Preliminary field and GIS-based assessment of tsunami hazard on Cyprus

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ABSTRACT

Cyprus has a long history of tsunami activity, as noted in written, archaeological and geological records. Records compiled thus far show that Cyprus experienced at least a moderate tsunami on average once every 30 years over the past two thousand years. Nearly all of the coastal sites display one or more of the geological/geomorphological indicators of past tsunami activity. We interpret these records to indicate that every part of the Cypriot shore has at one time been inundated by a tsunami. With that assumption in mind, GIS was used to create inundation maps based on coastal topography and hazard maps based on population density.

INTRODUCTION

The shallow earthquakes off the coast of Cyprus are accommodated often enough by seismogenic sea waves, more widely known as tsunamis. Kelletat and Schellmann (2001) were the first to identify the tsunamogenic depositional nature of large blocks and foraminifera-rich bimodal sand-gravel deposits on the coasts of Cyprus. More recent studies have mapped imbricate tsunami blocks and other features suggesting that seismic waves have reached almost the entire Cyprus coast (Noller *et al.*, 2005). Dated tsunamites off the coast of Caesarea in Israel correlating closely in age with the Thera eruption of 1630 -1550 B.C., provide concrete evidence for the past occurrence of tsunamis in the whole eastern Mediterranean (Goodman-Tchernov *et al.*, 2009). Similarly, the A.D. 365 western Crete earthquake destroyed Alexandria and killed thousands. With no doubt, these two events must have also affected Cyprus.

Much of the tsunami evidence comes from historical accounts dating back to Greek scriptures but also recent writings. Ogerius Panis and Marchisius Scriba, wrote in AD 1294 about a tsunami event in Lemesos and Pafos which is believed to have taken place in May AD 1222 (Rohricht, 1882):

> ... at Cyprus, the sea was lifted up by the shock and rushed inland; the sea in places opened up in huge masses of water big as mountains and surged inland, razing buildings to the ground and filling villages with fish ... Baffa (Pafos), they say, suffered most ... the harbor dried up and then the town was submerged by the sea ... the town and its castle were completely ruined and its inhabitants wiped out.

This account leaves no doubt about the occurrence of a tsunami for the May AD 1222 event. Archaeologists, historians but mainly seismologists and geomorphologists have often tried to collect and evaluate these past events. Nevertheless, it was not the scope of this study to provide a new tsunami catalogue for Cyprus but to provide a map of areas at risk of inundation and identify populations and land uses which are vulnerable in the risk areas.

REGIONAL GEOLOGICAL SETTING

The tectonic framework of the Eastern Mediterranean and Middle East region is dominated by the collision of the Arabian and African plates with the Eurasian plate (McKenzie, 1970) and more specifically the northward subduction of the African plate along parts of the Hellenic and Cyprus arcs (Figure 1). In the vicinity of the Cyprus arc, the African plate penetrates below the locally oceanic Mediterranean crust (Makris, 1983) in the western part of the arc, in the proximity of Anaximander and Florence continental crust Seamounts and this is evident from the deep earthquakes in this region (Ambraseys, 1992a,b,c; Ambraseys and Adams, 1992). The Cyprus arc becomes more of a collision boundary in its central part where the Eratosthenes seamount, a continental crust microplate, and the Cyprus Island are undergoing intensive shallow deformation. In the eastern part, there is a wide zone of wrench faulting (Ben-Avraham *et al.*, 1995) in the vicinity of the Latakia ridge which extends all the way to the Syrian coast. On land, the Troodos ophiolite (Troodos Terrane) is the main orographic feature of the island containing all components of an ophiolitic sequence, an ultramafic core, a diabase sheeted dyke complex, a volcanic sequence of mostly basaltic pillow lava flows and topped with iron and manganese rich hydrothermal sediments. The allochthonous Mamonia Terraneis juxtaposed on the southern part of the island and the Keryneia Terrane on the north. The base of the Circum - Troodos sedimentary succession is marked by clays and sandstones, extensively exposed in western Cyprus, and topped with pelagic chalks and cherts indicating slow emergence of Cyprus as an island in the Miocene. The deposition of gypsiferous marls dates to the Messinian Salinity Crisis of the Mediterranean and the Pliocene marls the subsequent flooding and shallow sea formation. The Quaternary uplift of the island has formed thick and extensive fanglomerates on the early Pleistocene foothills of the Troodos ophiolitic mountains. Prominent and extensive marine and alluvial terraces span the whole Pleistocene.

