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Combining earth sciences with archaeology to investigate natural risks related to the cultural heritage of the Marsica region (central Apennines, Italy)

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Abstract

Methods of Earth Sciences have been employed in archaeological sites of the Marsica region, central Italy, in two different perspectives: to enhance knowledge on past natural events which damaged/destroyed ancient settlements/monuments and to gather data useful/necessary for preservation of the local cultural heritage. Within this wide perspective, the paper deals with (i) recent archaeoseismological investigations at Alba Fucens and other sites of the Fucino Plain which add evidence of sudden building collapse to the already available (archaeoseismological and paleoseismological) data concerning seismicity of fifth-sixth century AD; (ii) archaeological investigations on remains of the Medieval church of San Bartolomeo showing that coseismic damage in 1349 caused the abandonment of part of the building and its (re)use for burials; (iii) evidence of slope instability which caused rapid mass deposition in the lowest sector of ancient Alba Fucens since around the half of the sixth century AD, inhibiting the occupation of the Roman town; (iv) capable faulting potentially affecting the westernmost sector of the huge hydraulic works made by Romans during the first-second century AD to drain former Lake Fucino.

Keywords Archaeoseismology · Active fault · Landslide · Historic earthquake · Cultural heritage · Preservation · Marsica region

1 Introduction

History of the cultural heritage, particularly ancient buildings and archaeological sites, is used in earth sciences to enrich knowledge on past catastrophes poorly documented in written sources. For example, the interdisciplinary field of archaeoseismology concentrates on the analysis of «seismic effects on ancient structures, uncovered by means of archaeological excavations or pertaining to the monumental heritage» (Galadini et al. 2006). The potential of these investigations became clear through pioneering scientific articles (e.g., De Rossi 1874; Agamennone 1935), and data from old publications may be included in seismotectonic datasets even today, once merged with other information (geological, paleoseismological, historical, geophysical …).

Another perspective is the analysis of natural damage to ancient buildings (e.g., related to earthquakes and slope instability). The current Italian law regarding the preservation of the cultural heritage (Legislative Decree of 22 January 2004, n. 42) and documents produced by different associations and institutions such as Icomos (International Council on Monuments and Sites) and the Italian Ministry of Culture place emphasis on the necessity of prevention with respect to potentially damaging events. Maintaining prevention as a main issue, article 29 of the cited Legislative Decree mentions "the whole activities necessary to limit situations of risk related to the cultural heritage in its context".

This perspective implies a proper knowledge of damage histories and causes, to be defined through a historic and/or archaeological approach, as indicated by the guidelines for

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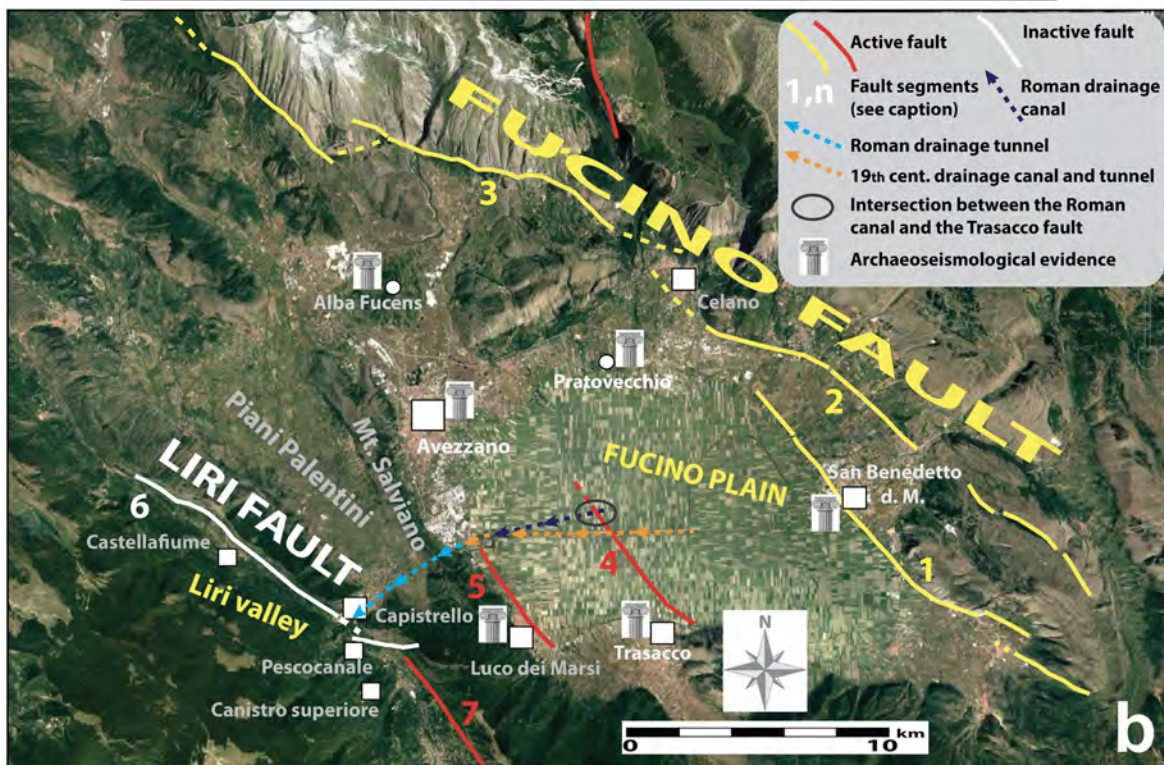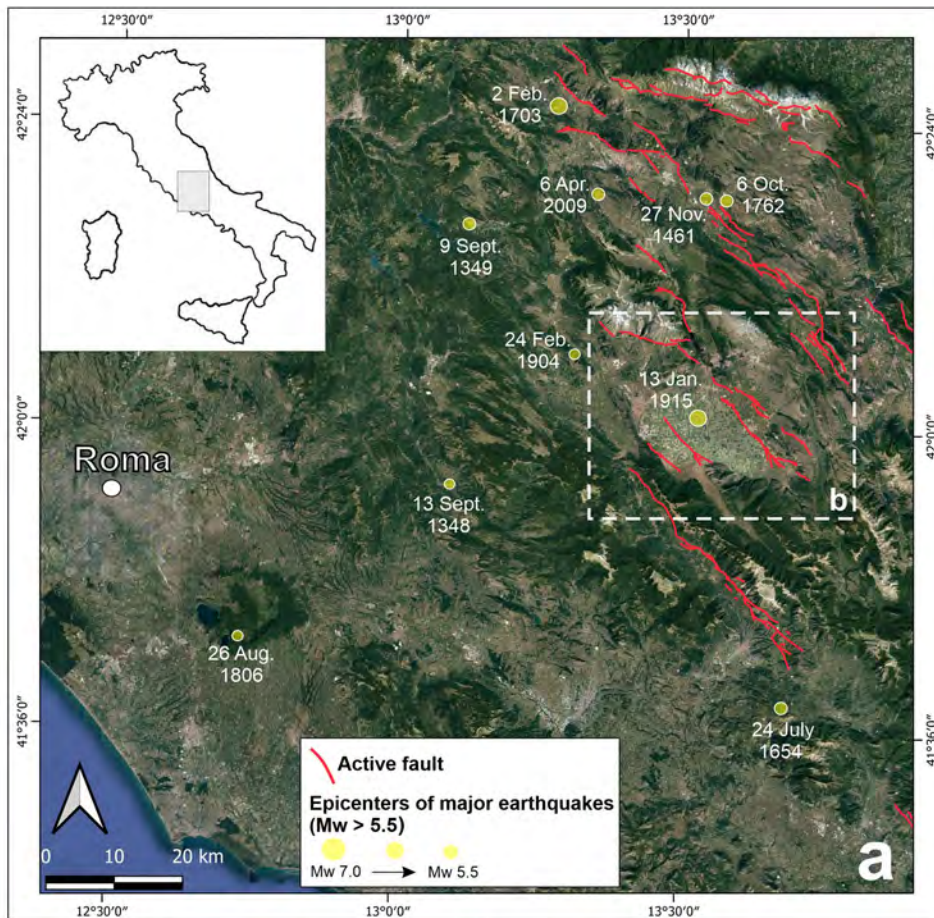
◄**Fig. 1** Location map of the investigated area. **a** Seismotectonic framework of the central Apennines in central Italy: earthquake epicenters are derived from Rovida et al. (2022), active faults from Maceroni (2022), including available literature (e.g., Galadini and Galli 2000; Boncio et al. 2004; Falcucci et al. 2011, 2016) and still unpublished data; mountain ranges are made of Meso-Cenozoic carbonate rocks, valley bottoms are carved into Cenozoic clayey-arenaceous flysch, while intermontane basins are filled by Plio-Quaternary continental sediments. **b** Central sector of the Marsica region in central Italy; archaeological sites investigated for archaeoseismology are shown together with the main active and inactive faults mentioned in the text: 1, 2, 3: Fucino fault segments (1, San Benedetto dei Marsi-Gioia dei Marsi; 2, Marsicana Highway; 3, Magnola Mts.-Mt. Velino); 4: Trasacco fault; 5: Luco dei Marsi fault; 6, 7: Liri fault (6, Castellafiume-Canistro segment; 7, Middle Liri Valley-Posta Fibreno segment). The yellow colour defines the fault segments composing the surficial expression of the Fucino seismogenic source

the assessment and reduction of seismic risk promoted by the former Italian Ministry of the Cultural Heritage (Ministero per i beni e le attività culturali 2006; an updated version was published in 2011 as a Directive of the President of the Council of Ministers, https://www.gazzettaufficiale.it/eli/gu/2011/02/26/47/so/54/sg/pdf) and by the Icomos Charter "Principles for the analysis, conservation and structural restoration of architectural heritage" published in 2003 (https://www.icomos.org/charters/structures_e.pdf).

The mentioned references indicate that preservation of the cultural heritage cannot be separated from the evaluation of natural hazards. We can also infer that one of the fundamental ingredients for this evaluation is the identification of natural events that interfered with ancient buildings or monuments (and related remains) during their centuries-old history.

Looking at the archaeological heritage, all the discussed aspects define a multiple utilization of the investigations on the past impact of natural disasters. Beside the traditional approach to enhance our knowledge on past catastrophes, i.e., the typical perspective of earth scientists already mentioned, the other goal, i.e., the reconstruction of the centuries-old relationship between an old town or a single monumental building and the natural environment, needs to be addressed. This includes to reveal the settlement history, the aim of the archaeological investigations, and it is one of the ingredients to define proper plans of interventions for preservation and promotion of the cultural heritage. For example, the usability of archaeological areas has to be planned also by considering the local environmental/natural dynamics to reduce risks due to natural extreme events.

Following these aspects, the present contribution is dedicated to the archaeological heritage of the Marsica region in central Italy (Fig. 1). Since the investigated area is located in the inner sector of the Apennine chain, within a mountainous territory characterized by high seismicity and uneven topography, we will deal with the effects of past earthquakes, faulting and slope instability. Evidence of ancient earthquakes is

therefore related to a multiple archaeoseismological perspective: (i) the improvement of our knowledge on the regional seismicity during Antiquity and the Middle Ages, periods for which written sources are sparse and (ii) the definition of the effects of past damaging earthquakes to have a more complete historical view of settlements and/or single buildings also in the perspective of their preservation. In turn, the latter is the main goal of the research dedicated to other sources of natural hazards (capable faulting, slope instability) related to monuments and archaeological sites.

After a brief description of the geological/seismological framework, the paper will deal with: (i) the results of investigations on the archaeoseismological evidence and on features consistent with the effects of ancient earthquakes in four localities of the Marsica region: *Alba Fucens*, Trasacco, Celano-Pratovecchio, Avezzano (Fig. 1); (ii) the slope instability at *Alba Fucens* during the Early Middle Ages and (iii) the potential capable faulting affecting the impressive Roman hydraulic works which drained Lake Fucino. The results from these studies are the basis for the discussion of the potential threats to the cultural heritage of the Marsica region.

2 Geological and seismological frameworks

The Marsica sector of the Abruzzi region, is located in the central Apennines, central Italy (Fig. 1). The landscape is dominated by the Fucino Plain, an intermontane basin whose formation and evolution has been conditioned by Pliocene and Quaternary extensional tectonics (Galadini and Messina 1994; Cavinato et al. 2002). Normal fault segments along the eastern and northern margin of the basin (known as San Benedetto dei Marsi-Gioia dei Marsi, Marsicana Highway and Magnola Mts.-Mt. Velino fault segments; Fig. 1), composing the Fucino fault, are geological and geomorphological evidence of Quaternary tectonics and have been considered (i) as the main tectonic structures driving the evolution of the Fucino half graben basin and (ii) as the surficial expression of a seismogenic source which caused large magnitude earthquakes (e.g., Gori et al. 2017 and references therein). Since the 1990s, paleoseismological investigations on the main fault bordering the basin and on secondary segments located within the basin (Trasacco fault) and along the western margin (Luco dei Marsi fault) indicated repeated fault activation (and hence repeated strong earthquakes) during the Late Pleistocene–Holocene and in historical times (in the Roman Age and in 1915 AD; e.g., Gori et al. 2017 and references therein).

In 1915, a catastrophic earthquake of magnitude 7.1 was generated by the Fucino seismogenic fault (Rovida et al. 2021). Shaking destroyed tens of villages (Intensity up to 11 MCS) and killed tens of thousands of people. The seismic

event also struck Rome (about 90 km west of Fucino basin; Fig. 1), causing low damage (Intensity 6–7 MCS; Locati et al. 2022). Surface faulting occurred along the faults mentioned above (Oddone 1915), documented in historical and paleoseismological investigations since the 80 s of the twentieth century (e.g., Gori et al. 2017 and references therein).

New villages were built after the earthquake, in many cases in locations different from those of the preceding settlements. The seismic destruction and the following reconstruction completely changed the landscape of the epicentral area during the twentieth century.

Seismically triggered modification of the natural environment and of the inhabited spaces followed another substantial change of the landscape in the Fucino Plain area. The basin contained originally the third largest lake of Italy until the second half of the nineteenth century, when water was drained towards the nearby Liri river valley to obtain new land for agricultural use. The impressive hydraulic works partly exploited the ancient Roman drainage system which was planned and carried out during first-second century AD (see Sect. 4.2 about the Roman hydraulic work; Fig. 1). The nineteenth century drainage ended the story of the lake which formed during the Pliocene and radically changed the natural landscape of this part of the Apennine.

