**ISSN** 8755-6839

SCIENCE OF **TSUNAMI HAZARDS**

Journal of Tsunami Society International

**Volume 41 Number 3 2022**

# HUNGA-TONGA-HUNGA-HA'PAI VOLCANIC ERUPTION/EXPLOSION AND TSUNAMIS OF 14-15 JANUARY 2022 – Overview and Analysis

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**ABSTRACT**

The explosive eruption/collapse of the submarine portion of the volcano Hunga-Tonga-Hunga-Ha'apai (HT-HH) on the Tonga Kermadec volcanic arc in the southwest Pacific on 15 January 2022 occurred at the end of many weeks of activity. It was a truly global event, as was the 1883 explosive eruption/collapse of the volcano of Krakatau in Indonesia and the 1490 BC explosion, caldera and flanc collapses of the Santorin volcano in the Aegean Sea, both generating destructive tsunamis. The eruption of HT-HH was a combination of a major submarine Surtsean (phreatomagmatic) and of a subsequent ultra-Plinian atmospheric explosion which generated a very damaging local tsunami by the crustal displacements of the volcano's caldera and flanc collapses, but also an atmospheric paroxysmal explosion similar to that of the Krakatau event. In recent years, the development of new instrumentation and of an expanded array of terrestrial and space instruments - including atmospheric pressure sensors, seismometers and a fleet of satellites monitoring the Earth across the entire spectrum of light – provided better global monitoring of the effects of this particular and unusual 2022 Hunga-Tonga volcanic event. Specifically detected were concentric atmospheric gravity waves, which also resulted in unusually-traveling ionospheric disturbances (CTIDs) – mapped on both of the earth's northern and southern hemispheres along conductive magnetic field lines, and which circled the earth three or four times many hours after the eruption/explosion. In addition to local destructive tsunami generation in the immediate area and elsewhere in the Paciific, the violent eruption created an impulsive Lamb wave propagation on the surface air pressure which, moving near the speed of sound at ~340 m., traveled faster than sea surface tsunami wave(s) and was observed globally - reaching Japan, Australia, Central and South America and elsewhere. Tsunami-like waves were observed or recorded, particularly along coastal areas of Central and South America. The present study provides an overview, an analysis and a brief comparison with past volcanic events and of their different tsunami generation mechanisms, as well as a brief description of the recorded atmospherically-generated waves and disturbances following the eruption/collapse of the HT-HH volcano.

## 1. INTRODUCTION

Hunga Tonga-Hunga Ha'apai (HT-HH) is a stratovolcano along the Tofua Volcanic Arc, a line of volcanoes fed by magma from the Pacific Plate's subduction beneath the Indo-Australian Plate. Its initial eruptive activity in December 2021, increased on 14 January 2022 and on 15 January 2022 the volcano exploded, creating atmospheric shock waves, sonic booms, tsunami waves and global sea level oscillations. Observed for many hours after the eruption were hurricane-speed winds and unusual electric currents in the ionosphere.

The final eruption of the HT-HH volcano (Tonga volcano) of 15 January 2022, was a combination of a major submarine Surtsean (phreatomagmatic) and of a subsequent ultra-Plinian atmospheric explosion which, not only generated a local and very damaging tsunami by the crustal displacements of its caldera and flanc collapses, but also an atmospheric paroxysmal explosion similar to that of 1883 Krakatau volcano in Indonesia (Pararas-Carayannis, 2004, 2006), and to the 1490 BC explosion, caldera and flanc collapses of the Santorin volcano in the Aegean Sea (Pararas-Carayannis, 2004; 2006; 2019).

The colossal explosion of the HT-HH volcano produced various types of atmospheric pressure waves that spread around the world. Repeated explosions of the event in the audible frequency range, were heard thousands of kilometers away.

Similar atmospheric air pressure perturbations can be also generated by large earthquakes involving significant vertical crustal displacements, as was the case with the 1964 Earthquake in Alaska, the 1975 Hilina Slump of the East Rift Zone of the Kilauea volcano in Hawaii, and elsewhere (Pararas-Carayannis G., 1967; 2018).

Tsunami or tsunami-like generation from volcanic sources may also result from a volcano's flank instabilities and subsequent gravitational collapses. Whether a strato-volcano has effusive or explosive eruptive activity is determined by the relative stability of its slopes. Thus, volcanoes with lavas of high andesitic composition and explosive type of eruptive activity tend to have steeper and more unstable flanks that often can fail massively. However, even shield stratovolcanoes - characterized by mainly effusive activity - can have significant flank failures and caldera collapses, although most are sub-aerial.

The following sections of the present study provide a brief description of the near and far-field effects of the tsunami generated by the 15 January 2022 Tonga volcanic eruption/explosion. Additionally included are a brief review of different mechanisms that can result in volcanic flank failures and the generation of tsunami or tsunami-like waves (Pararas-Carayannis, 1975, 2002; Toulkeridis EtAl. 2022). As further discussed, volcanic flank failures may result from isostatic load adjustments, extensive erosion, gaseous pressures, violent phreato-magmatic eruptions, magmastatic pressures, gravitational collapses of magmatic chambers, dike and cryptodome intrusions, as well as from the buildup of hydrothermal and supra-hydrostatic pore fluid pressures. Other sources of tsunami generation and of atmospheric disturbances may be caused by flank failures of coastal or oceanic volcanoes.

In addition to the volcanic sources, large magnitude earthquakes involving significant vertical crustal displacements can also generate atmospheric pressure waves. For example, the 1964 Alaskan earthquake generated such waves, which were recorded by distantly located microbarographs. Since the propagating speed of these atmospheric waves were faster than that of tsunami waves, the use of such microbarographs was proposed to serve as a precursory method of forecasting/warning about potential tsunami generation (Pararas-Carayannis. & Vitousek, 1967).

Furthermore, tsunami waves can be generated by a rapid, significant and progressive drop in atmospheric pressure which may be caused by a moving storm or hurricane, in which case the impact would be localized and directional, as was the case with the meteo-tsunami of 29 August 1916 at Santo Domingo, in the Dominican Republic – as documented in a report published by the Russian Academy of Sciences (Pararas-Carayannis, 2019). Finally, most of the mechanisms mentioned above have the potential of becoming sources of destructive tsunami generation.

What makes the present study of the Tonga volcanic eruption/explosion more interesting and relevant, is a better understanding of the far-field effects of the tsunami-like waves that were generated, based on the present technological ability to better measure the broad range of atmospheric waves generated by the force of the eruption, as well as by the instrumental detection of the atmospheric surface-guided Lamb wave perturbations that travelled at different propagation speeds - observed globally by ground-based and by space instrumentation. Also, it should be mentioned that historically less than 5% of volcanic eruptions/collapses have generated any significant tsunamis with far-reaching impacts, with the exception of that of 1490 BC of the Santorin volcano in the Aegean Sea, the 1883 A.D. Krakatau volcano in the Sunda Strait beteween Java and Sumatra in Indonesia, and a few other volcanoes in the Indian, Pacific and Atlantic oceans. Although rare, mainly local destructive tsunamis can also be generated by large scale sudden flanc failures of island statovolcanoes such those of Mauna Loa and Kilauea in 1868 and 1975, and of Cumbre Vieja on the island of La Palma in the Canary Islands (Pararas-Carayannis, 2002). However, greater source dimensions and longer wave periods are required to generate tsunamis that can have significant, far field effects.

The following sections of the present report present a brief description of the Tonga volcanic arc, ridge, adjacent trench and of the islands of Tonga, and an overview of the activity of the HT-HH volcano prior, during, and after the volcanic eruption/explosion of 15 January 2022, of the near-source and far-field tsunami generation, of the resulting atmospheric Lamb wave oscillations, of the ionospheric pertrubations, as well as of a cursory analysis and comparison of tsunami generation by other historical large volcanic eruptions, explosions and flanc collapses.

## 2. THE TONGA VOLCANIC ARC, RIDGE, AND TRENCH

The Kingdom of Tonga is a group of about 170 islands, of which about 45 are inhabited. The largest island of the group is Tongatapu, inhabited by about two-thirds of the country's population. It is a relatively flat coral island, where its capital Nukuʻalofa is located, as well as several towns and villages such as Muʻa, Nukunuku, Holonga, Pea, and the country's Fuaʻamotu International Airport. The Tonga island chain sits on an underwater mountain range, the 3,000 km long Tonga-Kermadec Rid**ge**, which is the most seismically active subduction boundary on planet Earth, and has the highest density and number of undersea volcanoes. Figure 1 below show the bathymetry of the Tonga Trench and Forearc.

