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Archaeoseismology: Methodological issues and procedure

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Abstract Archaeoseismic research contributes important data on past earthquakes. A limitation of the usefulness of archaeoseismology is due to the lack of continuous discussion about the methodology. The methodological issues are particularly important because archaeoseismological investigations of past earthquakes make use of a large variety of methods. Typical *in situ* investigations include: (1) reconstruction of the local archaeological stratigraphy aimed at defining the correct position and chronology of a destruction layer, presumably related to an earthquake; (2) analysis of the deformations potentially due to seismic shaking or secondary earthquake effects, detectable on walls; (3) analysis of the depositional characteristics of the collapsed material; (4) investigations of the local geology and geomorphology to define possible natural cause(s) of the destruction; (5) investigations of the local factors affecting the ground motion amplifications; and (6) estimation of the dynamic excitation, which affected the site under investigation. Subsequently, a 'territorial' approach testing evidence of synchronous destruction in a certain region may delineate the extent of the area struck by the earthquake. The most reliable results of an archaeoseismological investigation are obtained by application of modern geoarchaeological practice (archaeological stratigraphy plus geological–geomorphological data), with the addition of a geophysical-engineering quantitative approach and (if available) historical information. This gives a basic dataset necessary to perform quantitative analyses which, in turn, corroborate the archaeoseismic hypothesis. Since archaeoseismological investigations can reveal the possible natural causes of destruction at a site, they contribute to the wider field of environmental archaeology, that seeks to define the history of the relationship between humans and the environment. Finally, through the improvement of the knowledge on the past seismicity, these studies can contribute to the regional estimation of seismic hazard.

Key words archaeoseismology · historical seismology · geoarchaeology · environmental archaeology · natural catastrophes

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Introduction

The use of archaeological data to investigate unknown or poorly known historical earthquakes has continuously increased since the first reports of earthquake effects recorded in the archaeological heritage (e.g., De Rossi 1874; Lanciani 1918; Evans 1928; Agamennone 1935). For the past few decades, the word 'archaeoseismology' has been used to define the investigations related to the seismic effects on ancient structures, uncovered by means of archaeological excavations or pertaining to the monumental heritage. The increased interest is reflected in the publication of special volumes and articles in seismological and geological journals (e.g., Guidoboni 1989a; Stiros and Jones 1996; McGuire et al. 2000). Since 2002, a working group 'Archaeoseismology' is active within the European Seismological Commission. However, though the methodological aspects have been investigated in a number of publications (e.g., Karcz and Kafri 1978; Rapp 1986; Nikonov 1988; Santoro Bianchi 1996; Stiros 1996; Korjenkov and Mazor 1999a; Guidoboni 2000; Nur and Cline 2000; Noller 2001), this interdisciplinary branch of the seismological science has so far not had a development comparable to that of other related disciplines (e.g., historical seismology and paleoseismology). This is mainly due to: (1) the absence of continuous, systematic and combined efforts for the refinement and extension of the methodological background of this research field; (2) the necessity to involve, in most cases, a wide range of experts (archaeologists and historians specialized in specific fields, periods and areas, geologists, geophysicists, and engineers) dealing with the range of topics usually included in the archaeoseismological research; (3) the problem that what may usually be regarded as signs of an earthquake (e.g., widespread collapses, sudden abandonment of settlements, restorations) may have causes other than earthquakes or, inversely, (4) that various natural processes (e.g., landslides, floods, soil settlement) or even human activities (e.g., wars, revolutions) may have effects similar to those of earthquakes. More generally, methodological problems arise from the necessity to merge information collected with the different methods pertaining to the earth and engineering sciences and to the human-social sciences.

Being aware that these problems cannot be solved with simple remedies, or by a single paper, we believe that methodological treatises can promote the cause and improve the discussion of the complex subject matter represented by archaeoseismology. For this reason, in this paper we will discuss aspects related to (1) the displacement of archaeological remains along shear planes; (2) the use of off-fault paleoseismological information in the archaeoseismological perspective; (3) the traces of dynamic excitation on ancient buildings including secondary earthquake effects; (4) the archaeological stratigraphic evidence of destruction; (5) the use of architectural stratigraphy; (6) the quantitative *in situ* analyses; (7) the 'territorial' archaeoseismological approach, summarising the problems due to superposition of multiple earthquake effects and the contribution of historical information; (8) the quantitative characterization of an archaeoseismologically detected earthquake. Each one of these points represents the object of a specific section or sub-section. The points and their succession partly define a theoretical line of procedure.

The paper addresses the methodological aspects based on the authors' experience matured through the study of European cases. This regional perspective, however, is not considered as a limit since the archaeological, geological, seismological and historical practices are based on some methodological milestones which are the same worldwide.

The role of archaeoseismology in the investigations of past seismicity

The identification or characterization of past earthquakes defines archaeoseismology as one of the procedures suitable to enrich the knowledge of past seismicity, together with paleoseismology, historical seismology and instrumental recording of earthquakes. These disciplines are the backbone of any seismic hazard analysis.

Since archaeoseismological studies are related to the 'archaeological past', a context of chronological interest cannot be strictly defined. Indeed, the 'archaeological past' is strongly conditioned by cultural aspects and is therefore diachronous throughout the world, being closely related to the long history of civilization. In theory, archaeoseismological data may be derived from the analysis of archaeological features of ages preceding the building of settlements (e.g., the coseismic collapse of frequented caves) or from the archaeological excavation of coseismic ruins few decades after the occurrence of a recent earthquake. It is evident, however, that in case of earthquakes of modern or contemporary times, historical information often provides more reliable data on the coseismic effects than archaeological–architectural or purely archaeological investigations. Moreover, considering that the detection of seismic damage is conditioned by the presence of buildings or structures which may have been struck by the earthquake, periods of history preceding the organization of settlements in towns, or the beginning of a life-style dependent on the building of edifices are less significant in the archaeoseismological perspective. Therefore, since the historical information is sparser for the antiquity and the Middle Ages (European area) and settlements and buildings potentially recording earthquake effects already existed, the improvement of the seismological information from archaeoseismology is expected particularly for these periods.