West of the Fucino Plain and the adjacent depression of Piani Palentini, the upper Liri river valley is the main topographic feature of the area (Fig. 1). Normal fault exposures have been detected along its eastern flank, i.e., along the northern prolongation of a 24-km-long fault (Middle Liri Valley–Posta Fibreno fault, being part of Liri fault) which has been considered as active during the Late Quaternary (Saroli et al. 2003, 2006, 2022; Dixit Dominus 2020). However, recent activity of the northernmost segments of the Liri fault is debated and will be the object of Sect. 4.2.3 in this contribution. As for seismicity, moderate magnitude earthquakes originated in the Liri area, i.e., two earthquakes occurred in 1922 and 1927, both having M_w 5.2 (Rovida et al. 2021).

3 Evidence of earthquake damage from archaeological sites and effects of historical earthquakes on the monumental heritage

3.1 Evidence of building collapse consistent with earthquakes of the late antiquity at Alba Fucens, Trasacco and Celano

3.1.1 Alba Fucens

The effects of the earthquake which originated in the Fucino Plain during the Late Antiquity have been paleoseismologically (Galadini and Galli 1996) and

archaeoseismologically investigated (Galadini et al. 2010; Hinzen et al. 2015) in the past. Further archaeological data have been collected during the last decade at *Alba Fucens* and Trasacco (see Sect. 3.1.2) (Fig. 1; Table 1). The paleoseismological investigations, begun in the 1990s and continued in this century, revealed that shaking was originated by the activation of the Fucino fault, i.e., the same seismogenic source that in 1915 caused destruction in central Italy (Galadini and Galli 2001). As for the age, 484 or 508 AD were proposed, considering the seismic damage of Colosseum at Rome, mentioned in epigraphs kept at the main entry of the amphitheatre (Galadini and Galli 1996; Galadini et al. 2018).

Systematic archaeoseismological investigations were made since 2004 in the Fucino area, supposed to be the epicentral area of the fifth-sixth century AD earthquake, at San Benedetto dei Marsi, Luco dei Marsi, Avezzano and *Alba Fucens* (Fig. 1; Table 1), to uncover traces of the ancient earthquake and to better define chronological constraints (Galadini et al. 2010). In the whole, the chronological association with the fault activation and the attribution of the destruction to a period of political stability permitted to consider the widespread evidence of impressive sudden collapses (regarding used buildings) as resulting from seismic shaking.

Most research was made at *Alba Fucens* (Fig. 2), the main archaeological area of Abruzzi, because of (i) the almost continuous collection of data (i.e., excavations) since the end of the 1940s, and their publication in scientific articles of the twentieth century (e.g., Mertens 1981, 1991) (ii) the availability of data from public documents archived by the Abruzzi Superintendence (formerly Soprintendenza Archeologia, Belle Arti e Paesaggio dell'Abruzzo, Chieti), (iii) the more recent data collection during archaeological excavation campaigns which adopted modern stratigraphic approaches.

Remains of the coseismic destruction were continuously uncovered during the numerous archaeological interventions of the past decades. They mainly consisted of collapse units (made of entire walls, pillars, columns still having juxtaposed capitals, statues, etc.; Fig. 3; Table 1) stratigraphically overlying levels of occupation and underlying the colluvial deposits whose origin and age will be discussed in Sect. 4.1 below (Galadini et al. 2010). The combination of paleoseismological and archaeoseismological data has suggested the consistency of the chronological constraints with the 484/508 AD earthquake even in the last decade (Galadini et al. 2010; see Galli et al. 2012 and Gori et al. 2017 for further paleosesimological evidence).

However, also different hypotheses may be derived from recent literature. Indeed, the earthquake has been attributed to the fourth-fifth century AD based on the age of a

Table 1 Chronological data concerning evidence of destruction and possible consequences of damage attributed to seismicity of the Late Antiquity in the Fucino area by literature and this work

| Site/Locality	Evidence of destruction/consequence of damage	Chronological constraint	References
Alba Fucens	Collapse of pillars in Via dei Pilastri and other evidence of destruction from original excavation reports (mainly of the 1950s) ("1", "3", "4", "7" in Fig. 2b; Fig. 3a, b, c, d)	*Post quem* age: since the late fourth-fifth century AD	Galadini et al. (2010)
Alba Fucens	Collapse of walls and columns in the *Forum* area ("6" in Fig. 2b; Fig. 3f,g)	*Post quem* age: fourth-fifth century AD	Evers and Massar (2012); rev. in this work
Alba Fucens	Collapse of buildings in Via del Miliario ("2", "8" in Fig. 2b; Fig. 3h)	*Ad quem* age: fifth-sixth century AD	Galadini et al. (2010)
Alba Fucens	Collapse/damage of *Taberna* III in the *Forum* area ("9" in Fig. 2b)	*Ad quem* and *post quem* ages: 4th-5th cent. AD; 4th, 5th and beginning of the 6th cent. AD; since the 5th cent. AD	Liberatore (2011); Di Cesare and Liberatore (2017a, 2017b); Strazzulla et al. (2012); rev. in this work
Alba Fucens	Ruins within the water tank in the sanctuary of Herakles ("5" in Fig. 2b; Fig. 4)	*Ad quem* age: fifth-sixth century AD	Ceccaroni (2013); this work
Alba Fucens	Collapse of the *taberna* in Via del Miliario ("10" in Fig. 2b; Fig. 5)	*Ad quem* age: fifth-sixth century AD	this work
Avezzano	Collapse of *villa rustica*, Macerine	*Ad quem* age: fifth-sixth century AD	Galadini et al. (2010)
San Benedetto dei Marsi	Damage/collapse of the amphitheatre	*Post quem* age: half of the fourth century AD	Galadini et al. (2010)
San Benedetto dei Marsi	Repairs of buildings	*Ad quem* age: fifth-seventh century AD	Galadini et al. (2010)
Luco dei Marsi	Use of buildings originally related to the Augustan temple	Until fifth-seventh century AD	Galadini et al. (2010)
Trasacco	Destruction of the hut leant against the western wall of a Roman building (Fig. 1; Fig. 6)	*Ad quem* age: fifth-sixth century AD	Mieli (2016); this work
Celano	Collapse of *villa rustica*, Pratovecchio (Fig. 1; Fig. 7)	*Ad quem* age: fourth-fifth century AD	this work

stratigraphic unit following the destruction in the area of the sanctuary of *Herakles Epitrapezios* ("4" in Fig. 2b) and preceding a new settlement testified by a hut and other wooden structures (Liberatore 2011). However, the mentioned unit, containing materials of the fourth-fifth century and organic fragments, i.e., burnt wooden structures (one sample gave a radiocarbon age of 230–350 AD, cal. age, 1 sigma, sample Beta 223844), did not result from primary deposition, having a colluvial origin (Galadini et al. 2012a). This means that the mentioned chronological framework can only define a *post quem* age for the deposition itself and therefore it cannot define an *ante quem* age for the destruction (Table 1). This has been proved by further archaeological excavations in 2011–2013. A large water tank adjacent to the *Herakles*

sanctuary ("5" in Fig. 2b) was uncovered under the sediments attributed to the fourth-fifth century AD (Fig. 4). However, the reservoir was filled with materials younger than the mentioned time interval (see below).

An earthquake date similar to that proposed by Liberatore (2011), i.e., fourth-fifth century AD, is reported in another paper dealing with the different phases of a *taberna* (*Taberna* III) in the *Forum* area ("9" in Fig. 2b; Di Cesare and Liberatore 2017a). The chronology mentioned above was based on the age of significant restoration to the building. Elsewhere, the same authors mentioned the uncertainty of the earthquake dating, between fourth, fifth and the beginning of the sixth century AD (Di Cesare and Liberatore 2017b), while a later time interval (since fifth century AD)

Fig. 2 **a** Panoramic view of *Alba Fucens* (from Istituto Centrale per il Catalogo e la Documentazione, Aerofototeca Nazionale): 1, remains of the Roman town, main archaeological area; 2, remains of the Medieval settlement (Albe) founded in the San Nicola hill and destroyed by the 1915 earthquake; 3, hill of San Pietro, Medieval church and monastery; 4, new settlement of *Alba Fucens* following the 1915 earthquake. White arrows indicate the emergence of the Magnola Mts.-Mt. Velino segment of the Fucino fault.
b View of the main archaeological area in the Piano di Civita valley: 1, *Via dei Pilastri*; 2, *Via del Miliario*; 3, *sacellum* of the temple of *Herakles Epitrapezios*; 4, square facing the temple; 5, water tank located in the middle of the square; 6, buildings of the *Forum* of *Alba Fucens*; 7, *domus* of *Via del Miliario*; 8, building of *Via del Miliario* (2008 archaeological campaign); 9, *Taberna III*; 10, 2020 archaeological campaign: *taberna* located along *Via del Miliario*; 11, 2020 archaeological campaign: remains of the Roman road in the *Forum* area
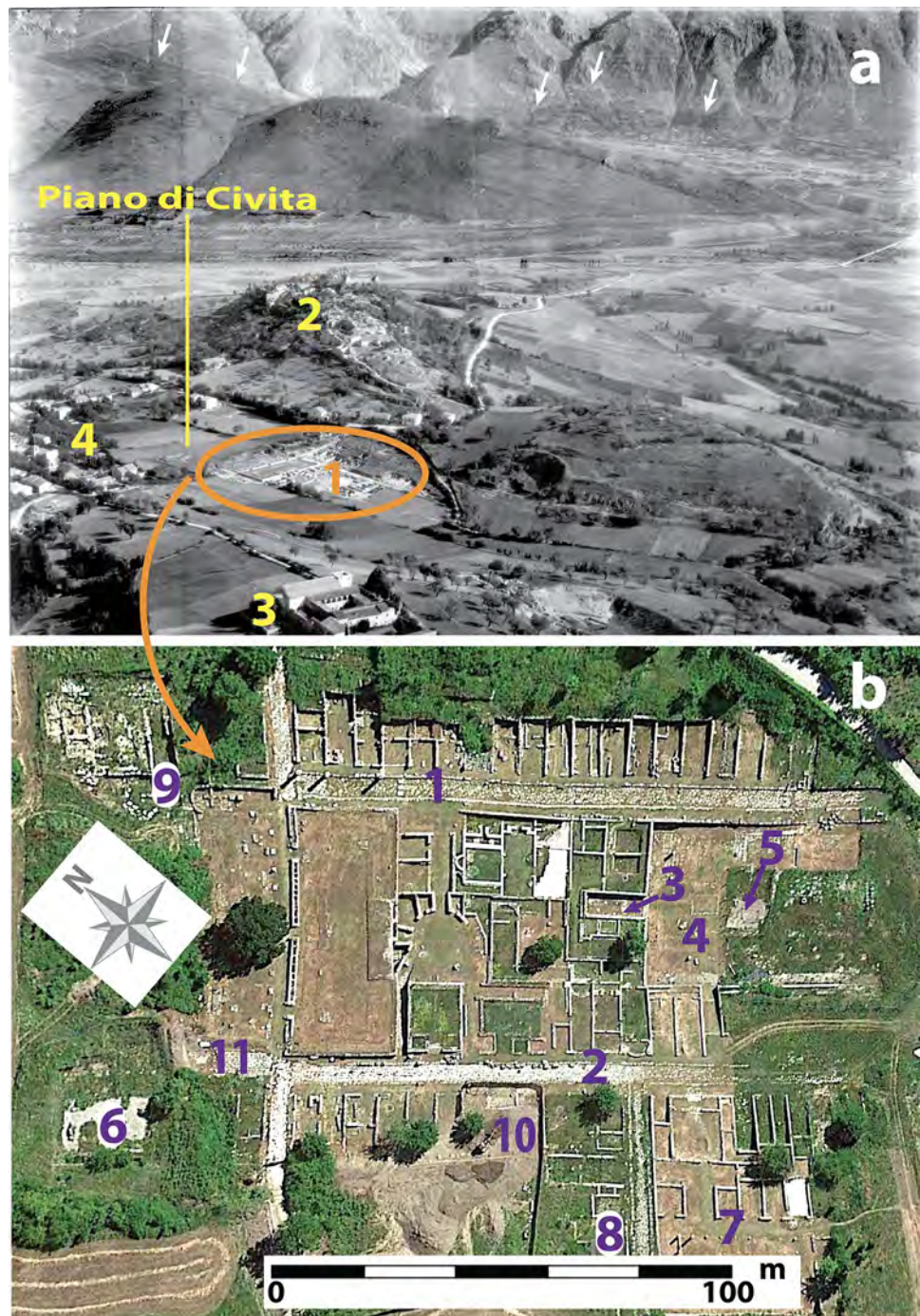
seems preferred in a previous contribution (Strazzulla et al. 2012; Table 1).

In other scientific articles, the destruction of *Alba Fucens* has been aged at the beginning of the fifth century AD basing on chronological constraints derived from the *Forum* ("6" in Fig. 2b; Evers and Massar 2012). These authors investigated the sediments filling a sewer, apparently derived from the collapse of nearby buildings. However, pottery ranging in age from fourth to the half of the fifth century AD found within this unit cannot exclude an age later than the beginning of the fifth century for the destruction (Table 1). The *Forum* also gave constraints on

the earthquake, 380–430 AD, based on the materials contained in detrital sediments covering an area from which ruins were previously removed (Evers and Massar 2013). However, also these sediments have a colluvial origin and the age derived from materials only gives a *post quem* date for the deposition.

The time of the earthquake has been better defined by data collected during the 2011–2013 excavation of the large water tank (about 4 m diameter and 7 m depth) close to the sanctuary of *Herakles* ("5" in Fig. 2b; Fig. 4). It was filled by an important archaeological deposit consisting of materials deliberately deposited in the tank and of the collapsed slabs and beams of the cover (Ceccaroni 2013). The accumulation, made of layers containing huge architectural remains (numerous columns and capitals) alternating with layers of finer materials (tiles, bricks, *cubilia*, …), testifies to the attempt to re-establish the occupation of the area adjacent to the sanctuary, previously inaccessible due to the presence of ruins from collapsed buildings. The deeper levels of the deposit filling the tank indicated that it was still used in the fifth-sixth century AD, since intact jugs attributed to this age were found (Fig. 4d, e). This chronological constraint is consistent with the age (not older than fifth century AD) of an oil-lamp and pottery fragments found in the overlying accumulation (Ceccaroni 2013). In the whole, the ruins included in the upper layers of the deposit filling the tank are consistent with destruction in the area of the sanctuary and with the effects of an earthquake which occurred in the fifth-sixth century AD (Table 1). After the destruction and accumulation of ruins in the tank, new occupation of the square of the sanctuary is indicated by remains of Early Medieval residential huts (Malandra 2011).