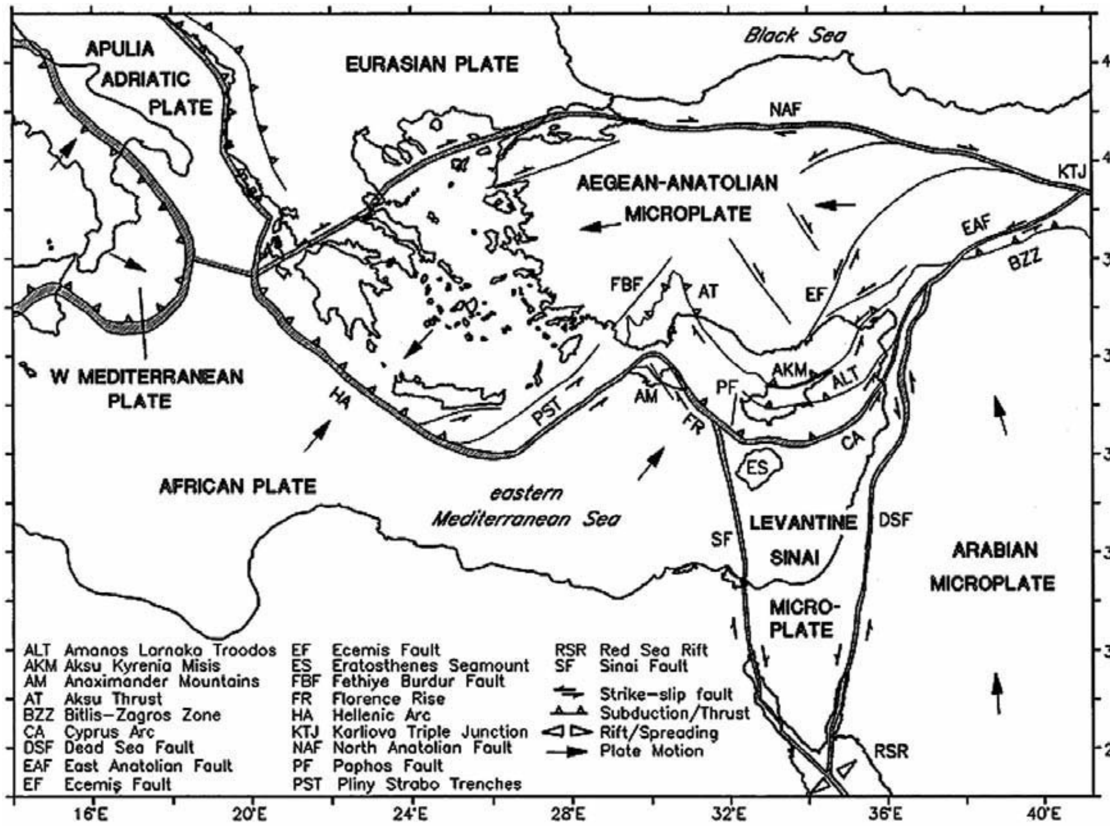

Figure 1. Tectonic setting of the Eastern Mediterranean showing the inferred location of the present-day Cyprus Arc (Aksu *et al.*, 2005).

METHODOLOGY

Reports of tsunami features presented here are the result of coordinated field and office study. This study applied geomorphological methods of field work, involving vehicle and foot travel to reach remote parts of the island. Field work was conducted between September 2003 and June 2004, with a short visit to field sites during the first week of February 2005, shortly after the tsunami event in Indonesia. Much of the coastal zone of Cyprus was studied in reconnaissance fashion, that is, areas accessible by 4WD vehicle and foot or within a short distance of a road (ca. 500 m). All of the major capes were inspected in detail, and many parts of the shorelines between these major landforms were inspected.

Geographic Information System (GIS) software (ArcGIS^{TM}, ESRI) and digital data were used to plan, compile and analyze the tsunami feature data. Data used during our analyses include topography and bathymetry, coastline, streams, roads, built-up areas, and satellite imagery (LandSat ETM and QuickBird). The DEM was clipped onshore at 1,500 m from the shoreline, and the bathymetry was clipped at several hundred kilometers distance. The onshore portion of the DEM was contoured at 5 meter intervals.

