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Archaeoseismological evidence of past earthquakes in Rome (fifth to ninth century A.D.) used to quantify dating uncertainties and coseismic damage

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Abstract

The transformation of Rome during the Late Antiquity and the Early Middle Ages has been investigated by archaeologists and historians. Social and political changes are the main aspects which led to a progressive modification of the urban framework; abandonment, spoliation and transformation of buildings are quite diffused as documented by the archaeological literature. The consequence of these practices is a higher vulnerability of the buildings which, from the seismological point of view, played a main role in increasing the effects of seismic shaking. A number of earthquakes have struck Rome during the period of investigation (fifth to ninth century A.D.), known from historical sources: 443, 484–508, 618, 801, 847; in some cases (443, 484–508, 801) damage has been documented. In contrast, the archaeological sources characterise collapse layers and evidence of destruction at different sites with changing and not always conclusive chronological constraints. Consequently, collapse and destruction have been alternatively attributed to the above-mentioned earthquakes. Through a geoarchaeological and stratigraphic analysis of potentially coseismic collapse units, we want (1) to describe the archaeoseismic evidence derived from recent excavations and from the available literature (e.g. Piazza Madonna di Loreto, Piazza Venezia, Palazzo Valentini Crypta Balbi, Colosseo, Basilica Hilariana, Basilica di Santa Petronilla, Santa Maria Antiqua,…); (2) to discuss the chronological problems and the uncertainty of attribution of the collapse units to known historical earthquakes; (3) to discuss the earthquake damage exaggeration due to erroneous attribution of seismic origin to the evidence of destruction derived from archaeological data. Finally, we will infer the role that earthquakes may have had on the development of the urban landscape in the fifth to ninth century A.D.

Keywords Geoarchaeology · Archaeoseismology · Natural disaster

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1 Introduction

Information on earthquakes that occurred in past centuries is generally derived from written sources. Their quantitative interpretation in the seismological perspective is the basis for compiling seismic catalogues (e.g. Rovida et al. 2016). However, due to the rare number of written sources, knowledge of the seismic history during Antiquity and the Middle Ages can only be improved by other types of information and methods of investigation. For this reason, these historical sources are often combined with the analysis of archaeological and geological data. Here the archaeoseismological investigations contribute to the widening and enhancement of the knowledge of past seismicity. These include the analysis of pre-instrumental earthquake effects on the remains of buildings that are uncovered by archaeological excavations or are persistent in the monumental heritage.

Archaeoseismology is interdisciplinary and the collected data: (1) are useful for the seismic characterisation of a territory; (2) are necessary for the archaeological reconstruction of site histories; and (3) contribute to the conservation of our archaeological heritage (e.g. reinforcing, restoration, intervention for public use). These aims depend on the correct characterisation of the archaeological traces of past earthquakes; i.e. by a combination of the archaeological data and methods with data derived from geological–geomorphological, geophysical, geotechnical, historical, seismological, and engineering investigations (Galadini et al. 2006).

The purpose of the present report concentrates on point (2) by exploring the role of past earthquakes in damaging the buildings of Rome between the fifth and the ninth century A.D. This kind of investigation can certainly be included in the historical perspective of archaeology.

After a brief discussion of the fifth to ninth century earthquakes documented in the historical information, the following sections present a critical review of some of the archaeological sources that report evidence for potential earthquake effects in the Rome area. We concentrate on collapse units that have been uncovered during archaeological excavations. One case deals with reconstruction measures after earthquake damage, showing the low level of reliability of such data.

The discussion focuses on the problem of the chronological constraints and the related consequences for the association of archaeological earthquake traces to historically documented events, and on the risk of exaggeration of seismic damage due to erroneous inclusion of unreliable earthquake traces in a coseismic damage picture.

2 Earthquakes in Rome in the late antiquity and the early middle ages

Reliable details of five earthquakes have been reported in the modern seismic catalogues within the time span of interest of the present study (fifth to ninth century A.D.), since the report of Guidoboni in 1989 (Guidoboni 1989). These events occurred in the years 443, 484 or 508, 618, 801 and 847 (Fig. 1). The earliest of these was mentioned in the *Fasti Vindobonenses Posteriores*, describing the collapse of statues and of the *portica nova* (Guidoboni 1989). These porticos were identified by Lanciani (1917) in the structures related to the "group of the Pompeian constructions, between via Arenula and Campo di Fiori", which was a well-known part of the old town centre of Rome. In his *Historia Romana*, Paolus Diaconus attributed the collapse of houses and of important buildings to this event (Guidoboni 1989). In summary, effects beyond the damage threshold can certainly be attributed to this 443 earthquake.

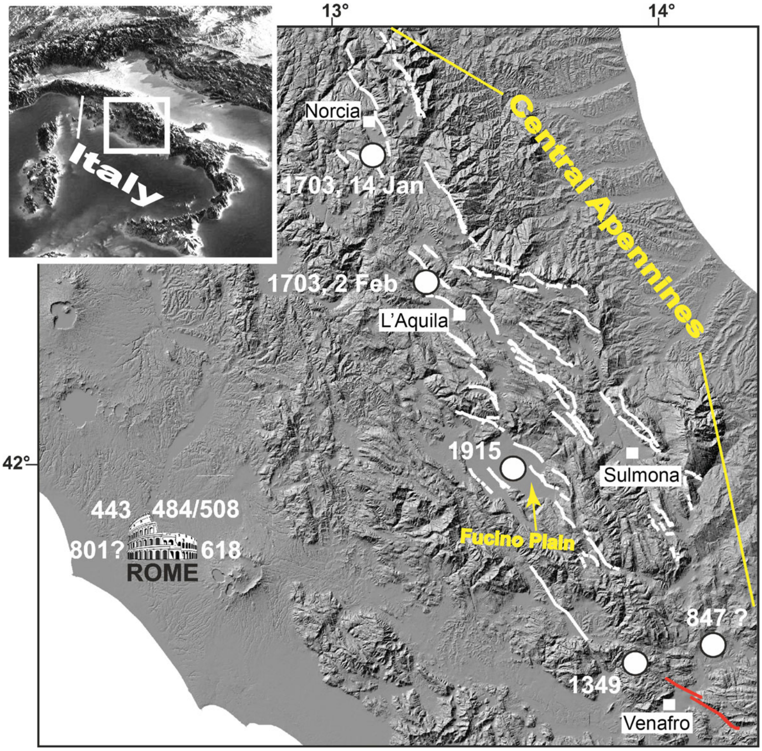

Fig. 1 Historical earthquakes mentioned in the text (epicentral location according to Rovida et al. 2016 and Guidoboni et al. 2018) and main active faults in the central Apennines. Apart from the 847 earthquake, the coseismic effects of the other pre-1000 A.D. events are attributed to Rome based on the available historical sources. For this reason this town represents the current epicentral location of 443, 484/508, 618 and 801 earthquakes in Guidoboni et al. (2018). However, the 484/508 event has been paleoseismologically and archaeoseismologically attributed to the fault of the Fucino Plain which more recently has caused the strong 1915 earthquake (Mw 7.0) (e.g. Galadini and Galli 1996; Galadini et al. 2010). Similarly, the 801 event probably originated in the central Apennines, based on the available written sources (Guidoboni et al. 2018). Finally, the attribution of the 847 earthquake to the Venafro fault (red line) (Galli and Naso 2009) would define a different epicentral location from that here reported (derived from Guidoboni et al. 2018)

The earthquake that has been dated to either 484 or 508 (which probably occurred slightly before one of these two dates) is known from two marble bases that are now located at the main entrance of the *Colosseum* (n. 1 in Fig. 2). The inscriptions recall significant restorations to parts of the amphitheatre (*arenam et podium*) which were promoted by *Decius Marius Venantius Basilius* after an earthquake that was described as "loathsome" (Guidoboni 1989; Lega 1993; Orlandi 1999a). These interventions have been confirmed by archaeological data (Rea 1999). A third marble base that also mentioned the restoration has been lost. However, we have a trace of it in a drawing by Pirro Ligorio (sixteenth century) that shows the base underlying a plinth where the name of *Venantius* was carved (Orlandi 1999a). Most probably these bases originally carried the statual portraits of the promoter of the reconstruction (Orlandi 1999a).

