Pymatuning earthquake in Pennsylvania and Late Minoan Crisis on Crete

Y. Gorokhovich* and G. Fleeger**

*Center of International Earth Science Information Network (CIESIN) at Columbia University, 61 Rt 9W, PO Box 1000, Palisades, NY 10964, USA (E-mail: *ygorokho@ciesin.columbia.edu*)

**Pennsylvania Geological Survey, Department of Conservation and Natural Resources

Abstract One of the previously published hypotheses on Late Minoan Crisis on Crete considers water loss in aquifers as a reason that forced late Minoan people to abandon their palaces and settlements. According to this hypothesis the water loss in aquifers is attributed to the activity of repeated earthquakes at that time. This hypothesis was supported by numerous case studies of the effects of earthquakes on aquifers in various geological regions around the world.

Presented study concentrates on detailed description of the one of the most interesting cases, the aquifer in Pennsylvania (USA) damaged by the relatively moderate Pymatuning earthquake in 1998, and compares its geological settings with similar conditions on Crete, specifically near Phaistos and Knossos palaces. Pymatuning earthquake resulted in devastating effect on approximately 120 households that lost drinking water from wells. The lessons from Pymatuning earthquake provide a unique insight into similar situation that could occur 3,600 years BP on Crete.

Keywords Crete; earthquakes; Minoan collapse; water supply

Introduction

The controversy about the collapse of Minoan civilization on Crete is a continuous topic of discussions for the last 100 years and as a result, three hypotheses were developed that linked the collapse with naturally occurring events such as earthquakes, tsunami and aquifer damage (Evans, 1928; Marinatos, 1939; Gorokhovich, 2005). The tsunami hypothesis did not stand the test (Dominey-Howes, 2004; Koenig, 2001), however the evidence of multiple repeated destructions in walls of Cretan palaces caused by earthquakes is strong (Driessen and Macdonald, 1997). Multiple repairs on walls of dwellings evidently show that ancient people living during the Late Minoan period were accustomed to earthquakes and did not leave settlements.

The hypothesis of aquifer damage due to the seismic events (Gorokhovich, 2005) linked earthquake activity with its probable effect on aquifers that provided vital water supply to Minoans. The study showed multiple examples from various geographic regions when earthquake activity affected aquifers. One of the cases mentioned in the paper refers to the Pymatuning earthquake in Pennsylvania in 1998. This is the only one well documented case comparable to probable scenario on Minoan Crete in terms of geological settings and social context.

During the Pymatuning earthquake more than 120 households in Pennsylvania lost their water supply from wells and were assisted by local and federal authorities. Considering that each household could have 3 people on average, the total number of affected population could reach approximately 400 people. Using gridded population of the world data set developed by the Center for International Earth Science Information Network (CIESIN), (see http://beta.sedac.ciesin.columbia.edu/gpw/), the estimated affected population there could reach 1,056 people. This is comparable to the number of inhabitants in palaces on ancient

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Crete more than 3,000 years ago. For example, later estimations of population in Knossos show 14,000–18,000 inhabitants (Whitelaw, 2004) and the trend among archaeologists is to reduce these numbers even further. Some estimates in Knossos reduce its population down to 10,000 (Warren, 2004).

Many Minoan settlements on Crete are located on high elevations, either hilltops or hill slopes, similar to the location of the area of water loss in Pennsylvania. These similarities make the comparison between two places an interesting case study that could shed more light not only on the cause of Minoan collapse, but also foster an interest in further studies of aquifer vulnerability to seismic effects.