RESULTS

The tsunami record on Cyprus comes from several sources, involving the disciplines of history, archaeology, geomorphology, soil science and geology. In the past some past strong earthquakes were associated with tsunami waves, the most important of them in 92BC, 551AD, 1034, 1068, 1202, 1222, 1303, 1546 and 1759 (Fokaefs and Papadopoulos, 2007). More recently, the earthquakes of 18 June 1949 and 10 September 1953 were reported to have caused small local tsunamis.

A recent computer simulation of the 1222 AD event (Yolsal *et al.*, 2007), models a 7.0-7.5 magnitude earthquake with an epicenter off the southwest coast of the island, a focal depth of 15 km, a 3m co-seismic displacement along a 50 km long fault. The propagation of the wave was generated using non-linear shallow water theory and produced results of wave height and arrival times for the whole eastern Mediterranean coast including the coasts of Cyprus. With an initial wave of about 1 meter at sea, tsunami waves reach the Cyprus coast in less than a minute and vary in height from 30 cm at Cape Akamas to 190 cmat the Pafos Airport. It also becomes evident from Yolsal's results that maximum wave heights occur at the capes, a phenomenon being verified with field work. An impressive 82 cm high wave reaches Alexandria in Egypt in approximately 71 minutes. Historical accounts do mention the castle at Pafos collapsing and the earthquake causing damage in Alexandria (Ambraseys *et al.*, 1994). Similarly, an 8.0 magnitude earthquake off the southeast coast of Crete will result in a 90 cm high tsunami on the western Pafos coast and smaller waves elsewhere on the Cyprus coast.

Large rock blocks (20 to 50 ton) lifted up by tsunamis and deposited on higher ground constitute the most impressive form of tsunami evidence. Similar findings are recorded on the coasts of Cyprus (Figure 2). These blocks are found on Cape Kormakitis, Cape Plakoti on the coast of Gialousa, Cape Greco, Agia Napa, Pafos Airport, Kissonerga coast, Lara Bay and the whole Akamas peninsula north of Lara bay. Nearly all of the coastal sites visited displayed one or more of the indicators of tsunami activity and so the overall picture is one of many tsunamis having struck the shores of Cyprus. The presence of these large rock blocks is almost always out of geological context, located inland at a distance much further than any possible storm deposit and many times displaying inverse stratigraphy. Records of these "tsunami blocks" have been used worldwide as indicators of tsunami activity. Scicchitano *et al.* (2007) record tsunami blocks located 2-5 m amsl, reaching 182 t in weight, isolated or stacked and having a variety of features suggesting that they were dragged from the mid-sublittoral or mid-supralittoral zones. Rock block analysis was also conducted for modern tsunami events, the 2004 Indian Ocean and the 2009 South Pacific tsunamis which help identify and interpret palaeo-tsunami imprints on many coastal landscapes (Etienne *et al.*, 2011).

