# On the Complexity of Earthquake Sequences: a Historical Seismology Perspective Based on the L'Aquila seismicity (Abruzzo, Central Italy), 1315-1915

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## Abstract

Most damaging earthquakes come as complex sequences characterized by strong aftershocks, sometimes by foreshocks and often by multiple mainshocks. Complex earthquake sequences have enormous seismic hazard, engineering and societal implications as their impact on buildings and infrastructures may be much more severe at the end of the sequence than just after the mainshock.

In this paper we examine whether historical sources can help characterizing the rare earthquake sequences of pre-instrumental times in full, including fore-, main- and aftershocks. Thanks to the its huge documentary heritage Italy relies on one of the richest parametric earthquake catalogues worldwide. Unfortunately most current methods for assessing seismic hazard require that earthquake catalogues be *declustered* by removing all shocks that bear some dependency with those identified as mainshocks. We maintain that this requirement has forced historical seismologists to focus only on mainshocks rather than also on the fore- and aftershocks.

To shed light onto major earthquake sequences of the past, rather than onto individual mainshocks, we investigated 10 damaging earthquake sequences ($M_w$ 4.7-7.0) that hit the L'Aquila area and central Abruzzo from the XIV to the XX century. We find that most of the results of historical research are crucial for modern seismology, yet their rendering by the current parametric catalogues causes most information to be lost, or not easily trasnferred to the potential users. For this reason we advocate a change in current strategies and the creation of a more flexible standard for storing and using all the information made available by historical seismology.

**Keywords:** earthquake sequences, historical earthquake catalogues, L'Aquila seismicity, Abruzzo seismicity, historical foreshocks, historical aftershocks.

## 1. Introduction

Damaging earthquakes often come in complex sequences that somehow violate standard aftershock decay models such as the Omori Law and the Bath Law. For example, since 1960 Italy has experienced 14 damaging earthquakes; 10 of them came as multiple or complex sequences, meaning that they were characterized by at least two shocks or sub-events whose magnitudes differed from each other by 0.3 units or less (Table 1). Extending the analysis to the full Italian historical earthquake record would return similar results. In fact, the Italian earthquake history is punctuated by catastrophic earthquakes sequences that progressively involved large portions of the Italian territory, much larger than the area struck by the first large shock, such as in the case of the 1349, 1456, 1693, 1703, 1783 multiple events and many others. Such complexity is not a characteristic of Italy alone, however, as complex earthquakes occur nearly everywhere on the planet.

Complex earthquake sequences challenge modern seismological wisdom in at least two ways. The first concerns the crustal volume involved, which by the end of the sequence is inevitably much larger than the volume affected by the first mainshock. The second concerns the impact on buildings and infrastructures, which again will inevitably be much more severe at the end of the sequence than just after the first mainshock. Many examples from recent and historical earthquakes prove that these conditions have enormous seismic hazard, engineering and practical implications. Yet, so far modern seismology has been surprisingly slow in recognizing the importance of earthquake complexity. Why is it so?

To our own surprise we have come to the conclusion that the ultimate reason for such forgetfulness is to be found in the introduction of Cornell's (1968) method for probabilistic seismic hazard assessment and its many subsequent modifications. Although the approach has been substantially modified over time, the assessment of the earthquake rates (or activity rates) of a given region has always required a "declustered catalogue" as the main input; a catalogue that had been deprived of all earthquakes – both foreshocks and aftershocks – that might alter the earthquake count by being (or appearing) "clustered" around the mainshock and hence not independent from it. Over time most earthquake catalogues have become more and more hazard-oriented, which implies that their compilers strived to improve the characteristics that are most relevant to improving the assessment of seismic hazard: these include the smoothness of the transition between intensity- and instrument-derived magnitudes, the completeness of the catalogue even for non-damaging earthquakes, the removal of duplicate and fake events. The most advanced of such catalogues (EMEC: Grünthal and Wahlström, 2012; SHEEC: Stucchi *et al.* 2012) were prepared in the framework of the recently completed EC-funded SHARE project (Giardini *et al.* 2013), that designed a new homogenized seismic hazard map for the whole of Europe, and hence currently represent a worldwide standard. These improvements, however, have been often achieved at the expenses of the description of the internal structure of each earthquake sequence, which ultimately caused a loss of consideration for the importance of this information for seismologists and earthquake engineers.

In this paper we use an especially interesting case-history taken for the seismicity of the Abruzzi Apennines (Central Italy) to demonstrate (a) that historical earthquakes sequences should always be investigated with the best possible level of detail, and (b) that the information retrieved should be incorporated in more comprehensive, innovative earthquake catalogues. Knowledge on the chronology of historical earthquake sequences and of their full complexity, including foreshocks, aftershocks and multiple mainshocks, is crucial for a number of independent reasons:

- improving the understanding of the global damage suffered as a result of the sequence, from its foreshocks to the late aftershocks, and exploring the relevant engineering aspects;
- improving the assessment of the magnitude of historical earthquakes, de-aggregating as much as possible the effects of individual shocks and developing an appreciation for the role played by strong foreshocks and extra-long aftershock sequences in modifying the damage scenario strictly associated with the mainshock;
- investigating the behavior of earthquake-struck communities in response to the characteristics of each individual earthquake sequence, not only as a function of the earthquake severity but also in response to the specific foreshock-aftershock pattern;
- gathering the full extent of the crustal volume that ruptured during the sequence, to be used for improving seismotectonic models and for obtaining time-dependent hazard estimates.

## 2. Earthquake complexity: an Italian perspective

The time evolution of earthquake sequences - and especially of their foreshocks - has become topical again in Italy following the earthquake that struck Central Abruzzo (Italy) on 6 April 2009 ($M_w$ 6.3, $I_0$ IX MCS). The earthquake hit the city of L'Aquila and many surrounding villages, which all suffered serious and extensive damage: 308 people died, and over 67,000 lost their homes (Azzaro *et al.* 2011; Tertulliani *et al.* 2012a; Dipartimento della Protezione Civile, 2010: see Data and Resources). The earthquake was preceded by a long sequence of foreshocks, which started in November 2008 and hence lasted for almost five months. After 1 January 2009, 188 foreshocks were recorded instrumentally, the strongest of which ($M_w > 4$) occurred on 30 March and in the evening of 5 April 2009 - respectively a week and five hours before the mainshock (Lucente *et al.* 2010). The mainshock was followed by thousands of aftershocks, two of which rather strong (7 April 2009, $M_w$ 5.6; 9 April 2009, $M_w$ 5.4); six additional aftershocks exceeded $M_w$ 4.5 (Chiarabba *et al.* 2009).

Every time a sizable earthquake (e.g. 5>M>4) strikes in a densely populated country such as Italy, local residents and authorities wonder whether the shock is an isolated one or rather the precursor of a bigger one. And every time a damaging earthquake strikes (M>5.5), seismologists, engineers and rescuers wonder how likely it will be for the first large shock to be followed by a comparable or even greater shock in the following hours, days or weeks. As shown in Table 1, this has often been the case in Italy, where the majority of damaging earthquakes that occurred over the past 50 years - 10 out of 14 - have shown some level of complexity in the pattern of seismic release.

The public perception of the importance of anticipating the evolution of an earthquake sequence has grown enormously in Italy following the Umbria–Marche earthquakes of September 1997–August 1998 (for a summary see Amato *et al.* 1998, and Chiaraluce *et al.* 2003). After the first shocks on the night between 3 and 4 September 1997 (the strongest having $I_0$ V–VI; $M_w$ 4.5), which only in hindsight were identified as precursory to larger shocks, a quake of $M_w$ 5.7 hit on 26 September at 2:33 a.m. local time. At 11:40 a.m. on the same day, another earthquake having $M_w$ 6.0, brought down – among many other buildings – an abutment of the Assisi basilica, just when a technical inspection to verify the damage caused by the previous shock was in progress. The collapse caused four deaths and was filmed live on television, becoming an icon of this earthquake all over the world. Was it a wise decision to start the inspection only a few hours after the first shock? What would have been the best conduct to protect the population from further strong shocks? Were public officials aware of the likelihood of a second and even a third major shock, and had they been properly informed by civil protection authorities regarding this possibility?

The 1997-1998 Umbria Marche earthquake indeed stirred the debate on how scientists, civil protection officials and administrators should interact in the immediacy of a damaging earthquake, and quickly became a paradigm of an entirely new approach to the problem. But things were slow to change. Five years later in the Molise region (Central Italy), two shocks both having $M_w$ 5.8 struck within 30 hours and a few km of each other: the second shock, that was largely unexpected, threatened the rescuers at work on the already collapsed buildings and caused further damage. Ten years later, on 20 May 2012, a shock of $M_w$ 6.1 hit a densely populated and heavily industrialized area of Emilia (Northern Italy), causing several deaths in poorly built factories: it was followed nine days later by a shock of $M_w$ 6.0, which caused deaths and injuries in reinforced concrete structures damaged by the main event, right when the authorities were about to lift a restriction on resuming production in the factories that had not been damaged in the first shock. Less than 20 years of Italian damaging earthquakes have hence demonstrated beyond any doubt that dealing seismic sequences is not just a matter for historical seismologists.

While accepting that much is still to be learned concerning the time evolution of earthquakes, there are at least three good reasons to focus future research efforts on Italian historical earthquake sequences:

1) to learn about the pattern of seismic release and the length of earthquake sequences in a given region - information of use in assessing the population's risk of facing a sizable build-up of effects as the sequence unfolds (Lolli and Gasperini, 2003);
2) to develop an appreciation for the inevitable increase of damage and losses caused by extended earthquake sequences, and particularly by the repetition of similarly-size earthquakes;
3) to assess the effective total extent of the rupture associated with a given earthquake sequence, a parameter than can be hardly assessed based on the magnitude of the mainshock alone.

In the following we will review these issues from the perspective of historical seismology. Owing to its long history and its large density of historical settlements, Italy makes a special case particularly for its great heritage of written documentation, stretching back over the centuries, which allowed the development of an extraordinary tradition of studies in historical seismology (Fréchet *et al.* 2008; Guidoboni and Ebel, 2009). No other country in the world possesses such a wealth of documentation on past earthquakes. Aside from any other consideration, ignoring such a wealth of data would indeed be a real waste of valuable scientific data.

We have chosen to discuss examples taken from earthquake sequences that struck L'Aquila and the Abruzzo region, in a journey through time and space that begins in the Middle Ages and ends in modern times (refer to **Figure 1** for the location of the area and all place names mentioned in the following). The question has recently been tackled by Amato and Ciaccio (2011), who analyzed and discussed the occurrence of historical earthquake sequences around L'Aquila "over the last millennium" (actually over the past 700 years). According to these investigators, in the 20th century at least 23 moderate-size sequences affected the Abruzzo region without turning into a large earthquake crisis, and only in three cases (1461, 1703, 2009) were the mainshocks preceded by a foreshock sequence (see discussion in Section 5).

To date, most of the efforts to understand and assess earthquake sequences in Italy have been based on empirical statistics and stochastic models like ETAS (Marzocchi and Zhuang, 2011) based on a few decades of instrumental seismicity only. This limited record does not enable scientists to refine their calculations or adapt them to specific tectonic domains. Historical information may hence be crucial in filling this gap and providing data to test and calibrate these models more precisely.

## 3. Dealing with earthquake sequences in Italian historical catalogues

While an earthquake sequence is in progress, there is no way of identifying an individual event as a foreshock; thus any strong event can be followed by an even stronger mainshock. While aftershocks or foreshocks are impossible to define by instrumental data if a sequence is still in progress, the same does not hold for historical data: they consider a sequence that has already happened and is hence already fixed in its timing.

