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Tracking Earthquake Archaeological Evidence in Late Minoan IIIB (~1300–1200 B.C.) Crete (Greece): A Proof of Concept

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Abstract Late Minoan (LM) IIIB (~1300–1200 B.C.) represents a crucial period in the history of Bronze Age Crete, heralding the transition to the Iron Age through a wave of site destruction and abandonment. According to the traditional view, earthquakes may have played a significant role in these events. A new archaeoseismological approach is proposed to test this hypothesis and to attribute destruction and abandonment to earthquakes. Potential earthquake archaeological effects (PEAEs) are defined and documented at LM IIIB sites. Synchronisms of PEAEs between sites are based on ceramic evidence. The reliability of the PEAEs is furthermore assessed using empirical ground-motion relationships defined for three types of earthquake mechanisms that can be considered to occur in the seismotectonic context of Crete: (1) normal-faulting earthquakes located within the overriding Aegean lithosphere; (2) earthquakes located on the subduction interface or on splay faults merging with the interface at depth; (3) earthquakes within the subducting African lithosphere. In the case of LM IIIB1/early Malia and Sissi (northeastern Crete), this proof of concept is successfully applied and supports the hypothesis that seismic shaking is likely to be responsible for the PEAEs observed. A 12 October 1856 A.D.-type earthquake located within the subducting African plate is suggested as the most likely earthquake mechanism. In other LM IIIB archaeological contexts, no convincing evidence for earthquake effects could be identified. The hypothesis of a seismic storm causing the demise of Minoan Crete is not supported by our analysis of archaeological evidence.

Online Material: Detailed LM IIIB ceramic and archaeological data.

Introduction

Since its advent early in the twentieth century, Minoan archaeology has been intimately related to seismicity in the Eastern Mediterranean. Sir Arthur Evans, excavator of Knossos and discoverer of the Bronze Age (Minoan) civilization of Crete (see Table 1 for detailed Cretan Bronze Age chronology), was the first to establish a direct link between destruction at Knossos and catastrophic earthquakes (Evans, 1928). Since then, seismic events have become a popular explanatory principle for otherwise inexplicable archaeological site abandonment or destruction, a principle strongly criticized as pure conjecture (e.g., Karcz and Kafri, 1978; Ambraseys, 2005; Sintubin *et al.*, 2008). The situation is perhaps best illustrated by the destruction of the so-called temple of Anemospilia (see Fig. 1 for Cretan archaeological sites mentioned in the text) at the end of the Middle Minoan IIIA (MM IIIA) period (Table 1). There, three skeletons found crushed under massive rubble were interpreted as earthquake victims, caught in the ruins of the building while attempting to avert final catastrophe by human sacrifice (Sakellarakis and Sapouna-Sakellaraki, 1981).

The scenario reconstructed by Sakellarakis and Sapouna-Sakellaraki (1981) typifies recurrent difficulties faced by Minoan earthquake archaeology, including little or no account of the Holocene seismotectonic setting of the island dominated by recurrent, moderate earthquakes (e.g., Becker *et al.*, 2006; Becker and Meier, 2010; Caputo *et al.*, 2010; Shaw and Jackson, 2010), limited observations from the wider, regional archaeological context of the sites studied (see La Rosa, 1995; Monaco and Tortorici, 2004), and lack of associated paleoenvironmental data (see Gorokhovich, 2005). Further uncertainties are also introduced by the use of relative chronological frameworks provided by pottery and/or architectural evidence to assess the contemporaneity of destructive events (Macdonald, 2001).

In the present paper, we attempt to address some of these methodological challenges by bringing forward an archaeologically grounded approach to ancient earthquakes in Minoan Crete. For this purpose, we focus on the Late Minoan IIIB (LM IIIB) period (Table 1), a relatively narrow time window of ~100 yr (~1300–1200 B.C.) largely

Table 1
Approximate Absolute Chronology for the Cretan Bronze Age

Cretan Bronze Age Phases	Approximate Dates B.C.
Early Minoan (EM) IA	3100/3000–2900
EM IB	2900–2650
EM IIA	2650–2450/2400
EM IIB	2450/2400–2200
EM III	2200–2100/2050
Middle Minoan (MM) IA	2100/2050–1925/1900
MM IB	1925/1900–1875/1850
MM II	1875/1850–1750/1700
MM III (A–B)	1750/1700–1700/1675
Late Minoan (LM) IA	1700/1675–1625/1600
LM IB	1625/1600–1470/1460
LM II	1470/1460–1420/1410
LM IIIA1	1420/1410–1390/1370
LM IIIA2	1390/1370–1330/1315
LM IIIB	1330/1315–1200/1190
LM IIIC	1200/1190–1075/1050

After Manning (2010); EM IA phase after Schoep *et al.* (2012).

coinciding with the final demise of Minoan society. As argued elsewhere (Jusseret and Sintubin, 2012), LM IIIB might represent a key target for assessing the effects of earthquakes on Minoan archaeological sites. Thanks to widespread site abandonment and limited reoccupation, the period potentially provides the possibility of studying minimally disturbed records of earthquake damage. At the same time, the restricted time span covered by LM IIIB reduces the likelihood of amalgamating the effects of several earthquakes into seismic events that are "beyond the limits of possible" (Ambraseys *et al.*, 2002).

Significantly, the time window investigated also corresponds to a period of major cultural change heralding the transition from the Bronze Age to the Iron Age throughout the Eastern Mediterranean. Although cultural mechanisms driving these large-scale transformations remain unclear (raids of the Sea Peoples, internal conflicts, inherent instability of Bronze Age palatial systems), there has been a long-held suspicion that increased aridity (Carpenter, 1966; Bryson *et al.*, 1974) and seismic activity (Schaeffer, 1968) at the end of the Bronze Age might have played a significant role. In particular, Schaeffer's earthquake hypothesis (see also Schaeffer, 1948) received renewed attention in the last decade through the work of Nur and Cline (2000) suggesting that increased seismic activity (i.e., a seismic storm) in the Eastern Mediterranean during the years 1225–1175 B.C. (the so-called Late Bronze Age paroxysm) could have been responsible for the partial or total destruction of a number of Eastern Mediterranean settlements, including Khania and Knossos on Crete (Jusseret and Sintubin, 2013). Although Nur and Cline (2000) acknowledge that other forces may have been simultaneously at work, their approach based on a restricted selection of archaeological sites clearly runs the risk of creating artificial earthquake destruction patterns,

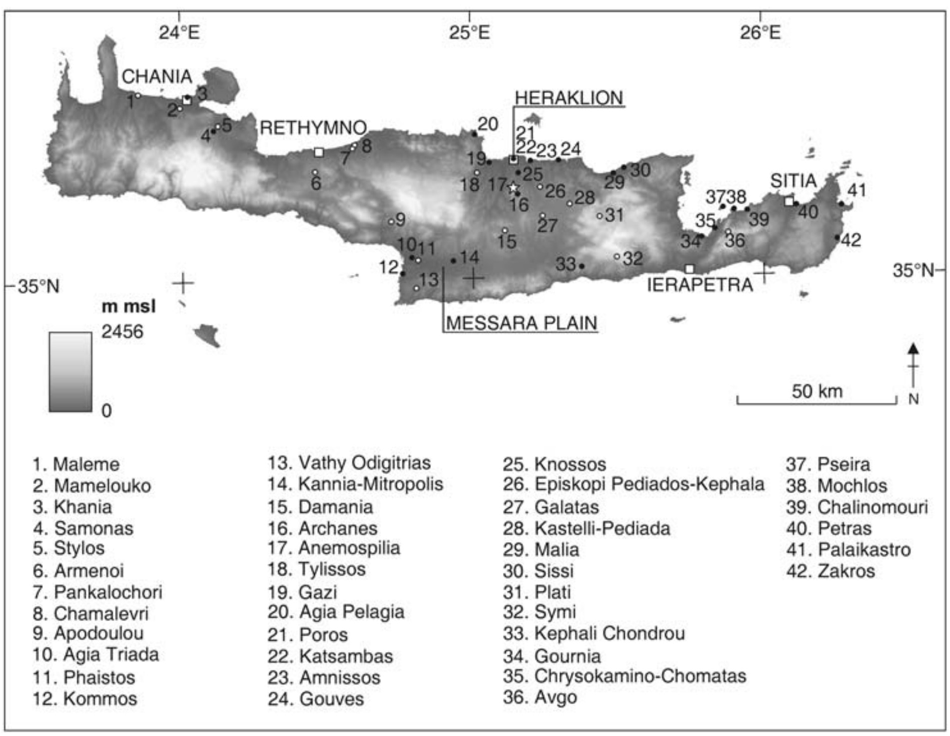

Figure 1. Location map of archaeological sites mentioned in the text. Black circles, LM IIIB archaeological sites selected for archaeoseismological analysis; white circles, other LM IIIB archaeological sites; star, MM IIIA archaeological site; white squares, modern towns; msl, mean sea level. (Background DEM courtesy of Laboratory of Geophysical-Satellite Remote Sensing & Archaeo-Environment [IMS-FORTH, Rethymno].)