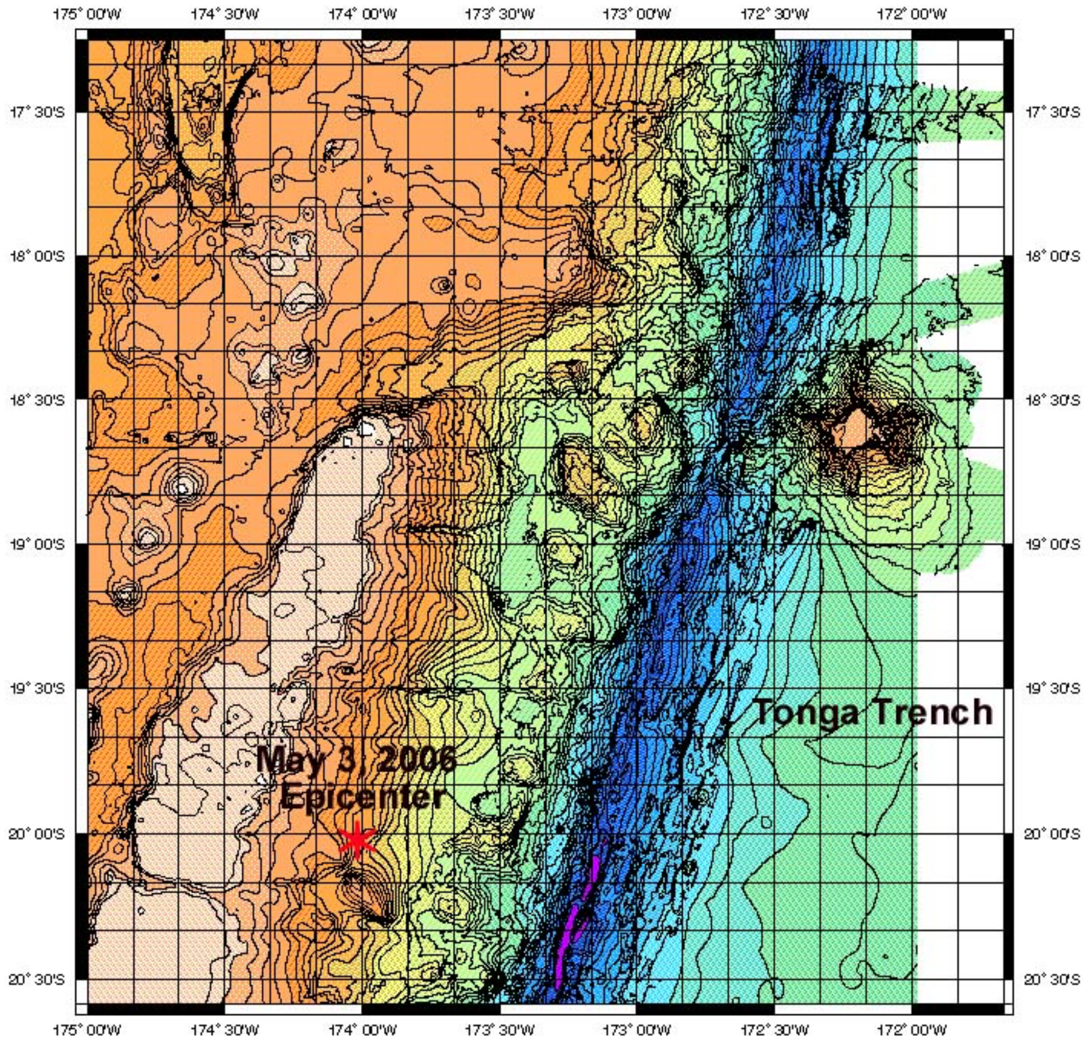



Figure 1. Bathymetry of the Tonga Trench and Forearc (after Pararas-Carayannis, 2006, modified map after Wright et al., 2000 - from http://dusk2.geo.orst.edu/tonga/fig9.gif)

The Tonga Ridge parallels the Tonga Trench, which is the deepest oceanic trench in the Southern hemisphere and the second deepest oceanic trench on Earth after the Mariana Trench, which is located east of Guam. The Horizon Deep South of the Tonga Trench is located about 220 km southeast of the main island Tongatapu and has a maximum depth of 10,800 m. To the west of the Tonga-Kermadec Ridge is the chain of underwater volcanoes, known as the Tonga Volcanic Arc (Colombier, EtAl. 2018; Dingwell, 2018). Within this arc are the island nation's volcanic islands of Hunga Tonga, Nomuka, Tofua, Kao, Late and Niuafo'ou. Tonga's highest mountain is the island of Kao - a volcano which rises 1,033 m above sea level. Figure 2 is a relief map showing the territory of Tonga, north of the Tropic of Capricorn, the Tonga Ridge, the adjacent volcanic arc, the Tonga Trench, and the location of the Horizon Deep. Subduction of the oceanic Hikurangi Plateau impacts on the Kermadec arc (Tim EtAl, 2014).

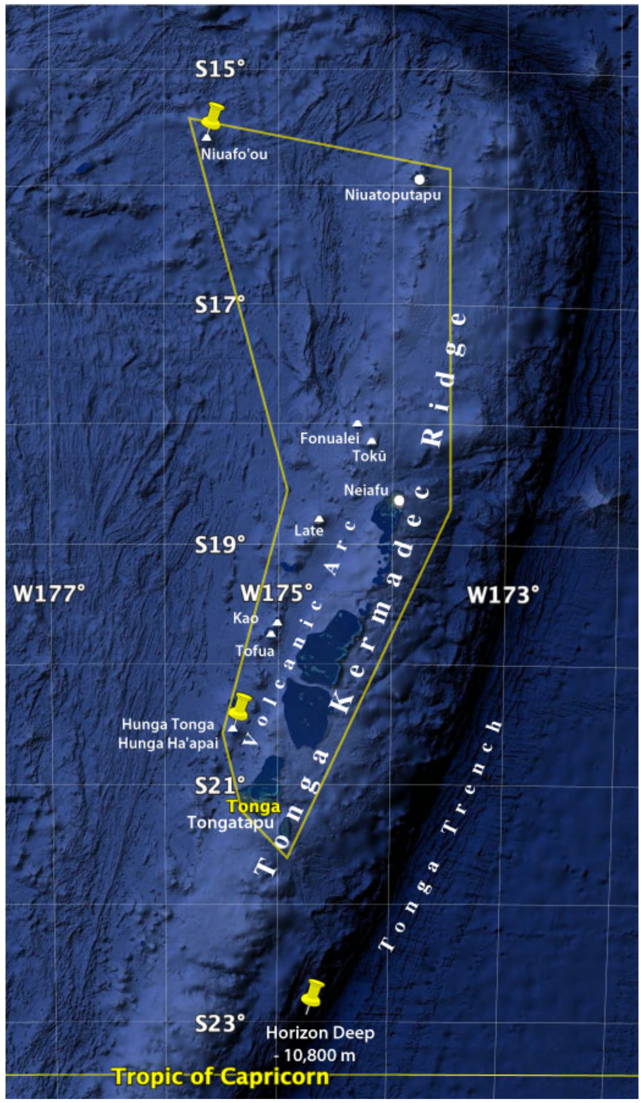



Figure 2. Relief map of the territory of Tonga, north of the Tropic of Capricorn, of the Tonga Ridge and the adjacent volcanic arc, of the Tonga Trench, and of the location of the Horizon Deep. (Source: Google Earth)

**2A. Geodynamic Setting and Underwater** Structure **of Hunga Tonga-Hunga Ha'apai Volcano**

Dacitic volcanism prevails along the Tonga-Kermadek volcanic arc where the HT-HH exists and was developed by subduction of slabs beneath the eastern Indonesia–Tonga region (Worthington EtAl. 1999; Hall & Spakman, 2002). The image below (Fig. 3 ) is a Planet Labs PBC/via REUTERS SkySat image which shows the upper, above-sea rim of the Hunga Tonga-Hunga Ha'apai (HT-HH) on January 15, 2022, two hours before the underwater volcano's hydro magmatic eruption/explosion at 5:10 p.m. on the same day (GoogleEarthTM, 2022).

