Bollettino di Geofisica Teorica ed Applicata Vol. 55, n. 2, pp. 469-484; June 2014
DOI 10.4430/bgta0097

# Tsunamigenic potential of local and distant tsunami sources threatening SW Peloponnese

G.A. Papadopoulos, E. Daskalaki, A. Fokaefs and T. Novikova

*Institute of Geodynamics, National Observatory of Athens, Greece*

(Received: July 5, 2012; accepted: April 8, 2013)

***ABSTRACT*** The area of SW Peloponnese situated in the western segment of the Hellenic Arc is characterized by high rate of seismicity. However, the tsunami hazard in the area is poorly understood. In this paper we focus our attention in the local and distant tsunami sources threatening coastal zones of SW Peloponnese and in the evaluation of their tsunamigenic potential. It was found that only three historically documented tsunami events were produced by seismic sources activated in SW Peloponnese: 1886, 1899, 1947. However, they were only local tsunamis very likely produced by submarine Earth slumps rather than by co-seismic fault displacements. One may not rule out, however, the possibility that local tsunami sources unknown so far would activate in the future. In addition, for the tsunami hazard assessment in SW Peloponnese one may consider tsunami sources bearing potential to produce distant or even basin-wide large tsunamis such as the seismic ones of A.D. 365 and 1303 and the volcanic one of Minoan times. Indeed, numerical simulations showed that those tsunamis may have arrived at SW Peloponnese coastal zones with hazardous wave amplitudes. This applies particularly to the Minoan and the 365 events.

**Key words:** tsunami, Peloponnese, earthquakes, SEAHELLARC.

## 1. Introduction

The area of SW Peloponnese, which is situated at the north part of the western segment of the Hellenic Arc (Fig. 1), was hit by several earthquakes during the historical and instrumental record of seismicity (Galanopoulos, 1941; Papazachos and Papazachou, 2003; Papadopoulos, 2011). SW Peloponnese was the test-area for the earthquake and tsunami hazard assessment within the framework of the EU-FP6 research project Seismic and Tsunami Risk Assessment and Mitigation Scenarios in the western Hellenic Arc [SEAHELLARC: see Papoulia *et al*. (2014)]. In view of this, a probabilistic seismic hazard approach was performed by SEAHELLARC Working Group (2010) on the basis of a new seismotectonic zonation and of an updated earthquake catalogue.

From historical documentation it results that SW Peloponnese is threatened mainly by tsunamis which are tectonically associated with the segment of western Hellenic Arc and Trench (HA-T) system. An updated tsunami catalogue for western HA-T and its value for the tsunami hazard assessment was published and discussed by Papadopoulos *et al*. (2010) who compiled

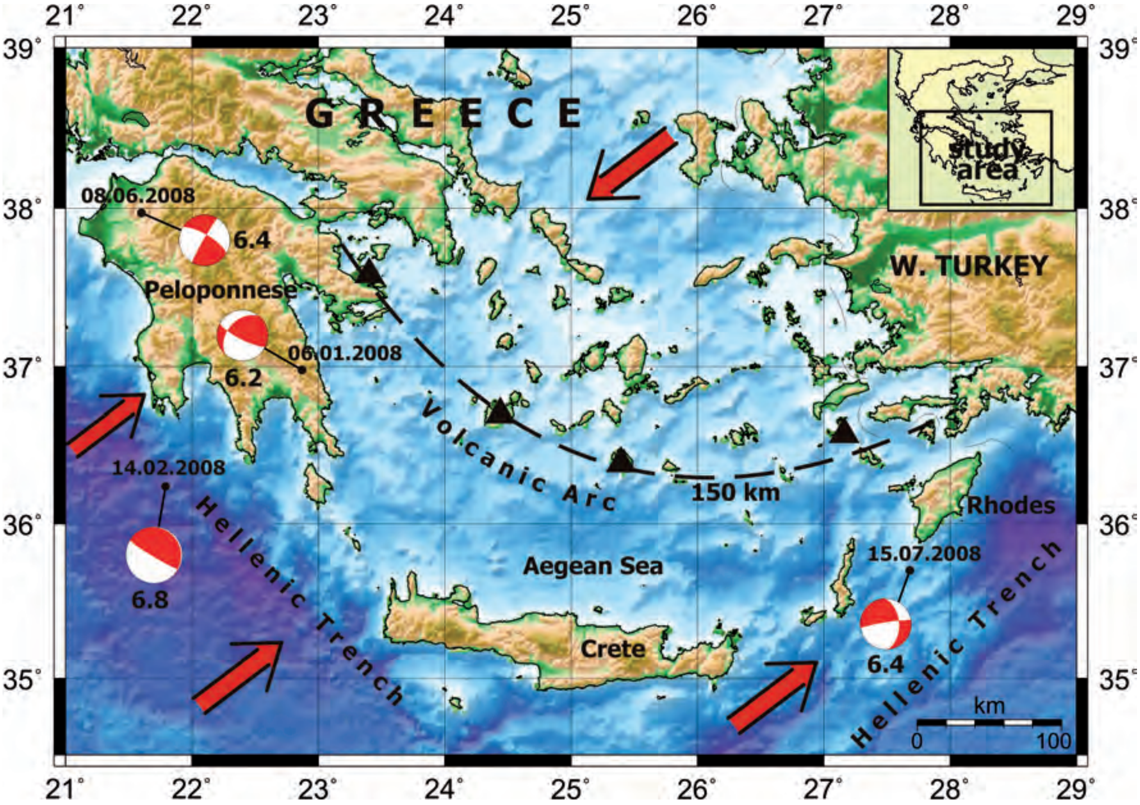

Fig. 1 - The high rate of seismicity along the Hellenic Arc is exemplified by the series of strong earthquakes that occurred there during 2008 (after Papadopoulos *et al.*, 2009). One of them was the large Methoni earthquake of 14 February 2008 which occurred offshore SW Peloponnese and is discussed in the text.

new data and evaluated critically past catalogues and data compilations published by several authors (Galanopoulos, 1960; Ambraseys, 1962, 2009; Antonopoulos, 1980; Papadopoulos and Chalkis, 1984; Soloviev, 1990; Guidoboni *et al.*, 1994; Papazachos and Papazachou, 1997; Soloviev *et al.*, 2000; Papadopoulos, 2001, 2009; Papadopoulos and Vassilopoulou, 2001; Guidoboni and Comastri, 2005). However, the seismic tsunami source which produced the large wave of 1303 in the eastern HA-T (e.g., Guidoboni and Comastri, 1997; Papadopoulos *et al.*, 2007; Papadopoulos, 2011) should be also considered as threatening SW Peloponnese. In addition, the extreme tsunami produced by the Minoan eruption of the Thera volcano should not be ruled out as a component of the long-term tsunami hazard assessment.

In this paper we have investigated the potential associated with local and distant tsunami sources threatening SW Peloponnese. To this aim we reviewed the tsunami history of the area from documentary sources as well as from coastal geological observations. In addition, the tsunami sources were determined and their tsunami potential was qualitatively evaluated. Then, the two extreme tsunamis of A.D. 365 and of the 17th century B.C. Minoan eruption were simulated numerically and water elevation parameters were calculated for Methoni and Pylos, that is for two coastal sites which were of particular interest to the SEAHELLARC research project.

