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An Updated, Homogeneous, and Declustered Earthquake Catalog for Albania and the Surrounding Region

By Klajdi Qoshi* & Edmond Dushi[±]

This paper presents a homogenized earthquake catalog for Albania and the surrounding region covering the period 1900 - 2024. The study area is defined by a geographical polygon bounded by latitudes 38.0°- 44.5° N and longitudes 17.0°- 23.5° E. The catalogue was developed by integrating data from multiple authoritative sources, including the Albanian National Earthquake Data Center (IGEO), the European-Mediterranean Earthquake Catalogue (EMEC) up to 2021, and the reviewed data from the International Seismological Centre (ISC) for the period 2022–2024. A rigorous data integration and quality-control procedure was applied to identify and remove duplicate events using spatial and temporal matching criteria. Catalogue homogeneity was ensured by converting all reported magnitudes to Mw using established empirical relations and a newly derived ML-Mw regression for Albania. The resulting catalog contains 10946 seismic events with magnitudes ranging from 3.5 to 7.2 Mw. To identify independent seismic events, three declustering methods were applied: Gardner and Knopoff (1974), Grünthal (as reported in Stiphout et al., 2012), and Uhrhammer (1986). Catalogue completeness was evaluated using the Stepp (1972) method, allowing the determination of completeness magnitudes and their temporal evolution. The resulting catalog represents an updated and homogeneous seismic database for Albania and provides a consistent basis for seismicity studies, seismotectonic analyses, seismic source characterization, and future probabilistic seismic hazard assessments.

Keywords: Homogeneous earthquake catalog, Albania, seismicity, declustering, catalog completeness (M_c), moment magnitude (M_w), ISC

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Introduction

Albania and the surrounding region are located within the active convergence zone between the Adria microplate and the Eurasian plate, part of the complex Dinarides-Albanides-Hellenides tectonic system. The ongoing interaction between these tectonic domains has generated significant level of seismic activity, making the region one of the most seismically active areas in the Mediterranean (Aliaj et al. 2010). Throughout its seismic history, the region has experienced several destructive earthquakes, including the 1905 Shkodër earthquake with magnitude M_s 6.6 (Koçiaj and Sulstarova 1980), the 1967 Dibër earthquake with M_s 6.6 (Sulstarova and Koçiaj 1980), the 1979 Montenegro earthquake with M_s 6.9 (Karnik 1996), and, more recently, the 2019 Durrës earthquake with M_w 6.4 (Moshou et al. 2019). Given the high level of seismic activity (Aliaj et al. 2010), the continuous development and updating of earthquake catalogues are essential for accurately documenting regional seismicity and improving seismic hazard assessments.

Earthquake catalogues represent a fundamental parametric database used for seismic hazard assessment (Danciu et al. 2024). These resources are the result of complex procedures ranging from network configuration to magnitude scaling that go beyond a simple documentation of time, location, and magnitude. The progressive development of instrumental seismic monitoring in the region has led to the publication of numerous earthquake catalogues over recent decades (Papazachos et al. 2010, Muço 1998, Sulstarova et al 2000, Aristotle University of Thessaloniki 1981). The objective of this study is to compile an updated, homogenized and comprehensive earthquake catalog for Albania and the surrounding region. We follow a rigorous methodology for compiling earthquake catalog for national seismic hazard maps similar to the steps described by Mueller (2019) and Weatherill et al. (2016). The primary dataset for this study was derived from the monthly bulletins of the Institute of Geosciences (IGEO). Different magnitude types reported in the IGEO database were homogenized to a common moment magnitude scale (M_w). The homogenization procedure included the development of a new ML - M_w regression equation for earthquakes reported by the Albanian Seismological Network. The adoption of M_w is critical as it avoids the saturation effects inherent in other magnitude scales, providing a physically robust and consistent measure of earthquake size across all magnitude ranges (Grünthal and Wahlström 2012). The homogenized IGEO catalogue was subsequently merged with the European-Mediterranean Earthquake Catalogue 2021 (EMEC-2021) compiled by Lammers et al. (2023). Since the EMEC catalogue extends only through 2021, the dataset was supplemented with ISC-reviewed events from the International Seismological Centre (ISC) Bulletin covering the period from January 2022 to February 2024. Earthquake magnitudes contained in the ISC Bulletin were originally reported in different magnitude scales, including ML , M_s , and mb . To ensure catalogue homogeneity, all magnitudes were converted to moment magnitude (M_w). The compiled uniform earthquake catalog consists of 14,852 seismic events with magnitudes ranging from 3.5 to 7.2 M_w , spanning the period from 1900 to February, 2024, and covering a region bounded by latitudes 38.0°N to 44.5°N and longitudes 17.0°E to 23.5°E . To evaluate the robustness of the compiled

earthquake catalogue, a comparative analysis was conducted against the International Seismological Centre (2026), ISC-GEM Earthquake Catalogue (Storchak et al. 2013, 2015, Di Giacomo et al. 2018), one of the most widely used global reference catalogues for significant earthquakes. For reliable seismicity analysis and seismic hazard assessment, the earthquake catalogue must be declustered to retain only independent events. In this study, three widely used window-based declustering algorithms were applied in order to minimize methodological bias. After the extraction of the mainshock catalogue, an assessment of catalogue completeness was performed. Earthquake catalogues are strongly influenced by the capability of seismic networks, and smaller events are frequently missing, especially during earlier instrumental periods. Because the detection threshold changes over time with improvements in seismic instrumentation and network coverage, the temporal variation of M_c was investigated.

The paper is structured as follows: Section 1 introduces the study, highlighting the importance of homogeneous earthquake catalogues for seismicity analyses and seismic hazard assessment, as well as the objectives of the present research. Section 2 reviews the relevant literature on earthquake catalogue compilation, magnitude homogenization, declustering techniques, and completeness assessment. Section 3 presents the methodological framework adopted for catalogue compilation, including data collection, magnitude homogenization, and validation through comparison with the ISC-GEM catalogue. Section 4 presents the declustering procedures applied to identify independent seismic events and evaluates the performance of different declustering algorithms. Section 5 analyses the completeness analysis of the resulting declustered catalogues and determines the corresponding completeness periods for different magnitude ranges. Section 6 summarizes the main conclusions drawn from this study.

Literature Review

A homogeneous earthquake catalogue is essential for reliable seismicity analysis and seismic hazard assessment. Recent methodologies for catalogue compilation, homogenization, and quality control have been comprehensively described by Mueller (2019) and Weatherill et al. (2016). Seismic hazard analysis requires earthquake catalogues to be homogenized to a common magnitude scale, most commonly moment magnitude M_w (Hanks and Kanamori 1979). Unlike traditional scales such as body-wave magnitude (m_b), surface-wave magnitude (M_s), or local magnitude (M_L), M_w provides a more stable and physically meaningful representation of earthquake size, particularly for strong events. Magnitude homogenization commonly relies on empirical relations that convert different magnitude scales to equivalent M_w values. Widely used global conversion models were developed by Scordilis (2006). Regional differences in magnitude determination procedures often require locally calibrated relations. Duni et al. (2010), for example, derived regional conversion relations for the Southern Western Balkan region to correct magnitude inconsistencies among local agencies. The statistical methodology used for magnitude conversion also plays a critical role in

the reliability of homogenized catalogues. Traditional least squares regression techniques may introduce bias because they neglect uncertainties associated with the independent variables. Consequently, more recent studies such as Das et al. (2013), and Di Giacomo et al. (2015), are using methods such as orthogonal regression or errors in variables approaches, which explicitly account for uncertainties in both magnitude scales. In addition to magnitude homogenization, earthquake catalogue compilation requires extensive quality control procedures to ensure consistency and reliability (Grünthal and Wahlström 2012). One of the challenges involves identifying duplicate entries that arise when multiple catalogues are merged. These duplicates are detected using spatial and temporal association criteria.