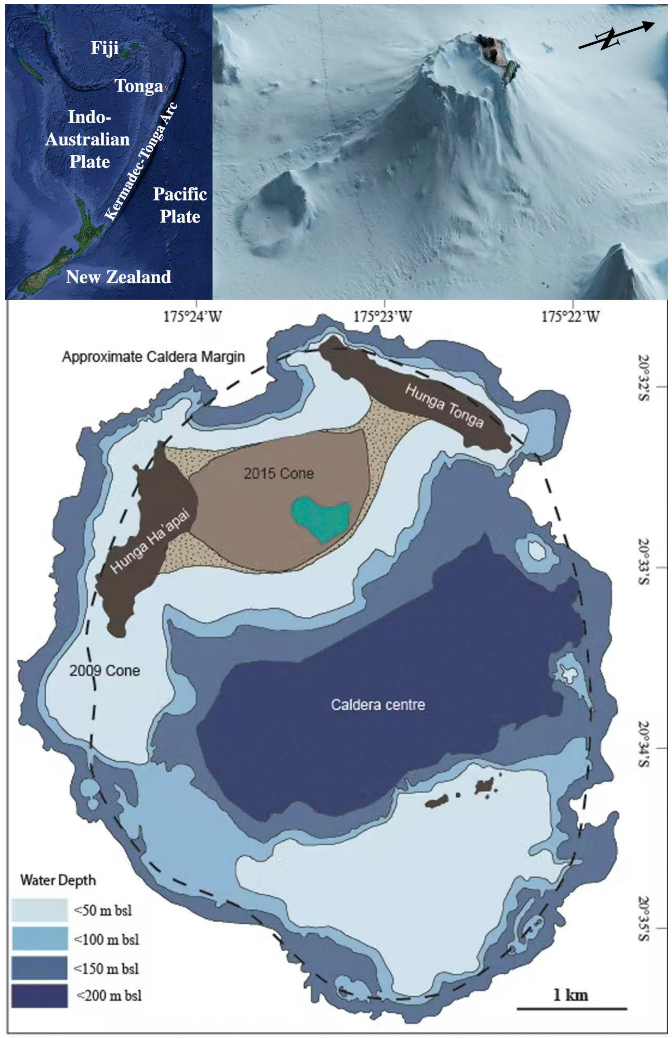



Figure 3. Upper left: Geodynamic setting of Tonga. Credit GoogleEarthTM (2022). Upper right: A rendering of the HT-HH volcano shows the part of the peak that is known as the two Tongan islands Hunga-Tonga and Hunga-Ha'apai. Credit Frederik Ruys; Below: Volcanic structure of Hunga Tonga-Hunga Ha'apai volcano based on elevation and a bathymetric map of the underwater portion of the volcano. Credit Shane Cronin / The Conversation, 2022. (After Toulkeridis EtAl., 2022).

This upper right portion of Figure 3 shows the geodynamic setting of the Tonga group of islands and the peak comprising of the two Tongan islands of Hunga-Tonga and Hunga-Ha'apai. The portion below the same image shows the above and below water volcanic structure of the entire HT-HH volcano - including both the above water elevation and its underwater bathymetry which appeared in a news report (Credit Shane Cronin /T Conversation, 2022), and also combined and reproduced in a paper published in the January 2022 issue of the journal Science of Tsunami Hazards (Toulkeridis EtAl. 2022).

## 3. THE HUNGA-TONGA-HAPA'I VOLCANO'S ERUPTION/EXPLOSION SEQUENCE

Figure 4 below are satellite NASA photos showing the eruption/explosion sequence before and following pre-existing smaller caldera's initial activity. All that remained locally after the paroxysmal expliosion were the two mentioned preexisting small islets of Hunga Tonga and Hunga Ha'apai, again separated by the sea.

Figure 4. Eruption/Explosion Sequence: Upper left: Hunga Tonga-Hunga Ha'apai prior to As eruption.(Credit GoogleEarthTM in2021). Upper right: Status of Eruption by January 7. 2022. (Credit: Planet Labs PBC/EYEPRESS/Shutterstock), Lower left: A Planet SkySat image shows Hunga Tonga-Hunga Ha'apai two hours before its eruption on January 15, 2022. (Credit:Planet Labs PBC/via REUTERS); Lower right: Remains of the island as seen on January 17, 2022. (Credit: Maxar Technologies Original Source: Copernicus/ESA/Sentinel Hub, PlanetLabs, Maxar (BBC))

### 3A. The Hunga-Tonga-Hunga-Ha'apai (HT-HH) Volcano's Prior Above-water Dimensions on the Northern Rim.

Monitoring and modeling the rapid evolution of the HT-HH volcanic island since its increasing activity in 2014-2015, begun in 2018 using high spatial resolution satellite observations (Garvin EtAl, 2018). But even earlier activity of the volcano was included in weekly reports of the Smithsonian Institution and of the U.S. Geological Survey (Global Volcanism Program 2009, 2014, 2015, 2021 a b and c., and 2022).

The HT-HH volcano is located about 65km (40 miles) north of the kingdom of Tonga's capital, Nuku'alofa, on the main island of Tongatapu. Before its latest eruptive activity which begun in November 2021, its maximum height from the bottom of the sea was about 1,800 meters, its width was about 20 km, and a portion of its height above sea level was 114 meters. Earlier volcanic activity in 2014 and 2015 had joined the Tonga volcano with the adjacent islands of Hunga Tonga and Hunga Ha'apai, both of which had been produced by older volcanic eruptions in the northern segment of the Tonga Kermadec volcanic arc (Fig. 5 ).

Following an earlier eruption of 20 December 2021, on 11 January 2022, the Tonga volcano was declared dormant. However, satellite photos taken by Planet Labs PBC from 17 November 2021 up to Friday, 14 January 2022 showed that a larger island had been created on the north side of the undersea volcano.


Figure 5. NASA satellite image of the uppermost, above water pre-existing part of the rim and secondary caldera of the HT-HH volcano of Hunga in December 2021.

The dimensions of the above water portion of the northern rim of the volcano that existed before the 15th January 2022 eruption/explosion were about 3.5 km in lenght and 1.7 km wide. On either side of this newly formed, above water section – and stil partly remaining – were the preexisting islets of Hunga Tonga and Hunga Ha'apai, which had been joined into a single landmass by an earlier eruption of the volcano in December 2014. Subsequently, and as shown in Figure 5, the above water middle portion of the volcano's upper land mass begun to grow in size due to the volcano's renewed activity of the above water smaller caldera, shown in the satellite photo above. By 14 January 2022, the volcano begun to erupt again with greater force, and a local partially destructive tsunami was generated. The source mechanism of this local preliminary tsunami is puzzling and needs to be further investigated. The question arises whether this initial and local tsunami was generated by uplift within a smaller caldera which may have been of the"Smith Caldera" type, similar to the one which followed the 2015 volcanic tsunami earthquake near Torishima in Japan (Fukao EtAl., 2018), or simply by a partial preliminary collapse of the rim of the HT-HH volcano. Whether such type of calderas exists along the

Tonga Kermadec volcanic arc is not known. However it is known that about 30 million years ago, massive ash and debris from nearby volcanoes had filled smaller calderas, which hardened into rock which resulted caldera-floor uplift of ~1.5 m when the volcanic tsunami earthquake of 2015 occurred on Torishima.

### 3B. Activity of the Hunga-Tonga-Hunga-Ha'apai (HT-HH) Volcano Prior to the Paroxysmal Eruption/Explosion of 15 January 2022

The HT-HH volcano was relatively inactive since January 2015, but reactivated on 20 December 2021, forming a large plume of ash visible from Tonga's capital city Nuku'alofa on the island of Tongatapu. The eruption continued until 2:00am on 21 December 2021 and included explosions, the sounds of which could be heard as far as 170 km away (Toulkeridis EtAl.. 2022; Fukao EtAl., 2022).

The volcanic activity reduced by 5 January 2022, but restarted strongly again on 13 January. On 14 January 2022, images of a strong eruption were captured by NOAA's GOES-17 satellite, and on the same day the National Emergency Operations Centre was activated. This included the outer island Emergency Operations Centers in Ha'apai and Vava'u. At 4:40am local time a nationwide Tsunami warning was issued by the Tonga Meteorological Servicesa for all the islands of the Kingdom of Tonga. At 11:12am abnormal sea level fluctuationa were observed at Nuku'alofa's waterfront. Tsunami waves up to 30 cm were initially recorded at the tidal gauge in Nuku'alofa. However waves of greater height arrived subsequnrly

Later in the afternoon of the same day, a Tonga Geological Services (TGS) team observed the eruption from a distance of 2 to 3 miles between 5:00pm and 6:30pm local time. (Fukao EtAl., 2022). The eruption continued until the next day, and probably resulted in the partial collapse of the HT-HH's caldera, leaving most of the volcano submerged and leading to the separation of the Hunga Tonga inlet from the Hunga Ha'apai inlet (as captured by satellite imagery the next day at 3:25pm on 15 January 2022 – in Fig. 6. A plume of ash, steam and gas rose to altitude 18 to 20 km above sea level. The plume expanded radially up to a radius of 240 km from the volcano, passing over the Tongatapu, 'Eua, Ha'apai and Vava'u island groups. Ashfall was observed in Tongatapu and other islands.

### 3C. Paroxysmal Eruption/Explosion of the Hunga-Tonga-Hunga-Ha'apai (HT-HH) Volcano on 15 January 2022

About 24 hours later after this local tsunami on 15 January 2022, a series of hydromagmatic explosions of the underwater portion of the volcano toward the south-east, obliterated the newly formed middle portion of the joined islets of Hunga Ha'apai islet and of Hunga Tonga. The big blast and caldera collapse of the undersea volcano occurred at about 5:15 pm local time on Saturday 15 January 2022 and lasted less than 60 minutes.