## 2. Historical tsunami sources

Historically known tsunami sources which are of interest for the tsunami hazard assessment in a relatively small target area of the Mediterranean Sea, such as SW Peloponnese, can be classified on the basis of two different criteria. The first criterion regards the maximum distance, $d$, of the epicentre of the causative earthquake from the target area. However, tsunami hazard is meaningful only if the wave arrives in the target area with amplitude of at least 0.5 m, since it is a minimum wave amplitude threshold capable to cause some damage. According to a consensus reached among specialists working for the North East Atlantic and Mediterranean Tsunami Warning System (NEAMTWS) coordinated by IOC/UNESCO, the criterion of distance classifies a tsunami as local or regional if $d < 100$ km or $< 400$ km, respectively. A tsunami is characterized as basin-wide one when $d > 400$ km. Although such a type of classification is arbitrary and certainly subjective it is a realistic one for the physiographic peculiarities of the Mediterranean Sea. By considering mean sea depth of $h = 500$ m and that the ray propagation theory is a good approximation for the tsunami travel times, we find out that a tsunami arrives at epicentral distance of $d = 100$ km or $d = 400$ km in less than 25 minutes or in less than 95 minutes, respectively; the tsunami velocity is calculated by the formula $v = (gh)^{1/2}$, where $g$ is the gravity acceleration.

Tsunamis caused not only in local but also in regional distances are of interest for the tsunami potential assessment in the SW Peloponnese. This point of view is justified by that distant but sizable tsunamis propagate well away from their sources and may significantly affect remote coastal zones. A characteristic example of this type was the large A.D. 365 tsunami which is believed that was generated offshore western Crete by a big earthquake measuring estimated magnitude on the order of 8.3 or even larger [e.g., see an exhaustive review in Papadopoulos (2011)]. Contemporary historical sources indicated that the 365 event was a basin-wide tsunami which inundated many coastal zones in the eastern Mediterranean basin, one of them being Methoni in SW Peloponnese as described reliably by Ammianus Marcellinus and other contemporary historians (Guidoboni *et al.*, 1994). Another example is the large tsunami of 1303, which was caused also by a big earthquake rupturing the eastern segment of HA-T between Crete and Rhodes and measuring estimated magnitude on the order of 8.0. That wave affected large part of the eastern Mediterranean basin and propagated also towards the Ionian Sea and the SW Peloponnese (e.g., Guidoboni and Comastri, 1997).

The second criterion for tsunami classification relies on the tsunami generation mechanism which is related not only to seismic but also to non-seismic sources, that is to volcanic eruptions and to coastal and/or submarine slumps. The term seismic source applies when the tsunami wave is caused directly by the co-seismic fault displacement. However, for historical tsunamis it is hardly verifiable given that the tsunami may be caused by slumps triggered by the earthquake process (e.g., Gerardi *et al.*, 2008; Billi *et al.*, 2010).

In the next section historic and pre-historic, local and distant tsunami events produced by seismic and non-seismic mechanisms, which were reported to impact SW Peloponnese are reviewed critically with the aim to evaluate their possible source areas and generation mechanisms.

## 3. Past tsunami record

### *3.1. Minoan tsunami, 17th century B.C.*

From the tsunamis listed in the existing catalogues the chronologically first, that may had some impact in the area of SW Peloponnese, was the large wave generated by the 17th century B.C., Late Bronge Age (LBA) eruption of Thera (Santorini) volcano, the so-called Minoan tsunami. Sedimentary deposits inferred to be from LBA tsunami inundation were described by several authors (see reviews: Papadopoulos, 2009, 2011; Novikova *et al.*, 2011) but documented ones were found in coastal sediments in Didim and Fethiye, SW Turkey (Minoura *et al.*, 2000); in north Crete in the archaeological sites of Gouves (Minoura *et al.*, 2000) and of Palaikastro (McCoy and Papadopoulos, 2001; Bruins *et al.*, 2008); within the LBA volcanic succession in Thera at two localities (McCoy and Heiken, 2000); on the continental shelf off Caesarea Maritima, Israel (Goodman-Tchernov *et al.*, 2009); and possibly in east Sicily (De Martini *et al.*, 2010). Additional evidence comes from the deep ocean with the discovery of reworked sea-floor sediments, known as homogenites (e.g., Kastens and Cita, 1981; Cita *et al.*, 1984). Based on the geological evidence one may reasonably suggest that the field of wave propagation was exceptionally large in the eastern Mediterranean basin and that wave amplitudes, with consequent coastal inundation and run-up, also may have been exceptional contrary to studies that suggested otherwise (Dominey-Howes, 2004; Pareschi *et al.*, 2006). Although there is no evidence for LBA tsunami inundation in SW Peloponnese, in the next section we investigated this possibility based on numerical simulation of the tsunami by assuming two main tsunamigenic mechanisms, that is caldera collapse and massive pyroclastic flows.

### *3.2. July 21, 365*

The earthquake and tsunami events of July 21, 365 were documented in a large number of documentary sources as well as by archaeological and geological field observations reviewed shortly in the next section. The historical, geological and archaeological evidence leave little doubt that the 365 tsunami was a basin-wide wave generated by 6-9 m co-seismic uplift in the area of western HA-T and that it may have inundated several coastal localities in the eastern Mediterranean basin including NW Crete, north Egypt in Alexandria, Panephysis and the Nile Delta, eastern Sicily, in unidentified areas of the Aegean Sea and possibly in Epidavros, today modern Cavtat near Dubrovnik in Dalmatia, Adriatic Sea. Of particular interest is what very likely happened in Methoni, SW Peloponnese. According to the contemporary historian Ammianus Marcelinus *"Some great ships were hurled by the fury of the waves on to roof tops (as happened in Alexandria), and others were thrown up to two miles from the shore. We ourselves on our travels saw a Spartan ship disintegrating after the long decay near the town of Mothone (Methoni)"* [translation in English by Guidoboni *et al.* (1994)]. However, it is not clear if ships thrown up to two miles from the shore were observed in Methoni or in Alexandria. We have suggested that SW Peloponnese did not escape tsunami inundation and, therefore, water elevation parameters were calculated based on numerical simulation of the 365 tsunami (see next section).

### *3.3. August 8, 1303*

This was a big earthquake documented in a long series of Greek, Venetian and Arabic historical sources (Guidoboni and Comastri, 1997, 2005). The earthquake caused extensive destruction in a large area of the eastern Mediterranean but mainly in the eastern and central parts of Crete. From ground failures observed as far as north Egypt, Papadopoulos (2011) was able to estimate earthquake magnitude on the order of 8.0. The basin-wide tsunami inundated not only near-field coastal sites, such as Heraklion in Crete, but also remote localities in Alexandria and in the Ionian and southern Adriatic Sea. However, very little is known about the geological signature of this large tsunami. In Cape Punta, SE Peloponnese, Scheffers and Scheffers (2008) observed marine organisms attached on many boulders proving that boulders were transported inland by extreme wave events, likely tsunamis, at a $^{14}$C-AMS date of around 1300 cal A.D., which may represent geological trace of the 1303 tsunami.

### *3.4. March 9, 1630*

This was a very strong earthquake known from several documentary sources and having its source possibly offshore NW Crete, to the west of Kythira Island [see review in Papadopoulos (2011)]. De Viazis (1893) published a series of documents archived in the Venetian administration of Zakynthos Island and containing 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 SE. Remnants of wrecks and bodies of shipwrecked persons were also observed. 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 time an earthquake of moderate strength was felt and that a slight inundation was observed at the pier. Such a strong tsunami very possibly was of seismic origin. There is no documentation that the tsunami affected the target area of SW Peloponnese.