Unfortunately, so far Italian earthquake catalogues have not taken advantage of the wealth of data made available by historical seismology. An insignificant portion of this information found its way into the first-generation catalogues (mid-20$^{th}$ century), in an imprecise and incomplete way that renders them almost useless today. A substantial revision of historical catalogues took place roughly between 1980 and 2005 with the main purpose of locating precisely the effects of the main events of each sequence and documenting the impact of strong earthquakes.

Surprising as it may sound, historians studying past earthquakes have never been asked by the seismologists to focus, or select data, on earthquake sequences, especially foreshocks, as only the mainshocks held interest. This tendency became even stronger following the introduction and widespread adoption of Cornell's (1968) method for probabilistic seismic hazard assessment. Such an approach is based on "declustered" earthquake catalogues, i.e. deprived of all earthquakes – both foreshocks and aftershocks – that could be seen as 'clustered' around the mainshock. A basic assumptions of the method is that major shocks follow a Poisson process (e.g. pages 1,590, 1,603). Cornell (1968) cited the possibility of releasing such assumption (page 1,603), but substantially stated that this would not be particularly useful because "*when swarms and aftershocks are excluded, data does not clearly reject the Poisson assumption* [...] *for the rarer, major events of engineering interest"*. One may conclude that some sort of aftershock declustering is implied by the standard application of the Cornell (1968) method.

Preliminary declustering is hence not mandatory when compiling earthquake catalogues. Recent papers by Boyd (2012) and by Marzocchi and Taroni (2014) not only raise doubts about the need to decluster earthquake catalogues to be used for probabilistic seismic hazard assessment, but warn against the underestimation of future seismicity rates, and hence of the probability of exceeding a given level of shaking, that the declustering inevtibaly involves.

In fact, some of the older catalogues in Italy's seismological tradition do list all known shocks: for example, the printed version of the PFG 1985 - *Progetto Finalizzato Geodinamica* - CNR catalogue edited by Postpischl (1985) contains earthquakes having epicentral intensity $I_0 \geq$ IV–V Mercalli Cancani Sieberg - MCS scale and $M_L \geq 3.5$ from the year 1000 to 1980 (the complete version of this catalogue was made available on microfiches distributed along with the printed volume).

The PFG (1985) catalogue was the outcome of a first revision and correction of the catalogue released by Istituto Nazionale di Geofisica a few years earlier (ING, 1981), but was never used for seismic hazard calculations (for an overview of this work of revision and correction see Guidoboni and Ferrari, 1989). Following the requests introduced by the Cornell approach into seismic hazard assessment practice, the new parametric earthquake catalogues started to present only mainshocks and all other events were removed. Constructing declustered catalogues thus became the standard procedure adopted in Italy and elsewhere over the past two decades. The first was NT4.1, published in 1997, that listed earthquakes having $I_0 \geq$ V–VI, $M_s \geq 4.0$ but excluded all shocks viewed as "*repliche*" (aftershocks), i.e. all shocks recorded within 90 days and within a 30 km radius from a large earthquake taken to be the mainshock of a sequence.

For this reason NT4.1 was described by its own authors with the motto "*Il catalogo che non ammette repliche*" (literally "The catalogue that allows no rejoinder", but really the motto is a pun based on the fact that the Italian word "replica" means both aftershock and rejoinder).

NT4.1 was soon followed by the first official release of the "Catalogo Parametrico dei Terremoti Italiani" (CPTI99, see Data and Resources). Both in the original 1999 version and in its 2004 update, CPTI did not list any foreshock or aftershocks, but unlike NT4.1 it included them in a separate list. This trend was somewhat reversed after the 2009 L'Aquila earthquake with the 2011 version of CPTI, which reportedly contains also "*...a certain number of records referring to foreshocks and aftershocks for which macroseismic and/or instrumental data are available...*" (CPTI11, see Data and Resources). Although the intentions underlying this latest version are commendable, so far this statement has not been followed by any change in the structure of the database nor by any new elaborations.

It should be recalled that at present CPTI is the official Italian earthquake catalogue, and as such it is the standard source used for such diverse tasks as estimating activity rates in the context of seismic hazard assessment, calculating deterministic earthquake scenarios or doing research on earthquake prediction. Because of the variety of information types and calculation methods employed over time, however, this catalogue proves to be highly heterogeneous, especially in its parameters and in the degree of completeness of the information supplied.

Despite the seismologists' limited interest in the time evolution of historical earthquake sequences, starting in 1995 and up to its most recent release in 2007 the "Catalogo dei Forti Terremoti in Italia" (Catalogue of Strong Italian Earthquakes in Italy, or CFTI: Boschi *et al.* 1995, 1997, 2000; Guidoboni *et al.* 2007, hereinafter referred to as CFTI4Med07) included many data on foreshocks and aftershocks, though in a qualitative and unsystematic form. Two specific sections of the database are called "Sequence of the earthquake" and "Full chronology of the earthquake sequence": hundreds of shocks that preceded or followed an earthquake studied in this catalogue are listed, at least in a provisional way. The parametric assessment of such qualitative information is restricted to a few cases where the historical-seismological literature has made use of it.

## 4. Investigating the chronology of the strong historical earthquakes: data and limitations

Given the growing interest in the time evolution of earthquake sequences, especially foreshocks, one may review the basic historical data already "on file" for many events (the reader may refer to **Table 2**). To work out the numerical parameters for such past sequences, however, one needs to evaluate a range of critical factors. For example, it is often problematic to pinpoint the location of foreshocks and aftershocks. Before or after a mainshock the historical sources often report information only for the cultural center(s) (monasteries or town) that produced written information on the shocks observed, which provides just a vague hint about the area of the greatest impact or perception.

Another difficulty with aftershocks concerns how to classify them against the intensity ratings of a macroseismic scale. How do we evaluate the minor tremors following a destructive quake? As an example, let us imagine a mainshock of intensity IX, a shock that by definition destroys a large portion of the existing buildings and infrastructures: how can one assess the size an aftershock (e.g. VI) occurring in such an already semi-destroyed location? No macroseismic scale is appropriate for such ratings. An attempt to tackle the problem through "fuzzy set logic" is found in Ferrari *et al.* (1995) and Vannucci *et al.* (1999). Their point is that in those cases it is hard to match the qualitative description with the scale of intensity: there is always a subjective margin in the intensity rating *vis-à-vis* the type of description. Some investigators, however, have proposed solutions for classifying the effects of aftershocks in the absence of instrumental data: for example Guidoboni *et al.* (2001, p. 131-146) for the January1693–September 1694 earthquakes sequence in Catania and eastern Sicily; Guidoboni e Mariotti (2003) for the April-June 1929 sequence in the Bologna area (Po Plain, Northern Italy); Margottini and Screpanti (1999) for the January 1915-January 1916 sequence in Abruzzo. The important thing is to clarify the criteria and calibrate the uncertainties. Getting over this problem requires formalizing the decision process leading to the estimate of macroseismic intensity. The reasons behind past descriptions of earthquakes were usually not the same we would like to find in a text: this explains why many sources often strike us as being reticent or obscure.

There is another intrinsic limitation in the current intensity scales, as they were created and updated to be used "in the field" and by direct observers of contemporary earthquakes (see for example Azzaro and Stucchi, 2000, on the EMS 98 scale). Classifying aftershocks is understandably hard when the effects are merely hinted at in the historical sources, or worse still, taken for granted as known to contemporaries. Fortunately, though, Italy's wealth of diverse sources and case materials makes a tentative classification possible (this will be discussed later on).

Finally, the reader should be aware that not all the earthquakes that will be discussed in the following have been investigated by the compilers of the CFTI catalogue as some were below the originally established magnitude/intensity threshold. Hence some of these earthquakes have been investigated specifically for this work (1646, 1702-1703 and 1809) and will be later incorporated in future releases of the CFTI.

## 5. Major Medieval earthquakes of the Abruzzi Apennines: 1315, 1349, 1456

In a recent paper Amato and Ciaccio (2011) looked closely into the earthquake history of L'Aquila to compare the 2009 earthquake with previous sequences. For some of the older earthquakes these investigators inferred the absence of foreshocks *ex silentio.* Performing a test *ex silentio* means deriving a conclusion based on the absence of contrary elements; but unfortunately the exegesis of Medieval texts does not allow us to make such an inference on the presence or absence of foreshocks. The occurrence of foreshocks is a crucial piece of information today, but not necessarily so for people living in the Middle Ages. In the historical critique the cases for which such evidence can be used are very rare, because such "test" is often arbitrary. In this specific case, the lack of mention of foreshocks in the medieval sources should not be interpreted as a real lack of foreshocks; in other words, we cannot rule out foreshocks simply because they were not described, neither can we infer any if there is no explicit textual mention.

To make our case more clear we will refer to the time evolution of the three medieval earthquakes of December 1315–January 1316, September 1349, and December 1456-May 1457. These long sequences have been studied in specific investigations and at different stages (Guidoboni and Comastri 2005, hereinafter MedCat05: see Data and Resources); looking carefully into history has gradually enabled certain important aspects like the timing and damaged area to be seen in better detail. Following is a brief summary of these three earthquake sequences.

The estimated parameters of the 1315 earthquake are indirectly based on the great social impact recorded in a royal document written in Latin (MedCat05, p. 373-374). A reassessment of this earthquake became possible when an institutional document produced at the time in the Court of Naples was unearthed (King Roberto d'Angiò, State Archives, Naples, 1317). In the cultural context of the time, the new elements suggested it was an event of great social impact, such as to alter the existing social equilibrium. The strongest shock came on 3 December 1315 and the *earthquakes*, always referred to in the plural, lasted for four weeks and more - hence very likely extending into January 1316 (see MedCat05). In contrast, nothing is known about foreshocks. The main parameters of this earthquake in CFTI4Med07 are $I_0$ VIII-IX MCS, $M_w$ 5.8; CPTI11, while quoting CFTI, gives different parameters: $I_0$ VIII, $M_w$ 5.6.

In September 1349 a broad area of Central Italy was hit by a major earthquake crisis. Four independent shocks have been distinguished based on the geographic distribution of the effects, covering a territory of some 24,000 km$^2$, about 8% of the size of present-day Italy. The historical sources date these earthquakes differently but indicate 9 or 10 September as the onset of the sequence, depending on where it struck. The few historical sources that give any indication of the time of day agree on 9 September between 8 and 9 a.m. local time. In one ecclesiastical source from Viterbo (near Rome) the canon chamberlain (responsible for book-keeping) left a blank space where he should have written the exact date of the earthquake (**Figure 2**): this curious circumstance suggests uncertainty as to when exactly the event began, maybe because other shocks were felt before and after the destructive one (Diocesan Archives of Viterbo, Sant'Angelo de Spata, cart. 1, fasc. 34, fol. 3r). A document of the time reports that a strong tremor was felt at Isernia on 22 January 1349, though without any damage, and nearly every month thereafter shocks were reported until the destructive one of 9 September 1349. This report was kept in the Isernia Ecclesiastic Chapter archives (MedCat05, p. 464).

The 1349 sequence is documented by many official contemporary documents. They include, in particular, those of the Papal Chancellery, presently kept in the Vatican Secret Archives, as well as numerous authoritative chronicles. According to two contemporary authors, Giovanni Villani and Buccio di Ranallo (both in MedCat05), the L'Aquila earthquakes of 1349 lasted for over eight days and the population of L'Aquila took refuge in huts for over nine weeks. For this sequence the CFTI4Med07 lists four distinct epicentral areas, two of them lying in Abruzzo: one located southwest of L'Aquila ($I_0$ IX MCS, $M_w$ 6.0), one near Sulmona ($I_0$ IX MCS, $M_w$ 6.0). Of these two earthquakes CPTI11 lists with full parameters only the L'Aquila shock (though it cites the CFTI study and parameters), whereas the shock that damaged Sulmona is listed as "non parameterized" (see **Table 2**). Rome too underwent serious widespread destruction as a result of this earthquake; the damage was described by the humanist Francesco Petrarca in three letters written in 1351, 1353, and 1368. According to many authoritative sources of the time, during the same month - September 1349 - additional earthquakes struck Viterbo and northern Latium

($I_0$ VIII–IX MCS, $M_w$ 5.8) and the boundary region between southern Latium and northern Molise ($I_0$ X MCS, $M_w$ 6.3).

