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THE EARTHQUAKE AND TSUNAMI OF 365 A.D. IN THE EASTERN MEDITERRANEAN SEA

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ABSTRACT

The geodynamic evolution of the Eastern Mediterranean region has been associated with a complex space-time distribution of tectonic events. There is ample evidence indicating that a great tsunamigenic earthquake with a magnitude of up to 8.3 occurred near the west coast of the island of Crete on July 21, 365 A.D. The tsunami was responsible for extensive destruction on Peloponnese, Sicily, Cyprus and Egypt and elsewhere. The combined catastrophic impact of the earthquake and tsunami, is believed to have been a significant catalyst in the declination of the Roman Empire and its subsequent division between the East and the West (Byzantine) in 395 A.D. The catastrophic event was a manifestation of ongoing complex interactive tectonic activity in the Eastern Mediterranean, which raises questions about the recurrence of another great tsunamigenic earthquake and its potential impact. The present study examines historical records, summarizes known destructive effects and analyzes the possible source mechanism of the tsunamigenic earthquake, in terms of current understanding of regional tectonics. Finally, based on such analysis and numerical modeling of the tsunami, the study draws conclusions about the recurrence of a similar catastrophic event.

Introduction

According to historic records, on July 21, 365 A.D, a catastrophic earthquake with epicenter near the western side of the island of Crete caused extensive destruction to cities in the Eastern Mediterranean and generated a destructive tsunami. The combined impact has been described by historian Ammianus Marcellinus (Roman History, Book XXIII, 6:32-36) as the "destruction of all the world". Other historians referred to this event as a disaster of biblical proportions. It occurred at a very critical time in history when the Roman Empire was slowly hemorrhaging with wars and political conflicts. Thus, the great devastation by the combined effects of the earthquake and tsunami, were major factors in the declination and eventual collapse of the empire. Many of the cities that were destroyed were never rebuilt. Some of the less-impacted cities did not adequately recover. Thirty years later, in 395 A.D., the Roman Empire was split between the East and the West (Byzantine), thus loosing considerable influence and grip in the region.

Although major earthquakes are frequent in the Eastern Mediterranean, great earthquakes as that of 365 A.D. are rare. However, given the seismotectonic history of the region, it is very likely that another great earthquake of similar great magnitude, will again strike. The recurrence frequency of such events is difficult to estimate, as there are many uncertainties about the relative motions between Africa, Eurasia and of the crucial role the Aegean--Anatolian plate plays in the tectonic evolution of the Eastern Mediterranean region. This evolution results from continuous continental collision, subduction and crustal shortening processes.

The present paper reviews available historic and recent data, summarizes briefly Eastern

Mediterranean region's evolutionary development and tectonic trends that give clues about the source mechanisms and energy of the 365 A.D. earthquake and tsunami and evaluates the present structural-tectonic setting that could result in a future catastrophic event.

Review of Historical Accounts

There is ample historical information about the impact of the July 21, 365 A.D. earthquake. Reportedly, strong ground motions were felt as far as Dalmatia, Sicily, Libya and parts of Egypt and Palestine. The greatest intensity was felt on Crete, Peloponnesus and the rest of Greece where many cities were destroyed, with the exception of Athens and other cities in Attica (Zosimus of Panopolis). Closer to the epicentral region, the ground motions were reported to be extremely intense. The earthquake destroyed the city of Patras (Triantafillos 1959). There was extensive destruction to many of the buildings, walls, supports and columns at the sacred city of Olympia and at the Doric temple of Zeus (Xiotis 1886, Pararas-Carayannis 2009). Skandia, the ancient harbor of Kythera island, was destroyed (Pararas-Carayannis, 2006). Most of the cities that were destroyed on Crete were subsequently abandoned (Xanthoulidis, 1925). A history of Crete states that in the year 360 A.D. the ancient city of Pannona (now known as Boulismeni) was destroyed by a terrible earthquake (Kriaris, 1930). Apparently the year given is wrong since this event occurred in 365 A.D. There was extensive destruction of Knossos, Gortyna and ten other cities (Sieberg, 1932; Perrey, 1948; Papazachos V. & Papazachos K., 1989). Knossos was practically leveled.