### *3.5. September 20, 1867*

This strong earthquake struck the area of Mani in SE Peloponnese, particularly the town of Gythion and the villages of Areopolis and Paganea where houses collapsed and several people were killed (Schmidt, 1879; Galanopoulos, 1950). In his detailed description, Schmidt (1879) reported that the sea flooded severely the coast of Gythion Bay 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 in Argostoli of Cephalonia Island, 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. The tsunami reached as far as Serifos and Syra, in the Cyclades island complex, south Aegean Sea. Flooding of the coast was also reported from Kalamata, SW Peloponnese, where many fish were left onshore. Papadopoulos (2011) suggested that the tsunamigenic source should be placed in Lakonikos Gulf offshore to the south of Gythion.

### *3.6. August 27, 1886*

This was a large, destructive, possibly interplate earthquake that ruptured the SW Peloponnese and causing very extensive destruction in Filiatra and in many other towns and villages; at least 326 persons were killed and more than 796 were injured [see reviews: Galanopoulos (1941) and Papazachos and Papazachou (2003)]. The earthquake was of long duration in Heraklion, Crete, being felt in remote places of the Mediterranean Sea, such as Malta, Trieste, Alexandria, Cairo, Syria and Asia Minor. Along a coastal segment stretching in SW Peloponnese at a length of ~ 35 km, from Agrilio to the north up to the bay of Navarino

(Pylos) to the south, 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 offshore to the south of Zakynthos (Stavrakis, 1890), which may indicate either submarine slumps and/or turbidite currents triggered by the earthquake. To conclude, at all evidence the 1886 earthquake caused submarine slumps offshore SW Peloponnese and a local tsunami of low intensity.

### *3.7. January 22, 1899*

The SW part of Peloponnese was hit again by a very strong shock which caused widespread damage in Kyparissia, in Filiatra as well as in many villages of the area. The coastal town of Marathoupole was inundated by a local tsunami not exceeding 1 m in height, while in Zakynthos a ~ 40 cm wave height was reported (Mitzopoulos, 1900; Eginitis, 1901). Galanopoulos (1941) suggested that this tsunami was possibly triggered by co-seismic submarine slump. The very local nature of the wave makes that suggestion a likely one.

### *3.8. October 6, 1947*

This was a large earthquake which 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 reported. In Methoni, a local tsunami advanced 15 m inland. Galanopoulos (1949) attributed the wave to an offshore slide which may have occurred about 6 km south-SW off the coast since the slope of the sea flour is particularly steep there.

## 4. Tsunami potential

From the historical review presented in the previous section it results that the area of SW Peloponnese is threatened by seismic sources of basin-wide tsunamis very likely produced by co-seismic fault displacements, such the 365 and 1303 ones. On the other hand, there are also sources which could be characterized as non-seismic in the sense that they caused only local tsunamis very likely not directly by the seismic faulting but rather by submarine slumps as a mechanism triggered by the earthquake. At all evidence this happened with the large earthquake of August 27, 1886 as well as with the strong earthquakes of January 22, 1899 and October 6, 1947. The possible impact in SW Peloponnese of the large tsunami caused by the Minoan eruption in Thera remains only as a hypothesis since no geological or archaeological evidence is at place.

The relatively low number of tsunamis reported in SW Peloponnese combined with the high uncertainty as regards the mechanisms of tsunami generation and the precise positions of the sources allow only for a qualitative evaluation of the tsunami potential in that region. In addition, we were able to perform numerical simulations and to calculate hydrodynamic parameters as components of the hazard associated with extreme tsunami events in the region. In this respect three basin-wide tsunamis are of interest; the Minoan tsunami of volcanic origin as well as the tectonic tsunamis of A.D. 365 and 1303. The simulation of the 1303 tsunami produced by a magnitude 8.0 seismic source striking in parallel to the Hellenic trench between Crete and

Rhodes has shown a very strong energy directivity from the source towards the Egyptian coast and particularly to the Alexandria coastal zone (Özsoy *et al.*, 1982; Tinti *et al.*, 2005; Hamouda, 2006). However, the wave attenuates strongly towards the west and, therefore, only small wave amplitudes are expected in SW Peloponnese coastal localities. In view of this, our interest was focused to the extreme tsunami produced by the big earthquake of A.D. 365, which is suggested that ruptured the western segment of the HA-T. Of interest was also the extreme Minoan tsunami produced by the LBA eruption of the Thera volcano. For both of these events we were able to assume alternative source mechanisms as well as to control our results in comparison with the results obtained by other authors.

### *4.1. Numerical simulation of the Minoan tsunami*

The tsunami generated by the LBA eruption of Thera was simulated by several authors who assumed as source mechanisms either the caldera collapse or the massive pyroclastic flows (e.g., Minoura *et al.*, 2000; Pareschi *et al.*, 2006; Bruins *et al.*, 2008). Recently, Novikova *et al.* (2011) assumed several alternatives as regards the tsunami generation mechanism and reproduced the expected water elevation in a number of synthetic tide-gauge records for selected nearshore (~20 m depths) sites of northern Crete, the Cyclades Islands, SW Turkey and Sicily. The first mechanism involved the entry of pyroclastic flows into the sea, assuming a thick flow (55 m; 30 km$^3$) entering the sea along the south coast of Thera in three alternative directions but all directed towards northern Crete. Flows were modelled as a solid block that slowly decelerates along a horizontal surface. The second mechanism assumed caldera collapse with two extremes as regards the volume, that is 19 km$^3$ as the minimum and 34 km$^3$ as the maximum. Caldera collapse was modelled as a dynamic landslide producing a series of rapid vertical displacements.

Modelling was performed with use of the software package GEOWAVE (Watts *et al.*, 2003), which is a combination of TOPICS and FUNWAVE. TOPICS uses a variety of curve fitting techniques and was designed (Grilli and Watts, 1999) as an approximate simulation tool that provides surface elevations and water velocities as initial conditions for tsunami propagation. The numerical model FUNWAVE (Wei and Kirby, 1995; Wei *et al.*, 1995; Kirby *et al.*, 1998, 2003; Kennedy *et al.*, 2000) performs wave propagation simulation, based on the fully non-linear Boussinesq theory using a predictor-corrector scheme. The simulation duration was 4 hours. For pyroclastic flow scenarios the maximum number, $n$, of time steps was 6,000 with a time step $\Delta T = 1.7$ s, while for caldera collapse scenarios we got $n = 10{,}000$ and $\Delta T = 3.1$ s. The nearshore wave amplitudes from the mean sea level calculated by Novikova *et al.* (2011) varied from a few metres to 28 m along northern Crete for three pyroclastic flows scenarios. However, pyroclastic flow penetration into the sea water causes very strong tsunami wave directivity and, therefore, the wave amplitudes obtained for those scenarios are strongly dependent on the azimuth of the pyroclastic flow penetration. For the caldera collapse with the conservative volume of 19 km$^3$ tsunami wave amplitudes ranging from 24 m in the near-field domain to 0.8 m in SW Turkey coastal localities were obtained. However, for the caldera collapse with the upper extreme volume of 34 km$^3$ tsunami amplitudes were generally 2.5 - 3.0 times larger than those generated by the smaller volume of collapse.