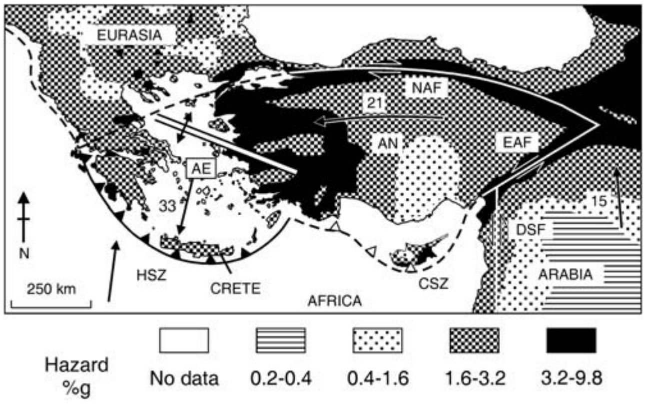

Figure 2. Seismotectonic setting of the Aegean region with seismic hazard (peak ground acceleration [%*g*] expected at 10% probability of exceedance in 50 years) according to Global Seismic-Hazard Assessment Program (see Data and Resources and Giardini, 1999). GPS-derived plate velocities (mm/yr) relative to Eurasia after Reilinger *et al.* (2006). HSZ, Hellenic subduction zone; CSZ, Cyprus subduction zone; AE, Aegean plate; AN, Anatolian plate; DSF, Dead Sea fault; EAF, East Anatolian fault; NAF, North Anatolian fault.

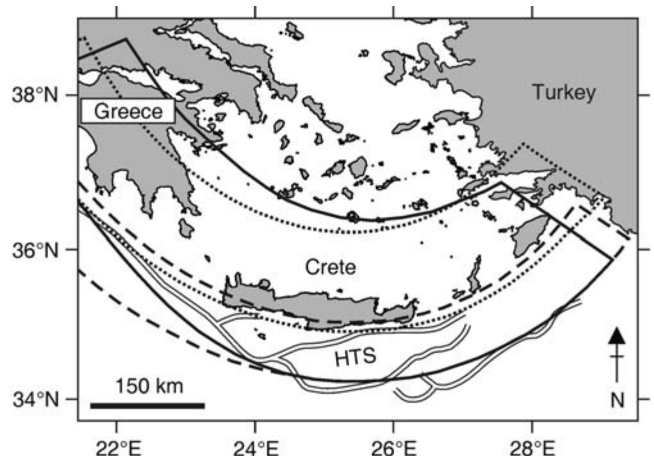

Figure 3. Schematic outline of areas of potential earthquake foci for the three main earthquake mechanisms identified near Crete. Thick black line, in-slab earthquakes (after Shaw and Jackson, 2010); dashed line, interface earthquakes; dotted line, north–south normal-faulting earthquakes (after Benetatos *et al.*, 2004). HTS, Hellenic trench system (after Shaw and Jackson, 2010).

which only detailed site-specific studies based on a systematic appraisal of all available archaeological evidence might reject or validate. Therefore, we introduce a novel approach of earthquake archaeological evidence taking better account of the seismotectonic context of Crete. As a proof of concept, LM IIIB archaeological evidence is examined in detail, allowing to evaluate the reliability of the earthquake hypothesis of Nur and Cline (2000).

Seismotectonic Setting

The seismotectonic context of the Mediterranean is dominated by the convergence of the African and Eurasian tectonic plates (Mather, 2009), resulting in the creation of large-scale back-arc extensional basins (e.g., Aegean and Tyrrhenian Sea basins) and orogenic arcs (Hellenic, Calabrian, and Gibraltar arcs) (Wortel and Spakman, 2000; Krijgsman, 2002). In the Eastern Mediterranean, convergence between Eurasia and Africa is taken up predominantly by the Hellenic subduction zone (e.g., Le Pichon and Angelier, 1979; Meulenkamp *et al.*, 1988; Shaw and Jackson, 2010; Kokinou *et al.*, 2012), whereas the differential motion between Africa and Arabia is mainly accommodated by the Dead Sea transform fault (e.g., Freund *et al.*, 1970; Garfunkel, 1981; Smit *et al.*, 2010) (Fig. 2).

Plate kinematics derived from Global Positioning System (GPS) data indicate the counterclockwise rotation of a broad region including the Arabian plate, adjacent parts of the Zagros and central Iran, Anatolia, and the Aegean. This rapid motion (~20–30 mm/yr) occurs within the framework of the slowly moving Eurasian, African, and Somalian plates (~5 mm/yr relative to each other; McClusky *et al.*, 2000; Reilinger *et al.*, 2006) (Fig. 2).

In Crete, extension since the Late Miocene has given rise to persistent fault systems oriented N100°E, N020°E, N070°E, and N160°E (ten Veen and Postma, 1999). Active faulting on the island is well documented (Angelier, 1979; Stewart and Hancock, 1991; Armijo *et al.*, 1992; Mouslopolou *et al.*, 2001, 2011; Caputo *et al.*, 2006, 2010; Gaki-Papanastassiou *et al.*, 2009) and corresponds mainly to dip-slip normal faults oriented west-northwest–east-southeast and north-northeast–south-southwest (i.e., arc-parallel and arc-normal directions). Caputo *et al.* (2010) identified 21 major active faults including onshore and offshore structures. Other active or potentially active fault segments omitted by Caputo *et al.* (2010) have been reported by Stewart and Hancock (1991), Fassoulas (2001), and Mountrakis *et al.* (2012). Normal fault scarps typically offset calcareous slopes near the mountain–piedmont junction (Armijo *et al.*, 1992), giving rise to relatively unweathered strips of rock forming conspicuous landscape features. Scarp heights commonly exceed 10 m and exhibit a range of micro- and macroscale structures related to variations in fault-zone evolution (Stewart and Hancock, 1991). Although a number of authors have suggested that these scarps represent the cumulative effects of postglacial (Holocene) morphogenic shallow earthquakes (e.g., Dufaure, 1977; Armijo *et al.*, 1992), this hypothesis was only recently confirmed by direct exposure dating (e.g., Benedetti *et al.*, 2002, 2003; Mouslopoulou *et al.*, 2011; see also Tucker *et al.*, 2011).

The Hellenic subduction zone represents the most seismically active region in Europe, with high intermediate-magnitude earthquake activity (Papazachos and Papazachou, 1997; Papadopoulos, 2011) (Fig. 2). Examination of focal mechanisms of instrumentally measured events that have affected Crete reveals three types of earthquakes (Fig. 3; Taymaz *et al.*, 1990; Bohnoff *et al.*, 2005; Shaw and Jackson, 2010; Yolsal-Çevikbilen and Taymaz, 2012):

1. *Earthquakes in the downgoing African lithosphere (here referred to as in-slab earthquakes).* In-slab earthquakes

Table 2
Data on the 21 July 365 A.D. and 12 October 1856 A.D. Earthquakes in the Hellenic Subduction Zone Based on Seismic-Intensity Data

Earthquake	Latitude (°N)	Longitude (°E)	Focal Depth (km)	Estimated Magnitude M_S	Maximum Intensity (Modified Mercalli Scale)	Reference
21 July 365 A.D.	35.2	23.2	? (interplate)	8.3 ± 0.3	VIII+ (Kissamos, western Crete)	Papadopoulos (2011)
12 October 1856 A.D.	35.6	26.0	100	8.2	?	Papazachos (1996)
12 October 1856 A.D.	36.1	25.2	? (intermediate)	7.6 ± 0.3	IX–X (Heraklion, central Crete)	Papadopoulos (2011)

show predominantly strike-slip or thrust mechanisms with *P*-axes parallel to the local strike of the subduction zone and *T*-axes aligned along the descending slab. Slab pull (Kokinou *et al.*, 2012) and along-strike shortening of the African lithosphere (Shaw and Jackson, 2010; Yolsal-Çevikbilen and Taymaz, 2012) represent possible deformation mechanisms accounting for these events. Updated catalogs of reliable earthquake source mechanism solutions indicate that in-slab earthquakes can be found in an ~200 km wide band north of the main bathymetric scarp of the Hellenic trench (Fig. 3). Maximum focal depths vary between ~100 km in the western sector of the Hellenic subduction zone and ~170 km in its eastern sector (Becker *et al.*, 2006; Shaw and Jackson, 2010; Yolsal-Çevikbilen and Taymaz, 2012). To the north of Crete, focal depths of at least 100 km are observed (Shaw and Jackson, 2010). According to Papadopoulos (2011), one or several in-slab earthquakes might have preceded the LM IA eruption of Santorini (~1627–1600 B.C.; Friedrich *et al.*, 2006) and explain the pattern of widespread destruction observed in archaeological contexts throughout the southern Aegean at the MM IIIB–LM IA transition (Table 1; see Warren, 1991).

2. *Thrust and reverse-faulting earthquakes along the subduction interface or on splay faults merging with the interface at depth, here referred to as interface earthquakes*. Earthquakes on the interface exhibit focal depths in the range 15–45 km (Benetatos *et al.*, 2004; Meier *et al.*, 2004; Becker and Meier, 2010; Shaw and Jackson, 2010) whereas events on splay faults are typically shallower (~5–30 km, Shaw and Jackson, 2010). Interface earthquakes concentrate in a 50–100 km wide region following the bathymetric scarps of the Hellenic trench (Fig. 3; Shaw and Jackson, 2010). Shaw *et al.* (2008) related the 21 July 365 A.D. M_w 8.3 earthquake (Table 2) to a splay fault marked by the Hellenic trench southwest of Crete (Fig. 3). Although microseismic studies (Meier *et al.*, 2004; Becker *et al.*, 2006) suggest along-arc variability in the spatiotemporal distribution of interplate seismicity, it remains presently unclear whether this behavior represents a long-term characteristic of the subduction zone or a consequence of the limited period of instrumental recording (Shaw and Jackson, 2010). Analysis of the seismicity in the area of the 365 A.D. earthquake epicenter (Papazachos, 1996; Shaw *et al.*, 2008; Caputo *et al.*, 2010; Stiros, 2010) by Becker and Meier (2010) nevertheless suggests that alternating periods of locking followed by moderate magnitude earthquakes (M_w 6) and aseismic sliding occurred on the plate interface southwest of Crete during the period 0–2006 A.D. Recurrence intervals of 365 A.D.-type interface earthquakes are estimated to ~5000 years along the south-western coast of Crete and to ~800 years for the entire Hellenic subduction zone (Shaw *et al.*, 2008) from the western coasts of the Peloponnese to Rhodes.