Just over a century later, in December 1456, a large earthquake affected Central and Southern Italy. This huge seismic disaster is one of the most documented and studied medieval Italian earthquakes and even has its own history of the interpretations that were made. The event is well documented by over 70 direct authoritative sources: 50 documents, mostly letters and reports, including the famous treatise that the famous humanist Giannozzo Manetti wrote in 1457 (Manetti, 1457 ms, 2013 edition), plus 20 coeval chronicles (see references in CFTI). A research update published in 2005 (MedCat05, pp. 625–724) and based on historical contemporary data that had not been used by previous investigators (population censuses and ecclesiastical documentation) made it possible to hypothesize that the sequence included at least four major earthquakes. One of the largest shocks ($I_0$ X MCS, $M_W$ 5.8, according to CFTI4Med07: not listed in CPTI11) occurred in Abruzzo, in the upper valley of the Aterno-Pescara River, southeast of L'Aquila, in the territory between this town and Sulmona (a summary is given in Guidoboni *et al.* 2012). Following these results and based on seismotectonic evidence, Fracassi and Valensise (2007) proposed the identification of three distinct source areas and the location of six strong aftershocks. For this entire sequence CPTI11 lists only one large shock in the Molise region ($I_0$ X, $M_w$ 7.2, reported as based on "cumulative effects").

Giannozzo Manetti, who is the most authoritative source for this earthquake, outlined a massive sequence with two distinct peaks. The most violent shock occurred on 5 December 1456 at 4 a.m. and was followed on the same day by weak aftershocks; witnesses in Naples spoke of two or generically "several" light shocks that only some of the population felt. The second violent shock occurred on 30 December.

Here is what Manetti wrote to the King of Naples, Alfonso d'Aragona:

> "*To be truthful, your highness the prince, two new and rare earthquakes, among many others, have occurred within a time-span of about 60 days during your blessed and fortunate rule, in the year four hundred fiftysixth after the millennium of the Christian salvation* [1456], *in the midst of wintertime; one, more powerful, occurred in the night of the ninth of December* [effectively the 5th, editor's note]*, the other, during the day, on the calends of January* [30 of December, editor's note]*, and ruined many neighborhoods, villages and cities, killing many people* [...]*"*[translated from Latin].

The diagram in **Figure 3** attempts to represent the aftershocks of this great earthquake as they were felt in Naples and its surroundings from 5 December 1456 until May 1457. **Figure 4** locates the epicenters of the 1315, 1349 e 1456 earthquakes affecting L'Aquila and Abruzzo.

In summary, this array of information does not allow anyone to rule out the likelihood that the three big events of 1315, 1349 and 1456 were preceded by significant foreshocks. Only for 1349 do the sources actually indicate this, mentioning a sequence in the Isernia area (Molise region, near the southeastern border of Abruzzo: see Figure 1) between January and September 1349. As to the localities involved in this earthquake crisis, one may reasonably wonder if the scarcity of information is due to lack of sources or lack of foreshocks. For 1315 and 1456 the aftershocks are known but not the foreshocks, yet we maintain that they cannot be ruled out *ex silentio*.

From a time evolution point of view, the analysis of these medieval earthquakes reveals a picture of important data that nonetheless do not meet the requirements of this research. The limitations are due not so much to the sources themselves, but rather to the cognitive approach of contemporaries, who were not too concerned with analyzing the details of the sequence of tremors they felt. This is not always and necessarily the case, however: in other geographical and cultural contexts earthquakes sequences were often minutely described day by day, even in earlier centuries. Such is the case of the earthquakes that struck Syria from 1138-1139 and 1156-1157 cited by Arabic sources, or of the March-September 1373 sequence in the Central-Pyrenees and Catalonia (Spain) (in MedCat05, pp.140-146; 153-165 and pp.497-519).

## 6. The 1461-1462 L'Aquila earthquakes: the first sequence documented day by

The earliest earthquake sequence affecting the Aquila area for which detailed information is available took place between November 1461 and March 1462 (CFTI4Med07, originally from MedCat05, pp. 733–742). Information on this sequence is drawn from several direct contemporary sources. The first tremor, which caused no damage, is attested to on 16 November. The strongest shocks, whose effects on the city of L'Aquila and on the neighboring villages were destructive, occurred on 27–28 November, within two hours of each other (at 22:05 and 00:05) ($I_0$ X, $M_w$ 6.3 from CFTI4Med07).

Historical sources (in particular the contemporaries Francesco d'Angeluccio and Alessandro de Rittis) mention many minor shocks: between 27 November and 11 December 1461 the population perceived more than 100, although the sources do not provide exact chronological data. On the night between 17 and 18 December 1461, at 1:10 a.m., another very strong earthquake caused further damage. Later on, between early January and late March 1462, several aftershocks were felt, including at least five strong ones. **Figure 5** outlines the chronological progress of the seismic sequence between mid-November 1461 and late March 1462.

The destruction suffered by L'Aquila was very severe (X MCS), affecting a large part of the city's monuments as well as lesser buildings. When the first two powerful shocks struck on 27–28 November, the people of L'Aquila began to flee from their houses. They sought refuge in the countryside, living in makeshift tent cities. Eventually most of the inhabitants returned to the city, but settled in the squares and other free open spaces within the walls, where they erected wooden huts.

To the best of our present knowledge, no information on earthquake sequences is available for about 150 years after the 1461-1462 sequence and other minor events that occurred in 1466 and 1498.

## 7. The April–June 1646 earthquake sequence

Between April and June 1646 an earthquake sequence struck L'Aquila and its environs with a medium-low impact. The literature on the subject does not address this earthquake crisis in depth: contemporary sources unearthed so far mention the event only in sweeping terms. This time as well, however, the strongest quake - which was far less destructive than the one in 1461 - was preceded by a long sequence of minor shocks.

There are two known scholars who described this sequence in L'Aquila. The first was the Filippo da Secinara, an eyewitness (his date of birth is unknown, but he died in 1652). Precisely owing to his own experience from this event he started to write his *Trattato universale di tutti li terremoti* (Universal treatise of all earthquakes), published in 1652. The second source of information is a famous erudite and historian from L'Aquila, Anton Ludovico Antinori (1704–1778), archbishop, who in his *Annali* (18$^{th}$ century, 1971–1973 edition) recounts the effects of this earthquake by referring to contemporary administrative sources and memoirs, most of which have been lost.

The series of earthquakes started on 28 April 1646 at about 8:00 a.m. (local time) with a shock that was very strong in L'Aquila. According to witnesses it "shook" buildings very hard, causing vaults and arches to crack and plaster to fall, in particular in the church of Santa Maria di Bagno. According to Camassi *et al.* (2011), the epicentral area of this first quake locates on the western side of the Monti della Laga mountain range, 20-30 km north of L'Aquila. Based on the sources mentioned above, we know that in L'Aquila a long series of smaller shocks followed, starting on 28 April. These continued for over a month until early June. On 7 June another shock – stronger than the previous ones – persuaded most people to leave their homes and to construct provisional wooden shelters in gardens and other open spaces. Some sources (Secinara 1652; Antinori 18$^{th}$ c.) revealed that during this time-span the *preside* (governor) of the province held his hearings in a garden in L'Aquila and the *magistrato* (a kind of city council) gathered in the cloister of the convent of San Francesco.

Another powerful quake struck on 19 June 1646, at 3:50 a.m. Half an hour later, at 4:20 a.m., the most violent shock of the entire sequence occurred in L'Aquila, where it was felt for "several dozen seconds". Thus the mainshock, for which we hypotesize $M_w$ 4.8, took place 52 days after the onset of the sequence. It made many chimneys and cornices collapse, and the great bell tower of the cathedral swayed dangerously. The series of earthquakes continued with smaller shocks until late June 1646. According to the sources, 166 shocks were felt in L'Aquila over a period of a little more than two months (**Figure 6**).

The CPTI11 lists the first sizable shock, dated 28 April 1646, and locates it in L'Aquila ($I_0$ V–VI; $M_w$ 4.5), but not the strongest shock of 19 June, whose effects are likely to have reached intensity VII MCS. The city of L'Aquila is the only site for which descriptions of the effects of the entire seismic sequence are known to exist.

## 8. The catastrophic earthquake sequence of September 1702-June 1703

The sequence of devastating earthquakes lasting from October 1702 to January-February 1703 was one of the worst seismic disasters in the history of modern Italy. Most of the regions of Central Italy (Umbria, Latium, Marche, Abruzzo) suffered heavy destruction caused by the cumulative effects of three violent earthquakes that took place on 14 January, 16 January, and 2 February 1703 as well as of hundreds of other

minor shocks. In all, about 10,000 people died. The earliest results of the study conducted on this sequence, which was rather difficult to assess, were published in CFTI (from the second release: Boschi *et al.* 1997, pp. 215–227) and included in CFTI4Med07.

Although this earthquake crisis is known as "the earthquake of 1703", it was in fact a long sequence that began in L'Aquila on 2 September 1702 and lingered with aftershocks intermixed with major shocks until April 1703. Lesser tremors then went on for over a year. The difficulty of getting a clear idea of this earthquake is because the sequence got interwoven with destructive quakes that struck other areas of the Central Apennines as well **(Figure 7b).** This seismic crisis was acutely felt in Rome, which became the center for information about the chronology of the perceptible tremors. The inhabitants of Rome lived for some months in a state of collective panic, which even caused difficulties for maintaining public order (Valesio, 1700-1742; Chracas, 1704; Baglivi, 1754).

The crisis had four high-energy peaks, respectively on 18 October 1702, 14 and 16 January 1703, 2 February 1703. Recent analysis of a manuscript codex in the Vatican Library (Urbinate Latinus no. 1699), sheds light on the tangled web of shocks and how the worst of them tie up with other areas affected in the Central Apennines. This codex is a collection of letters and reports from eye-witnesses (Morelli, 1972).

The first earthquake felt at L'Aquila occurred on 2 September 1702, as we read in a letter from L'Aquila written by the Gonfalonier (Lorenzani, Codex Urb. Lat. 1699, fols. 188v and 198r). At 7:55 a.m. on 18 October 1702 there began the long seismic sequence that devastated Umbria, particularly the upper Valnerina, a few tens of km north of L'Aquila. Here is an interesting account from a contemporary:

> *"Beginning on 18 October* [1702] *the day appointed for the feast of St Luke the Evangelist, at the 14th hour of the morning* [corresponding to 7:55 by modern calculations, editor's note] *the town of Norcia and its surrounds heard the earthquake, just as they did in Rome and other parts of Italy; it went on being heard in the above town and area, now more vigorous, now less, (so) that many of the inhabitants went to sleep outside in huts in the countryside. But as it [the earthquake] continued, the very continuation of it seemed to make the people grow familiar with it, forgetting how in various past centuries that area had had a similar event, to the point where few were afraid*" [Urb. Lat. 1699, fol. 176v, translated from Italian].

There was a series of foreshocks, probably causing some damage to Cascia and Norcia. The population evacuated the towns and in the months that followed almost grew used to the problem and underestimated it, having lost all "memory" of previous earthquakes. Numerous aftershocks followed for almost three months.