The construction of a complete, homogenized catalog is followed by procedure of declustering and completeness analysis. Windowing techniques represent one of the most widely used and conceptually straightforward approaches to seismicity declustering. These methods operate by separating mainshocks from dependent events through predefined spatial and temporal distance thresholds. Among them, the algorithm proposed by Gardner and Knopoff (1974) remains one of the most commonly applied methods in seismology because of its simplicity and computational efficiency. The approach applies magnitude dependent spatial and temporal windows to identify and remove aftershocks from earthquake catalogues. Alternative parameterizations of the interaction windows were later proposed. Grünthal (reported in van Stiphout et al. 2012) and Uhrhammer (1986) introduced modified empirical relationships for defining magnitude dependent spatial and temporal windows. Although the parameterizations differ, all three methods share the same fundamental operational principle. Catalogue completeness analysis is commonly performed using the statistical framework proposed by Stepp (1972), which is based on the assumption that earthquake occurrences follow a Poisson process. In a complete and stationary catalogue, the mean seismicity rate and its variance are expected to remain stable through time, while the standard deviation of the mean rate decreases systematically as the observation period increases. The method therefore evaluates whether the observed seismicity follows this expected statistical behavior. By identifying the magnitude level at which the catalogue satisfies the stationarity condition, the magnitude of completeness can be estimated. The Stepp method is particularly useful for analyzing temporal variations in catalogue completeness and changes in detection capability over time. However, the precision of the estimated completeness magnitude depends on the selected magnitude binning scheme, which may limit the resolution of the analysis.

Methodology for Catalog Compilation

The methodology adopted for earthquake catalogue compilation consists of the following steps:

- 1) Earthquake data source: Historical and instrumental earthquake data were collected from three principal sources: the Institute of GeoSciences (IGEO), the

European-Mediterranean Earthquake Catalogue (EMEC-2021), and the International Seismological Centre (ISC) Bulletin. The IGEO catalogue provides instrumental seismicity for Albania during the period 1996-2024, while EMEC-2021 provides regional seismicity for the period 1900-2021. To extend the catalogue beyond 2021, additional ISC-reviewed events were extracted from the ISC Bulletin up to February 2024. The study area was defined using a geographic polygon bounded by latitudes 38.0° - 44.5° N and longitudes 17.0° - 23.5° E.

2) Magnitude homogenization: Since the compiled datasets contained different magnitude types, including local magnitude (ML), coda magnitude (Mc), body-wave magnitude (mb), and surface-wave magnitude (MS), a homogenization procedure was applied to express all events in terms of moment magnitude (Mw). For the IGEO catalogue, coda magnitudes were first converted to equivalent local magnitudes using General Orthogonal Regression (GOR) following methodology by Castellaro et al. (2006). Subsequently, local magnitudes were converted to Mw using the empirical relationships proposed in this paper. For the ISC Bulletin and regional agency datasets, reported mb and MS values were converted to Mw using the relationships proposed by Scordilis (2006), while agency-specific conversion equations were adopted for events reported by THE (Thessaloniki), BEO (Belgrade), PDG (Podgorica), SKO (Skopje), ROM (INGV), and RHSSO (Banja Luka). The resulting catalogue was therefore expressed in a unified Mw scale, ensuring consistency and comparability among all seismic records.

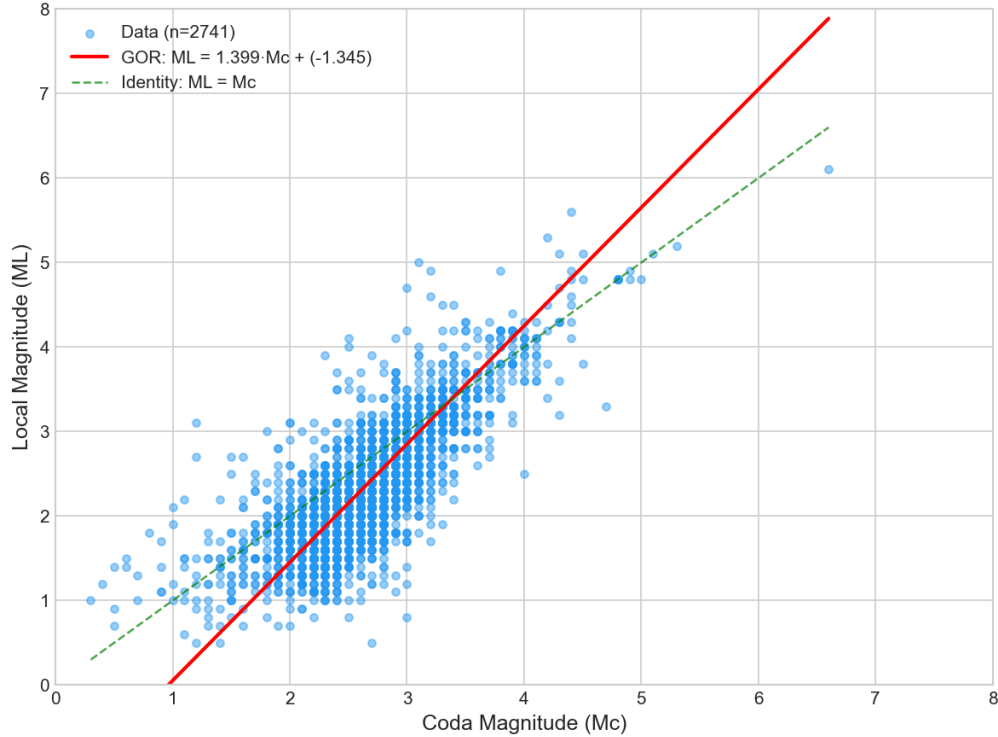
3) Merged earthquake catalogue: Following homogenization, earthquake records from the IGEO catalogue, EMEC-2021, and the ISC Bulletin were integrated into a single database. Because multiple agencies may report the same earthquake, a duplicate-identification procedure was implemented using spatio-temporal windowing criteria following Weatherill et al. (2016). Potential duplicate events were identified through temporal and spatial thresholds and subsequently verified manually before removal. This procedure ensured the construction of a consolidated catalogue free from redundant entries.

Earthquake Catalog Compilation

The initial seismic dataset was compiled from the Institute of Geosciences (IGEO) earthquake catalog for the period 1996 - 2024 and consisted of 23596 recorded events with magnitude range from 0.5 to 6.3. Examination of the available magnitude types showed that 20,855 events were reported exclusively with local magnitude (ML), 3,166 events contained only coda magnitude (Mc), while 2,741 events included both ML and Mc estimates. To obtain a homogeneous earthquake catalog expressed in a single magnitude scale, an empirical conversion relationship between Mc and ML was derived using the subset of 2,741 events containing both magnitude measurements. The conversion was performed through General Orthogonal Regression (GOR), following the methodology proposed by Castellaro et al. (2006). Unlike ordinary least-squares regression, GOR accounts for uncertainties in both variables and is therefore more appropriate for analyses of magnitude conversion. The resulting orthogonal regression relationship is given by:

