

# Abandonment of Minoan palaces on Crete in relation to the earthquake induced changes in groundwater supply

Yuri Gorokhovich

*Columbia University, Department of Earth and Environmental Engineering, 918 Seeley Mudd Building,  
500 West 120th St, New York, NY 10027, USA*

Received 6 June 2004; received in revised form 8 September 2004

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## Abstract

Mysterious abandonment of palaces on Crete during the Late Minoan period was always a challenging problem for archeologists and geologists. Various hypotheses explained this event by effects of tsunamis, earthquakes or climatic changes that were caused by the volcanic eruption of the Santorini volcano. While each of them or their possible combination contributed to the abandonment of palaces and following Late Minoan crisis, there is another possible cause that appeared as a result of studies within the last 20–30 years. This cause is depletion of groundwater supply caused by persistent earthquake activity that took place during the Bronze Age. This explanation is supported by field observations and numerous studies of similar phenomena in other locations.

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*Keywords:* Minoan period; Crete; Earthquakes; Groundwater depletion

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## 1. Introduction

The abandonment of Cretan palaces during the Late Minoan period (1300–1700 years BCE) is one event that awaits its own explanation. The majority of causes that were considered by the scientific community since the discovery of Cretan palaces during the late 19th century are related mainly to the post effects of the eruption of the Santorini volcano and high seismic activity in the Mediterranean region during the Late Bronze Age.

The Santorini volcano, located on the island of Thera, approximately 70 km north from Crete, was considered to be responsible for one of the main volcanic eruptions in the history of western civilization when it erupted somewhere between 1500 and 1700 years BCE. This event coincided with the archeological period known as Late Minoan, when palaces on Crete were abandoned and Mycenaean civilization replaced it

with a new type of art, culture and language. Thus, the Santorini eruption was also called the Minoan eruption. These geological and archeological events triggered a variety of speculations and theories, including the relation of Santorini to the lost ancient city of Atlantis.

The theory of tsunami triggered by the volcanic eruption of Santorini, the consequential earthquakes that destroyed palaces on Crete and led to the decline of the Minoan civilization was proposed by Professor Spyridon Marinatos [18]. He studied the island of Thera and in 1967 discovered there a city of Akrotiri buried by volcanic ash. Earlier, Sir Arthur Evans [8] had suggested that Cretan palaces were abandoned due to the repeated earthquake activity. After these theories were proposed, both geologists and archeologists started collecting evidence.

After more than 70 years of research, the only evidence upon which geologists and archeologists have agreed, was that of earthquake activity which precluded the Minoan eruption on Santorini and continued long after. In a fundamental monograph on the archeology of

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*E-mail address:* [yg119@columbia.edu](mailto:yg119@columbia.edu)

Cretan palaces [6] authors indicated that earthquake activities took place between Middle Minoan (MM) IIIB and Late Minoan (LM) IA (i.e. after the Santorini eruption) and that there was seismic destruction of walls before the volcanic eruption of Santorini. According to this study, the restored sequence of events for the Knossos Palace includes:

1. Middle Minoan (MM) destruction and some burning;
2. Evan's/Hood's MM–LM earthquake destruction (probably from Thera) and burning at the beginning;
3. LM IA earthquake destruction (possibly coincided with volcanic eruption of Thera);
4. LM IB partial earthquake destruction and burning.

The study also mentioned that of more than 59 sites on Crete, including palaces and remnants of dwellings, 18 certainly suffered from earthquakes, i.e. almost 1/3 of them.

Abandonment of palaces on Crete during the Late Minoan period is still a mystery. Many current ideas are based primarily on volcanic post effects of the Santorini eruption that include the tsunami impact on Crete or a tephra layer that would destroy agriculture. Currently, too little an amount of tephra was found on Crete [34]. The tsunami hypothesis did not receive support from modeling experts [13] and the latest geologic studies [5] and therefore more room is left for further hypotheses and data collections.

The evidence of earthquake activity, on which both geologists and archeologists agree, relates to the plate tectonics structure within the Mediterranean region. In the article on plate tectonics and earthquake storms during the Late Bronze Age, Nur and Cline [23] suggested that a series of earthquakes or so-called 'earthquake storms' were events that could have occurred in the Mediterranean region. Similar evidence of severe earthquake activity during the end of Protopalatial (1700 BC) and the Neopalatial (1450 BC) periods come from the research work of Monaco and Tortorici [20]. The Mediterranean region is highly seismic even now and constantly experiences major and minor earthquakes. From the point of view of actualism, the same processes were apparently happening during the LM period.