3. *Predominantly north–south-striking, normal-faulting earthquakes within the overriding Aegean plate, generally shallower than 20 km, here referred to as normal-faulting earthquakes* (Delibasis *et al.*, 1999; Papazachos *et al.*, 2000; Benetatos *et al.*, 2004; Meier *et al.*, 2004; Caputo *et al.*, 2010; Shaw and Jackson, 2010; Kokinou *et al.*, 2012). Normal-faulting earthquakes occur in a 150 km wide zone parallel and bounded to the south by the Hellenic trench system (Fig. 3).

Whereas the two first mechanisms accommodate some of the convergence in the subduction zone, normal-faulting earthquakes can be related to an along-arc extension evidenced by both GPS velocities and slip vectors of earthquakes on the subduction interface (Shaw and Jackson, 2010). According to Caputo *et al.* (2010), normal-faulting earthquakes in Crete are characterized by magnitudes of ~6.0–6.5 and recurrence intervals ranging from 200 to 800 years for the different fault segments. These numbers assume associated surface ruptures corresponding to the entire length of fresh fault scarps and therefore represent maximum credible earthquake scenarios (Caputo *et al.*, 2006). Assuming a random time-distribution model (Papadopoulos, 1996) for seismic events occurring on kinematically independent fault segments (Caputo *et al.*, 2010), Jusseret and Sintubin (2012) suggested the occurrence of at least one morphogenic (magnitude ≥ 6) normal-faulting earthquake per century for the entire island during the last 13 ka. Destructions of Minoan settlements at Phaistos and Agia Triada ~1700 and 1450 B.C. may have been associated with such normal-faulting earthquakes (Monaco and Tortorici, 2004).

Archaeological Data

For the purpose of this study, we established a catalog of archaeological sites showing LM IIIB occupation (Fig. 1). The majority of LM IIIB archaeological sites are located in the eastern sector of the island (Fig. 1). Although it is beyond doubt that this picture partly results from research biases, a link with the island's Holocene tectomorphological context may also be suggested. It remains, however, unclear whether the observed LM IIIB site pattern is solely the result of differential preservation and visibility due to more active tectonics and associated geomorphological processes in the west (see Caputo *et al.*, 2010) or the product of differences in the density of LM IIIB human populations (with the larger, tectonically active basins of eastern Crete [e.g., Heraklion, Ierapetra, and Sitia basins] and associated normal-fault escarpments creating more ecologically attractive conditions for human settlement; Bailey and King, 2011).

Archaeological data used in this study were gathered from available excavation reports and additional information was also provided by excavators (here referred to as personal communications). Moreover, unpublished archaeological data from Sissi and Malia-Block Nu were included (see Data and Resources). Only sites comprising architectural remains and stratified ceramic evidence were considered appropriate for archaeoseismological examination (Fig. 1). Hence sites showing scant and/or poorly dated architectural evidence, as well as limited and/or unpublished ceramic data were excluded from the present analysis (Fig. 1). Moreover, although much LM IIIB funerary evidence exists (e.g., Armenoi, Damania, Maleme, Apodoulou-Sopatakia, Knossos-Upper Gypsades, Knossos-Zapher Papoura), only excavated settlements and ritual sites were taken into account. Indeed, architectural characteristics of LM IIIB graves (mostly rock-cut chamber tombs) and lack of stratified archaeological material from funerary contexts were considered inappropriate for identification of LM IIIB earthquake-related damage. Similar limitations apply to cave sites (e.g., Mamelouko). Only a few new constructions can be reliably dated to LM IIIB (e.g., Khania Buildings 1, 3, 4; see Ⓔ Table S1, available in the electronic supplement to this article). This implies possible difficulties in separating the structural effects of LM IIIB earthquake(s) from those left by earlier events. Indeed, most of the sites retained in our study (Fig. 1) correspond to isolated constructions and small settlements reoccupying earlier structures.

Method

Identifying earthquake effects on LM IIIB archaeological remains and minimizing the risk of amalgamating several seismic events in a single destruction horizon imply the following (see also Galadini *et al.*, 2006; Sintubin and Stewart, 2008; Rodríguez-Pascua *et al.*, 2011):

1. accounting for the variability of these effects by distinguishing primary from secondary earthquake archaeological evidence;
2. assessing corresponding shaking levels and potential seismic sources; and
3. critically assessing the synchronicity of events within and between sites.

Potential Earthquake Archaeological Effects (PEAEs) on Minoan Archaeological Remains

Macdonald (2001) was the first to establish a preliminary list of criteria for the identification of earthquake effects from Minoan archaeological data. Several of the criteria (buckled walls, diagonal cracks in rigid walls, cracked ashlar masonry, cracked and uplifted slabs) are, however, mainly applicable to monumental architectural evidence and are therefore difficult to use in LM IIIB contexts characterized by rubble and mud brick architecture. In order to overcome this limitation, we extended Macdonald's checklist by integrating earthquake archaeological effects most recently summarized by Rodríguez-Pascua *et al.* (2011). Other diagnostic criteria derived from the works of Warren (1991), Knappett and Cunningham (2003), and Rucker and Niemi (2010) were also integrated in our list (Fig. 4). We define potential earthquake archaeological effects (PEAEs) to emphasize the uncertainty associated with the use of individual archaeological effects as evidence for ancient earthquakes. The division into primary (direct) and secondary (indirect) effects proposed by Rodríguez-Pascua *et al.* (2011) has been retained (Fig. 4) as a means to differentiate observations related to the physical effects of earthquakes from those resulting from relief and recovery efforts, respectively. The distinction between structural and stratigraphical seismic effects (Fig. 4) is introduced as a way of addressing the variable nature of Minoan archaeological remains: where architecture is absent or consisting of a few tens-of-centimeters high walls, stratigraphical effects are likely to represent the main basis of archaeoseismological observations (Galadini *et al.*, 2006).

For each LM IIIB archaeological site, we established an inventory of PEAEs and assessed their reliability as evidence for seismic shaking. This assessment was based on stratigraphical data, photographs, and interpretations provided by excavation reports and, where possible, by personal communication with the excavators. In cases where excavation reports did not provide sufficient detail about PEAEs and where nonseismic interpretations of PEAEs were provided by the excavators, primacy was given to the latter interpretations. Eventually, only sites where seismic shaking could be identified as a reasonable explanation for PEAEs were selected for assessing the corresponding levels of ground motion.

LM IIIB PEAEs: Evaluation of Corresponding Ground-Shaking Levels and Potential Seismic Sources

The next step in our approach was to provide a realistic estimate of the level of ground shaking sufficient for PEAEs to become visible in LM IIIB archaeological contexts.

Given the limited height of LM IIIB architectural remains (often reduced to a few stone rows), we expected that most identifiable PEAEs would belong to the stratigraphical category (Fig. 4). From a taphonomic perspective, it is reasonable to admit that PEAEs can only appear consistently

	PRIMARY (DIRECT) EFFECTS	SECONDARY (INDIRECT) EFFECTS
STRUCTURAL EFFECTS	-Fractures, folds and pop-ups on pavements -Shock breakouts in flagstones -Rotated and displaced buttress walls -Tilted walls -Displaced walls -Folded walls -Penetrative fractures in ashlar masonry -Conjugated fractures in walls made of mud brick or rubble -Displaced masonry blocks -Folded steps -Collapsed vaults (tholos tombs)	-Patched up/dismantled walls -Blocked doorways sealing off collapsed structures -Recycling of construction materials -Anti-seismic constructions
STRATIGRAPHICAL EFFECTS	**-Compact layer of rubble burying valuable objects and/or human remains**, suggesting sudden wall collapse **-Folded/faulted floor surfaces and archaeological deposits** **-Earth floor surfaces pock-marked by collapsed material** **-Localized fire damage** **-Broken, *in situ* vessels** **-Broken, fallen vessels** from furniture or upper floor **-Oriented fallen objects**	**-Mixed/disturbed archaeological deposits** through removal of victims and/or valuable objects, clearing/cleaning operations, including removal of construction material (stones, beams) **-Depleted artifactual record** through removal of valuable objects **-Discarded reparation material** (tools, stones) **-Stone heaps, large dumps of pottery (complete broken vessels, closely packed)** accumulated through street and building clearing/cleaning **-Floor reconstruction** (removal, relaying)

Figure 4. Potential earthquake archaeological effects (PEAEs) on Minoan remains. Adapted from Rodríguez-Pascua *et al.* (2011) and Macdonald (2001), completed by Warren (1991), Knappett and Cunningham (2003), and Rucker and Niemi (2010). See text for further explanation.

in LM IIIB stratigraphical records if a non-negligible proportion of the building stock is subject to partial or total collapse. Therefore, levels of ground shaking greater than or equal to modified Mercalli intensity (MMI) VIII appear necessary (see also Rapp, 1986). Architectural characteristics of LM IIIB buildings (low rise, rubble and mud brick construction bonded with mud mortar, clay roofs supported by wooden posts; Moody, 2009; Shaw, 2009) suggest that they can be classified within vulnerability class A (high vulnerability) of the European macroseismic scale (EMS-98, Grünthal, 1998). According to the fragility curves proposed by Spence *et al.* (1992) for comparable structures (unreinforced rubble stone masonry), MMI VIII correlates with partial or total collapse of 51% of the building stock. This number is much higher than that estimated for MMI VII (16%), suggesting that MMI VIII is a reasonable assignment for the level of ground shaking sufficient to be recognized in LM IIIB archaeological sites consisting of a limited number of isolated buildings.