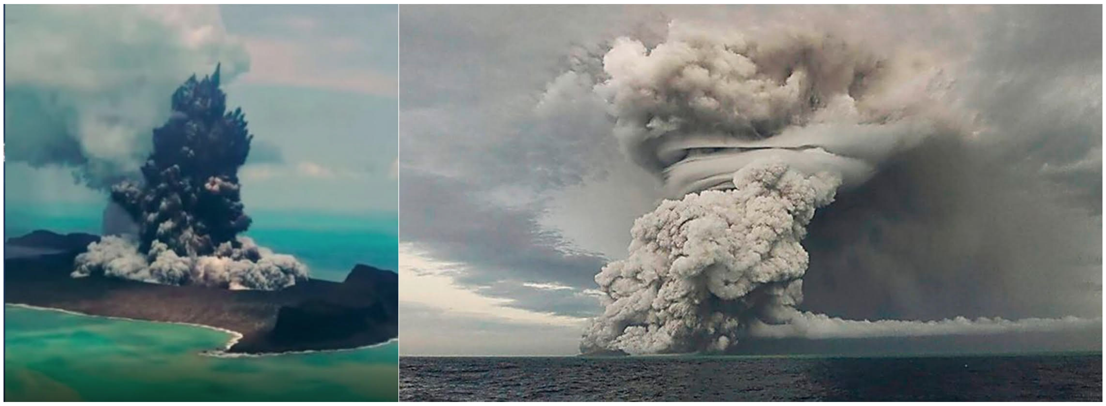


Figure 6 . Images of the eruption of January 15, 2022. Credit Left: Digicel Tonga (After Toulkeridis Et. Al 2022).

This eruption was captured by the GOES-17 and Himawari-8 (JMA) satellites (Fig.7 & 8). The main eruption column rose to a 35 km altitude**.** The 2022 Hunga Tonga event was probably the largest volcanic eruption in the 21st century and the largest since the 15 June 1991 eruption of Mount Pinatubo in the Philippines' Luzon Volcanic Arc - which had been the second-largest volcanic eruption of the 20th century after the 1912 eruption of Novarupta in Alaska. The Hunga-Toga eruption ejected about 10 $km^3$ (2.4 cu mi) of material in the atmosphere about the same as that of the devastating eruption of Pinatubo (Philippines) in 1991.

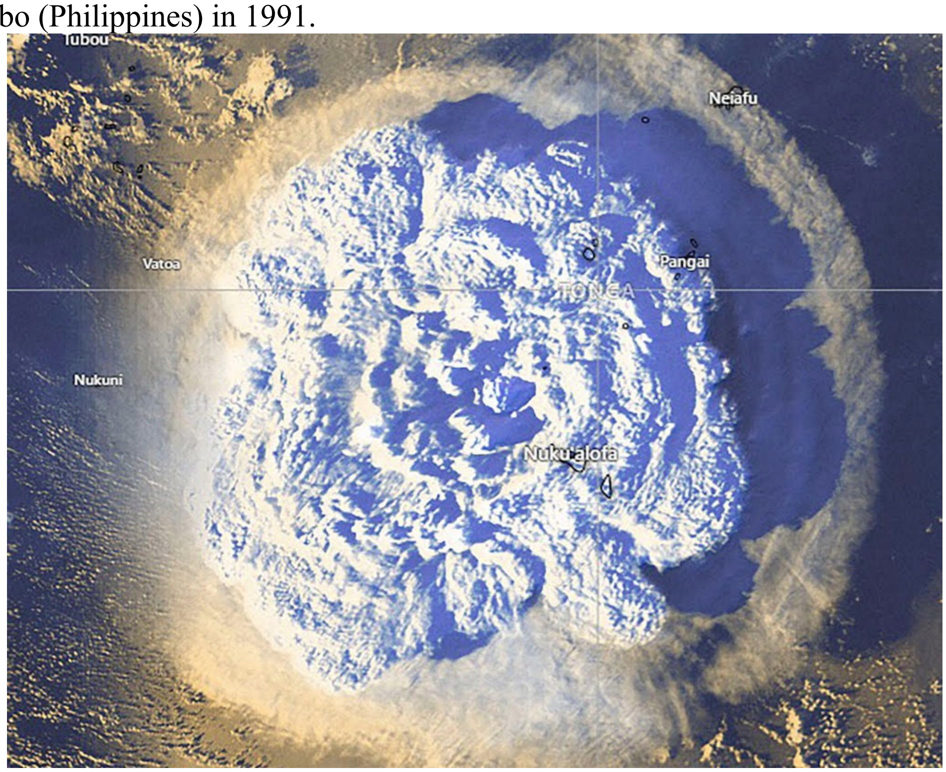



Figure 7. The enormous explosion as seen from the satellite. Credit US Geological Survey and Tonga Meteorological Services. Width of image is of about 600 km.

At 6.15pm of the same day and after the 5:19 and later in the same evening of 15 January 2022, the Tonga volcano continued to rain ash on the neighboring islands, and darkness covered the sky. The "volcanic mushroom plume" that was generated from the eruption, eventually reached the stratosphere and extended to cover Tonga's roughly 170 islands, where more than 100,000 people lived. Attempts from Australia and New Zealand to assess from the air the damage to critical infrastructure such as roads, ports and power lines, were delayed because of the ash cloud which had covered the islands. According to a report of New Zealand's meteorological service, by 3pm of 17 January the huge cloud of the volcanic ash spread to 160 miles (260km) in diameter and rose up to 19 miles (30km) high, and was seen drifting towards northern Australia at an altitude between 12-20km.

Also, the atmospheric pressure shockwaves generated from the violent eruption begun to be recorded as far away as Australia, New Zealand, United States, the United Kingdom and elsewhere. According to a bulletin of the Australian Bureau of Meteorology, the shockwave travelling faster than 1000 km/h – almost as fast as the speed of sound – resulted in a noticeable jump in the atmospheric pressure, reported earlier. Sonic booms from the eruption were heard across the Pacific, including Fiji, Vanuatu, and as far as Alaska.

Following the explosion of the HT-HH volcano, residents in Fiji and Vanuatu (more than 1600 Km away) reported that ground and buildings were shaking and that sonic booms were heard. Also, the United States Geological Survey (USGS) reported that an earthquake of magnitude 5.8 occured at 5:15 pm. Immediately that night tsunami warnings were isssued for the islands of Fiji and Samoa and massive evacuation of coastal areas begun (Fukao EtAl., 2018).

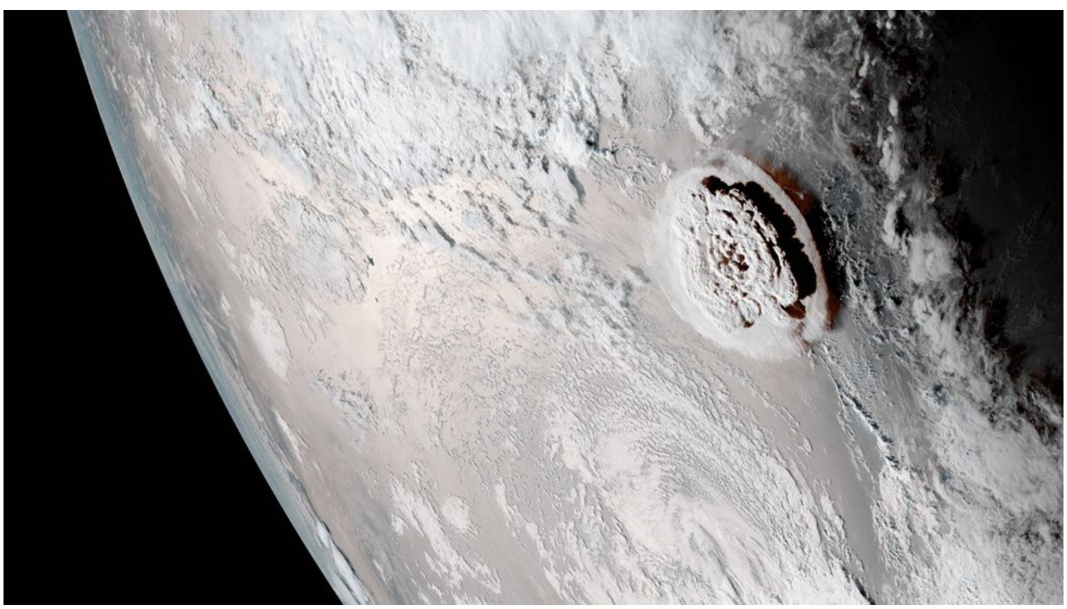


Figure 8. Global view of the eruption/explosion of the Hunga-Tonga volcano on the 15 January 2022, of the ash cloud formation and of the initial atmospheric pressure wave https://www.bbc.com/news/world-australia-60027360

Figure 8 is a global view of the eruption/explosion of the Hunga-Tonga volcano on the 15 January 2022, of the ash cloud formation, and of the initial expanding atmospheric pressure wave. The ultra-Plinian explosion and concurent crustal displacements of the volcano's caldera and flanc collapses, generated a very damaging near and far-field tsunami, but also an atmospheric paroxysmal explosion similar to that of 1883 Krakatau event, and a Pacific–wide tsunami, as well as far-reaching atmospheric Lamb wave perturbations and subsequent concentric wave-shape traveling ionosphere disturbances (TIDs oscillations) – the latter observed simultaneously in both the northern and southern hemispheres.