The tsunami affected the entire Eastern Mediterranean region. Several ancient texts describe destruction of coastal cities on Peloponnese, Sicily and Egypt. Kyrini, Faistos, Gortyna, Pafos, islands of Aiolou, Verona, Spain, Turkey and Palestine (Givonnas and others). From an excerpt of an ancient text it is concluded that the tsunami affected both the Adriatic Sea and the Aegean Archipelago (Zolotas, 1921). Excerpts (Georgiadis, 1904) from previous writers (Theofanis, Kedrinos and Zissimos) describe both earthquake and tsunami effects. Accordingly, inhabitants of coastal areas in Dalmatia and Greece were killed. A large portion of the Nile Delta was flooded. An account (Kedrinos) states that at the harbor of Alexandria, boats suddenly sat on dry land and that the tsunami drowned 5,000 people. The sea wave was so high that it reached tall structures, overtopped walls, flooded gardens and homes, before retreating (Theofanis). Apparently this account quotes a passage from Ammianus Marcellinus (Roman History, Book XXIII, 6:32-36). According to other accounts, many places in Crete, Achaia, Biotia, Epirus and Sicily were lost due to great waves. Reportedly, boats were thrown up on land and there was inundation of up to 100 stadia (18.5 km). Such extensive inundation could only be possible in flat areas of the Nile delta (Pararas-Carayannis 2001).

Source Characteristics of the Earthquake of July 21, 365 A.D.

The earthquake had an estimated Richter magnitude of 8.3. It is believed to have been the strongest ever in the Eastern Mediterranean. Based on field studies on western Crete, its estimated minimum seismic intensity was XI (MM scale). Although not reported in historical records, there must have been numerous large aftershocks. The epicenter was near western Crete, close to the leading edge of the subduction boundary, where the African tectonic plate pushes beneath the Aegean plate along the Hellenic arc. The leading edge of the subduction zone is close to Kefalonia, Zakynthos, Lefkas, southern Peloponnese and Crete, where strong, frequent, destructive, shallow earthquakes occur - with focal depths varying from 0-60 km (Pararas-Carayannis 2001). Recent destructive earthquakes on the same zone occurred on 11 August 1903 near the Island of Kythera and on August 1953 near the islands of Kefalonia and Zakynthos. The earthquake of January 8, 2006, occurred along the same wide zone near Kythera Island. However, its epicenter was further east, had greater focal depth and thus was not very destructive. Closer to the volcanic arc in the Central Aegean Sea, the angle of subsidence below the Aegean plate changes to about 35-38 degrees and earthquakes have deeper focal depths and are not as destructive.

The 365 A.D. earthquake was an exceptional episode of sudden strain release over a very wide area. Apparently, it resulted in significant stress transference to other segments near the western and southern boundaries of the Anatolian–Aegean plate, which subsequently triggered destructive earthquakes. There was unusually high seismic activity and clustering in the region during the fourth to the sixth centuries AD (Stiros 2001), characterized as the "Early Byzantine Tectonic Paroxysm" (EBTP, Pirazzoli *et al*. 1996). Strong earthquakes in 522 A.D. and 551 A.D. toppled the magnificent Doric temple of Zeus in Ancient Olympia, which withstood almost 1,000 years of earthquakes previously (Pararas-Carayannis 2009). Similar swarms of strong quakes occurred at different periods of time and had great impact on ancient civilizations. For example, earthquakes in the 17th Century B.C. destroyed the Minoan palaces on Crete (Pararas-Carayannis 1973, 1974, 1992, 2001).

Source Mechanism Analysis

To understand the source mechanisms of the 365 AD earthquake and tsunami, we must first review the tectonic setting of the Eastern Mediterranean and the prevailing kinematic and slip rates along the leading edge of the African/Aegean subduction boundary zone. Then, based on reported crustal displacements as determined by recent field surveys and investigations, we can estimate the source parameters of the 365 AD earthquake, such as the volume of crustal displacements, the amount of total energy release, the portion of energy that contributed to tsunami generation, the orientation and extent of the tsunami source, the volume of displaced water and the direction of maximum tsunami energy flux.

Seismodynamics of the Region - The seismotectonics of the Eastern Mediterranean region are dominated by the collision of Eurasia, Africa and Arabia plates and of two microplates - the Anatolian and the Aegean (McKenzie, 1972; Jackson, McKenzie, 1988). During the Cretaceous (144 to 66.4 million years ago), continuing tectonic processes resulted in the Alpine Orogeny and the formation of the Alps. Stresses of the colliding tectonic plates lifted and folded the upper limestone layers, as well as the deeper metamorphic rock layers of the Eastern Mediterranean Basin. Eventually, big landmasses begun to emerge from the sea, forming the Greek mainland and some of the islands of the present Aegean and Ionian Seas. Thus, during the Alpine orogenic process, the peninsular and western island regions of Greece had a complicated history of geologic development.

