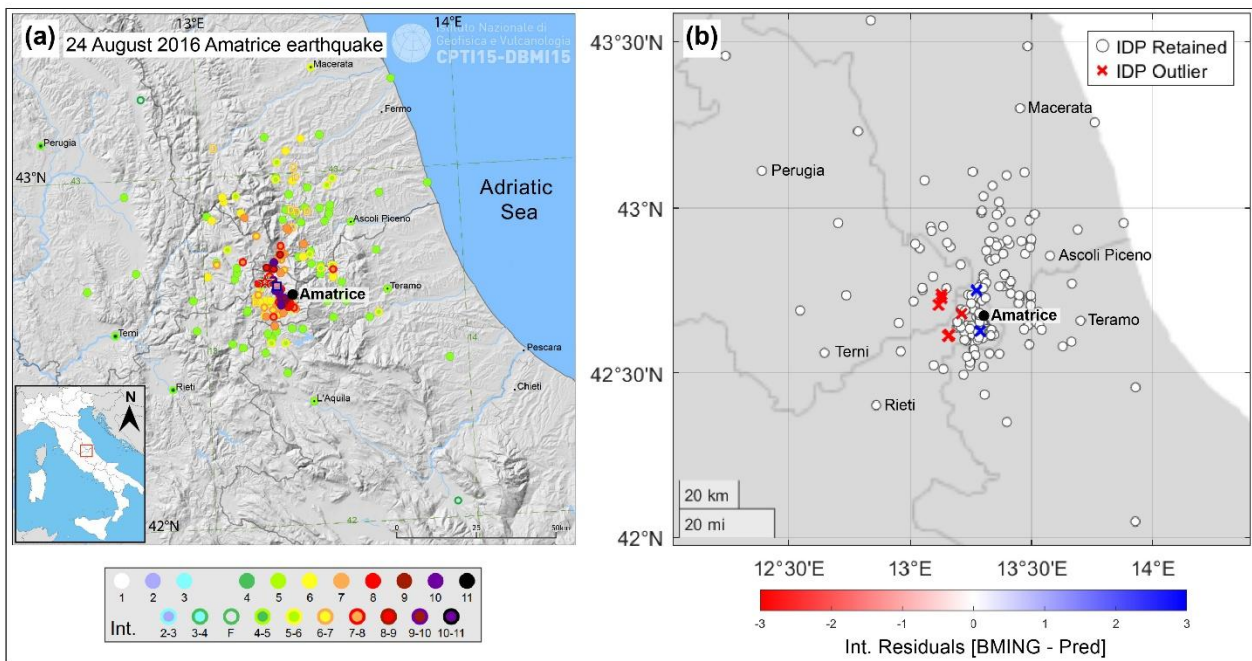


Figure 3 The August 24, 2016 (M_w 6.18) Amatrice earthquake. (a) Macroseismic intensity distribution of the ROSAL019 dataset from Rossi et al. (2019). (b) Intensity residuals between ROSAL019 observations and predictions from the adopted IPE. Blue crosses indicate intensity outliers with positive residuals (Pescara del Tronto and Amatrice, $I = 10$), whereas red crosses indicate outliers with negative residuals (Terracina, $I = 5-6$; Castel S. Maria, Cittareale, Savelli, and Valcaldara, $I = 5$). The map in panel (a) is derived from CPTI15-DBMI15 and uses the TINITALY DEM as background.

3 Seismogenic source reconstruction: methodological workflow

This section describes the integrated methodological workflow for seismogenic source reconstruction, which follows the initial pre-processing step and consists of three stages, as summarised in Fig. 4. In stage 1, we estimated earthquake parameters using the Boxer code (Gasperini et al., 1999, 2010) based on the revised macroseismic fields, and in stage 2, we used these parameters to reconstruct the seismogenic sources. Fault dimensions (length and width) are calibrated according to the scaling relationships by Wells and Coppersmith (1994). Although these empirical relations are widely adopted, source dimensions are indirectly inferred from estimated macroseismic magnitudes and may be affected by the intrinsic variability of the scaling relationships. In addition, for each source geometry, we defined credible parameters (e.g., strike, dip, rake, focal depth, and rupture vertices) by

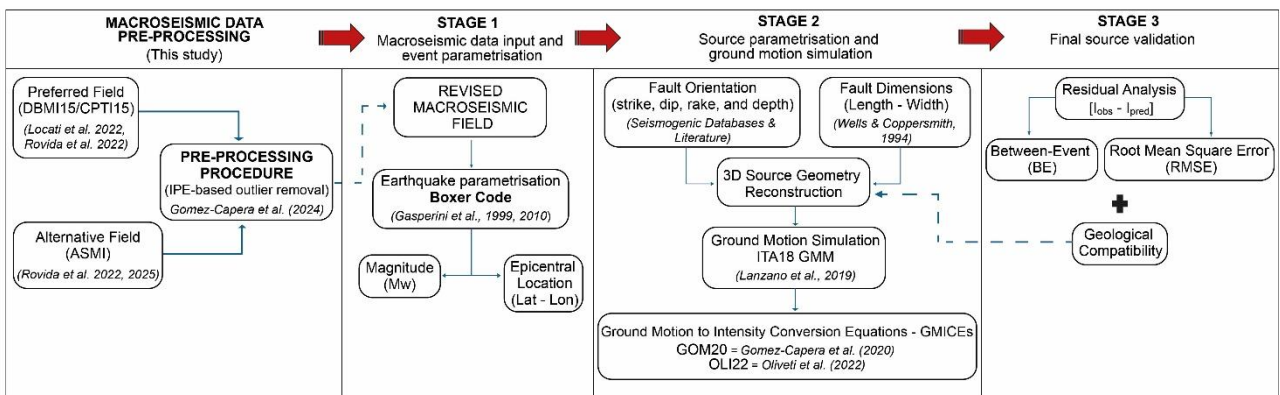
230 integrating data from several authoritative repositories: the Italian Seismic Bulletin (BSI; BSI
231 Working Group, 2015), the Catalogue of Absolute Locations (CLASS; Latorre et al., 2022, 2023),
232 the Engineering Strong-Motion Database (ESM; Luzi et al., 2020), the DISS database (Basili et al.,
233 2008; DISS Working Group, 2025, version 3.3.1), and the ITaly HAZard from CAPable faults
234 catalogue (ITHACA Working Group, 2019).

235 The 3D source geometries are modelled as rectangular planes centred on the hypocentre. We simulate
236 ground shaking including site effects using the ITA18 Ground Motion Model (GMM; Lanzano et al.,
237 2019) by hypothesising variable hypocentral depths and considering the rupture distance (R_{rup}) as
238 the source-to-site metrics. The resulting ground motion parameters (peak ground acceleration, PGA,
239 and peak ground velocity, PGV), expressed in $\log_{10}$ units, are then converted into intensity values
240 using two distinct GMICES: Gomez-Capera et al. (2020; GOM20) and Oliveti et al. (2022; OLI22).

241 While both equations generally align with the observed data, the quadratic formulations of OLI22
242 equations tend to exhibit a flattening effect of the regression curves for PGV greater than 5 cm/s and
243 PGA larger than 100 cm/s^2 , which may lead to a systematic underestimation of the highest
244 macroseismic degrees than GOM20 (see Figs. 6 and 7 in Oliveti et al., 2022).

