

# TSUNAMI HAZARD IN THE EASTERN MEDITERRANEAN SEA: STRONG EARTHQUAKES AND TSUNAMIS IN THE WEST HELLENIC ARC AND TRENCH SYSTEM

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The West Hellenic Arc and Trench (WHA-T) system is seismotectonically one of the most active in the European-Mediterranean region. Data on earthquake and tsunami phenomena occurring in the tectonic segment of the WHA-T from the antiquity up to the present have been updated, critically evaluated and compiled in the standard format developed for the New European Tsunami Catalogue. Most of the tsunamis documented are caused by strong earthquakes occurring in the area offshore Crete Island which is one of the most tsunamigenic areas in the entire Mediterranean Sea region. The major event of AD365 appears to be the largest ever occurred in the Mediterranean Sea at least in the last 2.5 millennia. The mean repeat time of strong tsunamis is calculated from intensity-frequency statistics and probabilistic hazard assessment is performed by assuming random temporal distribution of the events.

*Key words:* strong earthquakes, tsunami catalogue, tsunami hazard, Hellenic Arc

## 1. Introduction

The Mediterranean and connected seas are characterized by high seismicity with the basin of East Mediterranean Sea being the most active. This is also valid as regards the tsunamicity which gradually increases from west to east within the basin with Greece and the surrounding regions being of maximum seismicity and tsunamicity (Papadopoulos and Fokaefs, 2005, Papadopoulos, 2009).

The western segment of the Hellenic Arc and Trench system, hereafter called WHA-T, is one of the most active seismotectonic structures in the European-Mediterranean region. Large earthquakes, both shallow and of intermediate-focal depth have been historically documented and instrumentally recorded with magnitudes up to about 8.0. From earthquake and tsunami studies and catalogues it results that several earthquakes occurring in the WHA-T produced either local or regional tsunami waves (e.g. Galanopoulos 1960, Ambraseys 1962, Antonopoulos 1980, Papadopoulos and Chalkis 1984, Soloviev 1990, Soloviev et al. 2000, Papadopoulos, 2001, Papadopoulos and Vassilopoulou, 2001, Papazachos and Papazachou, 2003).

This paper is a step forward regarding the statistical tsunami hazard assessment in the East Mediterranean Sea. Geographically the region studied follows the arcuate structure of the WHA-T; namely, it starts from the area of Zakynthos Island to the north and through the South Ionian Sea and the Kythira Strait turns to the east and terminates to the east part of Crete. This region is illustrated in Figure 1. Only tsunamis having their sources within that region are examined here. Tsunami sources located in the Aegean Sea north of  $36^{\circ}$  N and east of  $23.5^{\circ}$  E will be examined in another paper since the seismotectonic setting there is different from that of WHA-T. The main steps of the procedure applied are common with those followed for other areas of the East Mediterranean Sea, such as the Corinth Gulf, Central Greece (Papadopoulos, 2003), Cyprus and the Levantine Sea (Fokaefs and Papadopoulos, 2007) and the eastern segment of the Hellenic Arc and Trench (Papadopoulos et al., 2007). Data were collected and evaluated from historical documentary sources, geological and archaeological field studies as well as from numerous reviews, books and catalogues (AOA, 1896, 1898, Galanopoulos 1960, Ambraseys 1962, Ben-Menahem 1979, Antonopoulos 1980, Papadopoulos and Chalkis 1984, Evagelatou-Notara, 1987/88, Soloviev 1990, Ambraseys et al., 1994, Guidoboni et al., 1994, Soloviev et al. 2000, Papadopoulos, 2001, Papadopoulos and Vassilopoulou, 2001, Papazachos and Papazachou, 1997, 2003, Guidoboni and Comastri, 2005). New information is provided for three events occurring on 1741, 2000 and 2006.

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The data were compiled according to the standard format introduced since 90's for the production of the New European Tsunami Catalogue (e.g. Tinti and Maramai, 1996; Papadopoulos, 2003). Then, the data were critically evaluated and used for tsunami hazard assessment on the basis of the classical size-frequency statistics, well known in seismology as Gutenberg-Richter (G-R) statistics, as well as of the random model for the temporal distribution of the events.

## 2. A New Tsunami Catalogue

The tsunami data are compiled in three sections: the Quick-Look Table (QLT), the Quick-Look Accounts File (QLAF) and the References File (RF), which all together compose the Quick-Look Catalogue (QLC). The RF consists of the sections of Press Reports, Historical Sources and References. The size of the tsunami events, in terms of maximum intensity,  $K$ , has been assessed by applying the new 12-point tsunami intensity scale introduced by Papadopoulos and Imamura (2001). At the same time, the tsunami intensity,  $k$ , based on the 6-point Sieberg-Ambraseys scale (Ambraseys, 1962) is also estimated. In those scales the impact of tsunami wave is described on the basis of macroscopic observations.

There is no doubt that several events included in this study were tsunami waves. It seems, however, that some others were rather sea-quakes than real tsunami events. The term *sea-quake* has been used to describe sudden shocks being felt on board ships in the epicentral areas of strong earthquakes (Bullen and Bolt, 1985). This phenomenon is well-explained by the incidence of seismic  $P$ -wave through the sea-water layer with the speed of sound in water, that is 1.5 km/sec, following refraction through the sea floor. In addition, at least in one case a seiche rather than tsunami wave was reported. *Seiches* are rhythmic motions of the water in land-locked bays or lakes and are sometimes excited by earthquakes and by tsunamis (Bullen and Bolt, 1985). Events that look like either sea-quakes or seiches are also included in the catalogue with the aim to provide all the relevant data that may help the more conclusive study of those events in the future. For such events, however, no tsunami intensity has been estimated.

One point that needs clarity regards some locality names used in documentary sources and their correspondence to modern names. In particular, this concerns the city of Heraklion in Crete island and the island of Zakynthos (modern names) which in documentary sources are referred to as Chandaka (or Candia) and Zante, respectively. As a general rule we do prefer to use modern names but in the reproduction of documentary sources we maintain the names used in the respective sources. Localities reported in this paper in association with tsunami inundation, sea-quakes and seiches are illustrated in Figure 1.

### 2.1 The Quick-Look Table

Table 1 is the QLT summarizing the main parameters of the tsunamis as well as of the respective earthquakes or other causative events. From the QLT it results that 30 events have been considered occurring from AD 66 onwards.

### 2.2 The Quick-Look Accounts File

This is the second section of the QLC. For each tsunami event it is arranged as follows:

*[code number]* date: year, month, day (in New Style for events occurring after 1582)/ place

*coordinates of the source:* geographic latitude (N)/longitude (E) (in degrees and minutes)

*cause:* (see key in Table 1)

*tsunami intensity:* 6-point scale/12-point scale

*reliability:* scaling from 1 to 4, where 1=improbable tsunami and 4=definite tsunami (see key in Table 1). For sea-quakes and seiches default reliability 1 is introduced to indicate that the event is an improbable tsunami.

The reliability of a tsunami event has been evaluated and its tsunami intensity has been assigned to on the basis of the description of the wave impact. In the next lines of this section 30 events are reviewed and evaluated. Epicenters of tsunamigenic sources are plotted in Figure 2. Tsunami waves which were

reported to inundate coastal segments along the WHA-T but had their sources in areas outside WHA-T are not included in the present QLC. However, they are shortly reviewed in the Appendix A1. Moreover, in Appendix A2 we review shortly a spurious event which was included in previous tsunami catalogues.

[1] AD 66, South Crete Island

*coordinates:* 35 00 24 42, *cause:* ER

*tsunami intensity:* 3/5, *reliability:* 4

According to documentary sources, reviewed by Platakis (1950) and Guidoboni et al. (1994), the island of Crete suffered a lot because of a large earthquake occurring around AD66. Flavius Philostratus, in a passage of his book *Life of Apollonius of Tyana* written around AD200, reports that while Apollonius was at Leben (Levena), the port of Gortyn situated to the southern coast of the island, an earthquake and tsunami occurred.

According to the description of Philostratus, the sea receded from the south coast of Crete for about seven stadia, that is about 1.3 km. However, there is no information about possible effects caused. Archaeological observations indicated a possible tsunami attack in the harbor of Phalasarna, NW Crete, during Hellenistic times (Hadjidaki 1988). Stratigraphic, geomorphological and radiometric observations (Pirazzoli et al., 1992, Dominey-Howes, 1996) imply that around AD66 a tectonic subsidence of 15 cm-25 cm occurred at Phalasarna and that, in association to this event, tsunami wave affected the area. Due to unsolved chronological problems, Guidoboni et al. (1994) suggested two different dates for this earthquake/tsunami event as an alternative of AD66: AD53 and AD62.

