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Long-term effect of seismic activities on archaeological remains: A test study from Zakynthos, Greece

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ABSTRACT

During the archaeological and geoarchaeological surveys on the island of Zakynthos, Greece, it has been noted that the distribution and preservation of archaeological remains of Zakynthos present spatially different characteristics. In general, archaeological pottery finds and architectural remains in the eastern part of the island appear to be more fragmented and more widely distributed than in the western part of the island. Due to the high seismicity in the region, the question has come up whether a correlation between seismic activity and distribution and preservation conditions of archaeological remains exists or not. In order to investigate the mentioned relationship, we looked at the cumulative effect of continuing earthquakes for the last hundred years on the island of Zakynthos. We used ground acceleration to quantify the earthquake-induced damage. The predicted cumulative destruction intensity is presented on a map, and it illustrates that we can cautiously attribute the distribution difference of the archaeological remains with different preservation conditions to the seismic activity on the island. It is hoped that this study will initiate new scientific research into the characteristics of the distribution of archaeological remains in seismically active areas. In addition, it is to be expected that this study will contribute to in situ preservation studies relating to the long-term effect of seismic activities on the archaeological record.

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INTRODUCTION

The Mediterranean area is well known for its archaeological richness and its frequent earthquakes. It is only very recently, however, that archaeologists, historians, seismologists, geologists, and engineers have begun to collaborate systematically in research and heritage management. At the moment, the common concern of these studies is mainly limited to determining, based on the archaeological and geological-geomorphological evidences, whether or not an earthquake of significance was a major cause in the destruction at a particular site, e.g., Stiros et al. (1996), Ellenblum et al. (1998), Galadini and Galli (2001), Marco et al. (2003), Koukouvelas et al. (2005), Caputo et al. (2006), Similox-Tohon et al. (2006), Reinhardt et al. (2006), and Marco (2008). The cause of destruction in an archaeological stratigraphy (e.g., earthquake, land instability, war) can be determined by examining the distortion on structures and the in situ geological data. With developing methodologies for the recognition of earthquake-induced damages, archaeologists can ascertain the reason for massive destruction at their site more reliably. Sometimes, the destruction layer recorded in the destroyed ancient site might be dated, using the archaeological context, or be correlated with a devastating earthquake event in the region, using historical sources of the expected time period mentioning such an event. The inferred earthquake is used by seismologists in the improvement of historical earthquake catalogues for the assessment of seismic hazard; by geologists in understanding of the geodynamic characteristics of the region; and by engineers in the development of new constructional methods to mitigate the seismic risk. However, the effect of seismic activities on archaeological remains does not simply conclude with one devastating event, it is an ongoing process that may continue to destroy the archaeological remains (Papastamatiou and Psycharis, 1993; Psycharis et al., 2000; Cerone et al., 2001).

In this paper, the effect of seismic activities on archaeological remains is not considered to be constrained to only one devastating event. The study concentrates on the probable continuing destruction of archaeological record by earthquakes before, during, and after the abandonment of sites. Seismic hazard studies will be used to begin to understand the archaeology of a seismically active region.

The area of study, Zakynthos (western Greece), is located in one of the highest seismic activity regions of the world and has been inhabited since the Paleolithic. During the archaeological and geoarchaeological surveys on the island in the period of 2005 to 2008, it was noted that the distribution and preservation of archaeological remains of Zakynthos present spatially different characteristics. In general, archaeological pottery finds and architectural remains in the eastern part of the island appear to be more fragmented and more widely distributed than in the western part of the island. Standing architectural remains also appear to be in a better condition in the west than in the east. It is believed that there may be a correlation between the ongoing seismic activities in the region and the distribution and preservation conditions of archaeological remains in Zakynthos. This paper particularly addresses the development of a method that may be used to investigate spatially such a probable link between the conditions of archaeological remains and the seismicity of the specific region.

STUDY AREA

Geological and Seismotectonic Background

Zakynthos—the southernmost of the Ionian Islands of western Greece—lies in a tectonically complex and active area (Fig. 1; Underhill, 1989; Papazachos and Kiratzi, 1996; Barka and Reilinger, 1997; Hinsbergen et al., 2006; Lagios, et al., 2007). In particular, the Ionian Basin of the African plate subducts beneath the Aegean continental microplate of the Eurasian plate, the Apulian continental crustal part of the African plate collides with the Eurasian plate in the north, and the Cephalonia transform fault zone connects these subduction and collision zones. The seismicity of the area is the highest in Greece, mainly consisting of shallow seismic activities (Papazachos, 1990; Papazachos et al., 1993; Clément et al., 2000). Figure 2 shows the spatial distribution and the magnitude occurrences of the earthquakes that were recorded between 1901 and 2006 (except the last 3 months) with $M_w \geq 4.5$ in the vicinity of Zakynthos, which also form our data set for the study. Within the defined area, there are 1975 events, including the most destructive earthquake of the last century in Greece, which occurred in the Ionian Islands on 12 August 1953 with a surface-wave magnitude of 7.2 (Stiros et al., 1994). Hatzidimitriou et al. (1985) calculated the return period of this and larger magnitudes of earthquakes for the vicinity as 29 yr, based on the data covering the last 81 and 181 yr periods.

The important local seismicity of Zakynthos occurs along the Ionian thrust, which also divides the island into two different geological units: Pre-Apulian and Ionian (Fig. 1). The Pre-Apulian (also called Paxos) unit is recognized on the island as the Vrachionas carbonate anticline. It is composed of thick Upper Cretaceous limestones and dominates the western part of the island. Marly limestones of Eocene and Oligocene age are exposed at its eastern slope. Miocene deposits are observed at the central lowlands as sandstones and bluish marls with gypsum intercalations. Toward the east, this range of hills suddenly leaves its place to a plain filled with recent alluvium deposits. The Ionian unit is exposed on the eastern part of the island, namely at the Vasilikos Peninsula. The peninsula mainly consists of Pliocene and Pleistocene marine mudstones and sandstones, and Triassic evaporates and limestones also crop out.