$$M_L = 1.3991 M_C - 1.3452$$

Figure 1. *GOR-Derived Relationship Between Coda Magnitude and Local Magnitude*

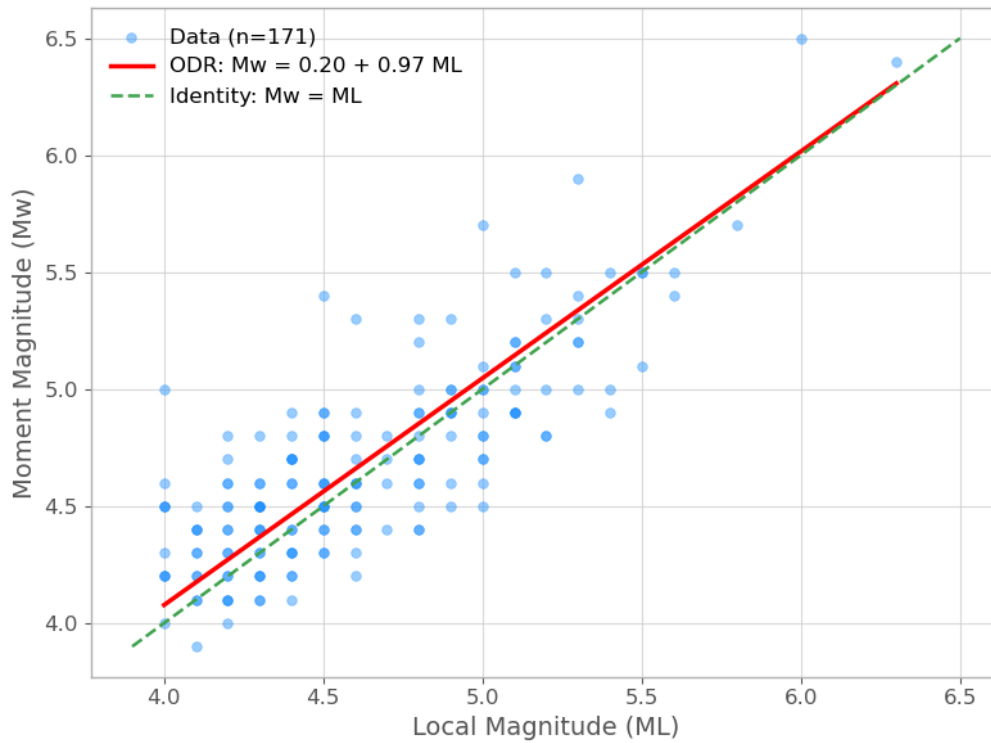


The regression analysis indicates a statistically significant and moderately strong linear relationship between the two magnitude scales. The derived equation was subsequently applied to estimate equivalent ML values for the 3,166 earthquakes for which only M_c values were available, thereby completing the homogenization of the seismic catalog in terms of ML.

A novel empirical conversion relationship was developed to convert local magnitudes (ML) reported by the Albanian Seismological Network (ISC network code: TIR) into moment magnitudes (M_w). A dataset of 171 earthquakes spanning the period 1985-2024 and covering the magnitude range 4.0-6.5 M_w was extracted from the ISC Bulletin. The dataset comprises events for which local magnitudes (ML) were reported by TIR and corresponding moment magnitudes (M_w) were available from moment tensor solutions provided by the Global Centroid Moment Tensor Project (GCMT), the MedNet Regional Centroid Moment Tensor Project (MED-RCMT) for the Euro-Mediterranean region, and the Swiss Seismological Service (ZUR-RMT). The ML- M_w conversion relationship was calibrated using GOR, yielding the following equation:

$$M_w = 0.97M_L + 0.2$$

The resulting model achieved a coefficient of determination of $R^2 = 0.62$ and a standard deviation of 0.27.

Figure 2. *GOR-Derived Relationship Between Moment Magnitude and Local Magnitude*

In addition, the European-Mediterranean Earthquake Catalogue (EMEC-2021), recently compiled by Lammers et al. (2023), was incorporated into the present study. The catalog was spatially filtered using a geographic polygon bounded by latitudes 38.0°N to 44.5°N and longitudes 17.0°E to 23.5°E. As it only extends to 2021, we have supplemented it with ISC-reviewed data from the ISC Bulletin up to February 2024, with magnitude greater than 3.5. As the study area polygon extends beyond the region routinely monitored by the Institute of GeoSciences (IGEO), and considering that several neighbouring seismological agencies contribute earthquake solutions to the International Seismological Centre catalogue, priority was assigned to ISC-reported events. Subsequently, earthquake parameters from the most relevant regional agencies were considered according to the geographical location of each event, including TIR, THE, ZAG, PDG, SKO, BEO, RHSSO, and ROM. Since the International Seismological Centre bulletin contains earthquake magnitudes reported in different magnitude scales, including local magnitude (ML), surface-wave magnitude (MS), and body-wave magnitude (mb), a homogenization procedure was applied to convert all reported magnitudes into a unified moment magnitude (Mw) scale, thereby ensuring the consistency and comparability of the compiled earthquake catalogue.

For the conversion of surface-wave magnitude (MS) and body-wave magnitude (mb) to moment magnitude (Mw), the empirical relationships proposed by Scordilis (2006) were adopted, as they represent some of the most widely applied and internationally recognized conversion relationships in seismological studies:

$$M_W = 0.67M_S + 2.07 \quad 3.0 \leq M_S \leq 6.1,$$

$$M_W = 0.99M_S + 0.08 \quad 6.2 \leq M_S \leq 8.2,$$

$$M_W = 0.85m_b + 1.03 \quad 3.5 \leq m_b \leq 6.2$$

In addition, magnitude reported by regional seismological agencies were transformed into equivalent moment magnitude (M_W) values using the empirical conversion relationships developed by Duni et al. (2010):

Podgorica	(PDG):	$M_W = 0.985 ML + 0.218$
Belgrade	(BEO):	$M_W = 0.963 ML + 0.324$
Skopje	(SKO):	$M_W = 0.880 ML + 0.912$
Thessaloniki	(THE):	$M_W = 1.010 ML + 0.383$

Earthquakes reported from the Republic of Srpska's Hydrometeorological Service's Seismological Observatory in ML are converted to M_W using the York regression (Herak 2020):

