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Scenarios and Tsunami Hazard Assessment of Tectonic Origin in the Ionian-Adriatic Seas

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Abstract. In this investigation, we study the tsunami hazard associated with the Ionian- Adriatic Sea fault system. In spite of the fact that the great majority of seismic tsunami is generated in ocean domains, smaller basins like the Ionian and Adriatic Seas sometimes experience this phenomenon. A scenario-based method is used to provide an estimation of the tsunami hazard in this region for the first time. Realistic seismic sources, with tsunami potential, are found to model expected coseismic deformation, which is translated directly to the water surface and used as an initial condition for the tsunami propagation. The results from seismicity indicate seven examined sources, only one possesses a very high threat causing wave amplitudes up to 4 m, one high, two intermediate and three low causing wave amplitudes smaller than 4 m at some tourist resorts along the Ionian-Adriatic shoreline.

***Keywords**: tsunami, waves, Ionian- Adriatic Basin, tsunamigenic sources, hazard*

Introduction

The Ionian-Adriatic region (Figure 1) has an unexpected economic and tourist growth with an increase in coastal population and the development of large leisure areas during recent years, with many parts of coastal cities being a couple of metres above sea level, making them prospective targets of a large-scale disaster, even if the height of the tsunami wave is moderate. We have one of the most seismically active areas and the entire Ionian-Adriatic region (Makropoulos & Burton, 1981; Jackson & McKenzie, 1988; Papazachos & Papazachou, 1997, Sulstarova *et.al.*, 2010, Ormeni *et al.*, 2013). This area has been repeatedly affected by large magnitude earthquakes (M>7.0) (Figure 1) that have caused severe destruction and human loss in the past centuries. Large tsunami events require the presence of a thick water layer that can be found only in the oceanic domain, but it can also occur in small basins such as the Ionian-Adriatic seas where many tsunamis have been reported during historical times. This situation requires urgent solutions for an effective risk management and mitigation plan. For this reason, it is essential to define the tsunami potential of the region and this study presents results of such an attempt. The lack of direct records, however, makes the rigorous estimation of the expected tsunami amplitudes rather difficult, and the analysis of available documents remains, somehow, controversial. Any attempt to assess a tsunami hazard, based on pure statistical methodologies, will not give reliable results because of data deficiency and because they use relationships linking earthquakes to tsunamis that may not be empirically well grounded. This means that alternative approaches to evaluate a tsunami hazard are called upon (*e.g.* Tselentis *et al*., 2006). This is the approach used in the present investigation, focusing on the tectonic deformation mechanics of the potential tsunamigenic faults and their effect on the tsunami hazard in the region.

The Data

Reliability of the Ionian-Adriatic Sea tsunami waves listed by Soloviev *et al*. (2000) were evaluated from Gerassimos A. Papadopoulos and Anna Fokaefsfrom. From the catalogue of tsunamis in Table 1 were compiled for Ionian-Adriatic Sea containing 44 reliable events. After reviewing documentary sources, scientific descriptions and other studies the maximum intensity K for each one of the 44 tsunami events was determined according to the new 12-point tsunami intensity scale introduced by Ambraseys (1962), and Papadopoulos and Imamura (2001).

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Table 1. Reliable Tsunami Events Known in the Ionian-Adriatic Sea, that is in Greece and Albania region