Updated empirical relationships between MMI and engineering ground-motion parameters in Greece suggest that MMI values ≥VIII correlate with peak ground acceleration (PGA) values $\geq 320\ \mathrm{cm/s^2}$ ($\sim 0.3g$) (Tselentis and Danciu, 2008). Although it is widely recognized that no single ground-motion parameter is able to capture the destructive potential of seismic shaking, we focus on PGA in this study due to its simplicity and frequent use to characterize the potential of ground motion to cause structural damage (e.g., Wald *et al.*, 1999; Douglas, 2003). We note that other authors suggested that peak ground velocity represents a more reliable indicator of damage than PGA (e.g., Cosenza and Manfredi, 2000; Bommer and Alarcón, 2006; Akkar and Bommer, 2007). Nevertheless, PGA forms the basis of the relationships of Atkinson and Boore (2003; presented below) and is a commonly adopted ground-motion parameter in archaeoseismological research (e.g., Wechsler *et al.*, 2009; Hinzen *et al.*, 2010; Tendürüs *et al.*, 2010; Yagoda-Biran and Hatzor, 2010). Therefore, its use in the present study is also justified by an effort to facilitate comparison with other archaeoseismological results.

Expected PGA values at LM IIIB sites were estimated based on the empirical ground-motion relationships proposed by Danciu and Tselentis (2007) for normal-faulting earthquakes and by Atkinson and Boore (2003) for in-slab and interface events. The Danciu and Tselentis (2007) relationships were preferred to earlier predictive equations proposed for the area of Greece (e.g., Theodulidis and Papazachos, 1992) due to the larger data set used by Danciu and Tselentis (2007). Applicability of Atkinson and Boore's relationships to the Hellenic subduction zone is, on the other hand, suggested by the good agreement found by Skarlatoudis *et al.* (2009) between observed and predicted values of PGA for the 8 January 2006 A.D. Kythera in-slab earthquake.

For normal-faulting earthquakes, we assumed maximum credible earthquake scenarios rupturing the entire length of the fault segments (Pavlides and Caputo, 2004). Accordingly, epicenters were plotted toward the center of the hanging wall, assuming hypocenters in the depth range 5–20 km (e.g., Papazachos *et al.*, 2000; Shaw and Jackson, 2010) and using dip angles provided by Caputo *et al.* (2010) for the 21 major normal faults recorded on the island and its offshore area. For other fault segments, we assumed dip angles of 45° based on characteristic dip ranges (30°–60°) of active normal faults (Jackson and White, 1989). Maximum expected magnitudes for the different fault segments were defined according to Pavlides and Caputo (2004) and Caputo *et al.* (2010).

According to local geological conditions at LM IIIB sites, two categories of sites were used to capture the influence of surficial geology on PGA estimates: pre-Neogene rock formations (i.e., rock soil, National Earthquake Hazards Reduction Program [NEHRP; Dobry *et al.*, 2000] soil category B) and Neogene–Pleistocene deposits (marl, clay, sand, sandstone, conglomerate; i.e., stiff soil, NEHRP soil category C) (see Sarris *et al.*, 2006; Tsiambaos and Sabatakakis, 2011).

Maximum magnitudes for interface and in-slab earthquakes were estimated to ~8.3 and ~7.5, respectively, based on the updated catalog of Papadopoulos (2011) for the area of Crete. Corresponding PGAs were estimated based on the relationship of Atkinson and Boore (2003) for different values of NEHRP soil category (B or C), focal depth (h), and closest distance to fault surface (D). According to Shaw and Jackson (2010), values of h were limited to 20–100 km for in-slab earthquakes and to 5–45 km for interface events. To assess minimum credible distances between the earthquake fault plane and the ground surface, we then considered values of h and corrected them for fault size (assuming hypocenters in the center of faults), using the empirical relationships of Strasser *et al.* (2010) that predict fault plane dimensions of subduction earthquakes as a function of magnitude. However, we also tested the relationships of Blaser *et al.* (2010) and found that both sets of relationships lead to the same interpretation of archaeoseismological evidence. Eventually, definition of damage zones with PGA values $\geq 320\ \text{cm/s}^2$ was based on fault plane geometric properties provided by Strasser *et al.* (2010) and assuming dip angles of 45° for interface earthquakes and 60° for in-slab events (see online supporting information of Shaw and Jackson, 2010).

Assessment of the Synchronicity of Events

Evaluation of the time resolution of seismic damage represents a crucial step to constrain the age of the causative event and evaluate the probability that each instance of damage was caused by the same earthquake. In the context of LM IIIB Crete, assessing the synchronicity of seismic damage is essential because previous research (Nur and Cline, 2000) suggested that a series of related earthquakes may have occurred in the Eastern Mediterranean region during the period 1225–1175 B.C. (end of LM IIIB–beginning of LM IIIC in Crete; Table 1). Because no radiocarbon dates are available for LM IIIB contexts, we evaluated the synchronicity of events based on ceramic evidence. Taking into account the limited temporal resolution of LM IIIB ceramic data (several decades, corresponding at some archaeological sites to two subphases: LM IIIB1/early and LM IIIB2/late) and considering recent examples of damage accumulation on sites associated with a series of closely spaced seismic events (e.g., Christchurch, New Zealand), we consider the "same earthquake" as the "collection of earthquakes consisting of the mainshock, its immediate aftershocks, as well as possibly triggered earthquakes on the same or neighboring fault segments during weeks to months after the mainshock that initiated the PEAEs."

For the purpose of this study, relative dating of seismic damage to LM IIIB1/early, LM IIIB2/late, or LM IIIB (without possibility of further chronological refinement) was established by reference to the list of diagnostic ceramic criteria presented in the Ⓔ electronic supplement to this article and through examination of site-specific stratigraphical records.

Results

LM IIIB PEAEs

According to the suggested damage typology (Fig. 4) and pottery-based chronological framework (see the Ⓔ electronic supplement), it has been possible to recognize PEAEs on LM IIIB1/early and LM IIIB2/late archaeological sites. Consistent with our expectations, stratigraphical effects represent the most common source of evidence. No primary structural effects could be identified based on available archaeological reports. A detailed presentation of all recorded LM IIIB PEAEs is proposed in the Ⓔ electronic supplement to this article (Table S1), which includes chronological and taphonomic interpretations of PEAEs as found in excavation reports and published articles. In some cases, new chronological interpretations could be suggested based on stratigraphical information and diagnostic ceramic criteria listed in the Ⓔ electronic supplement. These new interpretations are also presented in Ⓔ Table S1 (available in the electronic supplement) and served as a basis for constraining