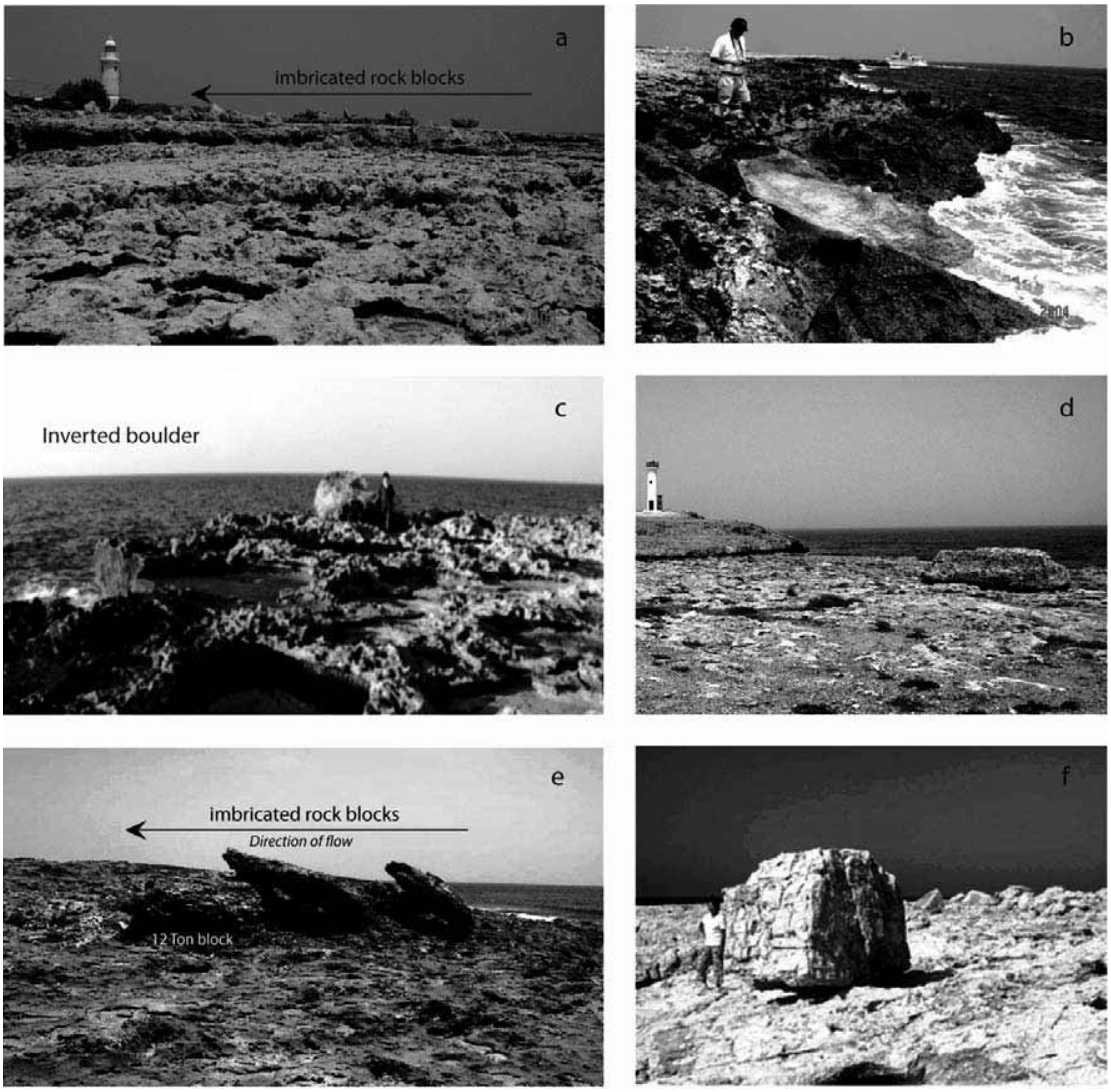

Figure 2.**a**. At Cape Greco a long line of imbricate boulders of Pleistocene calcarenite sandstone lies at an elevation of 4 m amsl. **b**. At Cape Greco, this recently dislodged boulder now lies about 15 minland. **c**. Area along shore at Davlos village is littered with large boulders. This boulder is inverted (top down). **d**. At Cape Plakoti in Karpasia, the area is scoured of soil and is littered with large boulders. The boulder in the photo lies 30 m inland **e**. View looking southwest at Cape Kormakiti. Here four 12 ton boulders originating from at or below sea level, with marine weathering features, are stacked in an imbricate manner. **f.** One of many examples of large tsunami blocks on the rocky coast of Akamas.

Cape Kormakitis presents the broadest expanse of landforms and deposits that are clearly developed by tsunamis. It is at this cape that one realizes storm waves cannot possibly explain the presence and orientation of large boulders (Figure 2e). The cape is barren of soil, with different sediment consisting of a bimodal particle size distribution of shelly sand and large boulders. Cape Plakoti in Karpasia is also largely barren of soil with some of the largest 'tsunami' boulders documented on Cyprus (Figure 2d). The distribution of marine-altered (e.g. bored by mollusks) artifacts of Neolithic and earlier age suggests deep-seated waves may have scoured the offshore region as well.

At Agia Napa the coastal aeolianite ridge hosts many large boulders at elevations approaching 8 m a.m.s.l. (Figure 3f). The aeolianite is scoured of soil, has a discontinuous shelly sand cover sediment, and has many marine-worn artifacts indicative of sudden marine deposition on the ridge top and inland. Many other areas of aeolianite all around the island have similar features, especially the entire coast from Cape Greco to Cape Pyla (Figure 3e). Much of the southern escarpment of Akrotiri (Lemesos) is stripped of soil and sediment (Figure 3d). Large boulders on some terraces, up to 30 m elevation, are suggestive of tsunami deposits. However, mass wasting processes and differential erosion could have created these deposits and features here.

Figure 3. **a**. Tsunami boulders, many with marine features indicative of extraction from the sublittoral zone at Eremiti bay.**b**. View looking south at Cape Zephyros with infilled quarries and offshore rock blocks. **c**. Invertedtsunami blocks at Eremiti bay. **d**. View looking north at Akrotiri *Aetokremnos*. Area is scoured of soil and is littered with large boulders up to 30 m elevation.**e**. Tsunami boulders on the bare shoreface of Ormidhia, east of Larnaka. **f.** View looking east along the accordant ridges of aeolianite along the coast of Agia Napa. Baseball cap for scale in foreground. Cape Greco is in the background.