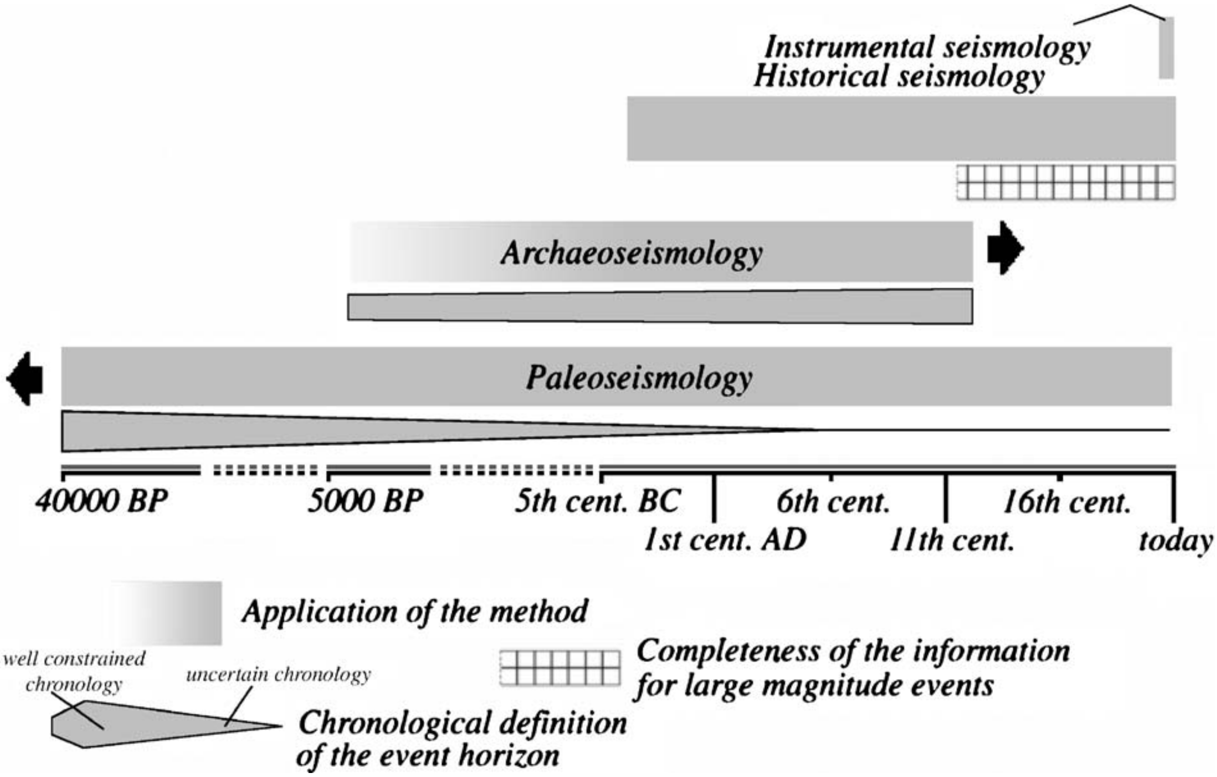


Figure 1 Chronological intervals of application of different researches on past earthquakes (Italian case). The *shade of the filling colour towards the left* in the rectangle defining archaeoseismology indicates that the application is much more limited back in time since the fifth century B.C. Indeed, the archaeoseismological practice is generally in need of building remains. Remains suitable for archaeoseismology are, in the Italian case, almost always younger than the above reported age. The *arrow on the right* of the archaeoseismological rectangle indicates that these investigations may be potentially performed in order to investigate more recent historical events, but it may be meaningless in facing more detailed historical information. In contrast, paleoseismological techniques may be performed in order to have a more detailed picture of coseismic geological effects which, usually, are not or not fully described in historical reports. The *arrow on the left* of the paleoseismological rectangle indicates that paleoseismology may be potentially performed in order to find traces of pre-Late Pleistocene events. But this may be meaningless if a list of Late Pleistocene-Holocene paleoearthquakes suitable for hazard evaluations is available. The lower chronological limit is conventionally constrained by the ages produced in commercial radiocarbon analyses (the most frequently dating technique used in paleoseismology). The ‘chronological definition’ of the event horizon has different meanings if applied to archaeoseismology or paleoseismology. In the former case, it indicates that for pre-historic/proto-historic events the chronology may be defined in intervals of centuries, while the chronological definition may be in the order of decades in case of historical events. In case of paleoseismology, the chronology is mainly based on numerical dating, often giving sigma values of centuries, and may be inadequate for historical events which necessitate a precise chronological definition. The completeness of the historical information is based on recent studies made on this issue (e.g., Stucchi and Albini 2000).

The diagram in Figure 1 illustrates the chronological application of the different analyses of past earthquakes in Italy. It may be drawn in a similar manner also for other regions. The intense gray colour of the archaeoseismological 'line' indicates that the best application is related to earthquakes which occurred between the third and second century B.C. and the Middle Ages. This is because: (1) large amounts of archaeological data have been produced and are being produced, testifying that the territory was densely inhabited and built; (2) historical sources are sparser; and (3) archaeological chronology, though usually not comparably precise as the historical chronology, is often more precise than typical numerical ages produced in paleoseismology of historical times. These are the reasons why most of the archaeoseismological literature deal with events which occurred in the early first millennium A.D. in Europe.

As for archaeoseismological practice, Table 1 illustrates the different kinds of analysis that may be applied to a potential archaeoseismic event. In order to define the procedural aspects, we divided the investigations which are necessarily conditioned by *in situ* activities from those made in laboratories, archives and libraries and which are mainly related to the historical research. The list of analyses results from an assimilation, re-proposition and update of lists already produced in previous methodological works (e.g., Karcz and Kafri 1978; Stiros 1996; Nur and Cline 2000). The different sources of information summarised in Table 1 are discussed in the next sections.

Recognizing forms potentially related to seismic effects

We divide the 'direct' evidence of seismic impact at an archaeological site due to ancient or sub-recent events into four main categories: (1) displacement along shear planes; (2) coseismic geological effects due to shaking and related effects on building structures; (3) deformation of building remains still in primary position; (4) evidence of destruction from the archaeologically defined site history.

These four points may define primary evidence of an archaeoseismic event. Further evidence derives from less conclusive archaeological information represented by (1) the archaeologically detected abandonment of a site and (2) the evidence of rebuilding and restoration (archaeologically detected and/or defined through the architectural stratigraphy of monuments still in primary position).

In the next sub-sections we will discuss the above mentioned points, and delineate potential problems and procedures of analysis. This will include the *in situ* data gathering summarised in lines 1 to 8 of Table 1. Since rarely a single form can be univocally

Table 1 Summary of the information of interest in the archaeoseismological practice

Line	*In situ* information/practice	*Extra situ* information/ practice
1	• Local geology/ geomorphology	• Archaeological documentation of past excavations
2	• Paleoseismology of shear planes displacing archaeological remains	• Relationship between archaeological and historical chronological constraints
3	• Off-fault paleoseismological information in the archaeoseismological perspective	• Historical framework of the archaeoseismic event
4	• Geotechnical information on the foundation soils	• Numerical modelling of 'fossile' strong motion seismograms
5	• 'On-building' structural analysis of the deformation	
6	• Archaeologic–stratigraphic reconstruction	
7	• Morphology and depositional features of the collapsed material	
8	• Architectural history of monuments ('Architectural stratigraphy')	
9	• Local seismic response	
10	• Dynamic behaviour of the buildings	
11	• 'Territorial' check of the archaeoseismological information	

related to an earthquake, we consider that the best archaeoseismic evidence derives from the summation of coseismic forms of different types. Each form potentially related to seismic damage should be checked in terms of alternative causes of deformation. The final attribution should result from the typical procedure of exclusion of other possible destructive events, natural or man-made. The attribution may strongly benefit from quantitative modelling of the deformation under dynamic conditions and from an analysis of the local seismic response. These approaches not only help to define the nature of the destructive event at an archaeological site but may also give quantitative seismic parameters such as the peak ground acceleration or the magnitude of the earthquake. For this reason the quantitative analyses will be the object of a specific section.

Displacement along shear planes

Many cases of displaced archaeological remains have been reported in the available literature throughout the world (e.g., Stiros 1988; Marco et al. 1997, 2003; Noller and Lightfoot 1997; Galli and Galadini 2001 and references therein). This deformation process involved buildings, fortified walls, canals and other kinds of manufacts. The case histories indicate that this type of event at an archaeological site is more frequent than one might assume. The displacement is related to (1) the activation of a fault during an earthquake or (2) of a shear plane in case of (a) differential settlement or (b) landsliding not necessarily induced by a seismic event. The general tendency to settle villages and towns in areas conditioned by recent tectonic activity, e.g., along the borders of tectonic intermontane basins (that is in areas affected by fault activity and/or slope instability), suggests that these kinds of phenomena may not be unusual. Particularly vertical offset may result from different processes as mentioned above (convergence of forms). Indeed, the displacement of foundations due to coseismic activity of a fault or due to aseismic differential settlement or sliding (along newly formed shear planes or inherited fractures and faults driving the gravitational displacement) may be completely similar (e.g., Karcz and Kafri 1978).

The correct interpretation of factors conditioning the displacement results from geological and geomorphological investigations at the archaeological site. Surveys should be made in order to define the role of slope instability in the observed displacement. The possible presence of landslide scarps, tensional cracks or other features suggesting gravitational movements should be investigated. Reconstruction of the morphology during the proposed time of the damage might be necessary, especially in places which were populated over long periods during which the morphology was anthropogenically altered. Geological information is necessary to understand whether the archaeological settlement was located along an active fault. Moreover, the estimation of the amount of offset may allow discrimination between coseismic tectonic and aseismic gravitational displacements. In case of faulting, throw is a function of fault dimension and is related to earthquake magnitude (e.g., Wells and Coppersmith 1994), while the amount of motion in sliding often largely exceeds that expected from fault activation (Galadini 2006). Moreover, translational and/or rotational sliding may produce deformations with extension and tilting in such amount that the displacement can not be attributed to tectonics.