The Alpine Orogenesis resulted in further complex geotectonic deformations that created the Hellenic Orogenic tectonic belt, the long range of mountains which transverses the western side of the Aegean microplate. Tectonic processes continued to stress and fold the earth's upper crust in the region, thus forming more islands, more mainland mass and lifting the mountains of

Greece to greater heights. The active tectonic collision of the converging African and Eurasian plates along the entire eastern Mediterranean margin resulted in extreme seismicity and volcanism - processes that continue to the present. The Hellenic Arc was created by such collisions and convergence (Fig. 1). As a result of continuing active interaction and movement along major faults, hundreds of earthquakes of all sizes are recorded every year throughout this region. Since 1964, more than 20,000 quakes have been recorded around Greece alone (Pararas-Carayannis, 2001).

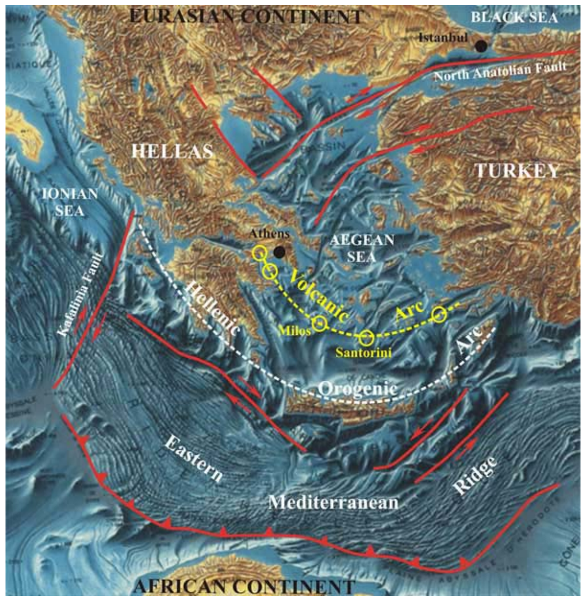

Fig. 1. Simplified geotectonic map of the Eastern Mediterranean and Aegean Sea. (*Image source: Dimitris Sakellariou, Hellenic Center for Marine Research).*

The geodynamics of the Eastern Mediterranean region are further impacted by the Arabian plate as it moves in a north-northwest direction relative to Eurasia at the rate of about 25 mm/y. This continuing movement has caused extrusion of the Anatolian microplate in a westward direction, thus preventing collision of the Arabian plate with Eurasia. Accordingly, the Anatolian microplate moves westward from the zone of intensive convergence in eastern Turkey (McKenzie 1972; Jackson & McKenzie 1988). The same studies proposed the existence of the Aegean microplate moving faster than the Anatolian in the southwest direction. However, there is still a great deal of controversy regarding the movements of the Anatolian and Aegean Sea microplates. Earlier geodetic studies of plate kinematics, postulated that both microplates were merged and moved together (Le Pichon et al., 1995; Reilinger et al., 1997). However, studies defining two regions of low strain rate - outlined by belts of deformation - support a distinctly different motion for the Aegean Sea subplate (Papazachos 1996; Papazachos 1998).

The kinematics of the Eastern Mediterranean region are further affected by the African plate moving in a northward direction relative to Eurasia at the rate of about 10 mm/y. Its leading edge is subducted along the Hellenic arc with a higher rate than the plate is moving (Reilinger, 1995). Also, the Aegean subplate appears to be traveling faster than the Anatolian in a southwestward direction, rotating counterclockwise and overriding the African plate along the Hellenic Arc. Stresses from the tectonic movements of the larger plates have also formed several extensional or compressional fracture zones and a series of deep-sea basins extending from Kefalonia to Rhodes along the leading edge of the African plate.