[2] 365 07 21, west Crete Island

*coordinates:* 35 12 23 12, *cause:* ER

*tsunami intensity:* 5/10, *reliability:* 4

On the basis of numerous historical documents, the destructive earthquake and the associated devastating tsunami of 21 July 365 have been considered as being of a "universal" impact in the Mediterranean Sea (see reviews in Galanopoulos 1960, Ambraseys 1962, Antonopoulos 1980, Jacques and Bousquet, 1984, Evagelatou-Notara, 1987/88, Guidoboni et al., 1989, 1994, Ambraseys et al., 1994, Papadopoulos and Vassilopoulou, 2001). It appears that the 365 earthquake has been one of the largest ever occurred in the Mediterranean Sea. Archaeological evidence for seismic destructions in Crete (Di Vita 1986, 1995, Markoulaki 1987, Themelis 1988), coastal tectonic elevations in W. Crete and Antikythira (Thommeret et al., 1981, Pirazzoli et al., 1992), seismic properties in the Hellenic Arc (Papazachos, 1996) and results from tsunami numerical simulations (Tinti et al., 2005, Lorito et al., 2008, Shaw et al., 2008) support the idea that the earthquake ruptured a large part of the WHA-T, between Peloponnese and Crete, where the tsunamigenic source should also be placed. Destruction caused by the 365 earthquake was reported mainly from Crete. However, the tsunami was described as of very widespread propagation in the eastern Mediterranean basin and of extensive destructiveness in several coastal zones.

In Methoni, SW Peloponnese, a Spartan ship was moved inland about 2 km from the seashore. In Alexandria, the wave penetrated inland to a long distance while some large boats were drifted over the roof tops. It is also reported that 5000 people were drowned. The wave inundated the area of Panephytis, near modern El Manzala lagoon to the east of Alexandria in the Nile river mouth, where it seems that penetrated in long distance inland. The wave also hit Sicily causing suffering to countless peoples there and in many other islands. In Epidavros, modern Cavtat near Dubrovnik in Dalmatia, Adriatic Sea, ships were hurled on to the rugged mountains and remained suspended there.

Geological evidence of the 365 tsunami supposedly found in the harbour of Phalasarna, NW Crete, gave rise to some debate. In the stratigraphy of harbour basin Pirazzoli et al. (1992) were able to identify two layers of "coarser material with blocks" in two out of three trenches. They interpreted that both of them represent tsunami layers deposited by the AD 66 tsunami at c. + 5.9 m in trench A and by the AD 365 tsunami at + 6.4 m in trench A and at + 6.7 m in trench B. They added, however, that the effects of the 365 tsunami were relatively limited in the Phalasarna sediment stratigraphy. On the other hand, Dominey-Howes et al. (1998), who performed sedimentary study in Phalasarna, although supported that the foraminiferal assemblage indicates tsunami sediment deposition around AD 66, claimed that there is no bio- or lithostratigraphic evidence to infer sedimentary deposition associated

with the 365 tsunami. According to them, it is difficult to understand why the stratigraphy at Phalasarna records no evidence of such a large displacement. The relatively limited effects of the 365 tsunami in Phalasarna sediment stratigraphy possibly is explained by that the Phalasarna site was already uplifted by 6.6 m, if only a few minutes before the wave arrived (Pirazzoli et al., 1992).

Sedimentological and geomorphological evidence, likelihood of tsunami origin, was documented by field observations performed by Scheffers and Scheffers (2007). They supported that in Phalasarna, boulders of weight that reaches up to 50 tons at 5 m asl have been moved from the foreshore inland by tsunami waves dated around AD 365 or later. The minimum wave run up has been estimated equal to 8 m. The likelihood for such a process of boulders movement is moderate to high. In Balos, north of Phalasarna, dislocated boulders (10–40 tons) with borings were observed and attributed by Scheffers and Scheffers (2007) to tsunami action dated AD 365 or later. The minimum wave run up has been estimated equal to 6 m. The likelihood for such a process of boulders movement is high. More impressively, in Balos dislocated boulders of 67 tons and 75 tons at 15-25 m asl indicate a high likelihood of tsunami run up more than 25 m. However, the geological documentation of the 365 tsunami inundation still remains questionable.

[3] c.800, Kythira Strait

*coordinates:* 35 30 23 00, *cause:* ER

*tsunami intensity:* 4/6, *reliability:* 2

According to the Kytherian writer Kassimatis (1978, p. 49): "*There is historical information that during the year AD800 a great and terrible earthquake occurred in our island, after the termination of which enormous sea waves were coming backwards to cover the empty eastern coasts of the island and attacked terribly and fiercely Skandia and destructed and swept away its last remaining ruins*". Regarding this there are two problems: (i) Kassimatis (1978) neglected to report on the source of the historical information used, (ii) no other relevant source was found so far. Papadopoulos and Vassilopoulou (2001) considered two alternative explanations: (a) indeed, Kassimatis (1978) just neglected to mention the documentary source used, (b) Kassimatis (1978) confused the year of occurrence of the 365 earthquake. The second explanation, however, is weakening since Kassimatis (1978) reported about the 800 earthquake in a chapter of his book devoted to the ruination of Kythira which occurred in the period of about AD 650-1000. An earlier ruination that occurred in the 4<sup>th</sup> century was discussed in a previous chapter of his book where Kassimatis (1978) suggested that the 4<sup>th</sup> century ruination might be caused by natural disasters, such as earthquakes. He declared, however, that no earthquakes were reported for that period. This implies that he was not aware of the occurrence of the 365 earthquake and as a consequence it was impossible to confuse the year of its occurrence. Therefore, the first explanation is the most likely and makes quite challenging the investigation of further information about the possible large earthquake/tsunami event of 800.

It is of interest to discuss the possible connection of the event reported by Kassimatis (1978) with the large earthquake which shook large part of the East Mediterranean on April 796. Epicentral coordinates determined by Poirier and Taher (1980) are 31.3°N–29.55°E, that is in the Mediterranean Sea to the south of the Hellenic Trench, which seems unlikely since from seismotectonic point of view no high seismic potential is expected from that location. The estimates of Ambraseys et al. (1994) and Papazachos and Papazachou (2003) put the epicentral location in the Hellenic Arc-Trench system, which appears rather realistic: 36°N–26°E and 34.5°N–24.4°E, respectively. The magnitude assigned by Papazachos and Papazachou (2003) is  $M_s=7.1\pm 0.5$ . No tsunami generation was reported in association with the 796 earthquake. However, the Arab chronographer As-Soyuti reported earthquake and tsunami inundation occurring in Missisah (Mopsueste) and Alexandrete (Iskenderum) Gulf during 187AH, that is between December 802 and December 803 (Antonopoulos, 1973, Poirier and Taher, 1980).

We decided to include with great reservation the supposed earthquake/tsunami event in the list of historical earthquakes and tsunamis that occurred in WHA-T. Should a large, tsunamigenic earthquake occurred around AD800, then it would be an interplate event associated with the Hellenic Arc-Trench system, possibly in the western part of it. Then, we adopt magnitude of the order of 7.5 and location in the SW Hellenic Trench segment.

[4] 1494 07 01, Heraklion, Crete island

*coordinates:* 35 30 25 30, *cause:* ER

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*tsunami intensity: 3/5, reliability: 4*

Casola (1498/1855), a Milanese priest and pilgrim to Jerusalem, wrote about a very strong shock that experienced himself in the city of Heraklion (see reviews in Platakes, 1950, Antonopoulos, 1973, 1980 and Guidoboni and Comastri, 2005). Widespread damage was caused in church towers and private buildings while the people got in panic. The shocks repeated at about the third hour of the night (i.e. 21.00 local time) 2 July 1494. The governor received messages reporting that destruction was caused in several places of Crete. The earthquake is erroneously reported by Theuet (1556) and Oliver (1807) as occurring on 1490. In the harbor of Heraklion big waves caused so violent collision of anchored ships as to seem that would all broken to pieces. The color of the sea water changed several times. A captain reported that such a thing never happened in the past. Tsunami was reported at Jaffa, Israel, where the sea receded “*a day’s walk long*” (Ben-Menahem, 1979; see also review in Fokaefs and Papadopoulos, 2007).

[5] 1612 11 08, Heraklion, Crete island

*coordinates: 35 30 25 12, cause: ER*

*tsunami intensity: 4/8, reliability: 3*

Crete was hit by a series of shocks felt in several places of the Mediterranean Sea during the last three weeks of November 1612 (Mallet, 1853, Raulin, 1869, Stavrakes, 1890, Platakes, 1950). It seems that a very strong earthquake occurred on 8<sup>th</sup> November. The trees appeared agitated, as if by a high wind, although the air was unusually calm. In Heraklion many buildings were thrown down, while in the harbor anchored or sailing ships sunk (Mercure Francais, 1612). The last information implies that possibly a strong tsunami was triggered by the earthquake.