Archaeological Investigations

Zakynthos is mentioned in various historical sources, indicating its long and intensive habitation. It is mentioned on Linear B tablets from Pylos showing the overseas connection of the island with the mainland in the Mycenaean period (Palaima,

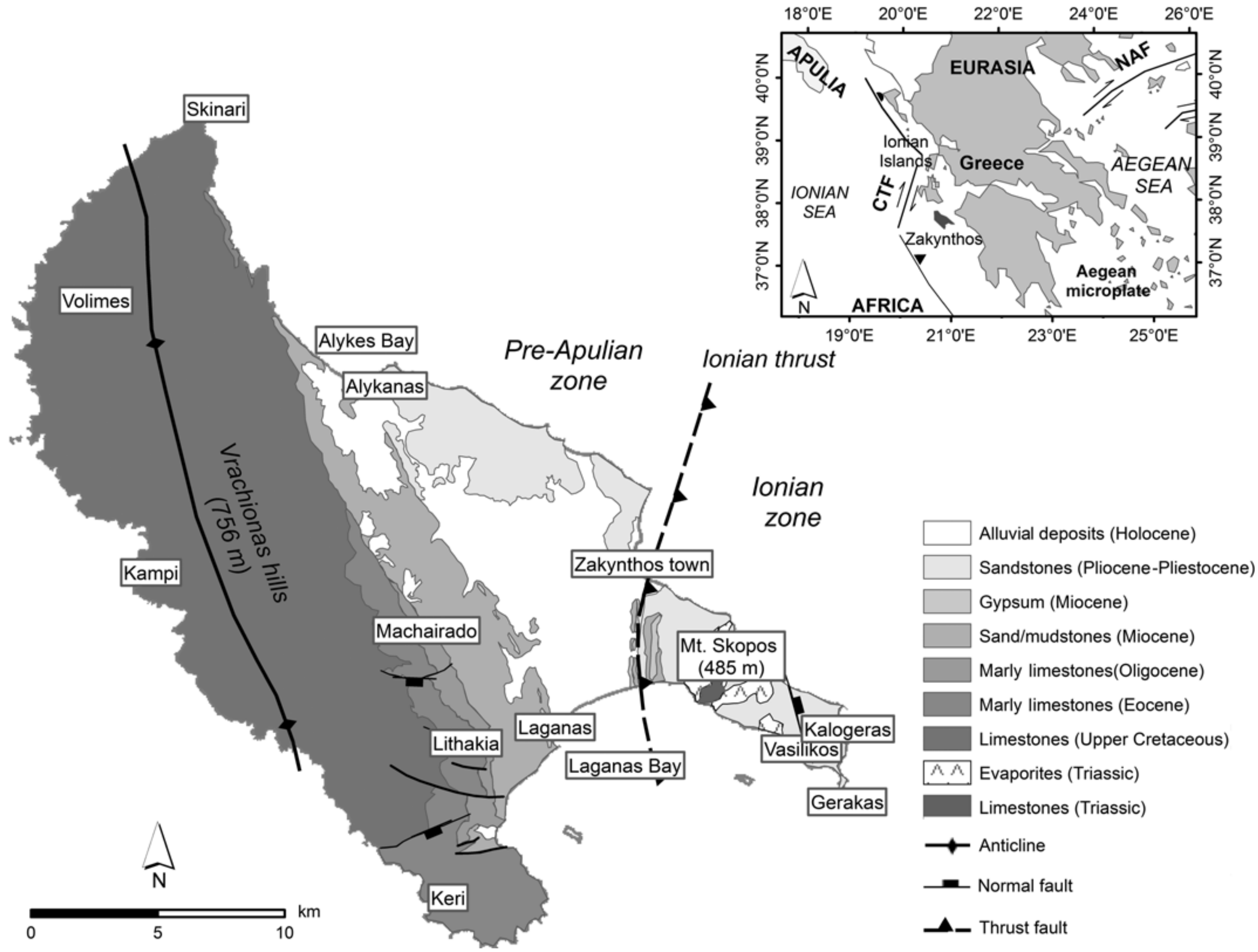

Figure 1. Plate boundaries and main tectonic features of Greece (Barka and Reilinger, 1997; Clément et al., 2000) and the geological map of the Zakynthos Island (Perry and Temple, 1980; Underhill, 1989). CTF—Cephalonia transform fault, NAF—North Anatolian fault.

1991). Homer mentions the island as a part of the territory of Odysseus (*Iliad* II: 634; *Odyssey* IX: 24). In Classical and Hellenistic periods, the island often was an ally of Athens (Kalligas, 1993). Pliny the Elder mentions the particular fertility of the island (*The Natural History* 4: 19: 12). During the Venetian period, Zakynthos was known as "the flower of the Levant" due to its beauty and fertility (Zois, 1955). In spite of its prosperous land and the suitable geographic location with regard to local and Mediterranean maritime traffic, the archaeology of Zakynthos is relatively little known.

Sylvia Benton of the British School in Athens was the first archaeologist to systematically describe several archaeological sites on the island (Souyoudzoglou-Haywood, 1999). She excavated a Mycenaean house in Cape Kalogeras on the Vasilikos Peninsula and a tholos tomb near Alykanas in the 1930s. Unfortunately, her results remained unpublished, and at the time of the 1953 earthquake, all the finds and records were lost. The Greek Archaeological Service carried out excavations in the early 1970s (Mylona, 2006). Their research focused on the hill rising just behind the modern town of Zakynthos and its surrounding area. Today, there is a Venetian castle with extensive British modifications standing on top of the hill facing Peloponnese. The uncovered archaeological artifacts and some standing architecture in the interior of the castle indicate occupation during the Bronze Age and during Archaic, Classical, Hellenistic, and Roman periods. Based on the archaeological evidence and ancient authors' texts, it can be concluded that the hill used to be an ancient acropolis already fortified by the mid-fifth century B.C.