Repeated earthquake activity could constantly ruin dwellings and create havoc in the lives of Late Minoan people but they were able to repair walls, roofs and get back to normal life as seen from the multiple repairs documented from archaeological excavations [6]. Apparently, an event other than earthquakes, volcanic eruptions or wars with people from the mainland affected the life of Minoan people and forced them to leave Crete.

## 2. Water resources in Cretan palaces

In a comprehensive study on Cretan palaces and mysteries associated with them, Driessen and Macdonald [6] wrote that '... water and food are necessary for survival and despite a century of Minoan archeology we are still largely unaware as to how Minoans provided themselves with these basic elements.' They also cited little evidence for the supply of fresh water to the palace of Knossos. At the same time, Knossos represents an example of the earliest use of the flush toilet, underground water storage and sophisticated systems of water mains. At Phaistos Palace, Minoans developed a fascinating system of storm drains. Apparently, there were enough people and water resources that created a need for such comprehensive hydraulic designs and systems.

The most substantial description of water engineering in Minoan times can be found in [1]. The authors propose that our knowledge of ancient water supply comes mainly from the Palace of Knossos, one of the best excavated sites on Crete. Other palaces and sites, like Phaistos and Zakros also contribute to the knowledge of water supply. Three main sources of water supply in these palaces were wells, springs and surface water. There were also underground cisterns for the storage of water.

Knossos Palace had both a well supply and spring source from the Mavrokolybos and Fundana springs located at higher elevations. Springs provided water to the palace via aqueducts that consisted of clay pipes connected by cement joints. The depth of the wells did not exceed 20 m and their diameters were 5 m or less. In the Zakros Palace, water supply depended on groundwater sources. Today, the spring is brackish due to the intrusion of seawater [1]. Phaistos depended primarily on surface water collected from rooftops, but also on wells and surface water from Ieropotamos, a stream located at the foot of the hill.

Assuming that most other palaces and sites on Crete had similar water supply systems, all of them would be vulnerable to the same factor of danger. This would include aqueduct rupture, depletion of groundwater sources (wells), climatic change resulting in decline of precipitation or change in water quality (like seawater intrusion). Besides seawater intrusion, three other factors are attributable to volcanic effects that are known to occur before or after volcanic eruption. One of them, a climatic change, would occur only after eruptions. It is known that volcanic particles and ash reduce sun radiation and make the local climate colder after eruption. Would this influence cause a decline in local precipitation for considerable amount of time? The answer is not clear due to the absence of direct measurements at that time, though we now know more about global climatic changes caused by volcanic eruptions [26]. Morris [22] suggests that the climate

before LM was more moist and became much dryer after LM period. This could create long-term problems with agriculture. Other factors such as a rupture of aqueducts and depletion of the groundwater sources could occur shortly before or after volcanic eruptions due to the seismic activity and have serious short and long-term effects on water supply.

While a rupture of aqueducts would involve productions of additional supplies of clay pipes and knowledgeable workers to make repairs, depletion of groundwater could last for uncertain periods of time. It would in fact scare local inhabitants who daily depend on God's influence. Groundwater depletion involves changes in permeability of aquifers and rocks underlying stream channels due to the seismically induced stress and strain.

### 3. Seismicity and related hydrogeologic changes

According to Darcy's Law, describing groundwater flow, the factor responsible for the water movement in rocks is the coefficient of conductivity. This coefficient depends on properties of rocks, specifically permeability and related porosity. Changes in permeability of rocks are associated with seismic motions and resultant stress and strain that these motions produce [28,29]. After analyzing data from 1989 on hydrogeologic changes associated with the Loma Prieta earthquake in California, the authors concluded that 'the mechanism which most likely explains the post earthquake hydrologic observations is a permeability increase caused by seismically induced formation of fractures and microfractures.' When the permeability of rocks increases, water drains faster through pores and does not support anymore horizontal or quasi-horizontal water flow. This can lead to a decline of water levels in wells and the disappearance of streams.

In a study of the effects of Northridge earthquake in 1994, the USGS team [25] concluded that 'in porous elastic aquifers, fluid pressure generally changes when aquifer undergoes volumetric strain'. This strain affects water level changes in wells.