With the aim to check the possible impact of the Minoan tsunami in SW Peloponnese, the numerical simulation performed by Novikova *et al.* (2011) was extended in two additional synthetic tide-gauge stations located in Methoni and Pylos. The tide-gauge station in Pylos was placed in the sea side of the small Island of Sfaktiria which occupies the opening of the Pylos bay to the Ionian Sea. To avoid high uncertainties involved due to poor bathymetry coverage in the shallow water domain the two synthetic stations were installed offshore Methoni and Pylos at sites of water depth 27 and 32 m, respectively. Calculations were repeated for alternative sites situated at water depth of 8.7 m for Methoni and 3.7 m for Pylos and showed no remarkable change of the results. Bathymetric 1 arcmin data set obtained from the GEneral Bathymetric Chart of the Oceans (GEBCO) were used for the simulation grid for eastern Mediterranean and southern Aegean Sea regions. In coastal areas of SW Peloponnese, however, supplementary bathymetric data from the Hydrographic Service, Greek Navy, on a grid of 0.5 arcmin, were utilized. For the Aegean Sea computations, based on GEBCO spatial domain a grid with 500 m uniform spacing was reconstructed with water depth measured from mean lower water level. For the caldera collapse mechanism, additional constraints concerning bathymetric variability in and around Thera Island varies from 380 m in the source of tsunami generation to 100 - 400 m in the area surrounding Thera.

Scenarios of thick (55 m; 30 $km^3$) pyroclastic flows directed from south Thera towards north Crete were determined by selecting three different azimuths for the flow penetration into the sea water: 120°, 145°, 200°. These three azimuths were selected since there is volcanological evidence indicating that the major amount of pyroclastic flow was directed from the volcanic cone to the south (McCoy and Heiken, 2000). Constant kinematics was considered for the three scenarios with flow velocity of 170 $m \cdot s^{-1}$, flow duration of 500 s and run-out distance of 40 km. The strong directivity in tsunami energy propagation is clearly illustrated in Fig. 2. In fact, the wave amplitudes recorded synthetically in both Methoni and Pylos decrease rapidly with the counterclockwise change of the penetration azimuth of the pyroclastic flow (Fig. 3). The highest peak-to-peak wave amplitudes were obtained for azimuth of 120°; 2.5 m in Methoni and 4.0 m in Pylos. For azimuth of 200° peak-to-peak wave amplitudes were only 0.25 and 0.65 m in Methoni and in Pylos, respectively. This result is absolutely consistent with the same pattern of systematic decrease of tsunami amplitudes from west to east along north Crete.

Remarkable water elevation disturbance was caused from the tsunami generated by the caldera collapse mechanism. The conservative scenario of caldera collapse volume of 19 $km^3$ produced peak-to-peak tsunami wave amplitude of the same order of 2.5 m in both Methoni and Pylos. However, the upper extreme of the caldera collapse volume of 34 $km^3$ produced amplitudes of 3.7 m in Methoni and 4.5 m in Pylos.

Regardless the tsunami generation mechanism, the synthetic wave amplitudes obtained certainly underestimate the real ones given that the synthetics were calculated for virtual tide-gauges installed at sites situated at water depths of 27 m in Methoni and 32 m in Pylos.

### *4.2. Numerical simulation of the A.D. 365 tsunami*

Most of the efforts to simulate the large tsunami of A.D. 365 (e.g., Tinti *et al.*, 2005; Fischer and Babeyko, 2007; Lorito *et al.*, 2007; Shaw *et al.*, 2008; Yolsal *et al.*, 2008) underestimated the wave amplitudes as compared to the ones expected from the historical and geological record of the tsunami. This may be due to a number of reasons, such as the source characteristics and the gross bathymetry particularly in the shallow water domain. Recently, Novikova *et al.* (2012) simulated the 365 wave by shifting the purely thrust seismic source of $M = 8.3$ along the

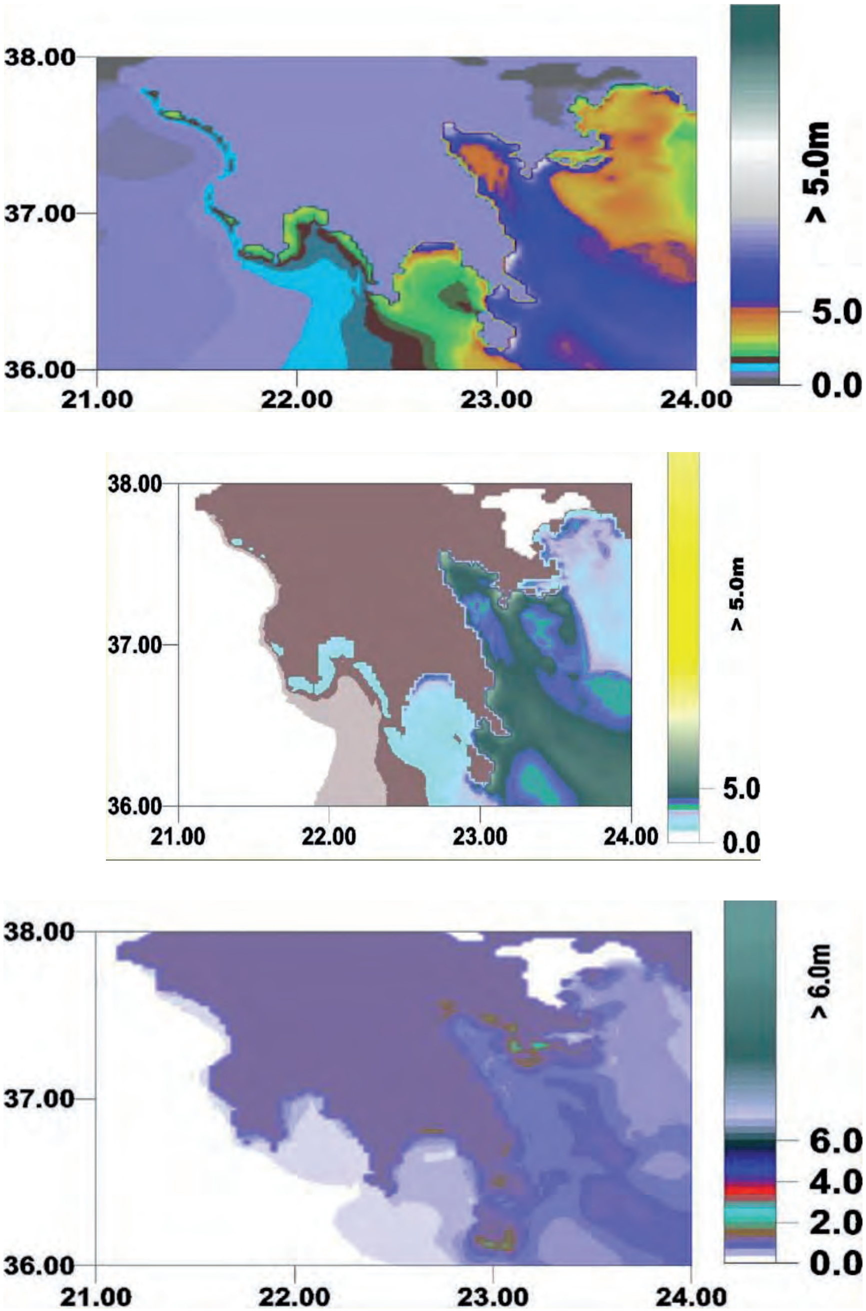

Fig. 2 - Water elevation in south Peloponnese due to tsunami produced by pyroclastic flow during the Minoan eruption of Thera. Pyroclastic flow penetration by counter clockwise azimuth of 120° (upper panel), 145° (middle panel) and 200° (lower panel).