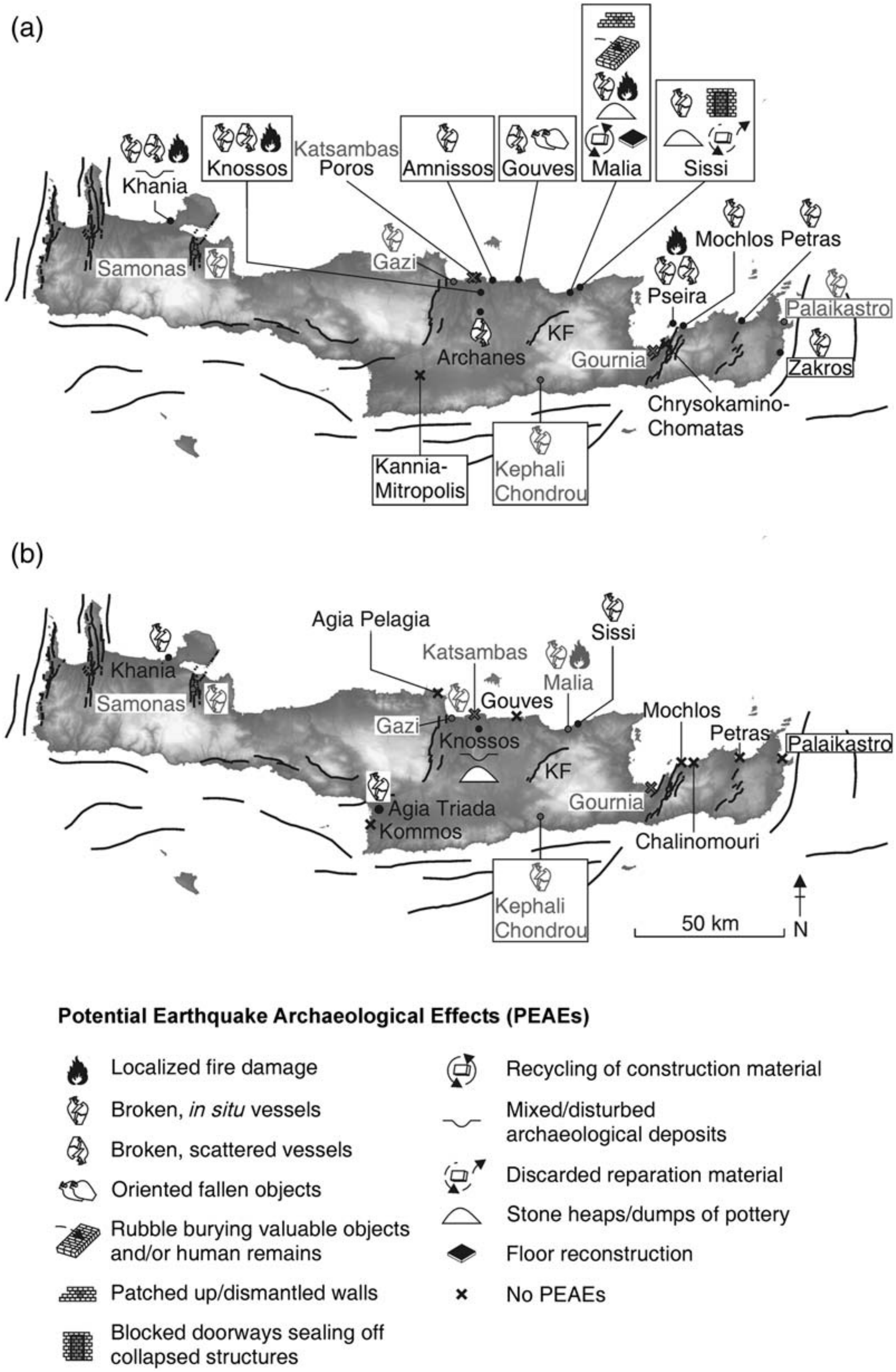

Figure 5. Potential earthquake archaeological effects (PEAEs) during (a) LM IIIB1/early; (b) LM IIIB2/late. Black lines, active normal faults according to Caputo *et al.* (2010), completed by Mountrakis *et al.* (2012). Gray, uncertain chronology; KF, Kastelli fault. (Background DEM courtesy of Laboratory of Geophysical-Satellite Remote Sensing & Archaeo-Environment [IMS-FORTH, Rethymno].)

the synchronicity of PEAEs in the present study. A synthetic representation of LM IIIB1/early and LM IIIB2/late effects is illustrated in Figure 5.

In most cases, PEAEs could not be confidently related to ground-shaking effects: the only credible evidence for earthquake-related damage was identified at the sites of Malia and

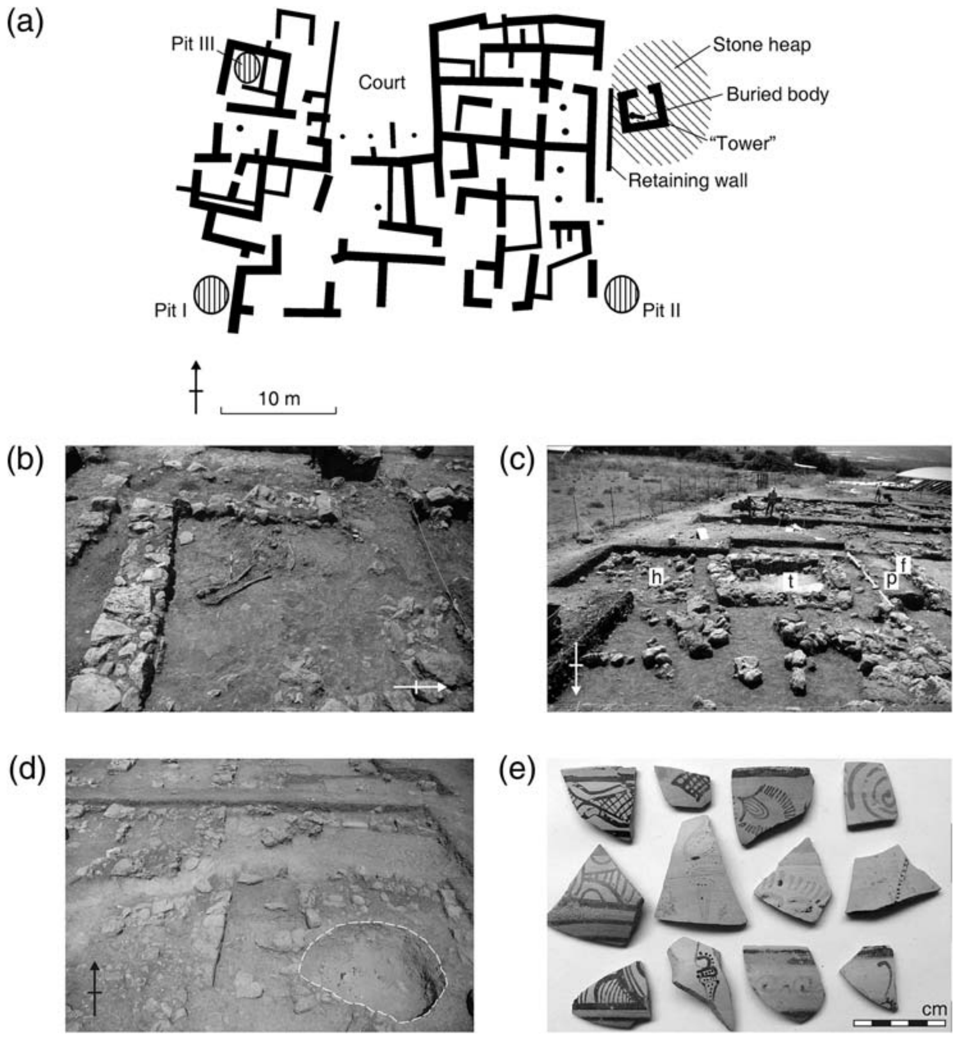

Figure 6. Potential earthquake archaeological effects (PEAEs) at Malia-Block Nu. (a) Schematic plan with features mentioned in the text (modified after Driessen and Fiasse, 2011); (b) skeleton found buried under rubble in the so-called "tower"; (c) heap of rubble (h) dumped to the east of the complex and partly over the "tower" (t), and retaining wall (white dashed line) constructed of collapsed debris and associated path (p) opened along the east façade of the complex (f); (d) pit II (outline in dashed white line); (e) LM IIIA2-IIIB1/early decorated sherds of fine drinking vessels from pit II. (Photos courtesy of École française d'Athènes.)

Sissi (northeastern Crete) and dated to LM IIIB1/early (Fig. 5a). In the following, we therefore focus on the PEAEs documented at LM IIIB1/early Malia and Sissi (see Ⓔ Table S1, available in the electronic supplement, for detailed references).

LM IIIB1/early evidence at Malia is restricted to two building blocks: Block Epsilon and Block Nu. Block Epsilon, an ~3000 m^2 building constructed in MM III (Table 1) and modified on several occasions, suffered minor destructions before its final occupation in LM IIIB1/early (Driessen, 2010). LM IIIB1/early remains are, however, scant, leading one of the excavators to assume a squatter occupation of the building (Pelon, 1970). Block Nu (~750 m^2, Fig. 6a), on the other hand, appears to have been constructed during LM IIIA2-B1/early (Table 1) on top of redeposited destruction material belonging to LM IIIA1/early 2 (Table 1; Driessen, 2010). Block Nu consists of four or five habitation units organized around a small court (Fig. 6a). To the east of the complex, a small square building (~10 m^2) was interpreted by the excavators as a tower (due to the massive character of the walls, ~0.75 m thick, and its prominent topographical position with respect to the rest of the complex) with a kitchen on the ground floor (Driessen and Farnoux, 1994). Localized fire damage was recognized as PEAE in both architectural complexes. At Block Nu, *in situ* broken vases and a skeleton found buried under rubble in the "tower" building (Fig. 6a,b) represent other PEAEs. Dismantling of walls to the north of the court, dumping of rubble to the east of the complex, and reuse of collapsed building material for the construction of a retaining wall along the eastern façade can be considered as possible relief and recovery efforts following earthquake damage (Fig. 6a,c). Dumping of a mixture of pottery and ash in three large pits (Fig. 6a,d) may be similarly interpreted as the result of cleaning operations following earthquake destruction. However, it must be stressed that it remains unclear whether the pits reflect unique (LM IIIB1/early) or multiple (LM IIIA2-B1/early) dumping events (Table 1). Likewise, the presence of large quantities of high-quality drinking vessels (Fig. 6e) among the pits' material does not exclude that some of it derived from feasting (Driessen *et al.*, 2008), perhaps organized as a means of mobilizing labor for rebuilding activities (Wright, 2004). Excavators further noted that the LM IIIB1/early destruction of Block Nu was in certain cases followed by the digging out of floors and reconstruction of new floors at a lower level. This observation may represent secondary evidence for earthquake damage of LM IIIB1/early floors, with deformation and/or pockmarking by fallen stones possibly necessitating thorough removal of floor packing.

