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Review

Tsunamis in the Greek Region: An Overview of Geological and Geomorphological Evidence

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Abstract: The Greek region is known as one of the most seismically and tectonically active areas and it has been struck by some devastating tsunamis, with the most prominent one being the 365 AD event. During the past decade significant research efforts have been made in search of geological and geomorphological evidence of palaeotsunamis along the Greek coasts, primarily through the examination of sediment corings (72% of studies) and secondarily through boulders (i.e., 18%). The published data show that some deposits have been correlated with well-known events such as 365 AD, 1303 AD, the Minoan Santorini Eruption and the 1956 Amorgos earthquake and tsunami, while coastal studies from western Greece have also reported up to five tsunami events, dating as far back as the 6th millennium BC. Although the Ionian Islands, Peloponnese and Crete has been significantly studied, in the Aegean region research efforts are still scarce. Recent events such as the 1956 earthquake and tsunami and the 2020 Samos earthquake and tsunami highlight the need for further studies in this region, to better assess the impact of past events and for improving our knowledge of tsunami history. As Greece is amongst the most seismically active regions globally and has suffered from devastating tsunamis in the past, the identification of tsunami prone areas is essential not only for the scientific community but also for public authorities to design appropriate mitigation measures and prevent tsunami losses in the future.

Keywords: palaeotsunamis; boulders; deposits; hazard; corings; Greece; Holocene

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1. Introduction

Globally, coasts are exposed to high vulnerabilities and hazards. Recent events, such as the Indian Ocean Tsunami 2004 [1], Hurricane Katrina 2005 [2], or the 2011 Tōhoku-oki tsunami in Japan [3], have highlighted the impact marine and coastal processes may have on coastal populations. During the last decades, the catastrophic impact of tsunamis has prompted a significant shift in public awareness and research on coastal risks changes globally [4–11].

It is widely considered by the general public that tsunamis are lacking in the Mediterranean Sea [12]. However, examination of existing tsunami records reveals that the Mediterranean has experienced such events in the past [12]. According to CIESM [13], almost all Mediterranean coastal areas are threatened by near-field tsunamis, which can impact nearby coastlines within 5 to 30 min. As coastal development and population densities continue to increase, as do the potential economic and social impacts of natural disasters. The study of past events, through historical tsunami records, are key for better understanding them and in order to develop models for the prediction of future events [12]. In addition, geological records can also provide valuable information in order to extend historical records and obtain information on inundation extend, run up, age of event [14]. This information can contribute to evaluate the size of past tsunami, the location of the source and the frequency of occurrence [14]. To this purpose, there are various sediments that may be deposited by tsunamis, and they may be characteristic in the coastal stratigraphy [15].

Although palaeo-tsunamis have been studied globally, uncertainties still exist regarding the particular fingerprints of tsunamis vs storms [16–19]. The understanding of tsunami sedimentation and erosion processes has been facilitated through the study of recent tsunami deposits, including the 2004 Indian Ocean event [5,20,21]. Several authors have described sets of typical features and typical sedimentary characteristics of onshore tsunami deposits [17,22–25]. In order to distinguish storm and tsunami deposits, a multiproxy approach is essential, which should include geological, biological, geochemical, geomorphological, archaeological, and other proxies when possible [9].

The recognition of past tsunami deposits is valuable in tsunami-prone regions, where historic records are limited or absent, but also in areas with a well-documented tsunami history, in order to confirm existing records and obtain palaeotsunami information extending the historical records [26]. A number of tsunami catalogues exist for the Eastern Mediterranean [27], however, the occurrence of any historic tsunami should be considered tentative, if it is not supported by geological and sedimentological evidence corroborating historic reports [28]. Little geological evidence has been identified in comparison to the large number of tsunamis reported in published catalogues and even for the investigated events [18,29–34] a patchy and geographically limited onshore geological record exists. Furthermore, tsunami catalogues may be exaggerated, occasionally based on secondary or more distant sources and may include non-existent earthquakes and tsunamis [8]. The need for more and better data on palaeo-tsunamis for the Mediterranean and Aegean Sea has been highlighted by a number of researchers [12,35].

According to demographic projections, almost 1 billion people will live in low-elevation coastal areas globally by 2030 [36]. In order to develop appropriate adaptive and mitigating strategies for future disasters, a better understanding of past coastal hazards, their impacts, magnitudes and frequencies, is essential, [9]. Earthquakes and tsunamis across the Eastern Mediterranean have caused thousands of victims in the last few centuries, while they have significantly contributed to the development of civilization and landscape evolution of the coastal areas [37,38].

In this context, the aim of this work is to provide an overview of geological and geomorphological evidence of past tsunamis in the Greek region, located in the eastern Mediterranean, through an extensive literature review. The improvement of the scientific knowledge of this evidence will allow to identify areas at risk, as well as areas that are, so far, understudied and thus highlight regions of scientific interest.

2. The Geological and Tectonic Setting of the Greek Region

The Mediterranean Sea, located between the European mainland, North Africa and the Middle East, is characterized by complex tectonics and geodynamic processes, owed to the interaction of three main lithospheric plates [39]. Greece, lying in the eastern Mediterranean, is characterized by active geodynamics and ongoing geological processes due to the convergence between the Eurasian and African continental plates [40], while it is the most seismically active region in the Mediterranean [12]. Amongst the main geodynamic processes are the westward extrusion of the Anatolian block along the North Anatolian Fault, the subduction of the Eastern Mediterranean lithosphere beneath the south Aegean, the back-arc extension of the Aegean region, and the collision of NW Greece with the Apulian block in the northern Ionian Sea (Figure 1) [40,41].