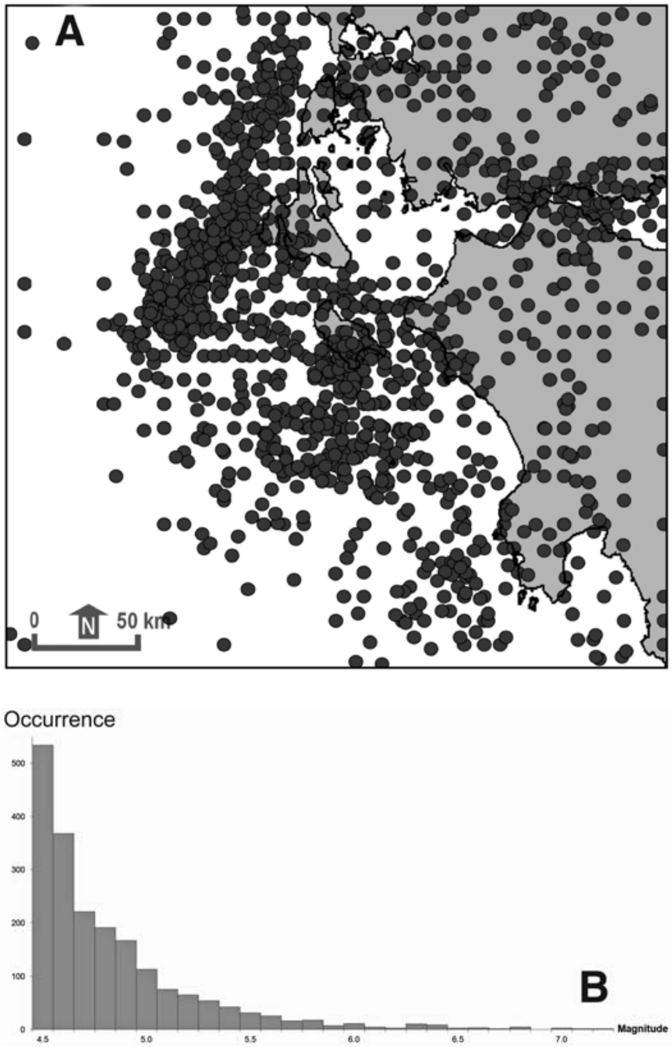

Figure 2. The spatial distribution (A) and the magnitude frequency (B) of the earthquakes recorded in the vicinity of Zakynthos between 1901 and 2006 (except the last 3 months). The presented data also form the data set of this study and cover the magnitudes of earthquakes M_w 4.5 and greater.

Currently, systematic archaeological research on the island has been continuing since 2005 as a joint project of the Netherlands Institute in Athens (NIA) and the 35th Ephorate of Prehistoric and Classical Antiquities: the Zakynthos Archaeology Project (ZAP) (Van Wijngaarden et al., 2006, 2007). The project aims to gain more insight into the archaeology of the island, and it combines archaeological surveys with geographic information system (GIS), aerial photography, and geomorphologic studies to better identify the human-nature interaction in the past and also to understand the effect of today's processes on the archaeological remains (e.g., Rink, 2005; Stoker 2006; Pieters et al., 2007; Horn Lopes, 2008; Storme, 2008; Tendürüs, 2009). In 3 years, the project showed that the island was inhabited in several periods. Lithic tools and flakes from the Paleolithic to Early Bronze Age, tholoi and settlement remains from the Mycenaean period, and other concentrations of finds, especially pottery, from Archaic, Hellenistic, or Roman times, medieval, and early modern periods have been recorded.

Archaeological Remains

Unlike many other areas in Greece, Zakynthos has very few standing archaeological remains that date back to more than a few centuries ago. The only excavation that was fully published is the Mycenaean cemetery at Kambi in the western mountains of the island (Agalopoulou, 1973). Other notable ancient remains, probably of Roman date, are found built into the little church St. Dhimitrios at Melinado, near Machairado (Fig. 3A; Foss, 1969; Kalligas 1993). Palaiokastro is another significant archaeological site on Zakynthos. It is located on the hills west of Machairado with an imposing view of the plain. The site was considered to be medieval, but the finds in 2007 and 2008 indicated activities also in prehistory and antiquity (Van Wijngaarden et al., 2009, 2010). Apart from the medieval structures, several walls, probably to be dated sometime in the period from Archaic to Hellenistic times, have been recorded on the ridges and the plateaus to the west of the top of the hill (Fig. 3C).

Figure 4 presents the archaeological sites known on the island from the literature and from the surveys of the ZAP. Among these sites, there are settlement remains (i.e., architectural remains like foundations and walls), graves, and surface finds (i.e., small finds including mainly pottery sherds and stone tools). In 2006, the survey conducted at the southeastern peninsula (Vasilikos) revealed large quantities of pottery and lithics, mainly lacking of local concentrations. Archaeological ceramics that were recovered, included sherds of considerable quality, but they were generally heavily worn. Standing ancient settlement remains were only observed at Kalogeras where the thick brushes were removed. A view from the discovered various eroding walls is displayed in Figure 3B. The majority of the pottery found in association with these walls dated to the prehistoric period, in particular, to the Middle and Late Bronze Ages (Von Stein, 2009). Elsewhere at the site, Archaic and Classical finds were more abundant. In comparison to the Vasilikos Peninsula, the distribution of archaeological artifacts in the vicinity of Keri, where a pilot survey was carried out in 2005, showed more concentrations of material, probably representing archaeological sites. In a few cases, these sites could be identified with certainty on the basis of the quantity, the quality, and the diversity of the surface material. In general, the archaeological record in the southeast appears to show a higher degree of disturbance and dispersion.