L'Aquila too suffered the strong tremor of 18 October 1702: CPTI11 lists only one epicenter located in Norcia (Umbria), having $I_0$ VII, $M_w$ 5.14 (the reference the PFG catalogue: Postpischl, 1985). The 18 October shock is not listed in CFTI because its epicentral intensity was lower than the threshold fixed for this catalogue. It frightened people at L'Aquila, but caused no damage. Earthquake activity went on in Valnerina (Umbria region) and was also felt at L'Aquila. Two high-energy shocks occurred on 14 and 16 January 1703, thus during a sequence of tremors lasting at least four months. The first, having $I_0$ XI MCS and $M_w$ 6.7, wrecked the towns of Cascia and Norcia (Umbria region) and a large number of smaller towns and villages. The second had an estimated $I_0$ VIII MCS and $M_w$ 6.2, but is listed only in CFTI; surprisingly, CPTI11 supplies no parameters for this shock, even though the reference study is the CFTI itself. The fact that these two shocks overlapped each other at many locations makes pinpointing their epicenters especially difficult.

These two events struck the Central Apennines, including the southern Umbria region and the neighboring parts of eastern Latium and southern Marche (State of Church). In all, they caused extensive collapses in numerous villages in the current provinces of Perugia (upper Valnerina, Umbria region), Rieti (upper valley of the Velino River, Latium) and Macerata, in the Marche region **(**State Archives, Rome, 1691-1704; 1701-1706).

L'Aquila itself was hit by the 14 and 16 January shocks. The first brought down many chimneys and demolished the façade of San Quinziano church, causing damage of intensity VII MCS, while the second caused serious cracks in many houses and churches; the cathedral bell tower cracked open and became unsafe, while cracks opened in other churches (VII MCS). Tremors went on for another two weeks and then, at 12:05 p.m. on 2 February 1703, there came the strongest earthquake of all ($I_0$ X; $M_w$ 6.7), which devastated L'Aquila. For this shock the CPTI11 makes reference to the CFTI4Med07, that assessed the intensity for 71 sites; the epicenter falls about 12 km northwest of the city.

This earthquake caused its worst effects in the area of L'Aquila and northwestern Abruzzo, in the Monti Reatini area and in northeastern Latium. Many villages in the present-day provinces of L'Aquila, Rieti and Teramo were destroyed or severely damaged, many of them having been already hit by the

January shocks (Uria de Llanos, 1703; State Archives, Naples, 1704; Colapietra, 1989). **Figures 7a and 7b** supply an overview of this sequence, showing also its time evolution.

An interesting letter written by a resident of L'Aquila to a relative living in Rieti (in northeastern Latium on the border with Abruzzo) gives an idea of this pattern of extremely strong aftershocks. The letter is dated 8 February 1703, six days after the big quake:

> *"In this place* [L'Aquila] *all hell has opened; two or three hundred times by day and night we have heard booms like artillery, and nearby there are huge earthquakes that make our hair curl. You there in Rieti are in paradise and what you feel is (by comparison) buffets of the wind"* [Vatican Library, Cod. Urb. Lat. 1699, fol. 199v, translated from Italian].

## 9. The 1762 and 1786 earthquake sequences

In October 1762 a damaging earthquake struck the middle Aterno valley in Central Abruzzo, centering on a few villages to the east-southeast of L'Aquila. The destructive mainshock came on 6 October 1762 at 1:10 p.m. (CPTI11: $I_0$ IX, $M_W$ 6.0; the reference study is CFTI4Med07) followed by numerous aftershocks. For nearly the whole month of October the population felt 20-30 shocks per day, with more sporadic ones continuing into mid-November (CFTI4Med07).

According to Tertulliani *et al.* (2012b, p. 1075) "*new information on the duration of the sequence*" suggests that it "*lasted approximately three months instead of about 25 days*"; unfortunately these investigators make no mention of any foreshocks and do not cite the specific source from which the information on the sequence length was drawn. Tertulliani *et al.* (2012b) confirmed the epicenter given in CPTI11 (from the CFTI study). Two years later the whole area suffered intense famine. A 1776 report from a Neapolitan government envoy described most of the population as still living in makeshift dwellings or caves (Morelli, 1967).

Though the number of localities involved was limited, the 1762 earthquake seems rather similar (in terms of destructiveness and area involved) to the 1461 earthquake which came in a long sequence of shocks. As far as we can tell from the CPTI11, which refers to CFTI data, both these earthquakes occurred in the middle stretch of the Aterno river valley, southeast of L'Aquila, with epicenters that are less than 4 km apart.

In 1786, another seismic sequence began in late July and continued at least until mid-October. It damaged buildings in L'Aquila and Lucoli, a village 8 km northwest of the city. The sources we have used for this event are a series of journalistic correspondence, published in various issues of the gazettes of the time (see CFTI4Med07 for the complete bibliography). The strongest shock took place on 31 July 1786 at about 4:35 p.m. Many buildings in L'Aquila suffered significant cracks. The cathedral façade was badly damaged. The Alfieri Palace became uninhabitable (*Gazzetta Universale*, 1786a; *Bologna*, 1786). The gazettes of the time reported that the earthquake was felt (without damage) in a few places in eastern Latium and even in Naples and in Rome, though very slightly. Yet no information is currently available regarding the effects in other areas of Abruzzo.

The first shock was followed by a long series of aftershocks (**Figure 8**). Two particularly strong shocks occurred on 13 October (at about 11:05 p.m.) and on 14 October 1786 (at about 6:05 a.m.). These caused further damage in L'Aquila, and in particular to the church of San Bernardino (*Gazzetta Universale*, 1786b).

CPTI11 lists only the first shock, the one that occurred on 31 July 1786, nor are cumulative effects assessed. As a result, the epicentral parameters of the 1786 earthquakes have been estimated differently: CPTI11 gives $I_0$ VI MCS and $M_w$ 4.94, referring to the 31 July shock only; CFTI4Med07 gives $I_0$ VII -VIII MCS and $M_w$ 5.6 because also the subsequent and stronger shock of 31 October is included in the assessment (see **Table 2**).

## 10. The August-October 1809 earthquake sequence

About twenty years later another seismic sequence hit the area of L'Aquila between August and October 1809. This earthquake is not listed in CFTI since its epicentral intensity is lower than the threshold fixed by this catalogue. The data presented here are hence the result of research done for this paper.

The limited information currently available comes from letters published in the gazettes of the time (*Gazzetta Universale*, 1809a-b; *Il Redattore del Reno*, 1809a-c). Although we still lack detailed information about the effects of this earthquake, it is interesting to note the development of its sequence. The first

shock, which was quite strong, was felt in L'Aquila on 1 August, at about 10:00 p.m. A second shock, described as equally strong, occurred at about 4:00 a.m. on 2 August 1809 and was followed by many other minor shocks (about twenty were felt by the local population). Once again on 2 August, at about 10:00 p.m., a very strong shock was felt, which lasted for several seconds. People were scared that another even stronger earthquake might occur. They were aware that they lived in a city that had been devastated by previous earthquakes. As a result, many of them fled from their houses, choosing to live in huts or makeshift shelters.

There were more shocks on 3 August 1809, all of them minor except for one, which was felt at about 10:00 a.m. The shocks were less frequent on 4 August, but two of them were quite strong. On 5 August and on the following days the shocks continued without causing any damage to buildings, but the increasingly frightened population suffered great discomfort. All in all, by 13 August the local residents had felt about 100 shocks. By that time the city was deserted. It was only on the next day, 14 August, at about 12:00 p.m., that the most violent shock occurred, damaging various buildings in the city. In CPTI the mainshock is evaluated $I_0$ VI, $M_w$ 4.72, but we contend that the damage was a little more serious, VI-VII MCS. We believe the Mw 4.7 estimate is reasonable yet is affected by a large uncertainty, being based on one intensity datapoint only. Notice that the mainshock took place more than 15 days after the earliest perceived shocks (**Figure 9**).

Many less intense aftershocks followed and continued until October 1809 (Mozzetti, 1836). For this event too information is only available for the city of L'Aquila. Capocci (1861-1863) noted that this earthquake affected other places in Abruzzo, but he did not name them. Evidence regarding the area of origin of this sequence can perhaps be found in some journalistic correspondence (*Il Redattore del Reno*, 1809c). Reference is made to extensive environmental effects and changes in the water discharge regime in the area "of the mountains known as *Chiarina*". This can perhaps be identified as Valchiarina in the area of Monti della Laga (on the border between Latium and Abruzzo), a short distance from the village of Amatrice and about 30 km north of L'Aquila. The historical reconstruction of this sequence outlines a crisis that lasted for at least three months.

It is normally assumed that the scientific interest for earthquakes that are too small to be perceived by humans, such as all those having M<3, has developed only in recent years, possibly as a result of the improvement of instrumental networks. This is not true: history shows that this interest existed well before the development of the early seismographs. In 1808, a year before the L'Aquila earthquake of 1809, the Abbé Vassalli-Eandi (1761–1825), a brilliant physicist and mathematician and also a seismologist, witnessed the earthquake sequence that was striking Pinerolo (Piedmont, northwestern Italy). The sequence lasted six months, from April to October 1808, starting with a $M_w$ 5.7 shock on 2 April ($I_0$ VIII). At the end of the sequence Vassalli-Eandi wanted to check whether earthquake activity continued undetected by people. To this end he designed an ingenious seismoscope made by a pendulum and by a receptacle containing a suspension of flour and water, even the slightest disturbance of which would leave a sort of scum-line on the sides (Morbo, 2008, p. 42).

## 11. The great 1915 Marsica earthquake: foreshocks and aftershocks

The earthquake of 13 January 1915 was one of the two most violent Italian events of the 20th century, reaching $M_w$ 7.0 (the other was the 28 December 1908 earthquake in the Straits of Messina, $M_w$ 7.1). It was an utter catastrophe that caused an extremely large number of deaths: 30,519 in all, 29,105 of them in the province of L'Aquila and 10,719 in the town of Avezzano alone (82% of its inhabitants): see Molin *et al.* (1999a, pp. 341–348) for a comprehensive summary.

The time evolution of this earthquake was investigated by the scientific literature in the late 1990s. Concerning the Marsica, the region of which Avezzano was the most important center, Molin *et al.* (1999b) published the list of localities affected by some foreshocks and by 50 aftershocks, throughout 1915 and until April 1919. Margottini and Screpanti (1999) examined over 900 aftershocks that occurred in the first half of 1915. Until then people had accepted Cavasino's (1935) opinion, written twenty years after the event, that there had been no foreshocks before the great quake of 13 January 1915. Cavasino, however, selected only shocks above intensity VI of the Mercalli scale, thus ignoring on purpose all minor tremors. If one takes a broader time perspective, however, this great earthquake was part of a period of enhanced earthquake activity for the whole western and central Abruzzo that began with the earthquake of 24 February 1904 (CPTI11: $I_0$ VIII–IX; $M_w$ 5.6), effectively a smaller counterpart of 1915 aligned with it along the same seismogenic structure. Earthquake activity became more frequent in the area in the two years prior to the 13 January 1915 earthquake: in the absence of instrumental data the six events listed below, reconstructed by Molin *et al.* (1999b, p. 268, and Appendix A, pp. 586–588) may only afford a

partial idea of such precursory activity:

1) *1913, 3 January, 2:39 p.m.*: an earthquake struck Gioia dei Marsi, Scanno, Sora and Trasacco, the effects having intensity V–VI MCS. Another 28 villages felt the shock without registering any damage ($I_0$ V–VI, $M_w$ 4.6).
2) *1914, 27 March, 3:26 a.m.*: a tremor was distinctly felt at Magliano de' Marsi (IV MCS).
3) *1914, 14 April, 3:49 a.m.*: another earthquake struck Gioia dei Marsi, Pescina, Avezzano, Trasacco and Celano, the effects having intensity between IV and V MCS; it was felt over a broad area including six localities in Latium. It was also slightly felt at Caserta (Campania). In CPTI11 this event is reported as having $I_0$ VI MCS, $M_w$ 4.7.
4) *1914, 21 April, 12:46 p.m.*: a tremor causing no damage was clearly felt at Avezzano (IV MCS).
5) and 6) *2 October 1914*: two further light tremors, perhaps reaching intensity III MCS, were felt by the population at Tagliacozzo at 1:30 a.m., and at Avezzano and Magliano dei Marsi at 7:59 a.m. (Cavasino 1935).