No	**Year**	**Month**	**Day**	**Region**	***k***	***h* (cm)**
1	−373	winter		West Corinth Gulf, Central Greece		
2	66			South Crete	3	
3	365	07	21	Crete Island	5	
4	1270	03		North Ionian Sea	3	
5	1303	08	08	Crete Island	5	
6	1402	06		Corinth Gulf, Central Greece	4	
7	1494	07	01	Crete Island	3	
8	1612	11	08	Crete Island	4	
9	1627	10	11	Gargano	5	
10	1633	11	05	Zante Island, Ionian Sea	3	
11	1667	04	06	South Adriatic Sea	3	
12	1742	02	21	West Corinth Gulf, Central Greece	3	
13	1748	05	25	West Corinth Gulf, Central Greece	4	1000
14	1794	06	11	Central Corinth Gulf	3	300
15	1817	08	23	West Corinth Gulf, Central Greece	4	500
16	1833	01	19	Albania	3	
17	1851	10	12	Vlora Albania	3	
18	1861	12	26	West Corinth Gulf, Central Greece	3	210
19	1866	01	02	Albania	4	
20	1866	03	02	Vlora Albania	3	
21	1866	03	06	Albania	4	
22	1866	03	13	Albania	3	
23	1867	02	04	Ionian Sea	2	
24	1869	12	28	Vlora Albania	3	
25	1883	06	27	North Ionian Sea	3	
26	1887	08	27	South Ionian Sea	3	
27	1887	10	03	Central Corinth Gulf	3	
28	1888	90	03	Central Corinth Gulf	2	
29	1893	06	14	Vlora Albania	3	
30	1898	06	02	Corinth Gulf, Central Greece	3	
31	1899	01	22	South Ionian Sea	3	100
32	1914	11	27	Lefkada Island, Ionian Sea	3	300
33	1914	11	27	Lefkada Island, Ionian Sea	3	
34	1920	11	26	Sazani, Albania	3	
35	1947	10	06	South Ionian Sea	2	
36	1948	04	22	Lefkada Island, Ionian Sea	3	100
37	1953	08	12	Kefalonia Island, Ionian Sea	2	
38	1963	02	07	West Corinth Gulf, Central Greece	4	500
39	1965	07	06	West Corinth Gulf, Central Greece	3	300
40	1979	04	15	Montenegro	4	
41	1983	01	17	Kefalonia Island, Ionian Sea	2	
42	1984	01	11	West Corinth Gulf, Central Greece	3	
43	1995	06	15	West Corinth Gulf, Central Greece	3	100
44	1996	01	01	West Corinth Gulf, Central Greece	4	200

- Key: *k* = tsunami intensity in the Sieberg-Ambraseys 6-point scale;
h = maximum wave height (amplitude) in the coast.

Sub-Regions and Selection Of Seismic Sources

Hellenic Arc

Together with Albania and Italy, Greece is characterised by the highest tectonic activity in the Mediterranean. Due to its very ancient civilization, its historical record of earthquakes and tsunamis is among the longest in the world. Greece is characterised by a very complicated tectonic setting, dominated by the subduction of the African lithosphere beneath the Eurasian plate along the Hellenic Arc and Albanian orogen, (see, among the others, Benetatos et al., 2004; Laigle et al., 2004; Papazachos *et al*., 1999, 2000a, 2006; and references therein). The Hellenic Arc is bounded at its north-western by one major transform faults, known as the Cephalonia (right-lateral) transform faults (respectively CFT in Figure 2). The subduction is accompanied by a prominent shallow seismicity with low-angle thrust faults along the Hellenic arc, normal faulting in the back-arc Aegean area, and intermediate depth seismicity forming a well-defined Benioff zone in the southern Aegean.

Figure 1. Ionian-Adriatic Region and earthquakes with M>7 occurred along its

The highest magnitude reported in earthquake catalogues for Greece (*e.g.*, Papazachos *et al*., 2000b) is 8.3, and refers to the July 21, 365 earthquake (*e.g.*, Papazachos, 1996; Stiros, 2001; Stiros & Papageorgiou, 2001). The hypocentre of this earthquake was probably located offshore western Crete, along a major thrust fault parallel to the western Hellenic trench. The earthquake generated a huge tsunami that was very likely destructive along the western Crete coast and is known to have destroyed the Nile delta area in Egypt (see Stiros, 2001; Stiros & Papageorgiou, 2001; Dominey-Howes, 2002; Papadopoulos, 2002). in the present study we focus on tsunamigenic earthquake sources and take into account one distinct sources along of the Hellenic trench. It is a two-segment source running parallel to the western section of the trench and mimicking the source that was very likely responsible for the 365 A.D., M = 8.3 earthquake and tsunami.

