Archaeoseismology

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Archaeoseismology is the study of earthquakes using evidence in the archaeological record. It is one of the disciplines that belong to the broad research field of earthquake sciences, which all share a common goal, that is, to reconstruct the earthquake history within a region with the purpose of assessing the seismic hazard and mitigating the seismic risk. The archaeological evidence for earthquakes comprises chaotic destruction layers, typical damage typologies to manmade constructions, displaced manmade constructions, indications of repairs, sudden abandonment of sites, sudden cultural changes, and so on.

Historically, earthquakes were used in the first half of the twentieth century by archaeological excavators to explain what otherwise could not be explained, at archaeological sites in earthquake-prone regions, such as the Mediterranean. Noteworthy in this respect was Sir Arthur Evans, the famous excavator of the Bronze Age Minoan site of Knossos on the island of Crete (Greece) in the eastern Mediterranean Sea. He was the first to consider earthquakes as the primary destructive agent, leaving clear marker horizons in the archaeological stratigraphy. The early development of archaeoseismology was subsequently grafted on archaeological work in the Mediterranean and Middle East, strongly dependent on identifying structural damage features to monumental buildings at archaeological sites (Stiros and Jones 1996). Earthquakes quickly turned out, though, to be used too easily as a "*deus ex machina*," provoking skepticism within the community of earthquake scientists, who questioned whether cultural material data could reliably serve as earthquake indicators at all.

The primary challenge of the earthquake sciences is to better constrain the earthquake hazard which a community is faced with today and will be confronted with in the future. Knowing the earthquake hazard, a community can take the necessary measures to mitigate the earthquake risk—that is, avoiding casualties and limiting damage to housing and infrastructure. The earthquake hazard is expressed as a probability that an earthquake of a certain magnitude or greater may occur, or that a certain level of ground motion may be exceeded, in a well-defined time period. Classically, a 10 percent probability in 50 years infers that the event considered has a return period of 475 years. This practice of probabilistic seismic hazard assessment (PSHA) is primarily based on the principle of elastic rebound. Over long periods of time, tectonic stresses build up in faults to a point that the friction on the fault is exceeded and the fault is activated, suddenly releasing the stored elastic energy, which radiates from the seismic source, causing an earthquake. This characteristic succession of interseismic periods of stress build-up and sudden events of coseismic stress release is known as the earthquake cycle. Another characteristic of active fault systems is a specific correlation between the magnitude of an earthquake and its frequency of occurrence, known as the Gutenberg–Richter distribution. Earthquakes with small magnitudes are rather common, and thus have a short earthquake cycle (months to years), while earthquakes with large magnitudes are rather rare, having a long earthquake cycle (centuries to millennia). To assess future seismic hazard, a reliable estimate of the parameters controlling the Gutenberg–Richter distribution (e.g., b-value) is a prerequisite. This can only be achieved by reconstructing the earthquake history in a region in as much detail and as far back in time as possible. However, seismic-hazard practitioners are confronted with the problem that the time window of instrumentally recorded earthquakes is too short; it only spans somewhat over a century. A magnitude–frequency correlation, solely based on a century of instrumental earthquake data, shows in most cases a margin of error, which is too wide to enable a reliable seismic hazard assessment. The archive of earthquakes therefore needs to be extended back in time, calling

The Encyclopedia of Archaeological Sciences. Edited by Sandra L. López Varela.
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DOI: 10.1002/9781119188230.saseas0040

upon all possible evidence for pre-instrumental earthquakes. On the one hand, information on pre-instrumental earthquakes can be found in all types of historical—written—records (historical seismology). On the other hand, paleo-earthquakes leave their marks in the geological and/or geomorphological record (paleoseismology and earthquake geology). In this broad research field of earthquake sciences, reflecting a continuum of overlapping and complementary disciplines, archaeoseismology, focusing on cultural material data spanning the last few millennia, occupies a unique position, bridging the gap between instrumental and historical seismology on the one side, and paleoseismology and earthquake geology on the other. Depending on the time span of occupancy, possibly expanding over one or more earthquake cycles, archaeological sites can provide crucial information to seismic-hazard practitioners.

Another issue seismic-hazard practitioners are confronted with is the nature of the pre-instrumental earthquake evidence. From their perspective, it is imperative to know the physical parameters of each earthquake, brought together in an earthquake catalogue. These parameters include the date of the earthquake, its magnitude, its seismic source, its epicenter, the duration, and the ground acceleration. All these parameters can be instrumentally measured, and are thus known for most of the instrumentally recorded earthquakes. However, pre-instrumental earthquakes can only be parameterized indirectly, based on the evidence found in the historical, archaeological, and/or geological record. This indirect evidence can be split into two categories. On the one hand, there is primary evidence, directly related to coseismic surface rupturing or ground failure. On the other hand, there is secondary evidence, related to coseismic ground shaking and ground motion. The challenge is to translate this indirect earthquake evidence into (semi-) quantitative parameters that can be used in a seismic hazard assessment.