The uncertainty of the dating is due to a coincidence of names of the *Venantius* who initiated the restoration. Two senators with the same name were consuls in different years; i.e. in 484 and in 508. This issue remains unresolved until today. On the one hand, by

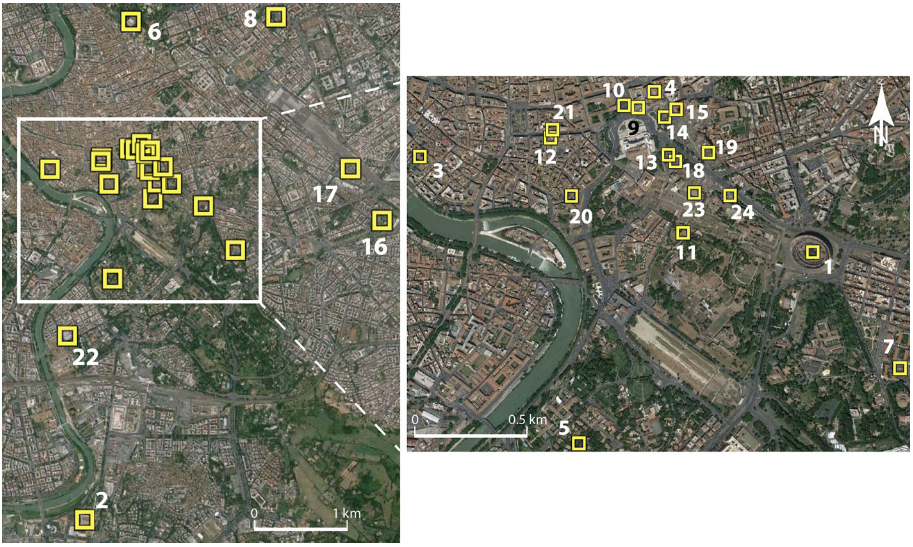

Fig. 2 Location of the described/discussed sites within the old town centre of Rome and its surrounding areas: 1, *Colosseum*; 2, Basilica of St. Paul; 3, Palazzo Spada; 4, Palazzo Valentini; 5, Sanctuary of *Iuppiter Dolichenus*; 6, Villa Medici; 7, *Basilica Hilariana*; 8, Aurelian Walls; 9, Piazza Madonna di Loreto; 10, Piazza Venezia; 11, Church of Santa Maria Antiqua; 12, *Crypta Balbi*; 13, Temple of *Venus Genetrix*; 14, *Basilica Ulpia*; 15, Palazzo del Gallo di Roccagiovine; 16, Palazzo Sessoriano; 17, Temple of *Minerva Medica*; 18, Forum of Caesar; 19, Temple of *Mars Ultor*; 20, Temple of *Apollo Sosianus*; 21, Temple of Via delle Botteghe Oscure; 22, New market of Testaccio; 23, *Basilica Aemilia*; 24, *Templum Pacis*

comparison with other epigraphic sources, the reference only to *Venantius* as the promoter of the works makes the hypothesis of 484 a better choice than that of 508 (Orlandi 1999a). The year 508 is less likely, because in this case one would expect also a mentioning of King Theodoric, although if reconstruction was financed in total by private money the King might have remained unmentioned (Orlandi 1999a). On the other hand, the archaeological information makes the later dating of 508 more likely (Orlandi 1999a), and this option was clearly adopted in the recent study of Galli and Molin (2014). However, as the correct dating remains unclear, in this report we refer to the earthquake with these two alternative dates, as that of 484/508.

The earthquake that occurred in 618 is known from the *Liber Pontificalis* and the *Abbreviatio Cononiana* (Guidoboni 1989). Both of these sources report evidence of strong shaking, but do not mention any damage in Rome. However, the lack of reference to damage in this historical information does not mean that no damage occurred.

Another strong earthquake caused damage in Rome in 801. It is documented in the *Annales Einhardi* and the *Liber Pontificalis* (Guidoboni 1989). These sources indicate that the earthquake originated somewhere (no further specified) in the central Apennines and caused severe damage to the Basilica of St. Paul (n. 2 in Fig. 2). In particular, the collapse of the roof and of the external portico were attributed to this event (Guidoboni 1989). When studying the building works of Pope Leo III, Lanciani concluded that this represents an almost total reconstruction, “from the introit to the presbytery, from the marble floor, to the summit of the roof” (Lanciani 1917). For this reason, he concluded that the effects of the seismic event had been stronger than those described in the historical sources.

Based on *Liber Pontificalis*, the 847 earthquake was felt strongly in Rome, although the source does not mention damage (Guidoboni 1989). However, as in the case of the earthquake of 618, damage can also not be excluded for the 847 event.

Published opinion is that the seismogenic sources of the earthquakes causing significant damage to Rome are located in the central Apennines (e.g. Galli and Molin 2014). This is supported by the fact that more recent earthquakes which damaged Rome in 1349, in 1703 (14 January and 2 February), and in 1915 had epicentres in the Apennines (Fig. 1). For the pre-1000 A.D. earthquakes, the historical information on that of 801 is consistent with an epicentral area in the central Apennines. Moreover, paleoseismological and archaeoseismological investigations have supported the hypothesis that the 484/508 event originated in the Fucino Plain (Galadini and Galli 1996; Galadini et al. 2010), and that of 847 in the Venafro zone (Galli and Naso 2009); i.e. in both cases, epicentres in the central Apennines are plausible.

For this earthquake in 847 historical information reports damage in the region surrounding Venafro, and in particular for San Vincenzo al Volturno and Isernia (Guidoboni 1989). In San Vincenzo al Volturno, archaeological investigations of the local monastery uncovered the traces of damage due to a medieval earthquake, thus confirming the historical information (Hodges 1995; Hodges et al. 1995).

In terms of the damage in Rome due to these five earthquakes in 443, 484/508, 618, 801 and 847, we can anticipate that some archaeological traces of building destruction consistent with their effects are persistent at various sites. However, we will show that the archaeological stratigraphy often cannot solve the problem of the link of a specific earthquake damage to a certain event among these. This issue is even worse if one considers that other strong earthquakes not historically mentioned may have struck Rome in the fifth to ninth century AD. For this reason, and in contrast to Galli and Molin (2014), instead of referring the presumed archaeoseismic evidence to any specific event, we will present the available data according to two different time spans: those from halfway through the fifth century to the beginning of the seventh century A.D., and those from the ninth century A.D. The association between a certain archaeological unit bearing traces of an earthquake with a specific seismic event is proposed only when the chronological constraints can be sufficiently narrowed. Otherwise, we maintain the uncertainty and attribute any such possible event to the entire time span. We show that the gathered information, rather than depicting the characteristics of any single earthquake reported in the catalogues, suggests a probable significant influence of the earthquakes on the modifications of the Late Antiquity-Early Medieval urban landscape of Rome.

3 Archaeological traces of earthquakes from the second half of the fifth to the beginning of the seventh century A.D

3.1 Basilica of St. Paul

For the earthquake of 443 A.D., the possible damage to the Basilica of St. Paul (n. 2 in Fig. 2) has to be mentioned. In particular, the written source (*Liber Pontificalis*) reported that this damage was actually due to lightning, which made some intervention necessary under the pontificacy of Leo I (ninth century A.D.).

However, an architectural analysis performed at the beginning of the twentieth century on the restoration, and therefore on the amount of the collapse and its dynamics, led Pesarini (1918) to assume that the 443 earthquake was the cause of the destruction. In particular, Pesarini recalled the large amount of damage, which was hardly consistent with the effects of lightning. Indeed, the restoration consisted of the replacement of 16 columns (out of 40) that were made of stone material different from the original one, and the addition of a further arch, to cover and reinforce the pre-existing triumphal arch that had "fissures" and "closed-up cracks". Although more doubtfully, this seismic hypothesis has also been reported in more recent publications (Krautheimer et al. 1980). However, these authors left open the possibility that the damage was caused by lightning.

3.2 Colosseum

Some restoration to the *Colosseum* (n. 1 in Fig. 2) has been traditionally interpreted as a consequence of the 443 A.D. earthquake. These interventions are known from an epigraph (CIL VI, 32089) that does not mention the cause of the repaired damage (Orlandi 1999b, 2004). The restoration was promoted by *Praefectus Urbis* Rufius Caecina Felix Lampadius, and certainly affected the arena and the stands, and probably the podium and the false doors around the arena that were used to hide the *bestiarii* during the *venationes* (Orlandi 1999b). Also, repairs to the *Colosseum* mentioned in another fragmentary epigraph (CIL VI, 32086-87) have been attributed to the 443 earthquake (Orlandi 1999a); in this case, the seismic cause was hypothesised by the complements of the text (Orlandi 2004).