Paleoseismological techniques should be used in order to define the history and the characteristics of the displacement along the shear plane (e.g., Noller and Lightfoot 1997; Galadini and Galli 1999). The classification of foundation soils is also fundamental to verify the possible occurrence of differential settlements due to laterally varying geotechnical characteristics. Structures founded in an area where sedimentary transitions between compressible and uncompressible sediments are present may experience differential settlement, with or without dynamic forcing/excitation. It is evident that the absence of compressible layers prevents the possibility that the displacement was conditioned by differential vertical movements. This kind of information is generally obtained by means of boreholes reaching depths of several tens of meters. Moreover, the geometry of the shear planes should be defined at depth. A shear plane may have a curvilinear shape in section or may detach in correspondence of a compressible layer in case of landsliding or differential settlement, respectively. This geometry is not typical of faults. Information on the shape of the shear plane is usually obtained by means of geophysical methods (e.g., Dolan and Pratt 1997; Demanet et al. 2001; Improta et al. 2003).

Through these analyses, the impact of different natural potential causes of displacement can be evaluated. The final hypothesis about the coseismic origin derives from the exclusion of other natural events (e.g., Nikonov 1988; Stiros 1996). Moreover, in case of fault activity, the exclusion of fault creep as the cause of displacement can result from the observation of widespread building destruction contemporaneous to the displacement (i.e., with additional archaeological information, see below) or from paleoseismological information on the fault behaviour.

Deformation/destruction of buildings due to shaking-related geological effects (off-fault paleoseismology)

The main coseismic geological effects which may damage buildings are liquefaction, lateral spreading, and landsliding. Liquefaction, with or without lateral spreading, may occur many kilometres away from an epicentral area (Galli 2000), and may cause foundation displacement and building collapse (Seed 1967). The identification of liquefaction features, like soft-sediment deformation, sand dykes, remains of sand volcanoes (e.g., Obermeier 1996), is generally a matter of the so called ‘off-fault paleoseismology’. In such cases, paleoseismological excavations focus on sedimentary structures suggesting the destructuration of sands resulting from the dynamically induced increase of pore pressure. Liquefaction phenomena caused by seismic shaking are often widespread. Identification of liquefaction effects is a strong argument for coseismic nature of observed damage.

Archaeological excavations often uncover remains involved in landslide deposits. In such cases wall remains can be mixed with blocks or debris of the landslide body or buried by the landslide accumulation. Even if this destruction at an archaeological site can be attributed to landsliding, other pieces of evidence (e.g., synchronous seismic damage elsewhere) are necessary to argue for a coseismic effect. Differently from liquefaction, landsliding cannot be univocally correlated with the occurrence of an earthquake, although landslides are often triggered by earthquakes (e.g., Keefer 1984; Jibson 1996).

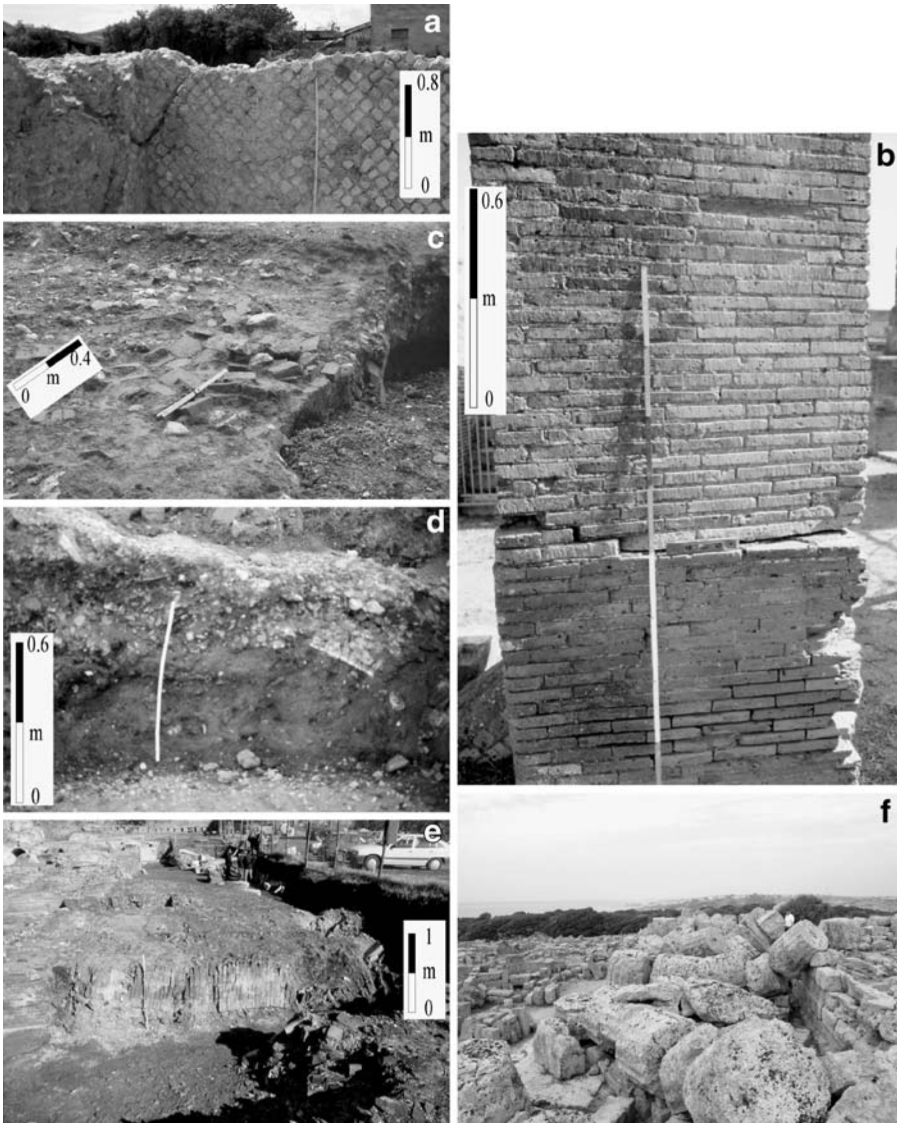
Deformation of building remains still in primary position

Only part of the monumental heritage has been uncovered by modern or contemporary archaeological excavations. In many cases (e.g., the Colosseum in Rome or the Parthenon in Greece), the emergence of monuments has persisted throughout many centuries. In these cases, the monuments have been affected by changes of the original use and form (e.g., restorations, superposition of more recent buildings, architectural modifications to permit a different use) due to various reasons sometimes difficult to define. But certainly a monument persistent throughout the centuries represents a structure potentially recording the effects of long-term seismicity, once the researcher is able to decrypt traces of earthquake impact below the heavy mantle of restorations and architectural modifications. A good example of this statement is represented by the Colosseum in Rome, whose primary function as arena for games ended in the sixth century (Rea 1999). Traces of earthquake damage due to events of the Late Antiquity, of the Middle Ages and also of the eighteenth century can be detected (Rea 1999).

Apart from the monumental heritage, modern archaeological excavations may uncover significantly large portions of structures still standing in their primary position. The traces of seismic shaking may have been preserved on the walls after their burial which occurred during the past centuries. Uncovering these structures may therefore permit investigation and eventual interpretation of these traces of deformation.