western HA-T segment from south of Crete to the NW of Crete and by utilizing three grids of bathymetry, a coarse for the Mediterranean Sea, an intermediate for the Aegean Sea and a fine for local application, e.g., in Alexandria. Uniform seismic slip of 10 m was adopted as an initial condition by applying the elastic dislocation model derived by the Okada's (1985) code but also by empirical relationships for the seismic source (Well and Coppersmith, 1994; Konstantinou

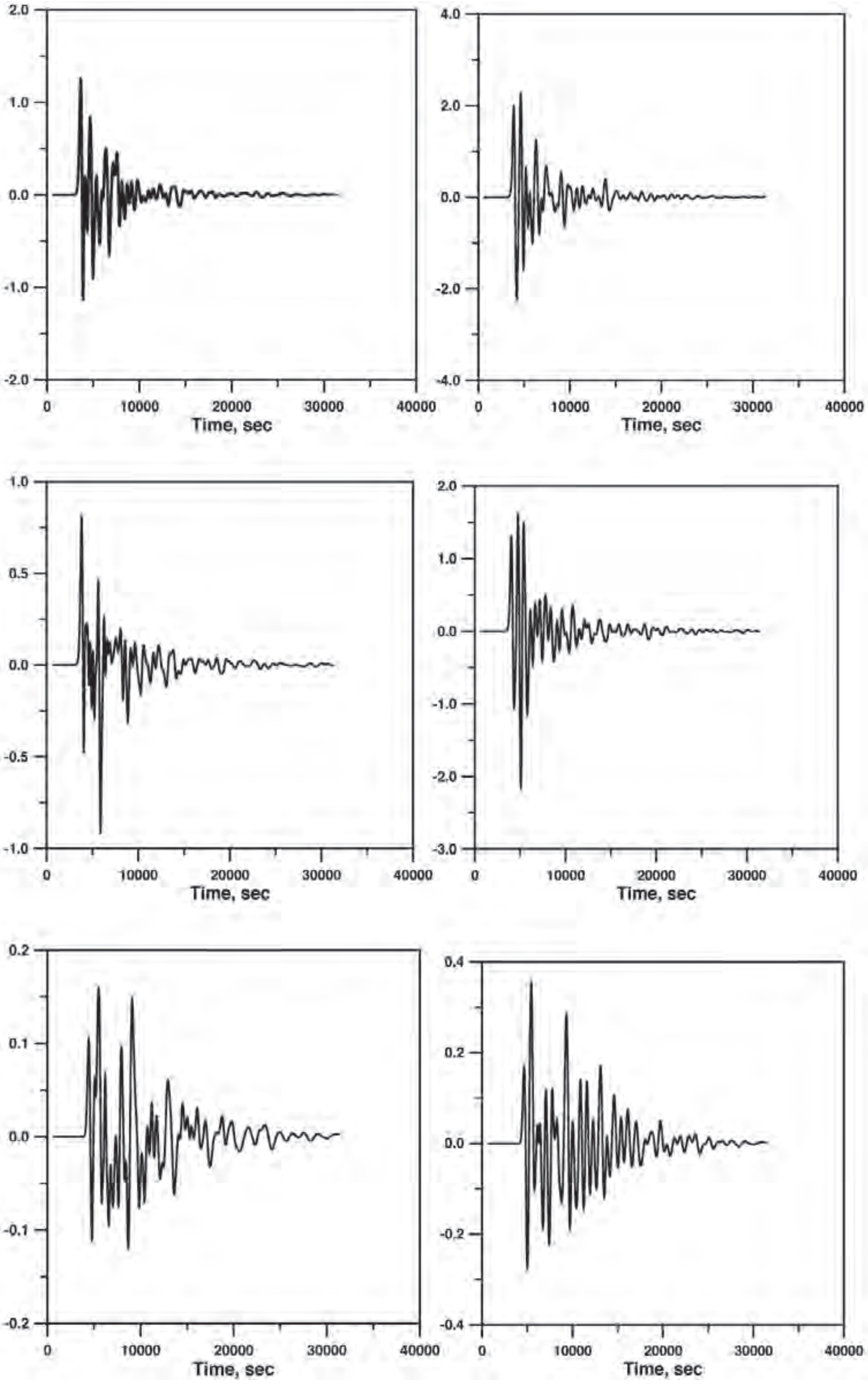

Fig. 3 - Synthetic tide-gauge records in Methoni (left) and Pylos (right) due to tsunami produced by pyroclastic flow during the Minoan eruption of Thera. Pyroclastic flow penetration by counter clockwise azimuth of 120° (upper row), 145° (upper row) and 200° (lower row).

*et al.*, 2005). Shear modulus of $\mu$ = 33 GPa was inserted in the calculations. A strong tsunami energy directivity was found depending on the position of the source. For near-field coastal sites, such as Phalasarna and Balos in NW Crete, maximum peak-to-peak wave amplitudes up to 7 m were found for a seismic source rupturing between Peloponnesus and west Crete at a strike of 345°. These amplitudes are absolutely consistent with the historically and geologically documented ones.

In this paper the same modelling scheme was applied to investigate hydrodynamic tsunami parameters in the coastal sites of Methoni and Pylos of SW Peloponnese. Table 1 lists the seismic source characteristics while the source geometry is illustrated in Fig. 4 along with the initial surface water elevation. The distribution of the maximum water elevation at all times after the tsunami generation clearly shows (Fig. 5) that the maximum wave amplitudes are observed in the near-field domain, that is in the Phalasarna and Balos sites of NW Crete where the peak-to-peak amplitudes exceed 6 m. Because of the NW-SE strike of the seismic source, strong tsunami energy directivity is observed towards SW in the Mediterranean Sea and partly in the

Table 1 - Earthquake source parameters of the 365 large tsunamigenic earthquake.

| | |
|---|---|
| Strike (deg.) | 345 |
| Dip (deg.) | 30 |
| Rake (deg.) | 90 |
| Centroid depth (km) | 20 |
| Fault length (km) | 258 |
| Fault width (km) | 56 |
| Seismic slip (m) | 10 |
| Magnitude (Mw) | 8.3 |

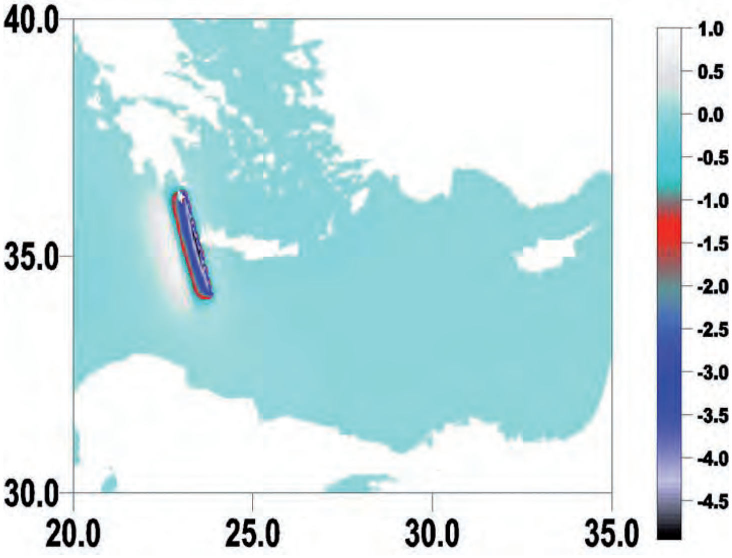

Fig. 4 - Initial surface water elevation after a tsunami generation produced by uniform seismic slip of 10 m in a $M_w$=8.3 source striking 345°. Other source parameters are described in Table 1.