An excavation during 2020 uncovered the remains of a *taberna* along *Via del Miliario* ("10" in Fig. 2b). After the removal of colluvial units (discussed below, in Sect. 4.1 dedicated to the episodes of mass sediment deposition at *Alba Fucens*), a thick collapse layer, made of overturned portions of walls, was found (Fig. 5a, b). Rotation during toppling has been invoked to explain the position of a wall (Fig. 5b). The collapsed roof of the building was found below the remains of walls (Fig. 5c) and once the entire destruction layer was removed, the underlying level of occupation was uncovered. Widespread evidence of burning and materials indicate that the building was still in use at the time of destruction (Fig. 5d). Pottery fragments, of the type *Terra Sigillata Africana*, have been attributed to the fifth century AD (Fig. 5e). The most recent fragment included in the collapse layer has been recognized as *Hayes 91-A*, related to about 450–500 AD (Fig. 5f; Hayes 1972). On the whole,

the age of occupation defines a *post quem* constraint for the destruction and, therefore, it is consistent with the previous chronological hypothesis on the earthquake occurrence in the fifth-sixth century AD.

3.1.2 Trasacco

The study of "areal" effects of the shaking of this earthquake in recent years showed that destruction layers are not limited to Alba Fucens (Galadini et al. 2010).

Further evidence of sudden destruction was found during 2014 close to Trasacco, at the southern margin of the Fucino Plain (Fig. 1; Table 1), where a complex history of settlement has emerged (Mieli 2016). The area of a previous building of Roman age was re-used during the Late Antiquity with the construction of two huts at different times. The older hut, which originally leant against the western wall of the Roman building, was destroyed by the collapse of the wall itself (Fig. 6). Destruction is also indicated by the thick layer of burnt material, including the hearth and a tens of earthenware pots. The distribution of the pottery fragments has suggested that pots fell from above, perhaps from a cupboard. The fragments of pottery in the layer containing burnt materials, and defining the occupation period preceding the collapse, can be attributed to the fifth-sixth century AD (Mieli 2016). This is consistent with the radiocarbon dating of a burnt wooden beam found in the layer underlying the collapsed wall (385/475-485/535 AD, cal. age, 2 sigma; sample Beta-420082). A new phase of occupation followed the destruction, with the building of a larger hut, with which six burials (attributed to a little later age) are associated. On the whole, the evidence and age of destruction seems consistent with the effects of the fifth-sixth century AD earthquake.

3.1.3 Celano

Between 2012 and 2015, a large area in the territory of Celano (Pratovecchio locality, Fig. 1) has been archaeologically investigated for the construction of a photovoltaic plant. Walls of a large *villa rustica* (an ancient farm) have been uncovered resting juxtaposed to remains of the building found in a thick collapse layer. Parts of the roof, stones and fragments of plaster from the walls were uncovered (Fig. 7a). The damage included the collapse of the thermae and the deformation of the related *suspensurae* (Fig. 7c, d). After the destruction, part of the collapse layer was altered to obtain a new level of occupation. Some burials also define this phase, as they are related to the new occupied surface. As for the chronological framework, a coin of *Flavius Iulius Crispus*,

◄**Fig. 3** Some archaeological discoveries attributed to the effects of the Late Antique earthquake: **a–d**, excavations of the twentieth century; **e–h**, excavations of the 21st century. **a** pillars in *Via dei Pilastri* ("1" in Fig. 2b) found in collapse position at the beginning of the 1950s; **b** collapsed column in the square of *Herakles* temple ("4" in Fig. 2b); **c** collapsed column with juxtaposed capital in the *domus* of *Via del Miliario* ("7" in Fig. 2b); **d** statue of *Herakles Epitrapezios* after the collapse over the floor of the *sacellum* ("3" in Fig. 2b); **e** collapsed wall in the square of the temple ("4" in Fig. 2b); **f**, collapsed column and adjacent capital in the *Forum* area ("6" in Fig. 2b); **g** large wall overturned in the *Forum* area ("6" in Fig. 2b); **h** floor vertically collapsed over the remains of an underlying room in a building of *Via del Miliario* ("8" in Fig. 2b) (a-d photo from Archive of Soprintendenza ABAP per le province di Chieti e Pescara; **e–h** photo F. Galadini)

Roman emperor between 317 and 326 AD, was found in the ruins (Fig. 7e, f). This defines an uncertain *post quem* age for the collapse, considering that circulation of coins of the fourth century (mainly bronze coins, e.g., *nummi* of the Costantinian Age) has been documented in Italy for a quite long period after the coinage, i.e., also in the sixth century AD (e.g., Rovelli 1993; Saguì and Rovelli 1998; Molinari 1995, 2002, 2015). Another chronological constraint is given by an amphora of the type *Dressel 30*, which may be dated to the third-fourth century AD (Fig. 7b). The well preserved remain consists of half of the original amphora possibly re-used as a burial of an infant and placed within the collapse layer after the destruction. Considering that the amphora has been re-used, the chronology may represent a *post quem* age for the destruction occurrence. Further constraints derive from burnt residuals of foodstuffs included in the collapse layer or related to the occupation of a new surface obtained after the destruction. These residuals, mainly made of peas and wheat, gave a radiocarbon age of 260-280/325-420 AD (2 sigma cal. age; sample Beta-420077). This may approximate the *ad quem* age of the destruction, between the second half of the third century AD and the beginning of the fifth century AD. The time interval may be reduced if considering the 1 sigma calibration, 340-400 AD, corresponding to 68% probability. In the whole, evidence of destruction at Pratovecchio seems preceding that detected in other archaeological sites of the Fucino area and the formation of the collapse layers previously discussed for *Alba Fucens* and Trasacco (Table 1). Destruction may be included within the possible effects of seismicity which did not originate in the Fucino basin but in seismogenic areas adjacent to the investigated one. The possibility that the earthquake was triggered by the activation of faults in the L'Aquila area, 30 km north of Celano, will be discussed in the concluding remarks.

3.2 The church of San Bartolomeo at Avezzano and the 1349 earthquake

3.2.1 The 1349 earthquake

The 1349 earthquake struck a wide area of central Italy, causing heavy damage in the inner sectors of the Apennines, between L'Aquila and Isernia, along a belt of the Apennine chain about 110 km long. Knowledge about this earthquake is still sparse, as a large uncertainty remains whether the widespread damage of September 9th was the consequence of a single shock or (more probably) of a seismic sequence. Consequently, knowledge on the seismogenic process and the causative fault(s) is far from being considered as conclusive. The seismic catalogue CPTI15 (Rovida et al. 2020, 2022) and the macroseismic database DBMI15 (Locati et al. 2022) split the earthquake effects into four parts, two of which result from distinct shocks (Fig. 8). A northernmost intensity distribution ("Appennino laziale-abruzzese"; Fig. 8a) includes heavy damage (I 9 MCS, following the Mercalli-Cancani-Sieberg scale) at L'Aquila and villages in the Rieti province. Rome is reported in this intensity map with I 7–8 MCS. The estimated magnitude by seismic catalogue is M_w 6.27 (Rovida et al. 2022) and a paleoseismologically based hypothesis on the seismogenic fault has been recently proposed (Galli et al. 2022). Heavy damage has been further attributed to a southern sector of the central Apennines ("Lazio-Molise"; Fig. 8b), with intensity up to 10–11 MCS (Venafro, in Molise region). This has been related to a seismic event (M_w 6.8 in the catalogue CPTI15) possibly caused by the *Aquae Iuliae* fault (Galli and Naso 2009). Two other clusters of intensity datapoints are reported in DBMI15: an easternmost one ("Maiella"; Fig. 8c) including the town of Sulmona (I 8–9 MCS), and a westernmost distribution ("Viterbese"; Fig. 8d) including the town of Viterbo (I 8–9 MCS). A magnitude was not associated with either of the clusters.

3.2.2 The church of San Bartolomeo

The town of Avezzano, located between the two intensity distributions reported as "Appennino laziale-abruzzese" and "Lazio-Molise", certainly suffered damage in 1349, although the related intensity datapoint is not reported in the seismic catalogue. In particular, damage to the Medieval church of San Bartolomeo (Avezzano) is documented in a eighteenth century copy of a notarial deed drawn up in 1355, mentioning restorations/repairs following the earthquake (Socciarelli 2016; Del Bove Orlandi 2020).

Fig. 4 Water tank in the square of the temple ("5" in Fig. 2b): **a** uppermost layer of the deposit filling the tank, prevalently made of columns from the square; **b** intermediate layers made of sparse columns and remains from destroyed walls and roofs of buildings (mainly stones, bricks and tiles with fragments of furnishings and house furnitures); **c** bottom layer with the collapsed calcareous slabs covering the tank and the beams supporting the cover; **d** almost intact jug found under the collapsed slabs and attributed to the fifth-sixth century AD; (e) jug found under the collapsed slabs and attributed to the 4th–5th century AD (photo E. Ceccaroni)
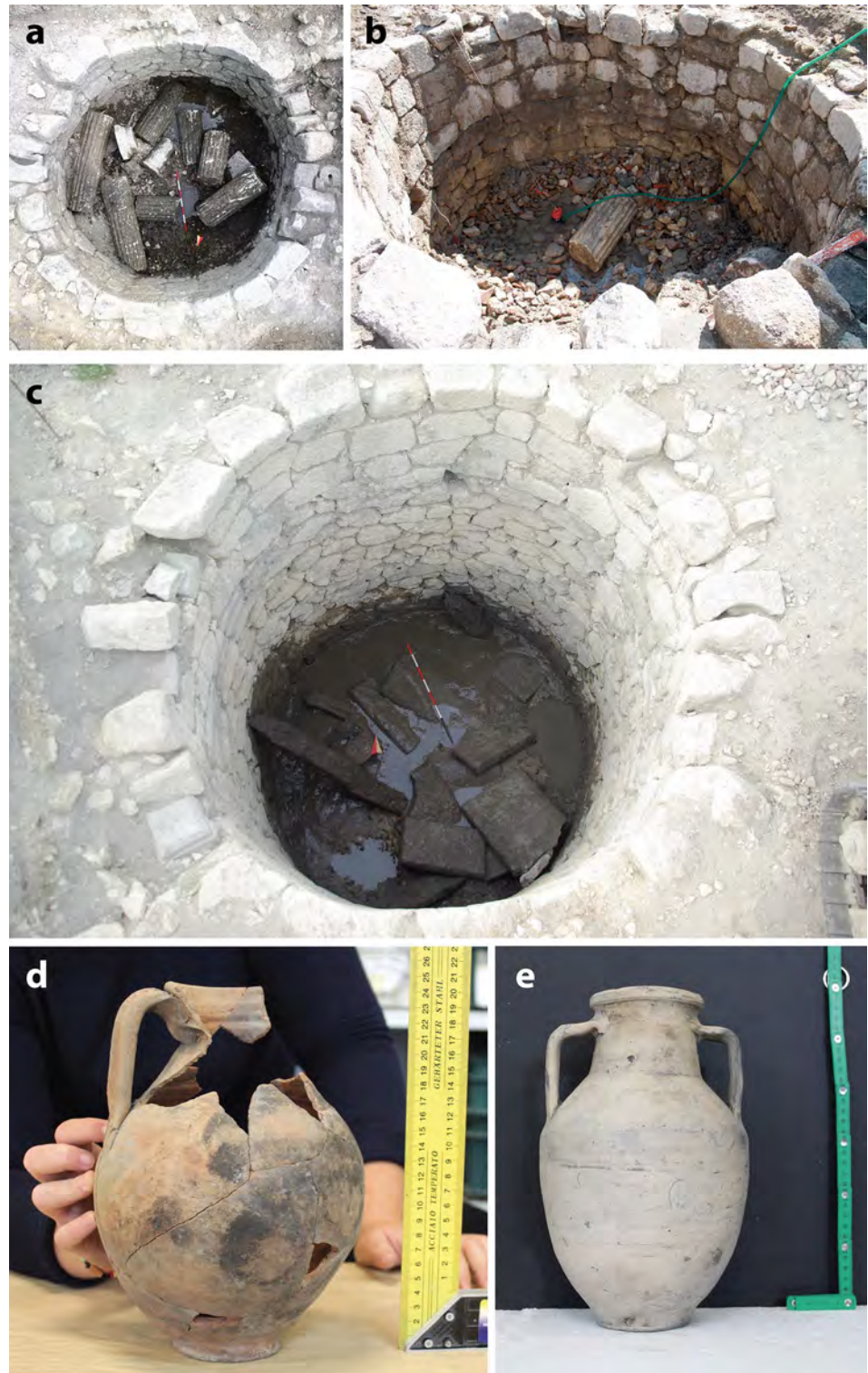
This church was replaced by a new building, with form and style different from the previous one, between the end of the sixteenth and the beginning of the seventeenth century (Del Bove Orlandi 2020). The modern church was in turn destroyed by the 1915 earthquake. Few remains are presently visible, i.e., a monument commemorating the last catastrophe (the reconstructed right sector of the façade adjacent to the lower portion of the bell tower) and remains of walls and pillars (foundations of the second and third pillars in the northern aisle and of the four pillars in the southern aisle) in the adjacent archaeological area mainly excavated in 2004 (Fig. 9; Saladino 2011).
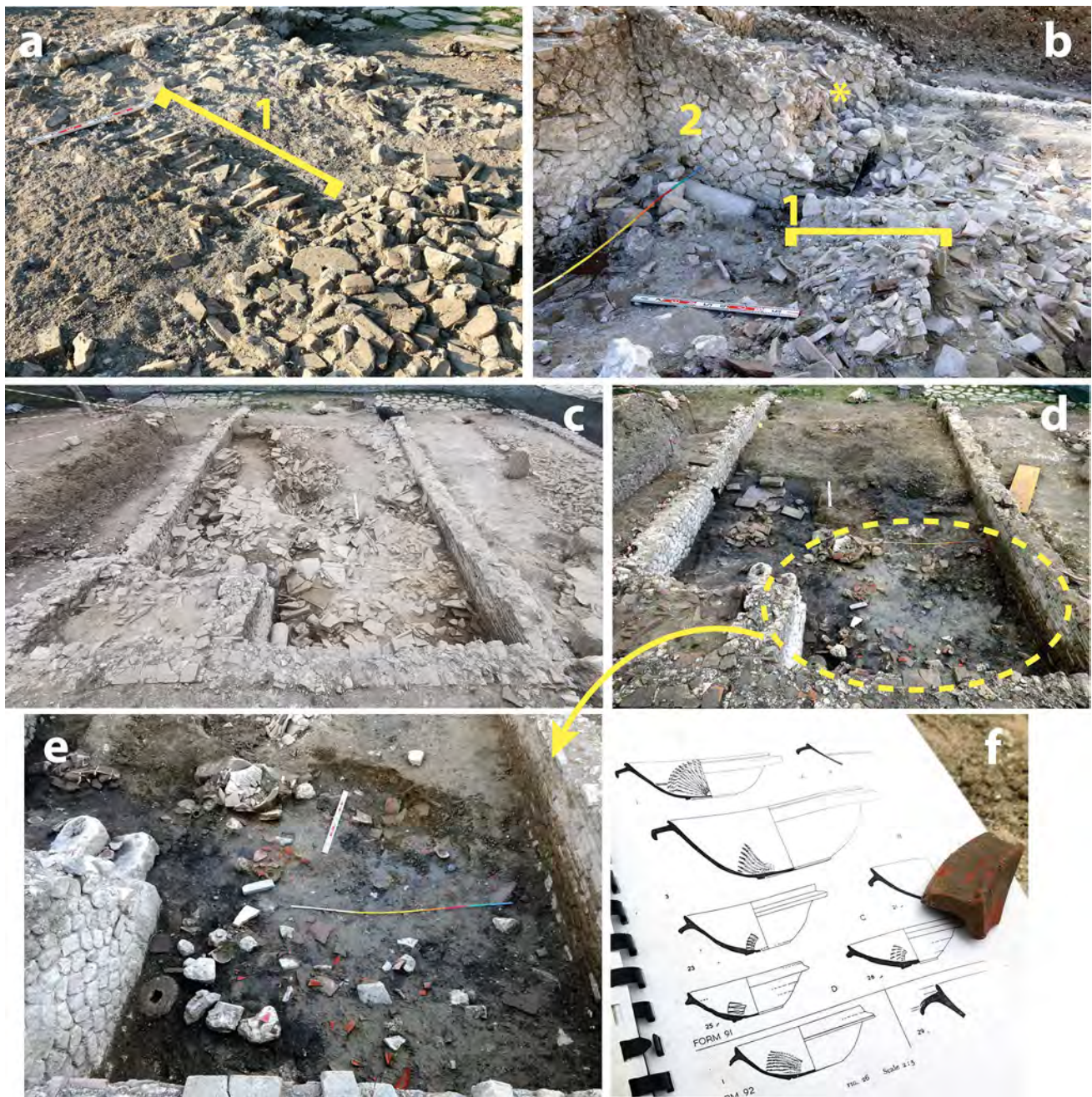
Fig. 5 Archaeological campaign of 2020: excavation of a *taberna* along *Via del Miliario* ("10" in Fig. 2b): **a** destruction layer made of reworked ruins and an untouched overturned portion of wall ("1"); **b** overturned portion of wall ("1"): the original position, perpendicular to the wall in *opus incertum* "2", is indicated by the yellow asterisk; **c** remains of the roof (tiles) underlying the collapsed walls, extended throughout the almost entire excavated space; **d, e** remains of house furnitures (fragments of pottery *Terra Sigillata Africana*) and extended traces of burning uncovered below the collapsed roof; (f) fragment of pottery *Terra Sigillata Africana* (Hayes 91-A) attributed to 450–500 AD, found in the remains of the collapsed roof (photo F. Galadini)