The Hellenic Arc is an arcuate depression created by this convergence. The Arc is characterized by a zone of active seismicity which extends from the lower Ionian Sea islands and Western Peloponnesus, continues in a southeast direction along the islands of Kythera and Antikythera to south of Crete, then changes to an eastward direction, continuing to Rhodes and Western Turkey. Different segments of the active boundary include the Hellenic Trough, the Strabo Trough, the Trough of Rhodes and the Pliny Trench. Major faults in the region have estimated slip rates, which are compatible with rigid-plate kinematics (Jackson, 1994; Westaway, 1994). Each segment is capable of producing major or even great earthquakes and destructive tsunamis such as that of 365 A.D., although the crustal block that extends from Kythera/Antikythera island to southwestern Crete, appears to be the more likely source of very destructive earthquakes and tsunamis.

However, not all of the earthquakes which occur in the region result in crustal displacements that align with known tectonic trends. Recent deeper earthquakes indicate the existence of an extensive and diffuse zone of active crustal deformation on the Aegean microplate that does not necessarily coincide with the overall tectonic trends or identifiable surface faults on the Peloponnese or elsewhere in Greece.

Crustal Displacements - There have been numerous scientific and archaeological field investigations of raised shorelines and submerged ancient harbors in this region that are indicative of major crustal displacements associated with significant earthquakes (Thommeret *et al*. 1981, Flemming & Pirazzoli 1981; Pirazzoli *et al*. 1982, 1996; Pologiorgi 1985; Pirazzoli 1999). In Antikythera Island there was evidence of uplift that ranged between +1.0 and +2.7 m and estimated to have occurred sometime between 311 AD and 539 AD.

The 365 A.D earthquake resulted in considerable upward crustal movement on the extreme western area of the island of Crete. Field studies of salt deposition and of erosional features indicate that the upward crustal displacements raised the land by as much as 6.66 meters on the average above the ancient sea level. Based on surveys of sediment distributions, the horizontal crustal displacements are believed to have ranged from 1m to as much as 20 m on certain areas. Also, satellite imagery shows that subsidence of a large land mass has occurred, but possibly at a later time.

Archaeological investigations (Flemming and Pirazzoli 1981) of submerged ancient harbors close to Ancient Falassarna on the western end of the Gramvoussas Peninsula identified an uplifted jetty made of "unhewn blocks". Remains of marine fauna on these blocks were found at heights of as much as 6.5 m above sea level, inferring that this must have occurred since the second or third century AD, when this ancient town was flourishing and its harbor was still functional (Pologiorgi 1985). A maximum uplift of about 9 m over a smaller area near Ancient Falassarna has been dated to have occurred between 261 and 425 AD and attributed to probable coseismic movement accompanying the 365 AD earthquake (Pirazzoli *et al*. 1992). Also, uplift ranging between 0-9 m was observed along a distance of more than 100 km of the western part of the island of Crete. Radiometric data supported that it must have occurred around AD 370±52 (Thommeret *et al*. 1981, Pirazzoli *et al*. 1982). However, Western Crete was found to be clearly free of any isostatic or volcanic effects and, consequently, the possibility of any aseismic slip or of any non-tectonic effects have been ruled out (Stiros and Papageorgiou 2001). Biological observations provided evidence that very rapid crustal movements had taken place during that period (Laborel and Laborel-Deguen 1994, Pirazzoli 1996).

It remains to be determined whether the extensive uplift observed on western Crete and believed to be associated with 365 AD earthquake was caused - at least partially - by localized crustal anisotropies along décollement boundaries that differ from the characteristic, long term, basal deformational patterns in this region. This particular earthquake appears to have been an unusual outer-rise event that forced tensional flexing of the subducting plate at an oblique angle and energized existing faults along the western side of Crete. Outer-rise earthquakes are known to generate more destructive tsunamis (Pararas-Carayannis, 2009).

Rupture Length – The well-documented uplift and distribution of crustal displacements on Crete indicate that the rupture occurred along a major thrust fault that had a strike of N30°W and along two northern sub-faults that had strikes of about N50°E. Based on initial field measurements, the rupture length of the 365 AD event was estimated to be 114 km and the seismic moment at 1.4×10^{20} N·m.

Focal Mechanism - The focal mechanism of the 365 AD earthquake corresponded to apparent reverse faulting that thrusted upward a good portion of the overriding Aegean plate along the segment of the subduction zone defined by the previously-described, 200 km long structural block that extends from the island of Antikythera to southwestern Crete - aligned in parallel to the Hellenic trench. Field investigations indicate that there was also considerable horizontal displacement along the same block, which is also indicative of counterclockwise rotation. From recent seismic history for this particular crustal block, we can draw certain conclusions. Data from first motion instrumental recordings of recent events (Fig. 2) indicates that the 365 AD earthquake must have occurred on a very shallow plane that dips approximately about 15 degrees below the Aegean plate along this segment of the leading edge of subduction – which is typical with the direction of subduction of the African plate.