[6] 1630 03 09, Kythira Strait

*coordinates: 36 00 24 00, cause: ER*

*tsunami intensity: 3/5, reliability: 4*

This earthquake is known from (i) an ecclesiastic code with a priest’s note about the shock (De Viazis, 1893), (ii) one memory published by Pallas (1936) and (iii) another two memories published by Tsiknakis (1988/89). According to these documentary sources the earthquake occurred on Saturday 27 February 1629 at the “*fourth hour of the day*”, that is around 10.00 am. The entire Crete was shaken; in Heraklion houses were thrown down and few people buried under the ruins. Churches were also damaged. In a more recent study of Tsiknakis (1994) it was shown that the reported year of 1629 has been a *more Veneto* one which means that the date should be corrected to 27 February 1630. The New Style date is the 9<sup>th</sup> of March, not the 10<sup>th</sup> of March as calculated by Papazachos and Papazachou (1989). The erroneous calculation of the latter was noted by Tsiknakis (1988/89) and corrected by Papazachos and Papazachou (1997, 2003). Papadopoulos and Vassilopoulou (2001) reviewed the event as well as the problem of its dating and calculated focal parameters which are adopted here.

De Viazis (1893) also found a series of official documents of the Venetian Administration of Zakynthos Island containing the independent testimonies of three captains sailing around Kythira strait at the time of the earthquake occurrence. Their descriptions leave no doubt that they ran a great danger because of strong tsunami waves traveling towards south and southeast. Two of the captains observed also remnants of wrecks and bodies of shipwrecked persons. When one of the captains arrived into the port of Kythira at the south of the island, today Kapsali port, he was told that at the same day and the same time an earthquake of medium strength was felt and that a slight inundation was observed at the pier.

[7] 1633 11 05, Zakynthos island, Ionian Sea

*coordinates: 37 43 20 52, cause: ER*

*tsunami intensity: 3/5, reliability: 3*

Girardi (1663) is likely the first who reported on the earthquake of 5 November 1633. His passage, reproduced by Bonito (1691, p. 763), reads as follows: “*1633: A 5 di Novembre nell’ isola del Zante fu un fierissimo Terremoto, caddero molte Case con morte di molte persone. Sibisso il Promontorio di S. Sosti, rovinarono alcune alte montagne, si aprì in piu luoghi la terra, d’ onde uscirono flamme , e’ l*

*mare grandemente gonsio con grandissimo spavento di tutti. Il giorno seguente il Terremoto si fè sentire in Mantova, Verona, ed Hostiglia. Era stato ancora in Costantinopoli nel mese di Luglio un terribile Terremoto*". It is clear that on 5 November 1633 a large earthquake occurred in Zakynthos causing the collapse of many houses and the death of many human beings; the promontory of St. Sosti (Άγιος Σώστης), Laganas bay, south side of Zakynthos Island, was submerged. Moreover, high mountains failed, the ground opened in several places and flames were coming out, and the sea rose up highly causing great fear to everyone.

This description implies that a tsunami was caused by the shock but it is not clear if the tsunami was observed in the town of Zakynthos or in Laganas bay or in both. According to Bonito (1691), the next day an earthquake was felt in Mantova, Verona and Hostiglia. Bonito (1691) also cited a relevant short description of Riccioli (1669) (see also a foot note in Barbiani and Barbiani, 1864, p.14). The accounts of Chiotis (1849, 1886) and Barbiani and Barbiani (1864, p.14) on the 1633 earthquake were based on a short version of the Girardi's (1663) description published by Coronelli (1762) who, however, reported that the Zakynthos earthquake was felt in Mantova and in Verona (*Il se fit sentir à Mantoue et à Vérone*). This point is of crucial importance since, in an attempt to calculate the size of the 1633 earthquake in terms of the perceptibility radii, the result would be strongly dependent on the epicentral distances of shaken regions. Girardi's (1663) information that in Mantova and Verona another shock was felt the next day is likely more realistic, given the large distance between Zakynthos and those cities of north Italy, although perceptibility at such a distance could not be excluded. Magniati (1688) reported on an earthquake that was felt in Mantova on 15 November 1633.

Another problem is that several authors confused the large 1633 earthquake with a small earthquake felt in Zakynthos on 1622. The publication of Katrames (1880) signifies the starting point of erroneous reporting that was followed by later authors. In fact, he did not mention at all the 1633 event and erroneously attributed its effects to the 1622 earthquake. This mistake was reproduced by Zoes (1893) who, however, included in his work the 1633 event. Confusion about the effects of the 1622 and 1633 earthquakes was propagated even to modern seismological studies. For example, Papazachos and Papazachou (1989, 1997) considered that both earthquakes were large events with similar macroseismic effects and estimated Richter magnitudes of 6.6 and 7.0, respectively. Lekkas et al. (1997) mentioned the confusion about the 1622 and 1633 earthquakes and suggested that only one shock occurred, that of 1633, which certainly is not correct. In fact, on the basis of a thorough examination of documentary sources, Papadopoulos and Plessa (2001) showed that indeed on 5 May 1622 a shock was felt in Zakynthos but it was only a small one. At all evidence the 5 November 1633 Zakynthos earthquake was a large, destructive event causing important secondary effects, such as several ground failures and a rather local tsunami wave.

[8] 1681 02 12, Chania, Crete island

*coordinates:* 35 42 24 00, *cause:* ER

*reliability:* 1

This is a large earthquake that may have taken place offshore NW Crete and caused destruction rather to Chania than to Heraklion (Ambraseys and Finkel, 1999). According to Raulin (1869), on 10 and 12 February 1681 two shocks were felt in the city of Chania, west Crete, and were also felt on board in the harbor (see also Stavrakes, 1890). We interpret this description as indicating rather sea-quakes than tsunami waves.

[9] 1741 02, Heraklion, Crete island

*coordinates:* 35 30 25 00, *cause:* ER

*tsunami intensity:* 3/5, *reliability:* 3

This is a little known earthquake event reported in local administration archives of the cities of Heraklion and Chania dated 25 February 1741 and 28 February 1741, respectively (Andriotes, 2006). It is reported that the earthquake caused a tsunami in the harbour of Heraklion and because of this a person on board a French boat died.

[10] 1791 11 02, Zakynthos island, Ionian Sea

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*coordinates:* 38 00 21 00, *cause:* ER

*tsunami intensity:* 3/4, *reliability:* 4

This is an extremely destructive shock known from several documentary sources, the most important being the historical notes of Saint-Sauver (1799), French Consul in Zakynthos. Another remarkable source is the diary of Nicolas Gradenigo Sicuro, comte de Scylla. Both sources were reproduced by Barbiani and Barbiani (1864) who noted that although Saint-Sauver experienced the earthquake in Zakynthos by himself, strangely enough he erroneously reported it as occurring on 1790 instead 1791. D. Barbiani, the first author of the Barbiani and Barbiani (1864) publication, experienced the shock himself in Zakynthos. According to him the shock occurred around 9 pm of 2 November 1791. This shock remained in the memory of the local people as the “St Jacob’s earthquake”. Mallet (1855) was based on newspaper correspondences and reported that on December 2, 1791 “*a violent shock occurred in the island of Zante and was followed by others up to the 18<sup>th</sup>*”. It is obvious that the month of the earthquake occurrence was mistaken.

The earthquake caused great destruction in the town of Zakynthos, the castle of the town and several villages particularly at the eastern side of the island. Twenty persons were killed under the ruins while thirty injuries were numbered. Notable damage was also caused in the western part of Peloponnese (Morea) to the opposite of east Zakynthos. Aftershocks were felt for about six weeks. According to Saint-Sauver (1799), the mainshock was followed by very strong waving moving from SE to NW that lasted for several minutes. Mallet (1855) noted that “*the most violent agitation of the sea occurred in the strait between Zante and the Morea*”.

[11] 1791 11 10, Zakynthos island, Ionian Sea

*coordinates:* 38 00 21 00, *cause:* ER

*reliability:* 1

Another less strong shock, very possibly aftershock of the previous event, occurring the night of 10 November (according to comte de Scylla) or 5 November (according to Saint-Sauver) was violently felt on board the Venetian warship “La Minerve” and other boats in Zakynthos port. It appears that it was rather a sea-quake than tsunami wave.

[12] 1810 02 17, Crete island

*coordinates:* 35 00 25 00, *cause:* ER

*tsunami intensity:* 2/3, *reliability:* 4

This was a large, possibly interplate earthquake located offshore Crete, which caused great destruction in Heraklion (Mallet, 1855, Stavrakes, 1890, Platakis, 1950, Ambraseys et al., 1994, Papazachos and Papazachou, 2003). Some damage was also caused in South Aegean islands as well as in remote places of the Mediterranean Sea such as Cairo, Rosetta and Alexandria in Egypt as well as in Malta. The shock was felt as far as Cyprus, Syria and central Italy. In Valletta, Malta, ships in the harbor were violently shaken while in Alexandria the earthquake set up waves in the harbor and in canals (Ambraseys et al., 1994). The account that in the harbor of Valletta ships were violently shaken indicates rather a seiche than tsunami wave. The estimation of tsunami intensity in the QLC concerns the tsunami-like waves observed in Alexandria.