### 3D. Ash Cloud Formation and Atmospheric Pressure Waves from the Eruption/Explosion of the Hunga-Tonga-Hunga-Ha'apai (HT-HH) Volcano

The eruption/explosion of the HT-HH volcano had many similarities to the 1883 eruption of Krakatau (Krakatoa), which caused a devastating tsunami in the Indian Ocean, but also had a global impact. Krakatoa's violent eruption was reported to have been heard 4,800km away, and atmospheric pressure waves generated tsunami-like waves at great distances, although there was not sufficient technological monitoring back then. However, recent technological developments and satellite monitoring allowed good documentation in real time of the Tonga volcanic eruption/explosion, of the ash cloud formation, and as stated of the atmospheric pressure waves.

### 3E. Power of the Hunga-Tonga-Hunga-Ha'apai (HT-HH) Volcano's Blast Explosion - Generation of Acoustic Gravity Waves

As reported by early research of the 1883 explosion of Krakatau (Press & Harkrider, 1966) acoustic gravity waves can excite water gravity waves (tsunami) having the same phase velocity. The distant sea level disturbances that were observed following the explosion of Krakatoa were correlated with recently discovered atmospheric acoustic and gravity modes having the same phase velocity as long waves on the ocean. These atmospheric waves jumping over land barriers re-excited the sea waves with amplitudes exceeding the hydrostatic values. An explosion of 100 to 150 megatons would be required to duplicate the Krakatoa atmospheric pressure pulse.

Observation of acoustic gravity waves from the Tonga explosion and images collected by the Atmospheric Infrared Sounder (AIRS), mounted on NASA's Aqua satellite, in the hours after the eruption of the Hunga Tonga–Hunga Ha'apai volcano showed that the HT-HH blast explosion generated atmospheric gravity waves, which appeared as concentric circles, involving vertical oscillations of air molecules in an air column extending from the surface to the ionosphere (elevation of about 50 km),

To what extend the acoustic gravity waves from the blast explosion of HT-HH contributed to the tsunami wave heights observed locally or at great distances is rather difficult to quantify. According to NASA estimates, the power of the blast of the HT-HH volcano was equivalent between 4 to 18 megatons of TNT only. This amount of energy was released by the fourth paroxysmal explosion that blew away the northern two-thirds of Rakata island and almost instantaneously was followed by the collapse of the unsupported volcanic chambers which formed the huge underwater caldera (Pararas-Carayannis, 1989, 2003).

For comparison, scientists estimated that the power of the 1980 explosion of Mount St. Helens in the State of Washington in the USA was 24 megatons, and the power of the 1883 Krakatau (Krakatoa) volcano's explosion in the Sunda Strait of Indonesia (Sunda Strait, Indonesia) was equivalent to 200 megatons of TNT, about 13,000 times the nuclear yield of the bomb that devastated Hiroshima. Apparently there is a discrepancy in the estimate of Krakatau volcano's force of eruption which was assigned a volcanic explosivity index VEI=6, the same as that of the HT-HH event – which was also equivalent with the catastrophic 1991 eruption of Mount Pinatubo in the Philippines.

The coupling of the acoustic gravity waves from the Krakatau volcanic explosion with the sea surface apparently generated earlier tsunami waves having the same phase velocity which were recorded in Honolulu, San Francisco and Cardiff in Wales - much too early to have been propagated entirely through the oceans (Press & Harkrider, 1966; Latter, 1981, Pararas-Carayannis, 2003; Gabrielson, 2010; Chunchuzov EtAl, 2021).

### 3F. Lamb Wave Generation of Tsunami

The Hunga Tonga undersea volcanic eruption was one of the most powerful ever recorded. It generated audible sound detected more than 10,000 kilometers from the source, as well as infrasound and seismic recordings (Kubota EtAl, 2022; Matoza EtAl., 2022). An atmospheric lamb wave - characteristic of energetic atmospheric events - circled the earth four times and was very similar to the 1883 Krakatau eruption (Pararas-Carayannis, 2003).

Briefly, a Lamb wave in the atmosphere is a type of acoustic wave that is trapped at the earth's surface, propagating only in the horizontal direction in an isothermal windless atmosphere (Lamb, 1932/1947). However, in the real non-isothermal earth's atmosphere, earthquakes, volcanic eruptions, rapidly moving storms, falling meteorites, atomic bomb explosions and various other types of pressure pulses, generate enhanced Lamb-type of waves (Garrett 1969). The 15 January 2022 eruption/explosion of the Hunga volcano in Tonga, generated a wide range of such waves, which were detected globally by both ground and space instrumentation. Most important of these oscillations was a Lamb wave with frequency ($\lesssim$0.01 hertz), which propagated for four (plus three antipodal) passages around Earth over a period of six days (Kubota EtAl, 2022; Lin EtAl, 2022; Matoza EtAl., 2022). The atmospheric wave contibuted to the generation of global tsunami waves arriving two hours earlier than expected Such was also the case with the 1883 volcanic eruption of Krakatau eruption/explosion and the tsunami-like waves observed in the Atlantic Ocean (Pararas-Carayannis, 2003). According to newspaper accounts and reports, the far field impact of the violent eruption of HT-HH and tsunami-like effects differed in many areas of Central and South America. For example the impact of tunami waves in Panama was not significant (El Siglo de Panamá , 2022), while in Peru the observed and recorded waves were substantial (El Universo, 2022).

## 4. MECHANISMS OF TSUNAMI GENERATION FROM THE HUNGA-TONGA-HAPA'I (HT-HH) VOLCANO'S ERUPTION/EXPLOSION

It has been well established that violent submarine volcanic eruptions can displace large volumes of water in a number of different ways, and have the potential to generate destructive tsunamis by different additional mechanisms. In general, such tsunami generation mechanisms may include: (1) displacement of large volumes of water and sudden sea surface oscillations; (2) flank failures and sub-marine landslides around the volcanic edifice; (3) flank caldera collapses into the empty magma chamber; (4) meteotsunamis triggered by atmospheric gravity waves following sub aerial volcanic blasts; and (5) meteotsunamis from rapidly moving storm fronts near a shore (Pararas-Carayannis, 2019).

Before discussing the specific mechanisms of near and far field tsunami generation from the 15 January 2022 eruption/explosion of the HT-HH volcano, there is a need to review the possible sequence of events that occur before, during and following similar such events. Generally, preceding a major eruption, there may be direct or channelized volcanic blast episodes, collapses of lava domes, as well as aerial and partial submarine volcanic edifice mass edifice flank failures. All such events may generate destructive local tsunamis. A subsequent violent eruption/explosion of a submarine volcano, associated with a major caldera collapse, can generate near and far field destructive tsunami waves. Furthermore such a violent eruption will also generate collateral, faster traveling atmospheric perturbations, other tsunami-like sea level oscillations, and Lamb waves. All these were generated by the blast of the HT-HH volcano.

In addition to the generation of tsunamis from flank failures of volcanic domes during an eruption, following massive explosive volcanic events associated with above or below water structural collapses - coupling with atmospheric waves in resonance - can and have caused very long period water waves at distant locations away from the point sources of origin (Pararas-Carayannis, 1967; 2003; Toulkeridis EtAl. 2022; Terry EtAl. 2022; Gusman & Roger, 2022).

The 14 January 2022 and the subsequent paroxysmal 15 January eruption of the HT-HH volcano indicate that a combination of the above listed mechanisms were responsible for the generation of both near and far-field destructive tsunamis, as well as for the faster-traveling atmospheric waves which, coupled with the sea surface, generated the earlier observed and recorded tsunami-like waves at distant shores.

Collapses of lava domes often precede major eruptions, which may vary in intensity from Strombolian to Plinian. Locally catastrophic, short-period tsunami-like waves can be generated directly by lateral, direct or channelized volcanic blast episodes, or in combination with collateral air pressure perturbations, nuee ardentes, pyroclastic flows, lahars, or cascading debris avalanches. Submarine volcanic caldera collapses can also generate locally destructive tsunami waves. Significant tsunamis may be also generated by fast moving storm fronts and nuclear explosions (Pararas-Carayannis **&** Adams, 1966).

## 5. TSUNAMI GENERATION BY THE ERUPTION/ EXPLOSION OF THE HUNGA TONGA HUNGA HA'PAI (HT-HH) VOLCANO

Near and far field tsunami and other volcano-induced sea level oscilations and effects generated by the 2022 HT-HH eruption were studied, simulated or reported by many researchers, and institutional sources globally (Toulkeridis Et.Al. 2022; Gusman & Roger, 2022; Kubota EtAl, 2022; NOAA, 2022; PTWC, 2022; Science.org 2022; Sekizawa and Kohyama, 2022; Terry EtAl, 2022; TelesurTV 2022).