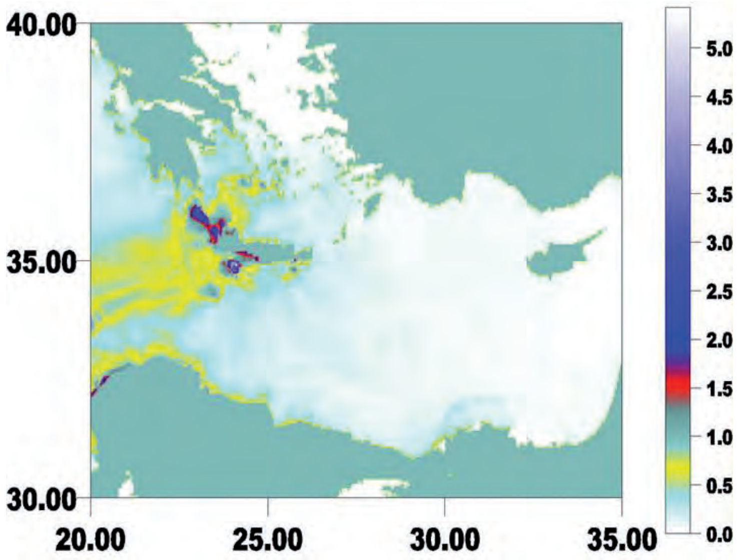

Fig. 5 - Maximum surface water elevation at all times after a tsunami generation produced by a uniform seismic slip of 10 m in a $M_w$=8.3 source striking 345°. Other source parameters are described in Table 1.

southwestern part of the Aegean Sea. However, as one may expect tsunami wave amplitudes drastically reduce towards NW, that is in the area of SW Peloponnese. In fact, the time histories of synthetic tide-gauge records in Methoni and in Pylos show that the peak-to-peak amplitudes were about 1.2 m and 1.5 m, respectively (Fig. 6). Again the expected real amplitudes should be significantly higher than the synthetic ones as explained earlier in relation to the Minoan tsunami simulation.

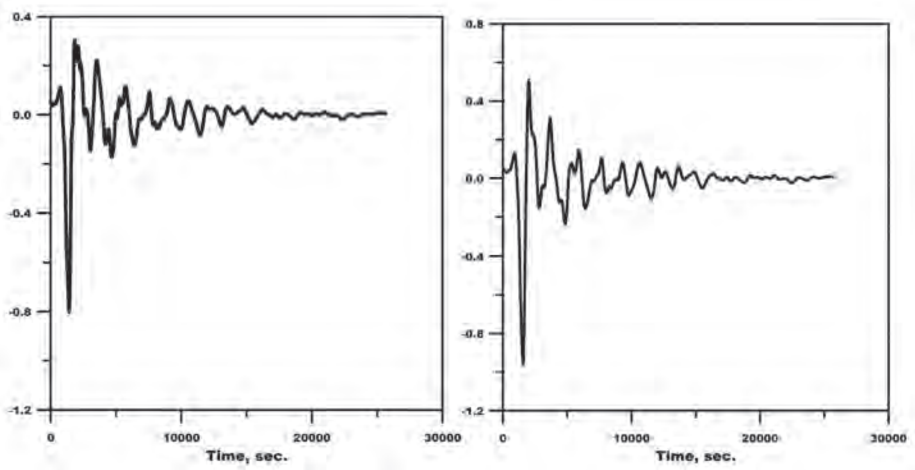

Fig. 6 - Synthetic tide-gauge records in Methoni (left) and Pylos (right) due to tsunami produced by a uniform seismic slip of 10 m in a $M_w$=8.3 source striking 345°.

## 5. Discussion

The number of tsunami events that reportedly hit the area of SW Peloponnese is relatively low as compared to the high seismicity rate of the western HA-T segment. The tsunamigenic mechanism remains unclear for several historical tsunamis caused by strong earthquakes such the 1630 and 1867 ones. Still, it is not well understood why some large earthquakes were tsunamigenic while others were not. For example, the earthquake of $Mw$ = 6.9 that ruptured offshore Methoni on February 14, 2008 did not cause even a small tsunami (Papadopoulos *et al.*, 2008) which still needs explanation. This was also the case of the large earthquake which occurred offshore to the south of Zakynthos with magnitude $Mw$ = 6.6 on November 18, 1997. The large historical earthquake of August 27, 1886 only caused a local tsunami due to submarine slumps occurring offshore SW Peloponnese. In view of those important uncertainties, the evaluation of the potential of tsunami sources threatening SW Peloponnese is possible to be described by qualitative rather than by quantitative approaches.

## 6. Conclusions

Historical documentary sources indicated that in SW Peloponnese local tsunamis were produced by three very strong earthquake events: August 27, 1886; January 22, 1899 and October 6, 1947. However, the local tsunami waves were very likely triggered by submarine co-seismic Earth slumps occurring in the Gulf of Kyparissia after the events of 1886 and 1899 and further southwards in Methoni and Pylos after the 1947 earthquake. No local tsunami sources are known to have activated in SW Peloponnese before 1886 but this may be due to poor documentation of the earthquake and tsunami history of the area. One may not rule out the possibility that local tsunami sources unknown so far would activate in the future.

The area of SW Peloponnese, however, is also threatened by regional or basin-wide large tsunamis such as the A.D. 365 and 1303 ones. Our numerical simulation of the 365 large tsunami has shown that for a magnitude 8.3 seismic source of pure thrust and striking 345° the nearshore peak-to-peak wave amplitudes expected in Methoni and in Pylos equal to about 1.2 and 1.5 m, respectively, which certainly are considerable from the hazard point of view, given that even higher wave should be expected along the shore.

The results of numerical simulations performed by other authors (Özsoy *et al.*, 1982; Tinti *et al.*, 2005; Hamouda, 2006) for the 1303 magnitude 8.0 seismic source in the eastern segment of HA-T lead to the conclusion that tsunami amplitudes in SW Peloponnese localities are not expected to exceed 0.5 m, which implies no serious hazard component. As regards the large tsunami produced by the big LBA eruption of the Thera volcano the numerical simulations that we performed showed that peak-to-peak tsunami wave amplitude exceeding 3 m and 4.5 m should have occurred in Methoni and Pylos, respectively, particularly for the caldera collapse scenario.

We concluded that in SW Peloponnese the potential for tsunami generation is relatively low but this may be only a conservative result due to the poor historical documentation and poor understanding of tsunami generation mechanisms in that area. However, for plans of tsunami hazard assessment, it is important to take into account that SW Peloponnese coastal zones are also threatened by distant and basin-wide large tsunami sources, such as the seismic ones of A.D. 365 and 1303 and the volcanic one of Minoan times.

**Acknowledgements.** This paper is a contribution to the research project SEAHELLARC, EU-FP6, contract no. 037004. The authors are thankful to two reviewers since their critical commentaries helped in improving the initial manuscript.

## REFERENCES

Ambraseys N.N.; 1962: *Data for the investigation of the seismic sea-waves in the eastern Mediterranean*. Bull. Seismol. Soc. Am., **52**, 895-913.