Pymatuning earthquake and its effects

Geologic settings

Pymatuning earthquake with a magnitude 5.2 occurred on September 25 and arrival of the P-wave was registered at 3:53 p.m. by the College of Wooster seismic station. In Advanced National Seismic System (ANSS) catalogue it has magnitude of 4.5 and depth of 5 km (http://www.ncedc.org/anss/catalog-search.html). This earthquake was strongest ever recorded in Pennsylvania (Armbruster *et al.*, 1998). Its major effect described in the United States Geologic Survey (USGS) study (Fleeger *et al.*, 1999) was the loss of water supply in household wells located along the ridge between Jamestown and Greenville (Figure 1). USGS study (Fleeger *et al.*, 1999) contains the following specific information directly related to the seismic effects on groundwater:

1. The ridge area provides recharge for the groundwater table that is located there at much deeper depth than in valleys; ridges can be considered as "hydrologic islands" totally isolated from other ridges and hills (Poth, 1963); the elevation of the ridge is 1,204 feet (367.2 m); the maximum relief in elevation from the top of the ridge to the bottom of the valley is about 250 feet (76.3 m).
2. Bedrock is represented by Carboniferous sedimentary rocks (predominantly shales and sandstone), covered by glacial deposits. These rocks lay in sequence shale-sandstone-shale-sandstone with Meadville shale formation (160 feet (48.8 m) thickness) on the top and Cussewago sandstone at the bottom. Meadville shale is dark-gray; it has lenses of siltstone and occasionally beds of limestone (Schiner and Kimmel, 1976). Rock sequences are nearly horizontal.

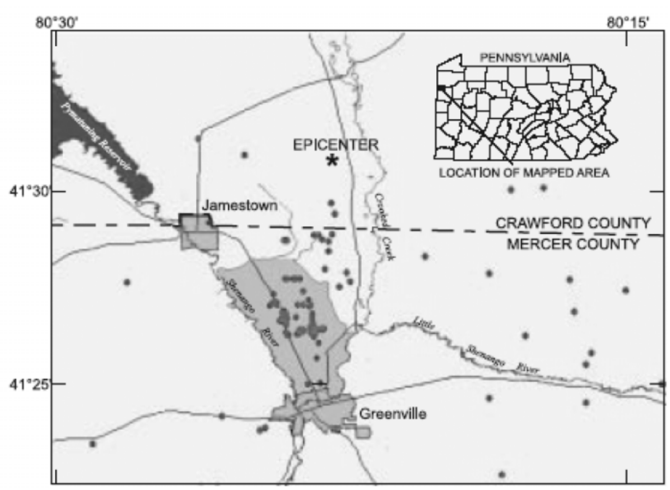

Figure 1 Area between Jamestown and Greenville. The dots are wells that went dry after the earthquake (adapted from Fleeger *et al.*, 1999)

The model of "hydrologic islands", also known as a local system of groundwater flow (Toth, 1963) was introduced in hydrogeology since 1960s (Norvatov and Popov, 1961). According to Toth (1963), this zone "has its recharge area at a topographic high and its discharge area at a topographic low that are located adjacent to each other". Norvatov and Popov (1961) defined this zone as "upper zone of active flow, whose geographical zonality coincides with climatic belts. The lower boundary of this zone coincides with the local base levels of rivers".

The idea of "hydrologic islands" was used in USGS study (Fleeger *et al.*, 1999) to explain a potential cause of the water loss in wells along the ridge between Jamestown and Greenville. Figure 2 shows approximate location of the boundary of this feature in relation to the area affected by Pymatuning earthquake. Elevations were derived from the global Shuttle Radar Topographic Mission (SRTM) elevation data (Jarvis *et al.*, 2004).

The boundary of "hydrologic island" follows contours of Meadville shale and valley bottom, making the area of approximately 14–18 square km. The disturbance of this specific area by seismic shocks could increase permeability of the Meadville shale and "drain" this unconfined aquifer into the valley. This model is supported by the evidence of groundwater flow increase in the valley (Fleeger *et al.*, 1999).

Using available geologic evidence and measurements in affected area between Jamestown and Greenville, USGS study created a hypothesis that the Pymatuning earthquake created new or widened old fractures that contributed to the increase of hydraulic conductivity and consequent increase of flow in discharge zones of "hydrologic islands". This hypothesis was supported by the results of developed ground-water flow model that showed that pre- and post- hydraulic conductivity changed from 0.004 to 0.0228 feet per day (Fleeger *et al.*, 1999).