Generally speaking, ancient structures can show deformations related to seismic shaking similar to those observed on masonry buildings due to modern earthquakes. Typical earthquake effects on manufacts (e.g., Stiros 1996; Korjenkov and Mazor 1999a, b; Nur and Cline 2000, for the archaeological features; e.g., Doglioni et al. 1994, for churches of various ages) are: (1) cross fissuring in the vertical plane (generally developing from the corners of windows or doors) due to the action of shear forces; (2) corner expulsion due to the orthogonal motion of walls (Figure 2a); (3) horizontal and independent motion, lateral and rotational, of single blocks within a wall (generally well visible in walls made of similarly shaped blocks, with rectangular section); (4) height reduction due to vertical crashing; (5) rupture or motion of the arch piers and internal collapse of the keystones; (6) wall tilting and distortion; (7) rotation of pillars or elements of pillars and drums of columns around vertical axes (Figure 2b). However, some of these deformations usually observed after damaging earthquakes may also originate without dynamic excitation (Karcz et al. 1977) and finding one piece of evidence only (or at a

Figure 2 (a) Corner expulsion detected on a typical Roman wall (cement and covering of *cubilia*), Amphitheatre of *Marruvium*, San Benedetto dei Marsi, central Italy; (b) rotation around the vertical axis affecting a pillar (cement and covering of bricks), Roman Ostia, central Italy; (c) reworking of collapsed material for subsequent use suggested by the exclusive presence of tiles in horizontal attitude, Avezzano, central Italy; (d) thick layer of abandonment and deterioration made of mixed small-sized (sandy) materials of various origin (also burnt wooden fragments) underlying chaotically disposed coarser fragments of walls, theatre of *Suessa*, Sessa Aurunca, southern Italy; (e) wall still maintaining its internal original organization toppled over a few-ten-centimeter-thick layer of abandonment, theatre of *Cales*, Calvi Risorta, southern Italy; (f) columns collapsed in the same direction, Selinunte, Sicily, Italy. Photographs (d) and (e) are from Galadini and Galli (2004).



single edifice only) cannot be considered conclusive (Stiros 1996; Mazor and Korjenkov 2001). This aspect is by no means trivial if one considers the convergence of forms deriving from different natural events potentially responsible for damage.

This is the case of the deformation mentioned at points 1, 3 and 6. Indeed shear forces may be induced by differential settlements or aseismic gravitational sliding (point 1). Motion of single blocks within a wall may be induced by root penetration (point 3). The distortion of walls may be induced by landsliding, soil creeping or to the poor characteristics of the building (point 6; Karcz and Kafri 1978). Moreover, in case of archeological remains, the height reduction (point 4) may also originate from the burial or the load due to more recent buildings superimposed over the older ones or due to natural deposition of sediments. However, apart from the ambiguous interpretation of the deformation, the identification of different types of deformations, or the repetition of a certain deformation on numerous edifices of a settlement can be considered as consistent with the occurrence of an earthquake, once other possible natural causes have been excluded, e.g., through the gathered geomorphological and geotechnical information (e.g., Ward-Perkins 1989; Stiros 1996).

Evidence of destruction from the archaeologically defined site history

Modern archaeological excavations performed following the stratigraphic criteria define precise and detailed successions of events, which conditioned the history of a site. Usually, the succession of events is defined within a chronological framework obtained by means of the age of the uncovered artifacts or, less frequently, by means of physical dating (generally 14C, TTL or dendrochronological methods). The chronological framework may be more or less detailed, depending on the quality (in terms of 'dating potential') and quantity of the found materials. This aspect is topical in archaeoseismology, since one of the main goals of these studies is constraining the earthquake date. For this reason it will be discussed in a specific sub-section.

When dealing with buildings, the identified events are often represented by the architectural modifications, the periods of frequentation (with definition of the typology of use), the phases of abandonment, the collapse of the structure or parts of it. This information is arranged in a vertical stratigraphic succession made of superimposed tamped earth floors, superimposed walls, alternating layers of reworked material denouncing abandonment of the structure, ruined blocks or material proving the collapse, etc. These data are important in the archaeoseismological investigation, provided that the different 'archaeological' events can be related to the effects of earthquakes. If the archaeological practice uncovers deformed walls still in primary position as described in the previous section, a link between the occurrence of an earthquake and the evidence of 'crisis' (abandonment, collapse, restorations or architectural modifications of the original structure) may be hypothesised. However, not all archaeological excavations uncover portions of walls bearing such evidence. In many cases walls in primary position are cut by subsequent layers and only a few tens-of-centimetres high ancient walls are available, thus hindering the analysis of deformations. In such cases, the analysis of collapsed materials becomes topical, though rarely conclusive if not corroborated by other pieces of evidence (Guidoboni and Santoro Bianchi 1995).

The analysis of the 'collapse layers'

Building collapses may be sudden, progressive or both. Materials suddenly collapsed which experienced subsequent reworking (e.g., for the recovery of precious furnishings or for subsequent land use, Figure 2c) may appear similar to that derived from the progressive collapse (Ward-Perkins 1989). The slow deterioration is generally demonstrated by the accumulation of wall, vault and ceiling fragments with different grain size, without internal organization, over one or more layers of reworked material or debris denouncing the abandonment of the structure (Figure 2d). The deterioration of walls results in accumulations having maximum thickness close to the wall feeding the material. The thickness decreases in a short distance from the wall. Generally, ancientness, abandonment and lack of maintenance are the main reasons for the deposition of the deterioration layers.

The sudden collapse of large portions of walls may occur together with the progressive deposition of fragments. This generally happens due to the deterioration of parts of the structure having a bearing function. The result is a stratigraphic succession made of (from bottom): (1) a tamped earth floor, (2) a layer or more layers of abandonment (reworked material and accumulation of debris), (3) a deterioration layer with various grain size made of abundant tiles or materials from the roof (abundance decreasing upward) mixed with and underlying chaotically disposed fragments of walls and vaults but generally not exceeding few tens of dm^3, (4) large portions of toppled walls and collapsed vaults (in case of vaulted buildings) which still maintain their internal organization, (5) as point 3, but tiles or material deriving from the ceiling are absent or almost lacking.

Since this kind of stratigraphy indicates a deterioration of a structure, external events (i.e., natural catastrophes), though possible, are not necessary to explain the archaeological data. Therefore we consider that, in such cases, no conclusive archaeological evidence of an earthquake is available.

Unfortunately, abandonment and lack of maintenance is a *leitmotif* of the Late Antiquity (third to sixth century A.D.) in the Roman Empire. This means that earthquake effects of this period are, in most cases and for a large part of Europe, mixed with the effects of the abandonments. Extrapolating the evidence of the former from a type of stratigraphy such as that described above is definitely problematic and only possible if additional evidence is available. Moreover, abandoned structures are also highly vulnerable. This means that they may suffer damage also in case of weak dynamic excitation. Consequently, even in cases of correct attribution of some collapses to earthquake effects, the earthquake size may be overestimated. Hence, archaeoseismological investigations related to earthquakes which occurred during the Late Antiquity in most parts of Europe are definitely more problematic than investigations related to preceding periods.

In contrast, the sudden collapse of a structure still maintained and functioning is indicated by large portions of toppled walls (maintaining the original internal organization; Figure 2e), collapsed columns (sometimes with drums having a ‘domino’ attitude; Figure 2f), large patches of tiles (often buried by the toppled walls) or huge fragments of the vaults over the tamped earth floor. Particularly the collapse of numerous columns in a preferred direction is considered as reliable evidence of seismic destruction (e.g., Karcz and Kafri 1978; Stiros 1996; Guidoboni et al. 2002; Bottari 2003). Sometimes, wide traces of burning can be found, e.g., remains of burnt wood planks, grey films of burnt material over the tiles, etc. Materials showing the use of the building at the moment of the destruction are preserved below the collapsed walls (coins, large pottery shards, remains of furnishings, jewels) and the layer denouncing the abandonment is lacking below the traces of destruction. The presence of these materials indicate that the inhabitants had no time to take them before the destruction. Skeletons of killed people or animals have been rarely uncovered (e.g., Sakellarakis and Sapouna-Sakellaraki 1981; Soren and Leonard 1989; Stiros and Dakoronia 1989; Kilian 1996; Nur and Ron 1996).

Layers of abandonment can be found over the collapsed buildings (but their interpretation is problematic, see next sub-section). Otherwise, a new occupation is demonstrated by the presence of a superimposed tamped earth floor and a complete architectural re-organization of the area which experienced destruction or pervasive restorations.

Once the occurrence of sudden destruction has been ascertained, the cause has to be defined. The sudden collapse of a structure still in use may have been induced by man, e.g., due to wars or local instabilities. Such a possibility has to be checked on the basis of historical information. In European countries it is quite improbable, however, that the reading of historical sources of the Antiquity can cast light on the occurrence of local struggles. In contrast, our historical knowledge allows an understanding of whether the destructive event occurred in periods characterised by political instability. For example, widespread destruction of inhabited buildings in the Sulmona Plain (central Italy) during the second century A.D. (a period of strong political stability in this part of the Roman Empire) cannot be attributed to wars or local struggles (Galadini and Galli 2001).