245 To identify the "best-fitting" seismogenic source (stage 3), we perform residual analyses of observed
246 and predicted intensities (or PGA/PGV values when accelerometric recordings are available).
247 Specifically, we compute the residuals for intensities derived from PGV, as this measure correlates
248 most effectively with damage distribution and macroseismic intensity (Akkar and Ozen, 2005;
249 Munafò et al., 2024; Tang et al., 2019; Gomez-Capera et al., 2020). Finally, the best-fitting source is
250 the one that minimises the mean of the residuals (Between-Event, BE) and their root-mean-square
251 error (RMSE). Thresholds of ± 0.5 for the BE and 1 for the RMSE are identified in intensity units to
252 consider a source as reliable. These thresholds are chosen to maintain an acceptable comparison
253 between observed and predicted intensity values and considering the intrinsic uncertainty of
254 macroseismic intensity data (± 1 degree). A BE error of ± 0.5 represents a conservative criterion,
255 corresponding to a maximum discrepancy of only half an intensity degree compared to the observed
256 value.

257 This approach allows us to generate multiple shaking scenarios and evaluate their consistency against
258 three key benchmarks: (i) the observed macroseismic field; (ii) recorded instrumental data (when
259 available); and (iii) geological evidence.



260
261 *Figure 4 Schematic representation of the integrated workflow adopted for seismogenic source reconstruction, including the*
262 *macroseismic data pre-processing step. Dashed blue arrows indicate that the revised macroseismic field serves as the primary input*
263 *to Stage 1, while the results from Stage 3 are iteratively used to validate and refine the 3D source geometry. Notes: GMM, Ground*
264 *Motion Model; GMICES, Ground Motion to Intensity Conversion Equations; BE, Between-Event error; RMSE, Root Mean Square*
265 *Error; GOM20, conversion equation by Gomez-Capera et al. (2020); OLI22, conversion equation by Oliveti et al. (2022).*

3.1 Test on instrumental events

To evaluate the effectiveness and robustness of the workflow of Fig. 4, we applied and tested it on three events characterised by instrumental metadata, chosen for their different characteristics. Specifically, the selected case studies are characterised by different magnitudes, robust macroseismic fields (> 50 IDPs), and debated or poorly constrained seismogenic sources. These events include the 1984 Monti della Meta earthquake with Mw 5.86, (https://emidius.mi.ingv.it/CPTI15-DBMI15/eq/19840511_1042_000), the 1989 Prealpi Vicentine with Mw 4.85 (https://emidius.mi.ingv.it/CPTI15-DBMI15/eq/19890913_2153_000), and the 2008 Parmense earthquakes (Mw 5.36; https://emidius.mi.ingv.it/CPTI15-DBMI15/eq/20081223_1524_000).

For the 1984 and the 2008 earthquakes, our analysis is also supported by accelerometric recordings from the Italian Accelerometric Archive (ITACA) v4.0 (Felicetta et al., 2023), which provide a further validation for the reconstructed seismogenic sources in addition to macroseismic and geologic constraints. The main features of these analysed events are summarised in Table 1.

Table 1 Summary of the selected case studies. Event ID, Event date, Time, and Epicentral Area are obtained from the CPTI15 catalogue (Rovida et al., 2022). Instrumental data indicate the availability of independent instrumental parameters (M = instrumental magnitude; H = hypocentral depth; W = accelerometric recordings). Focal mechanism indicates the fault kinematics (NF = normal fault; TF = thrust/reverse fault; SS = strike-slip fault).

Event ID	Event date	Time (UTC)	Epicentral Area	Instrumental data	Focal mechanism
19840507_1749_000	7 May 1984	17:50:--	Monti della Meta	M / H / W	NF
19890913_2153_000	13 September 1989	21:54:01	Prealpi Vicentine	M / H	SS
20081223_1524_000	23 December 2008	15:24:21	Parmense	M / H / W	TF

283

3.1.1 The 1984 Monti della Meta earthquake

The May 7, 1984 earthquake was the mainshock of a seismic sequence that affected the Abruzzo–Lazio area (Fig. 1b). The instrumental epicentral location and magnitude reported by the CPTI15 catalogue for this event are [41.665°N, 13.820°E] and Mw 5.86, based on CSTI1.1 (<https://doi.org/10.13127/csti.1.1>) and GCMT, respectively. CPTI15 also reports the macroseismic epicentral location and magnitude, which are [41.667°N, 14.057°E] and Mw 5.73, respectively.

The preferred macroseismic field in DBMI15, derived from the Catalogue of Strong Earthquakes in Italy (CFTI4med, Guidoboni et al., 2007), consists of 911 IDPs with intensities ranging from 2-3 to 8 MCS (Fig. 5a). The application of the pre-processing procedure on the preferred macroseismic field identified and removed 30 outliers, reducing the dataset to 881 IDPs. In this case, the recalculated parameters after the pre-processing remain unchanged, as the removed IDPs correspond to the lowest observed intensities. Although this event was instrumentally recorded, the hypocentral parameters reported by different seismic catalogues vary considerably. The macroseismic epicentre estimate differs by about 20 km from the instrumental locations provided by CSTI1.1, CLASS, and the Italian Seismicity Catalogue (Catalogo della Sismicità Italiana - CSI1.1; Castello et al., 2006, <http://www.ingv.it/CSI/>). Conversely, the estimated macroseismic magnitude (Mw 5.73) is consistent with the instrumental estimates.

To identify the best-fitting seismogenic source (i.e., the fault plane that minimises the misfit between observed and predicted intensities), we generated a set of 9 alternative sources by combining the

instrumental solutions provided by CPTI15 (from CSTI1.1) and CLASS and the macroseismic location and magnitude estimate, with three different hypocentral depths: 6.5 km (CLASS), 11.20 km (CPTI15), and 20.5 km (CSTI1.1), as shown in Table 2. For each configuration, we constructed a virtual box representing the 3D seismogenic source, assuming a NW–SE-oriented, W-dipping normal fault, in agreement with the literature (e.g., Westaway et al., 1989; Boncio et al., 1998).

Table 2 Instrumental earthquake parameters for the 1984 Monti della Meta earthquake, derived from CPTI15 (Rovida et al., 2022) and CLASS (Latorre et al., 2022) catalogues, and macroseismic estimates derived using Boxer (Gasparini et al., 2010). The tested seismogenic source configurations based on different parameter combinations are also reported.

Reference earthquake parameters	Data Type	Epicentre [Lat, Lon]	Mw	Strike/Dip/Rake (°)	Length (km)	Width (km)	Depth (km)	Tested Source
CPTI15 (Rovida et al., 2022)	Instrumental	[41.665°N, 13.820°E] CSTI1.1	5.86 GCMT	145/50/-90	10.4	7.3	6.5	META_001
							11.2	META_002
							20.5	META_003
CLASS (Latorre et al., 2022)	Instrumental	[41.713°N, 13.833°E]	5.90 GCMT	145/50/-90	10.9	7.5	6.5	META_004
							11.2	META_005
							20.5	META_006
Boxer method (Gasparini et al., 2010)	Macroseismic	[41.667°N, 14.057°E] Pref/Rev	5.73 Pref/Rev	145/50/-90	8.7	6.6	6.5	META_007
							11.2	META_008
							20.5	META_009