Figure 4 also indicates churches and monasteries of Zakynthos, the major architectural remains on the island. More of these monuments are located in or near the town of Zakynthos and in the western high areas. The churches at the town were reconstructed after the catastrophic earthquake of 1953, except the concrete reinforced church of St. Dionysios, built in 1948 (Facaros and Theodorou, 2003). Some of the churches and the

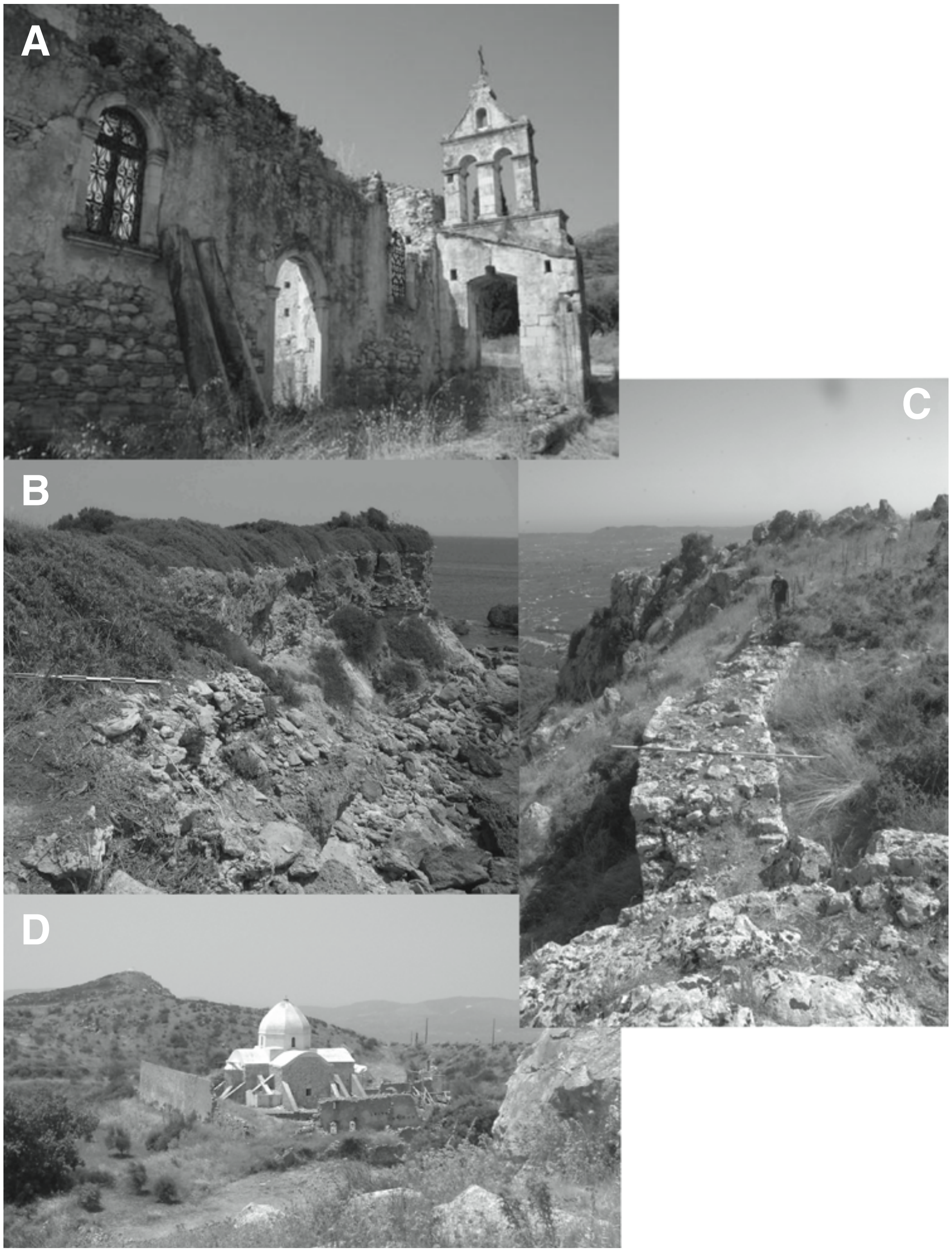

Figure 3. A few example views from the "standing" archaeological remains on Zakynthos. (A) The church of St. Dhimitrios in Melinado containing marble columns and blocks, probably of Roman date. (B) Part of wall remains at Kalogeras, probably from the second millennium B.C. (C) Part of wall remains at the site of Palaiokastro. (D) The monastery of Skopiotissa on Mount Skopos being restored.

monasteries in the western part of the island were also badly and partially damaged. The most serious damages mentioned are those on the church of St. Andreas at the northwest and the little church at the east foot of the Vrachionas (Foss, 1969). The monastery of Skopiotissa on Mount Skopos was also destroyed with the earthquake, but it is currently being restored (Fig. 3D).

METHOD

Human response to the damaging effects of earthquakes on archaeological remains has only recently improved further than trying to provide stability of some standing buildings with steel and concrete supports. Although short-term effects of earthquakes on the archaeological remains receive some attention, their long-term effects have been neglected in archaeological studies. Therefore, there is virtually no directly relevant literature available for our investigation. On the other hand, studies in the fields of seismology, geology, and civil engineering can help us to look into the spatial distribution of the combined effect of past earthquakes.