The Albanian orogenic front thrust contact with the Adria-microplate

Based on the oil and gas seismic explorations carried out by foreign companies, the convergent boundary between the Albanian orogen and the Adria microplate is now well constrained to be located in the Ionian and Adriatic offshore. The Albanian orogenic thrust front is cut and displaced by the Othoni Island-Dhermi, the north of Sazani Island, and the Gjiri i Drinit-Lezha strike-slip faults, which divide the orogen into separate segments showing diachronous development (Aliaj, 1998, 2000). The following segments of the orogenic thrust front of the Albania orogen have been recognized (Figure 2):

a. The NW-trending Lefkas-Corfu offshore segment
b. The NW-trending Karaburuni-Sazani Island offshore
c. The ~N-trending Frakulla-Durresi mainly onshore segment
d. The W-NW-trending Lezha-Ulqini offshore segment

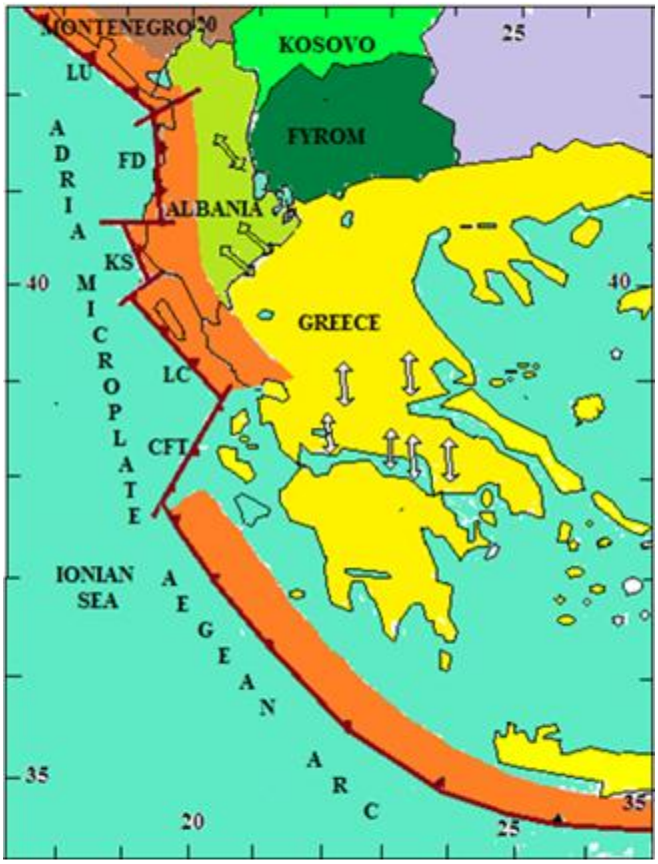

Figure 2. Southern convergent margin of Eurasia plate: Adriatic collision and Aegean Arc. Segments of Adriatic collision frontal thrust are noted by capital letters, as follows*: LC- Lefkas-Corfu, KS-Karaburuni- Sazani Island, FD-Frakulla-Durresi, and LU-Lezha-Ulqini. The strike-slip faults cutting the orogen front, from south to north, are as follows: The Othoni Island-Dhermi, the north of Sazani Island and the Gjiri i Drinit-Lezha faults.*

a. The NW-trending Lefkas-Corfu offshore segment

The NW-trending Lefkas-Corfu slope segment of the orogen front overthrusts the Apulian platform (Sorel, 1989). Further north-westwards, the orogenic front is cut by the NE-trending Othoni Island-Dhermi strike-slip fault, which coincides with the transition from the continental shelf to the Ionian offshore bathyal depths between the Island of Corfu and the town of Himara. Along this segment a thin imbricate section of the Ionian Zone was displaced southwest for about 45 km, and was overthrust on the Apulian platform.

b. The NW-trending Karaburuni-Sazani Island offshore segment

The orogenic front of the Sazani zone is present north of the Othoni Island-Dhermi strike-slip fault. The continental slope south-west of the Mountain Mali i Kanalit is deformed, and, as the result of minor thrusts, the transition from the Mali i Kanalit back-thrust monocline to the Apulian platform occurs along the Sazani zone orogenic front. Along this front Cretaceous carbonates are backthrust over Upper Triassic dolomites of the Çika anticline of Ionian zone, forming a triangular zone at the depth. North of the Gjiri i Ariut-Dukat strike-slip fault, there is a NW-trending thrust that marks the contact of the Karaburuni-Sazani thrust front with the Apulian platform (Figure 2; KS).