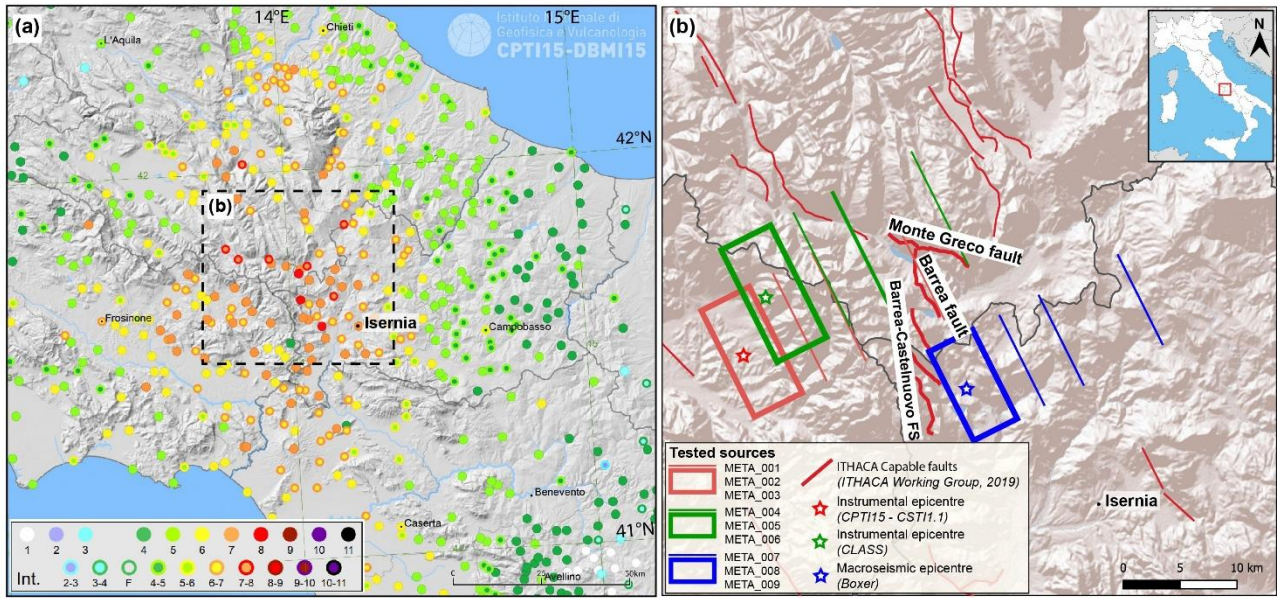
At this stage, the workflow consists of generating shaking scenarios for each source using the ITA18 GMM (Lanzano et al., 2019) to predict PGA and PGV. The simulated PGV values were converted into macroseismic intensity using the GOM20 and OLI22 equations. Subsequently, we compared the observed macroseismic intensities with the predicted ones by computing the BE residuals and their (RMSE). Additionally, since accelerometric recordings are available for this earthquake, we also calculated the residuals between the predicted ground motion parameters (PGA and PGV, in log10 units) and the logarithm of the values recorded at stations reported in ITACA (Felicetta et al., 2023).

The results of these residual analyses are summarised in Table 3. Among the tested source configurations, the one that minimises residuals in terms of macroseismic intensities corresponds to the code META_004, that is generated using the CLASS hypocentral location and the GCMT moment magnitude and has a length of 10.9 km, and a width of 7.5 km (Table 2 and Fig. 5b). This solution is further supported by the validation performed against accelerometric recordings; specifically, we observed that the $RMSE_{LogPGA}$ of 0.33 is of the same order as the standard deviation of the ITA18 GMM (e.g., 0.336), the same occurs for BE_{LogPGA} (e.g., 0.16 in ITA18), $RMSE_{LogPGV}$ (e.g., 0.29 in ITA18), BE_{LogPGV} (e.g., 0.13 in ITA18).

Table 3 Residual analysis for the tested seismogenic sources, relevant to the 1984 Monti della Meta earthquake. Between-Event error (BE_i) and the root-mean-square error ($RMSE_i$) are obtained from PGV using the GOM20 and OLI22 conversion equations. BE_{LogPGA} , $RMSE_{LogPGA}$, BE_{LogPGV} , and $RMSE_{LogPGV}$ are calculated as the mean difference between the base-10 logarithms of observed and predicted peak ground acceleration and velocity. The asterisk indicates the best-fitting seismogenic source.

Reference parameters	Source	BE_i - $RMSE_i$ (GOM20)	BE_i - $RMSE_i$ (OLI22)	BE_{LogPGA} (cm/s ²)	$RMSE_{LogPGA}$ (cm/s ²)	BE_{LogPGV} (cm/s)	$RMSE_{LogPGV}$ (cm/s)
CPTI15	META_001	0.41–0.80	0.64–0.92	-0.20	0.37	-0.08	0.34
	META_002	0.45–0.79	0.67–0.93	-0.23	0.37	-0.11	0.33
	META_003	0.55–0.83	0.76–1.00	-0.30	0.39	-0.17	0.34
	META_004 (*)	0.35–0.74	0.57–0.86	-0.19	0.33	-0.07	0.32
CLASS	META_005	0.39–0.74	0.61–0.88	-0.22	0.33	-0.09	0.32
	META_006	0.48–0.79	0.69–0.95	-0.28	0.37	-0.15	0.33
	META_007	0.54–0.89	0.76–1.02	-0.35	0.45	-0.24	0.39
	META_008	0.58–0.88	0.8–1.04	-0.37	0.46	-0.26	0.40
Boxer (Pref/Rev)	META_009	0.69–0.95	0.89–1.11	-0.43	0.50	-0.31	0.42

330 The source META_004 also exhibits the best overall agreement with the geological lineaments
 331 mapped in the study area, since its surface projection aligns with the Barrea–Castelnuovo fault
 332 system, as mapped in the ITHACA database of capable faults
 333 (<https://sgi.isprambiente.it/ithaca/viewer/>), and agrees with previous studies of the 1984 Abruzzo–
 334 Lazio seismic sequence (Boncio et al., 1998; Pace et al., 2002). Among the sources derived from
 335 macroseismic parameters (Table 2), the META_007 source exhibits the lowest BE error ($BE_I = 0.54$)
 336 and $RMSE_I$ (0.89). Although these values are broadly consistent with the adopted thresholds for
 337 selecting the best-fitting source, the surface projection of the META_007 fault trace shows poor
 338 consistency with the known geological structures in the area.



339 Figure 5 The May 7, 1984 (Mw 5.86) Monti della Meta earthquake. (a) Macroseismic intensity distribution of the CFTI4med dataset
 340 from Guidoboni et al. (2007). (b) Tested fault geometries as coloured rectangles; Red lines represent capable faults from the ITHACA
 341 database (ITHACA Working Group, 2019). Red, green, and blue stars represent the instrumental epicentral solutions from CPTI15
 342 (CSTI1.1), CLASS, and the macroseismic epicentre, respectively. The map in panel (a) is derived from the CPTI15-DBMI15 catalogue,
 343 which uses the TINITALY DEM as background, whereas panel (b) is generated using the Esri Shaded Relief basemap. Sources: Esri |
 344 Powered by Esri.