In archaeological contexts, earthquake archaeological effects (EAEs) can also be classified into primary and secondary evidence. Moreover, a third category of earthquake evidence can be distinguished in archaeological and historical contexts—that is, the postseismic, delayed-response effects of an earthquake, such as fire damage, repairs, recycling of building materials, complete or partial abandonment, and architectural and/or cultural changes.

Two types of primary or secondary EAEs can furthermore be distinguished: structural effects on manmade constructions and stratigraphical effects in the archaeological stratigraphy. While the former effects received the most attention in the development of the discipline, focusing on archaeological contexts with monumental constructions, the latter effects have attracted more interest recently, in particular when focusing on archaeological contexts dominated by rubble architecture.

The most obvious primary structural EAEs are archaeological remains that are displaced due to the coseismic surface rupturing on an active fault. These faulted relics not only enable the identification of active faults in the landscape, but also allow the determination of the type of faulting, the amount of coseismic slip related to a single earthquake, as well as the cumulative fault slip caused by multiple earthquakes during the existence of the displaced manmade construction; knowing the age of construction, a time-averaged fault-slip rate spanning centuries to millennia can be derived. In this respect, the study of faulted relics is very comparable to paleoseismological work. These fault-slip rates obtained from an archaeological context can be compared with slip rates, obtained from paleoseismological and geological contexts on the same active fault. Such comparison may reveal potential slip deficits, inferring a high seismic hazard.

Secondary structural EAEs, caused by coseismic ground shaking and ground motion, comprise typical strain structures in the building fabric. These earthquake-related damage features are most obvious on monumental buildings and constructions. Recognizing such structural damage features in rubble architecture, on the other hand, is a challenge. Coseismic ground shaking can generate a wide range of typical damage features, such as penetrative fractures in masonry walls, rotated and displaced drums in columns, dropped keystones in arches, collapsed stairways, domino-type collapsed walls and columns, and U-shaped gaps in walls. Coseismic ground motion, for example, due to liquefaction, can generate other types of damage features, such as folded and fractured pavements, and

tilted, rotated, and bent walls. All these structural EAEs are assessed semiquantitatively by using modern earthquake intensity scales, which are applied in assessing the earthquake damage caused by recent—and thus instrumentally recorded—earthquakes (e.g., the European macroseismic scale EMS-98). An additional challenge is to unambiguously distinguish damage caused by an earthquake and damage caused by other destructive agents, such as natural failure, storm, vandalism, looting, or warfare. Moreover, it is very difficult to attribute specific damage features to a single earthquake, in particular in earthquake-prone regions, where ancient buildings at archaeological sites have most probably experienced ground shaking from numerous earthquakes over their lifespan and even following final abandonment. The danger thus exists that by attributing damage features that may have been caused by a whole series of earthquakes to a single earthquake, unrealistic earthquake catastrophes emerge, which subsequently may find their way into earthquake catalogues.

The stratigraphical effects of earthquakes is materialized in archaeological destruction layers or deposits, defined as horizons showing evidence of sudden destruction caused by human and/or natural agents, commonly covering a "living surface," evidenced by, for example, in situ broken vases, buried valuable objects, and/or skeletons of victims. Earthquake-related destruction deposits further contain burned material, charcoal, collapsed architectural debris, and crushed and toppled objects. In archaeological contexts, lacking any structural EAEs, destruction layers may provide the only evidence for ancient earthquakes. Again, relating a destruction horizon to an earthquake is rarely unambiguous and remains a challenge for archaeoseismology. The principal issue with the study of destruction layers concerns the preservation and disturbance of destruction layers. Earthquake debris may have been cleared from streets and buildings and disposed of at particular dumpsites, so that no destruction layer is preserved in the archaeological stratigraphy. Valuables and/or victims may also have been recovered from the debris, while material may have been recycled in rebuilding efforts, resulting in very disturbed destruction horizons. The preservation of pristine destruction layers may therefore depend more on social factors, such as the degree to which the affected community was able to cope with the aftermath of the earthquake, than on physical parameters, such as the magnitude and proximity of the earthquake. This results in a very incomplete stratigraphical record of earthquakes, which is moreover not evenly distributed through time. This preservation issue concerns not only stratigraphical earthquake evidence but also structural earthquake evidence, resulting in an observation bias in archaeoseismology, focusing on periods of upheaval, destruction, abandonment, and so on.

