

Tremors—A Software App for the Analysis of the Completeness Magnitude

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Abstract: This paper introduces a software tool developed within the MATLAB environment, called Tremors, aimed at streamlining the pre-processing and analysis of seismic catalogues, with a particular emphasis on determining the Magnitude of Completeness. It will outline the criteria for event selection, as well as various techniques to derive the Magnitude of Completeness values, including the recent and widely used Lilliefors statistical method. The study also addresses the important issue of short-term aftershock incompleteness and proposes solutions for managing it. Moreover, the software generates high-quality, customizable figures, and georeferenced raster images in .tif format as output. A standalone version of the App is also available (i.e., the users do not need a MATLAB license on their PC/laptop).

Keywords: magnitude of completeness; b-value; Short-Term Aftershocks Incompleteness (STAI); statistical analysis



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1. Introduction

The realm of seismology necessitates a deep comprehension of seismic catalogs and the complex analyses they yield. These catalogs are invaluable to scientific research, aiding in the exploration of seismic processes and enhancing our grasp of the dynamics behind earthquake generation and propagation.

The proper usability of seismic catalogs hinges largely on the precise estimation of the Magnitude of Completeness (Mc). The Mc is the threshold magnitude above which seismic events are considered complete (i.e., no missing events above this threshold).

The determination of Mc is critical for computing subsequent parameters, such as the b-value of the Gutenberg–Richter law. Misjudging the Mc could result in inaccurate b-value estimations or a flawed assessment of the national seismic network's efficacy.

The domain of Mc estimation has undergone significant evolution over recent decades, with the advent of various innovative techniques and methodologies that have markedly impacted seismological studies. Among the methods documented in the literature [1–3], we find the MAXimum Curvature (MAXC), the Goodness of FiT (GFT), and the Absolute Magnitude Based Method (Mbass). These conventional methods have long served as benchmarks in seismology, establishing a reliable foundation for Mc estimation. With technological advancements and analytical algorithm evolution, the Lilliefors method has emerged [4]. This technique provides a statistically robust approach to determining Mc by testing the exponentiality of the magnitudes.

To streamline the intricate process of Mc estimation, we introduce an intuitive software application. Our tool is built to facilitate the calculation of the Magnitude of Completeness (Mc) on modern seismic catalogs, also addressing the challenges posed by time-varying incomplete data.

Moreover, our App strives to offer guidance for optimal catalog processing, enabling users to select data based on classical parameters such as time, magnitude, depth, and survey area. The App focused attention particularly on the problem of Short-Term Aftershocks Incompleteness (STAI) [5,6].

The challenge with STAI is linked to significant events that lead to temporary inflation in M_c , marked by a substantial increase in the seismicity rate. Modeling STAI periods automatically has not been successful yet. To catch them, seismologists must look at the incremental number vs. magnitude plot [4,7,8]. Therefore, this procedure necessitates subjective decisions to determine the number and length of STAI periods. For scientific reproducibility, it is essential to document all subjective decisions made by seismologists when they study the M_c of a seismic catalog, including the parameters used to exclude STAI periods [9].

With respect to ZMAP [10], one of the most used software for the computation of the M_c of seismic catalog, our App offers two advantages: it contains modern methods to compute the magnitude of completeness, along with a heuristic technique to catch STAI periods; it can be used as a stand-alone code, without a MATLAB license. This second advantage can be important, especially for those researchers who have fewer funds and cannot afford paid software.

This paper will delve into the App's principal features and demonstrate how it simplifies seismic catalog analysis, rendering it accessible even to novices in the field.

2. The Different Features of Tremors

Tremors has a graphical user interface (see Figure 1) with a horizontal navigation bar at the top that can be used to access the various functions described below.