346 3.1.2 The Prealpi Vicentine earthquake

347 The September 13, 1989 earthquake occurred north of Schio in the Veneto region (Northern Italy;
 348 Fig. 1b). The instrumental location and magnitude provided by CPTI15 for this event are [45.882°N,
 349 11.264°E], based on OGS-BFVG (Bollettino della Rete Sismometrica del Friuli Venezia Giulia,
 350 <http://www.crs.inogs.it/bollettino/RSFVG/>) and a Mw 4.85 (RCMT, Pondrelli et al., 2006). In
 351 addition, the Boxer-derived epicentral location is [45.870°N, 11.172°E] and the Mw equal to 4.99,
 352 respectively. The adopted macroseismic field consists of 779 IDPs spread over a wide area covering
 353 the southern Alps, Veneto and the Po plain (see Fig. 1b), with the light damage reported at two
 354 villages, Posina and Besenello, evaluated as intensity of 6-7 MCS (Bollettino Macrosismico ING;
 355 Gasparini et al., 1991a, Fig. 6a-b). The application of the pre-processing to this macroseismic field
 356 reduced the dataset to 766 IDPs. The removed outliers do not significantly affect the computation of
 357 epicentral location and magnitude. The Boxer-derived earthquake parameters remain unchanged in
 358 terms of magnitude (Mw 4.99), while the epicentral location shifts by about 4 km to [45.896°N,
 359 11.215°E].

360 From a seismotectonic perspective, the 1989 earthquake was the largest instrumentally recorded event
 361 that occurred along the Schio–Vicenza Fault System (SVFS) in Northern Italy, a complex transverse
 362 structure composed of a set of NW–SE-trending and NE-dipping high-angle faults. The main fault of

the SVFS is the Schio-Vicenza Lineament (SVL; Fig. 6b), a NW–SE, 120-km-long, subvertical strike-slip fault, which bounds to the east the Southern Alps (e.g., Castaldini and Panizza, 1991; Viganò et al., 2008; Vannoli et al., 2015; Zampieri et al., 2021). As reported by Vannoli et al. (2015) and Zampieri et al. (2021), the source of this event could be associated with a segment of the northern portion of the SVL. This is also supported by the focal mechanism from the RCMT (Pondrelli et al., 2006), which indicates a right-lateral strike-slip motion with strike (146°; 56°), dip (90°; 89°), and rake (− 178°; 0°). Although the scientific community generally agrees on the kinematics and the associated seismogenic source of this event, several instrumental solutions are available from different catalogues. For this reason, we tested several earthquake parametrisations to identify the source configuration that best fits the observed data and the geological fault system identified in the literature.

We generated 9 alternative seismogenic sources by considering both the instrumental solutions and the Boxer-derived macroseismic estimate. Specifically, we selected as representative solutions the instrumental locations provided by CPTI15 (from OGS) and CLASS, together with the moment magnitude (Mw 4.85) from the RCMT. For each configuration, we assumed a strike-slip fault geometry (strike = 146°, dip = 90°, rake = −179°), and three different hypocentral depths: 9 km (OGS), 12.3 km (CLASS), and 25 km to explore a deeper source (Table 4).

Table 4 Instrumental earthquake parameters for the 1989 Prealpi Vicentine earthquake, derived from CPTI15 and CLASS catalogues, and macroseismic estimate derived using Boxer. The tested seismogenic sources are also reported.

Reference earthquake parameters	Data Type	Epicentre [Lat, Lon]	Mw	Strike/Dip/Rake (°)	Length (km)	Width (km)	Depth (km)	Tested Source
CPTI15 (Rovida et al., 2022)	Instrumental	[45.882°N, 11.264°E] OGS-BFVG	4.85 RCMT	146/90/-179	2.6	3.4	9.0	VIC_001
							12.3	VIC_002
							25.0	VIC_003
CLASS (Latorre et al., 2022)	Instrumental	[45.874°N, 11.134°E]	4.85 RCMT	146/90/-179	2.6	3.4	9.0	VIC_004
							12.3	VIC_005
							25.0	VIC_006
Boxer method (Gasparini et al., 2010)	Macroseismic	[45.896°N, 11.215°E] Rev	4.99 Rev	146/90/-179	3.2	3.8	9.0	VIC_007
							12.3	VIC_008
							25.0	VIC_009

Since no accelerometric recordings are available for this event in the ITACA database, the analysis was therefore based only on the comparison between observed and predicted macroseismic data. Sources based on the CLASS instrumental parameters (e.g., VIC_004, VIC_005, and VIC_006) exhibit the largest BE_I and RMSE_I values, while the sources based on the instrumental parameters provided by the CPTI15 (i.e., OGS) provide intermediate results. In addition, an increase in BE_I and RMSE_I values is observed for source geometries with hypocentral depths larger than 15 km (e.g., VIC_003, VIC_006, and VIC_012), suggesting that this event could be originated at relatively shallow depths (~ 9–12 km). The sources derived from the Boxer macroseismic estimation show generally lower BE_I and RMSE_I values for both the GOM20 and OLI22 conversion equations.

Table 5 Residual analysis (BE_I and RMSE_I) for the tested seismogenic sources of the 1989 Prealpi Vicentine earthquake. The asterisk indicates the best-fitting seismogenic source among the considered models.

Reference parameters	Source	BE _I - RMSE _I (GOM20)	BE _I - RMSE _I (OLI22)
CPTI15	VIC_001	0.88–1.04	0.87–1.01
	VIC_002	0.91–1.06	0.89–1.02
	VIC_003	1.05–1.16	1.01–1.11
	VIC_004	0.90–1.05	0.90–1.02
CLASS	VIC_005	0.92–1.06	0.92–1.04
	VIC_006	1.04–1.14	1.02–1.12

	VIC_007 (*)	0.69–0.88	0.74–0.89
Boxer	VIC_008	0.72–0.89	0.76–0.90
(Rev)	VIC_009	0.87–0.99	0.89–0.99

From a geological perspective, among the tested source configurations, both the solutions based on CLASS instrumental parameters and those derived from macroseismic data are located close to the Schio–Vicenza Lineament, as mapped in the ITHACA database (Fig. 6b), which has been proposed in the literature as the potential causative structure for this event (e.g., Zampieri et al., 2021).

Although none of these sources fully satisfy the adopted selection thresholds, the lowest residuals are obtained for sources VIC_007 and VIC_008, corresponding to Boxer-derived epicentral location and magnitude with hypocentral depths of 9 km and 12.3 km, respectively (Table 5). Despite the BE_I being slightly higher than the adopted threshold ($BE_I = 0.69$) and the $RMSE_I$ being close to 1 ($RMSE_I = 0.88$), we identified the VIC_007 geometry as the best-fitting source.