Hydrologic effects

On September 26, the day after earthquake, residents in vicinity of Jamestown and Greenville towns found that water levels were declining and water colour was changing from

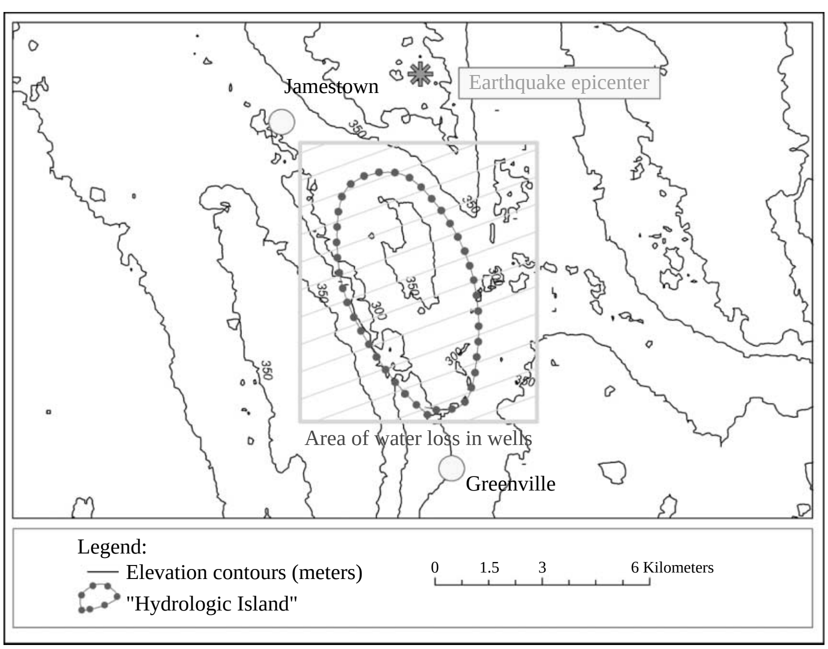

Figure 2 Pymatuning earthquake epicentre, elevations, location of area with water losses and "hydrologic island" boundary

clear to brown and dark. These declines were documented in 121 wells (Fleeger *et al.*, 1999). At the same time water levels on the sides of the ridge and in the valley went up by 1–4 feet. Water level went down in practically all wells above elevation 1,100 feet (335.5 m) which belongs to the Meadville shale. After the earthquake water levels have been monitored by the Pennsylvania Geological Survey and as of April, 2006 there has been no sign of recovery to pre-quake water levels.

Socio-economic effects

Local newspaper "The Herald" (Sharon, PA) covered most of the events that happened in affected community after Pymatuning earthquake. More than 90 homes lost well water after the earthquake, said Jim Thompson of the Mercer County Emergency Management Agency. Most homeowner's insurance policies did not cover well water loss, so residents had to drill new wells at their own expense. Newspaper reported that it took more than a month to provide residents with water since "it costs $3,000 to $4,000 to drill a new well, and most families can't afford it … " Other effects of earthquake included broken walls, windows, ceiling tiles, chimneys, loss of power and one injury (Armbruster *et al.*, 1998). Mercer County Emergency Management Agency and local municipal and charity organizations were involved in remediation and restoration efforts that included bottled water supply, filling up bath tubs and water tanks.

The community between Jamestown and Greenville does not belong to the wealthy class. Their average income in 1999 was $34,666 (for example, in Pennsylvania State the median income is $40,106) and almost 12% of people are below poverty level (US Census Bureau, http://quickfacts.census.gov/qfd/states/42/42085.html). Many people support themselves by farming. There is anecdotal evidence that only one household had "earth-quake" insurance and therefore the well for this household was drilled for free. The rest of the community had to find their own funding for well drilling. In an interview, one of the residents mentioned that if he would not have external assistance from the outside he "would leave" (Gorokhovich, 2004).

