

Proposal for the Revaluation of Intensities of Ancient Seismic Events

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Abstract. The Italian seismic catalogues have an inestimable historical, cultural and scientific value. They probably represent a unique case in the world in terms of quality and quantity of available information. Their use is extremely broad. They represent an inexhaustible source of scientific information available to researchers. Furthermore, they can widely used in various ways such as, first of all, to validate the procedures for assessing the seismic hazard of the national territory. In recent years, the potential for analysis and the ever-increasing availability of instrumental recordings have led to a review, which is also ongoing in the scientific field, of methods, procedures and analyses on specific cases to re-evaluate the seismic intensities of historical events. In this study, of a preliminary nature, the main problems are highlighted and a framework is prepared for the redefinition of the seismic intensities of historical events.

Keywords: Seismic intensities · ancient seismic events · Vulnerability Classes · Kinematic Function Method · 1349 earthquake sequence

1 Introduction

The Italian territory is distinguished by its moderate seismicity, with only eight events with M > 6 having occurred since 1976, the year that marked the inception of digital seismology on a global scale. To achieve a more uniform assessment of seismic hazard, it is imperative to consider the information contained in historical catalogues. The Italian seismic catalogues (CPTI15 and DBMI15, Rovida et al, 2020; Locati et al 2022) offer a comprehensive description of the macroseismic fields, measured in MCS, associated with numerous events. These catalogues are regarded as the most comprehensive historical catalogues worldwide, spanning from 1000 to the present. The CPTI15 catalogue and its counterpart DBMI15 represent the latest development of the earlier parametric catalogues. These catalogues are based on numerous relevant studies conducted on every known event that affected the Italian territory during the reference period. Seismic

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events were added to the catalogue when sufficient information was available for precise identification of the effects on the territory and estimation of the intensity. The format of macroseismic intensities is non-numeric, which complicates the determination of the intensity. The dearth of reliable data, particularly in regions where seismic events have not been documented for extended periods, poses a significant challenge in the comprehensive coverage of the nation's seismic activity. This issue is particularly pronounced for seismic events of medium-low intensity, as they are often underreported in official records, while events of higher intensity are more frequently documented. The advent of instrumental data, albeit limited and incomplete from 1903 onwards, has facilitated a more precise identification of seismic events, especially in delineating the macroseismic field. In this regard, we recall the substantial coincidence introduced by EMS98 with the previous macroseismic classifications.

It is evident that the recent advancements in data analysis and processing, coupled with the perpetual increase in the accessibility of instrumental recordings, have resulted in a perpetual cycle of study and potential revision of the information contained within historical catalogues. The present study, in its preliminary form, aims to elucidate the predominant issues and establish a framework for the re-definition of seismic intensities and macroseismic fields of historical events. Conclusively, a primary illustration is presented, with particular emphasis on the geophysical dimensions.

2 Proposed Framework

This proposed approach analyses the main elements that contribute to defining and analysing historical seismicity, with a particular focus on the oldest earthquakes. The study aims to analyse these seismic events in order to gain further insights into the intensities, macroseismic fields, vulnerability of buildings and possible seismogenic sources. This analysis could lead to a revision of the hazard of the affected areas. In this regard, the study proposes a multifaceted approach encompassing the utilisation of enhanced information resources, contemporary scientific research findings, and the application of novel operational tools that facilitate a more comprehensive analysis of individual seismic events. The study of historical earthquakes is predicated on the availability of data, with a particular emphasis on the macroseismic field. This work undertakes a concise analysis of potential sources of uncertainty, accompanied by the proposition of enhancements and/or quantitative and qualitative observations on the fundamental elements of macroseismic classifications.

In principle, the attribution of a macroseismic intensity to historical events should be based on virtual "experiments" or on the construction of damage scenarios. These can then be used a posteriori to evaluate the seismic intensity of the main event based on the damage description present in historical documents. This procedure clearly presents many uncertainties and inaccuracies. In the following, we attempt to identify and describe the main elements of uncertainty, and define a path for the evaluation of a seismic event considered as an example.

2.1 Improve the Vulnerability Estimation for Damage Evaluation

Macroseismic scales are predicated on a compromise, as elucidated by EMS98 (Grünthal 1998), in which the differentiation of the seismic capacity of buildings identifies the manner in which they respond to earthquakes. The universally accepted vulnerability classification is predicated on vulnerability classes, which represent an attempt to define criteria to manage the aspects inherent to the seismic resistance of buildings. This modality has represented a development of macroseismic scales compared to previous seismology, which considered only the type of construction. However, while it is evident that the characteristics of a building significantly influence its vulnerability, recent classifications are sufficiently acceptable for modern applications. However, they can represent a strong limitation to the characterisation of buildings for the most ancient seismic events.