For the earthquake of 484/508 A.D., we have already mentioned the repairs to the *Colosseum*. We know from archaeological investigations over the past decades that this event was actually the cause of the partial collapse of the columns in the arcades of the *summa cavea*; in particular, this collapse caused the destruction of the northeastern and southeastern sectors of the amphitheatre, and another portion of the colonnade fell in the western sector (Rea 1999).

Considering the convincing evidence of coseismic damage to the *Colosseum*, investigations into other archaeological traces consistent with the effects of this strong earthquake have been promising in recent years.

3.3 Palazzo Spada

Excavations in 1996 in the basement of Palazzo Spada (n. 3 in Fig. 2) produced data consistent with the 484/508 earthquake (Rinaldoni and Savi Scarponi 1999). Here, an impressive collapse unit was uncovered, which was made up of large portions of mosaic floors indicating the sudden fall of a multi-storey building (Fig. 3).

A sudden collapse of the building is backed by the large fragments of floor that are still intact and juxtaposed, with a tilted position resembling a sort of "domino style", and the absence of debris layers due to the slow decay. The destruction has been attributed to the 484/508 earthquake based on the presence of abundant pottery in the unit underlying the destruction layer. This pottery has been dated to the fourth to sixth century A.D. (with more frequent remains referred to the fifth century) (Rinaldoni and Savi Scarponi 1999).

3.4 Palazzo Valentini

The recent discoveries in the foundations of Palazzo Valentini (n. 4 in Fig. 2) provide further information about the collapse of buildings potentially related to seismic shaking. Excavations made in 2007 and 2009 uncovered a thick collapse unit in rooms 9 and 14 of

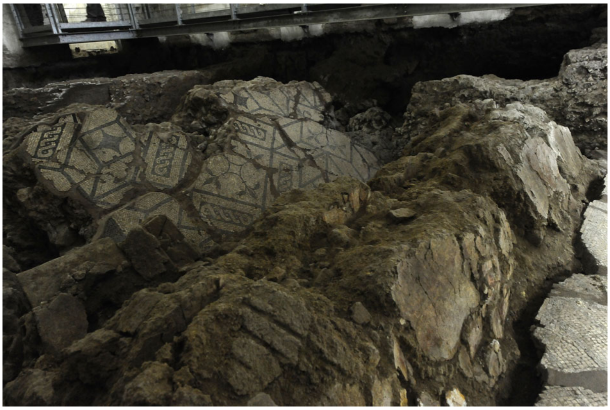

Fig. 3 Archaeological excavations at Palazzo Spada: fragments of the floor in the position after the collapse, during which they were tilted and juxtaposed

the so-called "Piccole Terme" ("little baths") (Baldassarri 2011, 2012; Baldassarri and Crespi 2014). This unit lay on top of a floor in *opus sectile*, and contained remains of a wooden-beam ceiling that was decorated with painted plaster, and of a floor that was also in *opus sectile*, which belonged to a room of the upper floor (Fig. 4).

The collapse layer can be dated to the fifth century based on the presence of several amphoras that were crushed below the collapsed materials, and which were produced until the second half of the fifth century A.D. The ruin generally sealed the floor in *opus sectile*, although, in some cases, it was found over the screed of the floor which was made of mortar and fragments of amphoras without the marble cover present elsewhere. This means

Fig. 4 Archaeological excavations at Palazzo Valentini: **a** Huge collapse unit over the floor in *opus sectile* in the so-called "Piccole Terme". **b** Detail from (**a**)

that the floor had some gaps when the collapse occurred; i.e. the room underwent spoliation in the decades preceding the destruction or it was not perfectly preserved or it was abandoned at the time of the building collapse. The chronological constraint mentioned above might also represent a *terminus post quem* for the sudden event. Thus, the chronological framework of the collapse unit suggests also in this case consistency with the 484/508 earthquake. However, the available data do not exclude the possibility that the sudden destruction occurred during the 443 earthquake.

In another site of the same palace, the excavations made within the so-called *domus B* indicated a sudden abandonment of the building, as shown by a rubble unit overlying a layer of burnt materials in contact with the floor constructed in *opus sectile* (Lumacone and Zampini 2008). In this case, the collapse unit is less pronounced than that of the "Piccole Terme" and the cause of the destruction is not clear. Some cracks were found in the walls. However, although possibly of coseismic nature, these features cannot be conclusively related to the effects of an earthquake. Among these, we observed: an open fracture in the eastern wall of the apsed room at the contact with the head of the southern apse (Fig. 5a), and fissures that affect one of the perimetric walls of the domus, which shows a tendency in its upper part to topple towards the external side (Fig. 5b).

The chronology of the abandonment is constrained by some coins which date to the age of the Constantine dynasty; i.e. to the fourth century, giving a *terminus post quem* for the destructive event. The abandonment is further constrained by a *terminus ante quem*, i.e. an interval between the fifth century and the beginning of the sixth century derived from the materials contained in the layers filling the remains of the *domus*. This chronological interval is relatively long, and it does not allow to associate the destruction with a specific Late Antiquity seismic event. Further, the layers filling the building show that the area was used as a dump (Lumacone and Zampini 2008); i.e. the sediments are secondarily

Fig. 5 Palazzo Valentini, *domus* B: **a** Open fracture in the eastern wall of the apsidal room. **b** Fissures in one of the perimetral walls of the *domus*, with the evident tendency for the toppling of the higher parts

accumulated, so their age does not necessarily define a *terminus ad quem* for closure of the building.

3.5 Sanctuary of *Iuppiter Dolichenus*

Although a detailed stratigraphic framework is lacking, the general chronological consistency can also be invoked for another interesting case related to archaeological discoveries of the first half of the twentieth century. The excavations made in the Sanctuary of *Iuppiter Dolichenus* (n. 5 in Fig. 2) on Aventino Hill brought to light a thick collapse unit that was interpreted as the result of a catastrophe (Colini 1935; Chini 2001). Although the sparse information about the characteristics of the collapse layer (made of ruins which "did not seem to have been reworked at later times"; Colini 1935) does not allow conclusions on the cause of the destruction, we can note that 29 coins of a post-Constantinian age were found in the vestiges, and 11 of Ostrogothic age (Colini 1935).

Based on this chronological constraint, the destruction might be consistent with the 484/508 earthquake. However, the following needs to be considered: (1) the *terminus post quem* is vague ("Ostrogothic age"); and (2) the coins should be considered with caution in the chronological definition if the information is not supported by other chronological data, as is known from various stratigraphic frameworks (Saguì and Rovelli 1998; Molinari 2002). Therefore, destructive events of an age later than 484/508 cannot be excluded (e.g. 618 A.D.).

3.6 Villa Medici

The case of Villa Medici (n. 6 in Fig. 2) is as interesting as those of Palazzo Spada and Palazzo Valentini. Since 1999, an excavation by the Ecole Française de Rome (Broise et al. 2000a, b; Broise and Jolivet 2002) has uncovered the remains of a collapsed imperial palace that has been dated to the beginning of the fifth century. The walls of the huge building and many surfaces (which were originally horizontal) were found to be completely disjointed and displaced (Fig. 6). The position of the wall portions after the collapse indicated a sort of "sinking" below the ground floor, with circular boundaries in plan view, which suggests that the destruction was conditioned by the formation of sinkholes (e.g. Nisio 2008). The building collapsed due to underground openings that were excavated for the extraction of the volcanic materials used for construction purposes. For the chronological constraints, the destruction occurred between the beginning of the fifth century (the age of the building) and the construction of a large reservoir, presumably in 536–537, during the so-called "Gothic War" (Broise et al. 2000a, b; Broise and Jolivet 2002). This time interval includes the earthquakes of 443 and 484/508. Therefore, we cannot exclude that the sinking of the surface and the consequent collapse of the palace were triggered by seismic shaking (Broise et al. 2000b; Broise and Jolivet 2002).

However, even if seismic ground motion is assumed as a cause of destruction, the wide chronological interval does not allow a specific causative earthquake to be determined. Therefore, in this case, the unclear dating does not help to constrain the cause of the destruction.