Correlation between Pennsylvanian and cretan geologic settings

Geomorphologic and hydrologic settings

Most of the palaces (Knossos, Phaistos, etc.) are located on hills or slopes. Elevation of Knossos above sea level is approximately 70 m and Phaistos is 120 m. The relief between valley and location of Phaistos palace is 87 m; in Knossos the relief is approximately 54 m. Figure 3 shows elevation contours developed from SRTM and location of two major Cretan palaces: Phaistos and Knossos. It also shows approximate contours of "hydrologic islands" or localized groundwater recharge zones.

The size of approximated "hydrologic islands" in the vicinity of palaces ranges from 8 to 9 square km. Since more detailed geologic data for Knossos and Phaistos are absent, it is hard to correlate the boundary of "hydrologic islands" with specific geologic deposits that could explain aquifer settings. In both areas near Knossos and Phaistos surface deposits are represented by Neogene carbonate rocks (Meulenkamp *et al.*, 1979). They were deposited since Miocene and consist of six groups represented by limestone, terrigenous clastic formations, marine marls and clays. There are also some marine terraces and continental deposits related to Pleistocene. However without detailed analysis of deposit structure and properties it is hard to explain potential effect of seismic waves.

Seismic conditions

For the past 100 years in the vicinity of the Pymatuning earthquake epicentre only four other earthquakes were recorded with magnitudes higher than 4.0: in 1964, 1966, 1986 and

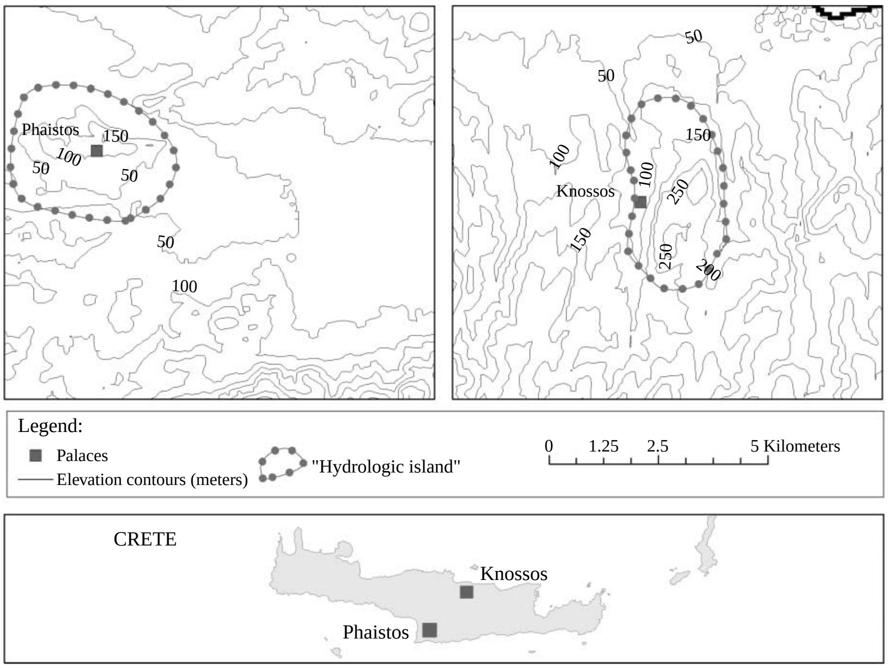

Figure 3 Cretan palaces in relation to elevations (derived from SRTM) and "hydrologic islands" derived from relief values

in 2001. The depth of these earthquakes ranges from 5 to 15 km. Besides hydrogeologic records of Pymatuning earthquake in 1998 and earthquake of 1986 (when according to USGS hydrologists in Ohio hydrologic changes were nearly identical to Pymatuning event) none of other earthquake events contains documentation about hydrogeologic response. It does not mean that hydrogeologic response was not present because it just could be not recorded or documented.