Fig. 6 Trasacco, 2014 archaeological excavation: **a**, **b** collapsed portions of a building overlying a level of occupation radiocarbon dated at 385/475–485/535 AD (cal. age, 2 sigma; sample Beta – 420082) (**a**, photo F. Galadini; **b**, photo G. Mieli)
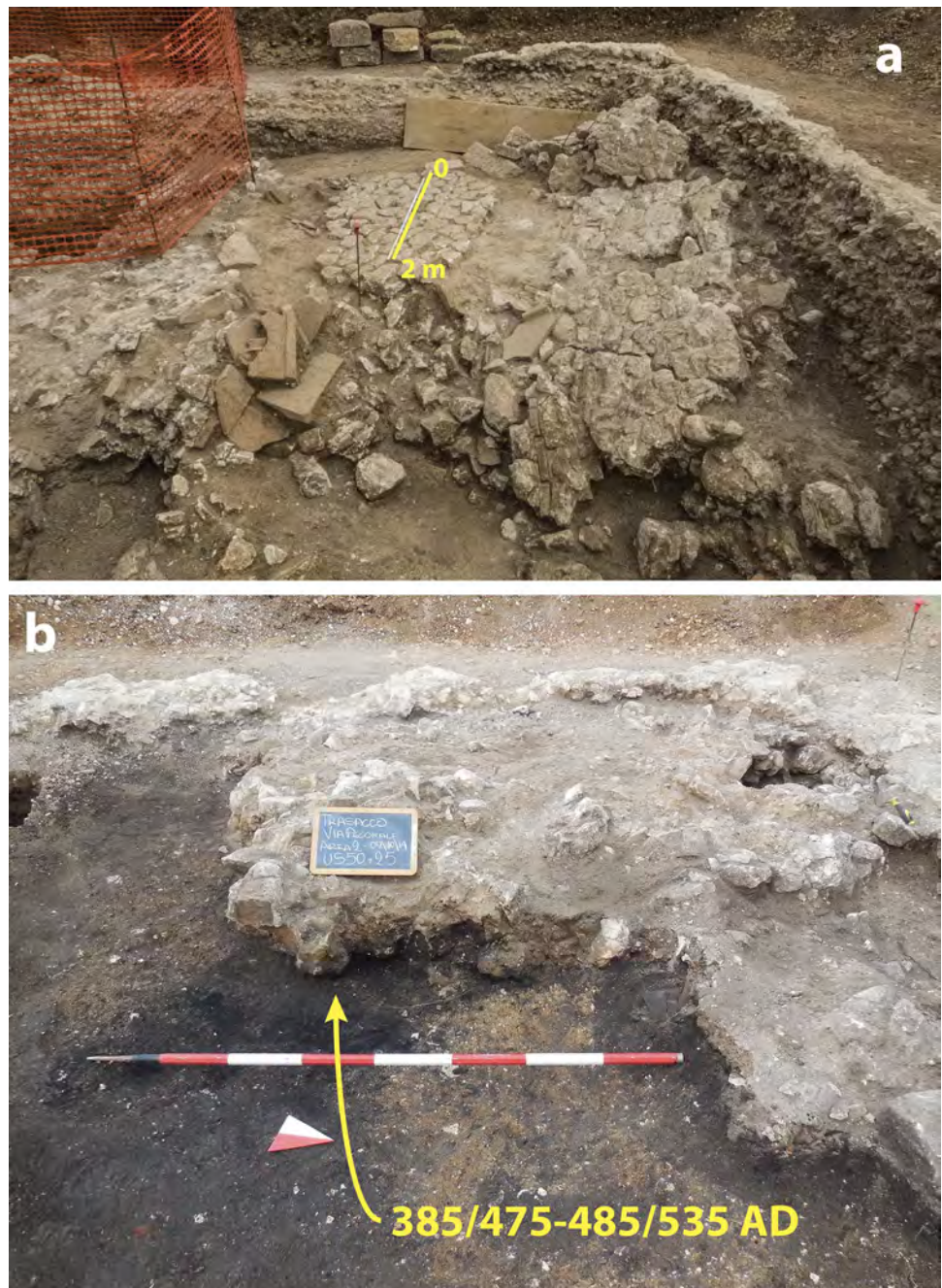
Data of possible effects of the medieval earthquake were provided by archaeological excavations in 2016–2017. Investigations on the presbyterial sector of the sixteenth-seventeenth century church uncovered some burials attributed to the fifteenth century AD overlying and sealing a collapsed and disused apsidal sector of the medieval building damaged in 1349 (Fig. 10a). The most significant chronological attribution derives from coins found in the burials and attributed to Ferdinand I of Aragon (ca. 1476 AD), king of Naples between 1458 and 1494 (Fig. 10b). Available data suggest the site history as follows: (i) damage of the medieval church caused by the 1349 earthquake (mentioned in the historical source); (ii) collapse and abandonment of the apsidal sector; (iii) use of the abandoned area as a space for burials in the second half of the fifteenth century.

The modern church of the sixteenth-seventeenth century had a nave and 2 aisles, round arches and 11 altars. Images of the façade show a tripartition (corresponding to
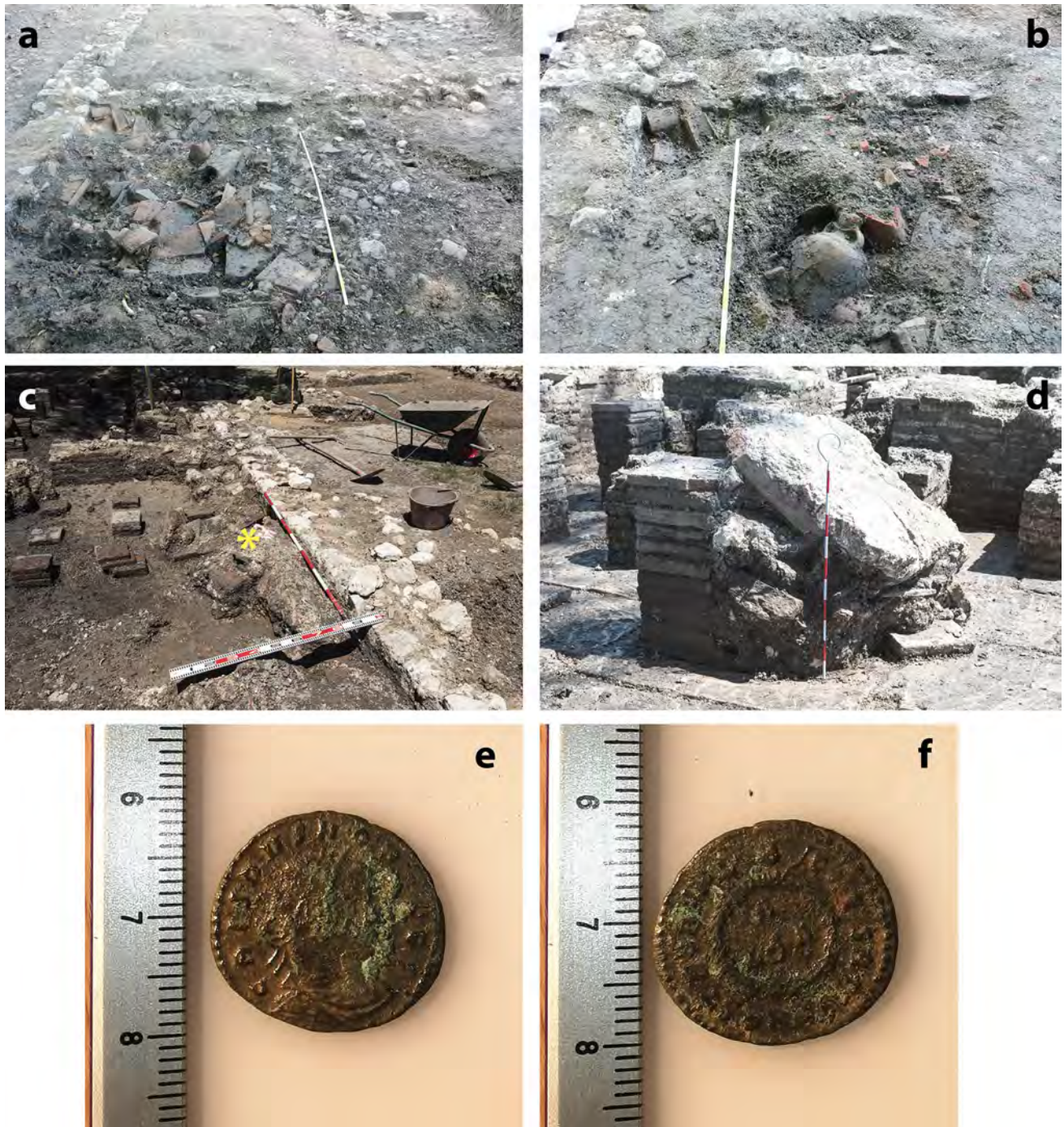
Fig. 7 Celano-Pratovecchio, 2012 archaeological excavation campaign: **a** remains of the collapsed roof in a room of the *villa rustica*; **b** amphora of the type *Dressel 30* (3rd–4th century AD) placed in the collapse layer (see text for explanation); **c**, **d** evidence of collapsed portions of building in the area of the thermae and related deformation of the *suspensurae*; the yellow asterisk in c indicates a collapse layer made of a thick accumulation of plaster; **e**, **f** coin of *Flavius Iulius Crispus*, emperor between 317 and 326 AD (**e** *recto*; **f** *verso*) (photo F. Galadini)