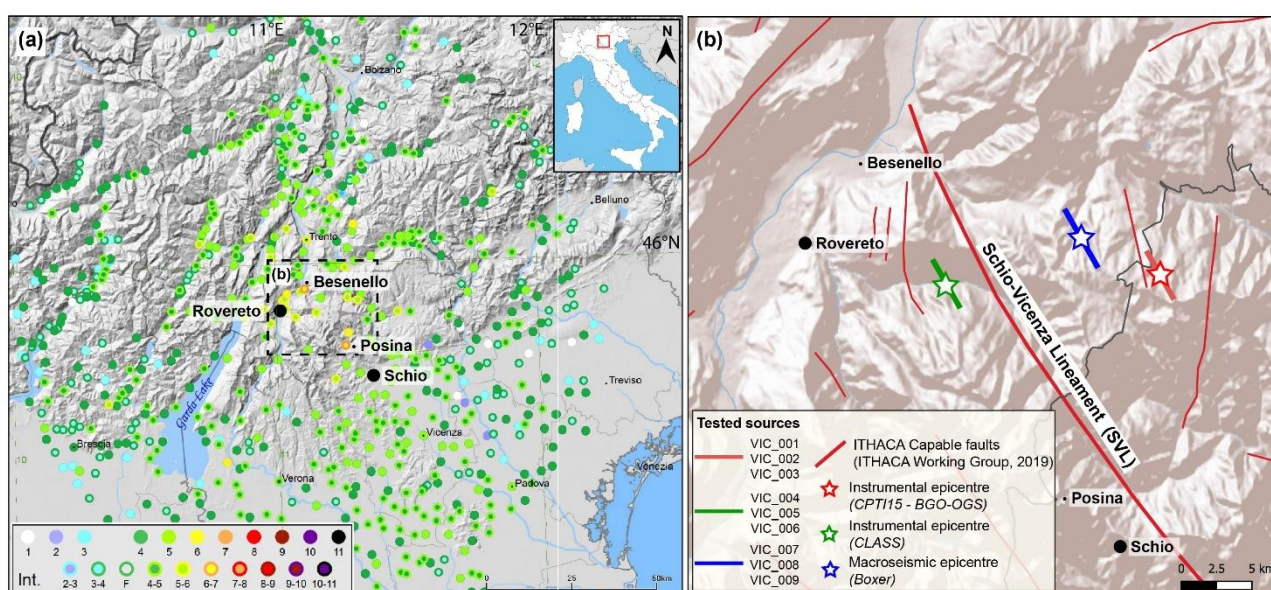


Figure 6 The September 13, 1989 (Mw 4.85) Prealpi Vicentine earthquake. (a) Macroseismic intensity distribution of the BMING dataset from Gasparini et al. (1991a). (b) Tested source configurations (coloured lines) corresponding to vertical fault planes (dip = 90°). Red lines represent capable faults from ITHACA database. Red, green, and blue stars represent the instrumental epicentral solutions from CPTI15 (BGO-OGS), CLASS, and the macroseismic epicentre, respectively. The map in panel (a) is derived from the CPTI15-DBMI15, which uses the TINITALY DEM, whereas panel (b) is generated using the Esri Shaded Relief basemap. Sources: Esri | Powered by Esri.

3.1.3 The 2008 Parmense earthquake

The December 23, 2008 Parmense earthquake struck the Emilia Romagna region (see Fig. 1b) between the provinces of Reggio Emilia and Parma (Fig. 7a). The instrumental location and magnitude provided by CPTI15 for this event are [44.544°N, 10.345°E], based on BSI (<http://bollettinosismico.rm.ingv.it>) and a Mw 5.36, based on TDMT INGV (Scognamiglio et al., 2006; <https://doi.org/10.13127/TDMT>), harmonised to RCMT according to Lolli et al. (2020). The macroseismic epicentre and magnitude provided by CPTI15 are [44.609°N, 10.261°E] and Mw 5.17, respectively. The adopted macroseismic field (Ercolani et al., 2009), consists of 291 IDPs with intensities ranging from 2 to 6-7 in the MCS scale (Fig. 7a). The application of the pre-processing did not modify the dataset; therefore, the Boxer-derived earthquake parameters remain unchanged.

From a seismotectonic perspective, this earthquake affected a sector of northern Apennines (see Fig. 1b) characterised by compressional tectonics and by a relatively high seismicity rate. In this region, shallow earthquakes are generally located along the highest peaks of the range, while deeper events (> 10 km) occur in the outer sectors. According to BSI, the hypocentre of this event was located at a

depth of about 23 km. Regarding the seismogenic source of the event, the DISS database attributed it to an Individual Seismogenic Source (ISS) labelled “ITIS135 Neviano degli Arduini”. This ISS represents a reverse faulting (strike = 98°, dip = 55°, and rake = 79°) based on the focal mechanism solution from the RCMT (Pondrelli et al., 2006).

For this event, the hypocentral parameters reported by BSI and CLASS are overall consistent in terms of location, magnitude, and depth. The instrumental locations differ by only 2 km, and the corresponding hypocentral depths are 22.9 km (BSI) and 19.6 km (CLASS). Additionally, ground motion recordings are available at 35 stations from the ITACA database (Felicetta et al., 2023). Despite this general agreement among the instrumental solutions, the application of our workflow allows us to explore which source configuration is most consistent with the available accelerometric recordings, macroseismic data, and geological constraints.

In this case, we generated three virtual seismogenic sources by considering the instrumental parameters provided by CPTI15 (from BSI) and CLASS, together with the macroseismic estimate (Table 6). For each source configuration, we assumed a S-dipping reverse source geometry, consistent with the “ITIS135” proposed by the DISS database.

Table 6 Instrumental earthquake parameters for the 2008 Parmense earthquake, derived from CPTI15 and CLASS catalogues, and macroseismic estimate derived using Boxer. The tested seismogenic source configurations are also reported.

Reference earthquake parameters	Data Type	Epicentre [Lat, Lon]	Mw	Strike/Dip/Rake (°)	Length (km)	Width (km)	Depth (km)	Tested Source
CPTI15 (Rovida et al., 2022)	Instrumental	[44.544°N, 10.345°E] BSI	5.36 TDMT	98/55/79	5.2	5.0	22.9	PARM_001
CLASS (Latorre et al., 2022)	Instrumental	[44.552°N, 10.366°E]	5.36 TDMT	98/55/79	5.2	5.0	19.6	PARM_002
Boxer method (Gasparini et al., 2010)	Macroseismic	[44.609°N, 10.261°E] Pref/Rev	5.17 Pref/Rev	98/55/79	4.0	4.4	22.9	PARM_003

The results of the residual analyses (Table 7) show that both PARM_001 and PARM_002 satisfy the adopted thresholds for the identification of the best-fitting source. PARM_001 is based on the CPTI15-BSI instrumental solution, whereas PARM_002 derives from the CLASS solution. Both configurations minimise the residuals for macroseismic intensities, indicating a good agreement between observed and predicted data. Consistently, the comparison between predicted ground motion parameters and recorded accelerometric data (PGA and PGV, in log10 units) shows comparable results for both source configurations. In particular, $RMSE_{LogPGV}$ and $RMSE_{LogPGA}$ values are 0.26 and 0.34, respectively, which are in line with the standard deviation of the ITA18 GMM (0.29 for PGV and 0.33 for PGA). However, PARM_001 is selected as the best-fitting seismogenic source, as it is consistent with the seismogenic source “ITIS135 Neviano degli Arduini” reported in the DISS database (Fig. 7b). In contrast, the PARM_003 source geometry, derived from macroseismic data, does not satisfy the adopted thresholds for either of the tested conversion equations ($BE_I > 0.5$ and $RMSE_I > 1$; Table 7), indicating a poorer agreement between observed and predicted intensities.

Table 7 Residual analysis (BE_I and $RMSE_I$) for the tested seismogenic sources of the 2008 Parmense earthquake. The table also reports the BE , calculated as the mean difference between the base-10 logarithms of observed and predicted peak ground motions, and $RMSE$ from the validation against instrumental recordings. The asterisk indicates the best-fitting seismogenic source among the considered models.