c. The ~N-trending Frakulla-Durresi (mainly onshore) segment

North of an E-W-trending transverse fault near Sazani Island, the transition from the Apulian platform to the Albanian Basin (=South Adriatic Basin) occurs in the Adriatic offshore (Figure 2; FD). The front of the orogen there is buried under molasses of Middle Miocene age exposed onshore on coastal terrains of the Periadriatic depression and may pass along the Frakulla-Durresi anticlinal line of quasi-northern extension (Aliaj, 1998; Bega, 1995). Seismic data show that the Mio-Pliocene anticlines of Periadriatic depression are associated with thrust or back-thrust faults (Aliaj, 1998; Biçoku, 1964). These have been termed over-fault anticlines (Aliaj, 1971) or determined by Biçoku (1964) as having been "placed in narrow zones of some big faults found under the Neogene cover". Some of these faults appear to be "flower" structures and "palm tree" structures associate with oblique thrusts (Aliaj, 2000). The north-trending Frakulla-Durresi anticline (Figure 2) has been subjected to dextral transpressional deformation associated with oblique northeast-southwest regional horizontal compression in post-Pliocene time. In the Durresi anticline the main fault is a west-dipping back-thrust that cuts marine Quaternary sediments that are still horizontal. The orogenic front along the Frakulla-Durresi segment is marked at the surface by thrusting and back-thrusting. Along the Ardenica and Durresi anticlines, the Oligocene to Quaternary age thick clastic sediments of South Adriatic Basin (Albanian Basin), have been detached from their carbonate substratum and have glided along a decollement at the level of the Oligocene caustics. The caustic sediments were largely back thrust on frontal thrust structures of the Ionian zone, forming triangular zones at depth.

d. The W-NW-trending Lezha-Ulqini offshore segment

The orogenic front, north of the Gjiri i Drinit-Lezha strike-slip fault, in the Adriatic offshore (Figure 2; LU), belongs to the Kruja Zone (Aliaj, 1998; Dragasevic, 1983). Local back-thrusting observed at Karaburuni-Sazani and Frakulla-Durresi segments of the frontal thrust of the Adriatic collision zone, is quite different from the regional back-thrusting in Western Alps caused by Eo-Alpine and Apulian lithospheric wedging (Roure *et al*., 1990). In the Albanian case the Adria microplate (=Adriatic plate) is unaffected by such wedging; instead it was rigidly subducted during Alpine deformation beneath the Albanian orogen. The external margin of the fold and thrust belt in Albania was thrust on the Adria microplate, partly over the Apulian platform and partly over the Albanian Basin.

Seismicity and Tsunami Activity in Ionian-Adriatic Region

Seismicity in the Ionian-Adriatic basin is strongly connected to the tectonic features outlined above. Albanian coastline region and the coastline region in the Ionian Sea that presents one of the most seismotectonically active regions of the Mediterranean. It is part of a region of intense deformation located between two major lithospheric plates, the European plate and the African plate. The African plate is moving northwards relative to Eurasia at a rate of 10 mm/year (DeMets et al., 1990). Its leading edge is being subducted along the Hellenic Trench in most of the cases. The major tectonic features, which set the Ionian-Adriatic Sea as an area of high seismicity are: the subduction of the African plate beneath the Aegean microplate and collision of Adria microplate to Albanian orogen. Fault plane solutions, for several shallow and intermediate depth earthquakes, have been published (Sulstarova *et al*., 1980 Taymaz et al., 1990; Papazachos *et al*., 1991, Muco *et al*., 1996; Ormeni *et al*., 2013) and we have make an aproch of this study. Only the earthquakes with magnitude greater than 6.5 are plotted. Furthermore, only shallow (depth ≤ 30 km) earthquakes are plotted, since the tsunamigenic potential of deeper events can be neglected. Since tsunamis in the Ionian-Adriatic basin, as well as in other parts of the world, are mostly generated by earthquakes, it is no surprise that the geographical distribution of the historical tsunamis in the region generally resembles the trend of seismicity. Taking into account the Ionian-Adriatic Sea tectonic regime and the tsunamogenic events depicted in Table 1, we have selected seven potential seismic sources that could represent a tsunami hazard in the region The presence of tsunamis have been observed a few times in the past, associated with offshore earthquakes (*i.e*. 1633 & 1886, 1931), affecting near field as well as remote coastal segments (Table 1). The western and easten Ionian and Adriatic offshore has repeatedly suffered large offshore earthquakes which have caused damage and human loss (Papazachos & Papazachou, 1997; Aliaj et al 2010). The damage was minor from these events, due to the sparse population of the region in the early years