Quantification of Earthquake-Induced Damage

Earthquakes have six major effects. Ground motion and faulting are two of them and cause damage directly. Others are fire,

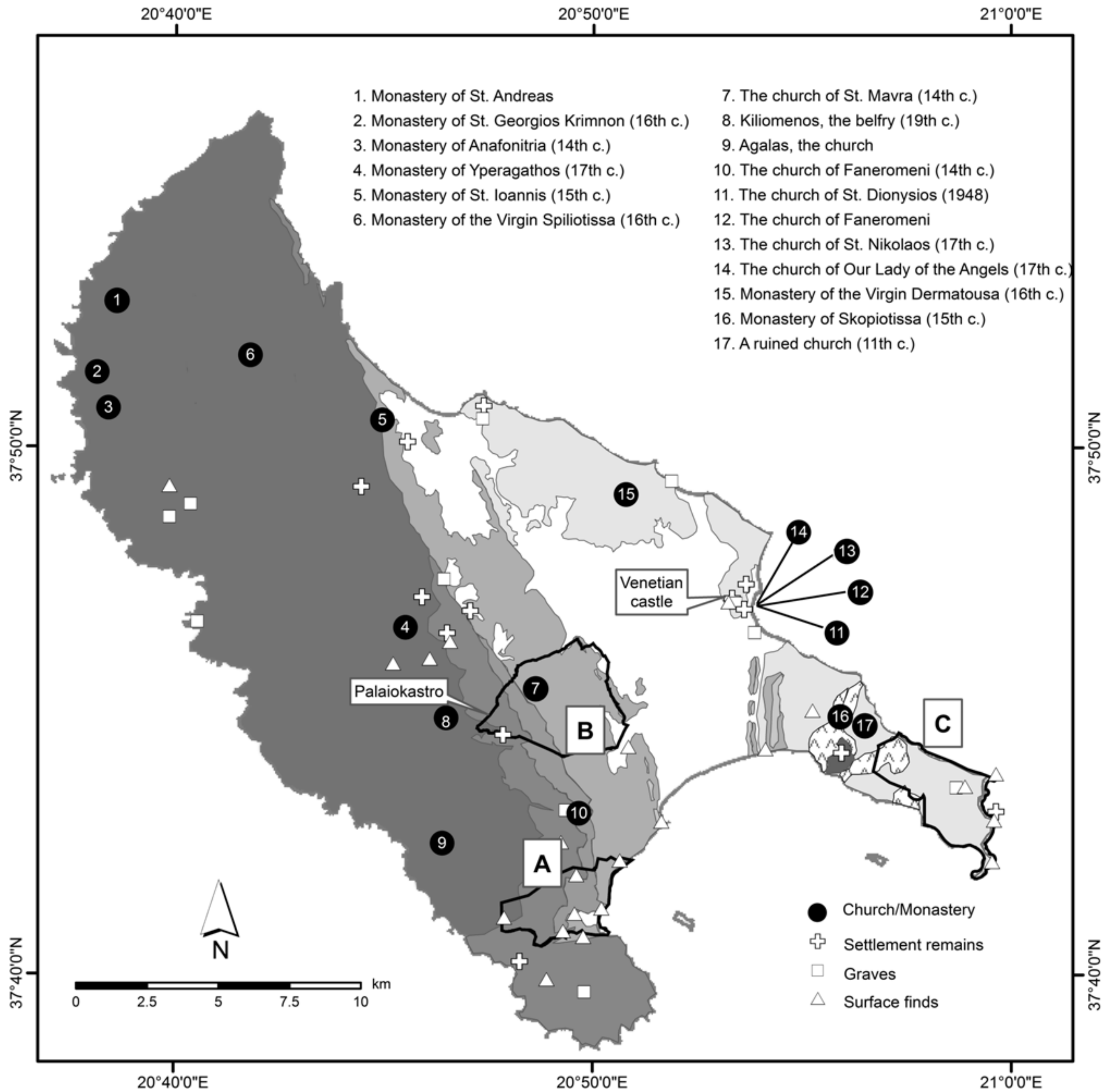

Figure 4. Geographic distribution of the archaeological sites, the churches and the monasteries of Zakynthos. A, B and C represent the intensive archaeological survey areas of the Zakynthos Archaeology Project. Areas A and C were covered in 2005 and 2006. The investigations at area B still carry on.

landslides, cliff collapse, or any mass-wasting movements, liquefaction, and tsunamis (initiated by earthquakes). These are secondary effects that cause damage indirectly (Yeats et al., 1997).

In our study, we used the ground motion to quantify the damage due to seismic activities because it is the most common way of determining the level of vulnerability of a region in seismic hazard assessment studies. The level of ground shaking caused by an earthquake at a site mainly depends on the magnitude of the earthquake, geographical proximity of the site to the seismic source, and local geological characteristics of the media. For instance, ground shaking decreases when the waves propagate outward from the source; soft sediments amplify seismic waves and create more ground shaking than hard rocks (Day, 2002).

The level of ground shaking, or damage, is usually measured as peak ground acceleration (PGA), which is often determined by attenuation models (Day, 2002; Bozorgnia and Campbell, 2004). An attenuation model is defined as a mathematical expression developed to estimate the peak ground acceleration at a certain distance from a seismic source, using a given data set of seismological parameters (deterministic method) or using all possible earthquake locations and magnitudes together with their expected probabilities of occurrence (probabilistic method).

There are a few attenuation relationships developed specifically for Greece and its neighboring regions. The attenuation model by Theodulidis and Papazachos (1992) provides a reasonable and geographically specific model to apply to PGA seismic evaluations for Greece (Burton et al., 2003) and was selected for the calculations in this study. The model was developed studying 36 shallow earthquakes from Greece with magnitudes M_s 4.5–7.0 and four from Japan and Alaska with magnitudes M_s 7.2–7.5. The attenuation relation is:

$$\ln a_g = 3.88 + 1.12\,M_s - 1.65\ln\left(R + 15\right) + 0.41S + 0.71P, \quad (1)$$

where a_g is the peak horizontal ground acceleration in cm s^{-2}, R is the epicentral distance in km, S is a parameter equal to zero at "alluvium" sites and equal to one at "rock" sites, and P is a parameter equal to zero for mean or 50 percentile values and one for 84 percentile values (taken as zero in our calculations).

Figure 5 shows the change of PGA values projected by this attenuation model when the waves are propagating further from the epicenter of an earthquake of magnitude M_s 4.5, 6.0, 7.5, and 9.0 in the same type of geological medium. While the effect of a M_s 4.5 earthquake remains local, an earthquake with a stronger-magnitude earthquake, e.g., M_s 7.5, is felt moderately at 60 km distance.

