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Local tsunamigenic earthquakes and subsequent tsunamis in the southern and southwestern Peloponnese and intensities based on the Integrated Tsunami Intensity Scale (ITIS 2012)

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Abstract: *The southern Peloponnese has been affected by destructive historical and recent earthquakes with considerable effects on human, nature, buildings and infrastructures. Among other earthquake environmental effects, tsunamis were also induced and affected the coastal southern and southwestern Peloponnese. It is concluded that the most affected and vulnerable by tsunami generation areas are the northern and western coastal areas of the Messinian and the Laconian Gulfs and the Ionian coast of Messinia. The effects of the tsunamigenic earthquakes of 1842, 1867, 1886, 1899 and 1947 mainly included coastal inundation, washing of ships on the shore as well receding of the sea from the coast and subsequent sea level rise. Severe damage of buildings and infrastructures of the coastal area was limited. The maximum ITIS 2012 intensities were $X_{ITIS\ 2012}$ in Laconian Gulf, $IX_{ITIS\ 2012}$ in Messinian Gulf and $VIII_{ITIS\ 2012}$ along the Ionian coast of Messinia.*

***Keywords**: earthquakes, tsunami, ITIS 2012, Peloponnese, coastal area*

INTRODUCTION

The Eastern Mediterranean region (Fig. 1) is one of the most rapidly deforming regions in the world and thus one of the most tectonically and seismically active. The maximum seismicity and the generation of tsunamis are observed along the Hellenic Arc (Papadopoulos, 2016). This activity is attributed to major geotectonic structures dominating the Eastern Mediterranean and producing earthquakes and subsequent tsunamis among other earthquake environmental effects (EEE). These structures include the Hellenic Arc, the Cyprus Arc and the Levantine Basin, while the most significant tsunami sources are observed along the western segment of the Hellenic Arc (offshore western Peloponnese, offshore western and northern Crete), along the tectonic rifts of Corinth and Evoikos Gulfs (Central Greece), within the Aegean Sea and along the North Aegean Sea trough (Fig. 1; Papadopoulos, 2016).

The study area is located in the southern and the southwestern part of Peloponnese. Onshore and offshore studies conducted by various researchers (Mariolakos et al., 1986; Papanikolaou et al., 1988; Mariolakos & Fountoulis 2004; Papanikolaou et al., 2007; Fountoulis & Mavroulis, 2013; Fountoulis et al., 2014) revealed that the study area is composed of major neotectonic macrostructures (megahorsts and megagrabens) bounded by N-S and E-W striking fault zones (Fig. 2). These onshore macrostructures are from E to W the following: (a) the NW-SE striking Sparta basin, (b) the N-S striking Taygetos Mt mega-horst, (c) the Kalamata-Kyparissia mega-graben striking N-S in its southern part and E-W further to the north, (d) the very complex morphotectonic mega-structure of Kyparissia Mts-Lykodimo Mt striking N-S and (e) the Gargallianoi-Pylos mega-horst located along the western coast of Messinia (Fig. 2; Mariolakos et al., 1986; Fountoulis & Mavroulis, 2013).

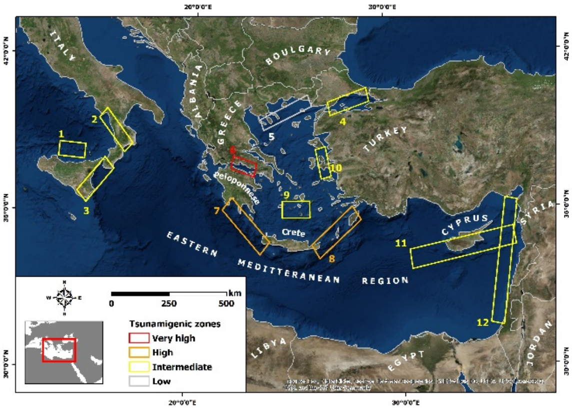

Figure 1: Generalized tsunamigenic zones of the Eastern Mediterranean Sea categorized by relative intensity and frequency of occurrence: 1: Calabria, 2: Aeolian islands, 3: Messina straits, 4: Marmara Sea, 5: North Aegean Sea, 6: Corinth Gulf, 7: West Hellenic Arc, 8: East Hellenic Arc, 9: Cyclades islands, 10: East Aegean Sea, 11: Cyprus Arc, 12: Levantine Sea (modified from Papadopoulos & Fokaes, 2005).