**5A. Near-field Tsunami Generation of the HT-HH Volcano on 14-15 January 2022.**

Eruption activity of the HT-HH volcano intensified in January 2022. On Friday the 14th of the month, crustal displacements within the volcanic cone generated tsunami waves that were locally destructive, as shown arriving at the main island of Tongatapu (Fig. 9). Figure 9 below is another photo taken by Tonga's geologist Taaniela Kula, which shows a local tsunami which occurred before the big explosion of the HT-HH volcano of Saturday 15 January, causing damage and destruction to a small fishing fleet at the harbor of Nuku'alofa.


Figure 9. Tsunami arrival at Tonga's main island of Tongatapu.

At 5:10 pm local time on that same day, a massive eruption/explosion begun to generate an enormous amount of energy and an initial volcanic explosion occurred and an ash plume of up to 12.5 km was formed. This ash plume grew, eventually rising to 30 km in height and spreading over an area of 260 km. At the same time volcanic ash begun raining over the islands in the region. Images from weather satellites recorded the great eruption which begun in the afternoon of 15 January 2022. The eruption and submarine crustal displacement severed a 514-mile fibre-optic cable which connected Tonga to Fiji and to international networks and damaged telephone and Internet lines.

**5B. Mechanism of the Near-field Tsunami Generation and Destruction from the Violent Eruption/Explosion of the HT-HH Volcano on 15 January 2022.**

According to the Australian Bureau of Meteorology, at 5.30 pm on 15 January 2022, about twenty minutes after the violent eruption of the HT-HH volcano, an initial tsunami wave of 1.2 meters in height struck the main island of Tongatapu and the city of Nuku'alofa, Tonga's capital. This wave and subsequent waves caused extensive destruction to the harbor seawall, to buildings and to local infrastructure (Figures 10 & 11). On Mango island, where about 50 people lived, all homes were destroyed. On Fonoifua Island only two houses remained and a woman lost her life. On Nomuka Island two people were lost. At Fua'amotu international airport, the runway was inundated and was partly covered by volcanic ash and sediments. Other satellite images show that flooding came in several blocks inland. Satellite imagery analyzed by the UN showed similar scenes in Kolomotu'a, Tongatapu, and Fafaa village, Kolofo'ou. Some buildings remained standing, others collapsed, and the entire landscape was coated with volcanic ash.


Figure 10. Initial tsunami damage and destruction of the small fishing fleet at the wharf of the Nuku'alofa boat harbor on 14 January 2022 (Photo: Mary Lyn Fonua / Matangi Tonga

Figure 11. Another photo of the destruction by the local tsunami of 15 January 2022 at Marangi (Photo: Mary Lyn Fonua / Matangi Tonga).

### 5C. Issuance of Tsunami Warnings

Although only an estimated 5% of tsunamis have historically resulted from volcanic eruptions, based on the intensity of the HT-HH volcano's eruption, beginning at 8:15 pm the same day, tsunami warnings were issued across the Pacific, including New Zealand, Australia and the west coast of the USA. In Japan, about 230,000 people across eight prefectures were ordered to evacuate from coastal areas. This event caused great difficulty in the issuance of timely and accurate tsunami warnings for the following three reasons. First, some agencies initially concluded that the earthquake itself, with magnitude 5.8, was not large enough to generate a tsunami with significant amplitude around the Pacific Ocean. Second, when tsunamis did arrive (Figure 12), their early arrival made it very difficult to reliably predict tsunami arrival times for use in warnings. Third, once it became clear that significant tsunami amplitudes had been generated, it was very difficult to reliably predict their heights for use in warnings because there was not sufficient information at that time on the coupling effect of atmospheric pressure waves. Figure --- below is tsunami travel chart based on the usual gravity wave propagation and not one the faster traveling waves generated by the atmospheric pressure disturbance caused by the volcanic blast.

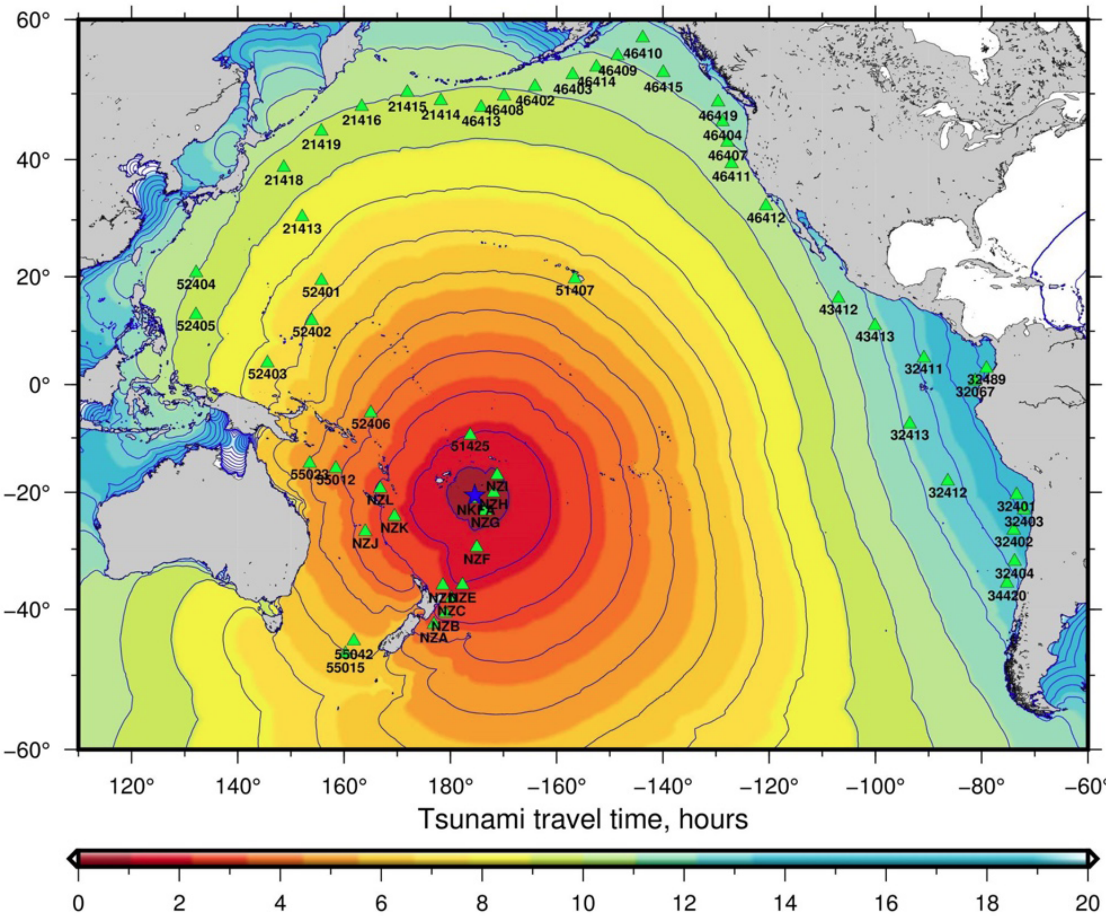



Figure 12. Tsunami travel time based on NOAA (NOAA, 2022a)

## 5D. Far-Field Tsunami Effects from the Violent Eruption/Explosion of the HT-HH Volcano.

The Hunga Tonga–Hunga Ha'apai volcanic eruption itself impacted widely and violently (BBC, 2022). Besides the near-field tsunami generation, large waves and strong currents resulting from the eruption/explosion of the Tonga volcano were recorded in many coastal areas on both sides of the Pacific Ocean. By the 16th of January, large waves and strong currents were recorded along Japan's North Pacific coast. Destructive waves of nearly 1.2 meters in height, arrived there in about 8 hours, about 2.5 hours earlier than the expected travel time of about 10.5 hours. In Sydney, Australia waves arrived in 2.75 hours - about 3 hours earlier than expected (Power, 2022).

There were also reports of damage from several islands of the South Pacific. A report from New Zealand stated that an undersea cable linking Tonga to Fiji was damaged. In the Lambayeque region of Peru unusually high waves were recorded, and 22 ports were closed. Along the west coast of the USA there was a report of flooding in Santa Cruz in California, and of damage to boats in the harbor.