Constraining the timing of the damaging earthquakes is one of the greatest challenges in archaeoseismology. Chronological control is achieved by bracketing earthquake evidence with a minimum (*terminus ante quem*) and maximum (*terminus post quem*) age. Alongside radiometric dating methods (e.g., radiocarbon dating), archaeological dating tools, based on, for example, architectural styles, ceramic style changes, coins, and inscriptions, are used in constraining the timing of earthquakes. The accuracy and precision of the age control largely depends on the type of dating applied and on whether or not multiple age determinations, using complementary dating methods, have been performed. The main issue with respect to archaeological earthquake evidence is rather poor temporal resolution, ranging from decennia to centuries, making it nearly impossible to pinpoint archaeological earthquake evidence to historical earthquakes. The danger, moreover, exists that ancient earthquakes, poorly constrained in time, are equated with historically documented earthquakes, based on an inherently incomplete earthquake catalogue. When, subsequently, the archaeological earthquake evidence is used as supplementary proof for the historical earthquake, a circular argument arises. Poor temporal resolution may also lead to erroneous interpretations of earthquake evidence as the result of a single oversized earthquake, on the one hand, the sequence of the main shock and its aftershocks, and on the other hand, a clustered series of earthquakes. Finally, poor age constraints hamper the territorial correlation of EAEs between different archaeological sites, again giving rise to the danger of amalgamating earthquake evidence for regionally distinct earthquakes into a single catastrophic earthquake. This problem of regionally

correlating archaeological earthquake evidence also limits our ability to quantitatively assess the physical parameters of ancient earthquakes.

Indeed, the magnitude of a pre-instrumental earthquake is assessed semiquantitatively based on the spatial distribution of secondary earthquake evidence, reflecting variable ground motion intensities away from the earthquake's epicenter. By comparing these earthquake intensity distribution maps of pre-instrumental earthquakes with intensity distribution maps of recent, instrumentally recorded, earthquakes in the same region, a reliable magnitude estimate of pre-instrumental earthquakes can be derived. In addition to the poor temporal resolution of archaeological earthquake evidence, hampering a valid regional correlation, the mapping of secondary archaeological earthquake evidence is strongly limited because archaeological sites are rather sparsely and unevenly distributed. Only in regions with a long and rich archaeological heritage does such regional mapping provide useful intensity distributions, which allow the magnitude of an ancient earthquake to be assessed. There is, though, a remarkable spatial bias that can be advantageous for archaeoseismological work. In earthquake-prone regions, human settlements are often located in the direct proximity of active earthquake faults, in what are called seismic landscapes, that is, landscapes resulting from the cumulative geomorphological effect of successive, surface-rupturing earthquakes. There is an increased likelihood of these archaeological sites having a record of both primary and secondary earthquake effects, caused by earthquake activity on the nearby fault. However, the dominant presence of nearby EAEs also obscures the possible presence of far-field EAEs, making regional correlations of EAEs much more difficult. On the other hand, the absence of EAEs at an archaeological site in a seismic landscape may reveal that the faults in the direct proximity of the site were not active during the occupancy of the settlement.

Before a magnitude can even be derived for an ancient earthquake, archaeoseismology is thus still confronted with a number of challenges. To address these challenges, modern archaeoseismology aims to integrate the principles and practices of a very wide range of sciences, from geophysics to structural engineering. Such a multidisciplinary approach requires a shared protocol and a standardized methodology (see Sintubin and Stewart 2008 and references therein). In recent years, a clear shift towards more quantitative and multidisciplinary approaches has definitively boosted the use of archaeoseismological evidence in seismic-hazard studies. Quantitative archaeoseismology (Hinzen et al. 2010) focuses on, for example, a forward modeling approach, based on earthquake engineering models applied to ancient manmade structures. Scenario-based earthquake ground motion simulations test realistic earthquake hypotheses to explain structural EAEs in ancient buildings. Such a modeling approach is helped by modern visualization techniques, such as 3D laser scanning (see AIRBORNE LASER SCANNING AND LIDAR), which allow the creation of a quantitative, high-resolution, three-dimensional structural model of the ancient building. Quantitative archaeoseismology not only assesses archaeological earthquake evidence with respect to ground motion parameters and magnitude estimates of ancient earthquakes, but also unambiguously discriminates between damage caused by earthquakes and damage caused by other natural or anthropogenic agents. While this quantitative archaeoseismological practice is very effective on sites with monumental architecture, a more semiquantitative, multidisciplinary territorial approach is more appropriate in archaeological contexts dominated by rubble architecture and associated destruction horizons (Jusseret and Sintubin 2013). This approach starts from the seismotectonic context of the archaeological site, identifying the different types of potential seismic sources, as well as their empirical ground-motion relationships. From an archaeological perspective, a well-documented, high-visibility archaeological context, characterized by distinctive and rapid ceramic changes, which provide a good chronological framework, is required. Subsequently, different earthquake hypotheses are tested in an iterative process, eventually leading to an earthquake scenario that provides the best explanation for the EAEs observed in the archaeological context studied.

Finally, by highlighting how communities in ancient times coped with earthquakes, archaeoseismology can boost earthquake awareness in

present-day communities living near archaeological sites bearing evidence of ancient earthquakes. In this respect, archaeoseismology can be part of public policy to mitigate earthquake risk.

SEE ALSO: Archaeological Fieldwork; Archaeology; Cosmogenic Dating; Dating in Archaeology; Disaster Archaeology; Geomorphological Survey; Ground-Penetrating Radar; Image-Based 3D Modeling; Lidar Data Visualization and Processing; Magnetometry

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