Ambraseys N.N.; 2009: *Earthquakes in the Mediterranean and Middle East - a multidisciplinary study of seismicity up to 1900*. Cambridge, UK, 947 pp.

Antonopoulos J.; 1980: *Data for investigation on seismic sea-waves events in the eastern Mediterranean from the birth of Christ to 1980 A.D.* Ann. Geof., **33**, 141-248.

Billi A., Minelli L., Orecchio B. and Presti D.; 2010: *Constraints to the cause of three historical tsunamis (1908, 1783 and 1693) in the Messina Straits region, Sicily, southern Italy*. Seismol. Res. Lett., **81**, 907-915.

Bruins H.J., MacGillivray J.A., Synolokis C.E., Benjamini C., Keller J., Kisch H.J., Klugel A. and van der Plicht J.; 2008: *Geoarchaeological tsunami deposits at Palaikastro (Crete) and the Late Minoan IA eruption of Santorini*. J. Arch. Sci., **35**, 191-212.

Cita M.B., Camerlenghi A., Kastens K.A. and McCoy F.W.; 1984: *New findings of bronze age homogenites in the Ionian sea: geodynamic implications for the Mediterranean*. Mar. Geol., **55**, 47-62.

De Martini P.M., Barbano M.S., Smedile A., Gerardi F., Pantosti D., Del Carlo P. and Pirrotta C.; 2010: *A unique 4000 year long geological record of multiple tsunami inundations in the Augusta Bay (eastern Sicily, Italy)*. Mar. Geol., **276**, 42-57.

De Viazis S.; 1893: *Megas en Kriti seismos kata to 1629 (a great earthquake in Crete during 1629)*. Parnassos, **16**, 218-221 (in Greek).

Dominey-Howes D.; 2004: *A re-analysis of the Late Bronge Age eruption and tsunami of Santorini, Greece, and the implications for the volcano-tsunami hazard*. J. Volcanol. Geotherm. Res., **130**, 107-132.

Eginitis D.; 1901: *Resultats des observations sismiques, faites en Grece pendant l'annee 1899*. Ann. Obs. Nat. Athènes, **3**, 21-27.

Fischer K.D. and Babeyko A.; 2007: *Modelling the 365 A.D. Crete earthquake and its tsunami*. Geophys. Res. Abstr., **9**, 09458.

Forster W.A.; 1890: *Earthquake origin*. Trans. Seismol. Soc. Jpn., **15**, 73-92.

Galanopoulos A.G.; 1941: *Das riesenbeben der Messenischen kóste von 27 August 1886*. Praktika tis Akadimias Athinon, **16**, 120-126.

Galanopoulos A.G.; 1949: *The Koroni, Messinia, earthquake of October 6, 1947*. Bull. Seismol. Soc. Am., **39**, 33-39.

Galanopoulos A.G.; 1950: *Die seismizität von Messenien*. Gerlands Beitr. Geophyz., **61**, 144-162.

Galanopoulos A.G.; 1960: *Tsunamis observed on the coasts of Greece from antiquity to present time*. Ann. Geofis., **13**, 369-386.

Gerardi F., Barbano M.S., De Martini P.M. and Pantosti D.; 2008: *Discrimination of tsunami sources (earthquake versus landslide) on the basis of historical data in eastern Sicily and southern Calabria*. Bull. Seismol. Soc. Am., **98**, 2795-2805, doi:10.1785/0120070192.

Goodman-Tchernov B.N., Dey H.W., Reinhardt E.G., McCoy F.W. and Mart Y.; 2009: *Tsunami waves generated by the Santorini eruption reached eastern Mediterranean shores*. Geol., **37**, 943-946.

Grilli S.T. and Watts P.; 1999: *Modelling of waves generated by a moving submerged body: applications to underwater landslides*. Eng. Anal. Boundary Elem., **23**, 645-656.

Guidoboni E. and Comastri A.; 1997: *The large earthquake of 8 August 1303 in Crete: seismic scenario and tsunami in the Mediterranean area*. J. Seismol., **1**, 55-72.

Guidoboni E. and Comastri A.; 2005: *Catalogue of earthquakes and tsunamis in the Mediterranean area, 11th - 15th century*. INGV - SGA, Bologna, Italy, 1034 pp.

Guidoboni E., Comastri A. and Traina G.; 1994: *Catalogue of ancient earthquakes in the Mediterranean area up to the 10th century*. INGV - SGA, Bologna, Italy, 504 pp.

Hamouda A.Z.; 2006: *Numerical computations of 1303 tsunamigenic propagation towards Alexandria, Egyptian coast*. J. Afr. Earth Sci., **44**, 37-44, doi:10.1016/j.jafrearsci.2005.11.005.

Kastens K.A. and Cita M.B.; 1981: *Tsunamis-induced sediment transport in the abyssal Mediterranean Sea*. Bull. Geol. Soc. Am., **92**, 845-857.

Kennedy A.B., Chen Q., Kirby J.T. and Dalrymple R.A.; 2000: *Boussinesq modelling of wave transformation, breaking, and run-up I: 1D*. J. Waterw. Port Coastal Ocean Eng., **126**, 39-47.

Kirby J.T., Wei G., Chen Q., Kennedy A.B. and Dalrymple R.A.; 1998; *FUNWAVE 1.0. Fully nonlinear Boussinesq wave model, documentation and user's manual, Res. Report CACR-98-06*. Cent. Appl. Coastal Res., Dep. Civil Eng., Univ. of Delaware, Newark, DE, USA, 80 pp.

Kirby J.T., Chen Q., Noyes T.J., Elgar S. and Guza R.T.; 2003: *Evaluation of low frequency prediction of a Boussinesq wave model: field cases*. In: Proc. Int. Soc. Offshore Polar Eng., ISOPE, Honolulu, HI, USA, pp. 396-403.

Konstantinou K., Papadopoulos G.A., Fokaefs A. and Orfanogiannaki K.; 2005: *Empirical relationships between aftershock dimensions and magnitude for earthquakes in the Mediterranean Sea region*. Tectonophys., **403**, 95-115.

Lorito S., Tiberti M.M., Basili R., Piatanesi A. and Valensise G.; 2007: *Earthquake-generated tsunamis in the Mediterranean Sea: scenarios of potential threats to southern Italy*. J. Geophys. Res., **113**, B01301, doi:10.1029/2007JB004943.

McCoy F.W. and Heiken G.; 2000: *Tsunami generated by the Late Bronze Age eruption in Thera (Santorini), Greece*. Pure Appl. Geophys., **157**, 1227-1256.

McCoy F.W. and Papadopoulos G.A.; 2001: *Tsunami generation during the Late Bronze Age eruption of Thera: evidence from tsunami deposits on Thera, Crete, west Turkey and the deep sea (abstr.)*. Am. J. Arch., **105**, 258-259.

Minoura K., Imamura F., Kuran U., Nakamura T., Papadopoulos G.A., Takahasi T. and Yalciner A.C.; 2000: *Discovery of Minoan tsunami deposits*. Geol., **28**, 59-62.

Mitzopoulos C.; 1900: *Die erdbeben von Tripolis und Triphylia in den jahren 1898 und 1899*. Petermann's Mittheil., **46**, 277-284.

Novikova T., Papadopoulos G.A. and McCoy F.W.; 2011: *Modeling of tsunami generated by the Giant Late Bronze Age eruption of Thera, south Aegean Sea, **Greece***. Geophys. J. Int., **186**, 665-680, doi:10.1111/j.1365-246X.2011.05062.x.