Data Collection

We put together a collection of the magnitude and location of past earthquakes for the vicinity of Zakynthos, forming our data set from the recent catalogue published by the Aristotle University of Thessaloniki (Papazachos et al., 2007). The selected seismic events have moment magnitudes of 4.5 and greater and occurred between 1901 and 2006 (except the last 3 mo). The area coverage of the data set is 300 × 300 km^2 within the frame bounded by the coordinates of 36.420°N–39.140°N and 19.072°E–22.500°E. The spatial distribution of earthquake events included in our data set and their magnitude occurrences are shown in Figure 2.

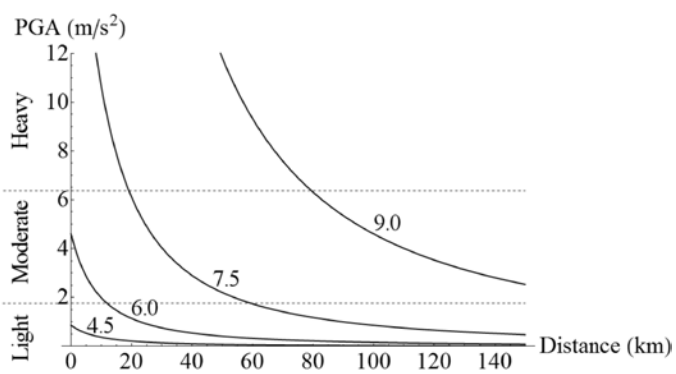

Figure 5. The change of peak ground acceleration (PGA) values projected by the attenuation model of Theodulidis and Papazachos (1992).

An earthquake of Richter magnitude M_L 4 is felt by almost everybody; it breaks some dishes and windows and can displace unstable objects (Table 1; U.S. Geological Survey, 2010). Since slight damages start appearing during earthquakes of M_L 4, equivalent to M_w 4.5 (please refer to the study of Papazachos et al. [1997] for the relationships between the magnitudes in the region), it is set as the threshold value for our data set. Due to their unstable nature, we considered that archaeological remains will be more prone to ground shaking.

Although the compiled earthquake catalogues of Greece extend back to 550 B.C.E. (Papazachos and Papazachou, 1997; Papazachos et al., 2000), we chose the earthquake records from 1901 (introduction of seismograph in Greece) onward as our data set because the historical records are lacking a considerable amount of seismic events, most importantly, in the lower-magnitude range (Ambraseys, 1996; Kouskouna and Makropoulos, 2004). Insertion of the earlier records into our data set would promote a few devastating events and omit a very large collection of smaller and unrecorded events, causing a deceptive geographical distribution in our results.

Cumulative Destruction Intensities

The cumulative damaging effect of past earthquakes, which we call cumulative destruction intensity, was calculated by accumulating the PGA values of each earthquake in our data set for the vicinity of Zakynthos using the attenuation relationship of Theodulidis and Papazachos (Eq. 1). First, the earthquake magnitudes of the data set were converted from moment magnitude to surface-wave magnitude using the following relationship (Papazachos et al., 1997):

$$\begin{aligned} M_w &= M_S, && 6.0 \le M_S \le 8.0, \\ M_w &= 0.56M_S + 2.66, && 4.2 \le M_S \le 6.0. \end{aligned} \quad (2)$$

Second, the geological units of the island were classified as alluvium and rock for the S parameter, a dummy variable taking the value of zero for "alluvium" sites and one for "rock" sites in the attenuation relationship. Figure 6 shows the rock sites of Zakynthos in gray color, including limestones, sandstones, mudstones, and gypsum, and the alluvium sites in white. Finally, the area covered by our data set was divided into 40,000 grid points, and PGA values were calculated on every grid point for each earthquake in the data set (Fig. 7). The computed PGA values for each grid point were accumulated in the process to obtain the total

TABLE 1. COMPARISON OF RICHTER MAGNITUDE AND MODIFIED MERCALLI INTENSITY SCALES

Richter magnitude	Modified Mercalli intensity	Description
1.0–3.0	I	Not felt except by a very few under especially favorable conditions.
3.0–3.9	II	Felt only by a few persons at rest, especially on upper floors of buildings.
	III	Felt quite noticeably by persons indoors, especially on upper floors of buildings. Many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibrations similar to the passing of a truck. Duration estimated.
4.0–4.9	IV	Felt indoors by many, outdoors by few during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.
	V	Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop.
5.0–5.9	VI	Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight.
	VII	Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken.
6.0–6.9	VIII	Damage slight in specially designed structures; considerable damage in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned.
	IX	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations.
7.0 and higher	X	Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations. Rails bent.
	XI	Few, if any (masonry) structures remain standing. Bridges destroyed. Rails bent greatly.
	XII	Damage total. Lines of sight and level are distorted. Objects thrown into the air.