[13] 1816 12 28, Pylos, South Ionian Sea

*coordinates:* 36 54 21 36, *cause:* ER

*reliability:* 1

Traveller Sieber (1823, p. 5) reported that sailing offshore SW Peloponnese “*...all at once, the ship trembled violently, and a hollow sound proceeded from the hold. The captain, who stood near me, was embarrassed, and knew not what to think. I fancied that some small quantity of powder, perhaps a musket, had gone off in the hold, when a second and a third weaker shock succeeded, and put an end to our silence; the sailors declaring it was only an earthquake, and we had nothing to fear. We were besides too far from land to dread a shoal or sand bank; and the phenomenon was scarcely over, when the wind violently increased, which proves that this slight earthquake had some influence on the*

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*atmosphere*". The shakes reported onboard possibly indicate the occurrence of sea-quakes caused by earthquakes in the area of SW Peloponnese (Papadopoulos and Plessa, 2001). The occurrence of tsunami is not documented. From Sieber's description it is not absolutely clear the date of the event. It occurred either on the 28<sup>th</sup> December 1816 or on the 1<sup>st</sup> January 1817. Schmidt (1879) lists an earthquake occurring in Zakynthos on 1 January 1817.

[14] 1820 12 29, Zakynthos island, Ionian Sea

*coordinates:* 37 36 21 12, *cause:* ER

*tsunami intensity:* 2/3, *reliability:* 3

This is a very strong earthquake that caused destruction in the island of Zakynthos as well as to the west Peloponnese. From a long number of documentary sources reviewed by several authors (Perrey, 1850, Mallet 1855, Barbiani and Barbiani, 1864, Montadon, 1953, Konomos, 1970, Zoras, 1973, Papazachos and Papazachou, 1989, 1997, 2003, Lekkas et al., 1997, Spyropoulos, 1997, Lymouris, 2001) it becomes clear that (i) the mainshock occurred at 03.45 am of 29 December 1820, (ii) another strong earthquake, possibly aftershock, occurred on 6 January 1821, and (iii) both earthquakes were accompanied by stormy weather with heavy rainfall and flash floods.

Some authors considered that a damaging tsunami was associated with the particular earthquake sequence (Ambraseys, 1962, Antonopoulos, 1980, Papadopoulos and Chalkis, 1984). Papazachos and Papazachou (1989, 1997) reported that "...6 people died and 29 were injured. Two people were drowned by the flood which followed...rough sea was observed" giving the impression that the earthquake and the flood were causally linked. They went on to estimate tsunami intensity of III+ in 6-point scale. Those estimates were uncritically reproduced by Soloviev et al. (2000). Papadopoulos and Plessa (2001), however, reviewed original documentary sources and showed that the earthquake of 29 December 1820 was not followed by tsunami waves and that flooding reported to follow the earthquake were due to storm surge. In the next lines we examine further this suggestion.

Captains of boats anchored in Zakynthos port reported that at the time of the mainshock a sea-wave was generated causing violent oscillation to the boats and "*it seemed that the boats were pushed towards the coast*" (Barbiani and Barbiani, 1864). No such a sea disturbance has been documented in other coastal places in association to that earthquake. Moreover, no coastal inundation was reported. Therefore, the above description implies that only a small, very local tsunami was possibly caused by the mainshock. An alternative is that standing waves similar to seiches were generated in the harbour of Zakynthos. In addition, Captain Petalas, sailing from Constantinople to Ionian Islands, reported later that being at 03.45 am of 29<sup>th</sup> at distance of 20 miles from Strofades islet, about 50 miles to the south of Zakynthos, felt a dull roar. It was followed by such a strong oscillation that it was impossible for the steerman to control the boat (Barbiani and Barbiani, 1864). At all evidence a sea-quake was described by Captain Petalas.

In conclusion, the documentary sources clearly indicate that the flash flood and the two persons that reportedly were drowned, all being observed after the earthquake of 29<sup>th</sup>, were due to stormy weather and were not causally linked to the earthquake. However, the mainshock caused either a small, local tsunami or a seiche in the port of Zakynthos. Should it was a tsunami, then its intensity is estimated equal to 2 and 3 on 6-point and 12-point tsunami intensity scales, respectively. On the other hand, sea-quakes were reported in the epicentral area of the mainshock. The spurious tsunami event that supposedly occurred on 6 (or 9) January 1821, is reviewed in Appendix A2.

[15] 1843 07, west Crete island

*coordinates:* 35 30 23 30, *cause:* ER

*reliability:* 1

Raulin (1869, p. 427) reported that on July 1843 two shocks were felt by people on board British ship sailing about 35 miles west of the western part of Crete (Stavrakes, 1890, Platakes, 1950). We are in favor of the interpretation that Raoulin described rather sea-quakes than tsunami waves. The shocks were accompanied by great noise, which looked like the noise of a carriage moving from NE beneath the ship. Sounding performed immediately after the occurrence of the two shocks showed sea water depth of at least 292 m.

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[16] 1846 03 28, Crete island

*coordinates:* 36 00 25 00, *cause:* ER

*reliability:* 1

This is a large earthquake that shook violently Crete and was felt in the Cyclades, the East Aegean Sea islands, in Rhodes and large part of Syria and Egypt, in the Greek mainland and Zakynthos as well as in Malta and Sicily (Schmidt, 1879). In Crete there were a lot of ruins, but nothing sure was mentioned about the loss of human life. In Chania, west Crete, the botanist Mr. Th v. Heldreich saw how the large earthquake tilted a minaret to a very worrying angle. However, a next shock brought the tower back in vertical position, so it didn't collapse. Mr Hitier, French Consul in Chania, in his letter to Raulin dated 15 April 1846, reported that the shock was strong enough, of long duration, possibly of 1 min, and caused fissures in 20 houses in Chania and in 100 houses in Heraklion, while a lot of people got in panic (Stavrakes, 1890, Platakis, 1950). On sea the earthquake could clearly be felt, according to a Lloyd captain (Schmidt, 1879). However, a rise of the sea did not take place, which implies that Lloyd's captain felt rather a sea-quake than tsunami wave.

[17] 1846 06 10, Messinia, SW Peloponnese

*coordinates:* 37 09 22 00, *cause:* ER

*reliability:* 1

This strong earthquake caused serious damage in the village of Mavromati but mainly in Mikromani where many houses collapsed and 15 out of the 780 inhabitants were killed (Schmidt, 1879, Galanopoulos, 1950, Stamatopoulos, 1997). In Mikromani, situated one hour walk from the sea, in a flat very low-lying area, 2-3 inches wide cracks were formed with a hand's breadth (approx. 6 inches) sand cones, from which liquid material was flowing out. These ground failures indicate soil liquefaction. At the mouth of Pamisos river, near Kalamata, the cracks were wider and partly filled in with mud. Botanist Mr. Sartori reported to Schmidt (1879) that the earthquake was also clearly felt on sea, which very likely is a sea-quake description.

[18] 1856 10 12, Crete island

*coordinates:* 36 00 25 30, *cause:* ER

*tsunami intensity:* 2/3, *reliability:* 3

This is a large, intermediate-depth earthquake which shook a very wide part of the Mediterranean Sea (see reviews in Raulin, 1869, Schmidt, 1879, Stavrakes, 1890, Platakis, 1950, Galanopoulos, 1955, Ambraseys et al., 1994, Papazachos and Papazachou, 2003). Destruction was reported from South Aegean Sea islands, mainly from Crete, Thera (Santorini) and Rhodes but also from Amorgos, Karpathos and Kasos. Damage was reported from the Greek mainland and as far as Alexandria, Cairo, Damaskus and Smyrna. Schmidt (1879), however, remained skeptical no so much about the extent of the destruction caused by the earthquake but rather for the exaggerated figures of victims reported by some newspapers. According to official documents, in Crete 538 people killed and 637 injured (Raulin, 1869, Stavrakes, 1890).

Nothing is reported of the unusual movement of the sea on October 12<sup>th</sup>, which probably was not observed because of evening time (Schmidt, 1879). The description that "...It was strongly felt by boats sailing off Egypt and as far as Central Italy..." (Ambraseys et al., 1994) indicates rather a sea-quake than a tsunami wave. However, Ben-Menahem (1979) and Amiran et al. (1994) reported that tsunami wave was observed at Haifa (Israel) and Lebanese coasts.

[19] 1866 02 06, Kythira island

*coordinates:* 36 12 23 20, *cause:* ER

*tsunami intensity:* 4/6, *reliability:* 4

This earthquake caused damage in Kythira island and triggered a tsunami with runup of 8 m that attacked coastal houses in Avlemonas village, eastern coast of Kythira (Fuchs 1886, Leonhard 1899;

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see review in Papadopoulos and Vassilopoulou, 2001). The earthquake was confused by Kyriazopoulos (1979) with another shock of volcanic origin that occurred (Galanopoulos, 1955) on 31 January 1866 at the volcano of Thera, South Aegean Sea, some 250 km to the east of Kythira. The French traveller Castellan (1808), who visited Kythira during 1797, published a gravure of the port of St Nikolas in Avlemonas showing the houses of the village lying very close to the seashore exactly as they are today. This indicates that houses in Avlemonas indeed were, and they still are, highly exposed to tsunami waves.