Fig. 8 Intensity datapoint distribution (MCS scale) of the 1349 earthquake in central Italy as from the macroseismic database DBMI15 (Locati et al. 2022). The widespread effects of the earthquake have been subdivided considering the distribution in the different areas which suffered damage: **a** "Appennino laziale-abruzzese"; **b** "Lazio-Molise"; **c** "Maiella"; **d** "Viterbese". According to DBMI15, the effects represented in a and b are related to two different shocks with M 6.27 and 6.8, respectively
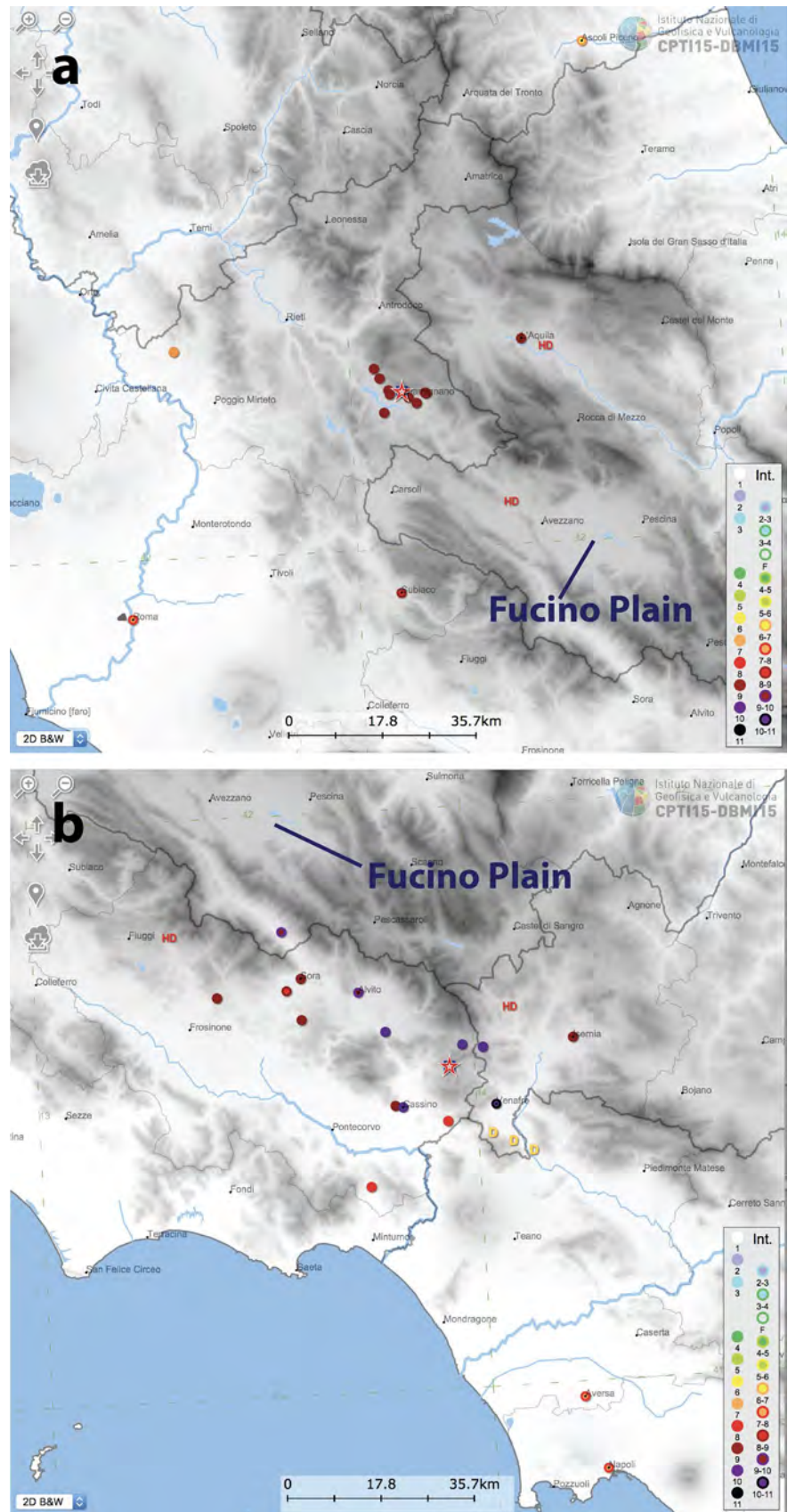
Fig. 8 (continued)
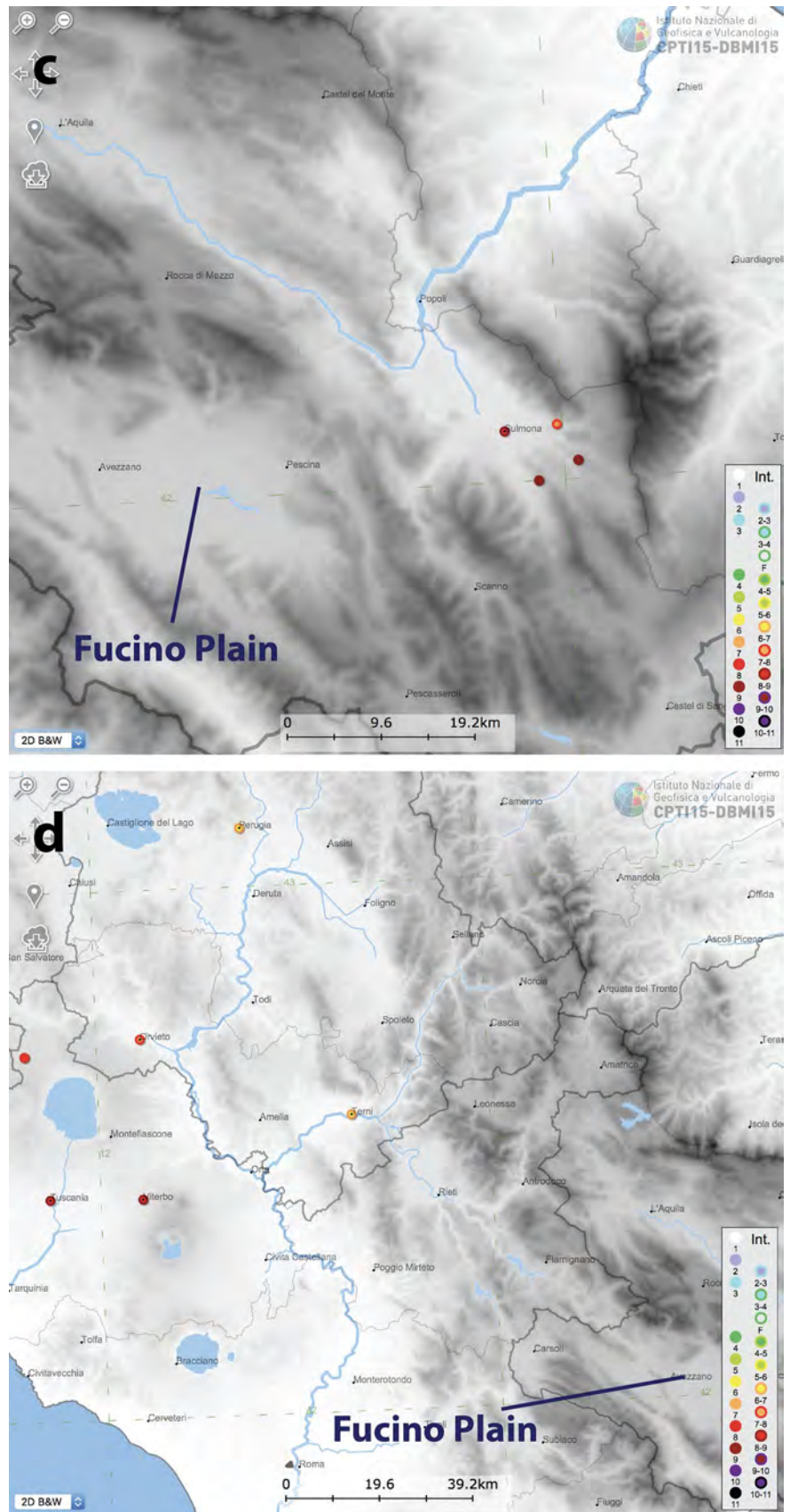
Fig. 9 a Avezzano: partial view of downtown area and location of the former church of San Bartolomeo; **b** remains of the church of San Bartolomeo: monument to the 1915 earthquake and, on the left, partial view of the archaeological area; **c** location of the HVSR measurements represented in Fig. 12 (b, photo F. Galadini)

the division of the internal volume) with spaces subdivided by a couple of pilasters (Fig. 11a). The church tower, built in 1780–1781 (Del Bove Orlandi 2020), was located to the right (i.e., south) of the façade.

A short time after the building (middle of the seventeenth century) interventions became necessary to reinforce the structure and some buttresses along the lateral walls were built (Mastroddi 1999). Historical sources indicate that heavy damage was caused by the earthquake that in 1703 struck the town of L'Aquila (epicenter 46 km north of Avezzano; M_w 6.67 according to Rovida et al. 2020). After the strong seismic shock, the repair works were only provisional,

and further definitive interventions were not made until the second half of the nineteenth century (Mastroddi 1999; Galadini 2012a).

The mentioned static problems conditioned the use of the church that was closed to the public access for safety reasons during the half of the nineteenth century (Mastroddi 1999). Archival documents indicate that plans for deeper interventions started in 1855. However, during the 60s of the nineteenth century, the gradual collapse of the roof began. A new plan for the restoration of the church was drawn in 1865, but the Italian Board of Public Works expressed doubts on the stability of the walls which would have had to carry the
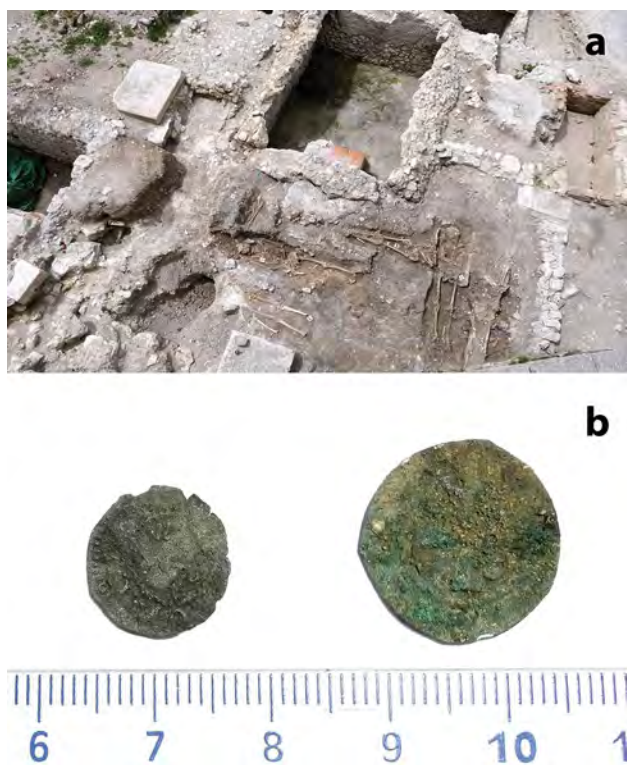
Fig. 10 Avezzano, San Bartolomeo archaeological area, 2017 excavation campaign: **a** medieval church, view of the apsidal area abandoned after the 1349 earthquake and used for burials; **b** coins of Ferdinand I of Aragon (ca. 1476 AD), king of Naples between 1458 and 1494, found in the burials (photo F. Galadini)

heavy new vault. Anyway, the works were in progress in 1869 and certainly ended in 1875 (Galadini 2012a). Forty years later, the 1915 earthquake caused the complete collapse of the church (Fig. 11b).

To better understand the reason of the repeated seismic damage suffered by the two churches founded at this site in the past centuries, a preliminary analysis on the local seismic site effects was performed in 2017 by means of four ambient vibration measurements (Figs. 9c, 12). The time-length of each measurement was 3 h, using a seismic equipment (Reftek digitizer and Lennartz3D_5s velocimeter) able to capture the properties of the seismic wavefield in a wide frequency interval (from 0.2 to 50 Hz). Data were analyzed with the geopsy software (www.geopsy.org; Whatelet et al. 2020) using the HVSR technique, which is based on the Fourier amplitude spectral ratios between the horizontal components (H) of the ground motion with respect to the vertical component (V). The peak of the H/V spectral ratio, under some assumption, is able to identify the fundamental resonance frequency of a site (Bonnefoy-Claudet et al. 2006; Molnar et al. 2022). For this reason, the H/V technique based on ambient vibrations is largely used in studies related to microzonation or site effects.

The results of the H/V analysis (Fig. 12a) show strong similarities among the four measurements. The H/V ratios return a clear fundamental resonance frequency around 0.6 Hz (left panel in Fig. 12a), with an amplitude peak of 4. The H/V ratios were also computed by rotating the

Fig. 11 Avezzano, church of San Bartolomeo (16th–17th century) before (**a**) and after (**b**) the 1915 earthquake (historical photos from personal archive of F. Galadini)

◄**Fig. 12** Avezzano, San Bartolomeo archaeological area, ambient vibration measurements carried out in April 2017: (**a** left) H/V spectral ratios for the four sites investigated; the continuous and dashed curves show the mean H/V and mean ± 1 standard deviation, respectively; the mean H/V of the four sites are overlaid in the bottom; (**a** middle) H/V curves rotated in the horizontal plane; the color scale is proportional to the H/V amplitude; (**a** right) Fourier Amplitude Spectra of the three components of ground motion (EW, NS and vertical); **b** view of the archaeological area during one of the ambient vibration measurements (yellow ellipse) (**b**, photo F. Galadini)

components in the horizontal plane (middle panel in Fig. 12a) aimed at looking for a possible magnification of the H/V peak along a preferential direction. However, the fundamental resonance at 0.6 Hz is characterized by an isotropic pattern without polarization phenomena linked to a specific direction. Further, the spectra of the three components of the motion (NS, EW and Z for north–south, east–west and vertical) also shows a consistent shape for the four measurements (right panel of Fig. 12a). The horizontal components show a spectral amplitude greater than the vertical one in the low frequency range; the largest difference in the spectral levels is in correspondence of 0.6 Hz where the vertical component shows a minimum. The spectral behavior of the three components differs at 3 and 15 Hz where the spectral amplitudes of the vertical component are larger with respect to the ones of the horizontal motion. HVSR value below 1 could suggest the effect of some velocity inversion in the Vs profile (Castellaro and Mulargia 2009; Di Giulio et al. 2016; Schwellenbach et al. 2020).

More HVSR measurements were carried out in different years not far from the remains of the San Bartolomeo church (Di Naccio et al. 2020), within the framework of the investigations for the ongoing seismic microzonation of level 3 of Avezzano (level 1 of microzonation available at https://comune.avezzano.aq.it/microzonazione-sismica/). These measurements (at sites close to the Orsini-Colonna Castle and to Torlonia Palace; see Fig. 9a) consistently show a low-frequency resonance around 0.6–0.8 Hz, indicating a deep seismic impedance contrast in this sector of the city. This velocity contrast is expected to be at a depth in the order of about 200 m within the velocity profile of the subsoil.

On the whole, available data suggest that the investigated church is located in an area suffering amplifications of the seismic motion at low frequency. Avezzano is settled at the NW border of the Fucino basin, and in such context trapped seismic waves traveling within the plain and edge-basin effects could occur during an earthquake, increasing the level of the input seismic motion (Paolucci et al. 2016). These effects could have influenced the shaking of buildings as large as the churches (both the Medieval and the Baroque one) of San Bartolomeo and conditioned damage in the past and the total destruction in 1915.

In a photograph taken after the complete collapse of 1915, the lower portion of the façade emerging from accumulations of debris is visible (Fig. 11b). Looking at this photo one can reflect upon the long wait for repairs that during nineteenth century appeared as necessary and upon the efficacy of the restoration. Delay of interventions and the type of engineering works probably increased the vulnerability of the building. The combination of seismic source characteristics, vulnerability and peculiar local seismic response certainly played a key role in damaging the church at a level not to allow any kind of subsequent repair.

4 Natural hazard and archaeological heritage

4.1 Episodes of mass deposition at Alba Fucens during the Early Middle Ages

4.1.1 Colluvial deposits in the Piano di Civita valley

The settlement at *Alba Fucens* did not end as a consequence of the Late Antique earthquake, following the general rule that, differently from the contemporary age, abandonment of sites during antiquity was rarely a consequence of earthquakes in the Mediterranean area (e.g., Ambraseys, 2005).