The geographic location, strike, length and other parameters of each source were derived from existing fault maps, available reflection profiles and relevant seismological references and are presented. Today, a large earthquake along the Ionian-Adriatic sea fault system would damage coastal communities, and its effect would be enhanced by sea waves triggered from the seafloor displacement (Daberdini & Ormeni, 2013, 2014). For each sub-region, will be possible tsunamigenic seismic sources, and take these as the basis to develop a scenario for the propagation of the tsunami from the source throughout the entire Ionian-Adriatic basin.

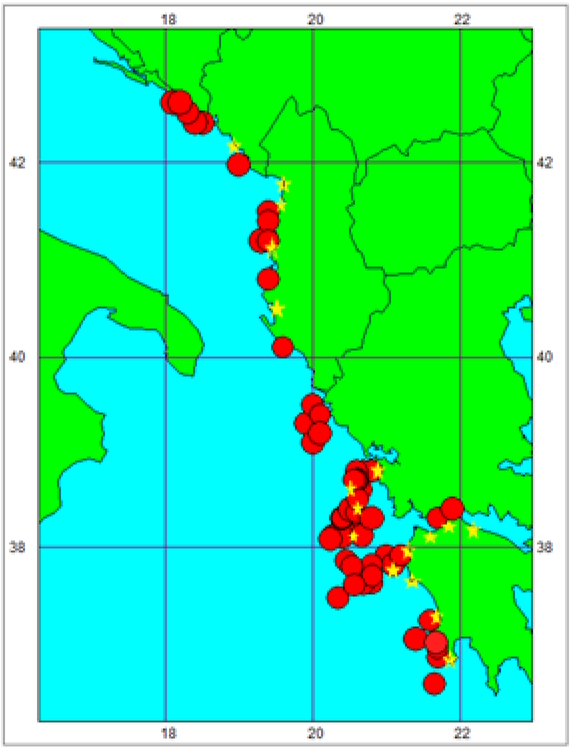

Figure 3. Earthquakes with M>6.5 occurred along the Ionian and Adriatic Sea and the potential tsunamigenic sources (numbers in yellow squares) considered in the present investigation. Stars, denote tsunami reported sides.

Tsunamigenic Sources in Ionian-Adriatic Basin

Most often, a solution to the problem is searched for, in terms of a scenario that considers the largest events known to have hit the area of interest in the past history and to simulate these events through numerical modelling. Because of the active lithospheric plate convergence, the Mediterranean Sea region is geodynamically characterized by high seismicity. Tsunamis are among the most remarkable phenomena associated with earthquakes, and landslides in the Ionian-Adriatic Basin. Until recently, however, it was a widely held belief that tsunamis either did not occur in the in the Ionian Sea or they were so rare that they did not pose a threat to coastal communities. Catastrophic tsunamis are more frequent on Pacific Ocean coasts where both local and transoceanic tsunamis have been documented. On the contrary, large tsunami recurrence in the Ionian-Adriatic Sea is of the order of several decades and the memory of tsunamis is short-lived. The damage was minor from these events, due to the sparse population of the region in the early years. Today, a large earthquake along the Ionian Sea fault system would damage coastal communities, and its effect would be enhanced by sea waves triggered from the seafloor displacement. Taking into account the Ionian Sea tectonic regime and the tsunamogenic events depicted in Table 1, we have selected four potential seismic sources that could represent a tsunami hazard in the region (Figure 4).

For these reasons, the scientific study of tsunamis in the Ionian-Adriatic Sea was rather neglected for a long period in comparison to other parts of the world. Up until the beginning of the 20th century tsunamis were sporadically mentioned in earthquake descriptions or catalogues. By the early and mid-20th century some research was carried out after large tsunami events such as the Messina event in southern Italy (28th December 1908). More systematic efforts to compile tsunami catalogues for the Ionian-Adriatic Basin began in the 60's, when some progress was made in the fields of numerical wave modelling and tsunami hazard assessment. The beginning of 1990's marked a key turning point for tsunami science in the Mediterranean Sea region and in Europe in general. As a result of a series of well-coordinated tsunami research projects, major progress has been made in the Ionian-Adriatic Basin region across the full spectrum of tsunami science, technology and risk mitigation. Figure 4 illustrates a map of the known tsunamigenic sources in the Ionian-Adriatic Basin region and a relative scale of their potential for tsunami generation calculated as a convolution of the frequency of occurrence and the intensity of tsunami events. The compilation of reliable tsunami data bases is of great importance for a wide range of tsunami related studies: statistics and hazard assessment, wave numerical modelling, risk evaluation, operation of early warning systems, public awareness.