Once the natural origin of the destruction has been hypothesized based on the collected data, the type of natural catastrophe should be hypothesized by merging the archaeological data with other *in situ* information. Supplementary information, mainly paleoseismological or from quantitative approaches (see below) may help in accepting or refusing the archaeoseismic hypothesis.

Abandonment of sites

The role of the site abandonment as a potential indicator of the occurrence of natural destruction is not unequivocal (e.g., Santoro Bianchi 1996). Indeed, the tendency to persistent human occupation/habitation of a site, especially for social–strategic reasons independent from the occurrence of natural destructive events can be derived from archaeological data and from site histories (e.g., Ambraseys 1971, 2005; Ward-Perkins 1989). This evidence can be seen by considering both the time interval following a catastrophe and the longer historical period. In the case of Egna, in the Adige Valley (northern Italy), the destruction and vertical displacement of the foundations which occurred at about the half of the third century A.D. was followed by frequentation, modern land-use and recent building, exactly across the active shear plane (Galadini and Galli 1999). On the other hand, the consideration of natural catastrophes as strong constraints of the civilization history has been made (e.g., La Rosa 1995; Driessen and Macdonald 1997 for the Minoan Crete; Stiros and Dakoronia 1989 for the overall problem).

However, the complexity of the relationship between environmental effects and responses at the scale of a settlement or of a civilization prevents the use of abandonment as a single indicator of environmental solicitations, especially if other pieces of evidence are not available.

Rebuilding, restoration

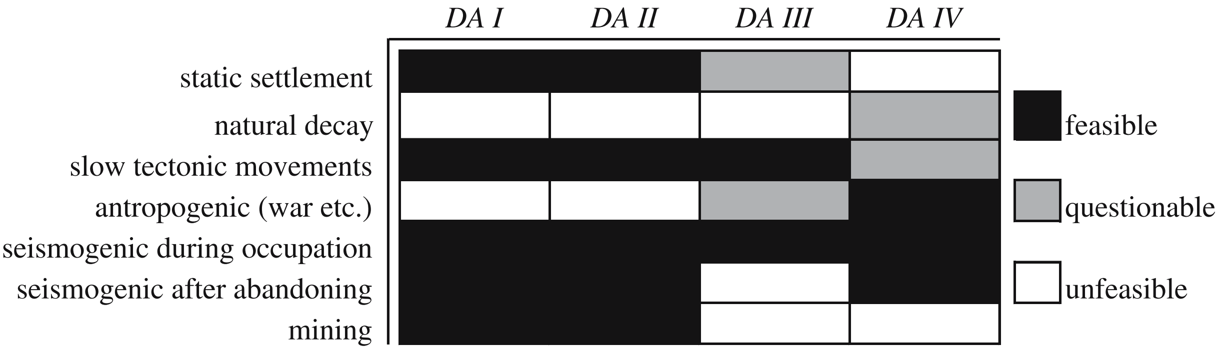
Archaeological reconstructions of the site history, may provide evidence for structural modifications, reconstructions or restorations induced by the earthquake damage (e.g., the Byzantine houses of Pergamon investigated by Rheidt 1996). While the procedure to chronologically constrain these events is the same as for the destruction or abandonment layers (see the following sub-sections) and based on the archaeological stratigraphy (plus a chronological input which may derive from the architectural characteristics of the new structures), their correlation with seismic effects is not unequivocal. For the ancient *Saepinum* in southern Italy, a town definitely affected by earthquake damage at about the half of the fourth century A.D. (Galadini and Galli 2004 and references therein), the extent of restorations in that period probably also had an 'evergetic' origin beyond the necessity of earthquake repairs (Gaggiotti 1991). Therefore, the relationship between repairs, structural modifications or complete rebuilding and the earthquake effect has to be proven by merging different pieces of evidence (e.g., Caputo and Helly 2000, for the Larissa, Thessaly – Greece, theatre in the third to first century B.C.).

In some cases, however, the relationship between earthquake and repair seems more evident, i.e. when the adoption of 'anti-seismic' solutions in the restoration or the building of reinforcing structures, such as buttresses or significant increase of foundation size can be detected (e.g., Hodges 1995; Stiros 1995; Korjenkov and Mazor 1999a, b, Hinzen and Schütte 2003).

The age of the event

The chronology of an archaeoseismic event is a fundamental aspect. It is not only important in order to characterise the specific earthquake, but also for the correlation of presumed earthquake effects at different archeological sites or the attribution of archaeoseismological evidence to a chronologically well defined historical event (e.g., Stiros 1996). Empirical earthquake frequency relations, the basis of probabilistic seismic hazard analysis, also depend on earthquake chronology. A chronologically constrained archaeological stratigraphy can define the occurrence of a certain event within chronological intervals. When the chronological information is particularly abundant, the occurrence of an archaeologically detected event can be defined within a few decades. Rarely the archaeological chronology can be more precise. Once the archaeological analysis is completed, reliable historical accounts may help to better constrain the date of the event (e.g., Ellenblum et al. 1998; Marco et al. 2003), although the correlation between historical and archaeological data may be problematic (see below).

Defining a date for the destruction is probably the most complicated issue (see also Bottari 2003, on this problem). The age of an event horizon is defined on the basis of the dating remains underlying the collapsed materials and setting a *terminus ante quem*. The best dating remains are generally pottery shards and coins. Since the materials are related to human activities, they may have been characterised by a prolonged use. For this reason, the most reliable lower chronological limit of the event horizon derives from the youngest remains of a significant amount of materials buried by the collapsed structure. In usual stratigraphic frameworks, the upper chronological limit (*terminus post quem*) should be defined by the materials contained in the unit subsequent to the destruction. However, in archaeology these units may contain older remains, preceding the destruction. This is due to the already mentioned persistent use of furnishings and coins (coins, for example, may be used for many decades after the coinage; e.g., Cesano 1913; Morrisson 1980; Reece 1984; Molinari 1994). For this reason the upper chronological limit should represent a sort of mean derived from the age of the materials contained in the unit subsequent the destruction, but only obtained from those remains younger than – or similarly aged to – the youngest piece buried by the collapse. However, archaeological excavations do not always uncover dating pottery or coins; sometimes the gathered remains are too sparse to define a narrow chronological interval. In most cases, undatable materials are uncovered and the information is not precise; e.g., an event occurred after the building of an edifice whose age is defined on the basis of the architectural characteristics and before the building of another edifice sealing the



	DA I	*DA II*	*DA III*	*DA IV*
static settlement	■	■	▨	□
natural decay	□	□	□	▨
slow tectonic movements	■	■	■	▨
antropogenic (war etc.)	□	□	▨	■
seismogenic during occupation	■	■	■	■
seismogenic after abandoning	■	■	□	■
mining	■	■	□	□

■ feasible

▨ questionable

□ unfeasible

Figure 3 Example of a feasibility matrix as a summary of the results of an archaeoseismological investigation. The columns *DA I* to *DA IV* represent four distinctive damages and the seven rows give possible causes. Rows and columns can be extended in larger surveys to cover the whole scenario and the result can be quantified as outlined in the text.

ruins, whose age is also architecturally defined. These chronological limits may constrain a time span of centuries. Similar problems arise with physically datable materials (e.g., by using the 14C method). Especially after a destructive earthquake older material might get placed on top of the destruction layer during repair works and new constructions.

In these archaeological sub-sections we presented fundamental characteristics of archaeological findings possibly related to seismic damage. It is evident that (1) the sedimentary features of a unit marking the collapse, and (2) a reliable stratigraphic reconstruction (including the correct attribution of the dating materials to the phase of collapse or to the units subsequent to the destruction) are topical aspects (also suggested by Guidoboni and Santoro Bianchi 1995). Particularly point 1 is not exactly the object of the archaeological investigation and the archaeological reports rarely describe the sedimentary characteristics of the collapse units in enough detail. Nor are the stratigraphic descriptions formulated in a perspective conducive to understanding the origin of catastrophic events. As observed by Guidoboni (1989b), archeologists sometimes underestimate the amount of information which can be derived from an archaeological excavation. This ‘avoided’ information cannot be recovered, considering the ‘destructive’ character of the archaeological analysis. This suggests that people involved in archaeoseismology should participate in the archaeological excavations, since the origin of the destructive events which struck an ancient building or a village are fundamental parts of the site history and of the seismic history of a region. This may be the only way to optimize the archaeological data. The practice of reading and interpreting archaeological reports in the archaeoseismological perspective years or decades after excavations (line 1 column 2 of Table 1) can only be considered a makeshift solution in the face of total absence of information directly collected in the field.