Historical tsunamigenic earthquakes in the eastern Mediterranean Sea have been discussed in the literature [8,27,28,42,43]. Amongst various events, the most notable are [43]: (a) the tsunami of 21 July AD 365 that impacted inundated coastal sites in North Africa, the Adriatic, Greece and Sicily, and (b) the tsunami of 8 August AD 1303, caused by an earthquake probably near Rhodes, that also brought about significant damages in the eastern Mediterranean [31]. According to Shaw et al. [31] an event similar to AD 365 has a return period of ~800 years and given that the last significant tsunami occurred in AD 1303 [28], Shaw et al. [31] and Valle et al. [43] indicate that the area may be "mature" for a new major event.

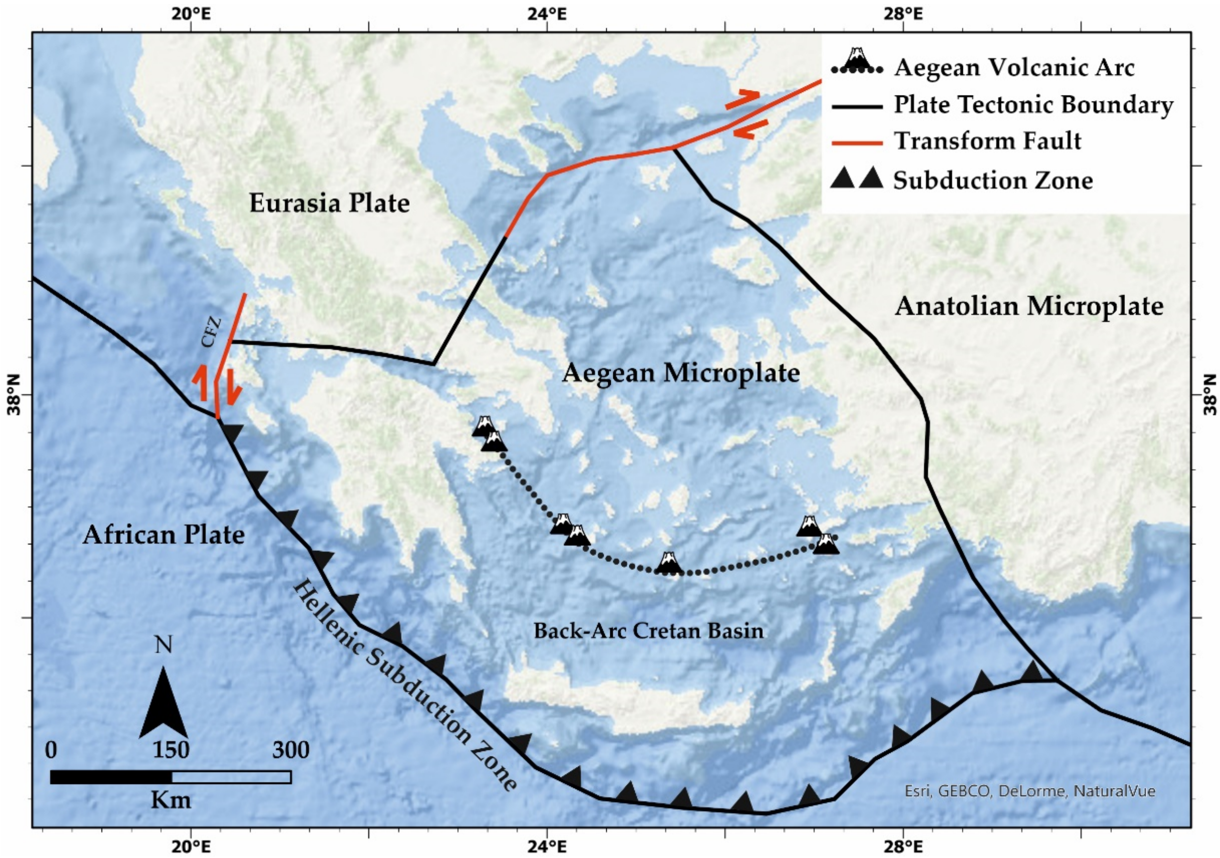

Figure 1. The main tectonic features of Greece.

3. Historical Tsunamis in the Greek Region

The historical tsunami record in the Mediterranean region goes back to the Greek antiquity (4th Century BC) [44]. The fact that most of the historical events have occurred in the Greek seas, makes the eastern Mediterranean the most tsunamigenic part of Mediterranean Sea.

The historical tsunamis in the Greek area can be organized in four regions, based on their spatial distribution: North Aegean, South Aegean, Corinth Gulf and Ionian Sea (Figure 2, Table 1). At the North Aegean as well as the North Ionian Sea, tsunami activity is significantly low; conversely the South Aegean, the Corinth Gulf and the South Ionian Sea are the most historically effected areas.

3.1. North Aegean

The 479 BC, M 7.0, Potidaea earthquake triggered a great tsunami in the homonymous sea and resulted in fatalities, damage to ships and several Persian soldiers were drowned [12,45].

The 426 BC strong earthquake was first reported by Thucydides (460–403? BC). Later on, geographer Strabo (64 BC–19 AD) reported that a tsunami, which was associated with the earthquake, violently inundated coastal localities of Maliakos Bay (North Euboean Gulf) [46,47].

The 20 March 1389, M 6.7, Chios earthquake triggered a tsunami that affected Chios city, where the sea reached up to the middle of the commerce place and forced people to evacuate the area [45,47].

The large earthquake of 28 June 1585, M 7.0, at Mt Athos, generated a local tsunami which was observed at the eastern side of the area [48].

The 13 November 1856, M 6.3, Chios earthquake caused a tsunami that has affected Chios. The sea rushed on the land and claimed the life of some residents [49].

The 3 April 1881, M 6.5 Chios earthquake generated a tsunami. Traces of this tsunami and more specifically spots of fresh sand have been detected in the parametric wall of a garden [49–51].