The big shock happened on 13 January 1915 at 7:52 a.m. and was hence actually preceded by a long period of activity that even caused some slight damage. After the mainshock, the Rocca di Papa Observatory (about 70 km west-southwest of the epicenter) recorded some 1,280 aftershocks.

The Marsica earthquake crisis went on for over four years (Cavasino, 1935). Margottini and Screpanti (1999, pp. 310–318) listed 935 aftershocks for the period from 13 January to 9 July 1915, all having magnitude $M_d$ (or $M_s$) ≥ 2.5 but none exceeding 4.7. Molin *et al.* (1999b, pp. 268–271 and Appendix A, pp. 605–615) listed 50 major aftershocks occurring between 13 January 1915 and 20 April 1919 and for which macroseismic information was collected. Six of these large aftershocks were above the threshold of damage and two caused peak effects of intensity VII MCS. **Figure 10** shows a map of the mentioned foreshocks whereas **Figure 11** shows a diagram of all shocks felt from 1913 to 1916.

## 12. Discussion and Conclusions

We analyzed a number of earthquake sequences that have struck L'Aquila and western Abruzzo over the past seven centuries **(Figure 12)**: 1315, 1349, 1456, 1461, 1646, 1702–1703, 1762, 1786, 1809 and 1915. Our sample includes both very strong earthquakes and low-medium impact sequences. All these earthquakes came as prolonged seismic crises with a complex evolution in time and space, documented by a wealth of coeval historical sources (**Table 2).** This impressive string of earthquake sequences provided abundant raw material to pursue the goals that were set at the beginning of this paper (see Section 2): demonstrating that complexity is an inherent characteristic of many large earthquake sequences, and proving that historical seismology comprises a unique opportunity to learn about it. In the following we review the three main issues that were set forth in the Introduction, discussing how the historical evidence may help addressing them.

*Learning about earthquake patterns*. How many times a large earthquakes has been preceded by sizable foreshocks? How likely will a large earthquake trigger similarly-sized events in adjacent portions of the same seismogenic zone? How long is a sequence going to last? While nobody would ever argue that these questions are crucial for the assessment of seismic hazard and risk, answering them requires acknowledging that the nature and duration of certain sequences in a given region is a cultural asset: one learns something about social history and how fear makes people behave in various historical contexts. In this respect the 1702-1703 sequence makes an interesting case. The way this complex sequence unfolded, with peaks occurring 3-4 months after the first shocks, caused in the population a state of exasperation and acute stress, not unlike what happens nowadays. The ability to assess how danger, damage or stress may increasingly affect the population as time passes is an important asset for administrators, planners and civil protection officials. But developing this ability requires the historical analysis of social, cultural and linguistic contexts, the basic tools of this approach. There are wide-ranging and even random reasons why contemporaries did or did nor leave written information on the shocks they felt before or after a large earthquake. The reasons vary greatly in time and may depend on the persons' cultural level or the object behind the written text.

More specifically, the research conducted on the Middle-Age earthquakes of 1315, 1349 and 1456 suggests that these entailed considerable sequences, but there is no explicit evidence of foreshocks. These cannot be excluded *ex silentio*, however, nor can they be conjectured. Nevertheless, it is interesting to note that remoteness in time is not always what prevents precise sequences being recorded by contemporaries.

Conversely, specific accounts of foreshocks and of numerous aftershocks have been collected for the 1461, 1702–1703, 1786, 1809 and 1915 earthquake sequences. How this kind of information depends on

the type of sources available is shown by the case of 1762: the administrative sources, though precise as to the effects sustained, make no mention of any foreshocks, but only refer generically to a sequence that lasted about three months. To gain information on the historical sequences one needs to consult a certain kind of source, such as chronicles, letters, reports and newspapers. Administrative and fiscal sources are less likely to disclose such information: this is particularly the case in the area analyzed in this work.

A different but not less insidious case is that exemplified by the 1646 earthquake, when powerful and damaging aftershocks struck the epicentral area more than two months after the mainshock, presumably at a time when the population had already started to recover.

*Develop an appreciation for the progressive accumulation of damage*. For historical seismologists it is normal to deal with "cumulative effects", and in fact separating retrospectively the effects of the mainshock from those of later shocks is perhaps the main challenge they face. The 1315, 1349, 1456, 1461 and 1702-1703 sequences - and to some extent also the others - provide a vivid account of the worsening of damage and living conditions as the sequence progresses and the number of potentially damaging shocks increases. The recent double and triple earthquakes listed in **Table 1** proves beyond any doubt that this is a recurrent character of all Italian earthquakes; additional damage and even total collapses of already stressed buildings may be caused by earthquakes occurring a few hours after the mainshock, as in the Umbria-Marche sequence of September 1997, nine days later, as in the Emilia sequence of May 2012, or even four months later, as in the case of the May-September 1976 sequence in Friuli, to mention just the most tragic cases. Each of these time intervals - hours, days, or months - is insidious in its own way and has a different impact on buildings and on the population.

Although the progressive worsening of damage belongs to the common perception of all those who lived through a devastating earthquake sequence, we suspect many seismologists and earthquake engineers tend to forget that the damage accumulated at the end of a complex earthquake sequence will inevitably - or at least very likely - be much larger than expected after the first large shock. Even deterministic earthquake scenarios tend to focus exclusively on the effects of one shock at a time - perhaps for fear that they may end up being too severe - and to express the ground motion only through peak ground acceleration (see for example Zonno *et al.* 2012) rather than in terms of the total duration of strong ground shaking or using other parameters of engineering interest. We believe that historical evidence of earthquake complexity may help engineering seismologists and structural engineers focusing on how the performance of a building will be worsened by subsequent strong earthquakes on adjacent faults. Raising this awareness, however, requires far better input data than those supplied by current parametric catalogues; ideally, modeling the ground shaking resulting from repeated earthquakes requires matching historical earthquake information with data on the geometry and size of the seismogenic sources such as those supplied by the DISS database (DISS Working Group, 2010).

*Assess the true extent of earthquake ruptures following a complex sequence*. A further recurring character of Italian earthquake sequences characterized by similarly large shocks is that they usually end up relieving tectonic stress over a much larger area than that suggested by the shock identified as "the mainshock" in hazard-oriented catalogues. Over time parametric catalogues have encouraged an overly simplified representation of earthquakes as "point sources"; under this simplification an earthquake sequence may be seen simply as "a cloud of point sources" with no consideration for the actual extent of the crustal volume affected by each individual shock. This way of storing and representing earthquake data is not only outdated, but is fundamentally self-referential as it does not allow scientists working in adjacent disciplinary areas to share information on past seismicity and on future earthquake potential.

Assessing the true rupture extent of historical earthquake sequences is a fundamental pre-requisite in time-dependent hazard applications, that must necessarily rely on a seismogenic source model such as DISS (DISS Working Group, 2010) or its European counterpart (EDSF: Basili *et al.* 2013). These databases attempt to assess earthquake budgets by assigning historical earthquakes to the relevant causative faults, with the aim to verify what fraction of an extended seismogenic source has ruputured in documented earthquakes and how much earthquake potential is left there, ready to be released in future earthquakes. Calculating earthquake budgets requires a careful assessment of the magnitude of each large shock, which is then converted into a rupture length analytically or using standard empirical relationships. Matching earthquakes with the actual seismogenic sources responsible for them hence requires that complex sequences be known in the best possible detail.

The largest sequences investigated in this paper (1349, 1456, 1702-1703) all involved multiple large shocks that somehow represent the cascade-style rupture of large fault segments that may or may not belong to the same extended seismogenic source. The removal of large shocks by declustering or the practice of collapsing all shocks into a single larger shock invariably results in an underestimation of the

crustal volume that released the sequence, if subsequent large shocks were caused by adjacent faults; conversely, collapsing multiple events in a single one may cause an overestimation, if the cumulative felt area reflects the activation of non-adjacent faults.

Having established that exploring the complexity of earthquake sequences is crucial for a number of different reasons, what prospect is there of understanding such an evolution, attributing parameters, and using them to improve the seismic hazard and risk estimates? As we argued in the Introduction of this paper, so far the the hazard-oriented standards adopted in Italy - and in fact in most of the world - for historical earthquake catalogues, and particularly their strictly parametric nature and the practice of "preliminary declustering", have represented a bottleneck for the progress of earthquake research. But while it is obvious that seismic hazard assessment is the most societally important application for an earthquake catalogue, still one does not see why any scientist should accept to use a dataset that has been preliminarily decimated, based on principles that have dominated the probabilistic assessment of seismic hazard for over 40 years but that are now being questioned by the hazard practitioners themselves. It goes without saying that, similar to any other experimental science, a process of rationalization of the existing data would require first to describe the phenomena – in our case the historical sequences - and only later to decide which model is best to adopt, what parameters are really relevant and which data is best to use.

One must conclude by saying that a lot of work is needed to improve historical catalogues that were designed as a direct or indirect application of Cornell's method. Though efforts were made in the past to standardize, assess and calibrate a considerable bulk of information, Italy still lacks a single reference database to draw on for various types of statistical and hazard analysis. In principle historical earthquake catalogues contain precious information for seismologists, engineers, geologists, and for scientists who are active in cultural and social history: but while current catalogues fulfill one objective - how to apply a specific and non-definitive method - we feel that they rule out all chances of more complex functions and goals. For this reason we support a major revision of current strategies and the creation of a new more flexible standard for storing and using the valuable information that historical seismologists have made available over the past few decades.

## Data and Resources

All the historical data on major earthquakes used in this paper came from published sources (MedCat05: Guidoboni and Comastri, 2005), and all reports are given proper references in the text wherever historical reports concerning inscriptions and medieval earthquakes of lesser intensity are reproduced or described.

All earthquake parameters came from:

- CFTI4Med – Catalogo dei Forti Terremoti in Italia CFTI4Med, 2007 version (see Guidoboni *et al.* 2007), available at http://storing.ingv.it/cfti4med/; also referred to as: Catalogue of Strong Earthquakes in Italy (461 B.C.–A.D. 1997) and the Mediterranean area (760 B.C.–A.D. 1500);
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All these catalogues were last accessed in June 2014.

The data concernig the damage and the number of casualties for the 2009 L'Aquila (Central Italy) earthquake have been taken from *Terremoto in Abruzzo 2009,* published in 2010 by Dipartimento della Protezione Civile (available at http://www.protezionecivile.it/jcms/it/emergenza_abruzzo.wp, last accessed August 2014).

## References

### *Historical sources*

We listed here only sources mentioned in the text. The complete references and the original sources regarding the medieval earthquakes can be found in MedCat05; for the events of the following centuries see CFTI4Med07 (http://storing.ingv.it/cfti4med/).