Based on the previous sections and as summarized in Table 1, a complete archaeoseismological survey must integrate aspects from different scientific disciplines. Conclusions are complicated by multifaceted observations, ranging from rotated column drums, shifted or tumbled parts of walls to the abandonment of sites. In practice it will not be possible to present proof that each of the observations must necessarily have a seismogenic cause. In order to structure the interpretation of results, Hinzen (2005a, b) proposed a feasibility matrix in a case study of the excavation of a Roman villa near Kerkrade (the Netherlands). Observations form the columns of the matrix, while possible causes form the rows. The matrix is then filled with a simple three-degree rating (feasible, questionable, and unfeasible) of the proposed cause as an explanation of the specific observation Figure 3). In the above-mentioned example the matrix was used for a small study; however, in principle it may also be extended to large surveys. The matrix concept helps structure the necessary discussion and allows a more gradual presentation of the results than the often requested ‘decision’ about whether the uncovered findings were caused by an earthquake. This concept also illustrates which questions are still open or might require further investigation. Therefore, for a proposed earthquake a certain level of probability of occurrence can be quantified: the fields in the matrix which show a dynamic cause as feasible are quantified by '1', those showing non seismic causes as feasible as '−1', and the questional cases as '0'. Half of the sum of the matrix values divided by the number of matrix fields plus 0.5 gives a number between 0 and 1 ranging from completely unfeasible to very probable coseismic effects, respectively. This number, which is 0.64 for the example in Figure 3, can directly be used as weighting factor for the branches in a logic tree approach of a probabilistic seismic hazard analysis.

Architectural stratigraphy

Architectural stratigraphy is the analysis of monuments from the architectural point of view, in order to reconstruct the building history. This field of study generally identifies restorations, modifications, spoliation and puts them in a stratigraphic order, possibly with chronological constraints.

Evidently, this type of analysis is applied to identify traces of past earthquakes or to clarify the amount of damage due to historical events. In this light, some works have used the architectural history of the buildings (usually churches) in order to improve the knowledge of the effects of earthquakes sparsely known (e.g., ENEL 1986; Galadini et al. 2001; Stiros et al. 2006). In case of the 1117 earthquake in northern Italy, an evident clustering of interventions to romanesque churches has been identified in the zones which, based on the sparse historical information, should represent the most damaged areas (ENEL 1986; Guidoboni et al. 2000; Galadini et al. 2001).

The main problem of architectural stratigraphy is the definition of the reasons for the architectural interventions (Guidoboni et al. 2000). For example, in case of the 1117 earthquake, political reasons may have conditioned the modifications in the same period of time, in order to create a new architectural style in northern Italy, different from that of the rest of Europe (Suitner 1991). In this case, we have a superposition of effects of processes (impossible to discriminate) affecting the architectural modifications in a time span of a few decades.

Quantitative *in situ* analysis

'Quantitative analysis' refers to investigations of the characteristics of the seismic source, ground motion, and of the building response in order to test the archaeoseismic hypothesis. It can be done provided that reliable archaeological data and sufficient geophysical input parameters are available. These aspects are summarised in lines 9 and 10 of Table 1.

Modelling of strong ground motion can be a fruitful procedure especially if the archaeological information is derived from various excavations or sites within a single ancient town. In such cases, a distribution of the presumably coseismic damage may be detected. If a relationship exists between the damage distribution and the geological characteristics of the substratum (in terms of potential amplification of the ground motion and of secondary effects), the coseismic hypothesis is corroborated.

The first step in *in situ* analysis is a 3D reconstruction of the local geology (e.g., Funiciello et al. 1995 for the Colosseum in Rome). Geotechnical parameters are defined for the different stratigraphic units in the foundation area of a settlement. Subsequently the fundamental resonance frequencies of the different rock units are defined, e.g., by means of instrumental recordings of ambient vibrations and model calculations (e.g., Hinzen and Schütte 2003; Fäh et al. 2006, this volume). When a model for the distribution of the engineering geophysical parameters (shear wave velocity, density, damping) for the substratum is defined, the frequency and possibly amplitude dependent ground amplification at the site can be calculated. Following this procedure, Fäh et al. observed that the collapsed parts of the ancient town of Augusta Raurica in Switzerland correlate with areas where the amplification of the ground motion occurs in the frequency band of the main building eigenfrequencies. The destruction was limited to the parts of the town built on soils prone to amplification of the ground motion and this evidently corroborates the archaeoseismic hypothesis. Through a comparable procedure, Hinzen and Schütte (2003) showed that secondary effects due to lateral spreading is a likely damage scenario for the probable collapse of the *Praetorium* in Cologne.

Engineering seismological models may describe the coseismic behaviour of a structure, once the architectural features of the ancient building are defined (e.g., Croci et al. 1995; Papastamatiou and Psycharis 1996). This procedure reveals the characteristics of the seismic motion necessary for the collapse or significant damage of the building. Generally, the first step of an analysis is the evaluation of the seismic input. A seismogenic source is defined on the basis of available seismotectonic information. The energetic parameters may be empirically and physically related to source dimensions (e.g., Kanamori and Anderson 1975; Wells and Coppersmith 1994).

Based on the seismotectonic model, strong ground motion seismograms are simulated and the seismic response at the investigated site is estimated from models based on the available geological/geotechnical information. Finally, based on the seismic input, the dynamic behaviour of a building is studied, generally with finite element models.

This procedure has been recently adopted for fostering the archaeoseismic hypothesis of the origin of damage observed along the Late Antique city walls of the locality of *Tolbiacum*, the present city of Zülpich (Germany; Hinzen 2005a, b). The author hypothesized a possible coseismic damage due to the activation of one of the known normal faults in the Lower Rhine Embayment. As for the investigated manufact, the frequency band of the building resonance was identified and compared with the characteristics of the ground motion obtained from the simulated earthquakes. The author discovered that some of the simulated earthquakes were strong enough to trigger the ground motion necessary to damage the city walls. In this way further evidence in favour of the coseismic origin of the damage was produced.

‘Territorial’ archaeoseismology

This term has been used in the methodological and research works by Guidoboni (2000) and Guidoboni et al. (2000) to indicate the correlation of archaeoseismic effects throughout a region in order to define the extension of the mesoseismal area. The extension is crucial because the main difference between earthquake damage and damage related to other natural causes is the distribution of the effects. Effects of landslides, collapse of caves, and floods generally affect areas smaller than those damaged by strong earthquakes. Only volcanic eruptions may be responsible for extended effects throughout a large region. However, the origin of volcanic catastrophes can be easily defined through the burial of the archaeological remains by thick volcanic deposits (e.g., Sigurdsson et al. 1982; Livadie 1999; Mastrolorenzo et al. 2002 for three Vesuvius eruptions in southern Italy). Moreover, only periods of war may cause sudden damage extended throughout a region. Extended human-induced destruction in periods of political stability, however, is improbable.

For these reasons, the identification of buildings which have been simultaneously damaged in several locations in periods of political stability (line 11 of Table 1) or reviewing published or unpublished archaeological material on this aspect (line 1, column 2 of Table 1) may be a logical method to test the archaeoseismic hypothesis (e.g., Galadini and Galli 2004; Guidoboni et al. 2000; Nur and Cline 2000; Jones and Stiros 2000; Stiros 2001).

However, one limitation of this procedure is the reliability of the archaeological chronology (Ward-Perkins 1989). In the sub-section dedicated to the chronological definition, we stated that a certain event can be defined sometimes only with a very large chronological uncertainty. A chronological resolution within a time span of a few decades (which is definitely a good archaeo-chronological result), may lead to the correlation of different seismic events throughout a region, especially in cases of areas affected with frequent damaging earthquakes (Stiros and Dakoronia 1989; Guidoboni 2000). For example, the uncertainty associated with archaeoseismic damage attributed to the 346 A.D. earthquake in southern Italy is caused by another earthquake in 375 A.D. nearby (Galadini and Galli 2004). Furthermore, in the Calabria region (southernmost portion of peninsular Italy), archaeoseismic evidence at different places has been attributed in different works (Guidoboni et al. 2000; Galli and Bosi 2002) to the same earthquake (historically known through an epigraph), which occurred in 374 A.D. This implied that the earthquake was attributed to different seismogenic sources in the mentioned works, based on the archaeoseismic evidence. A critical conclusion is that if the coseismic interpretation of the archaeological features is reliable in both works, the archaeoseismic observations are associated with more than one earthquake.