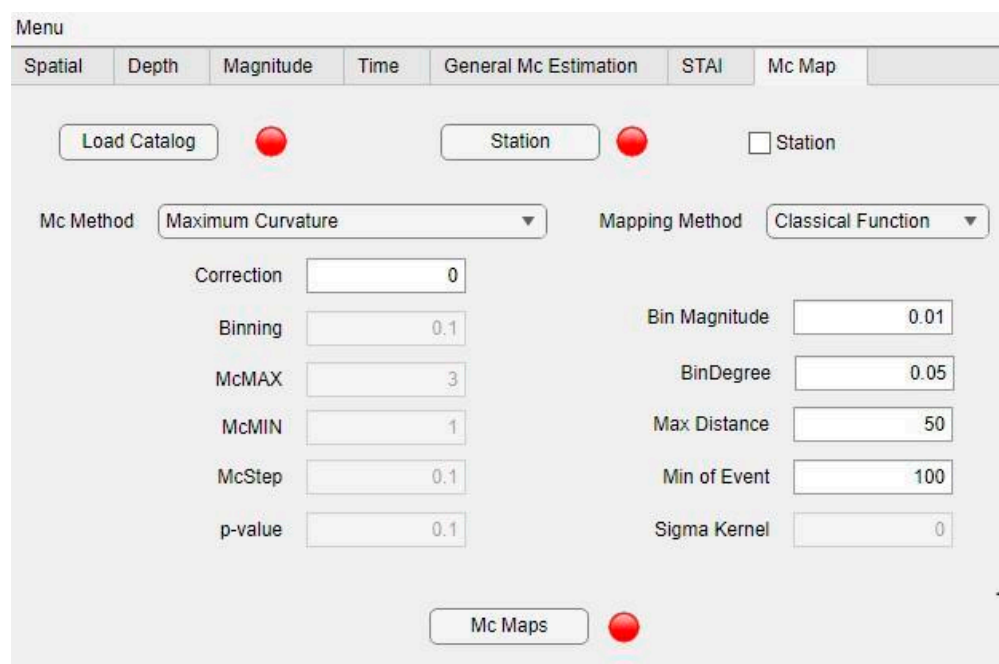


Figure 1. The graphical interface of Tremors.

Spatial Selection: The analysis of seismicity within a specific region requires careful assessment of the spatial distribution of earthquake epicenters. When defining the study area, it is crucial to consider potential disturbances that could lead to an over/under-estimation of the magnitude of completeness. Seismic catalogs generally show increased incompleteness with distance from seismic stations, due in part to the reduced robustness of data for more distant events, which are located using fewer seismic stations. A fundamental principle is to establish a perimeter to work within an area where the data are robust. The

Tremors tool allows users to draw a polygon or load an existing one to select the desired work area. The seismic catalog input format is the 10-column ZMAP format [10], ensuring full compatibility with ZMAP, which has been the predominant seismicity software over the past two decades.

Time selection: Seismic catalogs spanning several decades must be analyzed taking into account possible changes in the seismic network over time. Modern instruments capture a wide frequency range with highly sensitive and nearly real-time capabilities, influenced by the spatial distribution and density of installed stations. If significant dates for network updates are known, the catalog can be temporally segmented to analyze different periods separately, since M_c is strongly dependent on the seismic network.

Depth Selection: Analyzing a seismic catalog also involves considering depth, the third spatial dimension. Therefore, we have to determine a depth range where the location of hypocenters and the detection of seismicity are considered reliable. Human activities or natural events can contaminate the seismic catalog within the first few hundred meters, especially anthropogenic activities like quarry blasts or explosions, which distort seismicity parameters [11,12]. Moreover, as depth increases, so does M_c , due to the growing distance between seismicity and monitoring infrastructure. As a rule of thumb, the end-of-range depth should be determined by looking at the magnitude vs. depth plot.

Magnitude selection: This App also offers a sub-section where it is possible to cut the catalog according to a minimum magnitude threshold. We underline that this minimum magnitude threshold is not the completeness magnitude. This functionality could be useful in the case of catalogs with a very large number of events, to speed up the computations of the other sub-sections.