Possible time-Dependent Vulnerability Classes

The application of macroseismic scales, and in particular the European one (EMS-98), provides that masonry buildings (essentially the only ones present in the oldest earthquakes) are classified into typologies corresponding to decreasing vulnerability classes. For very old seismic events present in the seismic catalogue, it is foreseeable on the basis of existing studies (Dolce et al. 2003) that masonry buildings are predominantly non-engineered URM residential buildings and that they are all classifiable in class A, i.e. more vulnerable structures. The vulnerability assessment is carried out considering the following decreasing vulnerability classes: A, B, C, D, E, F. These classes are comprehensively delineated in the widely adopted procedure outlined in EMS-98 (Grünthal 1998), a standard reference in the field of vulnerability assessment. Consistent with the findings of this study, recent research has identified vulnerability class A as being particularly prevalent, often accounting for more than 50% of the observed cases. A significant presence of lower vulnerability buildings, classes B-D, is also widespread, both in new constructions and in the presence of seismic adaptation interventions, which are generally carried out after major and more recent seismic events. Furthermore, it is noteworthy that the municipalities in which the level of seismic vulnerability is highest are those furthest from the epicentre of the areas with greater seismicity, or in which the effects of the most recent seismic events have been negligible.

The determination of damage levels, as delineated by modern seismic damage scenarios, is contingent upon the definitions of vulnerability classes. Previous studies have demonstrated that the propagation of a specific damage level is not directly proportional to the vulnerability class; however, it is influenced by the distribution of the most vulnerable typologies. Finally, it should be noted that the highest vulnerability class (A) foreseen in EMS98 may not be sufficient to correctly represent the damage status of the buildings described and used for the attribution of the macroseismic intensity of very ancient events [REF]. In such cases, a significant variation for the vulnerability class A could be attributed, consistently with EMS98. In Fig. 1, the possible time-dependent vulnerability class A is reported as a more vulnerable class A, on a qualitative basis. Quantitatively speaking, this initial attempt to derive class A^{-} can be modelled on previous studies, derived from class A and other vulnerability classes.

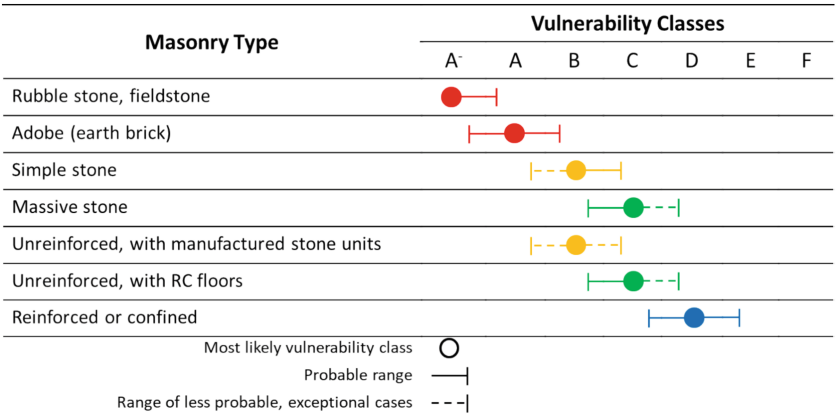

Fig. 1. Buildings vulnerability classification for URM (modified from EMS98).

In this study, class A⁻ has been deduced from the vulnerability classes foreseen in EMS98 and widely used in previous studies. From a historical and geographical point of view, the data used in previous studies (e.g. Chiauzzi et al. 2012, Vona et al. 2025) and therefore the derived DPMs, are consistent with the present study. However, special attention must be paid to the considerable evolution of the building heritage in the last 150 years.

Consequently, a further class with greater vulnerability (class A⁻) relating to buildings that were anciently present and lacking any anti-seismic measures or simple renovation, has been derived from the above-mentioned DPMs and the EMS98 scale (ESC 1998), according to the criteria explained below. The EMS98 provides the lexical quantities for buildings with different levels of damage and for different types of structures. Utilising these quantities and the extant DPMs, the DPM of class A- was derived, with reasonable assumptions on the continuity of the damage distribution on less damaged and undamaged buildings (see, for example, Dolce et al 2003), applying the fuzzy set theory to the assumptions: Few ≈ All/12, Many ≈ 4 x Few, Most ≈ 2 x Many. The Fig. 2 below illustrates the matrices relating to the vulnerability classes A, B, and the matrix obtained for class A⁻, scaling the intensity degree and obtaining the damage distributions.