[20] 1867 09 20, Gythion Gulf, South Peloponnese

*coordinates:* 36 30 22 42, *cause:* ER

*tsunami intensity:* 4/7, *reliability:* 4

A detailed description of this earthquake was published by Schmidt (1879) who was able to accurately calculate the earthquake origin time at the National Observatory of Athens: 05.44 am. In the evening of September 19<sup>th</sup> there was one tremor, but in the morning of the next day 3 or 4 tremors occurred within only a few minutes. The largest impact of the morning shocks caused destruction restricted to a small area of Mani province only, on the central of the three peninsulas of Peloponnese, and particularly in the town of Gythion and the villages of Areopoli and Paganea. Houses collapsed and several people were killed. According to press reports it was strongly felt in Messinia, SW Peloponnese (Galanopoulos, 1950). From anonymous meteorological notes it results that an earthquake was felt in Zakynthos at 6 am but no damage was reported there (Konomos, 1970).

Because of one of the morning earthquakes the sea flooded severely the coast of Gythion Gulf and left many fish on land. The sea disturbance was observed from early dawn till 09:00 in the morning. At Chania, Crete, as well as in Zakynthos and Argostoli (Kefalonia Island, Ionian Sea) the sea motion occurred slowly from 05:30 am till 10:00 am. The sea became calm again after repeated waves and periods of back wash. Flooding of the coast took place also in Kalamata, SW Peloponnese, where many fish were left onshore. The tsunami reached as far as Serifos and Syra, Cyclades island complex, South Aegean Sea. However, Schmidt (1879) noted that the largest impact of the waves was found in harbors opening to the south: Gythion, Della Gracia in Syra and Lixouri in Kefalonia. It was again similar to the December 26, 1861 tsunami in west Corinth Gulf: the more narrow the harbor, the higher and more violent the water.

According to a short, anonymous chronicle published by Konomos (1970), an earthquake occurred in Zakynthos at 6 am and the inundation that followed covered cultivated land up in the small town of Roidou. Strong flood reached up to the middle of the St Charalambos bridge. The sea movement forward and back washes repeated many times until 8 am.

[21] 1870 06 24, Crete island

*coordinates:* 36 00 26 00, *cause:* ER

*tsunami intensity:* 2/3, *reliability:* 3

This is another large earthquake similar to the 12 October 1856 one in that it was felt in a very large region. However, it appears that it was less destructive given that no victims were reported after the 1870 earthquake. The event affected the coasts of Arabia, Egypt and Syria, the archipelago next to Crete, the Greek mainland and Sicily (Schmidt, 1879). From a review of several documentary sources, Ambraseys et al. (1994) concluded that the shock caused slight damage in Alexandria, Cairo and Ismailia, while in Alexandria “...in the New Port area...the sea flooded the quay...”, which may indicate the generation of a small tsunami wave. In addition, “...the shock was felt on board ships in both the Old and New Ports and offshore opposite the quarries of Mex...”, which indicates rather sea-quake than tsunami wave. The estimation of tsunami intensity in the QLC concerns only the small tsunami reported in the New Port of Alexandria.

[22] 1886 08 27, Philiatra, SW Peloponnese

*coordinates:* 37 06 21 30, *cause:* ES

*tsunami intensity:* 3/4, *reliability:* 4

This is a large, destructive, possibly interplate earthquake that ruptured the SW Peloponnese and caused very extensive destruction in Philiatra and many other towns and villages; at least 326 persons

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were killed and at least 796 were injured (Galanopoulos, 1941, 1953, Papazachos and Papazachou, 2003). The earthquake had long duration in Heraklion, Crete, and was felt in remote places of the Mediterranean Sea, such as Malta, Trieste, Alexandria, Cairo, Syria and Asia Minor. Along a coastal segment about 35 km long, from Agrilio to the north up to the bay of Navarino (Pylos) to the south, a tsunami was observed and a coastal strip 10 to 15 m wide was inundated for a while (Galanopoulos, 1941). According to a report of Forster (1890), director of the East Telegraph Company in Zakynthos, and a correspondence of the newspaper of Heraklion “Nea Evdomas” (1886), a telegraph cable between Crete and Zakynthos was entirely cut at a distance of about 29 miles to the south of Zakynthos (Stavrakes, 1890), which may indicate either submarine slumps and/or turbidite currents triggered by the earthquake.

[23] 1893 04 17, Zakynthos island, Ionian Sea

*coordinates:* 37 45 21 00, *cause:* ER

*tsunami intensity:* 2/3, *reliability:* 3

This is a very strong shock which caused destruction in the main town and many villages of the island of Zakynthos killing 23 persons (Mitzopoulos, 1893, Philipson, 1893). According to a correspondence of the newspaper “Kythira” (1893) in the coastal segment of Estavromenos and Krioneri Zakynthos, the sea withdrawn for about 20 m.

[24] 1896 11 05, Zakynthos island, Ionian Sea

*coordinates:* 37 49 20 42, *cause:* ER

*tsunami intensity:* 2/2, *reliability:* 2

This is a moderate shock which occurred in the area of Zakynthos. According to AOA (1896) the dry torrent that streams from the villages Mouraki and Pissinontas and flows into the Laganas Bay, south side of Zakynthos Island, filled in with sea water. However, it is not clear if this indicates small local flood due to the shock or innunadation due to other cause.

[25] 1898 12 03, Zakynthos island, Ionian Sea

*coordinates:* 37 42 20 48, *cause:* ER

*tsunami intensity:* 2/2, *reliability:* 4

This is another strong shock which occurred in Zakynthos. According to AOA (1898) the sea rose 0.4 m and returned to its usual place between 10 am and 3 pm.

[26] 1899 01 22, Kyparissia, SW Peloponnese

*coordinates:* 37 12 21 36, *cause:* ES

*tsunami intensity:* 3/4, *reliability:* 4

The SW part of Peloponnese was hit again by a very strong shock which caused widespread damage in Kyparissia, Philiatra and many villages of the area. In Marathoupole, close to Kyparissia, a tsunami of height no more than 1 m was observed while in Zakynthos the wave height was about 40 cm (Mitzopoulos, 1900, Eginitis, 1901). According to Galanopoulos (1941) the tsunami was possibly triggered by submarine slump.

[27] 1947 10 06, Methoni, SW Peloponnese

*coordinates:* 36 54 22 00, *cause:* ES

*tsunami intensity:* 2/3, *reliability:* 4

This large, destructive earthquake caused widespread damage to many towns and villages in the area of SW Peloponnese (Galanopoulos, 1949). Three persons were killed and 20 injured. Landslides were also observed. In Methoni, a local tsunami advanced 15 m inland. Galanopoulos (1949) attributed the sea

wave to an offshore slide which may have occurred about 6 km south-southwest off the coast since there is known that the slope of the sea floor is particularly steep.

[28] 1983 01 17, Zakynthos islands, Ionian Sea

coordinates: 38 06 20 12, cause: ES

*tsunami intensity: 2/3, reliability: 3*

This was a very strong earthquake but only moderately damaging in Kefalonia Island. No damage was caused in the island of Zakynthos where local people reported that during the earthquake sea retreat for about 0.5 m was observed (Eleftheriou and Mouyiaris, 1983).

[29] 2000 04 05, Heraklion, Crete island

coordinates: 34 13 25 41, cause: ES

*tsunami intensity: 3/5, reliability: 4*

According to communication of the Heraklion port authority with the first author of this paper, oscillations of amplitude ~50 cm and period of 10-12 min. were observed in Heraklion port (35.21°N/25.09°E), north Crete, from 09.00 to 20.00 local time of 5 April 2000 (Papadopoulos, 2001). The wave was observed about 1.5 hours after a strong ( $M_s=5.7$ ) shallow shock occurring (UTC 04:36:59; epicenter 34.22°N/25.69°E) offshore south Crete. At the beginning of the sea disturbance small fishing-boats were moved ashore. It is unlikely that co-seismic fault displacement or meteorological causes triggered the tsunami since it was not reported from other observation points. Possibly the tsunami was caused by a small-scale submarine slide induced by the seismic ground motion. Recently, Kopf et al. (2007) reported on free-fall CPT measurements for submarine landslide characterization in the western Cretan Sea and were able to conclude that the area off ENE Heraklion is prone to landsliding due to earthquake activity.

[30] 2006 01 08, Kythira island

coordinates: 36 13 23 25, cause: ER

*reliability: 1*

This was a large ( $M_L=6.4$ ,  $M_s=6.9$ ), intermediate-depth earthquake which shook Greece and many places of the East Mediterranean Sea. Minor damage was only caused in the village Mitata of Kythira Island. According to the testimony of a captain sailing to the east of Kythira, that is in the epicentral area, people on board felt strongly the shock (newspaper "Ethnos", 2008). Obviously this is another case of sea-quake.

Apart from the tsunami events examined above, geological field evidence was published recently about tsunami inundation in the western part of Crete (Scheffers and Scheffers, 2007). In particular, four main tsunami episodes are indicated by sedimentological and geomorphological evidence. The first is dated around AD 365 or later as explained in the entry [2] devoted to the 365 tsunami. An older tsunami episode is dated to 5660±60 yrs BP. The third episode is dated as "Post 365" and the youngest is dated to 500±60 yrs BP. However, no further evidence, historical or other is available to correlate those tsunami episodes with seismic activity. Therefore, they still remain open for further investigation.