General M_c Estimation: The core function of this app is to estimate the completeness magnitude of a seismic catalog, taking into account constraints such as area, depth, magnitude, and time. This estimation can be performed using three different methodologies. One of the most recent methods is that of Herrmann and Marzocchi [4], which is based on the Lilliefors test [13], a statistically robust technique. This method checks the compatibility with the Gutenberg–Richter law, i.e., an exponential distribution for the magnitudes [14]. The catalog could be considered complete if the Lilliefors test does not reject the hypothesis of exponentiality for the magnitudes above a certain threshold. This threshold will be the magnitude of completeness of the catalog. This approach does not require any parameter, apart from the p -value of the test (we suggest setting the value $p \geq 0.1$, as in Herrmann and Marzocchi [4]). Another approach implemented, similar to the one of Herrmann and Marzocchi [4], is the method of Taroni (2023) [15]. It uses a simple random variable transformation ($\frac{X}{X+Y}$) to transform exponential random variables to Uniform [0, 1] variables, and it is more effective in the case of catalogs containing events with different b -values [15].

Finally, for fast computations, we also included the classical maximum curvature method [16]; this method requires a positive correction of about 0.2 or 0.3 to be reliable. The output of this sub-section is a figure containing the plot of the p -value of the test (in the first two approaches), the magnitude frequency distribution along with the estimated magnitude of completeness, and the incremental number vs. magnitude plot [8] (Figure 2). The latter is useful for identifying any time-dependent incompleteness in the catalog. Indeed, the previously described estimation methods are useful to compute the general completeness, i.e., the time-independent completeness threshold of the whole catalog. However, such a M_c value could be ineffective after the strongest events in the catalog. Looking at the lower panel of Figure 2, it is possible to notice areas with a low density of points at the bottom and vertical alignment of points forming small white (empty) triangles: these zones represent the temporal part of the incompleteness. To eliminate this type of incompleteness, we subsequently rely on the STAI-removing technique (next paragraph).

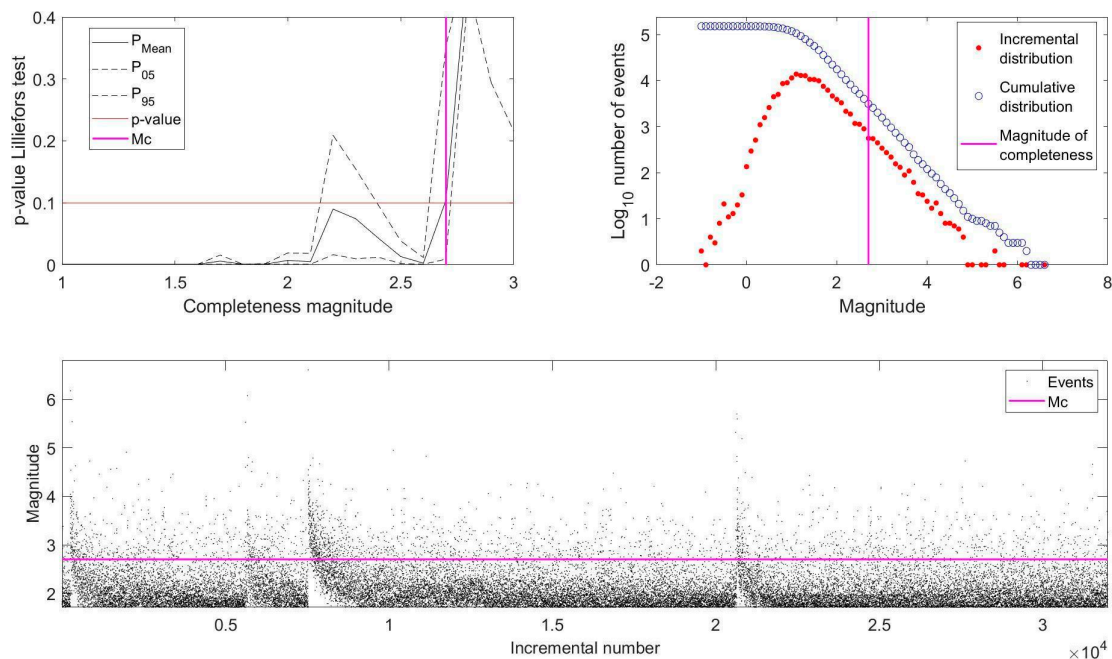


Figure 2. Upper left panel: p -value of the test as a function of the magnitude; the vertical magenta line represents the estimated magnitude of completeness; black solid and dotted lines represent the p -value of the test with the uncertainties. Upper left panel: incremental (red) and cumulative (blue) distribution of the magnitudes; the vertical magenta line represents the estimated magnitude of completeness. Lower panel: incremental number vs. magnitude plot; the horizontal magenta line represents the estimated magnitude of completeness; empty spaces in the lower bottom part indicate a short-term aftershock incompleteness.