Fig. 6 Villa Medici: **a**, **b** remains of the disjointed and displaced walls, at an elevation lower than that of the original surfaces

3.7 Basilica Hilariana

The archaeoseismological evidence of the next example, the *Basilica Hilariana* (n. 7 in Fig. 2), was uncovered during a series of excavations that have been carried out since 1987, necessary for the restoration of the Military Hospital on Celio Hill. Also in this case, remains of mosaic floors of an upper level of the building were found in the destruction layer (Gabucci et al. 1989), indicating an almost vertical collapse similar to those already described for Palazzo Spada and Palazzo Valentini.

This Basilica was built during the second century A.D. and underwent various restorations, such as the doubling of the pillars between the left and the central nave, and the addition of supporting structures adjacent to other pillars. These interventions are an indicator of severe structural problems of the building during its first period of life (Gabucci et al. 1989). The use of the building as a place of meeting and of pagan worship probably ended in the first decades of the fifth century A.D., when some filling generated new floors and interventions were made on various walls, to reduce the original spaces (Gabucci et al. 1989). After several transformations, the building was used again until the occurrence of the sudden collapse that brought the ruins to overlie the most recent floor.

Excavation data indicate that the pillars toppled towards the central nave. The remains of the upper floor were found below the ruins of the lower floor, which is typical in the case of seismic shaking (Gabucci et al. 1989). The pillars that did not topple are also those that showed no traces of past restoration, this suggests that the vulnerability of the building probably played a key role in its sudden collpase.

For the dating of the destructive event, archaeological remains are considered not to be later than the beginning of the sixth century A.D. (Gabucci et al. 1989); otherwise, the use of the building has been considered as continuous until the end of the sixth century A.D. (Palazzo and Pavolini 2006) or the beginning of the seventh century A.D. (Palazzo 2013). Different studies have suggested a consistency of the destruction with the effects of the 618 A.D. earthquake. The chronological framework reported in Palazzo and Pavolini (2006) makes the association of the observed effects with the 618 earthquake much more probable than that with the 484/508 event, which was proposed by Galadini and Galli (1996), and Galli and Molin (2014).

3.8 Aurelian Walls-Porta Pia

Concerning restorations due to previous coseismic damage, we describe here only one case that is propaedeutic to the discussion about the lack of reliability of this kind of information. The collapse of the Aurelian Walls to the southeast of Porta Pia (n. 8 in Fig. 2) and the subsequent restoration have been attributed to an earthquake that occurred in the fifth or sixth century (Cozza 1998). The repair consists of the insertion of bricks into the pre-existing walls (Fig. 7). As the insertion abutts the part of the walls that was built at the beginning of the fifth century by emperor Honorius, this has been attributed to the age of Theodoric (Cozza 1998). The 443 and 484/508 earthquakes are mentioned among the possible events that caused the damage. However, in the Discussion ("The risk of the earthquake damage exaggeration") we will consider further the problems that intrinsically affect the procedure of attributing some evidence of restoration (such as this case of the Aurelian Walls) to an earthquake.

Fig. 7 Aurelian Walls of Rome close to Porta Pia: the sector indicated by the arrows has been attributed to a restoration subsequent to an earthquake that occurred during Late Antiquity (see text for further details)

4 Archaeological traces of earthquakes in the ninth century A.D

4.1 Piazza Madonna di Loreto

One of the most impressive pieces of archaeoseismological evidence was uncovered within the archaeological site of Piazza Madonna di Loreto (n. 9 in Fig. 2) during works related to the building of an underground line. In 2009, an impressive collapse unit was discovered that contained the structural remains of rooms dated to the age of emperor Hadrian (Galadini and Falcucci 2010; Egidi 2010) (Fig. 8). Huge portions of walls and floors were still intact and included in a several-metres-thick collapse unit indicating the sudden vertical fall of the entire building. The excavation further uncovered remains of broken arches that collapsed over the floors, which were frequented at the time of the destruction, and huge portions of toppled walls and floors in a sub-vertical position. In this chaotic accumulation of ruins, the identification of the different levels from which the ruins originated was possible because of the characteristics of the first floor which showed a decimetre-thick layer of brownish sandy sediment, and it appeared as a curved surface due to a sort of continuous deformation (Fig. 9).

For the collapse dynamics, some evidence comes from the sedimentology of the collapse unit. The absence of fragments with a reduced grain size in the lower part of the

Fig. 8 Piazza Madonna di Loreto, building of Hadrian age: parts of the collapse unit. **a** Remains of the floor in a sub-vertical position within an accumulation of ruins. **b** Detail of the collapse which affected the ribs of the vault

Fig. 9 Piazza Madonna di Loreto, building of Hadrian age: large fragment of the vault in the deformed floor (indicated by the thin, darkish level of organic material)

accumulation is particularly diagnostic (Galadini 2009). This sedimentological picture is opposed to that of a typical slow collapse process due to ageing and lack of maintenance. As for the grain size, ageing and lack of maintenance are characterised by an upwards coarsening of the fragments, which change from sandy particles to wall remains of large dimensions (Galadini 2009). In contrast, at Piazza Madonna di Loreto, the large wall remains were on the walking horizon of the time of the collapse, without any systematic variation in the grain size within the destruction layer. Overall, these characteristics are consistent with the hypothesis of the sudden fall of a building that was still in a good state at the time of the collapse.

Moreover, the absence of layers that would indicate the occurrence of several falling events shows that only a single destructive event struck the building. For the cause of this fall, we can note that the characteristics of the walls (in particular their thickness) uncovered both in the collapse layer and in their original position contradict the hypothesis of structural weakness.

Therefore, considering this aspect and the above discussed sedimentological observation, we can conclude that the sudden collapse occurred due to a natural cause. As an alluvial event or a landslide can be excluded, because of a lack of any fluvial sediments and of a relief which might cause gravitational motions, the damage agrees with that expected from seismic shaking.

In summary, the collapse unit resembles a typical accumulation of seismic ruins, because of both the vertical fall of the buildings (that now often occurs due to the excessive load of the roof or of the upper floors), and the chaotic accumulation of wall remains of various dimensions over the lowermost floor that was still frequented at the time of the destruction (Fig. 10). The building collapsed over a floor where pottery was found, and it was dated to the first half of the ninth century. This chronological information is consistent with the 14C age obtained from a bone fragment of a small animal (perhaps a dog) that was found below the ruins (692–878 A.D.; cal. 2 sigma).

Fig. 10 Collapse of buildings due to the L'Aquila earthquake of April 6, 2009: **a** Castelnuovo: vertical collapse due to the excessive weight of the roof. **b** Onna: chaotic ruins lying over floors and the adjacent pavement

Moreover, the underlying units that were related to the phases of use and abandonment of the metallurgic workshop between the sixth century and the end of the seventh century to the beginning of the eighth century gave further 14C ages (604–668 A.D., 646–675 A.D., 660–772 A.D.; cal. 2 sigma) which are consistent with the general stratigraphic framework. For this reason, it has been concluded that the destructive event occurred about halfway through the ninth century A.D., and it can probably be associated with the 847 earthquake (Galadini and Falcucci 2010).

4.2 Piazza Venezia

Close to the site of Piazza Madonna di Loreto, at Piazza Venezia (n. 10 in Fig. 2), further investigations for the underground system since 2006 uncovered the remains of a block made of different rooms that probably represented *tabernae* close to the ancient Via *Lata*. Several phases of life have been uncovered by the subsequent archaeological excavation. Among these, a collapse of various building parts during the second half of the ninth century is of particular archaeoseismological interest. Two lintels that were originally placed over the entrances, portions of a barrel vault covered by *bessalis* bricks, and the remains of a mosaic that was probably part of an upper floor of a building were found in a collapse layer (Laudato and Saviane 2008; Serlorenzi 2010). The reconstruction of the local stratigraphy leads to the interpretation that the plaster underwent detachment from the walls before the collapse of the building. In addition, in the so-called 3 *N* room, the collapse of the walls sealed the stairs for access to the upper floors. This destruction has been explicitly attributed to the 847 earthquake (Laudato and Saviane 2008).

4.3 Church of Santa Maria Antiqua

The 847 earthquake is traditionally related to the history of the church of Santa Maria Antiqua (n. 11 in Fig. 2). The abandonment of the building and the relocation of goods and administration in the new church of Santa Maria Nova are considered as consequences of the partial destruction.