Continuity of life after the seismic destruction was already suggested by Mertens (1991), who stated that people lived in provisional shanties among the ruins of the town, using fragments of marble statues to obtain lime for new constructions. Moreover, new buildings were made by re-using pre-existing remains of walls. Another evidence of the continuity of life are the Early Medieval residential huts in the square in front of the *Herakles* sanctuary (Malandra 2011). This archaeologic evidence is consistent with the historical source mentioning the camp of the Byzantine soldiers during the Gothic War (Procopius of Caesarea, *Bell. Goth.*, II, 7). The town abandonment was due to the effects of natural non-seismic events and likely related to sudden mass deposition of sediments from the gentle (13–18° dipping) silty-sandy slopes bordering the Piano di Civita valley (Fig. 2b). This conclusion is derived from a study of the sediments filling this valley and sealing the archaeological remains, exposed in two different sections (Galadini et al. 2012a). Stratigraphic units made of natural and cultural deposits were found in two outcrops, indicating that accumulations of debris derived from centuries of human settlement, mixed with the silty-sandy surficial soil, were naturally removed from slopes and deposited in the valley. Sediments, in exposures about 1.5 m high, were made of fragments of tiles, bricks and stones from previously fallen walls, chaotically distributed within an abundant sandy matrix. The
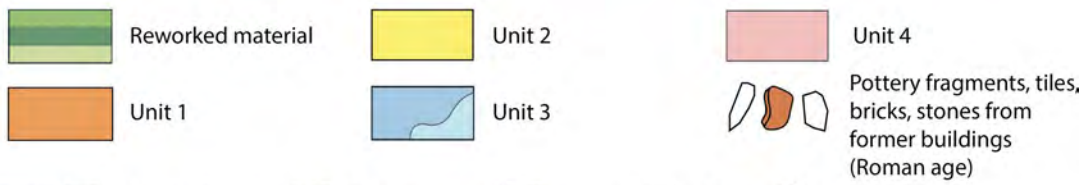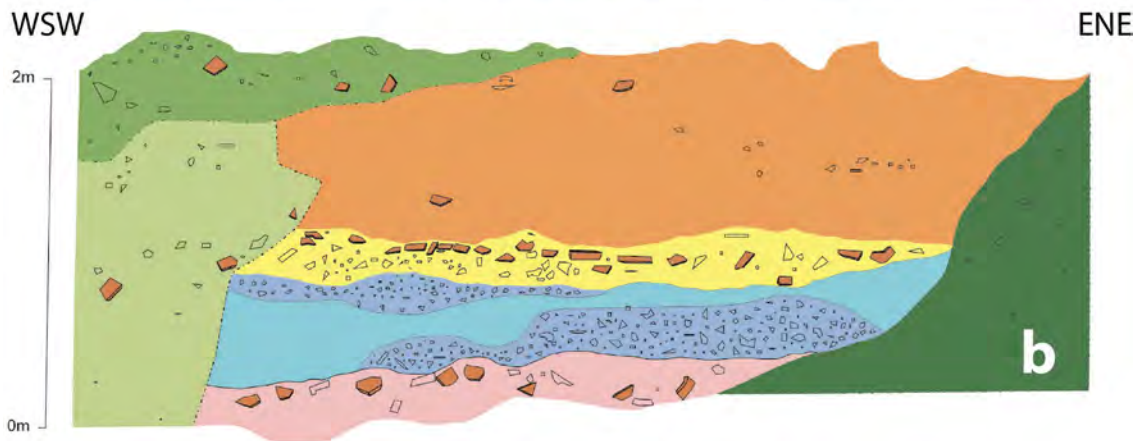
◄**Fig. 13** *Alba Fucens*, *Via del Miliario* (site "11" in Fig. 2b), 2020 archaeological campaign: **a** exposure of sediments covering the road (the rule in the middle rests on a paving stone of the Roman road); **b** log of the wall: units 1 and 4, colluvial deposits mainly made of greyish coarse sand including sparse fragments of stones and bricks; unit 2, fragments of tiles and bricks arranged to obtain a new road surface following the natural accumulation of debris; unit 3, colluvial deposit made of abundant clasts (lower and upper portions of the deposit) derived from bricks and stones of masonry buildings and greyish coarse sand with sparse clasts (intermediate portion); **c**, **d** coin of Justinian, Byzantine emperor between 527 and 565, found at the base of the investigated section, over the Roman road (**c** *recto*; **d** *verso*) (photo F. Galadini)

investigated units showed a matrix supported fabric, typical of diamicton resulting from debris flow episodes. This indicates that masses of sediments slid from the unstable slopes of *Alba Fucens* and filled the valley beneath. The presence of different units of mass deposits suggested that several flow episodes afflicted the area of the ancient settlement, which, consequently, became increasingly uninhabitable. The *post quem* date for the mass deposition was defined by the already mentioned huts of the Early Middle Ages, by the camp of the Byzantine soldiers (first half of the sixth century AD), by the youngest materials found in the water tank of *Alba Fucens* (sixth century AD) and by jugs, attributed to the sixth-seventh century (Redi 2001; Tulipani 2006), found in other reservoirs sealed by the colluvial/debris flow deposits.

Two further sections showing natural deposits sealing the archaeological remains were investigated during the 2020 archaeological campaign. Colluvial sediments were exposed in a section perpendicular to *Via del Miliario* and close to the *Forum*, i.e., at the base of the SW slope bordering Piano di Civita ("11" in Fig. 2b). Three colluvial units were identified, together with reworked materials indicative of human interventions (Fig. 13). The entire succession overlies the Roman road visible in the lower part of the photo in Fig. 13a. Colluvial deposits of units 1 and 4 are comparable, being mainly made of greyish coarse sand including sparse fragments of stones and bricks (Fig. 13b). Unit 3 is made of slightly different sediments, since clasts are more abundant, particularly in the lower and upper portions. However, also in this case, fragments of calcareous stones and bricks are included within a supporting greyish sandy matrix. The reworked materials are related to two interventions: *i*) the filling of an excavation on the left of the exposure (Fig. 13a, b), probably related to undocumented archaeological surveys of the twentieth century and *ii*) the accumulation of materials from adjacent excavations of the past decades, partly covering the investigated section on the right (Fig. 13b). Vestiges of human actions are included in units 2 and 4 (Fig. 13b), in forms of fragments of tiles and bricks arranged to obtain a new road surface following the natural accumulation of debris. These interventions indicate the will of the residents to maintain the local road passable despite the repetition of sudden depositional episodes. The attempts evidently ended with the deposition of the thick unit 1 which completely deleted traces of the past urban topography.

As for the chronology, a coin of Justinian, Byzantine emperor between 527 and 565, was found below the colluvial deposits, over the Roman road (Fig. 13c, d). The mentioned time span defines a *terminus post quem* for the deposition.

The occurrence of mass sediment deposition has been confirmed by the analysis of a second exposure at the site already discussed in 3.1.1 ("10" in Fig. 2b). The analysis of the outcrop revealed four colluvial units overlying remains (accumulation of tiles) of the collapse layer attributed to the earthquake (Fig. 14). The different colluvial deposits are characterized by the typical matrix-supported fabric, i.e., fragments of bricks, tiles, plaster and stones are included in abundant greyish-brownish coarse-grained sandy matrix. The thickness of the outcropping sediments, in the order of 1.5 m, confirms that the episodes of mass deposition strongly conditioned the occupation in the lowest sector of the ancient town. The valley of Piano di Civita became a local depocenter where, sliding from the flanks, sediments progressively accumulated.

In the same way as the previously described section, a *post quem* age for the deposition can be defined. A coin of Athalaric, king of Ostrogoths (526–534), was found in the thick colluvial cover (Fig. 14c, d). This means that the first half of sixth century AD gives a *post quem* date for the accumulation of mass deposits over the remains of ancient *Alba Fucens*. This age is consistent with the chronological framework deducible from the works previously mentioned.

4.1.2 The cause of the mass deposition

Gathered data do not significantly contribute to explain the cause of the repeated colluvial episodes which hindered the remains of the ancient town. Their origin may be included among the effects of the climate change following the so called *optimum* of the Roman age (first century BC-third century AD; e.g., Büngten et al. 2011, 2016; McCormick et al. 2012; Decker 2017), coinciding with a significant alluvial phase in the central Apennines, a period of high standing of Lake Fucino and an expansion of the southernmost European glacier, located in the Gran Sasso chain of the Abruzzi Apennines (Giraudi 2005). Alternatively, mass deposition may have derived from a change of land use with respect to the preceding centuries (e.g., Zolitschka et al. 2003; Leopold and Völkel 2007), e.g., the fall in population may have produced abandonment and lack of maintenance in previously settled sectors sloping towards the lowest and most important part of the ancient town. Another possible cause may be minor and paleoseismologically unknown
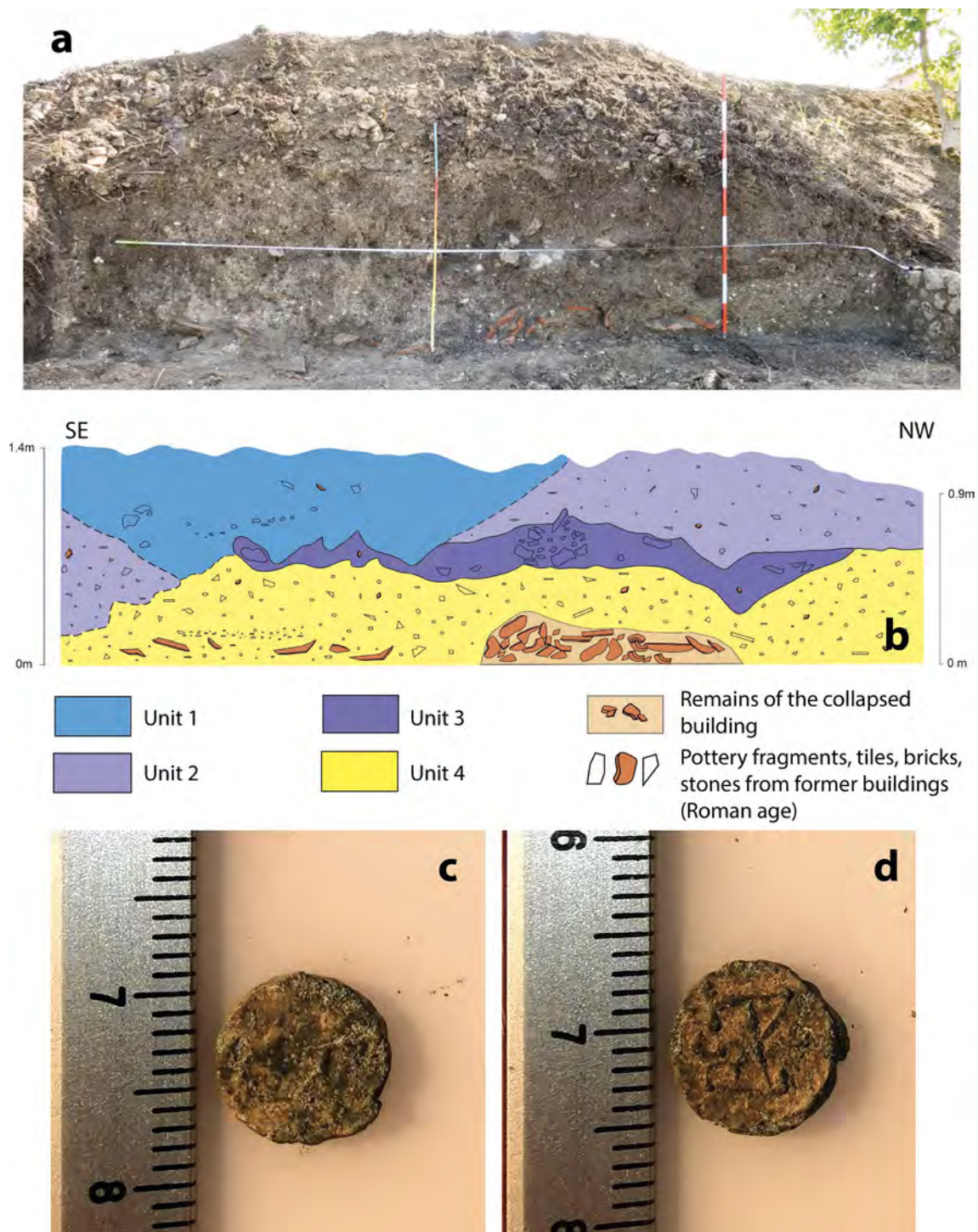
Fig. 14 *Alba Fucens*, *Via del Miliario* (site "10" in Fig. 2b), 2020 archaeological campaign: **a** exposure of sediments covering the collapse layer; **b** log of the wall: units 1–4, colluvial deposits made of fragments of bricks, tiles, plaster and stones in abundant greyish-brownish coarse-grained sandy matrix; **c**, **d** coin of Athalaric, king of the Ostrogoths (526–534), found in unit 4 (**c**, *recto*; **d**, *verso*) (photo F. Galadini)

seismic shaking, but the distribution of coeval colluvial sediments throughout the Apennines (e.g., Galadini et al. 2012b) favors a non-seismic hypothesis. Abandonment of the valley for repeated mass deposition is certainly one of the reasons for the medieval settlement in one of the adjacent hills where the village of Albe was founded ("2" in Fig. 2a). In a sort of repeat of history, Albe was completely destroyed by the 1915

earthquake and again a new small village was built adjacent to the present archaeological area ("4" in Fig. 2a).

It is not for sure whether colluvial deposition was conditioned by climate, anthropic modification of the landscape or if it was due to the combination of both factors. However, apart from the cause of this kind of deposition, weakness of the natural environment had a significant impact on the history of *Alba Fucens*. If the earthquake devastated the ancient town, mass sediment deposition was responsible for the end of the settlement. Apart from the cause of this natural hazard, geological data indicate that the slopes adjacent to the main archaeological area may become unstable under conditions similar to those of the Early Medieval age. This aspect should deserve proper attention in planning the current and future use of the archaeological area.

4.2 Active faulting and the Roman hydraulic work in Fucino plain and Liri valley

4.2.1 The Roman hydraulic work in Fucino Plain and Liri Valley

The present landscape of the Fucino Plain resulted from the drainage of the lake during the second half of the nineteenth century AD to obtain exploitable land for agriculture. The same purpose inspired hydraulic works already in the Roman period, during the first and second century AD, when a 4-km-long canal was excavated to channel lake water towards a 5.5-km-long tunnel, crossing Mt. Salviano and the depression of Piani Palentini west of Fucino (Fig. 1). Further west, a monumental tunnel mouth, still visible in its original form, is suspended on the left flank of the Liri river valley, where the drained water ends its course in a waterfall (Figs. 15, 16a, b).

Further preserved parts of the Roman hydraulic works are the tunnel (exploited and modified during the nineteenth century works) and the related inclined shafts which permitted the access from the ground surface. Moreover, a faint trace of the canal excavated in the lacustrine plain to drain water towards Mt. Salviano is still visible. By contrast, the tanks and the monumental façade at the tunnel entrance in the Fucino Plain have been destroyed during the works of the nineteenth century.

The Roman canal was investigated during the 1990s for paleoseismological purposes, as it is crossed and vertically displaced by the NW–SE trending Trasacco fault (Fig. 1). The paleoseismological analyses attributed the displacement to an earthquake preceding 1915, i.e., one that occurred in the fifth-sixth century AD, already mentioned in the archaeoseismology section (Galadini and Galli 1996, 2001).