The 8 November 1905, M 7.5, Athos earthquake triggered a tsunami by earthquake-induced landslides and rockfalls along the Mt Athos southern coast [48].

The 26 September 1932, M 7.0, Chalkidiki earthquake generated a tsunami, which affected the eastern coast of Strymonic Gulf, at Ierissos, with inundation 30 m, which retreated and flooded the coast 4–5 times [12,47].

The 9 February 1948, M 7.1, Karpathos earthquake triggered a tsunami, which affected the central part of the island in a distance of 1 km [12,47,52].

The 19 February 1968, M 7.1 Agios Efstratios earthquake generated a tsunami, observed in the southern coastal part of Limnos Island. The tsunami entered the land in a distance of 20 and 40 m respectively [47,49].

The 15 July 1983, M 6.4 Limnos earthquake triggered a light tsunami in Myrina coastal area of Limnos and in Lesvos [53].

The 12 June 2017, Mw 6.3 Lesvos earthquake triggered a small-scale tsunami. It was generated offshore southeastern Lesvos and was reported by residents in Plomari port. It was characterized as a small tsunami of peak-to-peak amplitude of ∼30 cm [52,54,55].

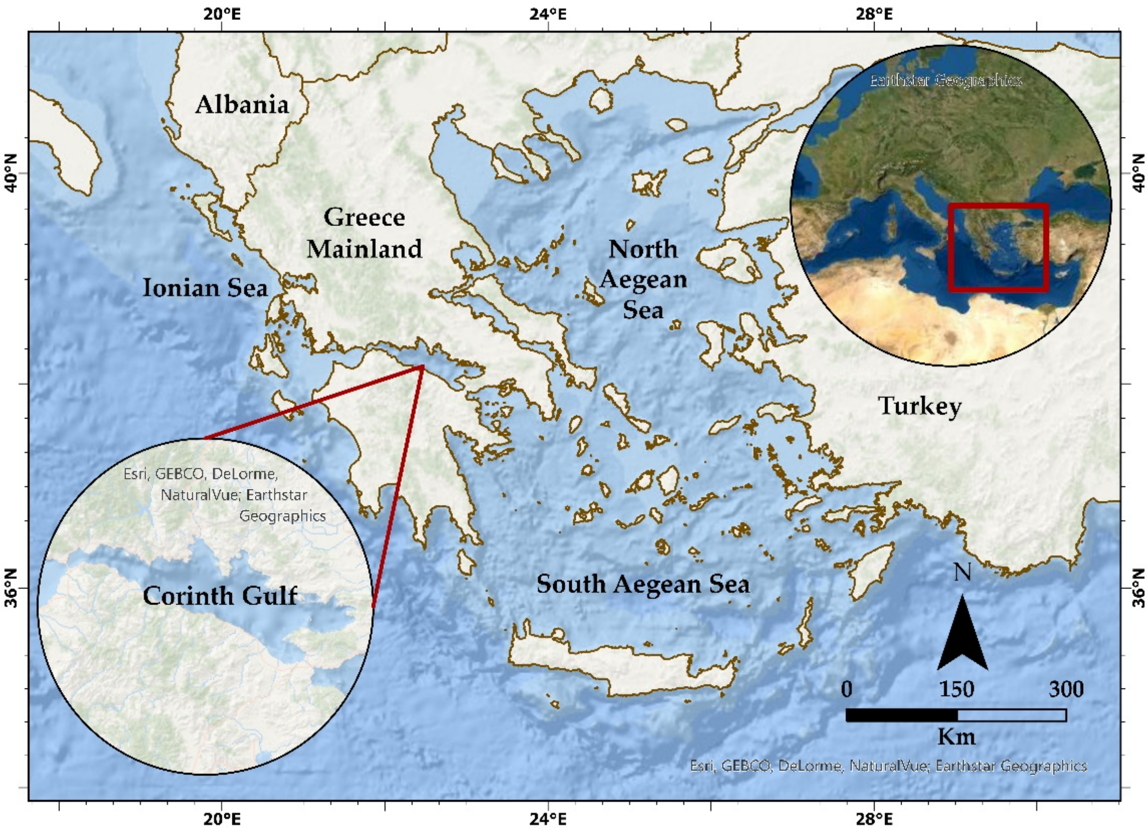

Figure 2. Regions of Greece based on the spatial distribution of historical tsunamis.

Table 1. Summary table of the main historical tsunamis in the Greek region.