In particular, the earthquake might have destabilised the tuffaceous border of Palatino Hill, and caused a landslide that hit the church below, which in turn caused widespread damage (Krautheimer 1981, Budriesi 1989, Luciani 2000). Indeed, the building was founded at the base of the northwest slope of Palatino Hill, in a zone classified as "prone to collapse, toppling, sliding" (Moscatelli et al. 2011).

The photographs taken during the excavations of 1900 by Giacomo Boni (reported in Romanelli and Nordhagen 1964) show the thick debris unit that filled the church, and that also contained some boulders. Moreover, a well-known drawing by Francesco Valesio that has been dated to 1702 shows the border of Palatino Hill overhanging the church (Fig. 11).

The slope drawn by Valesio probably includes the landslide scarp. The fall of the debris from Palatino Hill knocked down the vaults of the church (uncovered during the investigations in 1900), and the impact itself (or the seismic shaking, if this was the cause of the

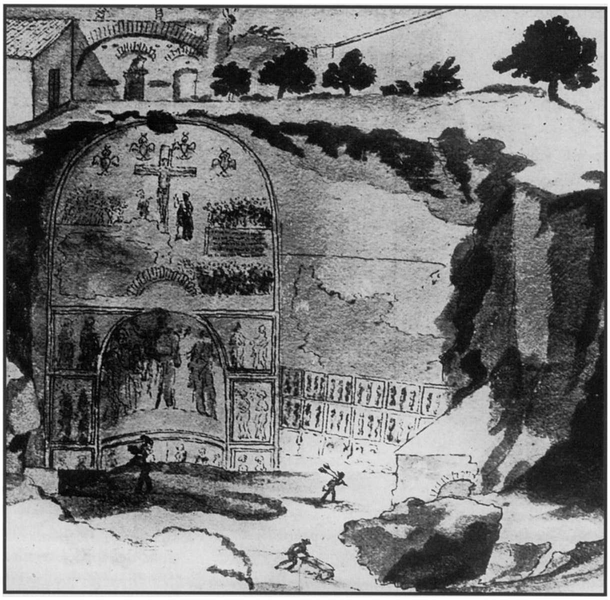

Fig. 11 Remains of the church of Santa Maria Antiqua, below Palatino Hill (drawing by Francesco Valesio)

landslide) generated cracks in the walls, which are in some cases still visible today (Osborne 1987).

It is worth noting that some of the pictures taken in 1900 show that the thick collapse unit contained large fragments of the building (presumably of the vault) overlying the remains of a column (related to the four-sided portico) which in turn was lying in a collapse position still adjacent to its base, and was positioned over the crest of the wall that bordered the so-called little chapel (see Table IV of Romanelli and Nordhagen 1964).

The cracks in the left apse close to the *atrium* also give a chronological indication (as a *terminus post quem*) for the destruction, as they cut the frescos that have been dated to halfway through the eighth century (Osborne 1987). We can add that the building of Santa Maria Nova (as a replacement of the Antiqua) on another site can be dated to halfway through the ninth century, although it has been verified that the *atrium* of the damaged church was used for two further centuries after the destruction (Osborne 1987).

In contrast with these views, in 1903, Dante Vaglieri suggested that the building was abandoned in the eighth century A.D. due to hydrogeological problems; i.e. due to the rise of the piezometric surface of the aquifer and to the change in the local climate, which became moist and unhealthy (Vaglieri 1903).

4.4 Crypta Balbi

One of the most convincing cases of archaeological evidence of destruction consistent with the 847 earthquake came from the excavation of *Crypta Balbi* (n. 12 in Figs. 2 and 12), which was about 400 m east-south-east of the Piazza Madonna di Loreto site. The

Fig. 12 *Crypta Balbi*: **a** Portion of the portico put back in its original position after the excavation of the thick collapse layer. **b** Pillar found in collapse position during the excavation (by courtesy of M. Cante)

available literature (Saguì 1985, 1990) gives a detailed picture of the great collapse of the upper part of the building in the zone of the exedra. Entire portions of the arcade (a pillar and the remains of the portico) were found perfectly preserved in the collapse position. Based on the stratigraphic data, this destruction has been attributed to the 847 earthquake (Saguì 1985, 1990).

4.5 Basilica of Petronilla, Nereo and Achilleo

Other archaeoseismological evidence can be found in the historical literature about excavations of the 19th and early 20th centuries. However, the chronological constraints are less well defined and we can only deal with these cases in terms of a general attribution to the ninth century A.D. In light of this, the studies of two seismologists, de Rossi and Agamennone, are particularly important. Michele Stefano de Rossi was a brother of the famous archaeologist Giovanni Battista, and in the 1870s he published data collected during the excavation of the basilica of Petronilla, Nereo and Achilleo along Via Ardeatina (a few kilometres south of the walls bordering ancient Rome, not shown in Fig. 2) (de Rossi 1874, 1879).

The description of the collapse unit demonstrates an approach to the archaeoseismological issues that can be still shared today: "the ruined monument […] was filled with its own rubble […] all the marble that formed the skeleton of the building, i.e. the columns, the capitals and the bases, were found, the former having suffered overturning, the latter being still in their original position […] the whole building collapsed suddenly and not slowly, nor did the fall gradually affect its different portions. Finally, a layer of ruins or soil was not found below the overturned columns; this means that the collapse occurred when the building was still covered by the roof […] after the destruction, the overturned columns had parallel positions, trending northeast to southwest […]" (de Rossi 1874). The author believed that the building had maintained its functionality until the eighth century, and he attributed the destruction to an earthquake that presumably occurred in 896 and was known in the old compilations (e.g. Baratta 1901).

4.6 Temple of *Venus Genetrix*

The same earthquake was invoked by Agamennone for the damage to the temple of *Venus Genetrix* (n. 13 in Figs. 2, 13) after some investigations into the causes of the destruction that were promoted by Corrado Ricci (Agamennone 1935), the famous archaeologist who was general manager at the Ministry of the Education between 1906 and 1919. The description of the collapse unit is particularly interesting also in this case: "I was impressed by seeing nine blocks of marble […] still in the position found during the excavation, that had fallen approximately in the same direction (south–southwest), oblique with respect to the southwest side of the temple […] Looking at the perimetric walls of the building, made of huge parallelepipedal blocks of tuff, and to the very solid concrete foundation which makes a sort of unique body with the tuff blocks, we cannot think that the fall of the temple was caused by sudden or progressive failure of the foundations […] it is difficult to think that the collapse was due to an anthropic action […] If the other causes of ruins are excluded, we can attribute the destruction to a violent earthquake […]" (Agamennone 1935).

In case of this temple of *Venus Genetrix*, however, the chronological information is lacking and the event was attributed to the same earthquake which presumably damaged

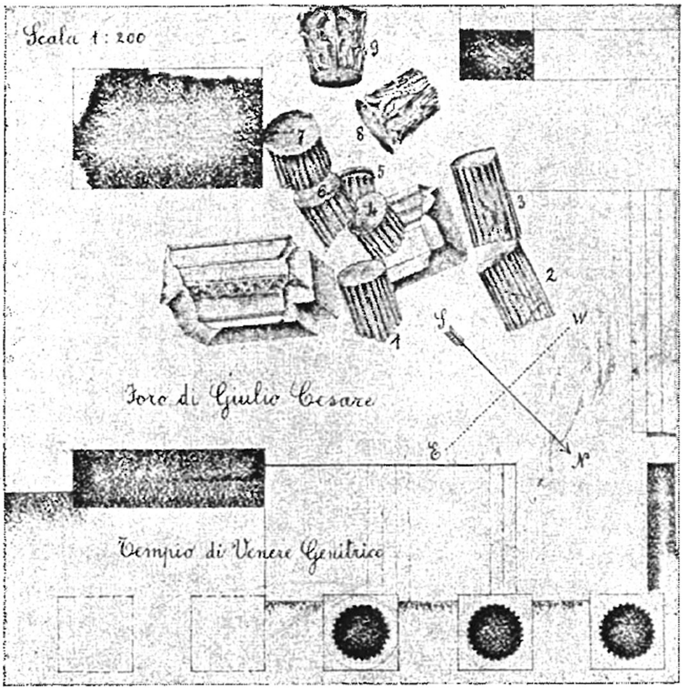

Fig. 13 Sketch of the collapse unit uncovered during the investigations of the temple of *Venus Genetrix*, by Agamennone (1935) (see text for further details)

Santa Petronilla based on inconclusive scientific observation (i.e. the same direction of the toppling of the columns). Moreover, the 896 earthquake is not included in the modern seismic catalogues anymore. Indeed this event that was mentioned as a cause of damage to Rome during the Early Middle Ages (e.g. Lanciani 1917) was actually inferred from the citation of the historical sources related to the collapse of Basilica Lateranense. However, the sources do not define the cause of the damage. Moreover, it appears probable that the collapse of Basilica Lateranense occurred due to the ageing of the original building (Marmo 1989). As it has been shown that a strong earthquake did not strike Rome in 896, at least based on the case of Santa Petronilla, what was related to the ninth century by de Rossi can be considered consistent with the event of 847. However, the chronological attribution is so vague that we cannot exclude that the damage resulted from the earthquake of 801. Indeed, this hypothesis was preferred by Budriesi (1989).