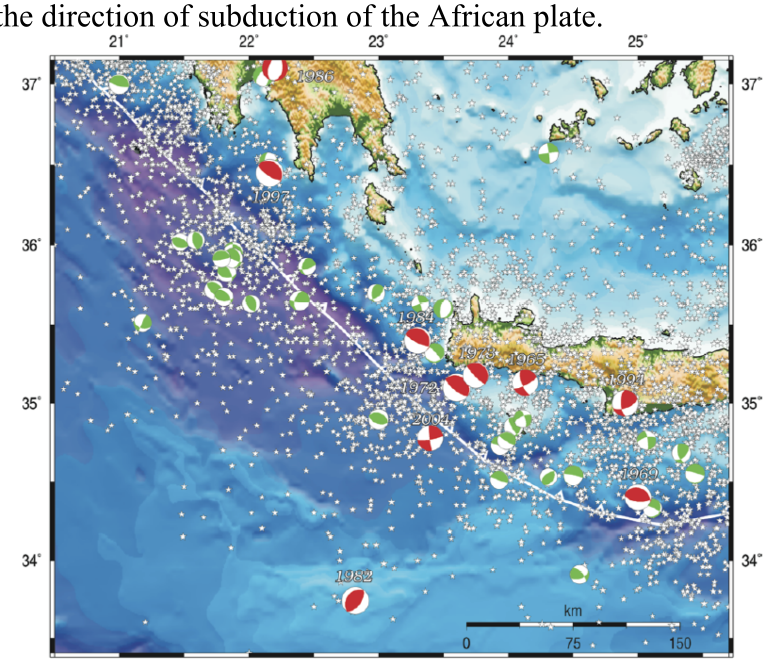

Fig. 2. Fault plane solutions of recent earthquakes along the southwestern segment of the Hellenic Arc *(Fig 2 of Papadimitriou and Karakostas, 2007).*

Also, based on the extremely strong ground motions that were reported in ancient writings, we may conclude that the focal depth of the 365 AD earthquake must have been between 12 to 20 km. Long period seismometer recordings and apparent directional changes in focal mechanism of recent events, also suggest that the 365 A.D. earthquake rupture must have terminated at an asperity near the Ptolemy trench to the SSE. Based on these observations, the limits of the tsunamigenic source can be estimated.

Estimated Source Parameters - All available data from field investigations supports that western Crete and the island of Antikythera belong to the same structural block, which is about 200 km long and aligned in parallel to the Hellenic trench. It is believed that the 365 A. D. earthquake involved almost the entire length of this structural block. This particular tectonic block on the southwestern flank of the Aegean plate appears to be unique, in that it involves frequent episodes of regional compression, folding and thrusting which deviate from the prevailing patterns of normal faulting and processes of extension that are the prevailing trends of crustal deformation in the central and northern regions of Greece. Thus, this block deserves special consideration - and should be of great concern - because it has a very high potential to generate extremely destructive tsunamigenic earthquakes. Based on the well-documented uplift and distribution of crustal displacements on Crete it can be concluded that the rupture of the 365 AD event occurred along a major thrust fault with a strike of about N30°W and along two northern sub-faults that had a strike of about N50°E. Based on the recent rupture modeling study (Papadimitriou & Karakostas 2007), the overall rupture length for this event was re-estimated to have been as much as about 96 nautical miles (177.8 km). Furthermore, by projecting the field measurements of vertical crustal displacements from Crete and Antikythera Island into the sea, we can estimate that the earthquake affected an area with elliptical dimensions with major and minor axes of about 244 kms and 94 kms, respectively (Fig. 3). Thus, we may estimate the approximate total area affected by the earthquake to be:

Total Area $= \pi . r_1 . r_2 = 3.14 \times 244 \times 94 = 72{,}019 \text{ km}^2$