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## Tables and captions

**Table 1** - Summary of the 14 largest Italian earthquake sequences ($M_w \geq 5.7$) since 1960 (data from CPTI11). Ten out of 14 of these sequences were multiple or complex events, i.e. they were characterized by at least two mainshocks or subevents whose magnitude is within 0.3 units of each other. Aside from other seismic hazard and engineering implications, earthquake complexity is a condition by which 14 sequences resulted in total of 33 potentialy damaging shocks. *Seismological analyses revelaed that the 23 November 1980 earthquakes was composed of three distinct rupture subevents occurring within roughly a minute; ** Tertulliani *et al*. (2012a); *** Tertulliani *et al*. (2012b). Modified from Burrato and Valensise (2008) and Vannoli *et al*. (2014).

| # | Mainshock date | Locality | $M_w$ | Intensity MCS | Single/Multiple |
|---|---|---|---|---|---|
| **1** | 1962, 21 August | Irpinia | 6.1 | IX | Multiple (3 shocks) |
| **2** | 1963, 19 July | Mar Ligure | 6.0 | VI | Multiple (2 shocks) |
| **3** | 1968, 14 January | Valle del Belice | 6.5 | X | Multiple (3 shocks) |
| **4** | 1976, 6 May | Friuli | 6.4 | IX-X | Multiple (3 shocks) |
| **5** | 1978, 15 April | Golfo di Patti | 6.0 | VIII | Single |
| **6** | 1979, 19 September | Valnerina | 5.8 | VIII-IX | Single |
| **7** | 1980, 23 November | Irpinia-Basilicata | 6.7 | X | Multiple (3 subevents)* |
| **8** | 1984, 7 May | Appennino abruzzese | 5.8 | VIII | Multiple (2 shocks) |
| **9** | 1990, 5 May | Potentino | 6.0 | VII | Multiple (2 shocks) |
| **10** | 1997, 26 September | Appennino umbro-marchigiano | 6.0 | IX | Multiple (3 shocks) |
| **11** | 2002, 6 September | Palermo | 5.8 | VI | Single |
| **12** | 2002, 31 October | Molise | 5.8 | VII-VIII | Multiple (2 shocks) |
| **13** | 2009, 6 April | L'Aquila | 6.2 | IX-X** | Single |
| **14** | 2012, 20 May | Emilia | 6.1 | VIII*** | Multiple (2 shocks) |

**Table 2.** L'Aquila and Abruzzo area: list of ten analyzed historical sequences and comparison between the CFTI4Med07 and CPTI11 catalogues. Notice that many earthquakes listed in CPTI11 are based on information derived from studies included in CFTI4Med07.

| Year | Date of mainshock | Foreshocks | Aftershocks | Sequence length | Catalogue | $I_o$ MCS | $M_w$ | References |
|---|---|---|---|---|---|---|---|---|
| 1315 | 3 Dec. | N/A | Until Jan. 1316 | 4 weeks | CPTI | VIII | 5.6 | CFTI4Med07 |
| | | | | | CFTI | VIII-IX | 5.8 | MedCat05 |
| 1349 | 10 Sep. *four epicentral areas* | Jan.-Sep.? | Many | 9 weeks | CPTI = CFTI | *(2) L'Aquila area IX* | 6.0 | MedCat05 |
| | | | | | CFTI | *(3) Sulmona area IX* | 5.8 | MedCat05 |
| | | | | | CPTI # | ----- | ----- | ----- |
| 1456 | 5 Dec. 30 Dec. *four epicentral areas* | N/A | Until May 1457 | 6 months | CPTI | XI C/E | 7.2 | Meletti et al. 88 |
| | | | | | CFTI | *(1) Abruzzo area X* | 5.8 | MedCat05 |
| | | | | | CPTI | ----- | ----- | ----- |
| 1461 | 27 Nov. | 17 Nov. | Many | 5 months | CPTI = CFTI | X | 6.4 | MedCat05 |
| 1646 | 19 Jun. | 28 Apr. | Hundreds | 2 months | CPTI | V-VI | 4.5 | Arch. Mac. 95 |
| | | | | | CFTI* | * | * | * |
| | | | | | this study | VII | 4.8 | see text |
| 1703 | 14 Jan. | Sep. 1702 | Thousands | 12 months | CPTI = CFTI | XI | 6.7 | CFTI4Med07 |
| | 16 Jan. | Sep. 1702 | Thousands | 12 months | CPTI# | ----- | ----- | ----- |
| | | | | | CFTI | VIII | 6.0 | CFTI4Med07 |
| | 2 Feb. | Sep. 1702 | Thousands | 12 months | CPTI = CFTI | IX | 6.7 | CFTI4Med07 |
| 1762 | 6 Oct. | N/A | Many | 3 months | CPTI = CFTI | IX | 5.9 | CFTI4Med07 |
| 1786 | | 31 Jul. 1786 | Many | 3 months | CPTI | VI | 4.9 | Monachesi Castelli 92 |
| | | | | | CFTI | ----- | ----- | ----- |
| | 13 Oct. | Jul. 1786 | Many | 3 months | CPTI | ----- | ----- | ----- |
| | | | | | CFTI | VII-VIII | 5.6 | CFTI4Med07 |
| 1809 | 14 Aug. | 1-13 Aug. | Many | 3 months | CPTI | VI | 4.7 | Arc. Mac. 95 |
| | | | | | CFTI* | * | * | * |
| | | | | | this study | VI-VII | 4.7 | see text |
| 1915 | 13 Jan. | Dec. 1914 ? | Many | 4 years | CPTI # | XI | 7.0 | Molin et al. 99 |
| | | | | | CFTI | XI | 7.0 | CFTI4Med07 |

**Key:**

**$I_o$** : Epicentral Intensity
**N/A** : Not available.
* : The event is not listed in CFTI4Med07 because it falls under the intensity threshold of this catalogue.
**C/E** : Cumulative effects.
= : For this event both the CPTI11 and the CFTI4Med07 list the same parameters.
\# : The catalogue lists additional unparameterized shocks.
*(1) (2) (3):* Among the 4 epicentral areas of the 1349 and 1456 sequences, we selected those regarding L'Aquila and Abruzzo; their numbering is that used in MedCat05.

## Figures and captions

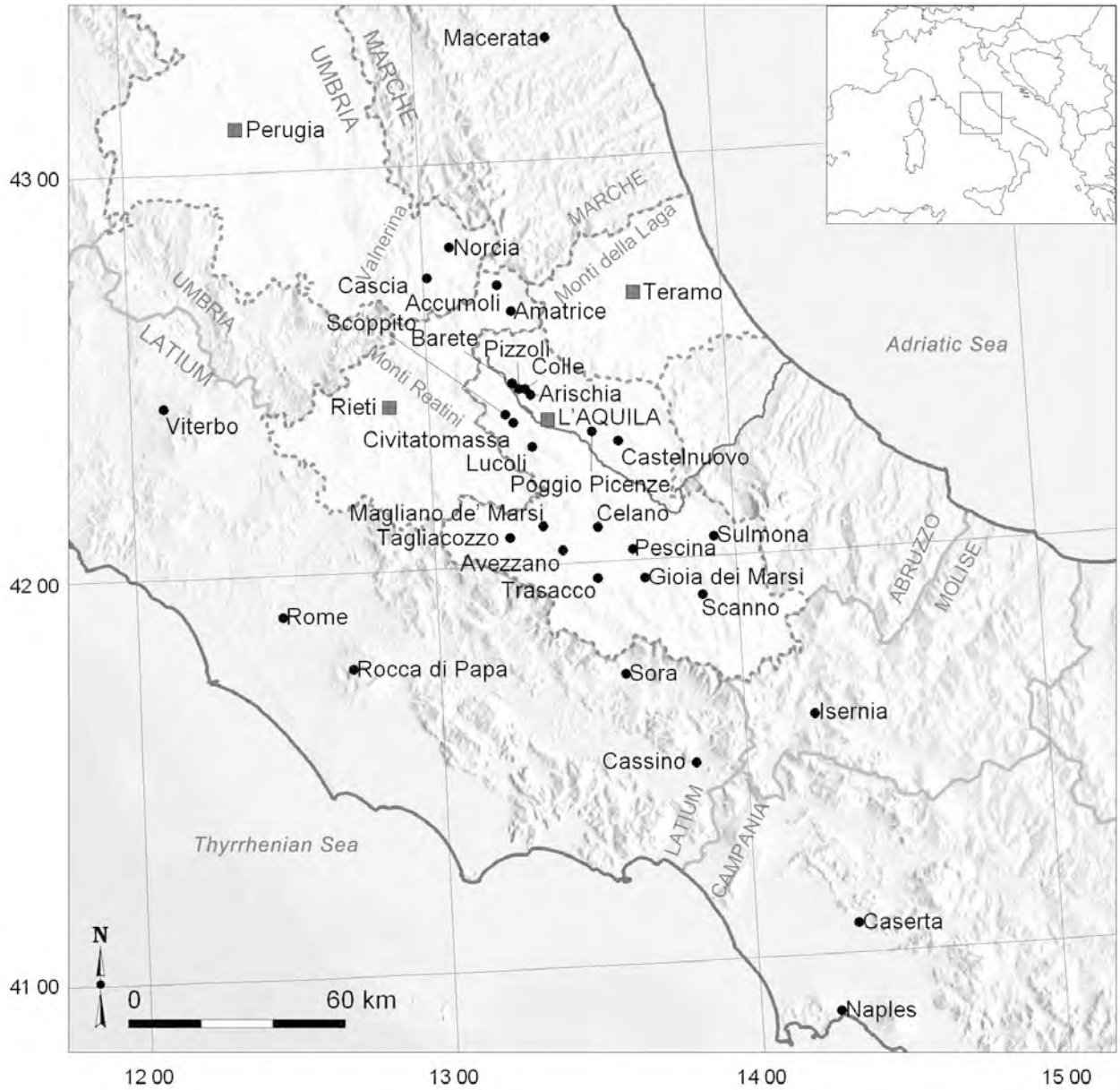


**Figure 1.** Map of all sites and administrative/geographical areas mentioned in the text. The names of the regions are indicated in all-caps and a solid light grey line marks their borders.

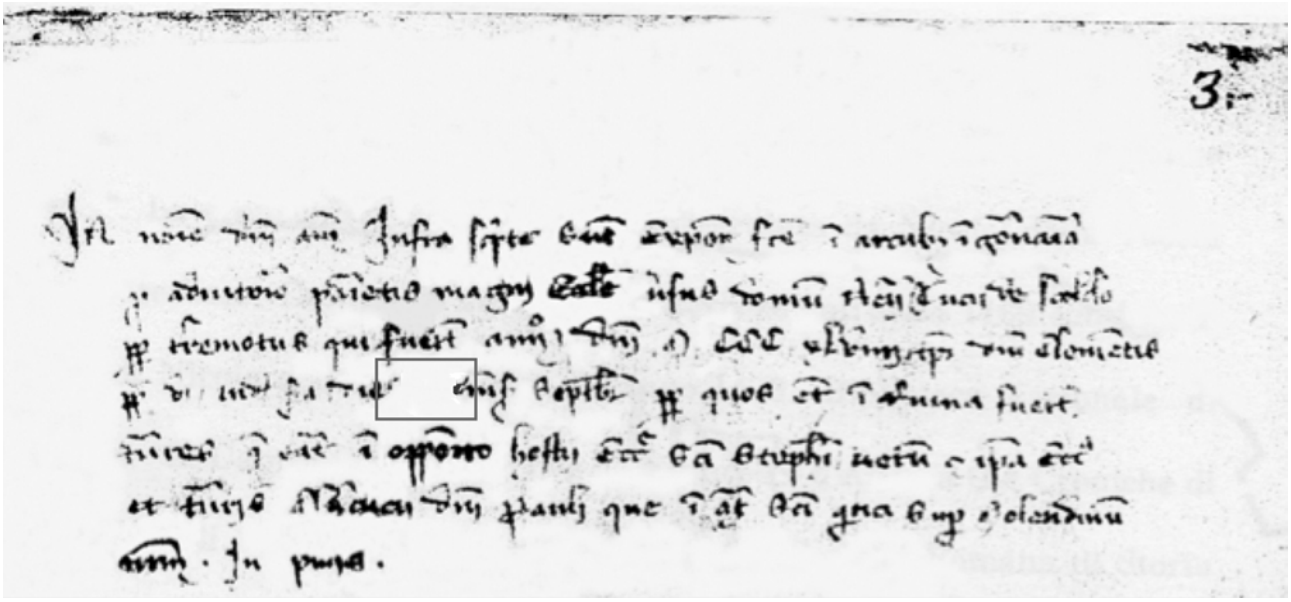

**Figure 2.** A historical source for the September 1349, earthquake sequence in Central Italy. The document reports about damage to the church of S. Angelo in Spata in Viterbo (northern Latium). The open gray rectangle in the fourth line down from the top indicates the space left blank by the local compiler of the document, who was uncertain about the exact date of the earthquake (from MedCat05, p. 445).