The hydraulic work is also crossed by the Liri fault in the area of the tunnel mouth at Capistrello (Figs. 1, 15).
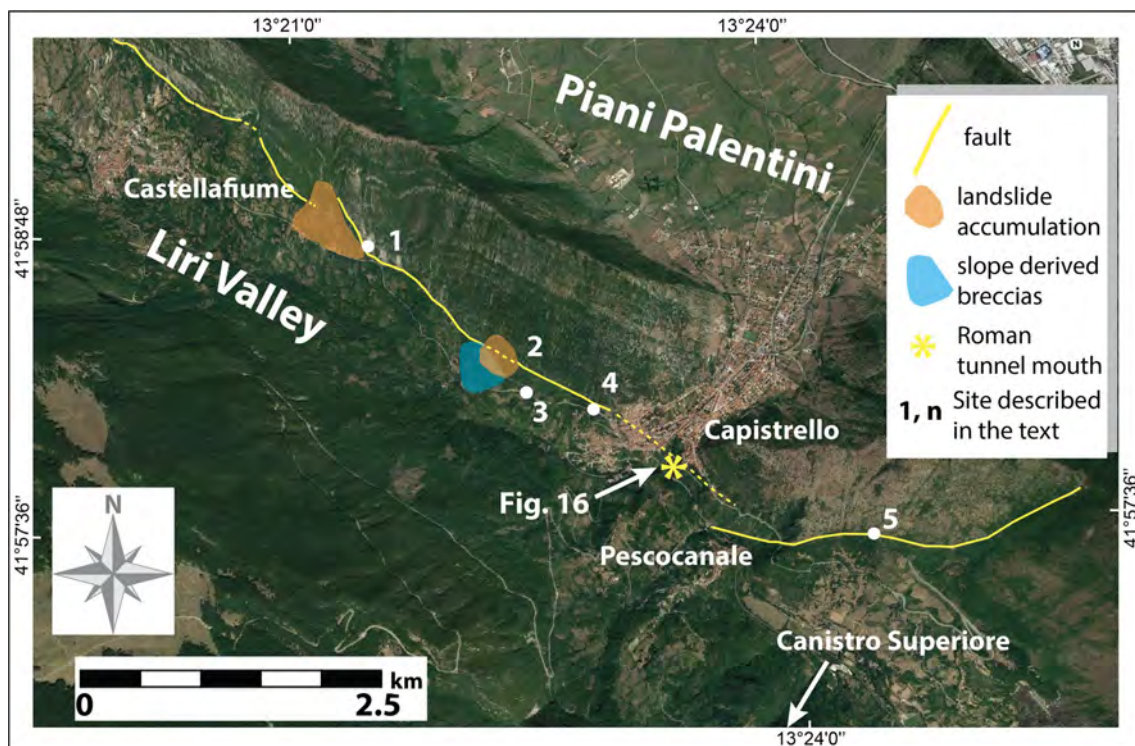

Fig. 15 View of the upper Liri river valley and trace of the fault emerging along the left flank, between Castellafiume and Canistro Superiore
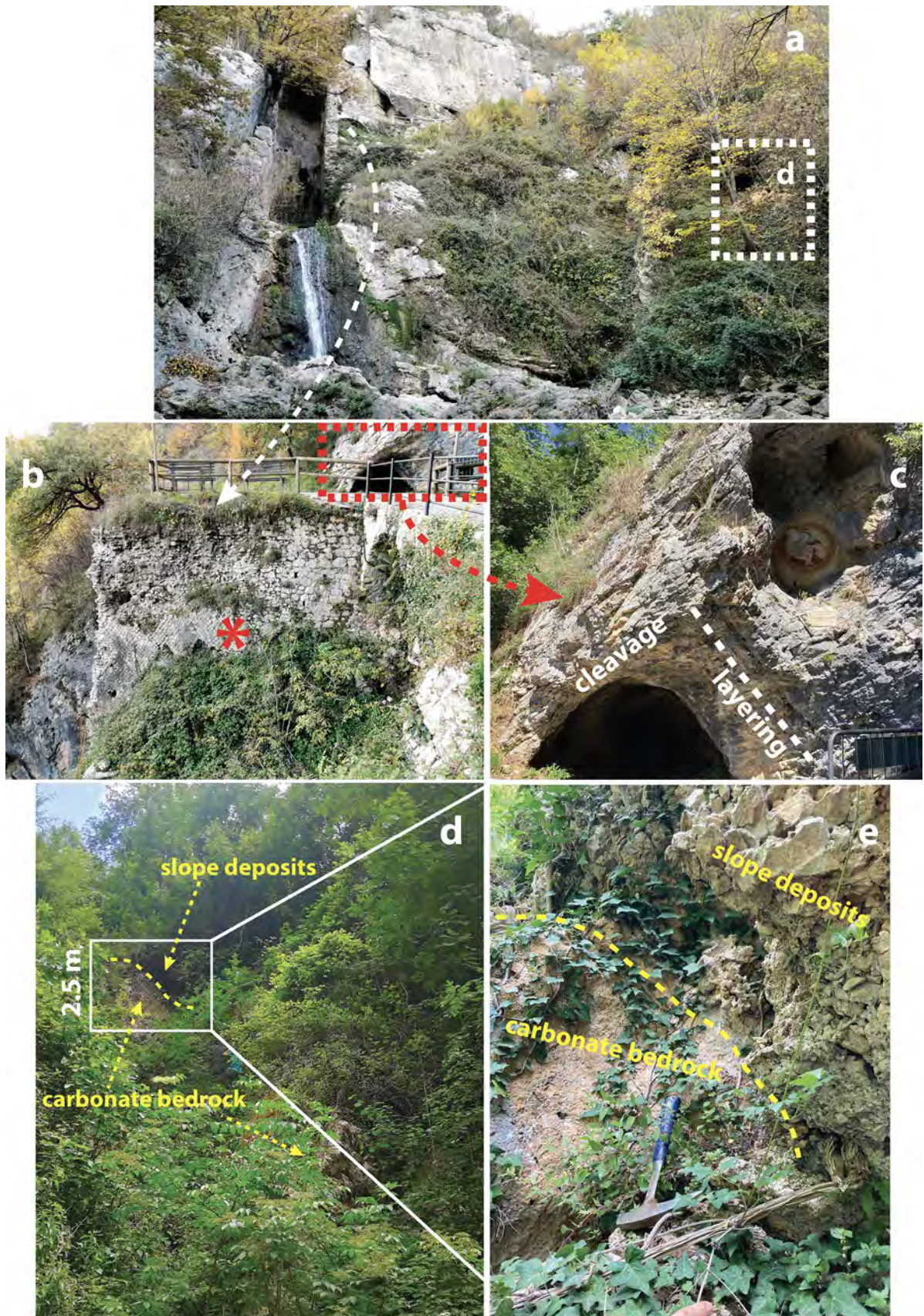
◀**Fig. 16** Roman tunnel mouth suspended on the left flank of the Liri Valley: **a** Panoramic view of tunnel mouth and waterfall; **b** face in *opus reticulatum* in the left flank of the tunnel mouth (red asterisk); **c** structural features of the rock mass supporting the tunnel mouth; **d**, **e** left flank of the incision draining water from the tunnel: Late Quaternary slope deposits overlying the carbonate bedrock do not display evidence of tectonic displacement (**a**, **b**, photo F. Galadini; **c**, **d**, **e**, photo D. Maceroni)

The fault has been considered as active in some scientific articles (e.g., Roberts and Michetti 2004; Papanikolaou et al. 2005; Faure Walker et al. 2021); it is also included in the database ITHACA of the capable faults (ITHACA Working Group 2019). Moreover, shaking due to the activation of Liri fault has been proposed as cause of the collapse of speleothems in caves located in the area of Liri valley (Pace et al. 2020; Alfonsi and Cinti 2021). Since a plan concerning the restoration of the hydraulic work is presently under development, the attribution of activity and capability to the fault has become an important issue in two different perspectives, i.e., (i) the seismogenic characteristics of the area (from which an expected seismic shaking derives) and (ii) the possible occurrence of surface faulting and permanent vertical ground displacements. For this reason, geological fieldwork was made to define the relationship between Quaternary sediments and the normal fault, to establish if sediments and related landforms are displaced as a consequence of a recent fault motion.

4.2.2 The monumental drain and the Liri fault

The Roman tunnel mouth located on the left flank of Liri Valley is founded on limestone, in an area which may be affected by the Liri normal fault (Fig. 15). The carbonate bedrock is continuously exposed along the path between Capistrello and the monumental drain. The rocks, stratified and dipping into the slope, show a NE-SW trending cleavage (Fig. 16c). Slope deposits of colluvial origin have been found close to the water discharge from the tunnel mouth. They are gently dipping towards the valley and consist of angular carbonate clasts of variable size (1–10 cm) in a yellowish-light brown sandy matrix. The slope deposits are lying over the carbonate bedrock in the fault zone and show no evidence of displacement, they simply overlay the carbonate bedrock with the attitude expected for the angle of the slope (Fig. 16d, e). At lower elevation, close to the Liri river-bed, sediments related to an alluvial fan have been found. They are made up of sub-rounded carbonate clasts (size up to 10 cm) in sandy-silty brownish matrix, passing upward to lenses of carbonate clasts (sub-angular to sub-rounded; size < 10 cm) also in sandy-silty brownish matrix. Even these alluvial deposits show no evidence of displacement which may be related to fault activity.

Radiocarbon dating is not available for the described sediments. However, their lithological characteristics and the relationship with the local base level permit to correlate them with similar deposits distributed throughout the central Apennines and attributed to the Last Glacial Maximum, i.e., about 25–15 ky (e.g., Dramis 1983). In the whole, slope deposits overlying the carbonate bedrock and the described alluvial deposits, showing no evidence of displacement or deformation, indicate that the area of the monumental drain is not affected by a capable fault.

To collect more data about the recent fault activity, geological surveys have been made along the left flank of the Liri valley, north and south of Capistrello, in a 9-km-long valley sector (Fig. 15). About 2.5-km SE of Castellafiume, slope deposits overlie the carbonate substratum close to the fault emergence showing no evidence of vertical displacement (1 in Fig. 15; Fig. 17a). Between Castellafiume and Capistrello, the main fault plane is seldom exposed along bedrock scarps; more often the geomorphic signature of the main structure are fault-line scarps due to the retreat of the carbonate slope by toppling of rock blocks, favoured by high angle fractures and shear planes, over the arenaceous flysch outcropping in the hanging-wall. About 1.3-km NW of Capistrello, the fault is sealed by a landslide accumulation, whose top surface is continuous across the fault (2 in Fig. 15; Fig. 17b). The landslide deposit, made of calcareous blocks, overlie slope-derived breccias not younger than the Early Pleistocene. The absence of a fresh landslide scarp on the slope and the lack of the deposits close to the valley bottom suggest an age of deposition not recent, i.e., younger than the Early Pleistocene but certainly predating the Holocene.

Displaced slope deposits have been detected about 1 and 0.5 km NW of Capistrello (3 and 4 in Fig. 15; Fig. 18a, b). However, this portion of the slope is affected by gravitative displacements which partly re-uses shear planes located in the hanging-wall of the main fault. At both sites, evidence of recent vertical motions should not be attributed to tectonic causes.

South of Capistrello, close to Pescocanale and Canistro Inferiore, the Liri fault is E-W trending and places the carbonate substratum in contact with the Miocene arenaceous flysch without evidence of Quaternary displacements (5 in Fig. 15).

The distribution of strath terraces in the area between Canistro Superiore and Capistrello also gives useful information about the recent fault activity. As described by Giraudi (1986), the whole distribution of landforms defines a course of an ancient Liri river different from the present one, i.e., draining towards north, from the area of Canistro towards Piani Palentini. Most of the terraces are carved into the pre-Quaternary substratum. However, an erosional terrace overlying lacustrine deposits attributed to the Middle
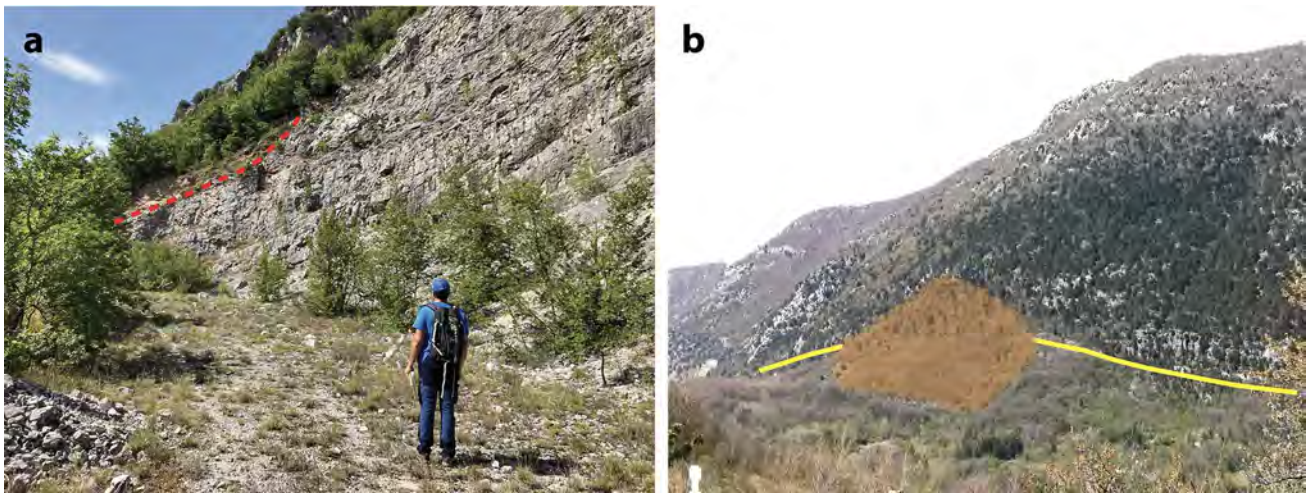
Fig. 17 Colluvial **a** and landslide **b** deposits detected in the Liri fault zone (sites 1 and 2 in Fig. 15). Colluvial deposits in (**a**), although exposed close to the emergence of the fault, do not display evidence of displacements. The landslide accumulation in (**b**) seals the fault (**a**, photo D. Maceroni; **b**, photo F. Galadini)
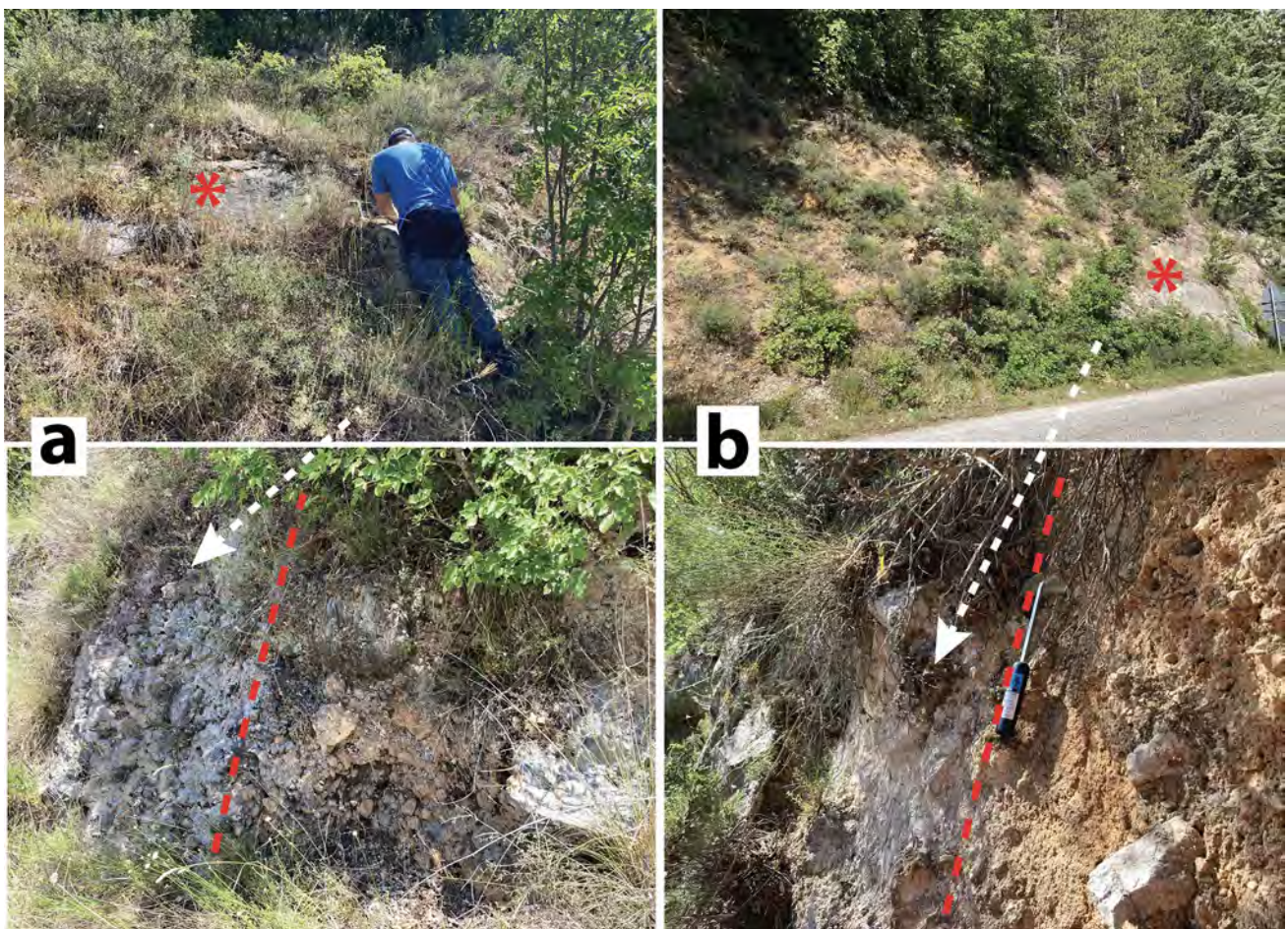