No	Event	Magnitude	Affected Area	Reference
			North Aegean	
1	April 479 BC	7.0	Potidaea, Chalkidiki Peninsula	[12,45]
2	426 BC		Maliac Gulf, Oreus Gulf, Euboean Gulf, Phthiotian coasts, Euboean coasts, Island of Skopelos	[46,47]
3	20 March 1389	6.7	Islands of Ikaria and Chios	[45,47]
4	28 June 1585	7.0	Mt Athos	[48]
5	13 November 1856	6.3	Eastern Sporades, Chios Island	[49]
6	3 April 1881	6.5	Chios Island	[49–51]
7	8 November 1905	7.5	Mt Athos	[48]
8	26 September 1932	7.0	Chalkidiki, Strymonic Gulf	[12,47]
9	9 February 1948	7.1	Karpathos Island	[12,47,52]
10	19 February 1968	7.1	Agios Efstratios, Limnos, Lesvos and Euboea Islands	[47,49]
11	15 July 1983	6.4	Limnos and Lesvos Islands	[53]
12	12 June 2017	6.3 (Mw)	Lesvos Island	[52,54,55]
			South Aegean	
1	142 AD	7.6	Rhodes, Kos, Serifos and Symi Islands	[12,47,56]
2	21 July 365	8.3	Crete, Methoni (SW Messinia), Epidaurus, Achaia (NW Peloponnese), Beeotian coasts, Epirus, Alexandria, Sicily (Italy), Dalmatian coast (Adriatic Sea)	[47,49,56]
3	August 556	7.0	Kos Island	[12,49,57]
4	18 August 1303	8.0	Rhodes Island	[37,49,58–60]
5	3 October 1481	7.2	Rhodes Island	[47,56]
6	1 July 1494	7.5	Heraklion (Crete)	[47,56]
7	April 1609	7.2	Rhodes Island	[12,56]
8	8 November 1612	7.2	Heraklion (Crete)	[61–63]
9	9 March 1630	7.3	Crete, Milos and Kythira Islands	[64]
10	31 January 1741	7.4	Rhodes Island	[12,56]
11	12 October 1856	7.7	Heraklion, Haifa and Lebanon	[56]
12	6 February 1866	6.0	Kythira Island, South coasts of Peloponnese	[12,47,56]
13	16 July 1955	6.9	Agathonisi and Samos Islands	[49]
14	9 July 1956	7.5	Amorgos, Astipalaea, Pholegandros, Patmos, Kalimnos, Crete and Tinos Islands, Asia Minor	[12,47,65]
15	21 July 2017	6.6 (Mw)	Kos Island	[54,66,67]
16	30 October 2020	6.9 (Mw)	Samos Island, East coast of Turkey	[68]

Table 1. *Cont.*

No	Event	Magnitude	Affected Area	Reference
			Corinth Gulf	
1	373 BC	at least 6.6	Eliki (Aigio)	[44,56]
2	June 1402		Xylokastro	[37,69]
3	1748		Aigio	[69]
4	11 June 1794		North coast of Corinth Gulf	[69]
5	23 August 1817		West coast of Corinth Gulf	[12,47]
6	7 February 1963		West coast of Corinth Gulf	[12,47,70]
7	6 July 1965		Gulf of Korinth. Itea bay.	[47]
8	11 February 1984		Corinth Gulf	[12]
9	15 June 1995		Corinth Gulf	[12]
10	1 January 1996		Aigio	[12,69]
			Ionian Sea	
1	5 November 1633	6.9	Lefkada Island	[12,47,50,56]
2	2 November 1791	7.0	Between Island of Zakynthos and mainland	[47,56]
3	6 and 9 January 1821		Gulf of Corinth, Alcyonic Sea	[47,56]
4	4 February 1867		Kefallonia and Lefkada Islands	[12,56]
5	20 September 1867	7.1	Ionian Sea, Peloponnese Peninsula and Ionian Islands	[47,56]
6	28 December 1869	6.9	Vlorë (Albania), Lefkada Island	[47,56]
7	27 August 1886	7.5	Gialova, Messenia, Pylos; Asia Minor, Smyrna	[47,56]
8	17 April 1893	6.4	Zakynthos Island	[47,56]
9	3 December 1898		Zakynthos Island	[47]
10	22 January 1899	6.6	Messinia, Kyparissia, Marathos, Zakynthos Island	[47]
11	27 November 1914	6.3	Lefkada Island	[47]
12	27 January 1915	6.6	Ithaca Island	[47]
13	6 October 1947	6.9	Methoni (Peloponnese)	[61,71,72]
14	22 April 1948	6.5	Lefkada Island	[47]
15	17 January 1983	7.2	Cephalonia Island	[28]
16	14 August 2003	6.3	Vlicho Bay (Lefkada Island)	[73]
17	17 November 2015	6.5	Lefkada Island	[74]
18	25 October 2018	6.8	Zakynthos Island, Katakolo, Kyparissia, Crotone, Le Castella	[75]

3.2. South Aegean

The 142 AD, M 7.6 Rhodes earthquake caused damage to Rhodes and Kos Islands. The city of Rhodes was seriously affected not so much by the earthquake but by the subsequent tsunami. Coastal cities in Kos, Serifos and Symi were also affected by the tsunami [12,47,56].

The 21 July 365 AD, M 8.3, Crete earthquake induced a great tsunami that affected the Eastern Mediterranean. A sea regression was initially detected resulting in the exposure of the sea floor. Significant impact of this tsunami has been also reported in almost hundred cities along the coast of Crete, in Methoni (Southwestern Messinia), in Achaia (Northwestern Peloponnese), in Sicily (Italy), in the Dalmatian coast (Adriatic Sea) [47,49,56].

The August 556 AD, M 7.0 Kos earthquake induced a tsunami that affected Kos Island. The sea rose significantly up and engulfed all coastal buildings resulting in fatalities and severe structural building damage [12,49,57].

The 18 August 1303, M 8.0, Rhodes earthquake is one of the largest earthquakes that have occurred in the Mediterranean Sea and was followed by one of the largest tsunamis ever reported and recorded in the area, based all historical and recent studies [37,49,58–60].

The 3 October 1481, M 7.2, Rhodes earthquake caused a tsunami that affected Rhodes city. The tsunami was about 3 m high in the coast and flooded the coastal area. A ship was destroyed after crashing against a reef and sank immediately. No damage was reported to buildings after the sea regression [47,56].

The 1 July 1494, M 7.5, Heraklion (Crete) earthquake induced tsunami, was reported in Heraklion and in Israel. In the first city, large sea waves were reported in the port, while in Israel sea regression was reported [47,56].

The April 1609, M 7.2, Rhodes earthquake induced many fatalities in the coastal part of Rhodes city [12,56].

The 8 November 1612, M 7.2, Heraklion (Crete) earthquake generated a tsunami and many ships sank in Heraklion port [61–63].

During the 9 March 1630, M 7.3 Crete earthquake, a tsunami was reported in the area between Crete, Milos and Kythira. In Kythira, the earthquake was slightly felt, and a small flooding of the coastal area has been reported in the port [64].