The chronological uncertainty limits the ‘territorial’ approach as a tool for defining the archaeoseismic origin of certain damage. If the effects of different earthquakes can not be unequivocally ascertained, the synchroneity of the seismic damage throughout a territory due to a single event cannot be invoked as a reliable tool to define the occurrence of an archaeoseimic event (see also Ambraseys 2005, on this aspect).

Moreover, if the archaeological information cannot be verified in the field (e.g., excavations of decades ago, with limited availability of published data) in order to corroborate the coseismic cause, the large time interval which defines the chronology of the destruction at the different sites cannot exclude the possibility that events with different origin (e.g., due to seismic shaking, ancientness, landsliding, etc.) are being correlated. In the next sections we will see how the chronological problem affects the definition of the characteristics of an archaeoseismic event.

The historical information

In many cases archaeoseismological investigations are related to earthquakes already included in seismic catalogues and known through historical information (see for example the archaeoseismological works dedicated to the 365 A.D. earthquake in the Mediterranean area; Stiros 2001 and references therein). Generally, in case of earthquakes of the Antiquity, the information is very sparse, sometimes limited to a single source (e.g., Guidoboni 1989a). Even in later periods up to the late Middle Ages original written sources might also be very sparse. It is evident that in such cases archaeoseismological data may give additional information about a poorly known event.

However, merging historical and archaeological data always implies the comparison of information with different chronological resolution (line 2, column 2 of Table 1; e.g., Santoro Bianchi 1996; Stiros 1996; Guidoboni 2000; Ambraseys 2005). Also in case of poor information, an historical event is usually defined in terms of the year of occurrence or of a time span of few years compared to decades in archaeology. This implies that relating observed destruction to an historical event, especially in regions of frequent destructive earthquakes, cannot be considered reliable (Guidoboni 2000; Guidoboni et al. 2000). Since the list of historical earthquakes cannot be complete, archaeoseismic evidence due to different events may be attributed only to the known historical earthquake. This procedure leads to the enlargement of the perceived destruction and consequently to an overestimation of the event size (Guidoboni 2000; Guidoboni et al. 2000; Ambraseys 2005).

In addition to the chronological resolution of archaeoseismology and historical seismology, it is also necessary to define the historical framework of the event (see for example the importance of this aspect in the case of the 365 A.D. earthquake; Traina 1989; Stiros 2001 and references therein). The main purpose of this operation (line 3 column 2 in Table 1) is the political, social and economic characterization of the period (e.g., Guidoboni 1996) in order to understand the degree of maintenance of the buildings or their ‘quality’ in response to the economic situation (e.g., Molin and Guidoboni 1989), or to exclude that human factors (wars, decadence and abandonment) conditioned the destruction. For example, interference between coseismic damage and war effects can be found in the archaeological dataset of the eastern Mediterranean area for the Late Bronze Age (Nur and Cline 2000). Furthermore, widespread evidence of architectural modifications and evidence of destruction at about the half of the third century A.D. in northern Italy has been traditionally attributed to the Aleman invasions (e.g., Buchi 2000). The definition of the areal extent of an earthquake which occurred in the Adige Valley in that period is, therefore, definitely problematic (Galadini and Galli 1999).

Reconstructing the characteristics of an archaeoseismic event

Important goals of the investigations on past earthquakes are the evaluation of epicenter locations, amount and direction of slip, and magnitudes. On-fault paleoseismology and historical seismology obtain these results in different ways: the former by relating high-magnitude events (generally responsible for surface faulting) to specific fault-sources and by estimating the magnitude from the observed offset per event, from the length of the surficial ruptures, or from the extension of the zone with secondary effects (e.g., liquefaction). Historical seismology analyzes the damage distribution and assigns intensities that characterize the different localities. An intensity value may be attributed to the archaeoseismic damage observed at a certain locality (e.g., Hinzen 2005a, b in the already mentioned case of Tolbiacum in Germany). Once the intensity has been defined, the magnitude may be derived by using one of the available empirical relations (e.g., Ambraseys 1985) linking the two parameters; however, a magnitude based on only one or very few intensity observations can be biased. If the damage is defined for more localities, the definition of the magnitude may be more precise and based on equations taking into account the extension of the damaged area (e.g., Gasperini and Ferrari 1997). Moreover, in such cases, magnitudes and epicenters might be inverted with procedures such as those described by Bakun and Wentworth (1997, 1999) and adopted by Hinzen and Oemisch (2001) for earthquakes in the Northern Rhine area or those described by Sirovich and Pettenati (2001) and Sirovich et al. (2002). In conclusion, archaeoseismological data in their final form may be close to the data expressed by historical seismology, i.e., localities bearing evidence of a certain coseismic damage may be plotted on a map and used to define seismic parameters.

The reliability of the areal distribution of archaeoseismic damage is strongly conditioned by the chronological problems discussed in the previous section. Damage at localities struck by different earthquakes which occurred in a time span of some decades may be considered as the effect of a single event. This might lead to an overestimation of the maximum observed magnitude of earthquakes which struck the region in the period under investigation and has an obviously misleading effect in the search for the epicenter. Also the effects of aftershocks, which always follow strong earthquakes, can add to the degree of damage and lead to an overestimation of the magnitude of the main event. The case of the 346 A.D. earthquake in southern Italy (Galadini and Galli 2004) may be used as an example of this kind of problem. The archaeologists have attributed presumed coseismic damage detected at numerous sites in central and southern Italy to this event. The result is a perceived damage distribution, which cannot be physically attributed to a single earthquake. It may result from a highly destructive seismic sequence, similar to the one which occurred in 1456 A.D. in the same territory and attributable to the progressive activation of three (or four) seismogenic sources in a time span of a few days. However, considering the scarce chronological definition of the archaeoseismic evidence at some sites, this hypothesis cannot be considered as conclusive. For this reason, a different and as much ‘extreme’ view has been proposed, by taking into account only the available information conclusively related to the 346 A.D. event (Galadini and Galli 2004). Thus, the mentioned authors proposed two completely different pictures of the earthquake damage, showing the uncertainty related to the archaeoseismic interpretation of the 346 A.D. earthquake.

Another aspect which has strong implications for the estimation of earthquake size is the vulnerability of ancient edifices during periods of decadence or political instability. For example, the abandonment of buildings such as theatres or pagan temples was quite common in the Roman Empire during the Late Antiquity (e.g., Liebeschuetz 2001). The edifices, without maintenance, experienced rapid decadence. In some cases they even suffered from the practice of spoliation. Huge monuments were considered as quarries for the extraction of materials which were used for new buildings (e.g., the Colosseum in Rome; Rea 1999). It is evident that the vulnerability of some of these buildings during the Late Antiquity was significantly high. Therefore some archaeoseismological investigations on seismic events of the Late Antiquity may lead to systematic overestimation of the earthquake size.

Quantitative analysis of the ground motion at an archaeological site may help in estimating the energy associated with an earthquake. For example, high-level damage may result from strong amplifications of the seismic waves or secondary effects. If such effects of wave spreading and ground motion are neglected, the obvious consequence is an overestimation of the earthquake magnitude. Ground motion amplification modelling at the ancient town of Augusta Raurica has led Fäh et al. (2006; this volume) to consider the possible archaeoseismic damage as strongly conditioned by site effects. For this reason, the authors have proposed that the previously estimated magnitude (M_W 6.9; Fäh et al. 2003), based on the amount of damage at Augusta Raurica, was overestimated. Moreover, the lower magnitude, and the destructive effect suggest that the earthquake probably originated in an area not far from the investigated site. In this way, the analysis of the amplification effects at the archaeological site also produced information about the possible epicentral location of the earthquake.