### 3. Tsunami Hazard Assessment

#### 3.1 Data Completeness and Intensity Distribution

The tsunami catalogue compiled here extends from AD66 to 2007 inclusive, that is it covers a time interval of 1942 years. Historical documentation, however, is incomplete. No documents reporting tsunamis generated in WHA-T before AD66 are known to us. The completeness of the data record was examined on the basis of two independent diagrams after removing from the catalogue the events which look like rather sea-quakes than tsunami waves, that is a number of 9 out of 30 (Table 1). In addition, the c.AD800 event has been excluded since it is quite questionable. In Figure 3 the

cumulative number of events is plotted as a function of time and shows that the data completeness changes with time. In fact, before the 15<sup>th</sup> century the historical reporting of tsunami events is very poor. From the 15<sup>th</sup> century onwards the record gradually increases with the majority of the events being reported in the last two centuries. On the other hand, the plot of tsunami intensity against time (Fig. 4) reveals that tsunamis of moderate and low intensity escaped reporting during the earlier time interval given that until the 18<sup>th</sup> century only tsunamis of intensity  $K \geq 5$  were reported. Reporting of tsunami intensities 3 or 4 started only by the end of the 18<sup>th</sup> century.

On the basis of the previous observations we roughly assumed that tsunami data from AD 365, 1612, 1741, 1886 and 1947 up to now may be complete for intensity  $K$  equal to or larger than 10, 8, 5, 4 and 3, respectively. To test the validity of this assumption the intensity-frequency relation was calculated, which is equivalent to the magnitude-frequency or G-R relation (Gutenberg and Richter, 1944) extensively used in seismology to describe the exponential decrease of the event frequency with the increase of the event size:

$$\log N_c = a_c - bK \quad (1)$$

where  $N_c$  is the cumulative number (frequency) of tsunami events of intensity equal to or larger than  $K$  observed in a time interval of  $c$  years;  $K$  is tsunami size in terms of intensity in the 12-point scale proposed by Papadopoulos and Imamura (2001);  $a_c$ ,  $b$  are parameters determined by linear regression on the data. Event frequencies were reduced to the total time interval covered by the tsunami catalogue, that is  $c=1942$  years. The graphical form of (1) shows (Fig. 5) that in general the linear trend of the frequency of events is well-shaped. However, the best fit to the observational data is found for  $K \geq 4$  ( $R^2 = 0.966$ ,  $R$ =correlation coefficient). We conclude that our assumption about the data completeness is valid only for intensities  $K \geq 4$ . Then, parameters of the relation (1) were recalculated by excluding frequencies of events with  $K \leq 3$ :

$$\log N_c = 3.282 - 0.310K \quad , K \geq 4 \quad (2)$$

### 3.1 Temporal Distribution

Integrating formula (1) in one year ( $c = 1$ ) then we get

$$\log N = a - bK \quad (3)$$

where

$$a = a_c - \log c \quad (4)$$

From (3) it comes out that the mean repeat time,  $T_K$  (in years), of events of intensity equal to or larger than  $K$  is

$$T_K = 10^{bK-a} \quad (5)$$

or the mean yearly rate of occurrence is the inverse of  $T_K$ :

$$r = \frac{1}{T_K} \quad (6)$$

In addition, the maximum intensity,  $K_{max}$ , which is the most probable to be observed within time interval,  $t$ , is given by the expression

$$K_{max} = \frac{a + \log t}{b} \quad (7)$$

Expression (7) was first proved as regards the maximum earthquake magnitude which is the most probable to be observed within time interval,  $t$  (Curtis, 1973). From (2), (3) and (4) we get that  $b = 0.310$  and  $a = -0.006$ . Then, the mean repeat time and the mean rate of occurrence of tsunamis of a given intensity range were calculated from (5) and (6), respectively. The results are summarized in Table 2. One may see that tsunamis of low or moderate intensity ( $4 \leq K \leq 2$ ) recur every few years that is rather frequently. Strong tsunamis, however, are rare, the repeat time of the very strong ones ( $K \geq 10$ ) being of the order of 1276 years. This is reflected also by the values of maximum intensity,  $K_{max}$ , calculated from (7) (Table 3).

From the mean yearly rate of tsunami occurrence we calculated the probability,  $P(x \geq 1)_t$ , to observe at least one tsunami of intensity  $K$  equal to or larger than a given value within particular time interval,  $t$ . The basic assumption is that the time distribution of the Mediterranean Sea tsunamis is Poissonian, that is random (Soloviev, 1990, Papadopoulos, 2003, Papadopoulos et al., 2007). Then, the probability to observe  $x$  events in  $t$  years is

$$P(x)_t = \exp(-rt)(rt)^x / x! \quad (8)$$

while the probability to observe at least one tsunami event in  $t$  years is

$$P(x \geq 1)_t = 1 - P(x = 0)_t \quad (9)$$

The results are summarized in Table 4.

#### **4. Conclusions**

We updated and critically evaluated the tsunami catalogue of the WHA-T, which seismically is one of the most active tectonic segments in the European-Mediterranean region. The updated catalogue, which is arranged in the format adopted in 90's by tsunami specialists for the New European Tsunami Catalogue, starts from AD66 and includes 30 events. At least 21 out of 30 events were tsunami waves while the rest were rather sea-quakes than real tsunamis. The south part of the segment is the most tsunamigenic with the big earthquake-tsunami of AD 21 July 365 being an extreme event. The tsunami intensity,  $K$ , assessed according to the 12-point tsunami intensity scale of Papadopoulos and Imamura (2001), reach up to degree 10 in the 365 wave.

Completeness analysis showed that the data may be complete from 365, 1612, 1494, and 1791 for intensity  $K \geq 10, 8, 5$  and  $4$ , respectively. For the complete part of the tsunami catalogue the model of exponential decrease of the frequency of tsunami events with the increase of  $K$  fits well-enough the observed tsunami frequencies. Then, from the intensity-frequency statistics it comes out that tsunamis of low or moderate intensity recur every few years that is rather frequently. Strong tsunamis, however, are rare, the mean repeat time of tsunami intensity  $K \geq 8, 9$  and  $10$  being of the order of 306, 626 and 1277 years, respectively.

#### **5. Discussion**

The last tsunami events of intensity  $K \geq 8, 9$  and  $10$  occurred in WHA-T on 1612, 365 and 365, respectively (Table 2). The actual times elapsed from the last events are equal to 396, 1643 and 1643 years, respectively. Then, the frequency of occurrence of large-size tsunamis is significantly overestimated by the intensity-frequency statistics. This discrepancy could be attributed to that large-size tsunami events possibly are missing from the historical reporting. This, however, is not reasonable at least for very large events similar to the 365 one. Another explanation is that the number of tsunami events involved in the statistics is very small, thus making the statistics extremely sensitive in the event frequencies introduced, particularly for large-size events which are of very low frequency.

An alternative is that the occurrence of large-size tsunamis has been long overdue because of seismotectonic factors, such as the long delay in the occurrence of large tsunamigenic earthquakes possibly because of strong lithospheric plate coupling along the WHA-T segment. Such a working hypothesis deserves to be further explored by all available means. Should the hypothesis be correct, then the random probabilities calculated for the occurrence of large-size tsunamis in particular time windows are underestimated (Table 3). In fact, the random model does not incorporate any kind of memory. Instead, conditional probability approaches may account for some memory in the model such as the time elapsed from the occurrence of the last event. Such an approach was successfully tested for

tsunami belts in the Pacific Ocean (Orfanogiannaki and Papadopoulos, 2007). Unfortunately, the very low number of large-size tsunamis makes it not applicable in the WHA-T.

The bathymetric map of the area examined (Fig. 2) indicates that the source of the large tsunamigenic earthquake of AD 365 is located at deep water in the Hellenic trench which, along with the large magnitude of the earthquake, possibly favoured the generation of high amplitude tsunami. This area is characterized also by thrust faulting due to the lithospheric plate convergence, a factor which again favours large tsunami generation. As for the rest tsunami cases, however, no particular correlation is observed between the sea depth and the locations of the tsunami sources. One may take into account, however, that the tsunamis are not so large as the AD 365 one. On the other hand, the locations of the sources suffer from large error since most of the events occurred in historical times and the epicentral determinations are only approximate.

#### **APPENDIX A1: Regional Tsunamis that Affected the Western Hellenic Arc**

This Appendix summarizes information about four strong tsunamis which had their sources outside the WHA-T but affected coastal zones along the WHA-T.

##### **(A1.1) c.1630 BC, Thera, South Aegean Sea, coordinates: 36 24 25 24**

This is the large tsunami caused by the giant, caldera-forming Minoan eruption of Thera volcano, South Aegean Sea, which is one of the most significant ever seen by humankind because of its very large size, its possible impact on Late Bronze Age (LBA) civilizations, and for distributing huge amounts of tephra creating an important marker horizon. Archaeological observations on Amnisos to the east of Heraklion, north Crete (Marinatos, 1939), tsunami sediment deposits found in north Crete and SW Turkey coastal sites (Minoura et al., 2000) and in Thera (McCoy and Heiken, 2000), as well as results of numerical simulations of the wave (Minoura et al., 2000, Novikova et al., 2006), leave no doubt that it was a large tsunami which inundated north Crete and other coastal zones of the WHA-T.