Fig. 18 Fault planes exposed in the hanging-wall of the main Liri fault (a = site 3, b = site 4 of Fig. 15). The displacement of the Pleistocene slope deposits visible in the enlargements is due to landsliding (photo D. Maceroni)

Fig. 19 a Distribution of main remnant paleolandsurfaces (min. and max. altitude reported) between Canistro Superiore and Capistrello, indicating the paleodrainage network from S (Canistro Superiore) towards N (Piani Palentini) already hypothesised by Giraudi (1986); the remnant landsurfaces have been mapped on a digital elevation model by cross-checking automatic sampling of all surfaces sloping 0–10° with view of aerial photographs and field survey; **b** Panoramic view of the Capistrello area: violet and green landsurfaces can be correlated across the Liri river; the altimetric continuity across the surficial expression of the fault (green surface: footwall; violet: hangingwall) indicates the lack of recent fault activity; **c** Interpretative section (vertical exaggeration 2x) along the line defined in (**a**), through the average altitude of the paleolandsurfaces; the continuity of the paleodrainage towards Piani Palentini suggests fault inactivity (**b**, photo F. Galadini)
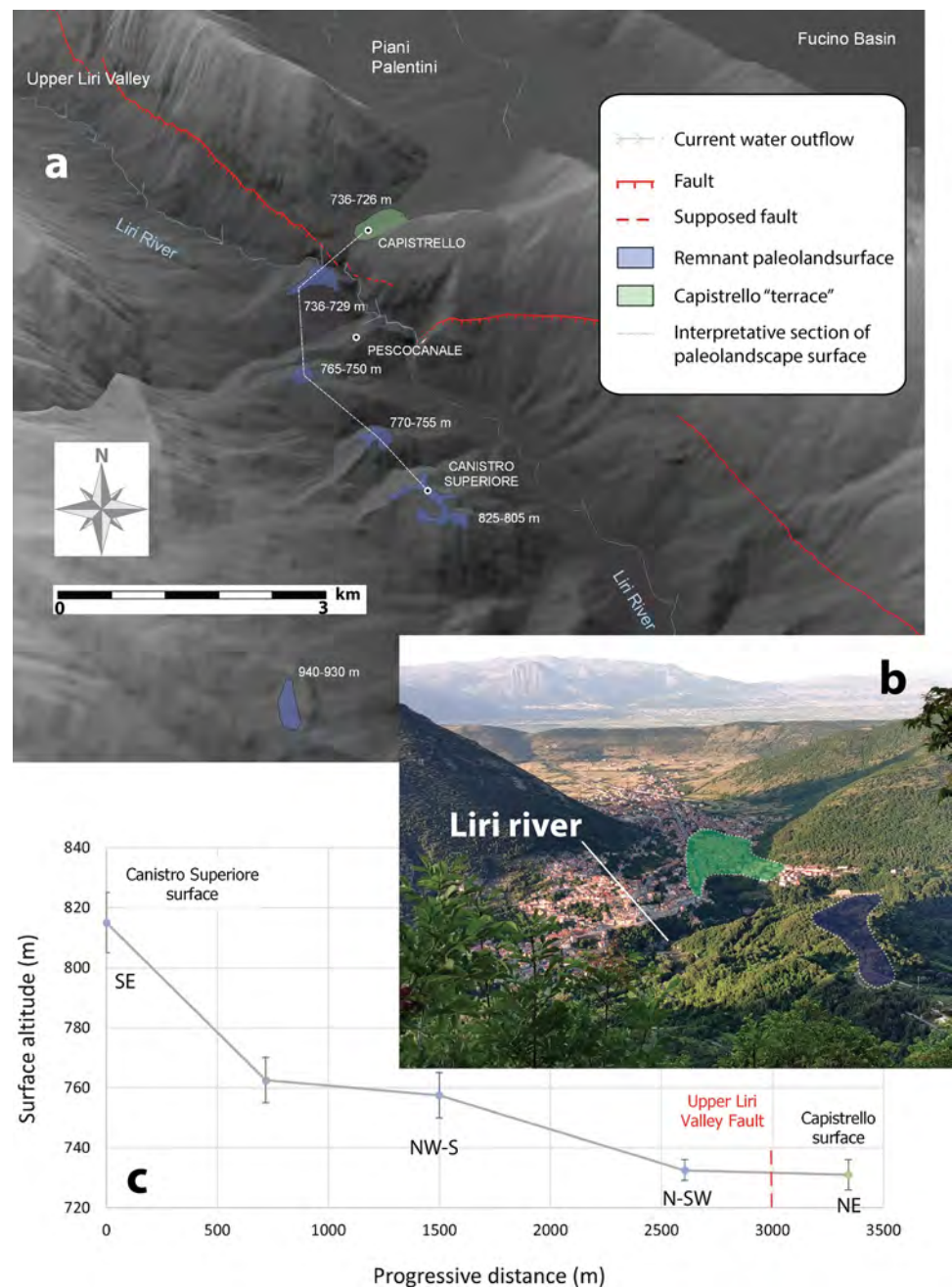
Pleistocene has been detected in the area between Capistrello and Pescocanale (Giraudi 1986). Some boreholes made at Capistrello during this century, in the part of the village founded in Piani Palentini, indicated that lacustrine and alluvial sediments are filling the depression (Santilli 2016). This confirms data collected in the nineteenth century during the excavation of the tunnel to drain Lake Fucino (Beneo 1936). On the whole, the available data define a landscape of the Early and Middle Pleistocene characterized by a drainage network completely different from the present one (Fig. 19). This reconstruction has implications in terms of fault activity since the correlation of the different terraces defining the ancient drainage does not display anomalies when crossing the fault zone at Capistrello, i.e., the profile of the ancient river course draining towards Piani Palentini is continuous between Canistro Superiore and Capistrello, indicating that no fault displacement occurred since at least the Middle Pleistocene (Fig. 19c).

4.2.3 Implications for the regional active tectonics

In conclusion, unlike reported by ITHACA database and literature (e.g., Roberts and Michetti 2004; Papanikolaou et al. 2005; Faure Walker et al. 2021), collected data do not

support hypotheses on the recent fault activity along this 9-km-long sector of the Liri valley between Castellafiume and Canistro. Indeed, (i) the landscape related to the former drainage of the Liri river has not been displaced by fault activity (Fig. 19); (ii) the mentioned landslide accumulation about 1 km north of Capistrello seals the fault (Fig. 17B) and (iii) slope deposits close to the fault trace do not display evidence of fault displacement related to fault activity (Fig. 17a). Moreover, the only traces of displacements involving Quaternary sediments have been attributed to slope instability of gravitative origin. As for the collapse of speleothems detected in caves along the Liri Valley and tentatively attributed to the activation of the Liri fault (Pace et al. 2020; Alfonsi and Cinti 2021), it has to be considered that, basing on the available geological data, the investigated fault could not produce large earthquakes (i.e., those associated to surface faulting). If the observed collapse of speleothems cannot be attributed to local earthquakes with M < 6, other seismogenic sources adjacent to Liri valley should be invoked for the necessary shaking.

Finally, the conclusions of a recent study on geodetic and stress data are consistent with the described geological evidence (Carafa et al. 2020). The very low slip rate (< 0.2 mm/yr) across this area suggested the mentioned author to doubt about activity of this section of the Liri fault.

These aspects have implications in planning interventions of restoration and strengthening of the monumental drain. Surface faulting close to the ancient hydraulic works should not be expected at the archaeological site. Moreover, as for the definition of the seismic action necessary to assess the expected ground motion, available geological data permit to exclude the presence of a seismogenic source potentially responsible for large magnitude earthquakes (greater than M≈6; e.g., Falcucci et al. 2016 and references therein) in the subsurface of the monumental drain. This seems confirmed by the recent seismic history of this Liri Valley sector. A magnitude of M_w 5.2 has been assigned to the two earthquakes which occurred during the twentieth century, i.e., in 1922 and 1927, responsible for scarce-to-moderate damage to Capistrello and nearby villages (Intensity 6 and 7 MCS; Locati et al. 2022). Stronger earthquake effects may derive from the activation of adjacent seismogenic sources, i.e., those related to the Fucino and Middle Liri Valley–Posta Fibreno faults, potentially the source of earthquakes with M 7 (Fucino, e.g., Galadini and Galli 2000) and M≈6.5 (Middle Liri Valley–Posta Fibreno; Dixit Dominus 2020; see also Cucci and Cinti 2022 for a seismotectonic discussion). The activation of the Fucino fault in 1915 caused damage to Capistrello estimated as Intensity I 8–9 MCS (Locati et al. 2022). However, paleoseismological data indicate that Apennine seismogenic sources are characterized by recurrence times of many centuries (or even a few millennia) as for the activation causing large magnitude earthquakes (Galli

et al. 2008). Therefore, activity of the Fucino fault to cause a seismic event similar by magnitude and surface faulting to that of 1915 should be considered improbable in a time interval of centuries. By contrast, knowledge on the Middle Liri Valley–Posta Fibreno fault is sparser and investigations on its seismotectonic characteristics are currently underway.

5 Concluding remarks

The geological, geoarchaeological and archaeoseismological investigations in the Marsica sector of the Abruzzi Apennines have two perspectives. The first one, more traditionally linked to the goals of Earth Sciences, is the attempt to increase our knowledge on the effects of natural hazards during periods (namely Antiquity and the Middle Ages) sparsely characterized from historical sources. Archaeoseismological investigations, combined to results from available literature, allow to cast further light on the earthquake which struck the Fucino area and caused damage in Rome during Late Antiquity, which probably occurred in 484 or 508 AD (Galadini et al. 2010, 2018). The same investigations indicated that the sudden collapse of a building in the area of Celano may be related to an earlier time span, possibly the fourth-fifth century AD. If the sudden collapse was caused by shaking, then probably the earthquake did not originate in the Fucino area but in one of the other seismic zones of the central Apennines. In this case, destruction may have been conditioned also by age and decay of the building (founded centuries before). For example, paleoseismological analyses in the L'Aquila area, about 30 km north of Celano, revealed one episode of fault activation between the Late Antiquity and the Early Middle Ages (Galli et al. 2010; Cinti et al. 2011; Moro et al. 2013). This is consistent with the seismic destruction of *Amiternum*, a Roman town about 9 km north of L'Aquila, attributable to the Late Antiquity, after the third century AD (Heinzelmann 2011; Tuteri 2011; see also the discussion in Moro et al. 2013).

The other archaeoseismological case, related to the damage of the church of San Bartolomeo at Avezzano in 1349, also contributes to the knowledge on past seismicity. In this case, the written source, though mentioning damage, does not give details on the effects of shaking. The excavation permitted to define the abandonment of a previously damaged/collapsed apsidal sector, as a probable consequence of the damage, and its use for burials during the fifteenth century. The seismic history continued with the damage of the modern (aged at sixteenth-seventeenth century) church in 1703 and its definitive destruction in 1915. Site effects may be significant in basin areas such as the Fucino Plain, and may have played a role in the damage history of the investigated monumental buildings.

The study of the rapid mass sediment deposition which afflicted *Alba Fucens* during the Early Middle Ages can also be ascribed to the improvement of knowledge on the effects of past natural events. Available information may be included in a regional dataset which can contribute to establish a possible relationship between landsliding and climatic history and/or anthropic conditioning.

The better knowledge on the past events, due to both seismicity and slope instability, also contributes to the second perspective of the investigations made in this sector of the central Apennines. The gathered information can be included in the site histories determined by archaeologists. From the engineering point of view, these histories are necessary to better plan actions for the preservation of the cultural heritage. Plans on the restoration of archaeological areas, sites or monuments cannot disregard the local natural hazards which may jeopardize heritage and consumers. Within this light, preservation has to include interventions dedicated to the safety against natural catastrophes. The investigation of the fault located along the left flank of the Liri valley is part of this wide range of studies dedicated to prevention. Excluding its capability (i.e., the possible occurrence of surface faulting) among the expressions of the local hazards has a key-role in planning the restoration of the Roman monumental drain.

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