These onshore structures are bounded by active fault zones and seismogenic faults (Fig. 2; e.g. the eastern marginal fault of Kato Messinia basin ruptured in 1986 Kalamata earthquake, the Sparta fault ruptured in 464 B.C., devastating Sparta). Offshore fieldwork in Messinian Gulf conducted by Papanikolaou et al. (1988) and in Kyparissiakos Gulf by Papanikolaou et al. (2007) demonstrated that active faults observed onshore continue in several cases offshore in the study area (Fig. 2, e.g. the onshore eastern marginal fault zone of the Kato Messinia basin continues offshore in Messinian Gulf). These macrostructures have been repeatedly affected by destructive earthquakes during the historical and recent times and suffered the impact of extensive EEE including the generation of tsunami waves.

The generation of the most significant and destructive tsunamis in the study area have been confirmed not only by several written and epigraphic sources (e.g. Galanopoulos, 1960; Soloviev et al., 2000; Ambraseys, 2009; Papadopoulos et al., 2014), but also by searching for palaeotsunami traces and especially for the Holocene tsunami imprint on the coastal part of the study area (Scheffers et al., 2008). It has been clearly shown that this part of Peloponnese is mainly affected by tsunamis strongly related to local earthquakes and coseismic submarine landslides generated in the western part of the Hellenic Arc and Trench system (HEAT) (Galanopoulos, 1960; Antonopoulos, 1980; Papazachos & Papazachou, 1997; Ambraseys, 2009; Papadopoulos, 2016; Papadopoulos et al., 2014). However, tsunami sources in other segments of the HEAT are capable to affect southern Peloponnese. More specifically, the seismic source that produce the 1303 AD earthquake and the subsequent tsunami is located at the eastern segment of HEAT between Crete and Rhodes and can be also considered as threatening the study area as it is concluded by geomorphological and sedimentological paleotsunami traces (Scheffers et al., 2008).

This study aims to the presentation of a complete list of the historical local tsunamigenic earthquakes that have greatly affected the southern part of Peloponnese and the subsequent tsunamis, the presentation of the tsunami quantitative characteristics where available, the detailed presentation of their impact on the coastal natural and built environment as well as the application of the Integrated Tsunami Intensity 2012 (ITIS 2012) scale for the evaluation of the tsunami intensity based on all the available tsunami information and data and the guidelines provided by Lekkas et al. (2013).

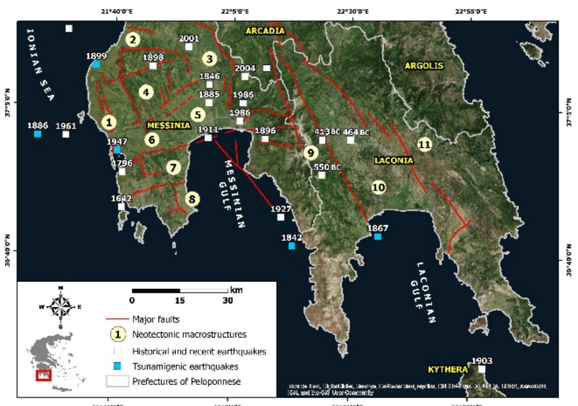

Figure 2: The southern Peloponnese along with the historical and recent earthquakes with impact on human, natural and built environment of the study area as well as the major onshore and offshore faults and the major neotectonic macrostructures: 1: Gargallianoi-Pylos mega-horst, 2: Kyparissia basin, 3: Ano Messinia basin, 4: Kyparissia Mts, 5: Kalamata (Kato Messinia) basin, 6: Vlahopoulo graben, 7: Lykodimo Mt horst, 8: Falanthi basin, 9: Taygetos Mt, 10: Sparta/Evrotas basin, 11: Parnon Mt based on Mariolakos et al. (1986), Papanikolaou et al. (1988) and Fountoulis (1994).

METHODOLOGY

For the present study, data and information on destructive earthquakes and subsequent tsunamis were obtained from verified catalogues and related scientific papers (e.g. Galanopoulos, 1941, 1947, 1949, 1950, 1960; Papazachos & Papazachou, 1997; Soloviev et al., 2000; Ambraseys, 2009; Papadopoulos, 2016; Papadopoulos et al., 2014). All derived data and information were used for the application of the ITIS 2012 scales for the evaluation of the seismic and tsunami intensities respectively.