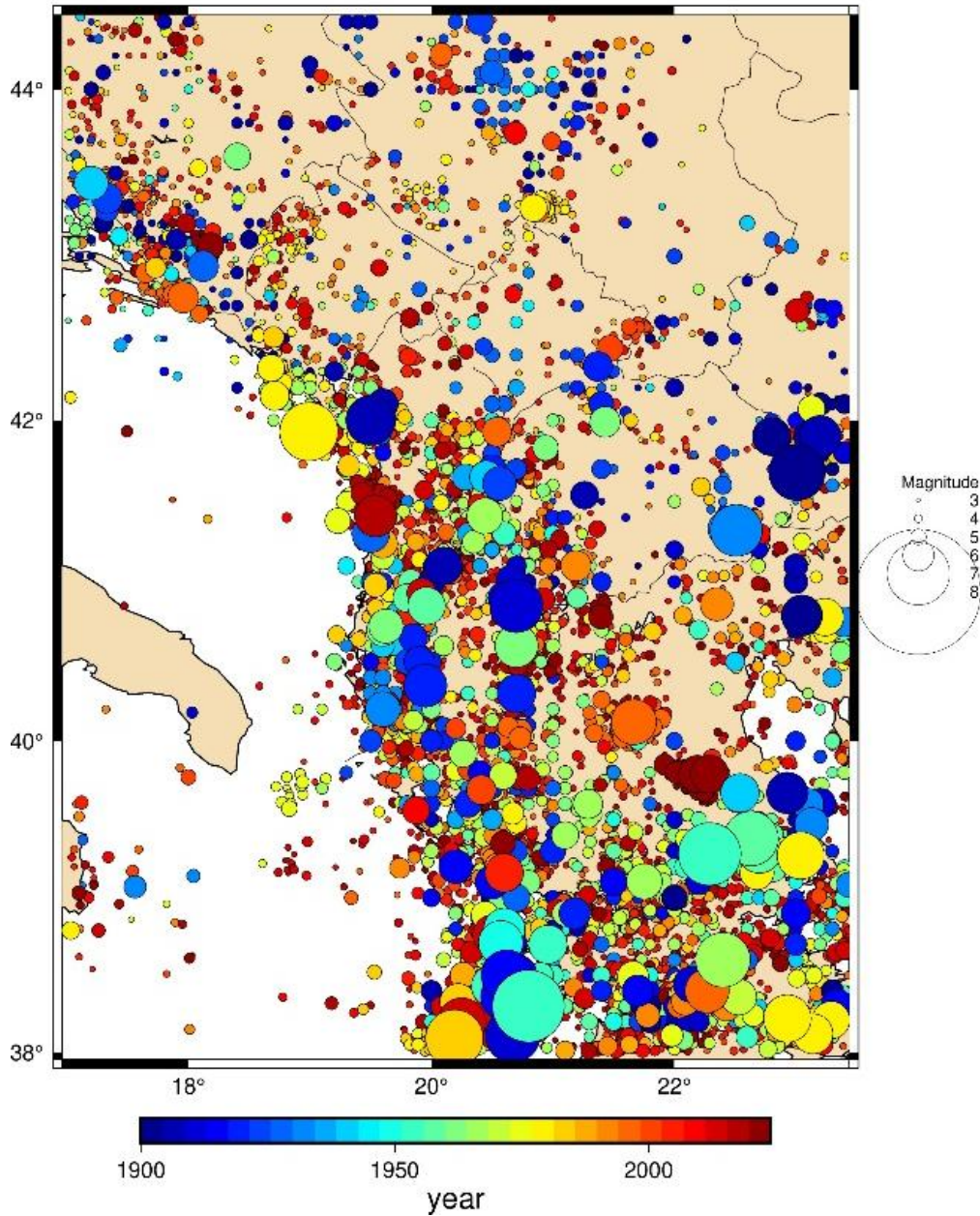
$$M_W = 0.992 ML - 0.062$$

For the event reported by Roma Center, National Institute of Geophysics and Volcanology (INGV) the equation proposed by Di Bona (2016) is employed:

$$M_W = 0.915 ML + 0.31$$

The final dataset was compiled by combining all records from three primary sources: EMEC-2021, the ISC Bulletin, and the IGEO catalog. Spatio-temporal windowing criteria were applied to identify and remove duplicate events, following methodologies recommended by Weatherill et al. (2016). Specifically, a temporal window of 60 seconds and a spatial threshold of approximately 110 km were utilized. All potential duplicate pairs detected by the automated filtering process were manually reviewed to confirm their duplication status before removal. The final catalog contains 10946 unique events with M_W magnitude greater than 3.5 from 1900 to February 2024.

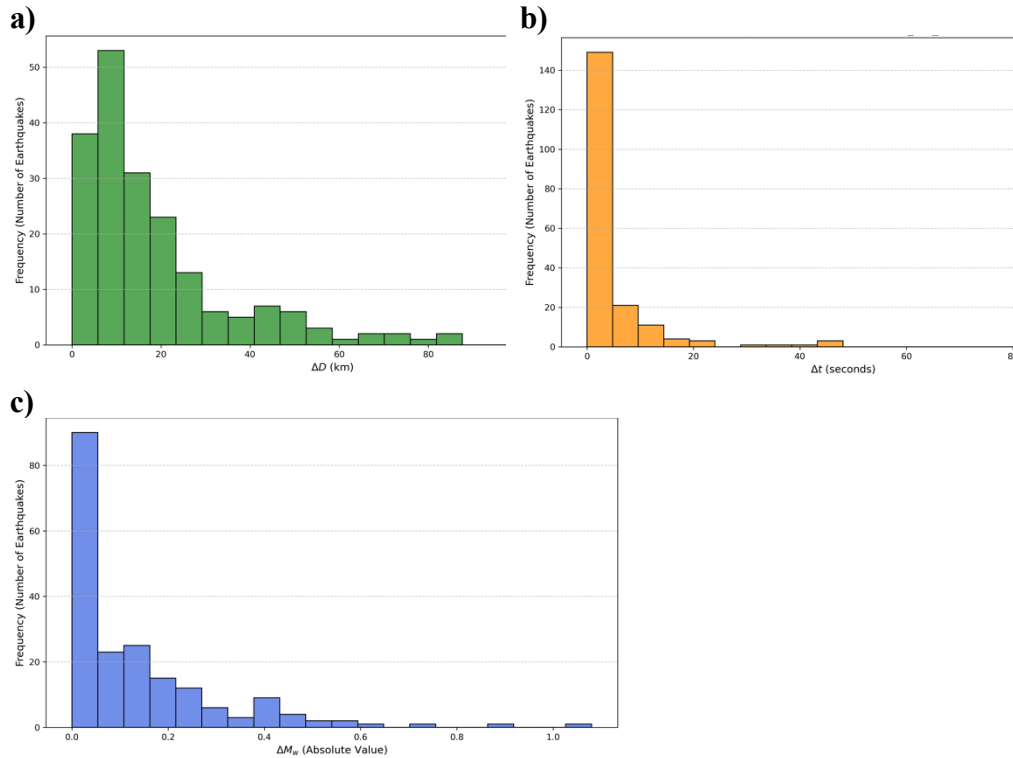
Figure 3. *Spatial Distribution of the Homogeneous Earthquake Catalogue Compiled for Albania and Adjacent Regions, Covering the Period 1900-2024*



To evaluate the consistency of the compiled catalogue, a comparison was performed between the compiled catalog and ISC-GEM catalogue (Storchak et al. 2013, 2015, Di Giacomo et al. 2018) for earthquakes with $M_w \geq 5.5$. Matched events were identified using temporal and spatial association criteria, and the resulting differences in magnitude, origin time, and epicentral location were analyzed. The magnitude comparison reveals a strong agreement between the two catalogues, as most events exhibit magnitude differences smaller than 0.2 M_w , with the highest concentration occurring below 0.1 M_w . This indicates that the magnitude homogenization procedures adopted in the compiled catalogue produce

results that are largely consistent with those reported in ISC-GEM. Likewise, the distribution of origin-time differences is strongly concentrated near zero, with most paired events differing by only a few seconds, demonstrating a high degree of temporal consistency. The spatial comparison also indicates satisfactory agreement, with the majority of epicentral differences being smaller than 20 km. Nevertheless, a limited number of events show larger discrepancies in both location and magnitude, forming a small set of outliers. These differences may reflect variations in the underlying datasets, event relocation procedures, and magnitude determination methodologies. In particular, ISC-GEM incorporates a comprehensive global relocation and magnitude reassessment procedure, whereas our catalogue integrates information from multiple regional and international sources. Despite the presence of a few outliers, the overall distributions of ΔM_w , Δt , and ΔD demonstrate a high level of agreement between the two catalogues, supporting the reliability and robustness of the compiled earthquake catalogue for subsequent seismicity and seismic hazard analyses.

Figure 4. *Distributions of Parameter Differences between Earthquakes in the Compiled Catalogue and the ISC-GEM Catalogue: (a) Epicentral Location Difference, (b) Origin-Time Difference, and (c) Magnitude Difference*



Decustering of Earthquake Catalog

A foundational principle of probabilistic seismic hazard assessment (PSHA) asserts that the catalog of earthquake occurrence data follows a Poisson distribution. To satisfy this assumption, it is necessary to distinguish mainshock events from dependent events such as foreshocks and aftershocks within the earthquake catalog.