The USGS publication [31] summarizes hydrogeological responses to earthquakes in relation to wells and surface water. The groundwater changes in wells occurred as 'an instantaneous water-level offset, or step, which may be either an increase or a decrease and may occur near or far from the epicenter.' The recovery of a water level change can take as long as minutes, days or months. According to authors, the surface water changes consist of 'increases in stream, spring, and seep discharge, some instances of springs going dry, or the appearance of new springs and a very few examples of decreases in spring discharge.'

General hazards to potential water supply in relation to earthquakes include dry wells, broken aqueduct

systems and turbid or gaseous (with carbon-dioxide) water. The case of carbon-dioxide enrichment of water supply in San Bernardino supply wells was well documented [27]. In relation to the Minoan crisis on Crete any of these changes could have dramatic consequences because they could be interpreted as 'God's wrath'. Also, the Minoan society highly depended on the water supply in the arid Cretan climate. The 'God's wrath' idea could be used by Minoan politicians at that time to scare off people and drive them away if it was the goal of the local political games at that time. The lack of water for days or months could slow down or stop agricultural activities and just drive people away in search of better places. The location of palaces on the highlands was good for protection and defensive reasons, but it also made palace inhabitants highly dependent on steady water supply.

### 4. World-wide observations of hydrogeological responses to earthquakes

The method of actualism, also known as 'uniformitarianism' is attributed to James Hutton who was a 'father of geology' and proclaimed that 'In the economy of the world I can find no traces of a beginning, no prospect of an end' [16]. Hutton expressed the actual meaning of his method in the following sentence: '... the ruins of an older world are visible in the present structure of our planet, and the strata which now compose our continents have been once beneath the sea, and were formed out of the waste of pre-existing continents. The same forces are still destroying, by chemical decomposition or mechanical violence, even the hardest rocks ...'[16]. This method is still usable in cases when we try to find keys to past events by evaluating current evidence.

During the past 15 years, numerous observations of earthquakes were made along with records and analysis of hydrogeological events associated with seismic activity. Before this, special studies provided a basis for the research on water-level oscillations [4,7,35]. These documented observations contained information on behavior of wells and aquifers under various seismic conditions. The summary of these observations allows the development of a new view on events during the LM 1A period.

In 1992, within Little Skull Mountain in Nebraska, USA, an earthquake occurred with a magnitude of 5.6. According to [24] this was the largest recorded natural earthquake that influenced the Nevada Test Site. In the study he mentioned that observations of water-level changes were up to 3 feet and lasted as long as 6 months.

On September 30, 1993, an earthquake with a magnitude of 6.4 hit western India districts of Latur and Osmanabad. This earthquake killed about 8000 people and destroyed nearly 30,000 homes. Describing its effect

on hydrological conditions [2] authors mentioned that ‘decline in the water-levels is observed in all the wells as a result of which all the dug wells and dug-cum-bore wells have gone dry.’

On September 25, 1998, an earthquake with intensity VI hit northwestern Pennsylvania region in USA. While analyzing hydrologic effects of this earthquake [10], also known as Pymatuning, geologists found that within hours local residents reported dry wells, flowing wells and the formation of new springs. This report mentions that ‘about 120 household-supply wells reportedly went dry within 3 months after the earthquake. About 80 of these wells were on a ridge between Jamestown and Greenville, where water-level declines of as much as 100 feet were documented’. At the same time water-level increase in the valley wells was as much as 62 feet.

On September 21, 1999 an earthquake with a magnitude 7.3 occurred in Taiwan near the town of Chi-Chi. Changes in groundwater levels, ranging from 1 to 11.1 m were recorded by 67 observation wells [36]. Observation wells were located within alluvial fan of the river Choshui. The recovery of water-level changes took minutes to months.

The United States Geological Survey (USGS) Volcano Hazards Program initiated studies in Long Caldera Valley, California, to provide data that would describe the response of hydrologic system to seismic activity in the region [32]. One of the findings at this site, based on data analysis from wells, was a record of water fluctuations in wells LKT, CH-10B, Santa Fe and CW-3. These wells showed responses to both, earthquakes and crustal deformations that resulted in water-level decline. Observations showed rapid water-level decline within a few days following the earthquake. The recovery of the water level took weeks and months. This study is still in progress.

On October 22, 2002, an Alaskan earthquake with magnitude 6.7 influenced water-level changes in Nebraska wells by 0.1–0.6 feet. This was recorded by Conservation and Survey Division at University of Nebraska-Lincoln [30]. The distance between Nebraska and Alaska is more than 2600 miles.