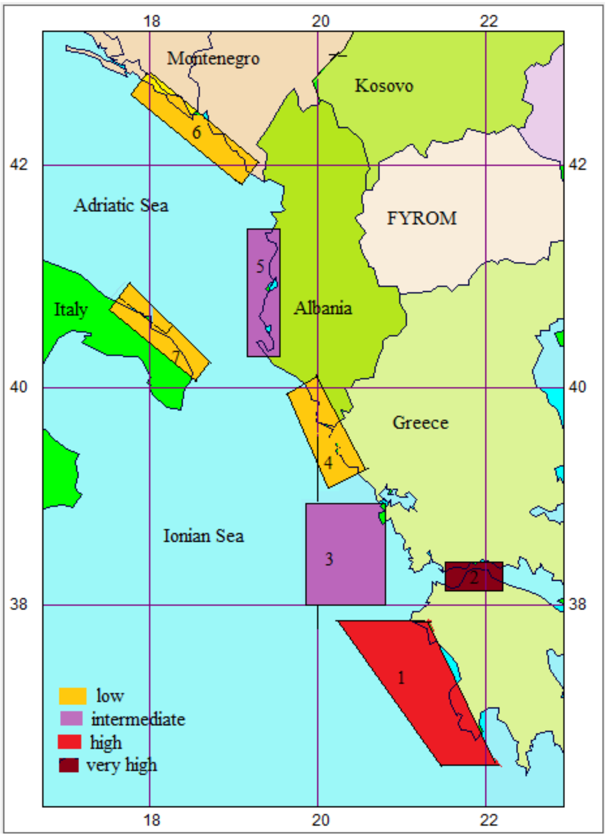

Figure 4. The tsunamigenic zones of the in the Ionian-Adriatic Sea*; 1 = West Hellenic arc, 2 = Corinth Gulf, 3 = Celafonia , 4 = Lefkada-Korfus , 5 = West Albania coastline islands, 6 = Lezha Ulqini, 7 = Gargano promontory, (the tsunami potential of each one zone is classified in a relative scale according to the frequency of occurrence and intensity of tsunamis)*

Conclusions

The main objective of this work was the analysis of possible tsunamis in the Ionian-Adriatic Sea. Special emphasis was given to the tourist resorts, where we computed the corresponding activation of each of the seven sources. From geographical point of view, the very strong events are associated either with highly seismogenic structures like the South Montenegro, Westen Albania, the South Italy, the Corinth Gulf, northenl Greece, and the Hellenic arc. On the contrary, not very strong tsunamis were found in the rest tsunamigenic zones of the Ionian-Adriatic Sea Sea region (Figure 4). It should be noted, however, that these results are valid as much as the tsunami record over the last centuries could be extrapolated to longer periods of time. From this point of view, the incompleteness of the data along with the very long repeat time that may characterize the tsunami occurrence in some tsunamigenic zones, pose a serious problem in approaching reliably the repeat time of very strong tsunamis in the Mediterranean Sea. From all the examined sources, only source 1 possesses a serious threat, causing wave propagation amplitude that reaches up to 4m at two locations. Since these locations are heavily populated during the summer season, the need for special tsunami risk mitigation measures is obvious. As a final consideration, our attention in this paper focussed on the time needed for the first tsunami signals to reach the remote coasts, but indeed deeper attention should be paid in a future study to the longterm features of the tsunami propagation for each scenario, in order to evaluate the expected total duration of the phenomena, the characteristic periods, the relative amplitude of the wave packets and the role of edge waves. Several groups of tsunami waves are expected to attack the coasts, with the highest amplitudes not necessarily associated with the first arrivals. Furthermore, sea-level oscillations remain significant for several hours after the earthquake, which represents another important issue in tsunami warning.

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