Gardner and Knopoff (1974) introduced a straightforward windowing algorithm. The core of their approach relies on identifying aftershocks using specific time and distance windows that scale directly with the magnitude of the mainshock. One of the algorithm's strengths is its ability to detect both foreshocks and aftershocks, simply by extending these time windows backward and forward from the main seismic event. Although numerous refinements and alternative parameterizations of the interaction windows have been developed in subsequent studies (van Stiphout, 2012), the original relationships proposed by Gardner and Knopoff (1974) remain widely adopted and can be approximated by:

$$\begin{aligned} d(\text{km}) &= 10^{0.1238M+0.983} \\ t(\text{days}) &= \begin{cases} 10^{(0.032M+2.7389)} & \text{if } M \geq 6.5 \\ 10^{(0.5409M-0.547)} & \text{otherwise} \end{cases} \end{aligned}$$

Grünthal (as reported in vanStiphout, 2012) proposes an alternative formulation:

$$\begin{aligned} d(\text{km}) &= e^{1.77+(0.037+1.02M)^2} \\ t(\text{days}) &= \begin{cases} |e^{(-3.95+(0.62+17.32M)^2)}| & \text{if } M \geq 6.5 \\ 10^{(2.8+0.024M)} & \text{otherwise} \end{cases} \end{aligned}$$

Alternatively, Uhrhammer (1986) suggested a different set of spatiotemporal windows, defined as:

$$\begin{aligned} d(\text{km}) &= e^{(-1.024+0.804M)} \\ t(\text{days}) &= e^{(-2.87+1.235M)} \end{aligned}$$

The compiled earthquake catalogue, consisting of 10945 seismic events, was declustered using the Gardner and Knopoff (1974), Grünthal, and Uhrhammer (1986) methodologies as implemented in the OpenQuake Engine (Pagani et al. 2014), in order to remove dependent earthquakes and retain a catalogue representative of background seismicity. This procedure is an essential prerequisite for statistical analyses and probabilistic seismic hazard assessment, where earthquake occurrence is commonly assumed to follow a Poissonian process. Following the removal of foreshocks and aftershocks, the resulting declustered catalogues provide a representation of the background seismicity consisting of independent mainshock events. The application of the Gardner and Knopoff algorithm resulted in a declustered catalogue containing 3506 mainshocks, while the Grünthal methodology produced a more restrictive catalogue with 2281 independent events. In contrast, the Uhrhammer approach retained 6061 earthquakes as mainshocks, yielding the largest declustered dataset among the three methods.

The figures below present the spatial and temporal characteristics of the declustered catalogues produced by the Gardner and Knopoff, Grünthal, and Uhrhammer methodologies. The spatial distribution maps depict the retained independent earthquakes, while the accompanying histograms illustrate the

magnitude-frequency and temporal distributions of the identified mainshocks and aftershocks. Together, these results facilitate a comparative evaluation of the three declustering approaches and their influence on the representation of background seismicity.

Figure 5. *Spatial Distribution of Independent Earthquakes Identified Using the Gardner and Knopoff Declustering Algorithm*

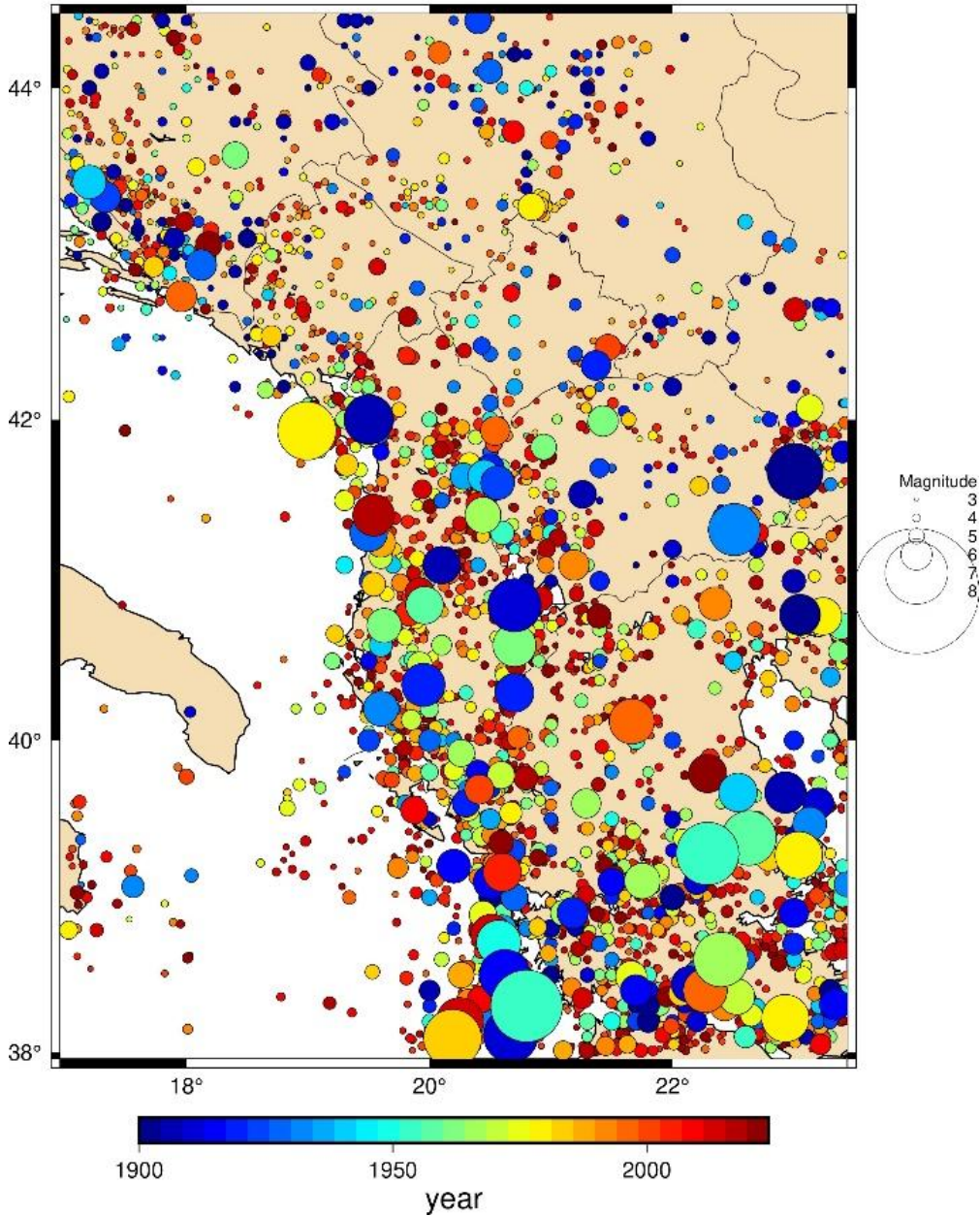


Figure 6. *Magnitude-Frequency Histogram (a) and Temporal Distribution Histogram (b) of Mainshocks and Aftershocks Obtained Using the Gardner and Knopoff Declustering Method*

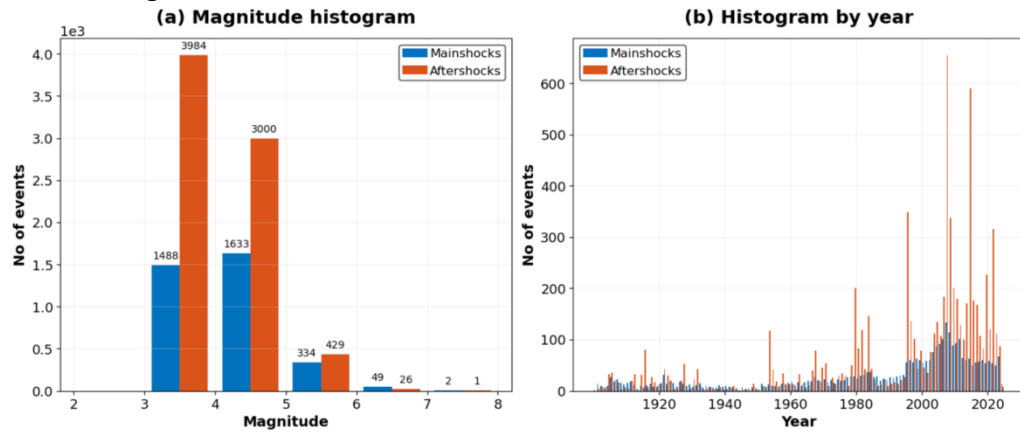


Figure 7. *Spatial Distribution of Independent Earthquakes Identified Using the Gruenthal Declustering Algorithm*