At the settlement of Sissi, located 4 km east of Malia on top of a coastal hill, LM IIIB1/early remains can be associated with a monumental architectural complex (Building CD, ~700 m^2) counting 29 ground floor rooms and spaces (Gaignerot-Driessen and Letesson, 2012) (Fig. 7). Inside the building, several rooms located in the northern and western wings yielded large deposits of *in situ* broken vases that can be confidently dated to LM IIIB1/early. A pit excavated next to Building CD also produced redeposited LM IIIB1/early material (Fig. 7a). The pit was found filled with pottery, fragments of plaster, mud brick, and tarazza (a mixture of lime and beach pebbles used as flooring material; Shaw, 2009). A pivot stone and a step found amongst the pit material strongly suggest cleaning operations following structural damage. A dense heap of stones covering the northern part of the pit strengthens this hypothesis (Fig. 7b). Indeed, ammouda (local sandstone) ashlar fragments and a window jamb were found amongst the stones and suggest material originating from wall collapse (Fig. 7a,c). The discovery of a second window jamb of identical manufacture and dimensions in Room 3.6 of Building CD (Fig. 7a,d,e) suggests that most, if not all the material from the pit derives from the cleaning of this building. Reconstruction activities are indicated by the discovery of percussive lithic tools in the pit material (Fig. 7f). According to Tsoraki (2012), the large size, heavy weight, and abrasive patterns of the tools suggest that they were used in building activities requiring heavy impact force. That most of the tools were not heavily worn moreover suggests a relatively short period of use followed by a single discard event. These observations fit well with the suggestion of Rucker and Niemi (2010) that earthquake reconstruction typically takes place soon after the event or not at all. Added blocked doorways should be added to these PEAEs sealing off LM IIIB1/early destruction debris in at least two rooms (4.7 and 4.9) of Building CD (Fig. 7a). Although several other doors of the building appear to have been blocked during LM IIIB (Fig. 7a), the uncertain date and/or unclear purpose of the blocking prevents considering this evidence as further proof for earthquake shaking during LM IIIB1/early. Likewise, chronological uncertainty associated with *in situ* broken vessels in some rooms of Building CD and nearby Building E means that they cannot presently be used as conclusive LM IIIB1/early archaeoseismic information. A lead vase—a rare and undoubtedly a highly prized object—found buried under an LM IIIA2/B1/early floor in Building E may, on the other hand, suggest rapid abandonment (Joyce and Johannessen, 1993; Devolder, 2009; M. Devolder, personal comm., 2012) or unexpected death of its owner during a destructive event.

Although sudden collapse related to soil instability cannot be entirely ruled out as an alternative cause of damage at Malia and Sissi, it seems unlikely that this factor alone could have caused the death of Malia-Block Nu's buried body and required the digging out of existing floor levels. Moreover, architectural complexes of Malia-Block Nu and Sissi-Building CD are constructed on flat ground, suggesting limited influence of soil creep. Limited soil thickness likewise suggests that differential settling of unconsolidated foundation materials cannot account for the sudden collapse of the structures (see Rapp, 1986). Considering the absence of traces of violence and the continuous occupation of both settlements after destruction, we conclude that earthquake ground motions represent a reasonable explanatory framework for the observed PEAEs.

Potential Earthquake Sources

In this section, we evaluate possible seismic sources (normal fault, subduction interface, subducting slab) for LM IIIB1/early PEAEs at Malia and Sissi.

Recurrence of moderate-to-strong normal-faulting earthquakes in Crete (at least one morphogenic event per century; Caputo *et al.*, 2010; Jusseret and Sintubin, 2012) suggests that such events should be considered as likely sources of earthquake-related damage. According to Figure 5, the only major active fault located at close distance from the sites is the Kastelli fault (see Caputo *et al.*, 2006). According to Caputo *et al.* (2010), this 13 km long structure is able to generate earthquakes of magnitude up to 6.7 with a mean recurrence interval of 812 years. Considering local geological conditions (limestone, NEHRP B) at Malia and Sissi, we estimated that an earthquake of M_w 6.7 would produce PGA values below the suggested threshold of 320 cm/s^2 (MMI ~ VIII). This result, presented in Table 3 for scenarios corresponding to minimum (5 km) and maximum (20 km) credible focal depths of normal-faulting earthquakes in the area of Crete, leads us to conclude that PEAEs at Malia and Sissi cannot be confidently related to earthquake activity on the Kastelli fault. This conclusion can in all probability be extended to two major fault segments reported by Fassoulas (2001) to the southeast of Malia and Sissi. Indeed, although these two faults terminate at close distance from the sites (≤5 km), absence of fresh fault scarps suggests that any Holocene earthquake activity did not rupture the ground surface and should therefore be associated with magnitudes ≤5.5 (see Pavlides and Caputo, 2004). In such circumstances, the Danciu and Tselentis (2007) relationships indicate PGA values ≤320 cm/s^2 at Malia and Sissi,

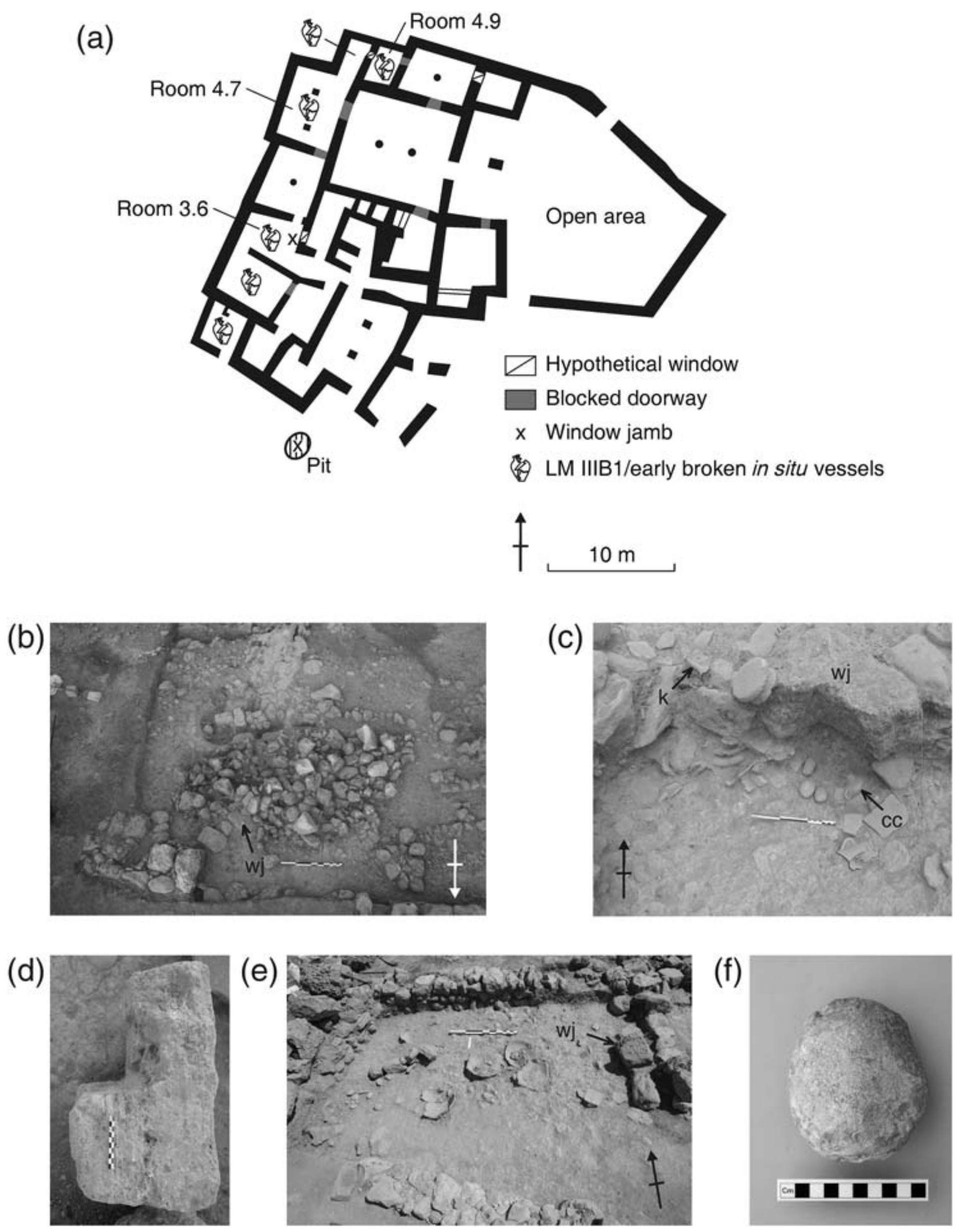

Figure 7. Potential earthquake archaeological effects (PEAEs) at Sissi. (a) Schematic plan with features mentioned in the text (modified after Gaignerot-Driessen and Letesson, 2012); (b) pit south of Building CD with northern part covered by a stone heap (photo by L. Manousogiannaki), with window jamb (wj) shown in (a) and (c); (c) section through pit showing ammouda (sandstone) window jamb (wj), champagne cup (cc), and foot of kylix (k) (photo by M. Devolder); (d) window jamb in ammouda found in Building CD, Room 3.6 (photo by F. Gaignerot-Driessen); (e) window jamb (wj) as found in Building CD, Room 3.6 (photo by F. Gaignerot-Driessen); (f) hammer-grinder from pit (Photo by B. Chan). (Photos courtesy of Sissi Archaeological Project.)

which we consider insufficient to have caused archaeologically recognizable damage.