Reference parameters	Source	$BE_I - RMSE_I$ (GOM20)	$BE_I - RMSE_I$ (OLI22)	BE_{LogPGA} (cm/s ²)	$RMSE_{LogPGA}$ (cm/s ²)	BE_{LogPGV} (cm/s)	$RMSE_{LogPGV}$ (cm/s)
CPTI15	PARM_001 (*)	0.53–0.78	0.64–0.80	-0.05	0.34	0.00	0.26
CLASS	PARM_002	0.45–0.76	0.54–0.75	-0.04	0.34	0.01	0.26

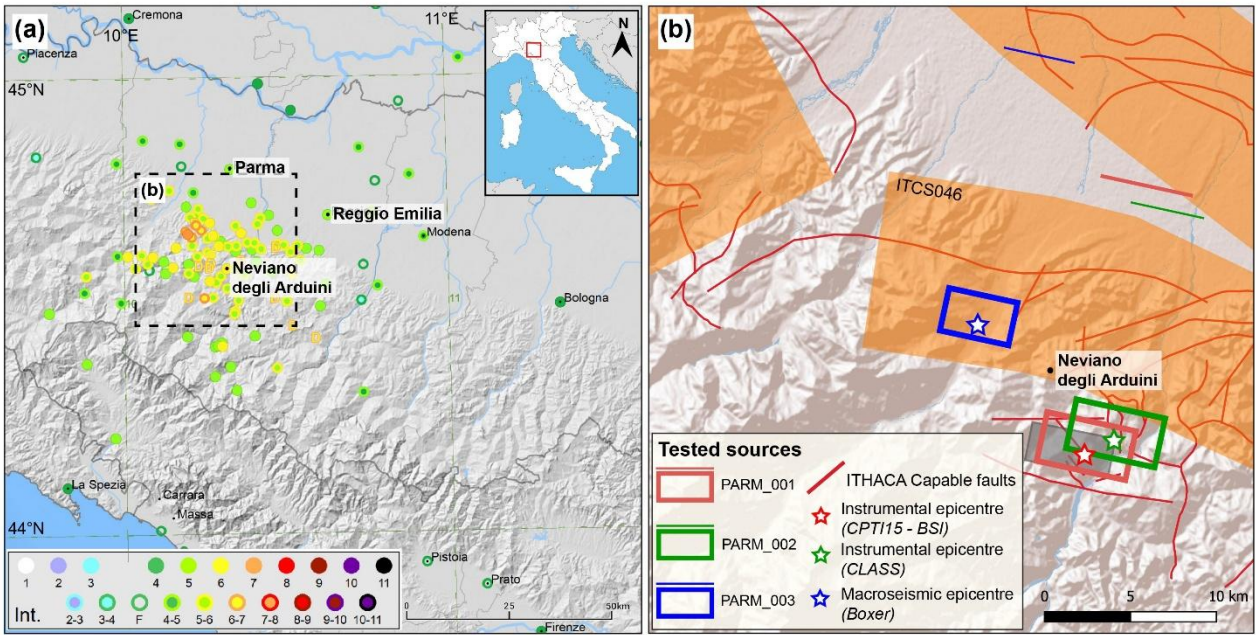


Figure 7 The December 23, 2008 (Mw 5.36) Parmense earthquake. (a) Macroseismic intensity distribution of the ERCAL009 dataset from Ercolani et al. (2009). (b) Tested source configurations (coloured rectangles). Red lines represent capable faults from ITHACA. The orange shaded area represents the Composite Seismogenic Source (CSS) “ITCS046”, while the grey rectangle represents the “ITIS135 Neviano degli Arduini” proposed by the DISS database (DISS Working Group, 2025). Red, green, and blue stars represent the instrumental epicentral solutions from CPTI15 (BSI), CLASS, and the macroseismic epicentre, respectively. The map in panel (a) is derived from the CPTI15-DBMI15, which uses the TINITALY DEM, whereas panel (b) is generated using the Esri Shaded Relief basemap. Sources: Esri | Powered by Esri.

3.2 Application to a historical event: The 1781 Cagli earthquake

For the application of the proposed workflow to a historical event, we selected the June 3, 1781 Cagli earthquake (https://emidius.mi.ingv.it/CPTI15-DBMI15/eq/17810603_0000_000). This earthquake was one of the largest and most damaging events that affected the Marche internal region in the last centuries (Fig. 1a-b).

Among the historical earthquakes included in our dataset, this event is characterised by the absence of a clear and unique seismotectonic interpretation. For this reason, it represents an appropriate case study to illustrate the application of the workflow to a historical event, i.e., where instrumental data are unavailable. In addition, it offers the opportunity to explore the influence of an alternative macroseismic field selected from those archived in the Italian Archive of Historical Earthquake Data (ASMI; Rovida et al., 2017, 2025) on the identification of the best seismogenic source.

According to CPTI15, the Boxer-derived epicentral location and magnitude of the 1781 Cagli earthquake are [43.596°N, 12.512°E] and Mw 6.51, respectively. These estimates were obtained from the macroseismic field adopted as the preferred in DBMI15. This intensity dataset (Monachesi, (1987; hereafter MONA987) consists of 157 IDPs with intensities ranging from 3-4 to 10 MCS (Fig. 8a). The alternative macroseismic field considered in this analysis was compiled by Guidoboni et al. (2018), hereafter CFTI5med. This dataset presents a slightly different spatial distribution of intensities and consists of 151 IDPs, ranging from 2-3 to 10 MCS (Fig. 8c). The macroseismic epicentre calculated from this dataset at [43.576°N, 12.548°E] results shifted to 3.6 km SE with respect to that from MONA987, and the corresponding magnitude estimate is Mw 6.33. The

488 application of the pre-processing on both the preferred and the alternative macroseismic field do not
489 affect the macroseismic parameters.

490 From a geological perspective, the 1781 Cagli earthquake is located between the northern-central
491 Apennine fold-and-thrust belt, in a zone currently undergoing crustal extension. However, according
492 to the literature, outcropping active faults capable of producing an event such as the 1781 earthquake
493 are not mapped in this sector of the Apennines (Fig. 8b-d).

494 Despite the absence of documented capable faults or clear geological evidence, the DISS database
495 suggests that the causative source of the 1781 Cagli earthquake is located on the Montiego thrust (Fig.
496 8b-d), a segment of a major thrust reactivated under the current extensional regime and emerging
497 along the Adriatic coastline. Based on this interpretation and the macroseismic parameters proposed
498 by CPTI15, the event is associated with the ISS labelled “ITIS047 Cagli”. This ISS represents a SW-
499 dipping structure (strike = 134°, dip = 30°, and rake = -90°), with the strike consistent with the general
500 orientation of the frontal thrusts of the Apennines in this sector (Fig. 8 b-d), while the rake reflects
501 regional geodynamic considerations. Conversely, De Donatis et al. (2020) documented the presence
502 of a fault system in the Monte Nerone area (Fig. 8 b-d). Specifically, this NW–SE to WNW–ESE
503 striking system of shallow normal faults shows stratigraphic, structural, and geomorphological
504 evidence of extensional tectonics, and they suggested that this fault system may be capable of
505 generating large earthquakes, as the 1781 Cagli event. However, no capable faults are currently
506 mapped in the Monte Nerone area in the ITHACA database (Fig. 8b-d).

507 To identify the best seismogenic source for this event, we applied the proposed workflow considering
508 both the seismotectonic interpretations described above and the two alternative macroseismic fields.
509 Specifically, we generated four alternative source configurations (Table 8): two (CAGLI_001 and
510 CAGLI_003) consistent with the orientation of the DISS hypothesis (ITIS047 Cagli) and two
511 (CAGLI_002 and CAGLI_004) consistent with the orientation of the fault system described by De
512 Donatis et al. (2020). For the latter two source hypotheses, we assumed a normal fault (strike = 110°,
513 dip = 55°, and rake = -90°). Each virtual source was constructed around the hypocentre, with rupture
514 length and width derived from the magnitude estimates using Wells and Coppersmith (1994). The
515 location and the dimensions of CAGLI_001 and CAGLI_002 are derived from the parameters
516 obtained with the MONA987 intensity dataset, those of CAGLI_003 and CAGLI_004 with the
517 macroseismic field from CFTI5med. For all source configurations, a fixed hypocentral depth of 10
518 km was assumed, consistent with the average depth of earthquakes in the area.