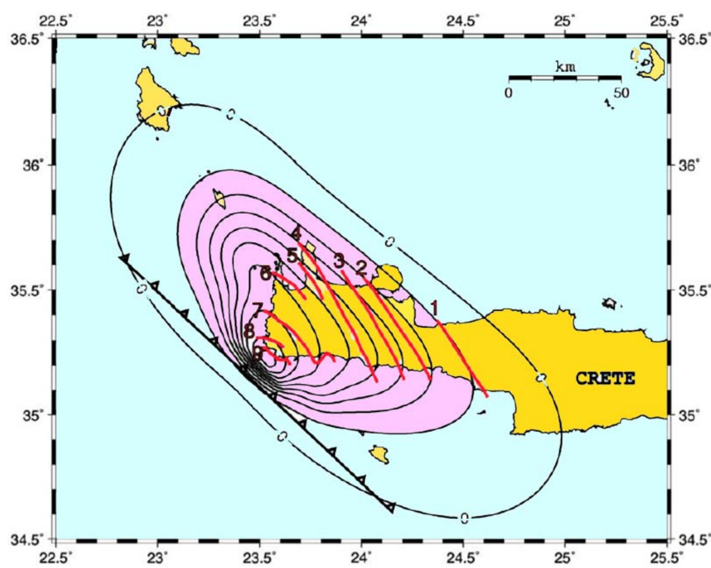

Fig 3. Crustal Displacements, Tsunami Generating Area (mod. from Papadimitriou & Karakostas, 2007)

To determine the tsunami source area we must deduct from the total area of 72,000 km^2, the land area affected by the earthquake on Crete and the islands. Since the affected land area is estimated at 4,710 km^2, the submerged portion that underwent vertical crustal changes is estimated at 67,290 km^2, and this is the postulated area of the 365 AD tsunami source region. By estimating the volume of displacements for that particular area, we can then estimate the portion of total earthquake energy that contributed to the generation of the tsunami. Since the total volume of displacements - the volume of the estimated isopach on land - is estimated to have been 6.63 km^3 and the overall total volume of the earthquake displacements - total isopach - is estimated at 16.929 km^3, the tsunami was generated by ocean floor displacements of about 10.299 km^3, which would also be the vertically displaced volume of water that generated the tsunami.

Numerical Modeling of the 365 A.D. Tsunami

Using the postulated source dimensions of the 365 AD tsunami a numerical modeling study was conducted using the SWAN shallow-water numerical code which solves the long wave, shallow water, nonlinear equations of fluid flow (Mader 2004). The modeling was based on a 600 by 280 grid and four-minute travel time increments and provided tsunami travel times, wave height attenuation with distance and estimates of tsunami energy distribution. Table 1 shows the depth of the sea for seven selected locations in the Eastern Mediterranean basin, the travel time for the tsunami to reach them and the calculated maximum wave height. Figure 4 provides the propagation of the 365 AD tsunami along the Eastern Mediterranean Basin at time increments O, 10, 33, 75, 117, 158, and 367 minutes after the earthquake. Note that no tsunami energy reaches the Western Mediterranean Basin, the upper Adriatic Sea or the Northern Aegean above the latitude of the Sporades Islands. Fig. 5 shows the locations and the tsunami heights in the open sea.

Table 1. Tsunami travel time and height attenuation at seven random locations in the Eastern Mediterranean Basin (Max. height scales with postulated source height of 50 meters).

Location	*Depth (meters)*	*Arrival Time (secs)*	*Max Height for 50 m. Potsulated Source (in meters)*
1	*29*	*7600*	*3*
2	*2059*	*1000*	*13*
3	*167*	*7400*	*7*
4	*1641*	*3200*	*7*
5	*3381*	*1600*	*13*
6	*2585*	*1600*	*3.8*
7	*2067*	*5500*	*1.0*