ITIS 2012 is a recently introduced 12-grade scale ranging from I (not felt) to XII (completely devastating) and it is based on the assessment of a large number of objective criteria, grouped in six categories (physical quantities such as tsunami wave height, flow depth, and inundation extent, impact on humans, impact on mobile objects such as boats and cars, impacts on infrastructure, environmental effects and impact on structures) (Lekkas et al., 2013). This scale works well for modern events where large amounts of data are available (Lekkas et al., 2013; Barberopoulou & Scheele, 2015), while Reicherter (2015) argued that such scales are of limited use in paleotsunami science due to the small data sets, the absence of instrumental records and the difficulties in obtaining the minimum necessary parameters for the evaluation of intensity. In this frame, the ITIS 2012 is applied for the intensity evaluation of historical tsunamis in the study area in order to examine its applicability in utilizing tsunami historical information and its future in hazard assessments.

HISTORICAL EARTHQUAKES AND TSUNAMIS - ESI 2007 and ITIS 2012 INTENSITIES

The 1842 April 18 earthquake and tsunami

This earthquake was generated in the southwestern coast of Peloponnese (Fig. 3a) and caused very heavy structural damage in many settlements located within the Pamisos River valley, in the western part of Messinia and in Laconia (Ambraseys, 2009). As regards the tsunami generation and its impact, the coast close to Koroni was inundated and ships were washed on the shore by the tsunami (V-$VI_{ITIS\ 2012}$) (Fig. 3a).

The 1867 September 20 earthquake and tsunami

The 1867 earthquake generated tidal waves which affected the southern and western part of Peloponnese (Fig. 3b), the Ionian Islands, the Cyclades complex in the Aegean Sea and reached also the eastern Italian coasts (Soloviev et al., 2000; Papazachos & Papazachou, 1997; Papadopoulos et al., 2014). The waves rolled onto the southern and western shores of Peloponnese and had considerable impact on the funnel - shaped gulfs and bays opened towards the earthquake epicenter (Soloviev et al., 2000; Papazachos & Papazachou, 1997). Thus, they severely affected the coastal areas of Laconian and Messinian Gulfs (Fig. 3b). Oscillations of the sea level within the focal zone of the waves presented a long duration ranging from 5.5 up to 10 hours before the sea calmed down again.

Gytheion was destroyed by the waves, which had a significant impact on the Cape Pagania, on the western shore of the Laconian Gulf and on the Messinian Gulf (Fig. 3b). In Gytheion, changes to sea level were observed. The sea initially receded from the shore and the sea bed was dried up. Afterwards, the sea rose for 6 m above its usual level and it looked like boiling ($X_{ITIS\ 2012}$ in Fig. 3b).

In Kalamata located in the northern part of the Messinian Gulf, low and high water were similarly observed with the sea receding slowly from the coast approximately for 15 m ($IX_{ITIS\ 2012}$ in Fig. 3b). Lower values of sea level fall were observed in Petalidi coastal area, where then the sea water level rose up to 2m and caused inundation of the coastal area ($VIII_{ITIS\ 2012}$ in Fig. 3b).

The 1886 August 27 Filiatra earthquake and tsunami

An earthquake occurred in the Ionian coast of Messinia (Fig. 3c; Galanopoulos, 1941, 1947). Tsunami waves were generated and affected a 35km long N-S coastal segment extending from Agrilos located north of Filiatra to the bay of Pylos. The waves washed several boats on the shore of Gialova (V-$VI_{ITIS\ 2012}$ in Fig. 3c) located north of Pylos. The sea close to Agrilos located to the north of Filiatra advanced resulting in coastal inundation ranging from 10 to 15 m for a short time period (VII-$VIII_{ITIS\ 2012}$ in Fig. 3c) (Galanopoulos, 1941a; Soloviev et al., 2000). It was reported that the tsunami was observed up to Izmir (Galanopoulos, 1960a; Karnik, 1971; Papazachos & Papazachou, 1997; Soloviev et al., 2000).

The 1899 January 22 Kyparissia earthquake and tsunami

This very strong earthquake occurred on January 22 causing no fatalities, many injuries and severe damage in many villages of Messinia (Galanopoulos, 1941b, 1947, 1955). The subsequent earthquake-induced tsunami was about 1m high and resulting in inundation of Marathopolis coastal area (VI-$VII_{ITIS\ 2012}$ in Fig. 3d), while in Zakynthos Island was about 20-40 cm ($VI_{ITIS\ 2012}$ in Fig. 3d) (Galanopoulos, 1941; Papazachos & Papazachou, 1997; Ambraseys & Jackson, 1990; Ambraseys 2009). Based on Galanopoulos (1941) the tsunami was possibly triggered by co-seismic submarine slumps, but no damage occurred to the submarine cables between Zakynthos and Peloponnese.