To investigate the possibility that subduction earthquakes may be responsible for the observed damage, we then calculated PGA values for M_w 6.5, 7.0, 7.5 (interface and in-slab events), and 8.3 (interface events only) on NEHRP B sites. The results of these estimates are presented on Figure 8a–c and Figure 8d–g for in-slab and interface events, respectively. Figure 8d–f reveals that maximum values of PGA for interface earthquakes of $M_w \leq 7.5$ are approximately 180 cm/s^2. This result suggests that ground shaking generated by interface

Table 3

Maximum Expected PGA Values at Malia and Sissi for Normal-Faulting Earthquakes (M_w 6.7 Earthquake on the Kastelli Fault)

Site	Focal Depth (km)	Epicentral Distance R (km)	PGA (cm/s^2)
Malia	5	13.1	232
	20	13.6	225
Sissi	5	16.8	190
	20	17.3	185

After Danciu and Tselentis (2007).

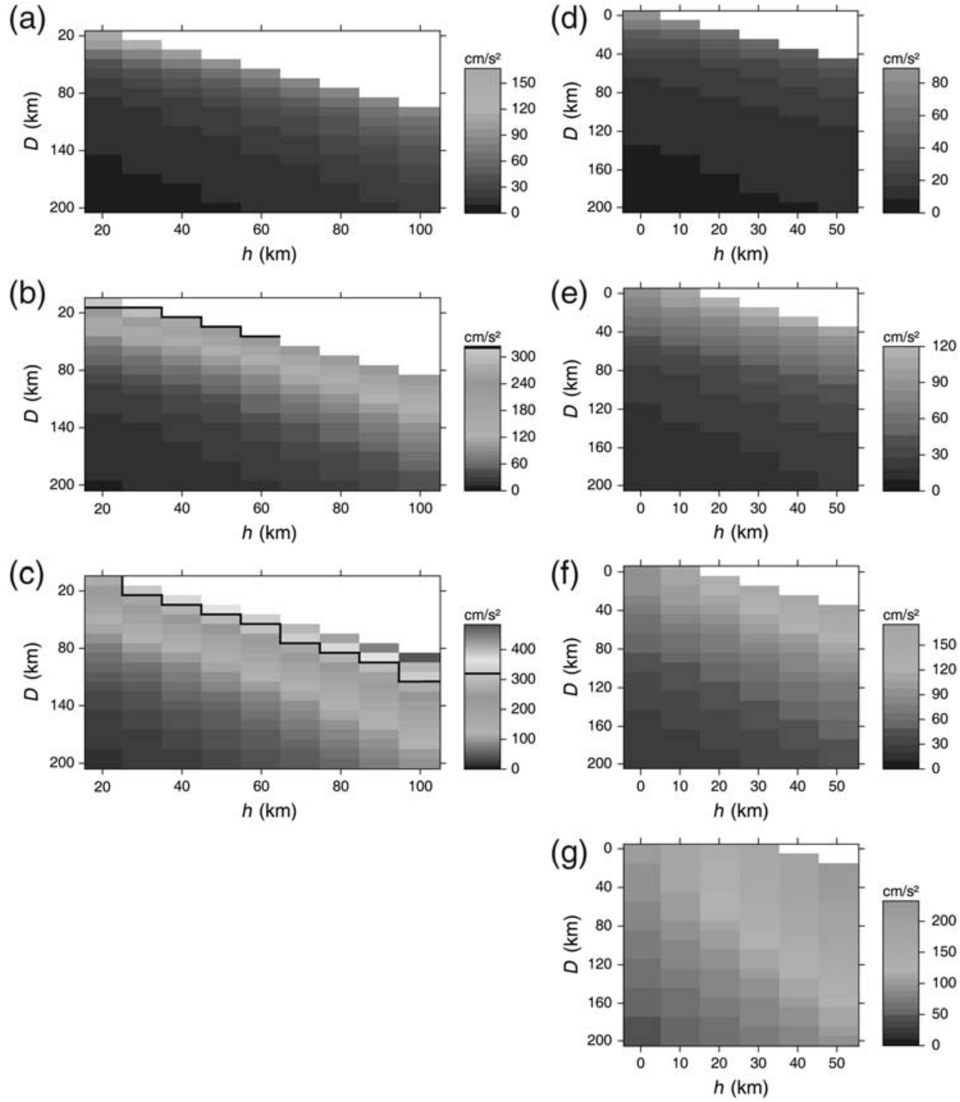

Figure 8. Predicted PGA for rock sites (NEHRP B) as a function of closest distance to the fault plane D and focal depth h based on the relationships of Atkinson and Boore (2003). In-slab events: (a) M_w 6.5; (b) M_w 7.0; (c) M_w 7.5. Interface events: (d) M_w 6.5; (e) M_w 7.0; (f) M_w 7.5; (g) M_w 8.3. Black lines indicate values of 320 cm/s^2. See text for further explanation.

earthquakes is probably insufficient to have caused significant damage at Malia and Sissi. Interestingly, this conclusion remains valid (PGA ≤ 230 cm^2, Fig. 8g) even for events of magnitude comparable to the destructive 365 A.D. earthquake (~M_w 8.3; Shaw *et al.*, 2008; Becker and Meier, 2010; Papadopoulos, 2011). This observation may be related to an inadequate choice of PGA threshold (320 cm/s^2), to the inaccuracy of PGA as an indicator of structural damage, to the lack of consideration of vertical acceleration components in the suggested PGA relationships, or to a combination of these factors. In the case of coseismic uplift such as during the 365 A.D. event (Shaw *et al.*, 2008), neglect of vertical acceleration components may conceivably explain part of the divergence between predicted PGA values and observed archaeological damage (see Stiros and Papageorgiou, 2001; Stiros, 2010).

Figure 8b,c, on the other hand, indicates that M_w 7.0 and 7.5 in-slab earthquakes are capable of producing PGA values greater than 320 cm/s^2. However, these damaging levels of ground shaking attenuate rapidly with distance from the fault plane. Hence for a scenario where M_w 7.5 and $h = 100$ km, PGA values ≥ 320 cm/s^2 are predicted to occur within 110 km of the fault on NEHRP B sites such as Malia and Sissi. A consideration of the location of events with well-constrained depths in the Hellenic subduction zone (see Shaw and Jackson, 2010) reveals that several combinations of magnitude, h, and D would potentially account for PGA values ≥ 320 cm/s^2 at Malia and Sissi. It is, however, worth noting that the rupture plane of an M_w 7.5 earthquake at a depth of 100 km within the African slab may realistically be positioned within 110 km of Malia and Sissi. The characteristics of such an event compare well with the parameters suggested by Papadopoulos (2011) for the 12 October 1856 A.D. earthquake in the Hellenic subduction zone (Table 2).

Discussion and Conclusions

In a recent review of the methodological issues underpinning archaeoseismological research, Galadini *et al.* (2006) highlighted two major difficulties faced by the discipline: (1) discriminating ancient earthquake effects from those associated with other natural and human-related phenomena and (2) excluding the possibility that the observed damage has been caused by more than one seismic event. In this research, it has been suggested that a temporally restricted approach (Jusseret and Sintubin, 2012) combined with an estimation of site-specific PGA levels can provide a methodological basis to overcome these difficulties in Minoan archaeological contexts. However, because it is likely that archaeoseismological observations alone will never be able to ascertain the reliability of seismogenic hypotheses (perhaps with the exception of direct faulting of archaeological remains or ground fracturing; see Galli and Galadini, 2001; Sintubin *et al.*, 2008; Hinzen *et al.*, 2011; Alfonsi *et al.*, 2012; Berberian *et al.*, 2012), cross validation through quantitative scientific approaches appears necessary before any firm conclusions can be drawn (e.g., paleoseismological trenching, McCalpin, 2009, and Rockwell *et al.*, 2009; cosmogeochronological studies of carbonate fault scarps, Mouslopoulou *et al.*, 2011; quantitative modeling of the effects of site-specific ground motions on Minoan constructions, Hinzen *et al.*, 2011). Once rigorously validated, physical effects of earthquakes (our PEAEs) may provide a unique way to understand "the type and dimensions of earthquake ground effects linked to different levels of seismic shaking" (Reicherter *et al.*, 2009, p. 4). In this perspective, archaeological sites may serve as seismoscopes (Sintubin, 2011) helping to define maximum credible shaking intensities in the region. Information derived from site-specific PEAEs may also be complementary to that offered by paleoseismology, because relatively fragile LM IIIB constructions may have suffered damage from smaller earthquakes than those recorded geologically (Galadini *et al.*, 2006). These prospects present great opportunities and challenges for a seismically active region such as Crete where prehistoric earthquake catalogs remain largely fragmentary (see Papadopoulos, 2011).

In this paper, we attempted to bring forward a methodological framework for the study of ancient earthquakes during the LM IIIB period as recorded by PEAEs in archaeological sites (Fig. 4). In contexts of isolated buildings and/or limited excavations, as is often the case in LM IIIB archaeological contexts, these effects are likely to appear for MMI values ≥ VIII (see also Rapp, 1986). Our approach relies on the assessment of the levels of PGA generated by normal-faulting, interface, and in-slab earthquakes (Atkinson and Boore, 2003; Danciu and Tselentis, 2007) (Table 3, Fig. 8). Considering the multidecadal time resolution provided by LM IIIB ceramic material, earthquake archaeological damage should necessarily be understood as the palimpsest (or superimposition) of the individual effects of seismic clusters comprising the mainshock, its immediate aftershocks and possible earthquakes triggered on the same or neighboring fault segments during a period up to several months (what we have defined as the "same earthquake").