In the case of Tolbiacum the modelling of the dynamic response of the damaged structure, based on a seismic input due to the activation of known

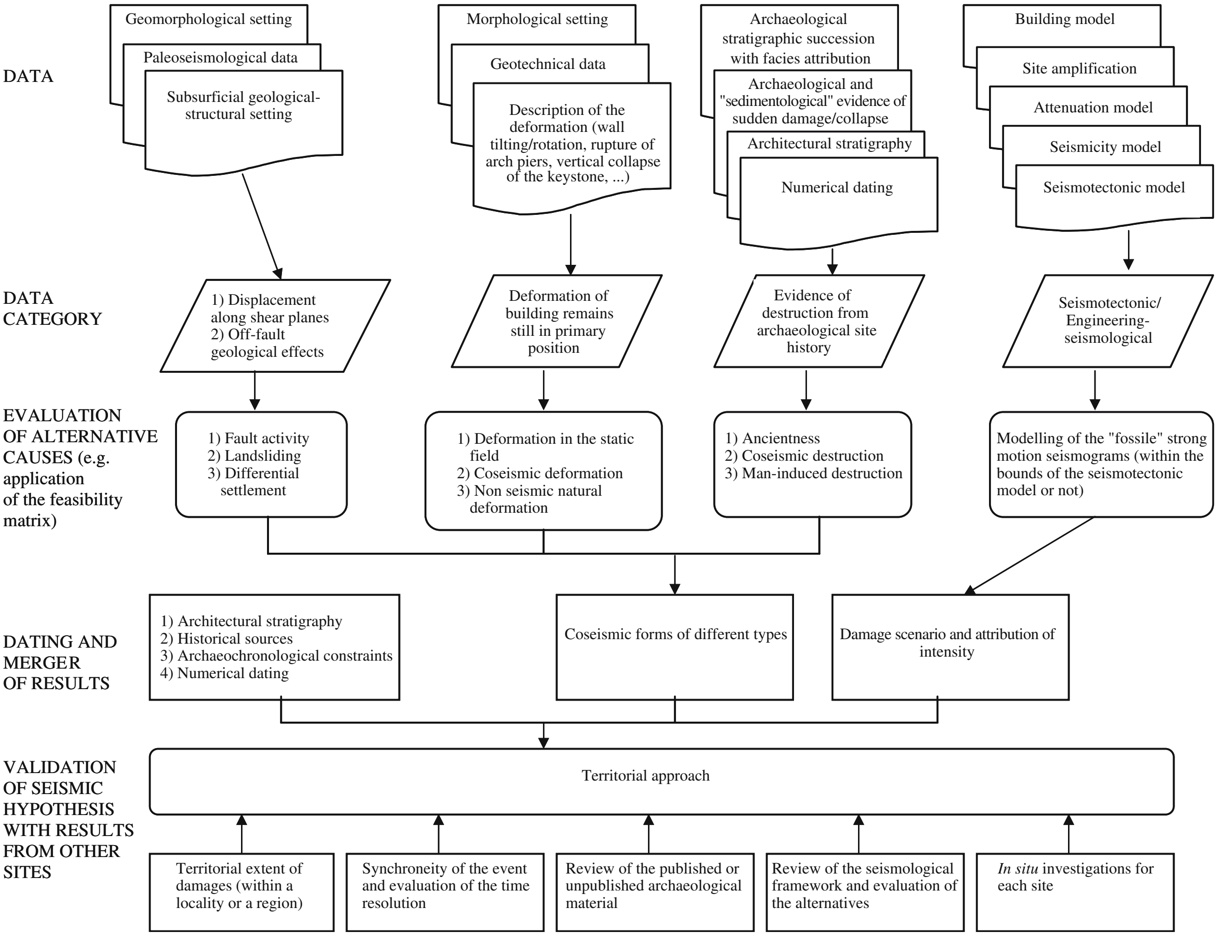


Figure 4 Schematized flow chart for archaeoseismological investigations.

seismogenic sources, has led Hinzen (2005a, b) to restrict the hypotheses about the seismogenic sources potentially responsible for the observed archaeoseismic damage. The two closest sources (known as the Stockheimer and Kirspenicher faults) may have produced the damaging earthquake. The associated magnitude is M_W 6.5.

Archaeoseismological analysis: Steps and the merger of practices

In the previous sections we have illustrated single aspects of the archaeoseismological investigation. Each data source is characterized by specific problems and caveats. However, reliable archaeoseismological analyses derive from the merger of various field and archive/laboratory practices (Table 1). Figure 4 presents a flow chart linking data sources, methods and results, based on the discussion of the previous sections. Due to the complexity of the issue, only the main aspects of the archaeoseismological research have been outlined. Since every field case is different, additions and alternative modelling might become necessary or steps can be or have to be dropped.

Concluding remarks

In this paper we discussed some aspects related to the investigation of the archaeological traces of past earthquakes. As stated in previous works, archaeoseismology needs contributions from many different pieces of information, derived from different disciplinary approaches. In contrast to previous discussions, we stress the importance of quantitative analyses in order to corroborate the archaeoseismic hypothesis. Moreover, the points discussed here indicate the centrality of the stratigraphic perspective (in agreement with Guidoboni and Santoro Bianchi 1995) and the neccessity of data collection sensitive to the archaeoseismological perspective. This implies that archaeoseismological information should be collected during an archaeological excavation in collaboration with the archaeologists.

The complicated procedure to investigate a presumed archaeoseismic event, the necessity of passing the evidence through numerous 'filters' before considering it reliable imply that only few cases of destruction recorded in the archaeological heritage can be considered as archaeoseismological evidence. Therefore even in regions with high seismicity and a long history of settlements the number of reliable archaeoseismologically detected earthquakes might be smaller than one would expect.

Both the qualitative interpretation of the origin of the presumed traces of past earthquakes and quantitative analyses need significant contributions from geological (surficial and sub-surficial) geomorphological and geophysical investigations. The merger of archaeo-stratigraphy, geological and geomorphological information implies that archaeoseismology largely results from field geoarchaeological practices, thereby classifying geoarchaeology as archaeological research, based on geological concepts and methods, sharing with archaeology part of the aims (e.g. Rapp and Hill 1998). The concept of 'aim' is central. It is evident that the aim of an archaeoseimologist is the characterization of past earthquakes, but it is also evident that a seismic destruction at an archaeological site is a particularly important event within the site history. With these goals in mind archeoseismological practice has a double function: to enrich the knowledge of past seismicity of the territory and to help reconstruction of the site history. Due to this second function, archaeoseismological information contributes to the archaeological environmental picture of a certain site, considering 'environmental archaeology' as the study of the long-term relationship between humans and the natural environment (e.g., Dincauze 2000).

We believe this perspective places archaeoseismology as an integral part of the necessary investigations at an archaeological site, rather than just a sub-branch of paleoseismology (as indicated by McCalpin, 1996) or a multidisciplinary procedure strictly related to historical seismological investigations of sub-recent seismicity.

While historic earthquakes in addition to instrumentally recorded events have always been used in both deterministic and probabilistic seismic hazard analysis, the importance of palaeoseismic information has become obvious only in the last few decades. We believe that with increasing systematic archaeoseismological investigations and wider acceptance of the methodology, the more reliable archaeoearthquakes will be considered in the procedures of hazard estimations. Within this perspective, we have to consider that archaeoseismology has a use which is potentially wider than that of paleoseismology. Indeed, buildings and other man made structures of archaeological importance might have suffered damage from smaller earthquakes than those causing significant geological effects, detectable by means of paleoseismological techniques.

The different aspects discussed in this paper and the perspective we present are the result of experience gathered over the last decade, derived from archaeological practice in the field and modelling results, and more recently from activities of the WG Archaeoseismology of the European Seismological Commission. We consider this paper as a positive step toward the definition of a standard procedure in archaeoseismology. Though the various aspects discussed here illustrate the unfortunately frequently inexact and undefined character of archaeoseismology, we are confident that the parallel practices of field investigations to uncover the archaeological traces of past earthquakes and the contemporaneous methodological elaboration will provide the necessary and increasingly more reliable information on poorly known or unknown historical seismicity of a region.

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