The 1947 January 6 Koroni earthquake and tsunami

On October 6, 1947, southwestern Peloponnese was hit by a strong earthquake that caused 3 casualties and 40 injured as well as severe damage in 54 villages of Pylia province (Galanopoulos, 1949). A tsunami was observed in Methoni coastal area (Fig. 3e) with inundation distance varying from 15m (Galanopoulos, 1949) to 60m (Ambraseys & Jackson, 1990) corresponding to $VIII_{ITIS\ 2012}$ intensity (Fig. 3e). This tsunami was attributed to submarine landslides generated along steep slopes of the seabed in a distance of 6 km SSW of the coast (Galanopoulos, 1949).

CONCLUSIONS

The southern Peloponnese has been affected by destructive historical and recent earthquakes with considerable effects on the local population, the natural environment, buildings and infrastructures.

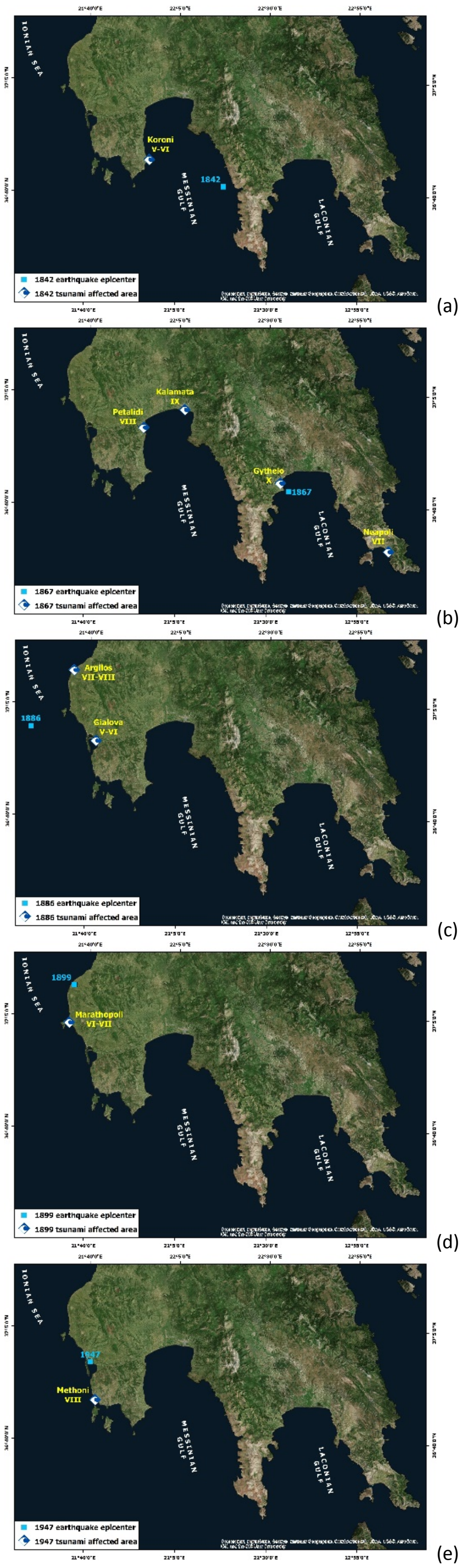

Figure 2: The local tsunamigenic earthquakes of (a) 1842, (b) 1867, (c) 1886, (d) 1899 and (e) 1947 with impact on the coastal areas of the southern and southwestern Peloponnese along with the assigned ITIS 2012 intensities.

Among other earthquake environmental effects, tsunamis were also induced and have affected the coastal southern and southwestern Peloponnese. This presentation supports earlier studies which suggest that post-disaster assessments for historical events (>25 years old) are scarce or limited as regards the related information. Moreover, these limitations and difficulties in the case of the historical earthquakes are attributed to small data sets, absence of instrumental records and difficulties in obtaining the minimum necessary parameters for the evaluation of intensities. However, based on the quantitative data and information from various sources, the ESI 2007 and the ITIS 2012 were applied.

Based on these applications, it is concluded that the most affected and vulnerable by tsunami generation areas are the northern and western coastal areas of the Messinian (e.g. Kalamata, Petalidi, Koroni areas) and the Laconian (e.g. Gytheio area) Gulfs and the Ionian coast of Messinia in the southwestern Peloponnese (e.g. from Agrilos area to Pylos bay). The effects mainly included coastal inundation, washing of ships and boats on the shore as well receding of the sea from the coast and subsequent sea lever rise. Severe damage of buildings and infrastructures of the coastal area was limited. The maximum ITIS 2012 intensities were $X_{ITIS\ 2012}$ in Laconian Gulf, $IX_{ITIS\ 2012}$ in Messinian Gulf and $VIII_{ITIS\ 2012}$ along the Ionian coast of Messinia.

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