The 31 January 1741, M 7.4, Rhodes earthquake generated a tsunami that affected Rhodes Island. The sea in Rhodes repeatedly retreated and flooded the coast with great violence resulting in the submergence of the opposite island and the total destruction of five or six villages located at a distance of 1 km inland [12,56].

The 12 October 1856, M 7.7, Heraklion earthquake generated a tsunami in the coastal areas of Haifa and Lebanon [56].

The 6 February 1866, M 6 Earthquake caused a seismic sea wave, set off by a severe shock on Kythira Island, which rose at Avlemonas (east Kythira) to heights of over 8 m [12,47,56].

The 16 July 1955, M 6.9 Agathonisi earthquake caused a tsunami, which affected the southeastern part of Samos Island and more specifically Pythagoreio and Heraion. It was 2 m high and entered the land at a distance of about 20 m [49].

The 9 July 1956, M 7.5 Amorgos earthquake triggered a tsunami that affected 16 islands across the Aegean Sea and the coast of Asia Minor [12,47,65]. Based on a quantitative database of 68 values of tsunami run-up conducted by Okal et al. [65], it was concluded that the tsunami run-up was up to 20 m on the southern coast of Amorgos.

The 21 July 2017, Mw 6.6 Kos earthquake was followed by a tsunami that hit eastern Kos Isl. and Bodrum peninsula [54]. The maximum tsunami run up at Kos port was ~1.5 m [54,66,67].

The 30 October 2020, Mw 6.9 Samos earthquake was followed by a tsunami, which mainly hit the north coast of Samos, but also affected the entire coasts in Samos, east coast of Turkey and other islands in the central Aegean [68].

3.3. Corinth Gulf

The Corinth Gulf is characterized by the highest rate of tsunami occurrence in the European—Mediterranean region.

In 373 BC, the coastal town of Eliki, located about 7 km east of the modern city of Aigio in southwest Corinth Gulf, was destroyed by a strong earthquake (estimated earthquake magnitude of at least 6.6) and its associated local tsunami [44,56].

In June 1402 a very strong tsunami occurred further east on the south coast of the Corinth Gulf. It was preceded by a large earthquake, probably near the coast, which had its source near the town of Xylokastro [37,69].

In 1748, a local but still powerful tsunami caused damage in the coastal zone of Aigio, West Corinth Gulf [69].

On 11 June 1794, a tsunami caused by landslides occurred along the north coast of Corinth Gulf [69].

On 23 August 1817, a locally generated but powerful tsunami caused human losses and extensive damage on the coast of west Corinth Gulf [12,47].

On 7 February 1963, an aseismic, damaging tsunami was generated by a sediment slump at a river mouth and hit both coasts of western Corinth Gulf, killing two people [12,47,70].

On 6 July 1965 [47], 11 February 1984 [12] and 15 June 1995 [12], tsunamis occurred caused by landslides.

The 1 January 1996, an intense wave was observed near Aigio [12,69].

3.4. Ionian Sea

The 5 November 1633, M 6.9 strong earthquake caused large rockfalls that took place on the southern shore of Lefkada island at Cape Agios Sostis. The sea rose, flooded the coast with a great force and caused damage [12,47,50,56].

The 2 November 1791, M 7 earthquake, tsunami intensity 3, validity 2. It is possible that a tsunami was observed between the Island of Zakynthos and the mainland [47,56].

The 6 or 9 January 1821 in association with the 6 January 1821 aftershock remains a questionable event so far. In fact, much confusion can be found in previous catalogues regarding the time and place of its occurrence as well as of its nature [47,56].

The 4 February 1867, islands of Kefallonia and Lefkada. Probably Tsunami [12,56].

The 20 September 1867, M 7.1 earthquake at Ionian Sea, Peloponnese Peninsula and Ionian Islands [47,56]. The earthquake generated tidal waves, which rolled onto the southern and western shores of the Peloponnese, and were also observed on the Ionian Islands, within the region of Shkoder in Albania, in southeastern Italy, in Brindisi where the sea receded from the shore comparatively far, on the Island of Sicily, in Messina and Catania where low water was observed at 7 h 9 m, on the Islands of Malta, Crete, Serifos, Syros, Cyclades. Oscillations of the sea level within the focal zone of the waves lasted a long time: from 5.5 up to 10 h before the sea finally became calm after rolling in and surging back many times. The waves became stronger in such funnel-shaped gulfs and bays, such as Laconia and Messini on the Peloponnese Peninsula, Lixouri on the Island of Kefalonia, and on the Island of Syros. Gytheio was destroyed by waves, and a lot of fish were thrown out onto the coast.

The 28 December 1869, M 6.9 earthquake caused three large tsunami waves that were observed in the sea near Vlorë (Albania), and Lefkada [47,56].

The 27 August 1886, M 7.5, earthquake probably caused a tsunami. The generated tsunami waves thrown several boats out onto the coast in Gialova (to the north of Pylos); the sea near Agrilos (to the north of Filiatra) advanced deep onto dry land for 10–15 m.

The 17 April 1893, M 6.4 Earthquake caused sea withdrawal in Zante [47,56].

On 3 December 1898, a strong earthquake occurred on the Island of Zakynthos. The water receded from the shore [47].

The 22 January 1899, M 6.6 earthquake caused a tsunami at Messinia, Kyparissia and Marathos with intensity III according to Antonopoulos [76]. The sea wave was about 1 m high, and flooded the coast at Marathos and other places, which are not specified, including the coast of Kyparissia. On the island of Zakynthos, the height of the wave was about 40 cm [47].

The 27 November 1914, M 6.3 earthquake caused a large landslide that occurred during the earthquake from the northern artificial coast of the estuary of the River Demossari. A wave 2–3 m high (from other data, 11 m) was generated as a result of this landslide [47].