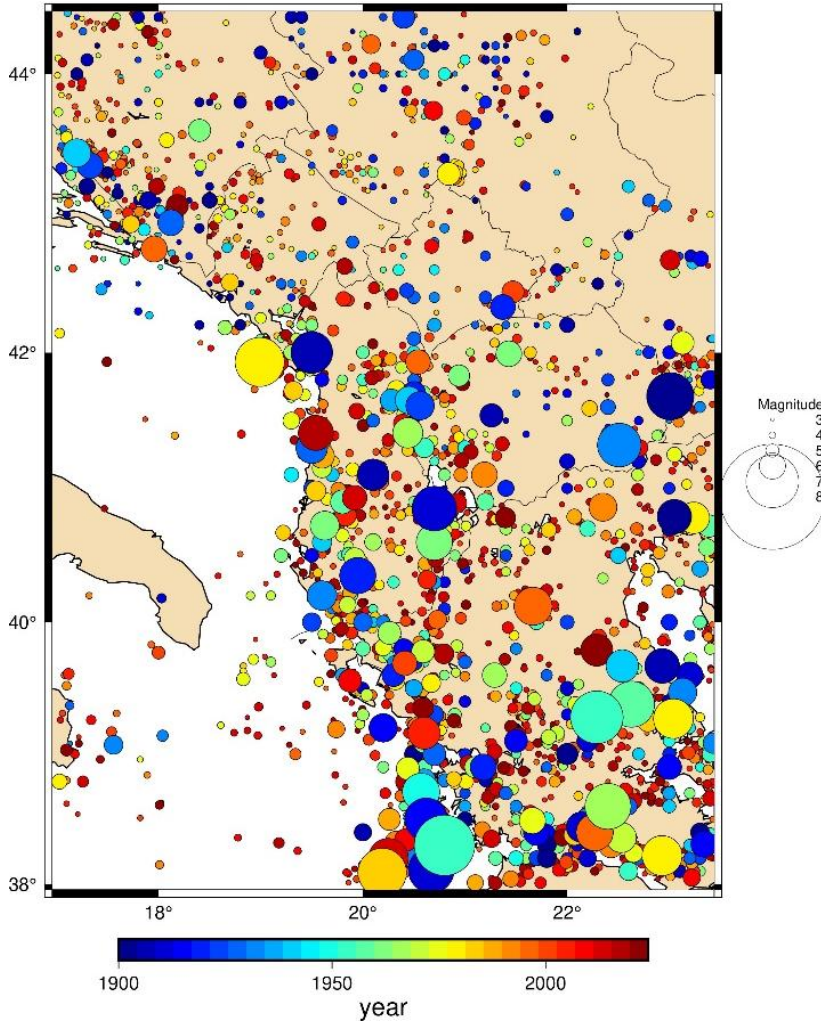


Figure 8. *Magnitude-Frequency Histogram (a) and Temporal Distribution Histogram (b) of Mainshocks and Aftershocks Obtained Using the Gruenthal Declustering Method*

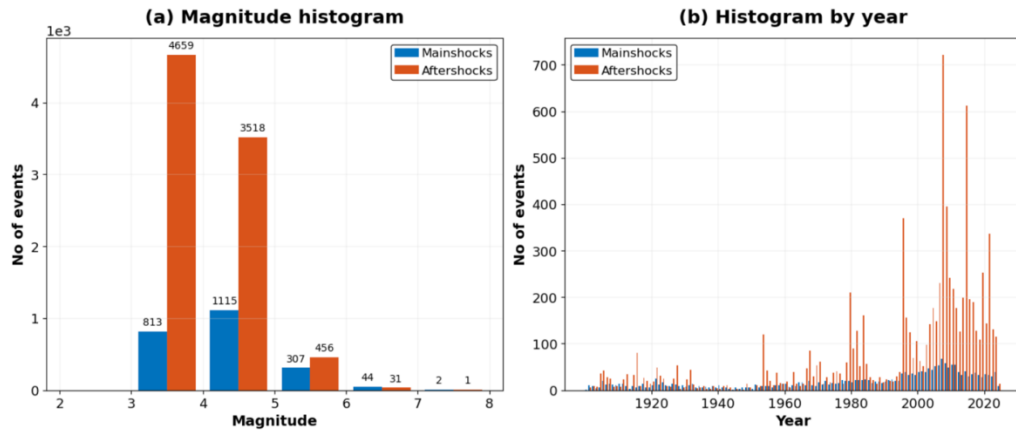


Figure 9. *Spatial Distribution of Independent Earthquakes Identified Using the Uhrhammer Declustering Algorithm*

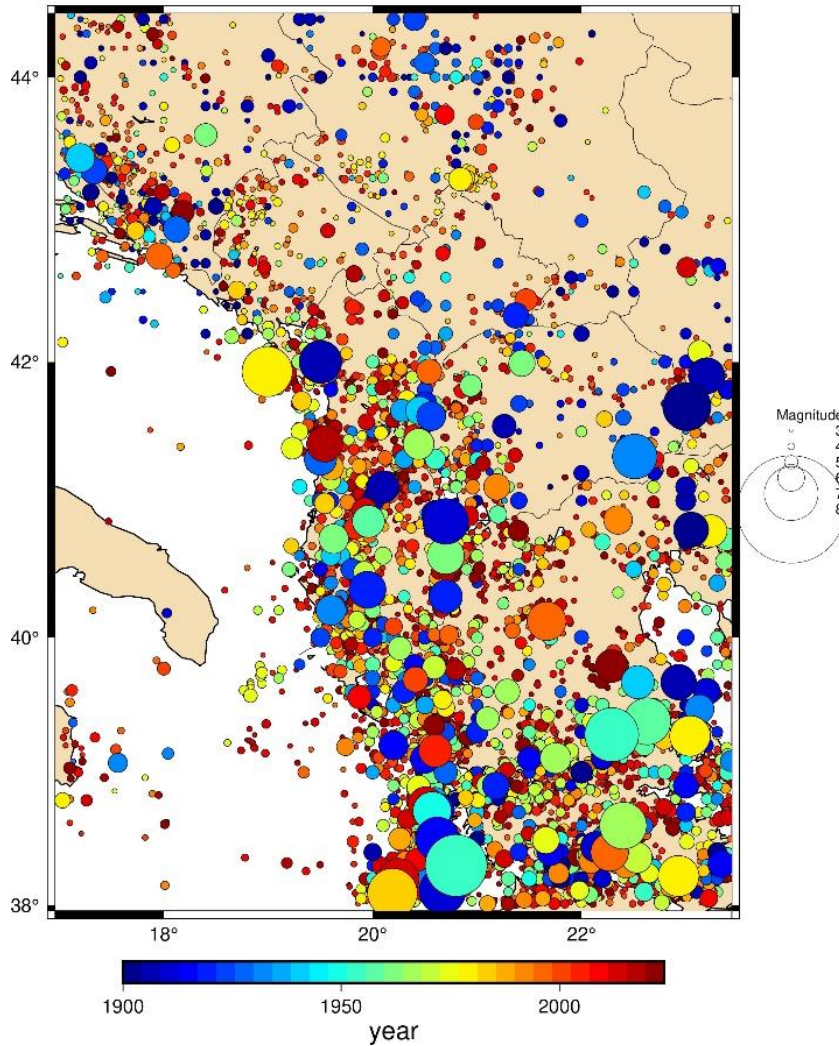
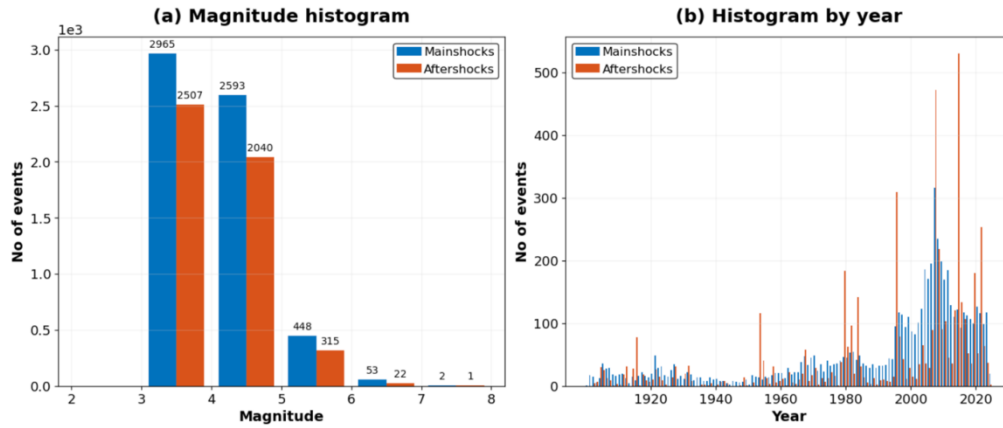