519 *Table 8 Tested sources for the 1781 Cagli earthquake. Source geometries (strike, dip, and rake) for CAGLI_001 and CAGLI_003 are*
520 *based on ITIS047 Cagli (Diss Working Group, 2025), whereas those for CAGLI_002 and CAGLI_004 are based on the orientation of*
521 *the Mt. Nerone fault system (De Donatis et al., 2020).*

Reference earthquake parameters	Epicentre [Lat, Lon]	Mw	Strike/Dip/Rake (°)	Length (km)	Width (km)	Depth (km)	Tested Source
MONA987 (Monachesi, 1987)	[43.596°N, 12.512°E]	6.51	134/30/-90	24.8	11.7	10	CAGLI_001
MONA987 (Monachesi, 1987)	[43.596°N, 12.512°E]	6.51	110/55/-90	24.8	11.7	10	CAGLI_002
CFTI5med (Guidoboni et al., 2018)	[43.576°N, 12.548°E]	6.33	134/30/-90	10.1	10.1	10	CAGLI_003
CFTI5med (Guidoboni et al., 2018)	[43.576°N, 12.548°E]	6.33	110/55/-90	10.1	10.1	10	CAGLI_004

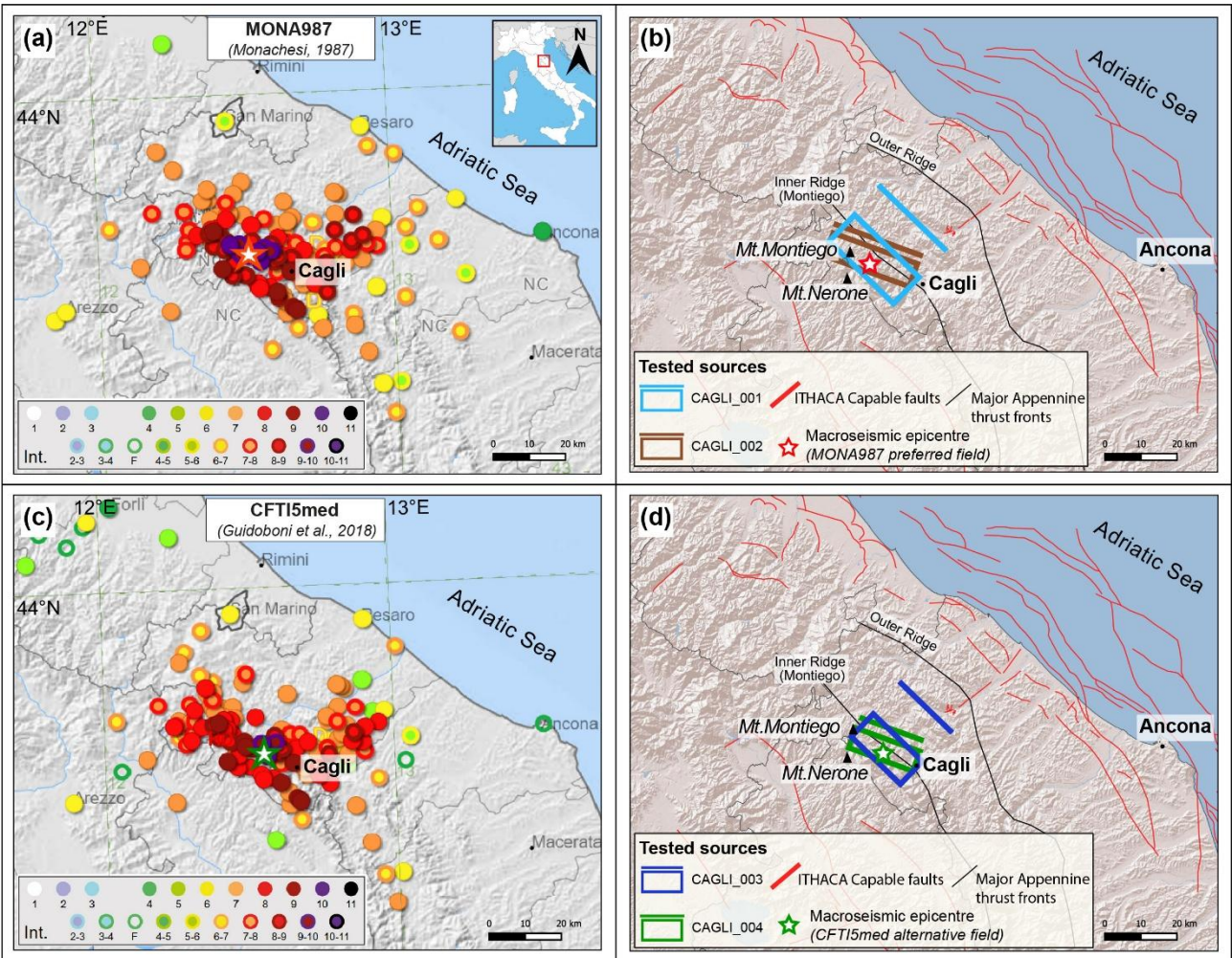
522 The results of the analysis are summarised in Table 9. The residuals obtained with the GOM20 model
523 exhibit negative BE_I values for all tested source configurations, indicating a general overestimation
524 of the observed intensities. In contrast, the residuals obtained with OLI22 indicate overestimation for
525 the CAGLI_001 and CAGLI_002 sources (Table 9 and Fig. 8b), and underestimation for CAGLI_003

526 and CAGLI_004 (Table 9 and Fig. 8d); nevertheless, they are significantly lower than those obtained
527 with GOM20.

528 *Table 9 Residual analysis for the tested seismogenic sources of the 1781 Cagli earthquake. BE_I and RMSE_I values are obtained from*
529 *PGV using the GOM20 and OLI22 conversion equations.*

Test macroseismic field	Source	BE _I - RMSE _I (GOM20)	BE _I - RMSE _I (OLI22)
MONA987	CAGLI_001	-0.71–1.22	-0.02–0.94
MONA987	CAGLI_002	-0.91–1.37	-0.17–0.97
CFTI5med	CAGLI_003	-0.37–1.01	0.23–0.97
CFTI5med	CAGLI_004	-0.56–1.10	0.06–0.90

530 Overall, the lowest BE_I and RMSE_I values, for both the GOM20 and OLI22 conversion equations,
531 are obtained for the CAGLI_003 and CAGLI_004 source configurations. Although the strike
532 orientation of CAGLI_003, consistent with the DISS source (ITIS047 CAGLI), is more compatible
533 with the regional structural setting, both configurations provide a comparable fit to the observed
534 macroseismic data. In particular, the predicted intensities derived from these fault models exhibit
535 smaller residuals irrespective of the adopted GMICE. The comparison between the two macroseismic
536 datasets indicates that the CFTI5med dataset (Guidoboni et al., 2018) systematically yields lower
537 residuals than the MONA987 dataset (Monachesi, 1987), suggesting that a lower magnitude (Mw
538 6.33) may be more consistent with this event.