Cape Zephyros is blanketed by a cover of sediment consisting of shelly sand and rounded cobbles that locally infill archaeological (Roman?) quarries and cover red soil up to at least 5 meters above sea level (Figure 3b). Blocks offshore, shown on photograph of Figure 3b could have been displaced by tsunamis. Cape Geronisos displays an excellent example of the impact of tsunamis on soil distribution. Near the coastline soil is stripped off the surface. Further inland, soil appears locally in deep, protected pits in the underlying calcarenite, and lichens are present on many rocks. Several hundred meters inland the soil and vegetation are thick, and lichens are large in size and cover nearly all exposed rock surfaces. Large boulders are present in at least two bars, one inland of the other, suggesting two phases of deposition or possibly two tsunami events.

Eremiti Bay, well documented by Kelletat and Schellmann (2001) and Whelan and Kelletat (2002), hosts impressive deposits of imbricate boulders, boulder bars, stripped soil boulder-armoured soil, lag gravels and other features. The evidence here strongly indicates a tsunami with a 15 m run-up (Figure 4).

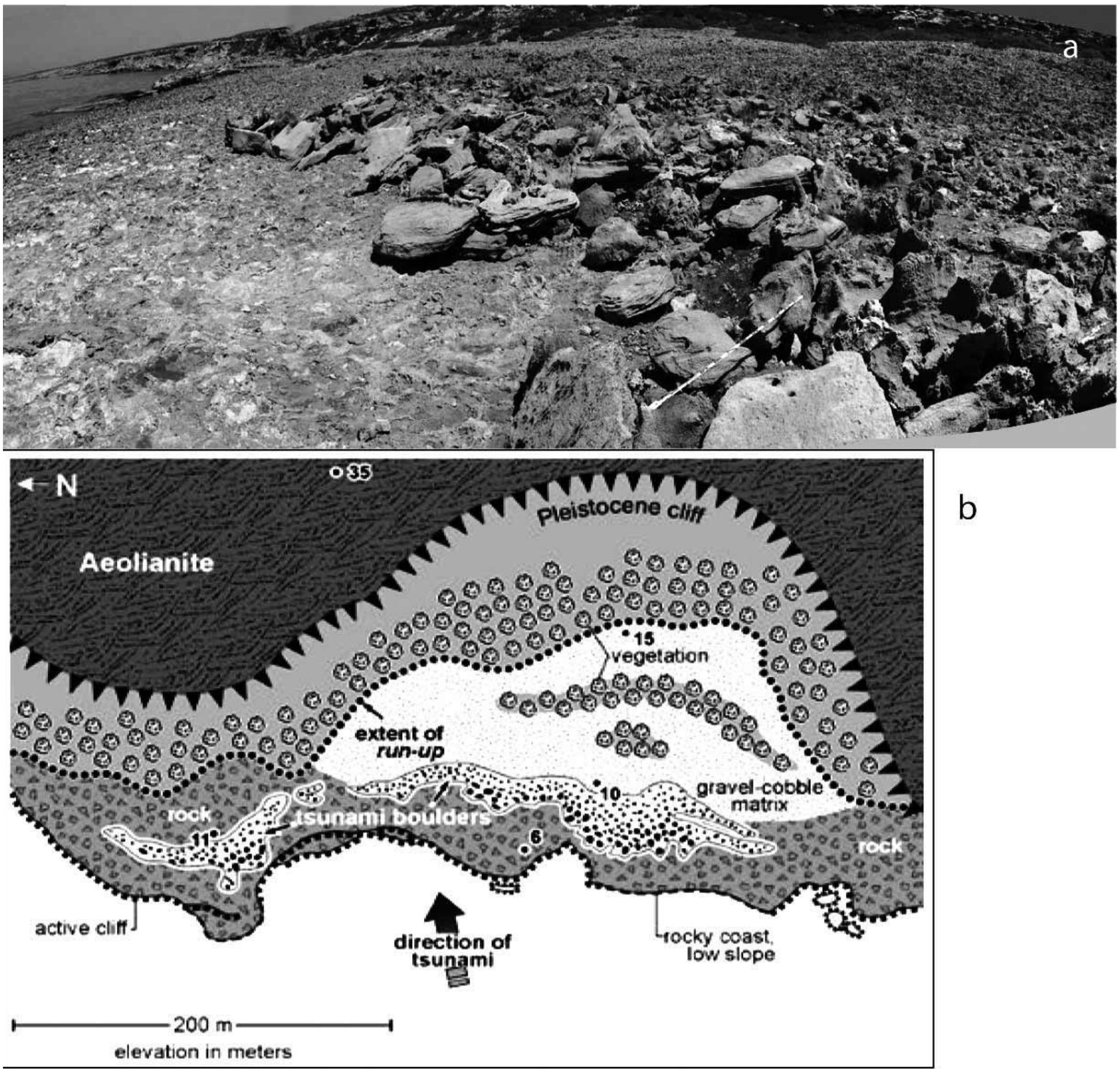