Figure 10. *Magnitude-Frequency Histogram (a) and Temporal Distribution Histogram (b) of Mainshocks and Aftershocks Obtained Using the Uhrhammer Declustering Method*



Completeness Analysis

Earthquake catalogs frequently display spatial and temporal heterogeneity. These variations stem from changing spatial coverage, evolving seismic networks, and improvements in recording equipment. Consequently, it is essential for a catalog to accurately reflect the frequency of seismic events over time. Because historical earthquake records are inherently incomplete across different magnitudes, a comprehensive completeness analysis was performed. Accurately determining M_c is fundamental for various seismological analyses. These calculations establish the a - and b -values of the Gutenberg-Richter relationship. As demonstrated by Ogata and Katsura (1993), underestimating M_c directly results in an underestimated b -value. Earthquake catalog completeness varies temporally, generally decreasing in older records. While large earthquakes are documented back to pre-instrumental periods, the reliable recording of small-magnitude events was only achieved in recent decades following advancements in seismic instrumentation.

The approach introduced by Stepp (1971) remains one of the foundational analytical methods for estimating the completeness magnitude (M_c). This technique relies on estimating the mean recurrence rate of earthquakes within specific time and magnitude windows. M_c is identified at the point where the observed rate of seismic events deviates from the statistically expected rate. Assuming the earthquake sequence follows a Poisson distribution over a time interval T_i , the unbiased estimate of the mean rate (λ) per unit time is calculated as:

$$\lambda = \frac{1}{n} \sum_{i=1}^n T_i$$

with variance:

$$\sigma_{\lambda}^2 = \frac{\lambda}{n}$$

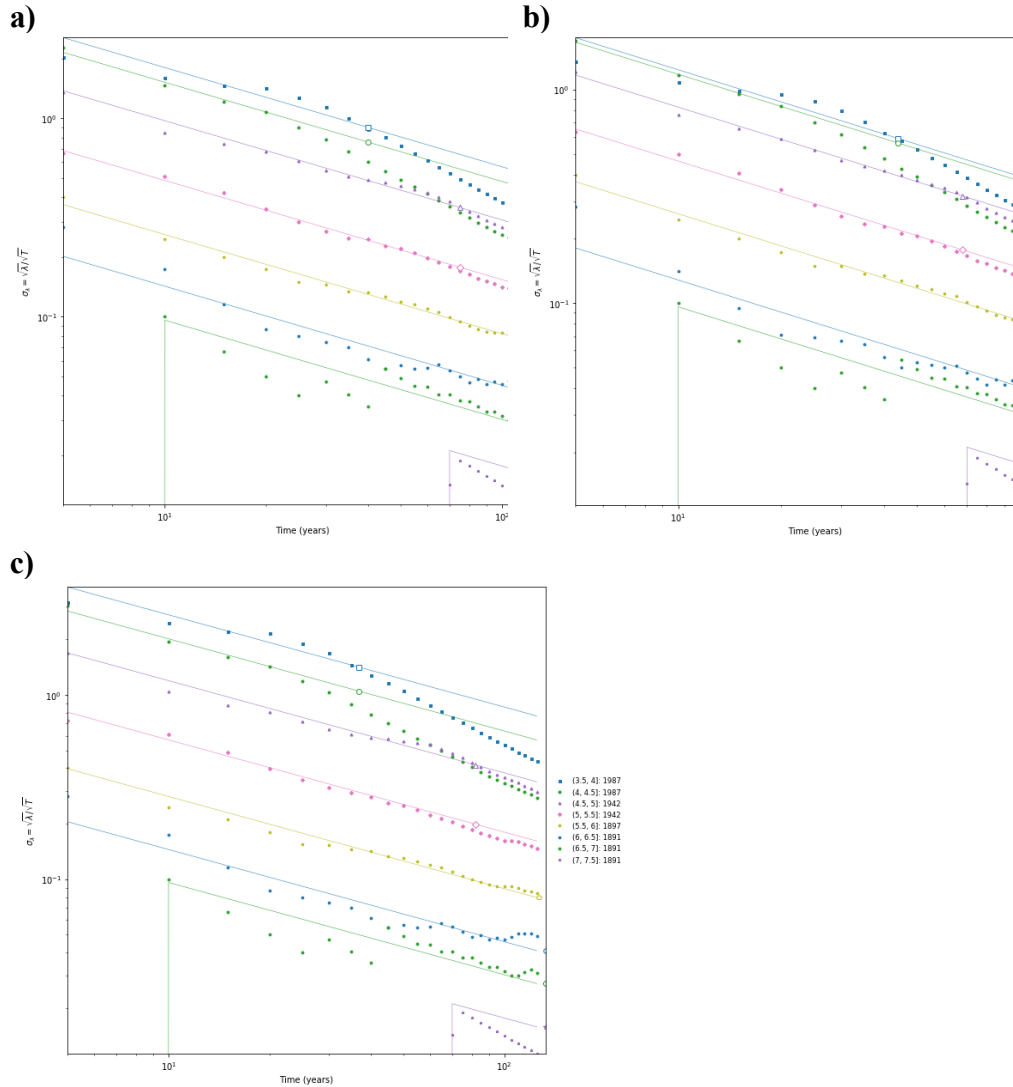
Assuming a one-year unit interval, the standard deviation of the estimate of the mean is:

$$\sigma_{\lambda} = \frac{\sqrt{\lambda}}{\sqrt{T}}$$

where T is the sample length. Since Poisson assumption indicates a stationary process, σ_{λ} behaves as $\frac{1}{\sqrt{T}}$ in the subinterval of the sample in which the mean rate of occurrence of a magnitude class remains constant.

The Stepp method was applied to the declustered catalogues using a magnitude bin of 0.5 and a time bin of 5.0 years, as implemented in the OpenQuake Engine (Pagani et al., 2014). The resulting graphical outputs of the method are presented below.