Earthquake situation on Crete is very different since Crete is located in active subduction zone next to Hellenic arc. Therefore, Crete constantly experiences multiple earthquakes. The Advanced National Seismic System (ANSS) catalogue maintained by the USGS contains 49 records of seismic activity since 1900 that exceed magnitude of 5.0 with highest magnitude of 6.3 in 1972. Figure 4 shows density of earthquakes based on magnitude value. This was

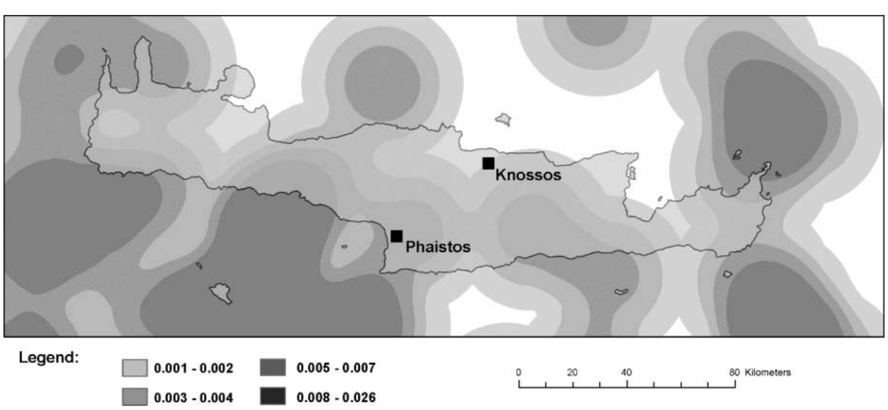

Figure 4 Density of the earthquakes (based on magnitude value and number of epicentres within 30 km radius) with magnitudes greater than 5 for the past 106 years

calculated using so-called "kernel" method described in (Silverman, 1986). This method is also widely used in crime analysis to define "hot spots" based on number of arrests and specific crimes (McLafferty *et al.*, 2000).

Most of the high density earthquake zones are located on the south and east from Crete. This coincides with location of subduction zone on the south (Hellenic trough) and possible strike-slip fault zone on south-east associated with South Cretan trough, Pliny trough and Strabo trough (Huguen *et al.*, 2001). Phaistos palace is much closer to the high density seismic areas with high magnitudes. Knossos is relatively far from them. Average depth of epicentres is 48 km with range from 10 to 87.4 km.

Conclusions

Though both, Phaistos and Knossos locations have similar geomorphologic characteristics, Phaistos has more similarity with "hydrologic island" settings in Pennsylvania than Knossos. However, more detailed analysis is needed near both palaces to identify specific geologic layers and formations. Knossos location on the slope of the hill does not specifically fit definition of "hydrologic island", however water supply in Knossos was only partially coming from wells and major part of water supply was coming from Mavrokolybos and Fundana springs located higher on the slope (Angelakis and Spyridakis 1996; Angelakis and Koutsoyiannis, 2003). Following "hydrologic islands" model these springs could cease to exist after seismic activity.

Seismic settings are different in Pennsylvania and Crete. Considering that seismic activity can influence hydrogeologic conditions, the higher density of earthquakes and their magnitudes on Crete suggests also higher probability of the aquifer disruption on Crete due to seismicity. The epicentre of the Pymatuning earthquake was located within 3–5 km from the affected "hydrologic island" and its depth was 5 km. These conditions, coupled with specific geologic structure resulted in the loss of aquifer. Considering high frequency of earthquakes on Crete during Bronze Age (Nur and Cline, 2000), there is a high probability that earthquake epicentre could be located close enough to the palace and resulting seismic activity would damage aquifer.

Social consequences of disrupted water supply in Pennsylvania included immediate measures from local and federal authorities, charities and churches to provide inhabitants of the "hydrologic island" between Jamestown and Greenville with water supply. These measures included filling bath tubs from fire trucks and supply of bottled water from local supermarkets and stores. In similar case in California in December 22, 2004, San Luis Obispo County residents had to trim their herds due to the loss of water from springs immediately after earthquake (Campbell, 2004). These cases are related to the 21st century with modern technologies, established public policies and disaster management plans. In ancient Crete, 3,600 years ago, similar effects would mean the retreat of population and search for new water supply sources.

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