##### **(A1.2) 1303 08 08, East Hellenic Arc, coordinates: 35 00 27 00**

This is a very large earthquake that ruptured the eastern segment of the Hellenic Arc and Trench between Crete and Rhodes islands, caused widespread destruction in the east part of Crete and generated a large, destructive tsunami which propagated to remote places of the East Mediterranean Sea (see reviews by Evagelatou-Notara, 1993, Guidoboni and Comastri, 1997, 2005, Papadopoulos et al., 2007). The tsunami was destructive in Heraklion where the sea swept into the city with such force that it destroyed buildings and killed inhabitants.

##### **(A1.3) 1650 09 30, Thera, South Aegean Sea, coordinates: 36 30 25 30**

Another large tsunami was generated during the eruption of Columbo, a submarine volcanic edifice lying 7.3 km to the northeast of Thera Island. The main volcanic activity began on 26 September 1650 (old style). During a pause of activity that followed the volcanism of 30<sup>th</sup> September, sea swell encircled whole Thera and the wave inundated the eastern coast and swept away churches, enclosures, boats, trees and agricultural land. On the east and west coast of Patmos Island and on Ios Island, tsunami runup heights of 30 m, 50 m and 16 m respectively, were reported. Ships and fishing boats moored at Heraklion, north Crete, were violently swept offshore, while vessels were crushed when the wave overtopped the city walls. The volcanic and seismic quiescence that prevailed before the tsunami struck implies that it was generated by submarine, landsliding or collapse of the volcanic cone rather than by a strong earthquake or volcanic explosion (Dominey-Howes *et al.*, 2000). Sediment deposit of the 1650 tsunami has been found on the coastal site of Kamari village, east Thera (Papadopoulos, 2009).

##### **(A1.4) 1956 07 09, Cyclades, South Aegean Sea, coordinates: 36 38 25 58**

The most recent large tsunami in the Mediterranean Sea occurred in the Cyclades island complex, South Aegean Sea on 9 July 1956 after a  $M_s=7.4$  crustal earthquake associated with normal faulting (Papadopoulos and Pavlides, 1992). The tsunami-generating source was about 100 km in length within the NE-SW trending basin formed by the Thera, Amorgos and Astypalaea islands. Initial estimates of the near-source wave height varied between 15 m and 30 m in Amorgos and Astypalaea

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(Galanopoulos, 1957; Ambraseys, 1960). A co-seismic submarine landslide probably was involved in the tsunami generation mechanism (Perissoratis and Papadopoulos, 1999). Extensive destruction was noted in port facilities, small and large vessels, cultivated land and property, while four people were drowned. In north Crete wave heights of 2-3 m were reported.

Reviews on the above four large tsunamis can be found in Papadopoulos (2009).

### **APPENDIX A2: Cases of Sea Disturbances not Included in the Tsunami Catalogue (A2.1) 1821 01 09, Patras, coordinates: 37 30 21 24**

In tsunami catalogues a destructive sea-wave is listed that reportedly occurred on 6<sup>th</sup> or 9<sup>th</sup> January 1821 in association with the 6 January 1821 Zakynthos strong aftershock of the very strong mainshock of 29 December 1820 (Mallet, 1855; Galanopoulos, 1955, 1960; Ambraseys, 1962; Antonopoulos, 1980; Papadopoulos and Chalkis, 1984; Papazachos and Papazachou, 1989, 1997; Soloviev et al., 2000) (see entry [14] in the sub-section 2.3). However, much confusion can be found in tsunami catalogues regarding the time and place of its occurrence as well as of its nature. This problem was noted by Papadopoulos and Plessa (2001) who found that the only original documentary source of information was Pouqueville (1824). These authors examined carefully the text of Pouqueville (1824) and concluded that the wave was rather a storm surge than a real tsunami event since it was associated with thunders and a storm accompanied by rainbow appearance.

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Flavius Philostratus, *V. Apo* 4/34.

#### **Press Reports**

Mercure Francais, 1612

Nea Evdomas, 20 August 1886 (OS) (in Greek)

Kythira, 20 April 1893 (in Greek)

Ethnos, 9 January 2006 (in Greek)

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Table 1. Tsunami catalogue of the western Hellenic Arc and Trench. Key: ID = identification number, YY=year, MM=month, DD=day, hh=hour, mm=minute, ss=second, Rel = reliability of the time of occurrence, Region M1=Greece and adjacent regions as defined in the European Tsunami Catalogue, Lat = north latitude, Long = east longitude (both in degrees and minutes), Rel = accuracy of the location in minutes, I= seismic intensity in MM, M = surface-wave magnitude, H= focal depth (in km), n=shallow event (when the tsunami was due to an earthquake event), Runup = maximum vertical tsunami run-up reported (in cm), k = tsunami intensity (in Sieberg-Ambraseys 6-grade scale), K = tsunami intensity (in Papadopoulos-Imamura 12-grade scale), Rel =reliability of the tsunami event, TM = tsunami magnitude (in the Murty - Loomis scale), Y / N = an indication on whether the tsunami parameters were revised (Y) or not (N) with respect to previous catalogues. The reliability of the time of occurrence is measured in units of the last entry of the time of occurrence.

The genesis causes classification are those adopted by the GITEC group: ER=submarine earthquake and ES=earthquake marine slide. For the reliability of the tsunami events a modified version of the tsunami reliability scale of Iida (1984) was adopted (0=very improbable tsunami, 1=improbable tsunami, 2=questionable tsunami, 3=probable tsunami, 4=definite tsunami). Some additional symbol explanation is needed: (+) after a particular value means "equal to or larger than"

ID	YY	MM	DD	hh	mm	ss	Rel	Region	Subregion		Short Description				VEI	Runup	k	K	Rel TM	Rev
								Cause	Lat	Long	Rel	I	M	H						
1	66	spring					4	M1 ER	South Crete Is.									4	Y	
									35 00	24 42	27	8(+)	6.0(+)	n		3	5			
2	365	07	21		night		0	M1 ER	West Crete Is									4	Y	
									35 12	23 12	27	10	8.0	n		5	10			
3	c.800						0	M1 ER	Kythira Strait									2	Y	
									35 30	23 00	27		7.5			4	6			
4	1494	07	01				2	M1 ER	Heraklion, Crete Is.									4	Y	
									35 30	25 30	27	8	7.0	n		3	5			
5	1612	11	08				5	M1 ER	Heraklion, Crete Is.									3	N	
									35 30	25 12	27	8	7.0	n		4	8			
6	1630	03	09				1	M1 ER	Kythira Strait									4	Y	
									36 00	24 00	27	8(+)	6.8(+)	n		3	5			
7	1633	11	05				0	M1 ER	Zakynthos Is., Ionian Sea									3	Y	
									37 43	20 52	11	9	7.0	n		3	5			
8	1681	02	12				1	M1 ER	Chania, Crete Is.									1	Y	
									35 42	24 00	11	8	6.8	n						
9	1741	02					1	M1 ER	Heraklion, Crete Is.									3	Y	
									35 30	25 00	27			n		3	5			
10	1791	11	02				1	M1 ER	Zakynthos Is., Ionian Sea									4	N	
									38 00	21 00	11	10	6.8	n		3	4			
11	1791	11	10				0	M1 ER	Zakynthos Is., Ionian Sea									1	N	
									38 00	21 00	11	7		n						
12	1810	02	17				0	M1 ER	Crete Is.									4		
									35 00	25 00	27	?		?		2	3			
13	1816	12	28				4	M1	Pylos, South Ionian Sea									1		



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29	2000	04	05	04	36	59	1	MI	Heraklion, Crete Is.	Sea oscillation in Heraklion					4	Y
								ES	34 13 25 41	11	?	5.7	38	60	3	5
30	2006	01	08	11	34	00	0	M1	Kythira Is.	Sea-quake					1	Y
								ER	36 13 23 25	9	7	6.9	54			

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Table 2. Mean repeat time,  $T_k$  (in years), and mean rate of occurrence,  $r$  (in events/year), of tsunamis in the West Hellenic Arc and Trench. Key:  $K$  = tsunami intensity in the 12-point scale of Papadopoulos and Imamura (2001),  $b = 0.310$ ,  $a = -0.006$ , *last event* = year of occurrence of the last tsunami event of the respective intensity.

<b><math>K</math></b>	<b><math>T_k=10^{bK-a}</math></b>	<b><math>r = 1/T_k</math></b>	<b><i>last event</i></b>
2	4	0.23646	1898
3	9	0.11581	1983
4	18	0.05672	1899
5	36	0.02778	2000
6	73	0.01361	1866
7	150	0.00666	1867
8	306	0.00326	1612
9	626	0.00160	-
10	1277	0.00078	365

Table 3. Time interval  $t$  (years) and maximum intensity,  $K_{\max}$ , calculated from formula (7).