On 27 January 1915, a very strong earthquake M 6.6 caused sea waves to the coasts of Ithaca [47].

The 6 October 1947, M 6.9 strong earthquake occurred on the south–western shore of Peloponnese. Landslides took place within the focal area on the coast and, possibly, on the sea bottom. Tsunami waves over 1 m high originated. The sea in Methoni advanced

15 m deep onto dry land. A strong tsunami wave was observed entering 15 m landward at Methoni. It could have been caused by a submarine landslide which occurred 6 km south-southwest off the coast. A tsunami associated with this event inundated Methoni, a coastal town on the SW Peloponnese, from 15 m to 60 m [71]. Papadopoulos and Chalkis [72] reported a 15 m inundation at an unnamed location. Soloviev [61] lists a submarine landslide triggered by the earthquake as the probable tsunami source.

The 22 April 1948, M 6.5 earthquake caused a tsunami wave about 1 m high, which was noted in Vasiliki, Lefkada [47].

The 17 January 1983, M 7.2 very strong earthquake caused sea withdrawal in Cephalonia [28].

The 14 August 2003, M 6.2 earthquake caused a very small tsunami, no more than 0.5 m, which hit Vlicho Bay south of Nydri and caused minor damage to boats and coastal constructions [73].

The 17 November 2015, M 6.5 earthquake in Lefkada caused a landslide and generated a small tsunami wave [74].

The 25 October 2018, M 6.8 earthquake, south of Zakynthos, caused a small tsunami wave [75]. EMSC European agency reported sea levels had risen slightly, by about 20 cm, but the increase could be higher locally. It later tweeted sea level changes were also observed in Italy. The earthquake generated a small tsunami recorded by some tide-gauges, including those of Katakolo and Kyparissia in Greece and Crotone and Le Castella in Italy.

4. Holocene Record of Tsunamis in Greece

4.1. Main Geological and Geomorphological Evidence

Tsunami events cause abrupt changes in the sedimentological and environmental conditions, which are related to particular geomorphological processes. Such processes may have a temporary character and cause a temporary interruption of the dominant geomorphological conditions, which are resumed after a specific time period. These events are frequently expressed in the stratigraphic record as distinct marker horizons and they often allow for a multiproxy reconstruction of their spatial and temporal dimensions as well as their impact on coastal landscape evolution. However, the identification of tsunami deposits and their distinction from storm deposits remains still a problem as both deposits share common characteristics [18,19,77]. A recent review by Chagué-Goff et al. [78] has demonstrated that geochemical proxies when combined with a good knowledge of the geological context of the studied site and of depositional and chemical processes, can be a powerful tool to differentiate tsunami deposits. New proxies also include ancient DNA for the characterization of microbial communities or microfossil assemblages in sediments [79,80].

Additionally, an important tsunami signature can be the dislocation of large boulders from the shoreline [81] that bear evidence of their transportation from their original location in the intertidal or subtidal zone. Boulders have been widely used in Mediterranean studies in the study of tsunami deposits [82–86]. Such boulders or mega-blocks are often found isolated or in groups on the coastal zone (Figure 3). Although the origin of such boulders may be from further inland, the identification of coastal or marine organisms determines their intertidal or subtidal origin. Deciphering the origin of boulders, i.e., tsunami vs. storm waves, is commonly achieved through the application of hydrodynamic equations [24,87–90], although uncertainties still remain in their interpretation [91]. Overall, the marine origin of a boulder, in combination with the application of hydrodynamic equations and a geochronology that allows to link the high energy event to a historical or prehistorical tsunami may be the key criteria to attribute such a deposit to a tsunami event.

(a)

(b)

Figure 3. (**a**,**b**) Clusters of boulders at Cape Greko, Cyprus. They lie at an elevation of about 4.5 m above sea level. According to Evelpidou et al. [86], their geomorphic characteristics suggests that their current location is owed to at least one tsunami event.

Despite all uncertainties, much research has also taken place after modern events, providing valuable information for the identification of palaeotsunamis on coastal landscapes [11,21,92,93]. In fact, post-tsunami surveys of recent events such as the Indian Ocean Tsunami 2004 [1] or the 2011 Tōhoku-oki tsunami in Japan [3], have provided significant new insights to better understand the nature of sedimentological, geochemical and paleontological features, following a tsunami event. Following the 2011 Tōhoku-oki tsunami, field survey research included geochemical studies [94], inundation mapping and modelling [95], tsunami deposit characteristics and spatial variability [96,97], aerial video analysis [98]. It was found that tsunami deposits generally lacked a significant marine signature [99], which, in combination with numerical modeling, suggests that the bathymetry influences the processes of onshore marine sediment transport [11], while sediments derived from the beach, sand dunes, lagoons and inland soils [10]. The thickness of sand and muddy deposits after the event reached about 30 cm, while it was smaller inland [10]. On the other hand, coarse grain deposits, i.e., gravels, were characterized by up to 1 m thickness [96]. According to Goto et al. [10], the aforementioned suggest that tsunami deposits may also be represented by discontinuous sand sheets; hence it would be insufficient to obtain a comprehensive overview of palaeotsunami record and recurrence through the study of just one or a few cores. Tsunami-induced erosion may also result in false dating, when using radiocarbon to date the material just below the tsunami deposit. However, recent methodological developments in radiocarbon dating, such as Bayesian statistical analysis, has significantly improved the accuracy of age determination by reducing errors [100].

Overall, it is clear that the lack of a significant marine character in a possible palaeotsunami deposit should not be a rejecting factor, but the bathymetric profile of the study area should be taken into consideration as well. Geochemical proxies can greatly contribute to the identification of a palaeotsunami layer as marine markers, such as Sr, Na and Cl, appear to be well preserved long after the event [94].