Figure 4 **a**.Eremiti Bay hosts an excellent display of tsunami deposits. **b**. Graphical representation of the deposits by Kelletat and Schellmann (2001).

SUMMARY OF FIELD OBSERVATIONS

Tsunami impact well explains the diverse, distributed nature of landscape features in the coastal zone of Cyprus (Figure 5). In general, the coastal zone within 100 to 400 m of the shoreline presents one of the following features: (1) slopes barren of soil; (2) a discontinuous, thin cover of sediment consisting of a bimodal particle size distribution of shelly sand and large boulders; (3) oriented large boulders tens of meters from shoreline; (4) particles showing marine indications such as vermetid borings, coralline algae deposits, pitting, and marine erosional landforms. Although compelling, other agencies of surficial processes could be responsible for many of the features documented herein, including wind erosion, soil erosion, human activities, very-large storms, tectonism, mass wasting, river action and so forth. Only with concentrated efforts, such as a drilling program in estuarine environments, will tsunamis be more firmly established and dated.

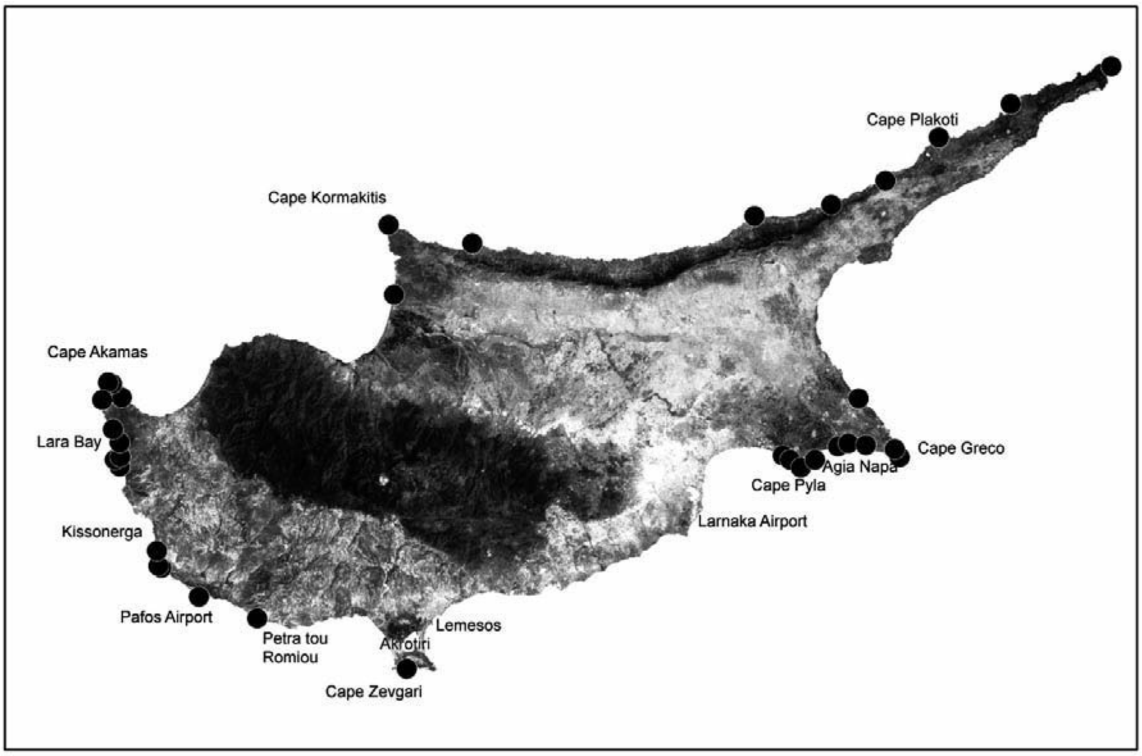

Figure 5. Landsat image of Cyprus with locations mentioned in text, showing distribution of geomorphological features indicating or suggesting tsunami processes.