<b>t (years)</b>	<b><math>K_{\max}</math></b>
10	3.2
50	5.5
100	6.4
1000	9.7

Table 4. The probability to observe at least one tsunami of intensity  $K$  equal to or larger than a given value within particular time interval,  $t$ .

<i>t(years)</i>	<i>K</i> ≥2	<i>K</i> ≥4	<i>K</i> ≥6	<i>K</i> ≥8	<i>K</i> ≥10
1	0.21	0.06	0.01	0.003	0.001
10	0.91	0.43	0.13	0.03	0.01
100	1.00	0.99	0.74	0.28	0.08
1000	1.00	1.00	1.00	0.96	0.54

Figures

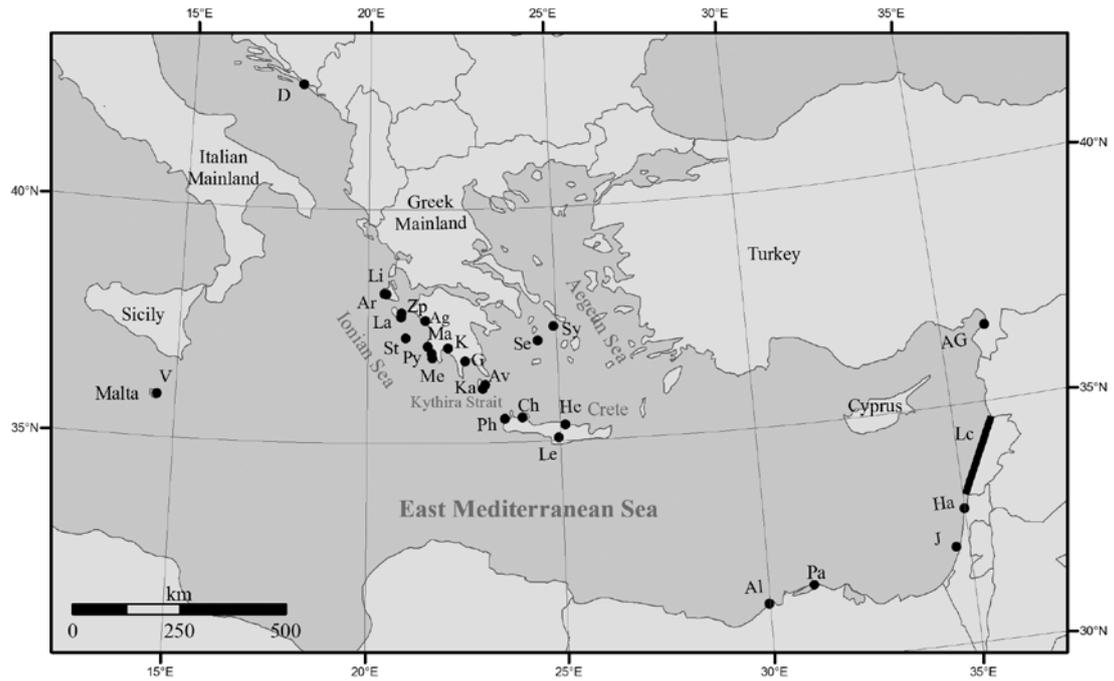


Figure 1. Localities reported on in association with tsunami inundation, sea-quakes and seiches. Symbol key: Heraklion (He), Leben (Le), Chania (Ch), Phalasarua (Ph), Serifos (Se), Syra (Sy), Kapsali (Ka), Avlemonas (Av), Gythion (G), Kalamata (K), Methoni (Me), Pylos (Py), Marathoupole (Ma), Agrilio (Ag), Strofades (St), Zakynthos port (Zp), Laganas bay (La), Argostoli (Ar), Lixouri (Li), Panephris (Pa), Alexandria (Al), Valletta (V), Dubrovnik (D), Alexandrete Gulf (AG), Jaffa (J), Haifa (Ha), Lebanese coast (Lc).

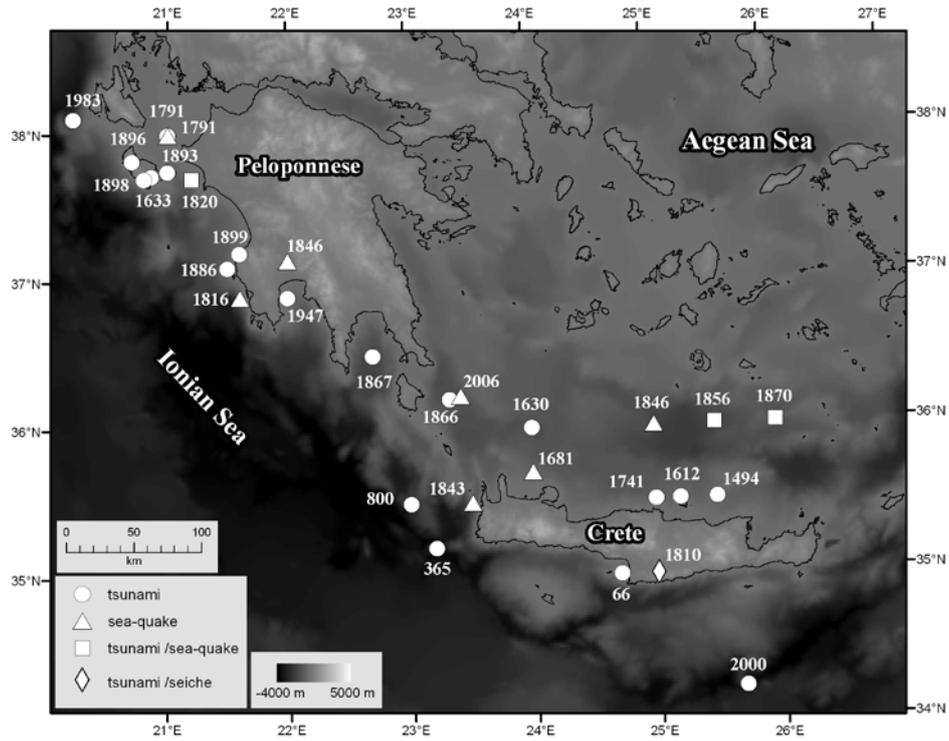


Figure 2. Sources and year of occurrence of the 30 tsunamis, sea-quakes and seiches analyzed in the text.

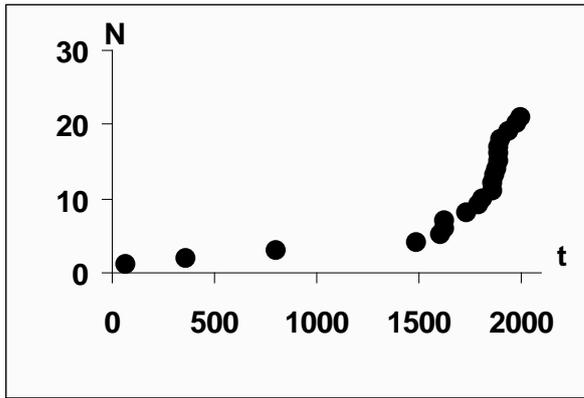


Figure 3. Cumulative number of tsunami events reported in the WHA-T from AD66 up to 2007 inclusive.

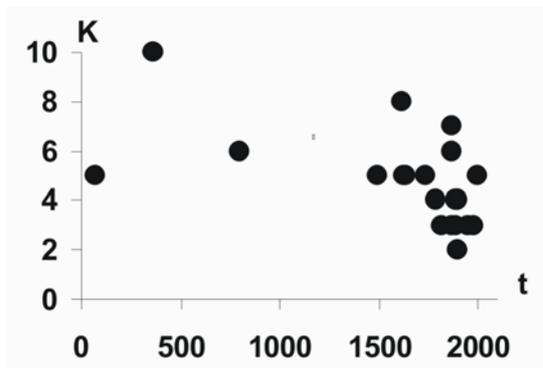


Figure 4. Time distribution of the tsunami intensities,  $K$ , reported in the WHA-T from AD66 up to 2007 inclusive.

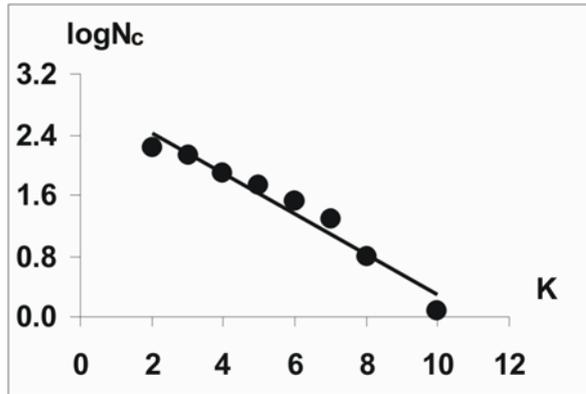


Figure 5. Intensity-frequency relation for the tsunamis reported in the WHA-T. Symbol key:  $N_c$  = cumulative number of tsunamis with intensity  $\geq K$  reported in the time interval  $c$  from AD66 up to 2007 inclusive.