Figure 13 below of a study in Japan (Watada. 2022), illustrates that coupling of the acoustic gravity waves with ocean gravity waves having similar phase velocities, and acting in resonance, were the cause of enhancing the height of the observed and recorded far-field tsunami waves

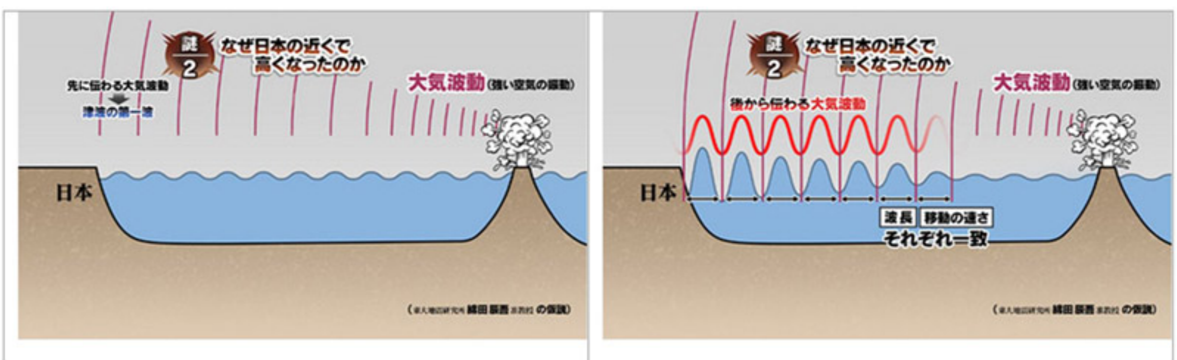
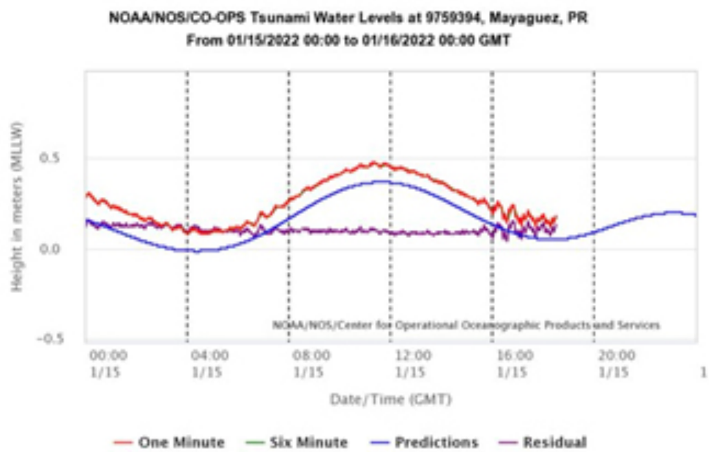



Figure 13. Left: Generation of the initial tsunami by the acoustic gravity wave close to the recording site. Right: Generation of later arriving tsunami by the coupling of the acoustic gravity waves with ocean gravity waves having similar phase velocities, causing resonance. (Source: Watada (2022).

Provided in the next sections of the present report are brief reviews of the above cited events of the eruptions/explosions of the Krakatau and Santorin volcanoes, and of the tsunami generations mechanism of major volcanic eruptions in the Eastern Caribbean regions, in the Pacific and the Indian oceans, and of a few other significant volcanic events elsewhere around the world.

The recordings of this water level oscillation and of the barometric pressure wave are shown in Figure 14 (provided by Dr. Greg Dudek of NOAA), which indicate that an acoustic wave arrived in Mayaguez just before the sea level oscillation - thus suggesting that this acoustic wave acted as a local source.



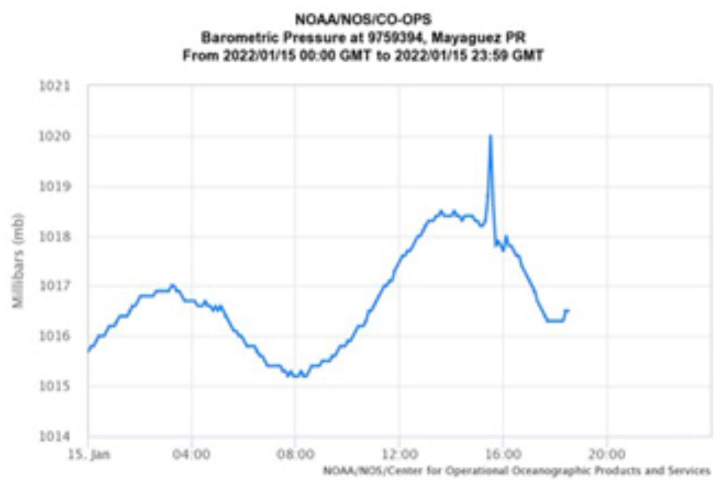




Figure 14. Tide gauge recording (top) and of a barograph (bottom) of the Tonga explosion at Mayaguez, Puerto Rico. The purple line in the top panel shows the record after removal of the tides. (Source: Dr Greg Dusek, NOAA).

## 6. COMPARISON OF THE 2022 OF THE HUNGA TONGA HUNGA HA'PAI (HT-HH) VOLCANIC ERUPTION/EXPLOSION AND ITS TSUNAMI GENERATION MECHANISMS WITH PAST AND RECENT MAJOR VOLCANIC EVENTS

As stated previously, the eruption of the HT-HH volcano on the 14 January 2022 resulted in the collapse of the caldera, leaving most of the volcano submerged. This earlier eruption and collapse was recorded as only minor disturbance on the tide gauge record at Nuku'alofa, in Tonga as shown on the right side of Figure 14, thus indicating that it was not the source of an early Pacific-wide tsunami. However, the major eruption/explosion of the volcano on the next day 15 January 2022 generated a major tsunami in the Pacific by the interaction and coupling of acoustic gravity waves with the sea surface. Additionally to such enhanced tsunami waves in the Pacific, small sea level oscillations were also recorded in Mayaguez, Puerto Rico in the Caribbean Sea. Such small sea level oscillation and a barometric pressure wave were observed following the Tonga volcanic explosion. The 15 January 2022 eruption/explosion/collapse of the submarine portion of the HT-HH volcano on the Tonga Kermadec volcanic arc in the southwest Pacific was a unique event but not unprecedented. Although tsunami generation from volcanic sources is not frequent, the historic record indicates that many such tsunamis were generated in the past, by volcanic events having similar as well as different source mechanism characteristics.

What makes the 15 January 2022 volcanic event more significant is the present improvement in the technical ability to better understand and measure collateral effects that such violent volcanic events have on a global scale, particularly on the atmosphere and the ionosphere. Thus, another pending paper will be provided in the near future by the present author, with a brief review and comparison of the recent Tonga eruption/explosion and of its tsunami generation mechanisms and collateral impacts, with other volcanically-generated tsunamis elsewhere around the world's oceans and seas. Specifically, will be reviewed are some of the destructive volcanically-generated tsunamis in the Pacific and in the Caribbean region, as well as tsunami generation mechanisms caused by different arc stresses, and tensional back-arc spreading, due to down-dip tectonic tensions (Seno & Yamanaka, 1998).

Other similar to the 2022 HT-HH volcanic eruption/explosion mechanism – and of a combination of related mechanisms – will be discussed in greater detail in the subsequent report. This report will include the 1883 eruption of the Krakatau volcano in Indonesia, the 1690 BC eruption/collapse of the Santorin volcano in the Aegean Sea, and tsunami-generating eruptions of volcanoes in the Caribbean Sea, the Indian Ocean in the Pacific Ocean and elsewhere around the world.

## CONCLUSIONS

The final explosive eruption/collapse of the volcano Hunga-Tonga-Hunga-Ha'apai (HT-HH) on the Tonga Kermadec volcanic arc on 15 January 2022 was a truly global event, and almost as great as that of the 1883 explosive eruption of the Krakatau volcano in Indonesia both resembling the 1490 BC explosion, caldera and flanc collapses of the Santorin volcano in the Aegean Sea, the latter considered even much greater. These three events generated destructive volcanogenic tsunamis. The eruption of HT-HH was a combination of a major submarine Surtsean/ phreatomagmatic events and of a subsequent ultra-Plinian atmospheric explosion which generated a very damaging local tsunami. In addition to local destructive tsunami generation in the immediate area, the violent eruption created impulsive Lamb surface air pressure waves.

Recent development of instrumentation and of an expanded array of terrestrial and space instruments - including atmospheric pressure sensors, seismometers and a fleet of satellites monitoring the Earth across the entire spectrum of light – provided good global monitoring of the effects of this particular and unusual HT-HH volcanic event. The interaction of acoustic gravity waves caused by the explosion, interacting with the sea surface, generated tsunami waves, which arrived much earlier and were much larger than expected and were observed globally. Also, the eruption resulted in unusually traveling ionospheric disturbances (CTIDs) – detected and mapped on both of the earth's hemispheres.