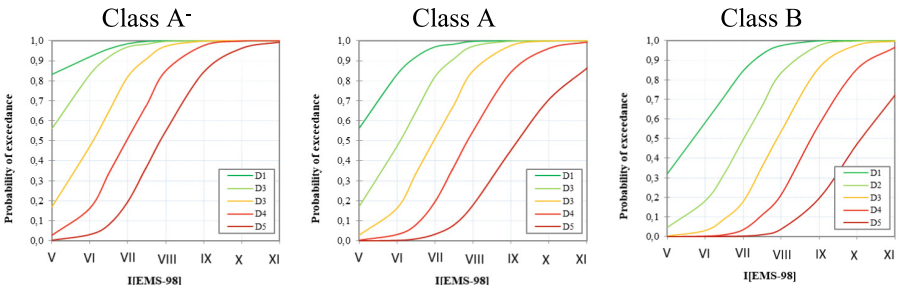

Fig. 2. The existing vulnerability classes A, B and define Class A⁻.

2.2 Seismic Events and Macroseismic Fields

The CPTI15 catalogue (Rovida et al. 2020) provides a comprehensive overview of instrumental seismic data in Italy, dating back to the early 20th century. It is evident that primary seismic events are frequently preceded by foreshocks and subsequently followed by aftershocks. It is evident that over the past 120 years, there has been no occurrence of a seismic crisis affecting a large geographical area, similar to that experienced in 1349 (a subject to be addressed subsequently) and in 1456/1457. Since 1976, the Italian catalogue (Lolli et al. 2020) has been consistently complete and accurate in terms of magnitude, with 83 shallow events documented, 77 of which have been associated with a moment tensor solution. The events are outlined in Table 1. It is important to note that the 23rd November 1980 and 30th October 2016 events are both composite events, occurring on multiple fault systems. As illustrated in Tab.1, the majority of significant events are associated with complex sequences, with the epicentral area of these sequences typically encompassing a roughly rectangular space of approximately 50x20 km. This characteristic is consistent with the observations of earlier events, dating back to the inception of instrumental records. However, it should be noted that the CPTI15 catalogue, which serves as a reference point, commences in 1000 AD.

Table 1. Events with Mw $\geq$ 5 since 1976, after Lolli et al. (2020). Events with the same color belong to the same sequence. Bold, events with Mw $\geq$ 5,7.

Date	Lat	Lon	Depth	Mw	σ Mw
1976-05-06T20:00:13	46,250	13,250	17	6,45	0,10
1976-05-09T00:53:43	46,267	13,383	19	5,08	0,10
1976-09-11T16:31:10	46,267	13,167	16	5,25	0,10
1976-09-11T16:35:01	46,300	13,317	9	5,60	0,10
1976-09-15T03:15:19	46,267	13,150	16	5,93	0,10
1976-09-15T09:21:18	46,300	13,183	21	5,95	0,10
1976-09-16T23:48:08	46,280	12,980	21	5,53	0,27
1977-09-16T23:48:07	46,300	12,983	14	5,26	0,10
1978-03-11T19:20:44	37,967	16,183	5	5,22	0,10
1978-04-15T23:33:47	38,267	15,100	24	6,03	0,10
1978-09-24T08:07:44	40,667	16,117	27	5,05	0,18
1979-09-19T21:35:37	42,717	12,950	6	5,83	0,10
1980-11-23T18:34:52	40,800	15,367	18	6,81	0,10
1980-11-24T00:24:00	40,833	15,283	18	5,04	0,10
1980-11-25T18:28:21	40,633	15,383	16	5,39	0,10
1981-01-16T00:37:45	40,890	15,440	0	5,22	0,10
1982-03-21T09:44:02	39,834	15,748	0	5,23	0,10
1982-08-15T15:09:54	40,943	15,320	10	5,32	0,10
1983-11-09T16:29:52	44,653	10,342	18	5,04	0,10
1984-04-29T05:02:59	43,204	12,585	9	5,62	0,10

(*continued*)

Table 1. (*continued*)