4.7 Basilica Ulpia

When referring to the ninth century, we have to mention the impressive evidence of widespread collapse that was uncovered during the excavation of *Basilica Ulpia* (n. 14 in Fig. 2) in 1932. The interventions brought to light many fallen columns, capitals and large fragments of the vaults, the concrete of which was recently analysed (Bianchi and Meneghini 2010). Although at the time of the excavation the destruction (which was expressed in a sort of "cemetery of columns") was attributed to the 801 earthquake, recently, Galli and Molin (2014) discussed the archaeoseismological evidence within the framework of the present knowledge of the 847 event.

However, the numerical ages collected by these authors do not allow the issue of the chronological attribution to be settled. In particular, during the excavation in the Palazzo del Gallo di Roccagiovine (n. 15 in Fig. 2), the 14C dating of charcoal fragments found below the collapsed remains gave a *terminus post quem* of 670–708 A.D. (Galli and Molin 2014). This age is consistent with both the 801 and the 847 earthquakes. The 14C age of the beaten level overlying the collapse unit (1150–1220 A.D.) gives support to the hypothesis that at least one of the seismic events in the ninth century caused the collapse of *Basilica Ulpia* (Galli and Molin 2014).

5 Discussion

5.1 Open chronological issues

Apart from the cause of the destruction, the dating of different collapse units, as represented in the summarising Fig. 14, appears to be quite well constrained for Palazzo Spada

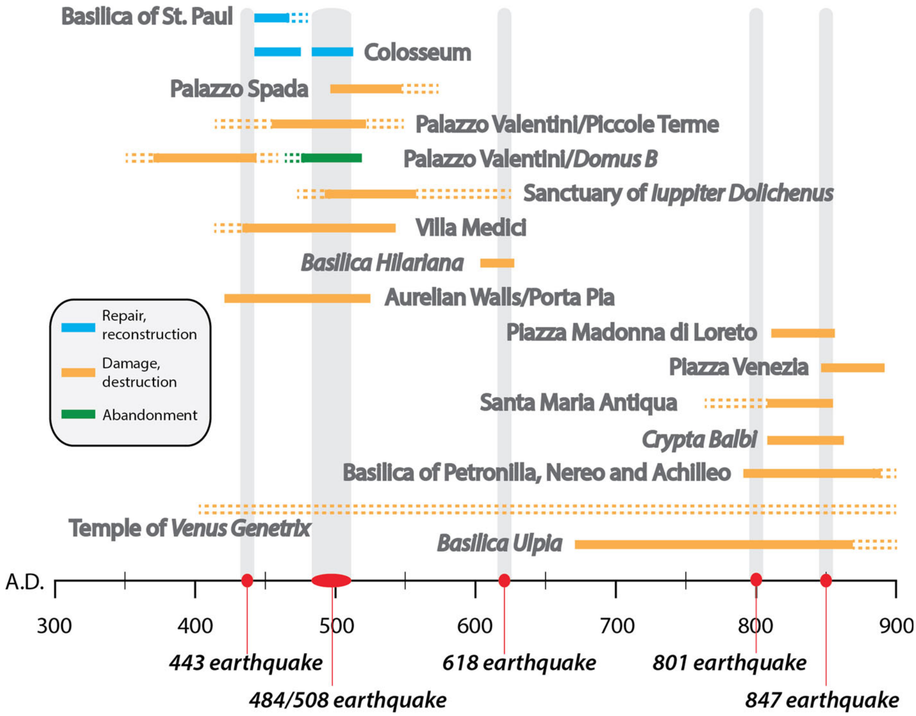

Fig. 14 Timeline for archaeological sites/monuments of Rome discussed in the text. Interventions of repair/reconstruction (light blue), episodes of damage/destruction (yellow ochre) and abandonment (green) are represented with respect to the time interval concerning the archaeoseismological cases and the earthquakes known from written sources. The length of the bars clarify the chronological uncertainty due to archaeological data and numerical ages. Dashed lines define larger time uncertainties. Numerous destructive episodes which may be consistent with ground motion cannot be chronologically attributed to a specific historical earthquake

(consistent with the 484/508 earthquake), *Basilica Hilariana* (as for 618 A.D., following Palazzo and Pavolini 2006; Palazzo 2013), Piazza Madonna di Loreto, Piazza Venezia, *Crypta Balbi*, and Santa Maria Antiqua (all attributed to 847).

In contrast, the consistency with 484/508 is not conclusive for Villa Medici. Indeed, the destruction occurred between the building of the palace at the beginning of the fifth century and the Gothic War (begun in 535 A.D.). Within this wide time span, we have to consider the 443 earthquake in addition to the later in 484/508. The same inconsistency can be invoked for Palazzo Valentini ("Piccole Terme"). In this case, the available data suggest that one of the two mentioned earthquakes might have caused the collapse layers, but at present, it cannot be decided if the destruction occurred due to the 443 earthquake (as univocally in Galli and Molin 2014), or to the 484/508 event.

Apart from the correct interpretation of the damage cause (see next section), the same chronological range and uncertainty can be invoked for the case of the Aurelian Walls. The restoration was subsequent to the intervention due to emperor Honorius (early fifth century), and belonged to the period of Theodoric (493–526 A.D.). As already discussed for Villa Medici and Palazzo Valentini, this long time interval is consistent with both the 443 and 484/508 events.

The chronological uncertainty is different for the Sanctuary of *Iuppiter Dolichenus*. In this case, the *terminus post quem* is fixed by coins of the "Ostrogothic age" in the collapse unit. This might be consistent with 484/508, although when it is considered that the coins might have been in use for quite a long time after being struck, later earthquakes (reported or not in the seismic catalogues) might also have caused the destruction of the Sanctuary. In light of this, a later earthquake that would possibly be consistent with the archaeological data is that in 618 A.D., which was perhaps related to the destruction of *Basilica Hilariana*.

For the earthquakes of the ninth century, although *Basilica Ulpia* was included in the section dedicated to 847 by Galli and Molin (2014), its consistency with the 801 earthquake cannot be excluded (and it was indeed not excluded by Galli and Molin 2014) on the basis of the available 14C dating of the layers underlying and overlying the collapse layer.

A similar uncertainty exists in case of the Basilica of Santa Petronilla, with its destruction originally attributed to an earthquake (896 A.D.) that is not included in the modern seismic catalogues anymore. The only chronological information given by de Rossi (1874, 1879), i.e. the fact that it was still frequented during the eighth century, makes this case consistent with both the 801 and 847 earthquakes.

Finally, the destruction of the temple of *Venus Genetrix* is certainly poorly defined from the chronological point of view. In this case, we can only conclude that its collpase probably did not occur before the fifth century A.D.; i.e. in periods during which the Roman monuments were not abandoned. For this reason, we consider this case as potentially consistent with the entire chronological interval considered in this report; i.e. with one of the five earthquakes previously discussed. On the whole, few archaeoseismological cases presented here can be considered to be reliably constrained from the chronological point of view. Actually, eight cases are definitely poorly constrained, which is often due to the impossibility to better define the archaeological stratigraphic record with respect to the narrow chronological closeness of the seismic events (443, 484/508; 801, 847). For this reason, in our opinion, it is not possible to define in detail the effects of these five earthquakes that are reported in the catalogues.

In short, we believe that some of the impressive collapse units previously discussed are archaeoseismological traces for Rome for Late Antiquity and the Early Middle Ages. However, due to the chronological uncertainties, we consider that the definite attribution of the described effects to one or another earthquake remains generally debatable. For this reason, we suggest the use of these traces as a whole, to define the general severe impact of the earthquakes in the periods mentioned above, while avoiding the practice that is typical of the catalogues, to link specific earthquakes to specific effects.