ANALYSIS OF FIELD RESULTS

Tsunamis were one of the many natural hazards that occurred in the ancient world and were recognized by early writers as extraordinary phenomena. Because of the work of Ambraseys (1962) *et al.*, there exists a rich bibliography of a literary record relating to tsunamis in the Eastern Mediterranean. Most recorded tsunamis struck within hours the ports and coastal population centers of Cyprus, Syria and Egypt, where most original written materials are found. With respect to the geological evidence of tsunamis on Cyprus, such as boulder deposits, the dates of Whelan and Kelletat (2002) and Kelletat (2002) cluster into four periods. There is an apparent coincidence inseveral of the timing of historical tsunamis with that of the geologically determined events.

TSUNAMI RISK

Microzonation mapping is a key part of multidisciplinary assessment of the impact of natural hazards to population. Tsunami hazard becomes important because six of the seven densely populated areas on the island are on the coast and supporting one major economic sector of Cyprus, that of tourism. Large and important infrastructure is located almost entirely within a few meters from the coast, such as power plants, airports, water desalinization plants and oil refineries. Tsunami hazard maps produced here are a first approximation of the areas at risk, and relative caution should be taken.

A classified land use map was developed showing six classes of occupancy. The land use map was developed in ArcGIS™ using 2003 Quickbird™ images (having 60 cm pixel size) set as basis for drafting boundaries. Occupancy is based on the estimated number of persons per unit area and duration of occupancy of the area in a zone 1,500 m from the coast. For example, the land use areas with high-rise apartments, house the most people per map unit area and have the highest rate of occupancy. To estimate the population at risk to tsunamis we calculated the area affected by tsunamis and then determined the minimum number of people affected by such an event. We then chose the 5 m contour as a first approximate distance of tsunami penetration, and used it to clip, that is select, only the portion of built-up areas within this zone. Areas of each land use class were tallied and estimated land use densities were calculated (Table 1).

Table 1. Matrix of land use zones and estimated population densities.*

Land Use Zone	**Population Density (per m^2)**	**Category**
1-2 story buildings	0.0048	1
2 or more story buildings (town centers)	0.025	2
Hotels and tourist apartments	0.0143	3
Summer homes and summer recreation areas (water parks, restaurants)	0.012	4
Industry (industrial zones, fish farms)	0.0055	5
Infrastructure (ports, airports, power stations, petroleum depots)	0.01	6

Vulnerability was high in lowland coastal areas on all the coastal cities including the western and eastern beaches of Akrotiri peninsula. The eastern beach, known as Ladies Mile beach is the busiest beach in the summer with thousands of bathers. Assuming a wave run-up of 5m, the coastal population at risk is about 200,000. At the time of an event the actual population at risk depends on the source of the tsunami and the variable affect it will have on the whole coastline, i.e. an earthquake with a southwestern epicenter will not create a tsunami wave on Keryneia coast and an earthquake in the southeast will similarly not affect Kormakitis Cape. Lemesos and Larnaka display the highest vulnerability because the historical centers of these cities are located right on the coastline. Other towns like Pafos and Agia Napa respond differently to the hazard since their tourist centers are on the coast but the town centers on higher ground, in Pafos being well over the 5 m assumed tsunami run-up. Figure 6 shows an example from the town of Larnaka.