1984-05-07T17:49:42	41,666	13,820	11	5,86	0,10
1984-05-11T10:41:49	41,650	13,844	10	5,47	0,10
1986-09-27T18:08:17	38,737	15,277	10	5,25	0,33
1987-07-03T10:21:58	43,199	13,903	3	5,06	0,10
1990-05-05T07:21:30	40,650	15,882	0	5,77	0,10
1990-12-13T00:24:28	37,313	15,313	14	5,61	0,10
1991-05-26T12:25:59	40,689	15,822	0	5,08	0,10
1995-09-30T10:14:34	41,790	15,971	28	5,15	0,10
1996-10-15T09:55:60	44,799	10,679	1	5,38	0,07
1997-09-26T00:33:13	43,023	12,891	4	5,66	0,07
1997-09-26T09:40:27	43,015	12,854	10	5,97	0,07
1997-10-03T08:55:22	43,043	12,825	12	5,22	0,07
1997-10-06T23:24:53	43,028	12,847	4	5,47	0,07
1997-10-12T11:08:37	42,906	12,920	0	5,19	0,07
1997-10-14T15:23:11	42,898	12,899	7	5,62	0,07
1998-03-21T16:45:09	42,949	12,914	1	5,00	0,07
1998-03-26T16:26:17	43,146	12,809	45	5,26	0,07
1998-04-03T07:26:37	43,185	12,757	2	5,10	0,07
1998-04-12T10:55:33	46,283	13,571	15	5,64	0,07
1998-06-20T02:25:49	38,414	12,795	24	5,17	0,07
1998-09-09T11:28:00	40,060	15,949	29	5,53	0,07
1998-09-14T05:24:50	38,698	13,793	7	5,00	0,07
2002-09-06T01:21:29	38,381	13,654	27	5,91	0,07
2002-09-27T06:10:46	38,376	13,685	24	5,10	0,07
2002-10-31T10:32:59	41,717	14,893	25	5,74	0,07
2002-11-01T15:09:02	41,742	14,843	21	5,72	0,07
2003-09-14T21:42:53	44,255	11,380	8	5,24	0,07
2004-07-12T13:04:06	46,357	13,637	5	5,12	0,07
2008-12-23T15:24:22	44,544	10,345	23	5,36	0,07
2009-04-06T01:32:40	42,342	13,380	8	6,29	0,07
2009-04-06T02:37:04	42,360	13,328	9	5,07	0,07
2009-04-06T23:15:37	42,463	13,385	10	5,09	0,07
2009-04-07T09:26:29	42,336	13,387	10	5,08	0,07
2009-04-07T17:47:37	42,303	13,486	17	5,54	0,07
2009-04-09T00:52:60	42,489	13,351	11	5,39	0,07
2009-04-09T19:38:17	42,504	13,350	9	5,21	0,07
2009-04-13T21:14:24	42,498	13,377	9	5,02	0,07
2012-05-20T02:03:50	44,896	11,264	10	6,09	0,07
2012-05-20T02:07:29	44,874	11,270	6	5,15	0,19
2012-05-20T03:02:47	44,860	11,152	9	5,04	0,07
2012-05-20T13:18:02	44,814	11,441	3	5,15	0,07

(*continued*)

Table 1. (*continued*)

2012-05-29T07:00:03	44,842	11,066	8	5,88	0,07
2012-05-29T10:55:57	44,865	10,980	4	5,49	0,07
2012-05-29T11:00:02	44,856	10,941	9	5,15	0,19
2012-10-25T23:05:25	39,875	16,016	10	5,32	0,07
2013-06-21T10:33:57	44,131	10,136	7	5,32	0,07
2013-07-21T01:32:24	43,509	13,723	8	5,10	0,07
2013-12-29T17:08:43	41,395	14,434	20	5,16	0,07
2016-08-24T01:36:32	42,698	13,234	8	6,18	0,07
2016-08-24T02:33:29	42,792	13,151	8	5,54	0,07
2016-10-26T17:10:37	42,875	13,124	8	5,53	0,07
2016-10-26T19:18:07	42,905	13,090	10	6,08	0,07
2016-10-30T06:40:17	42,830	13,109	10	6,61	0,07
2017-01-18T09:25:40	42,545	13,277	10	5,32	0,07
2017-01-18T10:14:10	42,531	13,284	10	5,70	0,07
2017-01-18T10:25:24	42,503	13,277	9	5,60	0,07
2017-01-18T13:33:37	42,473	13,275	10	5,19	0,07
2018-08-16T18:19:05	41,874	14,865	20	5,26	0,07
2018-12-26T02:19:14	37,644	15,116	0	5,05	0,07
2022-11-09T06:07:25	43,983	13,324	5	5,73	0,07
2022-11-09T06:08:29	43,913	13,345	8	5,35	0,19
2023-09-18T03:10:14	44,050	11,590	8	5,14	0,07
2024-08-01T19:43:20	39,467	16,778	24	5,13	0,07