5.2 The risk of earthquake damage exaggeration

It is evident that attributing a seismic cause to certain evidence of destruction based on vague data implies potential erroneous exaggeration of the earthquake effects. A summarising image of this issue is represented by the "plausibility matrix" (Hinzen 2005; Galadini et al. 2006; Hinzen et al. 2013; 2018) proposed in Fig. 15, where different causes of damage (from storms to landslides through earthquakes and natural decay) are proposed for the main archaeoseismological cases previously discussed and other unreliable examples mentioned in the next.

Two of the cases described can help to illustrate this issue; e.g. Villa Medici and Santa Maria Antiqua.

For Villa Medici, the destruction of the building was due to the collapse of underground openings. This can happen with and without earthquake triggering, although the formation and evolution of sinkholes have been frequently documented as a secondary effect during seismic shaking (Nisio 2008). The same applies for the landslide that struck the church of Santa Maria Antiqua. A seismic trigger is not necessary to cause a landslide, although landslides are a common phenomenon in the case of seismic shaking. Overall, the uncertainty derives from the undocumented association of earthquakes with geological processes that are not necessarily the direct consequence of the ground motions.

Within the framework of uncertainty relating to the origin of the damage, the cause of restorations in archaeoseismic context is also arguable, and this uncertainty increases the risk of exaggeration of earthquake effects. The restoration of the Aurelian Walls (Fig. 7) during the age of Theodoric is an example for the methodological problems that are inherent when presumed post-seismic interventions are interpreted. In case of the Aurelian Walls this association is debatable, particularly if it is considered that recent episodes of collapse along the walls (16 April, 2001; 1 November 2007) have been related to the effects of ageing and persisting lack of maintenance, and they occurred during periods of

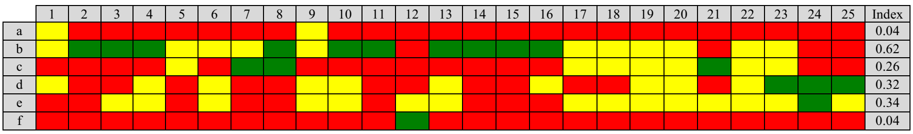

Fig. 15 Plausibility matrix (Hinzen 2005; Galadini et al. 2006; Hinzen et al. 2013, 2018) summarising the available data on archaeological sites/monuments. The columns represent sites/monuments discussed in the text; the rows represent different destruction causes. Legend: 1, Basilica of St. Paul; 2, Colosseum; 3, Palazzo Spada; 4, Palazzo Valentini-Piccole Terme; 5, Palazzo Valentini-*domus* B; 6, Sanctuary of *Iuppiter Dolichenus*; 7, Villa Medici; 8, *Basilica Hilariana*; 9, Aurelian Walls-Porta Pia; 10, Piazza Madonna di Loreto; 11, Piazza Venezia; 12 Santa Maria Antiqua; 13, *Crypta Balbi*; 14, Basilica of Petronilla, Nereo and Achilleo; 15, Temple of *Venus Genetrix*; 16, *Basilica Ulpia*; 17, Palazzo Sessoriano; 18, Temple of *Minerva Medica*; 19, Forum of Cesar; 20, Temple of *Mars Ultor*; 21, Temple of *Apollo Sosianus*; 22, Temple of via delle Botteghe Oscure; 23, *Horreum*, Testaccio; 24, *Basilica Aemilia*; 25, *Templum Pacis*; a, typhoon, storm, lightning, intense rain; b, earthquake; c, static settlement, sinkhole; d, anthropogenic interventions (spoliation, architectural modifications, etc.); e, natural decay, ageing; f, landslide, flood, hydrogeological problems. The green box defines a feasible cause of damage for a specific site; the yellow and red boxes define questionable and unfeasible causes of damage respectively. The index gives an estimation of plausibility of a single damage cause for the whole discussed case studies

intense rain (Fig. 16). In contrast, significant damage to the walls due to earthquakes in the past centuries is well known from the historical sources (e.g. during the earthquakes of 1703, 1899 and 1915; Molin et al. 1995) and also occurred recently, during the earthquake which struck central Italy on October 30, 2016 (Fig. 17). The uncertainty of the damage cause, due to the lack of conclusive information, has to be taken into account in case of the Aurelian Walls for the period investigated in this report.

Another example of presumed post-earthquake restorations arises from *Crypta Balbi*, which has been previously mentioned in terms of the collapse unit attributed to the 847 earthquake. In this case, the influence of previous earthquakes has been suggested based on building interventions and transformations that were made in time intervals close to the 443 and 618 earthquakes (Ricci 2004). Obviously, there is no conclusive evidence that links this construction activity to the effects of a preceding earthquake.

From the methodological point of view, these data are unreliable evidence of seismic effects. We have to consider that the city of Rome is located far from the epicentral areas of almost all of the historical damaging earthquakes (Molin et al. 1995, Galli and Molin 2014). Therefore, the possibility of large seismic effects has to be verified on the basis of

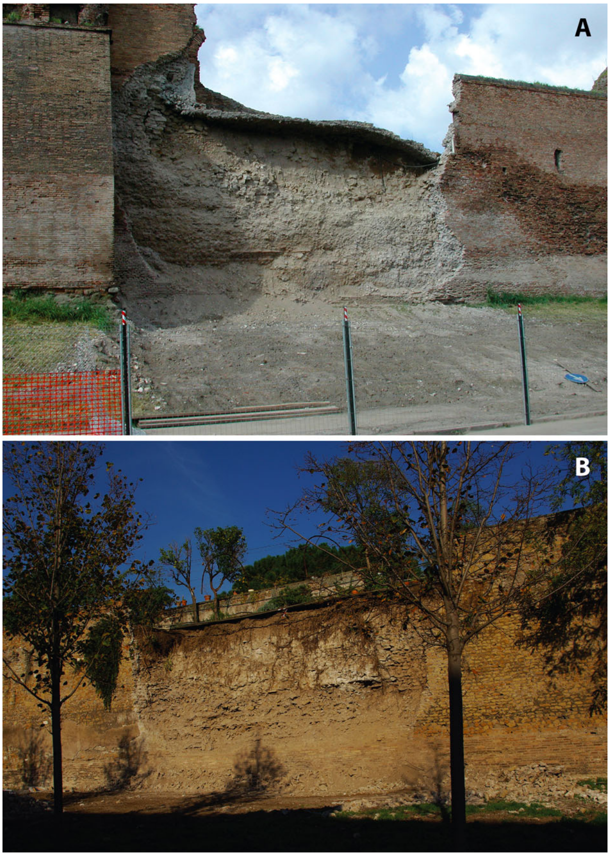

Fig. 16 Aurelian Walls of Rome: huge collapse due to ageing, lack of maintenance, and episodes of intense rain. **a** 16 April, 2001 (viale di Porta Ardeatina, southern sector of the Aurelian Walls); **b** 1 November, 2007 (viale Pretoriano, NE sector of the Aurelian Walls)

Fig. 17 Aurelian Walls of Rome: damage due to the earthquake (Mw 6.5) which originated in the central Apennines on October 30, 2016 (viale del Policlinico, northern sector of the Aurelian Walls)

robust data, and not just proved by putting together inconclusive evidence. This aspect is particularly relevant if it is considered that the investigated period was characterised by building modifications that were related to political, social, and cultural reasons.

Overall, the logical consequence of the interpretation of building transformations that are only based on chronological consistency has the (unjustified) potential to increase the coseismic damage pattern. Similarly, structural interventions to buildings, such as construction of buttresses or arches, have not been considered here, although these actions are quite common to reduce the vulnerability of a structure. Indeed, most structural improvements are due to different forms of instability, and will not necessarily be related to dynamic actions. Examples that are related to the effects of earthquakes (Giuliani 2011) would perhaps be the building of buttresses at Palazzo Sessoriano (n. 16 in Fig. 2) and for the temple of Minerva Medica (n. 17 in Fig. 2). In these cases, the repairs have been attributed to damage caused by one of the earthquakes that occurred during the fifth century (Giuliani 2011).

In summary, the doubts that accompany the true reasons for interventions for buildings that had a lifetime of many centuries during Late Antiquity and the Early Middle Ages suggest that it is best to avoid the use of such restorations in the archaeoseismological perspective, although it is possible that some (a few) of these undetermined actions might have occurred as repairs following seismic effects.