This methodology led us to suggest that PEAEs at the LM IIIB1/early sites of Malia and Sissi (Ⓔ Table S1, available in the electronic supplement, and Figs. 5–7) had a good probability to have been caused by earthquake ground motions. Estimates of PGA values generated by normal-faulting and subduction earthquakes indicate that an in-slab earthquake comparable to the 1856 A.D. event would be capable of producing the observed levels of damage. The 1856 A.D. event (Table 2, Fig. 9), tentatively located a few tens of kilometers off the coasts of northern (Papadopoulos, 2011) or northeastern Crete (Papazachos, 1996), is reported by historical sources to have caused heavy shaking (MMI ≥ VIII) in the region of Heraklion and in the eastern part of the island (see Ambraseys, 2009; Papadopoulos, 2011). An event comparable to the 1856 A.D. earthquake may therefore have been responsible for PEAEs at Malia and Sissi. Although the regional extent of damage (PGA ≥ 320 cm/s^2 or MMI ≥ VIII) would have been relatively limited for NEHRP B sites such as Malia and Sissi ($D \leq 110$ km), estimates based on the relationships of Atkinson and Boore (2003) for NEHRP C sites (Neogene and Pleistocene deposits) suggest much larger meizoseismal areas ($D \leq 130$ km; Fig. 9). Applied to our hypothetical 1865 A.D.-type event, meizoseismal areas defined by $D \leq 130$ km would cover most of central and eastern Crete (Fig. 9). This result compares well with the damage distribution of the 1856 A.D. earthquake reported by Sieberg (1932), Ambraseys (2009), and Papadopoulos (2011) (Fig. 10). In particular, we note that regions reported to have suffered the most from the 1856 A.D. earthquake (Heraklion, Ierapetra; Fig. 10) are dominated by Neogene and Pleistocene deposits (NEHRP site class C; Fig. 9) favorable to local ground-motion amplification. Interestingly, two archaeological sites located on NEHRP C soils in central Crete (Gouves, Archanes; Fig. 9) exhibit LM IIIB1/early PEAEs explicitly related to earthquake ground motions by their excavators (Ⓔ Table S1, available in the electronic supplement). At Gouves, PEAEs include broken fallen vases and north-northeast–south-southwest-oriented fallen objects (Vallianou, 1996). Widely scattered fragments of objects have likewise been identified as PEAE at the site of Archanes (Sapouna-Sakellaraki, 1990).

On the other hand, no conclusive archaeological evidence can be found for the onset of a seismic storm around 1225 B.C. (LM IIIB2/late) as suggested by Nur and Cline (2000). Indeed, only limited evidence for seismic damage is available for LM IIIB2/late (Ⓔ Table S1, available in the electronic supplement, and Fig. 5) and earthquakes do not seem necessary to explain the observed PEAEs. Therefore, our results do not presently support a geophysical cause for the demise of Bronze Age Crete. Our approach, though, demonstrates the feasibility of developing transparent and

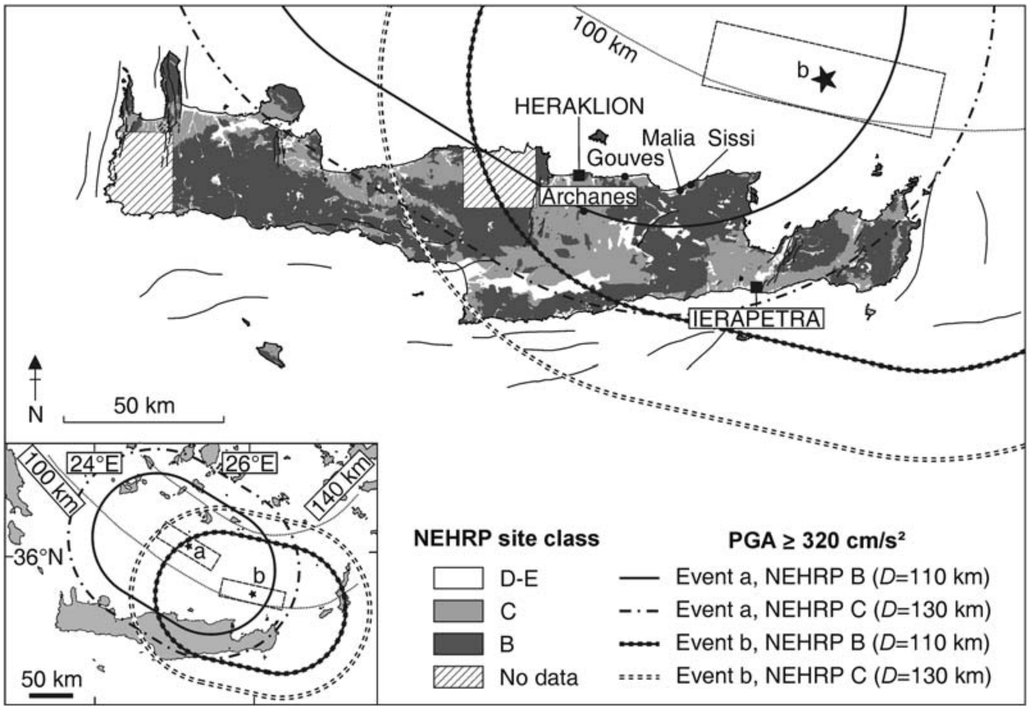

Figure 9. Estimated zones with PGA values ≥320 cm/s^2 as a function of NEHRP site classes (B, C) for an in-slab event of M_w 7.5 (focal depth 100 km) and epicentral coordinates corresponding to the 12 October 1856 A.D. earthquake (a, epicentral location according to Papadopoulos, 2011; b, epicentral location according to Papazachos, 1996). NEHRP B, pre-Neogene rocks; NEHRP C, Neogene–Pleistocene deposits; NEHRP D–E, Holocene deposits. Black lines indicate active faults according to Caputo *et al.* (2010) and Mountrakis *et al.* (2012). Dashed rectangles correspond to the surface projection of the presumed fault planes (after Strasser *et al.*, 2010). Dotted lines indicate the depth of the African slab after Hatzfeld and Martin (1992). A full representation of zones with PGA values ≥320 cm/s^2 is shown in the inset. (NEHRP site classes derived from geological data courtesy of Laboratory of Geophysical-Satellite Remote Sensing & Archaeo-Environment [IMS-FORTH, Rethymno].)

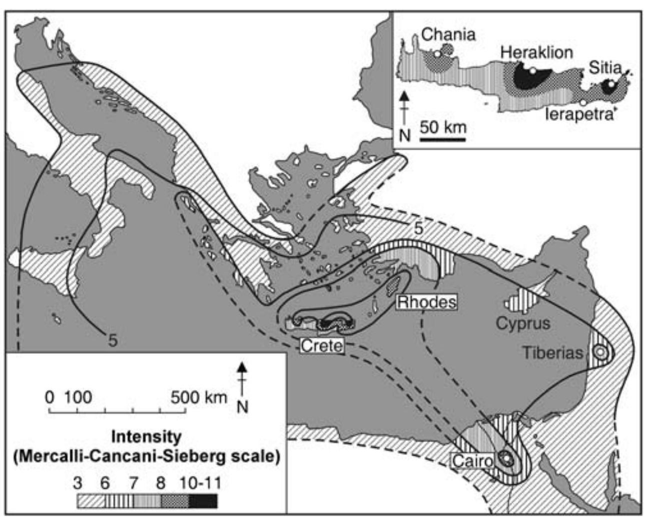

Figure 10. Isoseismal map of the 12 October 1856 A.D. earthquake, redrawn after Sieberg (1932). The inset map presents a detailed view of Crete, including main modern towns.

empirically testable archaeoseismological hypotheses (see Hinzen *et al.*, 2011), undoubtedly an important step in the overall acknowledgment of archaeoseismology as a reliable and useful discipline in the broader field of seismic studies.

Data and Resources

Most data used in this article come from published sources listed in the references. Sources of unpublished information concerning LM IIIB archaeological sites are acknowledged in the Ⓔ electronic supplement (Table S1). Photographs from the excavations at Sissi were retrieved from the Sissi Archaeological Project database at UCL. Photographs and unpublished archaeological information from Malia-Block Nu were obtained from Jan Driessen's personal database at UCL. The outline of the seismic hazard zones in the Aegean region (Fig. 2) is taken from the Global Seismic Hazard Assessment Program (http://www.seismo.ethz.ch/static/gshap/index.html, last accessed June 2013), through the U.S. Geological Survey Earthquake Hazard Program database (seismic-hazard map of Greece, http://earthquake.usgs.gov/earthquakes/world/greece/gshap.php; seismic hazard map of Turkey, http://earthquake.usgs.gov/earthquakes/world/turkey/gshap.php; last accessed June 2013). The list of earthquake archaeological effects in Minoan contexts (Macdonald, 2001) was retrieved from http://edinburgh.academia.edu/ColinMacdonald/Papers/476257/Defining_Earthquakes_and_identifying_their_consequences_in_North_Central_Crete_during_the_Old_and_New_Palace_Periods (last accessed June 2013).

Data used for the construction of background maps illustrated on Figures 1, 5, and 9 were provided by the Laboratory of Geophysical-Satellite Remote Sensing & Archaeo-Environment (IMS-FORTH, Rethymno).

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