In numerous instances, an MCS macroseismic field has been documented (Locati et al 2022). This characteristics introduces a certain degree of ambiguity to the representation of events, particularly as the temporal distance from the present increases. The fragmentation of records becomes more pronounced as time progresses, often hindering the evaluation of vulnerability. The quantity and quality of information is extremely poor, and mostly refers to a few structures that represented an important point of reference for the community. In this regard, for the oldest earthquakes present in the catalogue, even the possibility of using any improvements to the vulnerability definition (see above) is extremely limited.

To this must be added that a significant proportion of the data contained within the historical catalogue, derived from inadequate information, has evidently not been processed in accordance with the most accurate seismological and engineering criteria of the 21st century. Consequently, it is frequently impossible to distinguish between cumulative effects, detail and accuracy of information and vulnerability.

Cumulative Damage Effects

The damage detected in the post-earthquake phases does not only concern the main

shock, but a significant portion of the seismic sequence, which frequently exhibits aftershock events of intensity approaching or equal to the main shock (see only for example Picozzi et al. 2010; Di Cesare et al. 2014). A substantial corpus of researches and studies have been dedicated to the study of mainshock-aftershock scenarios, including seminal contributions by Gutemberg and Richter (1955), Utsu T. (1961), Båth (1965), and Shcherbakov (2005).

Consequently, the potential cumulative damage to structures subjected to seismic sequences should be utilised to investigate historical earthquakes, with a focus on the possible modification of the seismic intensity of historical earthquakes. Historically, it is not feasible (particularly for older events) to understand the effects of cumulative damage on structures and buildings.

Historically it is not extremely difficult if not impossible (especially for older events) to understand the effects of cumulative damage on structures and buildings. Many modern studies have been conducted on a numerical basis, using modern non-linear calculation software, and laboratory tests but they generally refer to reinforced concrete structures. For masonry buildings, as mentioned those present in historical earthquakes, it is possible to refer to recent events and to a much smaller number of experimental studies (in the laboratory and numerical).

3 A Preliminary Case Study

The 1349 earthquake sequence in central Italy was selected for investigation as a case study. The CPTI15 catalogue subdivides this sequence into four separate events, primarily due to the distance between them, which is approximately 200 km. However, there is a high probability that the MCS intensities, originally assessed in the CFTI5Med catalogue (Guidoboni et al. 2019), were overestimated, as they were based on a limited amount of data. This is further compounded by the fact that, during the period in question, Italy was experiencing a significant outbreak of the plague. Consequently, existing documentation primarily focuses on the most prominent effects, providing an incomplete overview of the affected region. Furthermore, the absence of precise dates complicates the analysis. The present study employed the iteration method developed by Sirovich and Pettenati (1991), as modified by Harabaglia et al. (2024), to ascertain whether a single source could account for the full range of observed macroseismic intensities. The number of free parameters was kept to a minimum, with different epicentral locations and strikes permitted during the inversion process. The objective was to identify a solution that would minimise fault length and magnitude. The analysis encompassed both pure strike-slip and dip-slip solutions. The results obtained indicated that a pure strike-slip solution (Fig. 3) was capable of satisfactorily explaining the entire macroseismic field. It is acknowledged that distances of approximately 250 km may exceed the method's

applicable threshold; nevertheless, the outcomes are noteworthy. It is evident that an M = 7 event, at most, is sufficient to explain the macroseismic field considering a fault of about 50 km. The sequence of events in 1349 remains uncertain, and it is improbable that this information will be revealed. However, irrespective of whether it was a sequence or a single main event, it is sufficient to consider a rather restricted fault system to explain most of the damage. Furthermore, if the intensity of the seismic event was slightly overestimated, or if the vulnerability of the area was particularly high, a magnitude 7,0 event might not be necessary, and a magnitude 6,8 or 6,9 event might suffice.

It is worth noting that the large part of the resulting source does not appear to overlap with any known source in DISS (2021) (see Fig. 4). This could lead to the hypothesis that the current solution is somehow problematic, were it not for the points of maximum intensity surrounding it (see Fig. 3), thus lending credibility to this model.