Besides earthquakes, data concerning hydrogeological effects also come from man-made experiments, like underground nuclear testing [9,15]. Detonation provokes changes in hydrogeologic properties of rocks that influence changes in water levels. These changes can last for years. Studies indicated both declines and increases of water levels in wells, based on analysis of 1963–1998 data from 65 observation wells.

The Gujarat earthquake in India that occurred on January 26, 2001 with magnitude of 7.6 was one of the strongest in India’s history. That earthquake killed more than 19,000 people and destroyed 348,000 houses. Right after this earthquake the World Bank and Asian Development Bank sponsored the Gujarat Earthquake

Recovery Program. The assessment report of this program, published in March, 2001 [11] includes observations of the earthquake’s impact on aquifers and groundwater movement. In particular, it has the following observation: ‘The increase in water table and improvement of quality are considered positive impacts of the earthquake, although restricted to very limited areas. However, the reports of decline in the level of the water table and increase in salinity appear to be common in earthquake-hit areas, which on a long-term basis has serious negative impact on agricultural production system and thus the economy of the region.’ Another study [12] indicated a rise in the water table from 10 cm to 5.4 m in some wells and decline of water levels in others.

According to the Heat Flow Studies Group [33], ‘The Hector Mine earthquake resulted in a dramatic coseismic water level decline in water wells supplying the Marine Corps base at 29 Palms.’ Hector Mine earthquake occurred on October 16, 1999. Water level fluctuations were recorded by USGS gauges before and after earthquake.

Recent studies [3,17,21] provided additional documentation of groundwater response to seismic activity. Brodsky and colleagues [3] were able to obtain oscillatory response records of wells in relation to seismic activity in Oaxaca (Mexico). Montgomery and Manga [21] concluded that within tens to hundreds of kilometers from the epicenter of the earthquake, streamflow changes are more likely to occur, while changes in wells and groundwater levels can occur within hundreds to thousands of kilometers away from epicenter. Manga and his colleagues [17] observed streamflow changes from three earthquakes and found increase in flow due to the dynamic strain in rocks. Hydrogeologic studies by State Hydraulic Works in Turkey [14] revealed water oscillations up to 1.48 m in various wells located within 2000 km radius from epicenter of earthquakes. While studying the Haibara well in central Japan in response to earthquakes, Matsumoto and his colleagues [19] concluded that groundwater-level changes are more related to ground motion than to coseismic strain. All water-level changes in that well were decreases.

## 5. Conclusions: application of hydrogeological and seismic observations for the explanation of abandonment of Minoan palaces on Crete

Several conclusions can be drawn from the above studies and field observations:

1. Regardless of geological conditions and locations, all cases discussed here confirm occurrences of well fluctuations caused by earthquake activities. Studies in California and Japan show that both mechanisms

can be involved in water-level oscillations, i.e. coseismic strain and ground motion. Both mechanisms cause water-level fluctuations and can increase or decrease water levels.

2. Studies by USGS in California and evidence from the Pymatuning earthquake in Pennsylvania agree that water-level decline occurs on the ridges or high elevation areas and that the rise of water levels occurs in valleys. Studies in California [17] confirm that stream flow increases during earthquakes. However topography might not always correlate with the strain field.
3. The majority of observations do not exclude the possibility that water levels would require a long time (weeks or months) to recover.
4. Only one study [11] mentions the collapse of earth dug wells. Other studies lack records of this because monitoring of hydrogeologic wells requires special casings and protection. This draws attention to a new point of concentration in archeological research: the study of well conditions in archeological sites within potential earthquake zones. Collapse of well walls by earthquakes could interrupt water supply for a long time.

Conclusions drawn from the cited studies suggest that earthquake activity could potentially influence the decline of water supply in palaces, which are usually located on high elevations. Earthquakes could break aqueduct systems and increase permeability of the rocks on higher elevations. Crete consists mainly of a series of nappes made of limestone. This geologic structure can be highly vulnerable to a repeated series of earthquakes that could increase its permeability after ground motions, induce possible groundwater salinization and cause a decline of groundwater for a long period of time, influencing local people to migrate in search of a new water supply and better places to live.

The future testing of presented hypothesis requires integration of archeological and geological methods. Archeological methods would provide geologists with specific locations of wells and other hydraulic structures. Geologists would use geophysical methods together with analysis of the soil structure and abnormal chemical compositions potentially associated with aquifer collapse. However, this would require conducting several preliminary studies of soil structures and chemical compositions of already damaged aquifers to develop morphological and chemical indicators of depleted aquifers due to the earthquake activity.

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