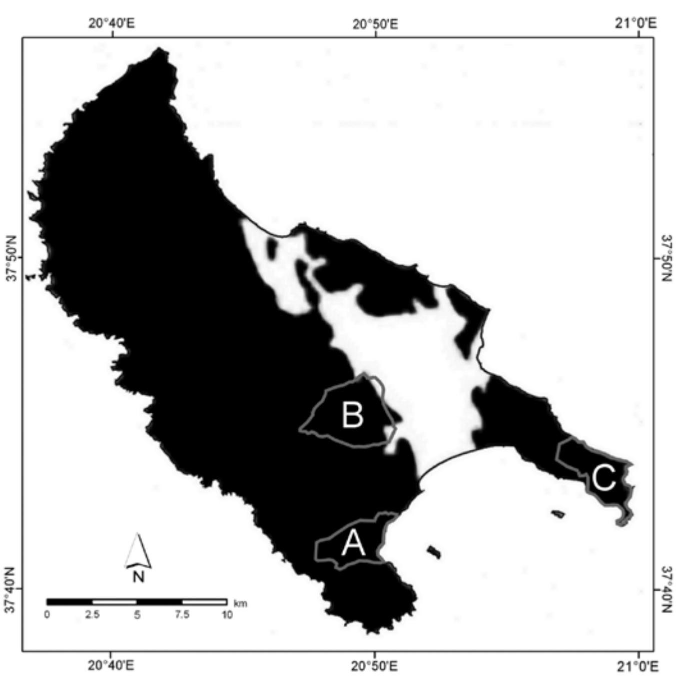

Figure 6. Two basic geological units of Zakynthos: rock sites (gray) and alluvium sites (white). A, B and C represent the intensive archaeological survey areas of the Zakynthos Archaeology Project. Areas A and C were covered in 2005 and 2006. The investigations at area B continue.

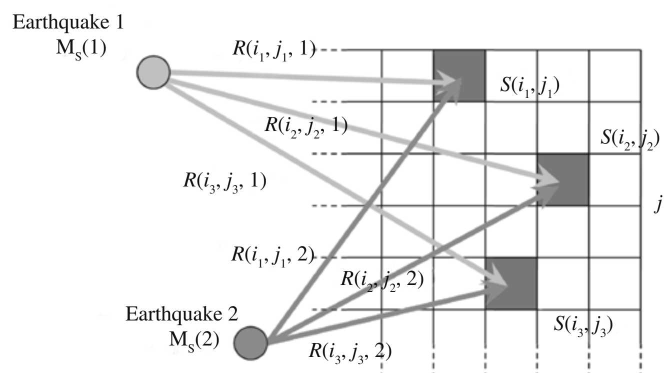

Figure 7. A simple sketch of the calculation procedure of cumulative destruction intensity values. There are 40,000 grid points in the defined area and 1975 earthquakes in the considered period.

damage induced by all the earthquakes during the considered time period, using the formula

$$CPGA(i,j) = \sum_{k=1}^{N} a_g(i,j,k), \quad i = 1\ldots L, j = 1\ldots L, \qquad (3)$$

where i and j are the horizontal and vertical grid indices, L is the grid resolution, N is the total number of earthquakes in the data set, and $a_g(i, j, k)$ is the peak ground acceleration at grid point (i, j) caused by earthquake k. Using Equation 1, this is ultimately

$$CPGA(i,j) = \sum_{k=1}^{N} \exp\left\{3.88 + 1.12M_s(k) - 1.65\ln\left[R(i,j,k)+15\right] + 0.41S(i,j) + 0.71P\right\}, \qquad (4)$$

where $M_s(k)$ is the surface magnitude of the kth earthquake, $R(i, j, k)$ is the distance of grid point (i, j) to the epicenter of the kth earthquake, $S(i, j)$ is either zero or one according to whether grid point (i, j) is considered alluvium or rock, and P is the percentile parameter, as described earlier for the attenuation relation given in Equation 1.

RESULTS AND DISCUSSION

The accumulated PGA values or the cumulative destruction intensities for the last hundred years for the vicinity of Zakynthos are shown in Figure 8. The higher are the cumulative PGA values, the larger is the expected accumulated damage on archaeological remains. However, at this stage of this test study, a comparison of the cumulative destruction intensities with the accumulated damage on the archaeological remains will be possible only relatively.

The central part of the island, where recent alluvial sediments are deposited, accommodates the greatest cumulative destruction intensities in the resulting map. Today, this extensive plain is very poor in terms of availability of churches and monasteries. However, since the archaeological surveys from this part are not complete yet, it is difficult to attribute the absence of ancient architectural remains in this area to seismic activities. On the other hand, in the book *The Earthquakes of Greece*, by Papazachos and Papazachou (1997), one of the most comprehensive accounts concerning strong earthquakes in Greece, the town of Zakynthos and the hill behind it accommodating the Venetian