Novikova T., Papadopoulos G.A., Ezz M. and Kijko A.; 2012: *The large 365 earthquake and tsunami in the Hellenic arc revisited: implications for tsunami hazard assessment*. Geophys. Res. Abstr., **14**, 9600.

Okada Y.; 1985: *Surface deformation due to shear and tensile faults in a halfspace*. Bull. Seismol. Soc. Am., **75**, 1135-1154.

Özsoy E., Ünluata Ü. and Aral M.; 1982: *Coastal amplification of tsunami waves in the eastern Mediterranean*. J. Phys. Oceanogr., **12**, 117-126.

Papadopoulos G.A.; 2001: *Tsunamis in the east Mediterranean: a catalogue for the area of Greece and adjacent seas*. In: Proc. Workshop Tsunami Risk Assess. Beyond 2000: Theory, Practice, Plans, Moscow, Russia, pp. 34-42.

Papadopoulos G.A.; 2009: *Tsunamis in the Mediterranean Sea*. In: Woodward J. (ed), The physical geography of the Mediterranean, Oxford University Press, UK, pp. 493-512.

Papadopoulos G.A.; 2011: *A seismic history of Crete: earthquakes and tsunamis 2000 B.C. - 2011 A.D.* Ocelotos Publ., Athens, Greece, 415 pp.

Papadopoulos G.A. and Chalkis B.; 1984: *Tsunamis observed in Greece and the surrounding area from antiquity up to the present times*. Mar. Geol., **56**, 309-317.

Papadopoulos G.A. and Vassilopoulou A.; 2001: *Historical and archaeological evidence of earthquakes and tsunamis felt in the Kythira Strait, Greece*. In: Hebenstreit G.T. (ed), Tsunami research at the end of a critical decade, Kluwer, Dordrecht, The Netherlands, pp. 119-138.

Papadopoulos G.A., Daskalaki E., Fokaefs A. and Giraleas N.; 2007: *Tsunami hazard in the eastern Mediterranean: strong earthquakes and tsunamis in the east Hellenic Arc and trench system*. Nat. Hazard Earth Sys. Sc., **7**, 57-64.

Papadopoulos G.A., Tinti S., Armigliato A., Charalampakis M., Fokaefs A., Karastathis V., Gallazzi S., Pagnoni G. and Tonini R.; 2008: *The Mw 6.9 earthquake of February 14, 2008 offshore SW Peloponnese: understanding its non-tsunamigenic nature and the implications from the tsunami warning point of view*. In: Proc. 31st Europ. Seismol. Comm. General Assembly, Crete, Greece, p. 310.

Papadopoulos G.A., Karastathis V., Charalambakis M. and Fokaefs A.; 2009: *A storm of strong earthquakes in Greece during 2008*. EOS Trans. AGU, **90(46)**, doi:10.1029/2009EO460001.

Papadopoulos G.A., Daskalaki E., Fokaefs A. and Giraleas N.; 2010: *Tsunami hazard in the eastern Mediterranean sea: strong earthquakes and tsunamis in the west Hellenic Arc and trench system*. J. Earthquake Tsunamis, **4**, 145-179.

Papazachos B.C. and Papazachou C.B.; 1997: *The earthquakes of Greece*. Ed. Ziti, Thessaloniki, Greece, 304 pp.

Papazachos B.C. and Papazachou C.B.; 2003: *The earthquakes of Greece*. Ed. Ziti, Thessaloniki, Greece, 286 pp. (in Greek).

Papoulia J., Makris J., Mascle J., Slejko D. and Yalçiner A.; 2014: *The EU SEAHELLARC project: aims and main results*. Boll. Geof. Teor. Appl., **55**, 241-248, doi: 10.4430/bgta 0100.

Pareschi M., Favalli M. and Boschi E.; 2006: *Impact of the Minoan tsunami of Santorini: simulated scenarios in the eastern Mediterranean*. Geophys. Res. Lett., **33**, 1-6.

Scheffers A. and Scheffers S.; 2008: *Tsunami deposits on the coastline of west Crete (Greece)*. Earth Planet. Sci. Lett., **259**, 613-624.

Schmidt J.F.; 1879: *Studien über erdbeben*. A. Georgi, Leipzig, Germany, 360 pp

SEAHELLARC Working Group; 2010: *Preliminary seismic hazard assessments for the area of Pylos and surrounding region (SW Peloponnese)*. Boll. Geof. Teor. Appl., **51**, 163-186.

Shaw B., Ambraseys N.N., England P.C., Floyd M.A., Gorman G.J., Higham T.F.G., Jackson J.A., Nocquet J.M., Pain C.C. and Piggott M.D.; 2008: *Eastern Mediterranean tectonics and tsunami hazard inferred from the A.D. 365 earthquake*. Nat. Geosci., **1**, 268-276, doi:10.1038/ngeo151.

Soloviev S.L.; 1990: *Tsunamigenic zones in the Mediterranean Sea*. Nat. Hazards, **3**, 183-202.

Soloviev S.L., Solovieva O.N., Go C.N., Kim K. and Shchetnikov N.A.; 2000: *Tsunamis in the Mediterranean Sea 2000 B.C. - 2000 A.D.* Adv. Nat. Tech. Hazards Res., Kluwer Academic Publichers, Dordrecht, The Netherland, vol. 13, 237 pp.

Stavrakis N.; 1890: *Statistiki tou plithysmou tis Kritis meta diaforon geografikon, istorikon, archaeologikon, ekklisiastikon ktl. eidiseon peri tis nisou.* Anastatiki Ekdosi, D.N. Karavia, Vivliothiki Istorikon Meleton, **125**, 1978, Athens, 207 pp. (in Greek).

Tinti S., Armigliato A., Pagnoni G. and Zaniboni F.; 2005: *Scenarios of Giant tsunamis of tectonic origin in the Mediterranean*. ISET J. Earthquake Tech., **42**, 171-188.

Watts P., Grilli S.T., Kirby J.T., Fryer G.J. and Tappin D.R.; 2003: *Landslide tsunami case studies using a Boussinesq model and a fully nonlinear tsunami generation model*. Nat. Hazards and Earth Syst. Sci., **3**, 391-402.

Wei G. and Kirby J.T.; 1995: *Time-depended numerical code for extended Boussinesq equations*. J. Waterw. Port Coastal Ocean Eng., **121**, 251-261.

Wei G., Kirby J.T., Grilli S.T. and Subramanya R.; 1995: *A fully nonlinear Boussinesq model for free surface waves. Part 1: highly nonlinear unsteady waves*. J. Fluid Mech., **294**, 71-92.

Wells D.L. and Coppersmith K.J.; 1994: *New empirical relationships among magnitude, rupture length, rupture width, rupture area, surface displacement*. Bull. Seismol. Soc. Am., **84**, 974-1002.

Yolsal S., Taymaz T. and Yalçiner A. C.; 2008: *Earthquake source rupture characteristics along the Hellenic Arc and simulation of the A.D. 365 Crete earthquake and its tsunami*. Geophys. Res. Abstr., **10**, 00065.

*Corresponding author:* Gerassimos A. Papadopoulos
Institute of Geodynamics, National Observatory of Athens
P.O. Box 20048, 11810 Athens, Greece
Phone: +30-210-3490165; fax: +30-210-3490165; e-mail: papadop@noa.gr