Along the Greek coastal zone, field data ascribed to tsunami events are primarily represented by (a) boulders accumulations [81,84,101–104], and (b) sediment layers in cores, archaeological excavations [105,106], or exposed on coastal cliff surfaces [107] (Figure 4).

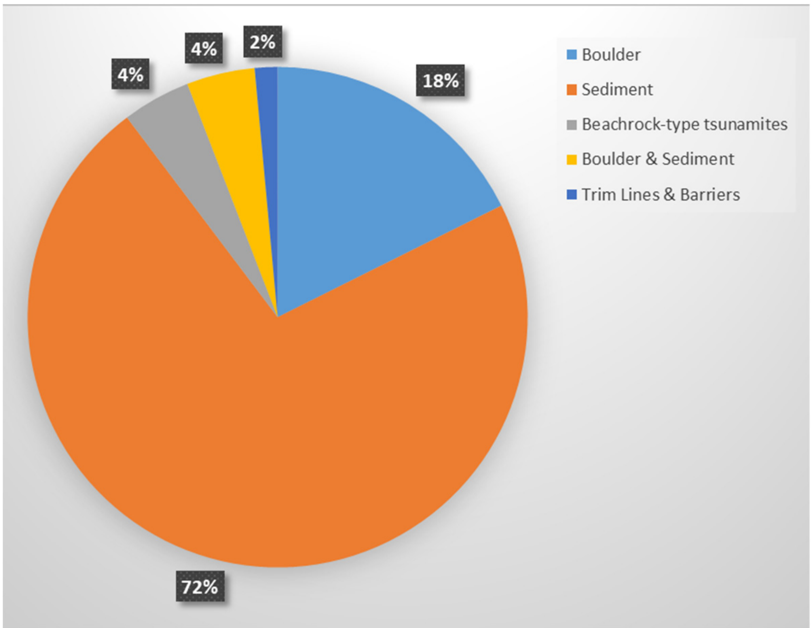

Figure 4. Types of field data, in percentage, from the Greek coastlines that have been used to decipher tsunami events.

4.2. An Overview of Field Data from Greece

In order to provide a detailed overview of palaeo-tsunami field data from the Greek coasts, we performed a detailed literature review of related work. In total 40 publications have discussed evidence on palaeo-tsunamis since 1992; the first paper by Pirazzoli et al. [105] identified deposits from Phalasarna harbor corresponding to two tsunami waves that were ascribed to events occurring in 66 A.D. and 365 AD. It is not surprising then that the majority of research, almost 85%, has been accomplished after 2004, following the devastating Indian Ocean earthquake and tsunami. This trend in tsunami related research has also been noted by Marriner et al. [108]. Research during the 1990s mainly focused on Crete and the 365 AD earthquake and tsunami, and in the central Aegean [107] relating to the 1956 Amorgos event.

A considerable percentage of palaeo-tsunami field data studies, i.e., 72%, (Figure 4) have deciphered palaeo-tsunami events primarily through sediment corings in coastal marshes and lagoons [109–115]. Conversely, boulder studies represent approximately 18% on the total of palaeo-tsunami studies. Tsunami related boulder deposits have only been reported sporadically, in Crete, Peloponnese, Akarnania, Euboean Gulf and Lesvos (Figure 5). On the other hand, coring related studies have primarily focused on the Ionian Sea, western Peloponnese, and Crete. The Aegean Sea has received little attention so far in tsunami field studies.

A closer look at the published data also shows that some deposits have been correlated with the well-known 365 AD earthquake and tsunami or the 1303 AD event [12,45], the Minoan Santorini Eruption [12], or other historical known events, such as the 1956 Amorgos earthquake and tsunami [116–118]. This is particularly the case for Crete Island, where most findings, either boulders or sedimentary layers, have been related with historically known tsunamis. In fact, the 365 AD tsunami has so far been reported in Crete (SW, NW) and in sedimentary studies in western Greece (i.e., Corfu, Kyparissia, Lakonia, Kyllini and Akarnania). The 1303 AD tsunami has been identified through boulders [102] and sediment layers [119] in south and east Peloponnese [120]. Evidence of the tsunami from the Minoan Santorini eruption has only been reported in Crete [115,121,122]. Field evidence of the 1956 tsunami in central Aegean has only been reported from the nearby Astypalaia island [107]. A field survey with testimony from elderly witnesses for the 1956 Amorgos tsunami by

Okal et al. [65] reported 10 m run-up at Astypalaia, but for other islands such as Amorgos and Folegandros, values as high as 20 m and 14.6 m respectively, were also noted.