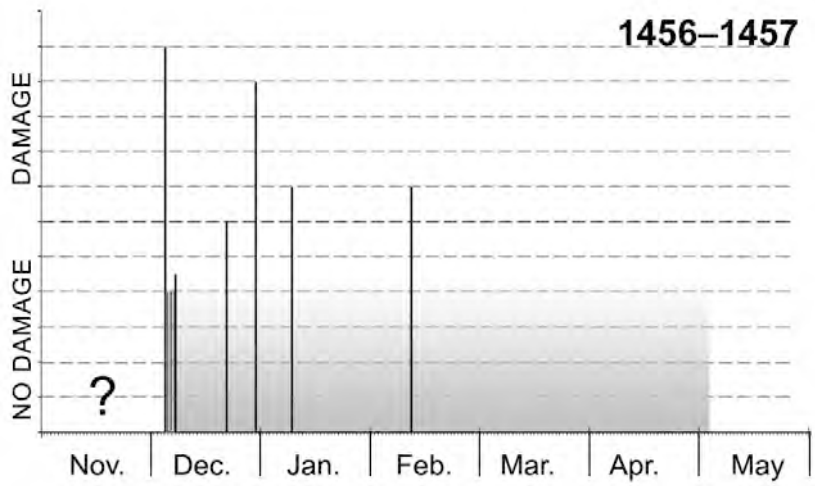


**Figure 3.** Time evolution of the 1456 earthquake sequence: mainshock and aftershocks felt in Naples. The pale grey background indicates continuing earthquake activity perceived by people, mentioned in sources as ongoing seismicity but not dated (elaboration from MedCat05).

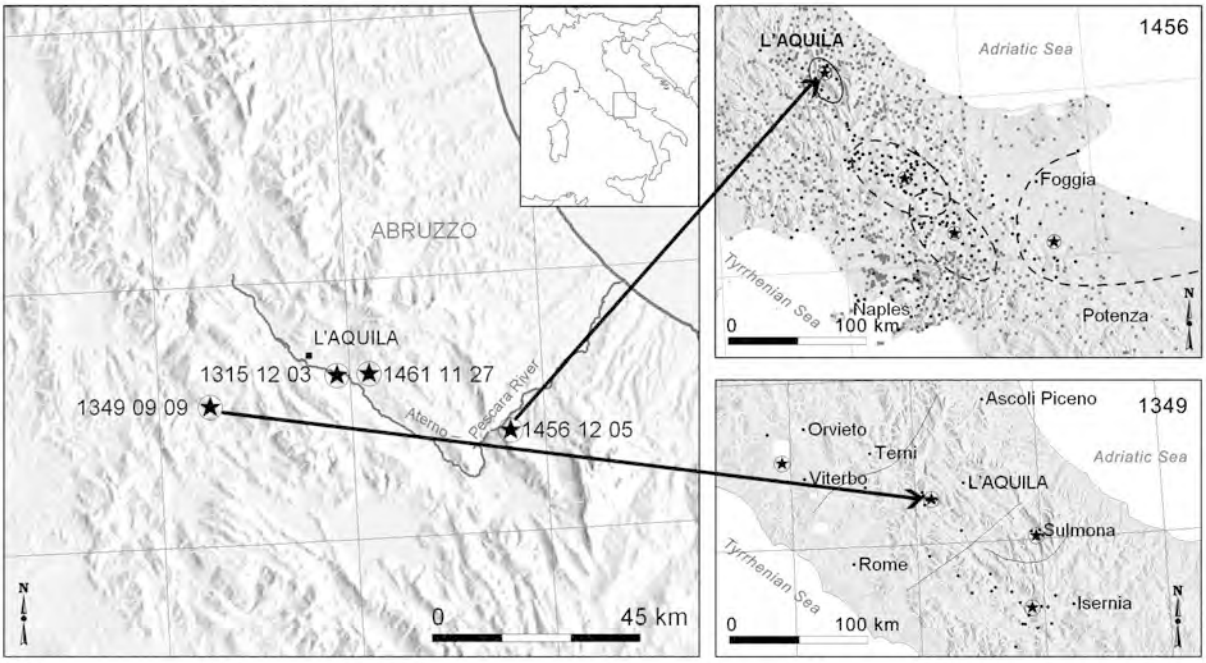


**Figure 4.** Location of the 1315, 1349 and 1456 earthquakes. For the 1349 sequence the damage pattern includes four separate mainshock epicenters, conjectured from the location of the most heavily damaged areas. For the 1456 sequence four conjectural mainshocks are shown; solid dots points show localities that existed and where inhabited at the time of this sequence, 206 of which where damaged (in black), whereas 838 were not (in grey) (elaborated from MedCat05).

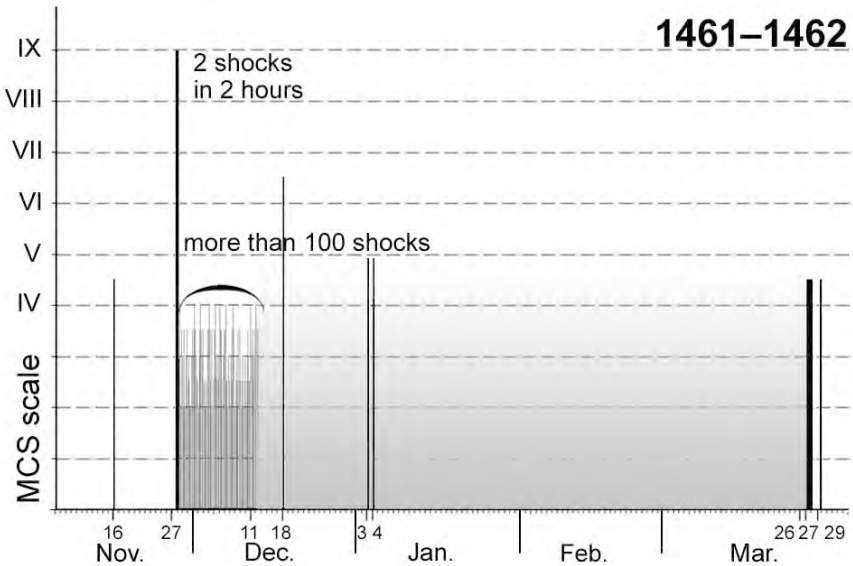


**Figure 5.** Time evolution of the seismic sequence that developed between mid-November 1461 and late March 1462. The shocks are described as "ongoing", but precise chronological information is provided only for some of them. For this sequence CPTI11 lists only the shock on 27 November (from CFTI4Med07); the diagram was constructed based on aftershocks listed in MedCat05.

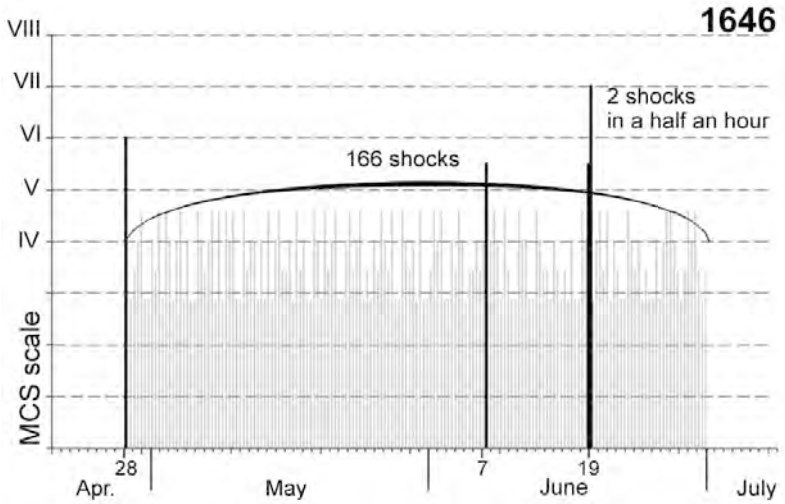


**Figure 6.** Time evolution of the sequence that hit L'Aquila and its environs between April and June 1646. For this sequence CPTI11 lists only the first shock felt in L'Aquila (V-VI MCS) on 28 April; the mainshock occurred on 19 June. The diagram was constructed based on aftershocks retrieved in the present study.

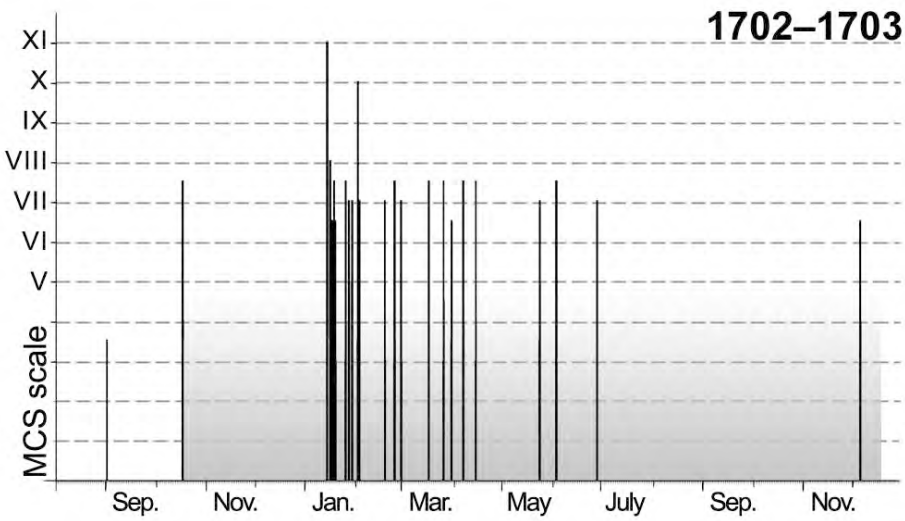


**Figure 7a.** Time evolution of the 1702-1703 earthquake crisis. One early foreshock was documented in L'Aquila on 2 September 1702. The largest shocks came about four months later. A total of 23 strong aftershocks can be dated. Earthquake activity was reported persisting for several years, but no further dating is available.