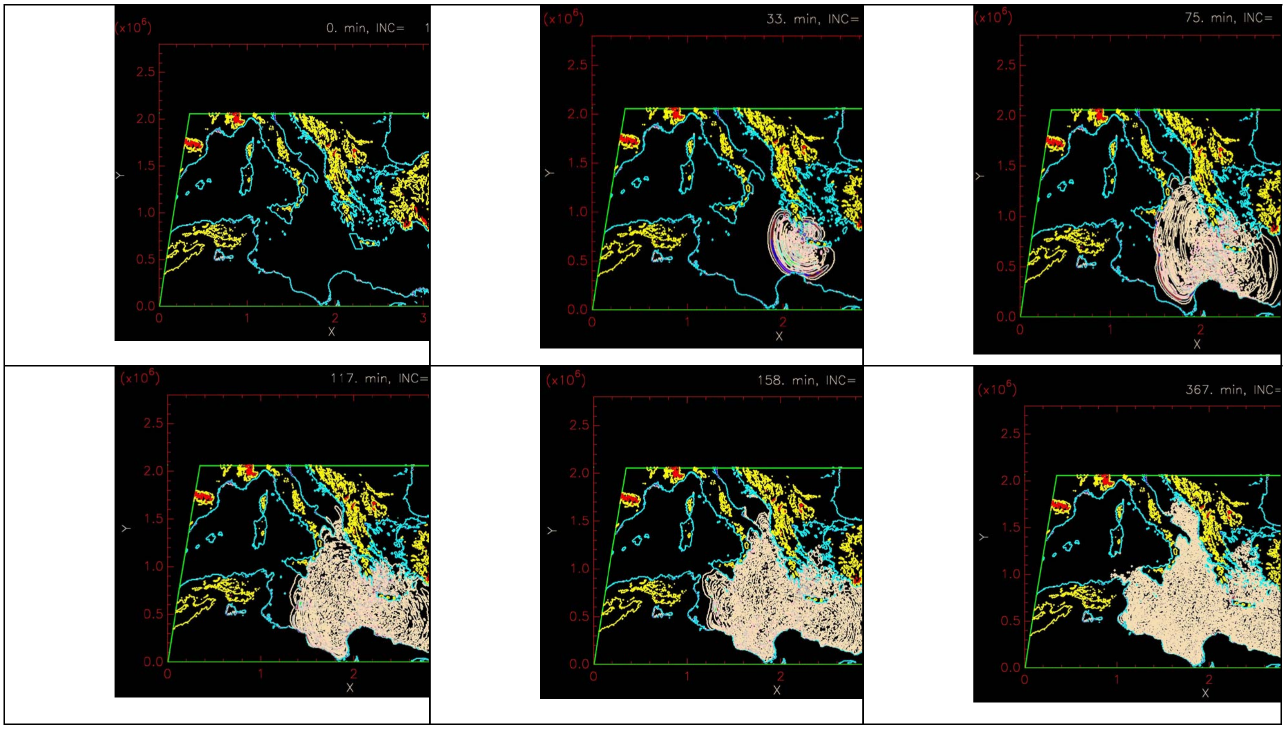

Figure 4. Propagation of the 365 AD tsunami in the Eastern Mediterranean Basin. Time increments O, 10, 33, 75, 117, 158, and 367 minutes after the earthquake. Note that no tsunami energy reaches the Western Mediterranean Basin, the upper Adriatic Sea or the Northern Aegean above the latitude of the Sporades Islands.

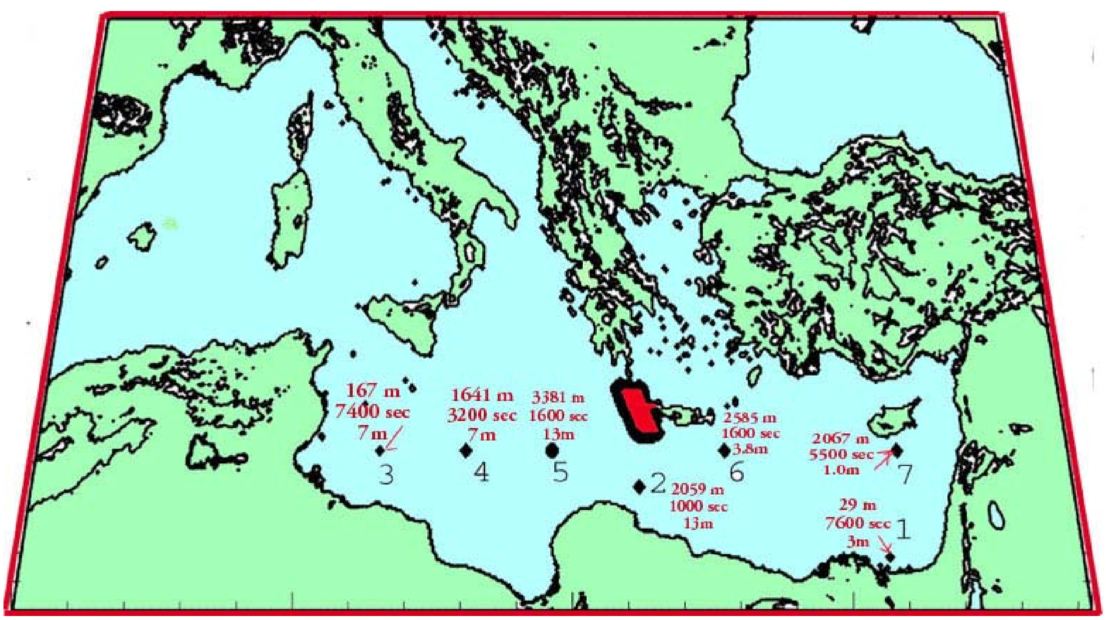

Figure 6. Tsunami travel time and height attenuation at selected locations in the Eastern Mediterranean Basin. (Postulated source displacement 50m).