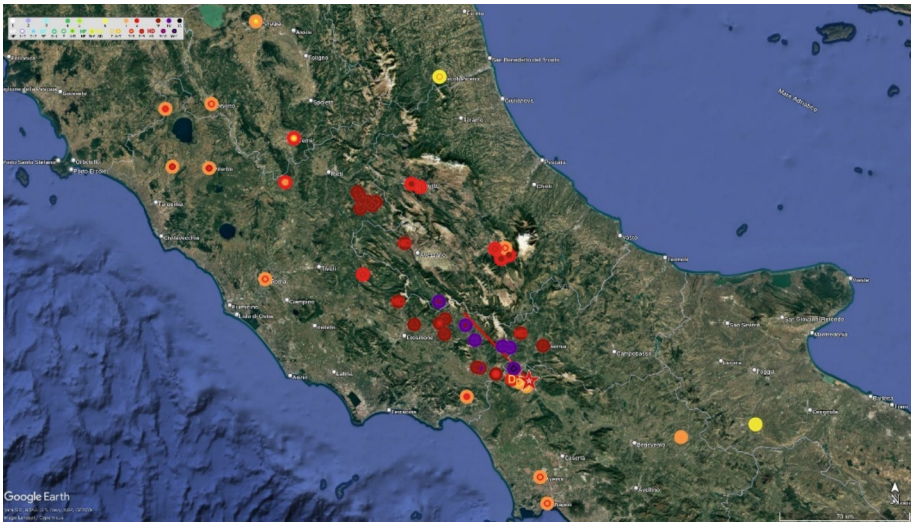

Fig. 3. a combined macroseismic field of the 1349 sequence. Inner portion of the symbols refers to observed data, outer portion to calculated ones. Star refers to macroseismic epicenter and red line to rupture trace. Assumed parameters: rake 0°, dip 70°, depth 15 km, inverted parameters: epicenter 41.43°N, 14.14°E, strike 316°, fault length 50 km, rupture velocity 0.79 S-wave velocity, Mag = 6.99.

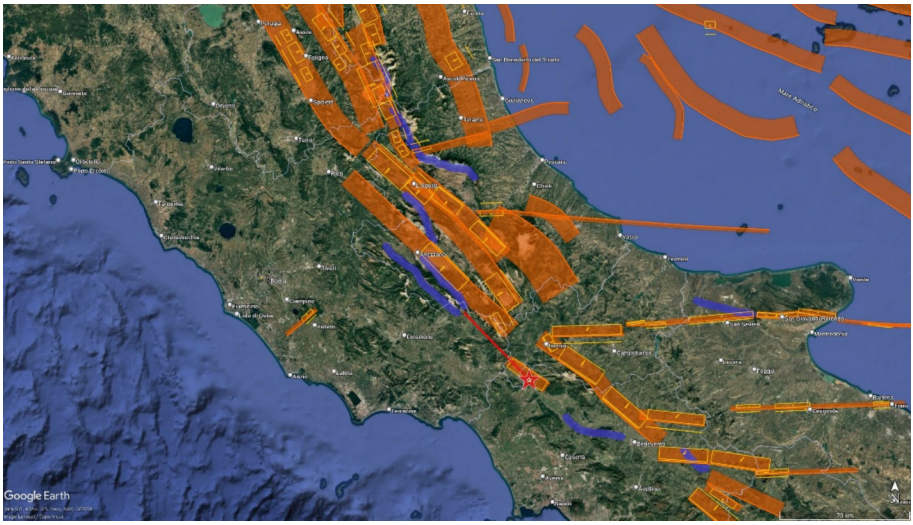

Fig. 4. Overlap of the resulting fault with known source in DISS (2021).

4 Conclusions

The necessity of a review of the oldest earthquakes with more modern criteria, tools and parameters is essential to facilitate the investigation of seismicity in the areas. The fundamental elements to be considered in the proposed study are the seismic vulnerability of the buildings, the analysis of the macroseismic fields, and the effects of cumulative damage.

In order to ascertain the seismic vulnerability of the buildings, a methodology has been proposed. This methodology has been developed on the basis of the initial historical information analysed and the experience of the authors. It has resulted in the definition of a new and more vulnerable class (A-).

The macroseismic fields are analysed with recently improved analytical tool. This analysis yields interesting results. The adopted tool will be the subject of future improvements. These improvements will consider the new vulnerability class, the historical data, the effects of the cumulative damage, and possible local effects (Puglia et al. 2012). The case study treated is of extreme importance.

The area under consideration has been the focus of attention due to its potential designation as a nuclear waste storage facility (Anelli et al. 2025), and a thorough examination of the hazard characteristics of the region could yield significant operational implications.

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