STAI investigation: Handling Short-Term Aftershock Incompleteness (STAI) periods presents challenges due to their complex characteristics. These periods typically follow the strongest seismic events in the catalog but exhibit variability influenced by multiple factors. While one potential solution involves removing STAI periods using methods described in the existing literature [7,17], the Tremors App takes a different approach to prevent data loss. Instead of outright removal, it temporarily increases the magnitude of completeness after significant events in the catalog. This strategy balances the need for robust data while preserving valuable information (Figure 3).

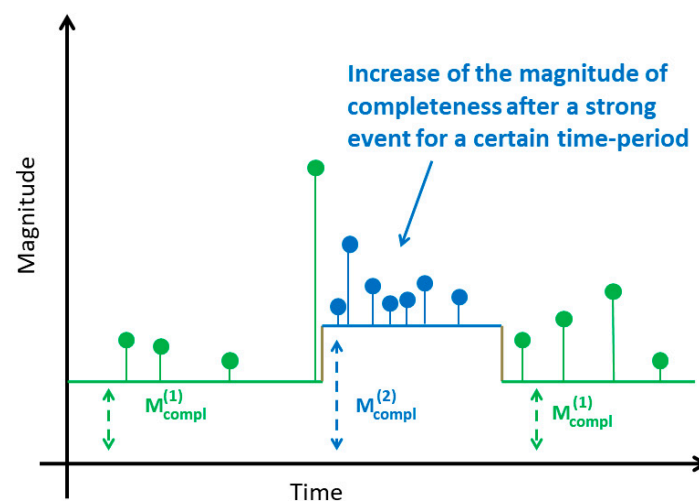


Figure 3. A simple scheme to illustrate the increase in the completeness magnitude (blue color) with respect to the background value (green color) after a strong event.

To properly identify STAI periods we used the incremental number vs. magnitude plot [8]. Our methodology involves the use of three parameters that allow the result obtained to be uniquely reproducible. The first one is M : a magnitude threshold that defines the minimum magnitude of events that generate the STAI. Usually, STAI periods start to become evident after events with a magnitude larger than 5.0, but this threshold also depends on the general magnitude of completeness. The second one is T : it defines the length of the STAI period expressed in days. The last parameter is the Delta Magnitude of Completeness (DMC), i.e., how much increases the completeness level after the strong event M . Once these three parameters are defined, it is possible to remove events in the identified STAI periods. This procedure could be applied repeatedly and for different M magnitude thresholds. Tremors provide three magnitude thresholds, each with its own set of parameters. This is a “try and catch” procedure: the user has to try different parameters to frame the STAI periods. In Figure 4 we show an example of STAI investigation using the catalog of the Amatrice-Norcia 2016–17 sequence [18]. At the end of the processing, a plot of the incremental number versus $M-M_c$ (the magnitude of the events minus the corresponding completeness threshold) will help verify whether all STAI periods are adequately treated [7] (Figure 5). This plot is very similar to the one suggested by [8], but it uses $M-M_c$ instead of magnitudes. When we obtain a plot without “white holes” or vertical alignments of points, we can consider this procedure complete. We underline that a precise description of the STAI periods via the set of parameters used is essential to increase the reproducibility of any seismic analyses.