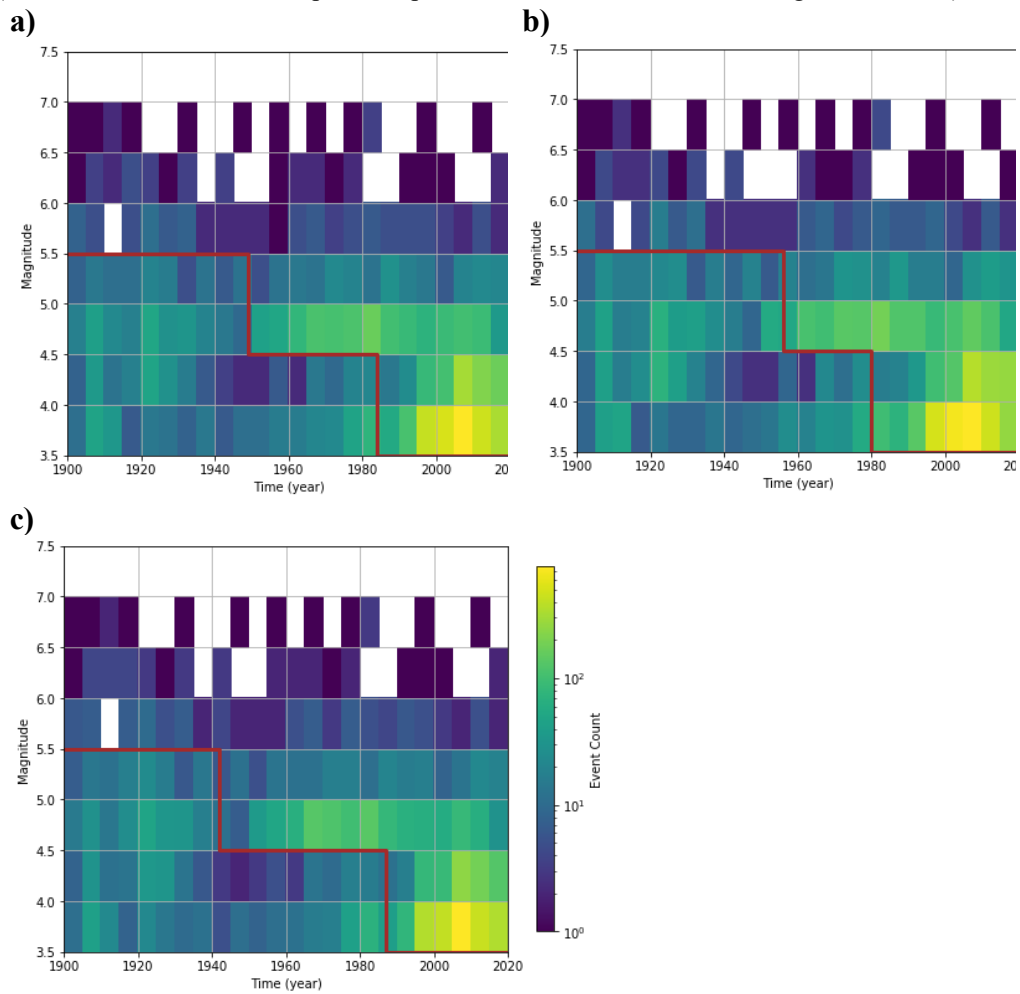
Figure 11. *Temporal Completeness Analysis Using the Stepp (1972) Method for (a) the Gardner–Knopoff Declustered Catalogue, (b) the Grünthal declustered Catalogue, and (c) the Uhrhammer Declustered Catalogue*



The heatmap representations shown below provide an alternative visualization of the completeness intervals derived from the Stepp (1972) method. By displaying the temporal evolution of earthquake occurrence rates across magnitude classes, these plots provide a clearer representation of catalogue completeness. The red contours indicate the estimated completeness periods for each magnitude range. Moreover, the comparison between the Gardner and Knopoff, Grünthal, Uhrhammer declustered catalogues allows a clearer assessment of the variability in completeness intervals resulting from the different declustering methodologies.

Figure 12. *Temporal Variations in the Magnitude of Completeness (M_c) Derived Using the Stepp (1972) Method for (a) the Gardner-Knopoff Declustered Catalogue, (b) the Grünthal Declustered Catalogue, and (c) the Uhrhammer Declustered Catalogue*

(Red contours indicate the completeness periods identified for the different magnitude classes.)



The completeness periods obtained for the declustered catalogs differ according to the declustering methodology employed, highlighting the influence of declustering on the temporal distribution of seismicity and, consequently, on the

estimation of catalog completeness. Since each declustering algorithm identifies and removes dependent events using different criteria, the resulting catalogs exhibit distinct characteristics that affect the determination of completeness intervals. For the Gardner and Knopoff declustered catalog, completeness is achieved for earthquakes with $M_w \geq 5.5$ during the period 1900–2024, for $M_w \geq 4.5$ during 1949–2024, and for $M_w \geq 3.5$ during 1984–2024. The Gruenthal declustered catalog is complete for $M_w \geq 5.5$ over 1900–2024, for $M_w \geq 4.5$ over 1956–2024, and for $M_w \geq 3.5$ over 1980–2024. In contrast, the Uhrhammer declustered catalog is complete for $M_w \geq 5.5$ throughout 1900–2024, for $M_w \geq 4.5$ during 1942–2024, and for $M_w \geq 3.5$ during 1987–2024. These differences underscore the sensitivity of completeness estimates to the declustering procedure and emphasize the importance of considering methodological effects when evaluating the temporal reliability of earthquake catalogs.

The completeness analysis results obtained using the Stepp method for the three declustered catalogs are summarized in Table 1. In the earlier stages of instrumental seismic monitoring, earthquake records were predominantly limited to moderate and large magnitude events, whereas smaller earthquakes were frequently omitted due to insufficient network coverage and lower instrumental sensitivity. The subsequent expansion of seismic networks, together with advancements in recording technology, has significantly improved the detection capability for lower magnitude events. The completeness assessment indicates that the catalogs are complete for small to moderate magnitude earthquakes over approximately the last four decades, reflecting the progressive enhancement of seismic monitoring and data acquisition capabilities within the study region.

Table 1. *Completeness Periods for Different Magnitude Classes*

Magnitude	Gardner and Knopoff	Gruenthal	Uhrhammer
$M_w \geq 3.5$	1984–2024	1980–2024	1987–2024
$M_w \geq 4.5$	1949–2024	1956–2024	1942–2024
$M_w \geq 5.5$	1900–2024	1900–2024	1900–2024

Conclusions

In this study, a homogeneous earthquake catalogue for Albania and the surrounding region was compiled for the period 1900–2024 through the integration of seismic data obtained from national, regional, and international sources. The catalogue was developed using a systematic workflow that included data collection, magnitude homogenization, duplicate-event identification and removal, and the merging of individual datasets into a unified database. The homogenization procedure included the development of a new empirical M_L - M_w conversion relationship for earthquakes reported by the Albanian Seismological Network. The resulting harmonized catalogue, expressed entirely in terms of moment magnitude (M_w), provides a reliable representation of regional seismicity over more than a century. Following the compilation of the homogeneous catalogue, declustering procedures and completeness analyses were conducted to identify independent

earthquakes and assess the temporal completeness of the seismic record. Application of the Gardner and Knopoff, Grünthal, and Uhrhammer declustering methods showed that different declustering approaches lead to substantially different sets of independent earthquakes, reflecting the sensitivity of seismicity analyses to the selected methodology. Subsequent completeness analyses using the Stepp method demonstrated that the estimated completeness periods vary according to the adopted declustering approach, particularly for lower-magnitude events. The compiled catalogue constitutes a robust and comprehensive seismic database for Albania and the surrounding region and provides a valuable foundation for future studies of seismicity patterns, earthquake recurrence, and probabilistic seismic hazard assessment.

Note

All figures presented in this manuscript were prepared by the authors.

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