More archaeological data from Rome exist, which might be discussed in connection with the earthquakes addressed in this study. However, we consider these too uncertain to shed more light on the earthquake history of the city. We refer, for example, to the collapse of the columns of the arcade in the Forum of Caesar (n. 18 in Figs. 2, 18; Rizzo 1999, 2001; Santangeli Valenzani 2007a), of the temples of *Mars Ultor* (n. 19 in Fig. 2; Santangeli Valenzani 2007b), *Apollo Sosianus* (n. 20 in Fig. 2; Lugli 1946; Marchetti Longhi 1976; La Rocca 1980–1981; Vitti 2010) and Via delle Botteghe Oscure (n. 21 in Figs. 2, 19; Manacorda et al. 1994; Manacorda and Zanini 1997), of a large wall portion related to a *horreum* in the new market in the quarter of Testaccio (n. 22 in Fig. 2; Festuccia et al. 2008), of *Basilica Aemilia* (n. 23 in Fig. 2; Bartoli 1912), and of *Templum Pacis* (n. 24 in Fig. 2; Fogagnolo and Moccheggiani Carpano 2009). The discussion of these cases would certainly be of interest in the framework of possible earthquake effects

Fig. 18 *Forum* of Caesar: columns of the southern sector of the arcade in the collapse position

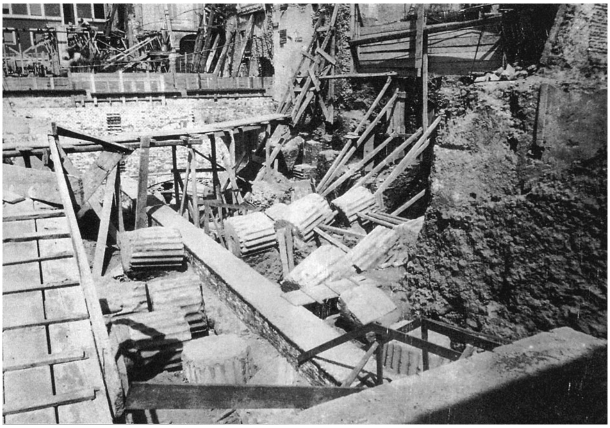

Fig. 19 Temple of via delle Botteghe Oscure: columns in the collapse position, as uncovered during the excavations of 1938

from the fifth to the ninth century A.D. However, although included in the detailed review by Galli and Molin as positive evidence of past earthquakes (Galli and Molin 2014), some of these archaeoseismological cases (e.g. *Basilica Aemilia*, temple of *Apollo Sosianus*, *Templum Pacis*) do not show characteristic collapse units that can be reliably attributed to the effects of earthquake ground motion.

In the case of *Basilica Aemilia*, the description of the stratigraphic evidence of the rubble does not allow to conclude for sure a sudden fall of the building. Bartoli stated that a single collapse layer including structural remains and burnt materials (which would suggest sudden destruction by earthquake or fire, or both) was lacking, while in contrast, three different layers were detected, which can correspond to three different phases of decay (Bartoli 1912). In case of the temple of *Apollo Sosianus*, the destruction should be evaluated in the light of the instable building-ground, which has caused differential settling of the modern buildings surrounding the archaeological area. Finally, only one column of the *Templum Pacis* was found in a collapse position over a floor that was still frequented at the time of the destructive event (Fig. 20). In our opinion, this is not enough evidence to conclude with certainty a seismogenic cause. This conclusion is supported by the evident traces of spoliation, which have been widely documented for this area and which have been attributed to Late Antiquity and the Early Middle Ages (Santangeli Valenzani 2007a; Fogagnolo and Rossi 2010). This is consistent with the report that the other column that was uncovered during the excavations between 2000 and 2007 (Fogagnolo and Moccheggiani Carpano 2009) was positioned differently from what was reported in Galli and Molin (2014). Indeed, this was found laying on top of a thick layer of rubble that accumulated during the phase of abandonment in Late Antiquity, at the margin of one of the medieval spoliation holes (Fogagnolo 2005) (Fig. 20b). This present position of the column can be interpreted as a consequence of the removal of materials from the site (Fogagnolo and Moccheggiani Carpano 2009).

However, the collapse unit of Piazza Madonna di Loreto, Piazza Venezia, *Crypta Balbi*, Basilica of Petronilla, Nereo and Achilleo, of the temple of *Venus Genetrix*, of Palazzo Spada and Palazzo Valentini, and of *Basilica Hilariana* show characteristics that are completely consistent with the effects of seismic shaking. Reasons are: (1) the thickness and extension of the destruction layers that lie over floors that were still in use at the time of the collapse; (2) the sedimentological features that suggest the sudden fall of the buildings (instead of gradual decay), with environmental conditions excluding the occurrence of natural catastrophes different from seismic ones; and (3) the chronological consistency with known seismic events.

Considering the characteristics of the collapse units, the high level of the associated coseismic damage might be surprising. Indeed, such an assumption implies damage that has no similar cases in the detailed historical information that is related to the effects of

Fig. 20 *Templum Pacis*: **a** Panoramic view of the excavation, showing two huge columns in the collapse position; note that only the biggest fragment is lying over the floor in *opus sectile* (by courtesy of S. Fogagnolo). **b** Opposite view, showing the smallest fragment overlying a debris unit

more recent strong earthquakes in Rome (Galli and Molin 2014). It is clear, however, that since (at least) the fifth century, the earthquakes struck a building heritage that had high vulnerability due to their centuries-old life, to reduced maintenance, to the praxis of spoliation, and to modifications of the original constructions for change of their use. All of these aspects have been widely documented in the literature dealing with archaeological excavations that have cut and analysed Late Antiquity/Medieval stratigraphic successions (Manacorda 1993; Pani Ermini 1995, 1999, 2001). The implication of this picture is a level of vulnerability and a related increase in the seismic damage that has been greater than what would have characterised Rome during the splendour of the early Imperial Age. Considering that the available data are certainly a limited part of the whole archaeoseismological information that might be potentially collected, a further consequence is that during Late Antiquity and the Early Middle Ages the contribution of seismicity to the change in the original structure of Rome might have been significant. This issue is summarised by the "index" defined in the left column of the "plausibility matrix" of Fig. 15. Index 0.62, attributed to earthquakes as damaging cause of the archaeological heritage, is much higher than that estimated for other natural and anthropogenic causes. In summary, earthquakes appear to have fed the formation of an urban landscape characterised by the widespread presence of run-down or collapsed buildings, typical of the later Antiquity and of the Early Middle Ages.

6 Final remarks

Overall, the difficult interpretation of archaeological traces that resemble those typical of seismic shaking and the open chronological issues are critical aspects of any archaeoseismological investigations. Both of these methodological difficulties hinder the good grasp of the damage pattern that can be related to each of the five earthquakes that occurred during the period from the fifth to the ninth century A.D. in central Italy. This suggests the need to avoid the systematic linking of stratigraphic evidence to the destructive effects of any specific natural catastrophe known from historical sources. The negative consequence of this practice is the potential for erroneous exaggeration of the real effects of a natural event that is not fully supported by the available data.

In the case of Rome, the above-mentioned methodological problems prevent the possibility to archaeoseismologically define with accuracy the impact of each single seismic event. As these methodological deficiencies are intrinsic to archaeological research, it is quite improbable that in the near future more refined pictures of single earthquake effects for the period from the fifth to the ninth century A.D. will become available.

However, even considering these uncertainties, the available data allow the conclusion that significant seismic damage did strike the buildings of Rome during the period investigated here. In particular, the archaeoseismological information appears convincing considering the Colosseum, Palazzo Spada, Palazzo Valentini, Piazza Madonna di Loreto, Piazza Venezia, *Crypta Balbi*, the Sanctuary of *Iuppiter Dolichenus*, and others.

This damage level is definitely higher than that of more recent strong earthquakes that occurred in the period from the fourteenth to the twentieth century. As the occurrence in Late Antiquity and the Early Middle Ages of earthquakes stronger than those of modern times cannot be supported based on geological and paleoseismological data, the strong damage appears to be a consequence from the relatively high vulnerability of the buildings. This is the main reason why the earthquakes in the period from the fifth to the ninth century

A.D. had an important role in the change of the original structure of Rome, contributing to the formation of a landscape characterised by widespread ruins.

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