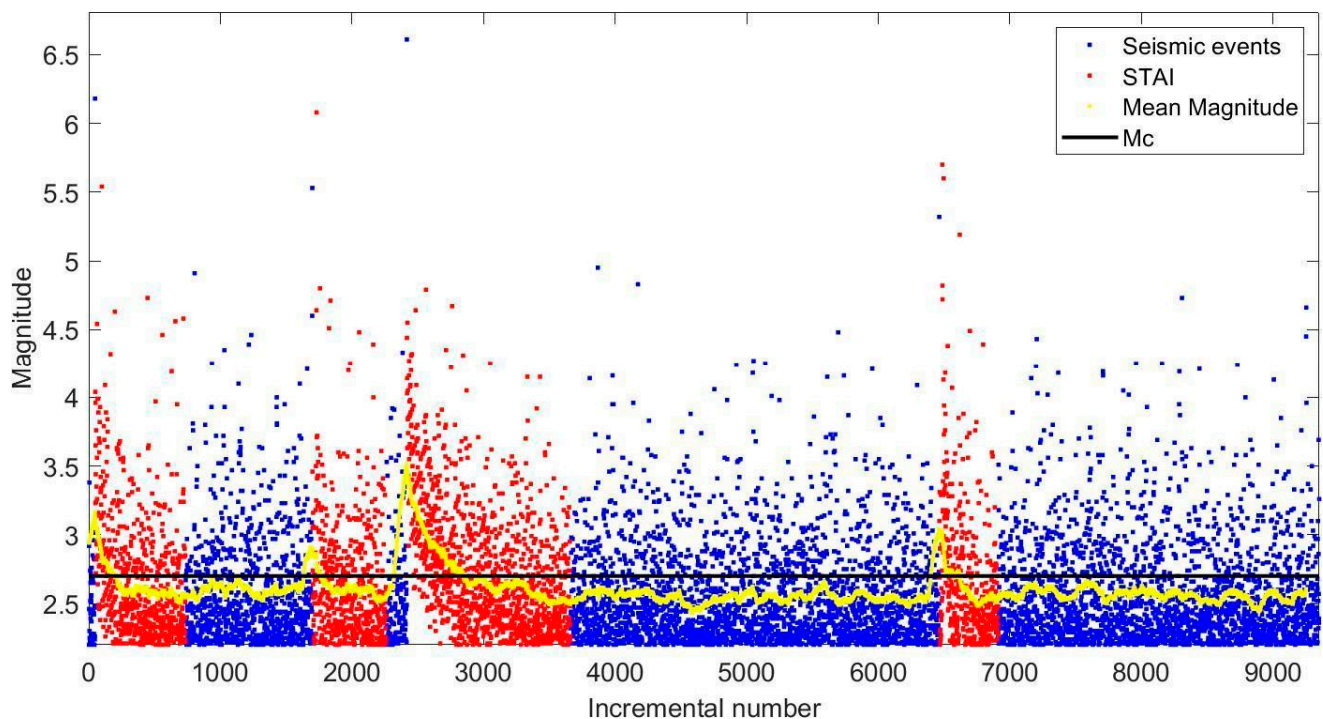


Figure 4. Incremental number vs. magnitude plot. Red dots represent events during STAI periods, while blue dots are relative to normal periods. The black horizontal line is the general M_c computed for the whole catalog. The yellow curve is the rolling-window average magnitude; it increases during STAI periods, and it helps to catch incomplete time periods.

M_c map analysis: In this last section of the App, we show how it is possible to analyze the spatial variation of the magnitude of completeness. Regional catalogs, with a spatial distribution of epicenters spanning hundreds to thousands of km, must be analyzed with techniques that allow for spatially dependent M_c [16,19]. The spatial analysis of the M_c allows us to understand whether the national seismic network in that particular

area has significant gaps [20,21]. We propose three types of spatial M_c calculations from the literature [4,16]. Figure 6 shows the result of the analysis performed on the Italian instrumental catalog from 2005 to 2022 [22] with the MAXC+0.2 method. We underline that these results are useful for understanding relative variations of the M_c but are not reliable for estimating the M_c in a certain zone (also because this spatial analysis does not consider the STAI problem). In any case, the results obtained from the application of the spatial calculation of the magnitude show that most of the peninsula has a M_c value around 1.4 to 1.8, with most of the lower values in Central Italy, where we have a greater coverage of the national seismic network.