539 *Figure 8 The June 3, 1781 Cagli earthquake. (a) Macroseismic intensity distribution of the MONA987 dataset from Monachesi (1987).*
540 *(b) Tested source configurations (CAGLI_001 and CAGLI_002). (c) Macroseismic intensity distribution of the CFTI5med dataset from*
541

542 *Guidoboni et al. (2018). (d) Tested source configurations (CAGLI_003 and CAGLI_004). Red lines represent capable faults from*
543 *the ITHACA database, while black lines indicate the main frontal thrusts of the Apennines, including the Montiego thrust cited in the*
544 *text. Red and green stars represent the macroseismic epicentre derived from MONA987 and CFTI5med datasets, respectively. The*
545 *maps in panels (a) and (c) is derived from the CPTI15-DBMI15, which uses the TINITALY DEM, whereas panels (b) and (d) are*
546 *generated using the Esri Shaded Relief basemap. Sources: Esri | Powered by Esri.*

547 4. Discussion and conclusions

548 In Italy, a few methodological approaches have been proposed over the last decades for the
549 reconstruction of historical earthquake sources. Such previous studies include the pioneering work of
550 Gasperini et al. (1999) which presents the first attempt to infer source geometry directly from the
551 spatial distribution of macroseismic observations, demonstrating that the elongation of the intensity
552 field contains valuable information on source orientation and dimensions. Nevertheless, the
553 methodology relies on simplifying assumptions. In particular, the orientation of the inferred source
554 geometry is estimated from the azimuthal distribution of the highest intensity observations using a
555 circular mean, providing a strike between 0° and 180° without resolving the fault dip direction. In
556 addition, a fixed dip angle of 45° is assumed for all the seismogenic boxes, regardless of the
557 geological characteristics of the candidate seismogenic structures.

558 Visini et al. (2009) demonstrated the potential of combining ground motion simulations with
559 macroseismic data to evaluate competing seismogenic hypotheses for the 1693 Sicilian earthquake.
560 Their approach evaluates a set of predefined fault models through synthetic ground motion
561 simulations and statistical comparison with the observed intensities. Nevertheless, the geometry of
562 the analysed sources is assumed a priori from previously proposed tectonic models, rather than being
563 derived from the earthquake magnitude. Furthermore, the conversion between simulated ground
564 motion parameters and macroseismic intensity relied on empirical relations not calibrated on Italian
565 earthquakes.

566 More recently, Sgobba and Pacor (2023) proposed a non-ergodic empirical framework for
567 reconstructing shaking scenarios of historical earthquakes, accounting for source, path and site effects
568 specifically of Central Italy, by incorporating spatially variable source, propagation and site
569 corrections. However, the approach requires the earthquake magnitude and fault geometry (i.e., fault
570 vertices, strike and rupture dimensions) to be defined a priori. Consequently, its applicability depends
571 on the availability of an independently constrained seismogenic source, making it particularly suitable
572 for well-characterised historical earthquakes but less appropriate when the source itself remains
573 uncertain.

574 Nevertheless, a common limitation of these studies is the absence of standardised metrics for source
575 validation. This study aims to fill this gap by proposing an integrated and reproducible workflow that
576 combines geological constraints, empirical fault-scaling relationships, regionally calibrated intensity-
577 to-ground-motion conversions, and ground motion simulations. Candidate seismogenic sources are
578 objectively ranked through quantitative statistical metrics, including between-event (BE) residuals
579 and RMSE values, allowing the identification of the best-fitting source according to predefined
580 thresholds.

581 This approach integrates an initial pre-processing stage for the identification and removal of potential
582 outliers, followed by three main stages: (i) earthquake parameter estimation using the Boxer code,
583 (ii) seismogenic source reconstruction and ground-motion simulation, and (iii) validation of the
584 inferred source geometries through residual analysis (see Sect. 3) and comparison with geologic
585 lineaments.

586 The pre-processing procedure aims at identifying macroseismic fields that require closer scrutiny or,
587 in some cases, exclusion from the analysis. Although the presence of some possible over- or
588 underestimated intensity value does not significantly change the macroseismic location and
589 magnitude obtained with the adopted Boxer method, it may significantly affect the analysis of the
590 residuals and, consequently, the interpretation of the geometry and dimensions of the seismogenic
591 source.

592 The application of the proposed workflow to the selected instrumental earthquakes shows that
593 macroseismic-derived parameters can provide realistic seismogenic source geometries that are mostly
594 consistent with those derived from instrumental solutions. The validation has been performed for a
595 wide magnitude range and with the aid of accelerometric recordings and mapped geological structures
596 (e.g., 1984 Monti della Meta, 1989 Prealpi Vicentine, and 2008 Parmense earthquakes). The
597 reliability of these results is confirmed by the fact that the residual values (BE and RMSE) obtained
598 from accelerometric data align closely with the standard deviation (σ) of the adopted ITA18 GMM
599 by Lanzano et al. (2019).

600 The application of the proposed workflow to the 1781 Cagli earthquake allows to select between
601 alternative macroseismic fields for discriminating the best-fitting seismogenic source. Two
602 alternative and reliable intensity datasets (Monachesi, 1987; Guidoboni et al., 2018) were simulated
603 with four source hypotheses. The comparison of the residuals obtained from the simulations of the
604 two datasets indicates that the seismogenic sources based on parameters derived from the CFTI5med
605 dataset provide a better fit to the observed data in terms of BE_I and $RMSE_I$ values.

606 The results further suggest that shaking scenarios simulated with a lower magnitude estimate (i.e.,
607 Mw 6.33) could be more consistent with this event. This implies that the coherence between intensity
608 data points (IDPs), earthquake parameters, source geometry, and ground motion simulations can lead
609 to a more comprehensive reconstruction of both the earthquake effects and the causative fault.

610 Based on the findings of this study, the workflow can be systematically applied to reconstruct the
611 seismogenic sources of the strongest Italian historical earthquakes ($M_w \geq 5.5$) reported in CPTI15-
612 DBMI15, and for which consistent intensity distributions are available.

613

614 Data availability

615 The data used in this study are publicly available. The selected dataset and the reference macroseismic
616 earthquake parameters are obtained from the Catalogo Parametrico dei Terremoti Italiani (CPTI15, version
617 4.0; Rovida et al., 2022; <https://emidius.mi.ingv.it/CPTI15-DBMI15/>). The macroseismic data are retrieved
618 from the Italian Macroseismic Database (DBMI15, version 4.0; Locati et al., 2022) and the Italian Archive of
619 Historical Earthquake Data (ASMI; Rovida et al., 2017, 2025; <https://emidius.mi.ingv.it/ASMI/>). Instrumental
620 earthquake parameters are obtained from both CPTI15 v4.0 and CLASS (Catalogue of Absolute Locations;
621 Latorre et al., 2022; <https://ingv.github.io/class/locations/>). The DEM used in figures provided by the CPTI15-
622 DBMI15 catalogue is the TINITALY (Tarquini et al., 2007, 2023), accessible at
623 <https://doi.org/10.13127/tinitaly/1.1>. Other basemaps used in the figures include Google Satellite imagery
624 (map data ©2015 Google) and Esri Shaded Relief basemaps (Sources: Esri | Powered by Esri). The revised
625 macroseismic earthquake parameters, the epicentral distances (in km), and the magnitude differences between
626 preferred and revised macroseismic estimates, as well as between macroseismic and instrumental solutions
627 (when available), are reported in Table S1.

628 Author contributions

629 VG and LL conceptualized the study. VG developed the methodology, performed the analysis, and wrote the
630 manuscript. LL, AA, and AR contributed to the interpretation of the results and critically revised the
631 manuscript. All authors reviewed and approved the final version of the manuscript.

632 Competing interests

633 The authors declare that they have no conflict of interest.

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