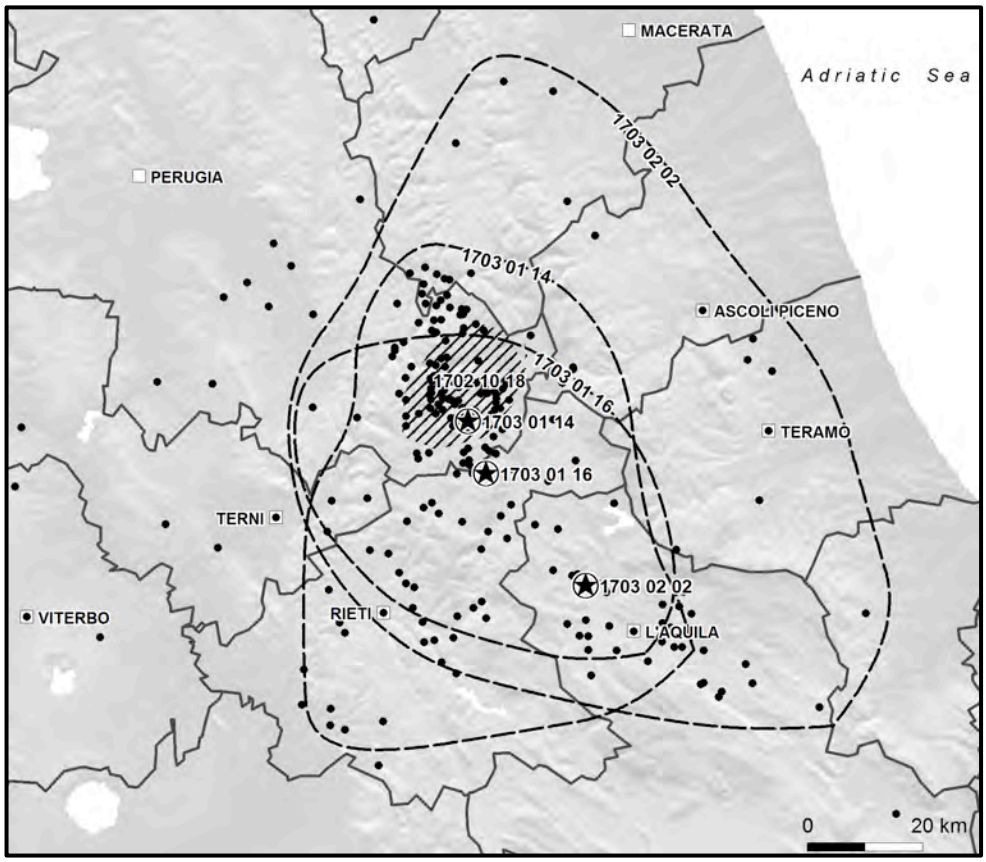


**Figure 7b**. Heavy damage areas (intensity VIII and larger) for the largest shocks of the 1702-1703 Umbria-Abruzzo sequence. Local intensities are available for four mainshocks (shown by dashed areas): 18 October 1702 ($I_0$ VII, $M_w$ 5.14, Norcia) from CPTI11 (originally from PFG); 14 January ($I_0$ XI, $M_w$ 6.74, 199 sites), 16 January 1703 ($I_0$ VIII, $M_w$ 6.0, 22 sites), and 2 February 1703 ($I_0$ X , $M_w$ 6.72, 71 sites), all from CFTI4Med07.

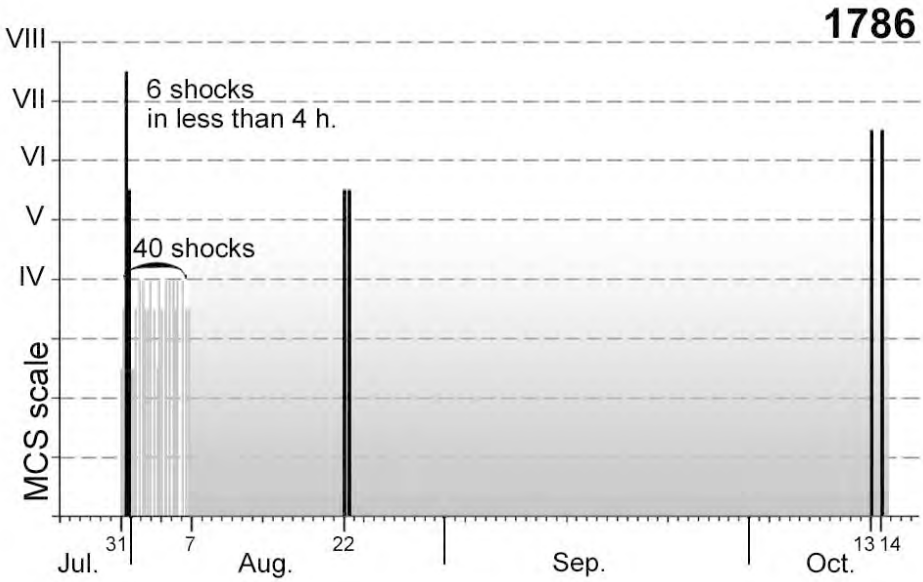


**Figure 8.** Time evolution of the earthquake sequence that hit L'Aquila from 1 August to mid October 1786. The first large shock was followed by a long series of aftershocks. Two stronger aftershocks occurred on 13 and 14 October, at the very end of the sequence. For this sequence CPTI11 lists only the first shock felt in L'Aquila. The diagram was constructed based on aftershocks retrieved in the present study.

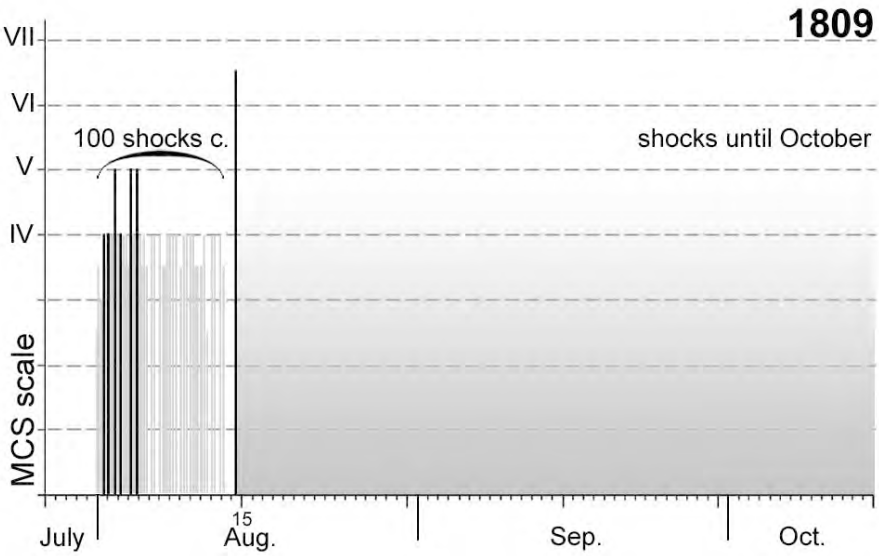


**Figure 9.** Time evolution of the earthquake sequence of August 1809 in L'Aquila area. The mainshock took place more than 15 days after the earliest foreshocks. For this sequence CPTI11 lists only the 14 August shock assigning intensity VI MCS to L'Aquila. The earthquake does not appear in CFTI4Med07 because it falls below the magnitude threshold for this catalogue. The diagram was constructed based on aftershocks retrieved in the present study.


**Figure 10.** Foreshocks of the Marsica sequence of 13 January 1915 ($M_w$ 7.0): location of the six low-intensity earthquakes that occurred between 1913–1914 and respective felt areas (data from Molin et al., 1999b). During the same time-span also the Isernia area was activated (about 80 km southeast of the 1915 mainshock). This area is well known for its destructive earthquakes and for being the locus of one of the four major shocks comprising the 1349 sequence (see Figure 4b).

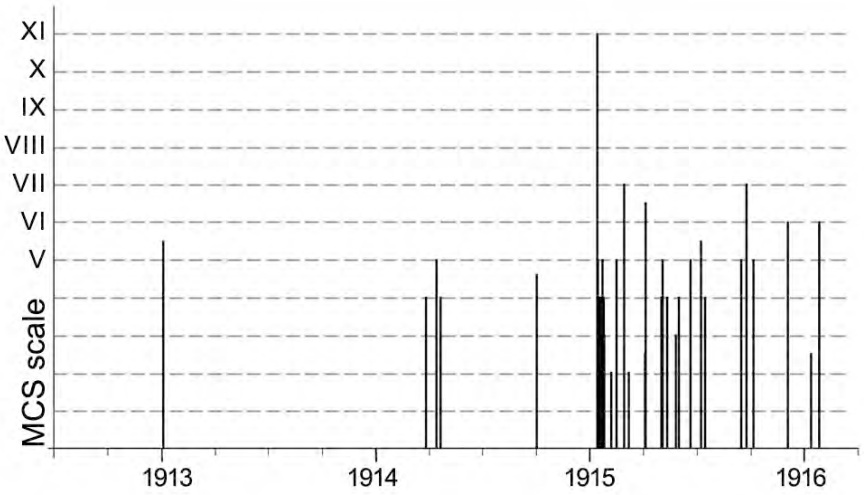


**Figure 11.** Time evolution of the 1915 Marsica earthquake sequence. Information on shocks expressly mentioned by local residents - hence presumably above magnitude 3.0 - ranges from 3 January 1913 to 26 January 1916: the diagram shows the 47 shocks whose effects were described accurately enough to be assigned a macroseismic intensity (elaborated from Molin *et al.* 1999b). In addition to the 13 January mainshock CPTI11 lists 14 additional aftershocks, that occurred in January, identified by their date but unparameterized.

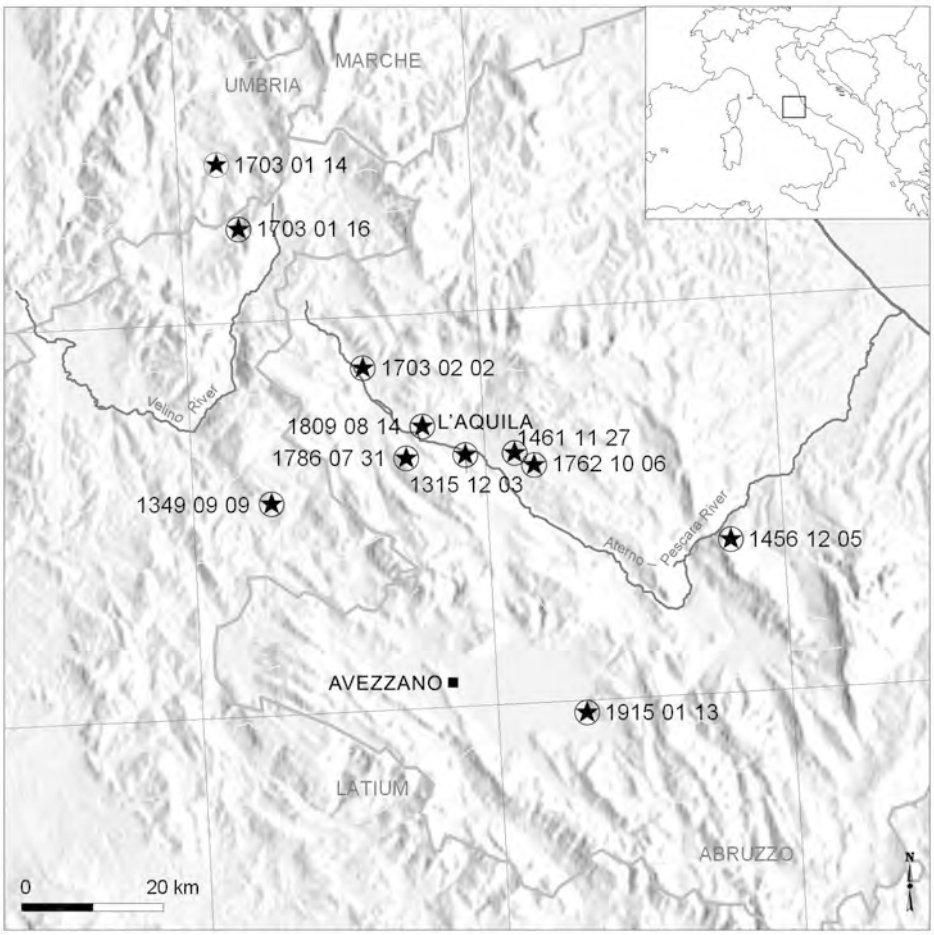


**Figure 12.** Map of the central Abruzzo area, showing the mainshocks of the ten sequences analyzed in this work.