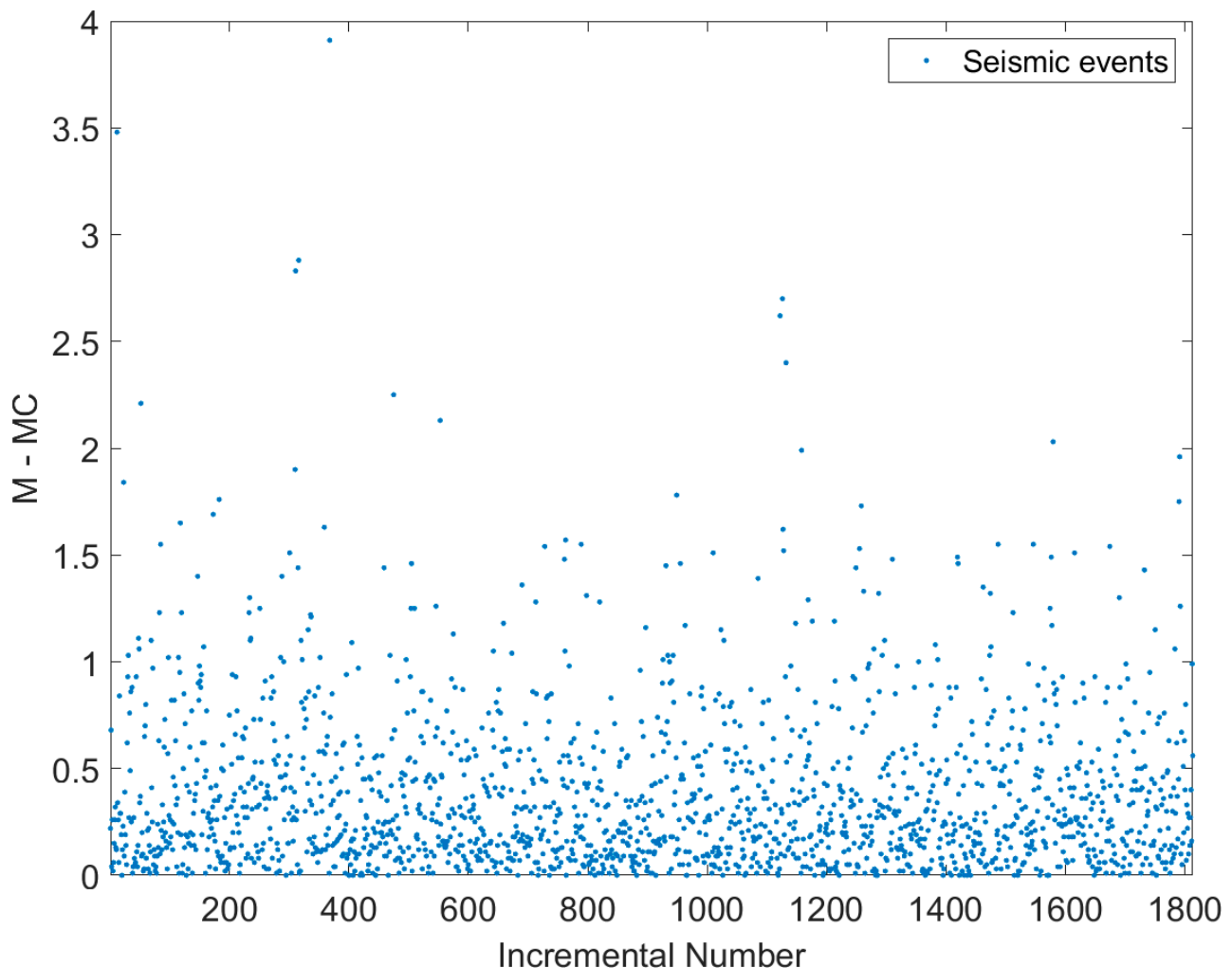


Figure 5. Incremental number vs. $M-M_c$ plot. As the incremental number vs. magnitude plot, it helps to catch possible incompleteness in the catalog. It is useful to understand if the STAI periods were properly treated.

There are some gaps caused by the lack of data and the algorithm cannot estimate the M_c (central part of Piedmont, Sardinia, Southern Apulia). In the Po plain, we notice a very high magnitude of completeness tending to 2.8. In this case, this value is the result of various aspects, including the constant presence of industries that tend to produce considerable seismic noise and the thick sediments that characterize that plain. Other areas where we have a high magnitude of completeness are near the Sicilian offshore, where network coverage is poor and onshore stations cannot detect small events.