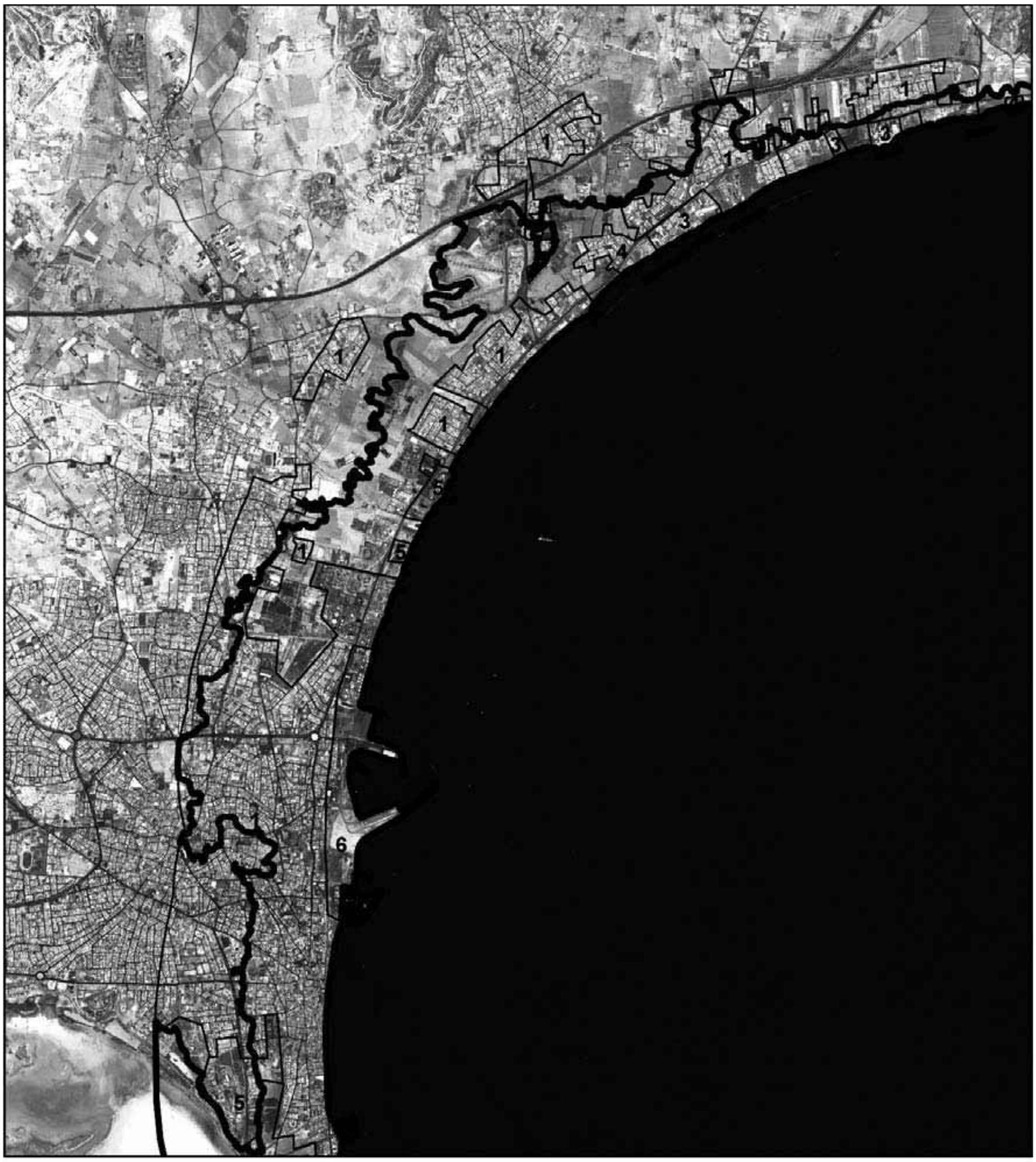

Figure 6. Map superimposed on satellite image showing areas of risk to tsunami damage in the town of Larnaka. The thick black line is the 5 m elevation line and marks the upper limit of local tsunami penetration, especially along channels and inland of low-sloping beaches. Boxed areas within a 1,500 m buffer from the coast show land use categories (marked from 1 to 6 according to Table 1).

Summary and conclusions

Cyprus has a long history of tsunami activity, as noted in written, archaeological and geological records. We interpret these records to indicate that every part of the Cypriot shore has been inundated by tsunamis. As such, the record compiled thus far shows that Cyprus experienced at least a moderate tsunami on average once per 30 years over the past two thousand years. Some, of these events must have been damaging in nature. Similarly, probabilistic studies by Fokaefs and Papadopoulos (2007) with updated tsunami catalogues estimate an average recurrence of 30, 120 and 375 years for moderate, strong and very strong tsunami occurrence.

Given the importance of the coastal resource in Cyprus' economy it is vital that the vulnerability of the tourism, commerce and residential sectors to tsunami be fully characterized so that mitigation measures may be designed and implemented. The very next step towards realizing this would be an intensive field study involving drilling of coastal sediments and dating of tsunami features to characterize the hazard of tsunamis. Attention to the historical and archaeological records is obviously an important part of establishing the ages of these events.

Acknowledgements: this work was funded partly by the Fulbright Commission and partly by the Cyprus Geological Survey.