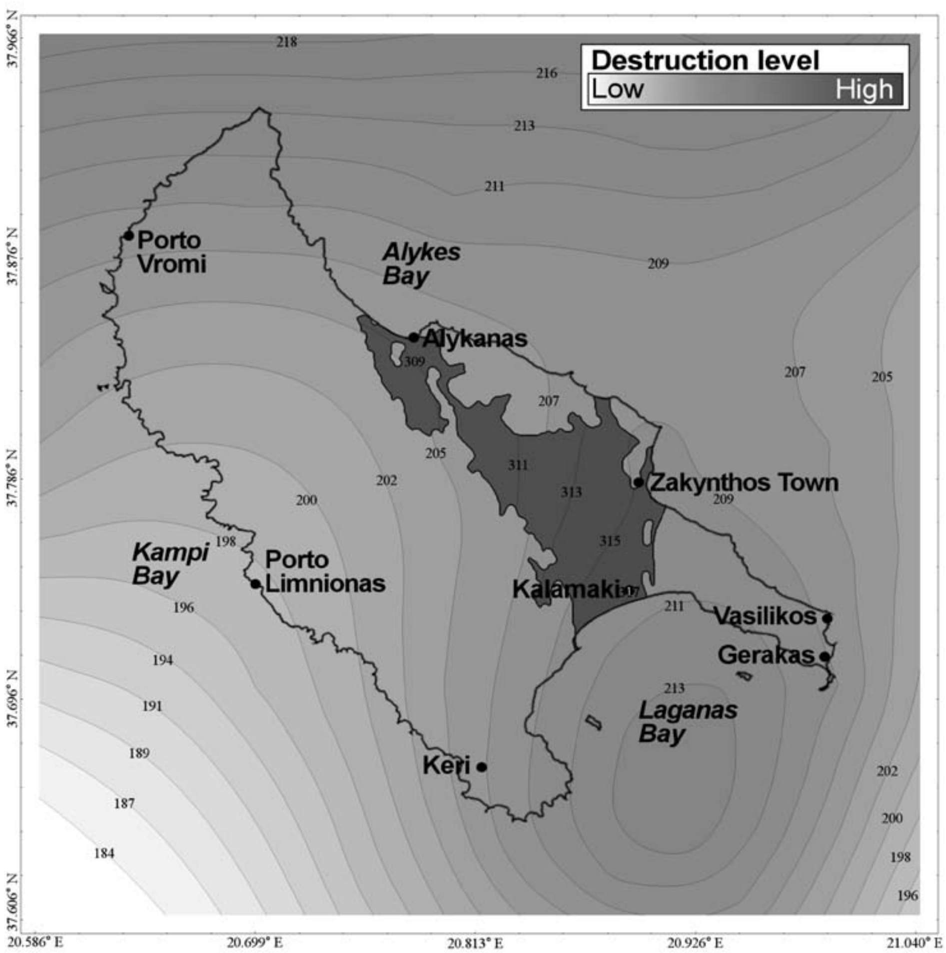

Figure 8. The cumulative peak ground acceleration (PGA) values in m s^{-2} for the period of 1901–2006 and $M_w \geq 4.5$.

castle are listed most frequently among the heavily damaged areas on the island. After the last catastrophic earthquake, the town was almost entirely rebuilt. It is also known that the castle has undergone many repairs since the Venetian period (Mylona, 2006). Accordingly, Figure 8 indicates that these two sites are subjected to high levels of cumulative destruction due to earthquakes.

The cumulative PGA values of the southeastern part of the island (the Vasilikos Peninsula) are found to be comparable to those of the area of the hill behind the town of Zakynthos. The rare preservation of the settlement remains and the relatively less concentrated distribution of the small finds on the peninsula might be explained with these high destruction intensity values in the vicinity. The intense fragmentation of the constructions may result in significant displacement of the pieces by the intervention of humans and nature.

Additionally, the noted damages on the church of St. Andreas on the north and the monastery of Skopiotissa on Mount Skopos (listed as number 1 and 16 in Fig. 4) and the archaeological survey results on the west show a good match with the destruction intensities of the resulting map. The church of St. Andreas takes our extra attention because of its contradictory condition with the base rock type underneath. It also agreeably follows the contour lines for the cumulative PGA values on our cumulative destruction intensity map and indicates the value of studying the probable cumulative effect of seismic activities on archaeological remains. A similar situation can be considered for the area south of the Vrachionas mountain range as well. While the archaeological sites have been assigned according to the amount and concentration of the small finds in the vicinity of Keri, the allocated archaeological sites in the central part of the Vrachionas consist of all types of find collections following suitably the picture on the cumulative PGA map.

Our cumulated ground acceleration map, once more, points out the significance of the local geological conditions in the ground motion studies and illustrates the vast divergence observed between the destruction levels of alluvium and rock sites. Unfortunately, attenuation models generally use simple binary categories to describe the ground composition, in which local site conditions are classified simply as soil or rock. Campbell and Bozorgnia (2003) showed the importance of a refined geological classification, including soft soil, firm soil, soft or primarily sedimentary rock, and hard rock, in the prediction of ground acceleration. Zakynthos is formed of various geological units such as limestone (also in various ages and characteristics), gypsum, sandstone, and mudstone. The Vasilikos Peninsula mainly consists of Pliocene and Miocene sandstone, in which the shear waves travel slower than in the massive limestone outcrop on the western part of the island, causing more shaking of the ground. Some examples of shear wave velocity for different materials are given in Table 2. Results from a new attenuation relation specific to Zakynthos will certainly be more detailed and more representative.

Another important point to mention is that the attenuation model includes only the direct damage caused by ground motion created by earthquakes. However, surface faulting and auxiliary effects such as liquefaction, landslides, rockfalls, tsunamis, fire, looting, etc., can also have considerable roles in the destruction of sites. These types of damages may also be introduced into a cumulative destruction map or be studied separately. Such studies would confine the damage to a local level.

TABLE 2. P AND S WAVE VELOCITIES OF SOME SELECTED MATERIALS

Material	P wave velocity (m/s)	S wave velocity (m/s)
Steel	6100	3500
Concrete	3600	2000
Granite	5500–5900	2800–3000
Basalt	6400	3200
Sandstone	1400–4300	700–2800
Limestone	5900–6100	2800–3000
Sand (unsaturated)	200–1000	80–400
Sand (saturated)	800–2200	320–880

CONCLUSIONS

This paper aimed to draw attention to the possible correlation between local seismic activity and the different distribution and preservation conditions of archaeological remains. It has shown that the spatial distribution of total destruction intensities of past earthquakes that affected archaeological sites can provide additional insight into the present distribution of remains.

However, we recognize that, being a test study, this research will lead to many further questions and discussions on the topic. First, the qualification of the degree of weathering and of the dispersion of archaeological remains has not been done systematically yet. In the near future, we plan to develop methodologies to investigate these issues more systematically. Second, the distribution of archaeological remains in the landscape is subject to many different factors. The influence of seismic activity with regard to the distribution of archaeological material and its relationship to factors such as erosion and sedimentation, and agricultural and cultural factors, still need to be assessed.

On the other hand, our study shows that relationships between seismic activities and characteristics of the archaeological record are likely. This result merits similar investigations at other archaeologically rich and seismically active areas in order to validate whether the cumulative destruction intensity maps also show spatial correlation between the ongoing seismic activity and the preservation conditions of the remains.

It is hoped that this research may stimulate new studies concerning the interaction of long-term seismic activities and archaeological remains, especially in view of archaeological site preservation. This interaction depends on many factors that can be studied further by employing in situ or experimental methods. For instance, standing or collapsed remains, buried or exposed remains, stone or mud brick remains will respond differently to earthquakes. Results from such studies can potentially be

important as an additional decision factor in setting up excavations or making preservation plans for a site.

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