All the figures can be saved in .png or .mat (MATLAB) format, and also in a georeferenced .tiff format; in this way, the user can plot the calculations using other software.

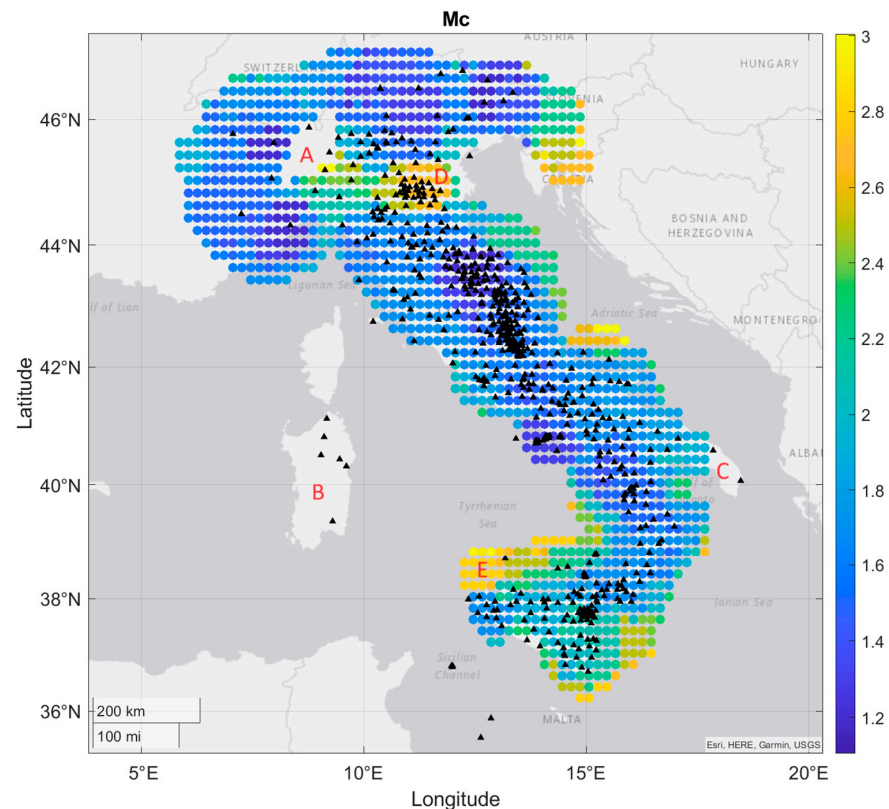


Figure 6. Map of the completeness magnitude analysis, with the stations of the seismic network (black triangles). Red letters indicate the zones cited in the text (A for Piedmont, B for Sardinia, C for Southern Apulia, D for Po plain, E for Sicilian offshore).

3. Conclusions and Future Developments

In conclusion, the Tremors App allows performing all the magnitude of completeness (Mc) estimation steps and facilitates the creation of a catalog for subsequent processing tasks, such as b-value estimation. The App is meticulously designed to augment the user experience by offering functionalities for spatial, depth, magnitude, and temporal selections, complemented by a variety of techniques for calculating Mc. Its user-friendly interface simplifies the workflow for seismologists, enabling them to concentrate on the fundamental aspects of seismic analysis.

Looking to the future, there are numerous exciting opportunities to enhance the app's functionality and utility. A notable forthcoming enhancement is the integration of b-value analysis techniques, both spatially and temporally. This development promises to provide a more comprehensive understanding of seismic activity by examining the variations in b-values across different regions and over various time periods.

Author Contributions: A.F. conceived the app and conducted analysis, G.V. conducted the development of the App, M.T. implemented algorithms and functions for catalog analyses, A.D. analyzed the results. All authors reviewed the manuscript. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Additional Information: To download the code, there is a repository named “Tremors” at <https://github.com/GammaArietis/Tremors>. The app was developed using MATLAB 2022b, with all toolboxes installed, and App designed. A standalone version of “Tremors” is also available in the same repository. For any questions, contact giovanni.vitale@ingv.it, matteo.taroni@ingv.it.

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