References *(Partial listing)*

Ammianus Marcellinus, Roman History, Book XXIII, 6:32-36, The Complete Online Library of Ancient Sources. http://www.thedyinggod.com/chaldeanmagi/sources/ammianus.html

Jackson, J., McKenzie, D., 1988. The relationship between plate motions and seismic moment tensors, and the rates of active deformation in the Mediterranean and Middle East – *Geoph. Journal 93*, 45-73.

Jackson, J. (1994), Active tectonics of the Aegean region, *Annu. Rev. Earth Planet. Sci.* **22**, 239-271.

Laborel, J., and F. Laborel-Deguen (1994), Biological indicators of Holocene sea-level variations and of co-seismic displacement in the Mediterranean area, *J. Coast. Res*. **10**, 395-415.

LePichon, X., Chamot-Rooke, N., Lallemant, S., Noomen, R., Veis, G. 1995. Geodetic determination of the kinematics of Central Greece with respect to Europe: implication of eastern Mediterranean tectonics. - *J. Geophys. Res,* 100, 12675-12690.

Mader L. Charles, 2004, Numerical Modeling of Water Waves - Second Edition. CRC Press (2004) book, ISBN - 0-8493-2311-8

McKenzie, D.P. 1972. Plate Tectonics of the Mediterranean region. - *Nature 226*, 239-243.

Papadimitriou E. & V. Karakostas, 2007, Rupture model of the great AD 365 Crete earthquake in the southwestern part of the Hellenic, Arc. Acta Geophysica vol. 56, no. 2, pp. 293-312, 2007

Papazachos, B. C. and K. Papazachou, 1997. Earthquakes of Greece, Ziti Editions, Thessaloniki, 304 pp.

Pararas-Carayannis, G., 1974, The waves that destroyed the Minoan empire, Revised for Grolier Encyclopedia, Science Supplement, Man and His World, pp. 314-321.

Pararas-Carayannis, G., 1992. The Tsunami Generated from the Eruption of the Volcano of Santorin in the Bronze Age Natural Hazards 5::115-123,1992. 1992 Kluwer Academic Publishers (Netherlands.)

Pararas-Carayannis, G., 2001. The Potential for Tsunami Generation in the Eastern Mediterranean Basin and in the Aegean and Ionian Seas in Greece. http://www.drgeorgepc.com/TsunamiPotentialGreece.html

Pararas-Carayannis, G., 2006/ The Earthquake of January 8, 2006 in Southern Greece. http://www.drgeorgepc.com/Earthquake2006Greece.html

Pirazzoli, P.A., J. Laborel, and S.C. Stiros (1996), Earthquake clustering in the eastern Mediterranean during historical times, *J. Geophys. Res.* **101**, 6083-6097.

Reilinger, R., McClusky, S., Oral, M., King, R., Toskoz, M., Barka, A., Kinik, I., Lenk, O., Sanli, I. 1997. GPS measurements of present-day crustal movements in the Arabia-Africa-Eurasia plate collision zone. - *J. Geophys. Res*, 102, B5, 9983-9999.

Stiros, S., 2001. The AD 365 Crete earthquake and possible seismic clustering during the fourth to sixth centuries AD in the Eastern Mediterranean: a review of historical and archaeological data, *J. Struct. Geol.* **23**, 545-562.

Stiros, S.C., and S. Papageorgiou (2001), Seismicity of western Crete and the destruction of the town of Kissamos at AD 365: Archaeological evidence, *J. Seismology* **5**, 381-397.

Thommeret, Y., J. Laborel, L. Montaggioni, and P. Pirazzoli (1981), Late Holocene shoreline changes and seismotectonic displacements in western Greece (Greece), *Z. Geomorph.Supl.* **40**,127-149.