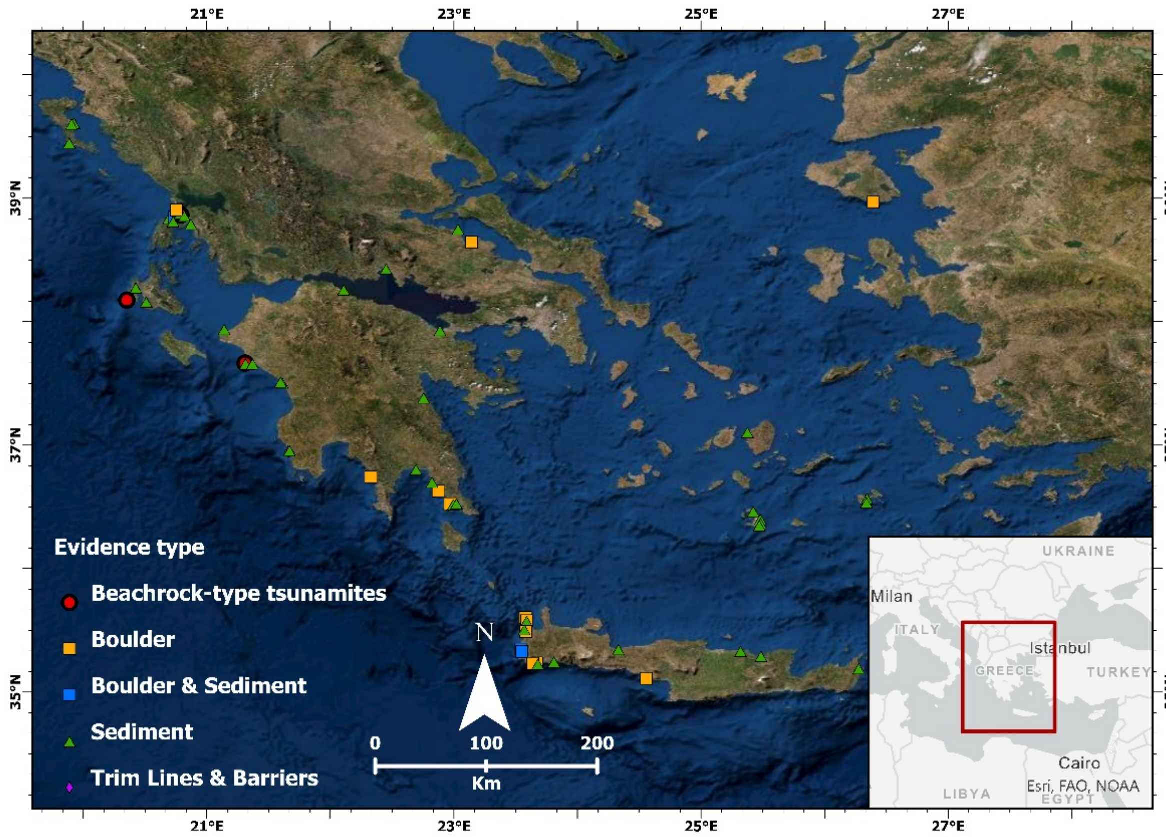

Figure 5. Summary map of palaeo-tsunami studies on the coastal zone of Greece, categorized by evidence type. An interactive version as webmap is available at https://arcg.is/1n4GPP (accessed on 15 December 2021).

The reported tsunami deposits have been dated using radiocarbon dating, optically stimulated luminescence (OSL), by correlation with archaeological data, or a combination of the above. The timespan of these tsunami deposits goes back as far as the 6th millennium BC [110,123]. Apart from historically known tsunamis, coastal studies primarily from western Greece have reported up to five tsunami events, deciphered from coastal stratigraphic analysis, which date as far back as the late Holocene (6th millennium BC; [110]) and therefore cannot be correlated with known events.

It should be noted here that a number of publications (e.g., [63,124–127] among others) have raised a discussion on whether some of the reported tsunami event layers correspond to actual tsunamis or whether most events should actually be ascribed to periods of heightened storminess (for relevant discussion see [9,128]).

One striking feature discussed in some publications is "Beachrock-type tsunamit es" [124,129,130]. In fact, Vött et al. [124] point out that *"beachrock is recommended not to be used as sea level indicator in future studies unless a tsunamigenic formation can be definitely excluded"*. The main weakness with this argument, however, is that the definition of beachrock *sensu stricto* that they are proposing draws our attention solely on the final product (rock) and on the cementation rate. Vött et al. [124] definition of "beachrock *sensu stricto* as hard coastal sedimentary formation out of beach material rapidly cemented by calcitic or aragonitic carbonate precipitation", does not include the main characteristics that define a beachrock and its formation. Vött et al. [109] omit in their definition where beachrocks are formed, and most importantly where does the cementation take place, and what types of characteristic cements are precipitated. Such a misleading interpretation of the term beachrock can lead to serious consequences with regard to the reconstruction of local geological history and rock forming procedures. Beachrock is typically hard, well-cemented layers of beach grainstone consisting of the same grains that are found in the beach sand and develops within the intertidal zone by the precipitation of needle-like (acicular) carbonate cement [131–137]. The lithification takes place below the beach surface, and beachrocks only become exposed as storms remove the overlying sediment [132,135,137]. The above integrated definition of beachrock does not rule out the possible provenance of the original beach sediment as being from tsunami deposits. However, a thorough petrographic examination, could identify the type and morphology of cements, determine the sequence of diagenetic events, and conclude safely whether the under-examination rock is a beachrock or not.

5. Limitations and Knowledge Gaps/Concluding Remarks

Although a significant number of large magnitude tsunamis have been reported for the Greek region, few field investigations of the geological records of these tsunamis have been accomplished [35] and the vast majority of research has focused on the Ionian Sea and the western Peloponnese. The Aegean Sea still remains understudied although events such as the 1956 earthquake and tsunami are known to have struck the central Aegean. Even more recently, the 2020 Samos earthquake caused significant coastal changes [138] and a tsunami [68,139].

Multidisciplinary studies are strongly needed in the Greek region, combining not only geological and geomorphological data but also tsunami modeling [8]. Further multiproxy analysis of well-established palaeotsunami deposits that have been corelated with historical and prehistorical events will improve our knowledge on the characteristics of these deposits for the Greek region and facilitate new studies. Discussion related to the unambiguity of tsunami deposits has been greatly facilitated with field and modelling studies, as well post-field surveys of recent tsunamis. Since Greece is amongst the most seismically active regions and has suffered from devastating tsunamis in the past, better knowledge of tsunami prone areas is essential not only for the scientific community but also for public authorities dealing with natural hazards. Geological and geomorphological data from the historical period to the late Holocene also from the Aegean Sea will provide further knowledge into the impacts that known events have brought about the coastal zone, leading to better prevention and mitigation measures for the coastal communities [140].

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