## REFERENCES


BBC (2022). Tonga eruption: How its impact spread so widely and violently. https://www.bbc.com/news/world-australia-60027360

Chunchuzov, I. P., S. N. Kulichkov, O. E. Popov, and V. G. Perepelkin. "Infrasound Generation by Meteorological Fronts and Its Propagation in the Atmosphere", Journal of the Atmospheric Sciences 78, 5 (2021): 1673-1686, https://doi.org/10.1175/JAS-D-20-0253.1… #JAtmosSci

Colombier, M., Scheu, B., Wadsworth, F. B., Cronin, S., Vasseur, J., Dobson, K. J., Hess, K-U., Tost M.,Yilmaz, TI, Cimarelli, C., Brenna, M., Ruthensteiner, B.and Dingwell, DB. 2018. Vesiculation and Quenching During Surtseyan Eruptions at Hunga Tonga-Hunga Ha'apai Volcano, Tonga. Journal of Geophysical Research: Solid Earth 123(5):3762-3779 May 201**DOI:**10.1029/2017JB015357

Dingwell, D. B. (2018). Vesiculation and Quenching During Surtseyan Eruptions at Hunga Tonga‐Hunga Ha'apai Volcano, Tonga. *Journal of Geophysical Research: Solid Earth*, *123*(5), 3762-3779.

El Siglo de Panamá (2022). Erupción de volcán en Tonga no ha generado amenaza en costas panameñas. http://elsiglo.com.pa/panama/erupcion-volcan-tonga-generadoamenaza-costas-panamenas/2419182

El Universo (2022). Perú registró oleajes anómalos e inundaciones leves tras erupción volcánica en Tonga. https://www.eluniverso.com/noticias/internacional/peruregistrooleajes-anomalos-e-inundaciones-leves-tras-erupcion-volcanica-en-tonga-nota

Fukao Y., Sandanbata O., Sugioka H., Shiobara H., Watada S., and Satake K., 2018. Mechanism of the 2015 volcanic tsunami earthquake near Torishima, Japan. Science Advances. April 2018, Vol. 4, Issue 4. DOI: 10.1126/sciadv.aao0219

Gabrielson, T.B., 2010. KRAKATOA AND THE ROYAL SOCIETY: THE KRAKATOA EXPLOSION OF 1883. Acoustics Today pp.14 -18 April 2010

Garrett, C.J.R., 1969. Atmospheric edge waves. Quartely Journal of Royal Meteorological Andersen, K. (2018). Monitoring and modeling the rapid evolution of earth's newest volcanic island: Hunga Tonga Hunga Ha'apai (Tonga) using high spatial resolution satellite observations. *Geophysical research letters*, *45*(8), 3445-3452.

Global Volcanism Program (2009). Report on Hunga Tonga-Hunga Ha´apai (Tonga). In: Sennert, S.K. (ed.), Weekly Volcanic Activity Report, 18 March-24 March 2009. Smithsonian Institution and US Geological Survey

Global Volcanism Program (2014). Report on Hunga Tonga-Hunga Ha´apai (Tonga). In: Sennert, S.K. (ed.), Weekly Volcanic Activity Report, 24 December-30 December 2014. Smithsonian Institution and US Geological Survey

Global Volcanism Program (2015). Report on Hunga Tonga-Hunga Ha´apai (Tonga). In: Sennert, S.K. (ed.), Weekly Volcanic Activity Report, 21 January-27 January 2015. Smithsonian Institution and US Geological Survey

Global Volcanism Program (2021a). Report on Hunga Tonga-Hunga Ha´apai (Tonga). In: Sennert, S.K. (ed.), Weekly Volcanic Activity Report, 15 December-21 December 2021. Smithsonian Institution and US Geological Survey

Global Volcanism Program (2021b). Report on Hunga Tonga-Hunga Ha´apai (Tonga). In: Sennert, S.K. (ed.), Weekly Volcanic Activity Report, 22 December-28 December 2021. Smithsonian Institution and US Geological Survey

Global Volcanism Program (2021c). Report on Hunga Tonga-Hunga Ha´apai (Tonga). In: Sennert, S.K. (ed.), Weekly Volcanic Activity Report, 29 December-4 January 2022. Smithsonian Institution and US Geological Survey

Global Volcanism Program (2022). Report on Hunga Tonga-Hunga Ha´apai (Tonga). In: Sennert, S.K. (ed.), Weekly Volcanic Activity Report, 12 January-18 January 2022. Smithsonian Institution and US Geological Survey

Gusman, A.R. & Roger, J. (2022). Hunga Tonga - Hunga Ha'apai volcano-induced sea level oscillations and tsunami simulations. GNS Science webpage, Accessed at https://doi.org/10.21420/DYKJ-RK41

Hall & Spakman, 2002. Hall, R. & Spakman, W. Subducted slabs beneath the eastern Indonesia-Tonga region: Insights from tomography. Earth Planet. Sci. Lett. 201, 321-336 DOI:10.1016/S0012-821X(02)00705-7

Heinrich, F., Roche, R., Mangeney, A., and Boudon, G. 1999b. Modeliser un raz de maree cree par un volcan, La Recherche, 318, 67

Hibiya, T., Kajiura, K. Origin of the*Abiki* phenomenon (a kind of seiche) in Nagasaki Bay. *Journal of the Oceanographical Society of Japan* **38,** 172–182 (1982). https://doi.org/10.1007/BF02110288

Gushchin R.A., Kopeikin V.M., Belikov I.B., Gubanova D.P., Karpov A.V. & TikhonovA.V. , 2022. Acoustic-Gravity Lamb Waves from the Eruption of the Hunga-Tonga-Hunga-Hapai Volcano, Its Energy Release and Impact on Aerosol Concentrations and Tsunami. *Pure and Applied Geophysics* volume 179, pages 1533–1548 (2022)

Gusman, A.R. & Roger, J. (2022). Hunga Tonga - Hunga Ha'apai volcano-induced sea level oscillations and tsunami simulations. GNS Science webpage, Accessed at https://doi.org/10.21420/DYKJ-RK41

Kubota T, Saito T, and Nishida K., 2022. Global fast-traveling tsunamis driven by atmospheric Lamb waves on the 2022 Tonga eruption. Science 12 May, Vol. 377. Issue 6601, pp. 91-94 , DOI: 10.1126/science.abo4364

La Crítica Panamá (2022). Sinaproc no hay amenaza de tsunami por erupción de volcán Tonga. https://www.critica.com.pa/nacional/sinaproc-no-hay-amenaza-de-tsunamipor-erupcion-de-volcan-tonga-620825

Lamb, H. 1932/1947. , *Hydrodynamics*, 6th ed. (Cambridge Univ. Press, Cambridge, 1932; Gostekhizdat, Moscow, 1947).

Lin, J. T., Rajesh, P. K., Lin, C. C., Chou, M. Y., Liu, J. Y., Yue, J., ... & Kung, M. M. (2022). Rapid Conjugate Appearance of the Giant Ionospheric Lamb Wave in the Northern Hemisphere After Hunga-Tonga Volcano Eruptions. Preprint February 2022 DOI: 10.1002/essoar.10510440.1

Lipman, P. W., Normark, W. R., Moore, J. G., Wilson, J. B., & Gutmacher, C. E. (1988). The giant submarine alika debris slide, Mauna Loa, Hawaii. *Journal of Geophysical Research: Solid Earth*, *93*(B5), 4279-4299.

Mangeney A., Heinrich F., Roche, R., Boudon, G., and J. L. Chemin. 2000. Modeling of debris avalanche and generated water waves. Application to real and potential events in Montserrat. Phys, Chem. Earth 25(9-11), 741-745.
Matoza EtAl., 2022. Atmospheric waves and global seismoacoustic observations of the January 2022 Hunga eruption, Tonga. *SCIENCE* 12 May 2022. Vol 377, Issue 660**1** pp. 95-100 DOI: 10.1126/science.abo706
NOAA (2022a). Hunga Tonga 2022 tsunami travel time. https://ngdc.noaa.gov/hazard/img/tsunami-timeline/
Nomikou, P., Druitt, T. H., Hübscher, C., Mather, T. A., Paulatto, M., Kalnins, L. M., ... & Parks, M. M. (2016). Post-eruptive flooding of Santorini caldera and implications for tsunami generation. *Nature communications*, *7*(1), 1-10.
Otsuka S., 2022, Research Letter 15 April 2022. Visualizing Lamb Waves From a Volcanic Eruption Using Meteorological Satellite Himawari-8. Open Access http://creativecommons.org/licenses/by/4.0/
Pararas-Carayannis G**.** & Vitousek M., 1966, On the Utilization of Atmospheric Data for the Evaluation of Potential Tsunamis. Res. Group Rec. No. 8, 4 pp. Honolulu: Hawaii Inst. Geophys.-Tsu., October 1966. **http://www.drgeorgepc.com/TsunamiEvaluationAtmospheric.pdf**
Pararas-Carayannis G. **&** Adams, W.M., 1966. Relative Susceptibility of the Hawaiian Islands to Waves Generated by Storms and Nuclear Explosions. (Report to the U.S. Atomic Energy Commission.). Oct.1966.
Pararas-Carayannis, G, 1967. A Study of the Source Mechanism of the Alaska Earthquake and Tsunami of March 27, 1964, Water Waves. In Contributions of the H.I.G. University of Hawaii for the Year 1967. Honolulu: s.n., 1967, pp. 237.cont. No. IR4
Pararas-Carayannis, G., 1975. Verification Study of a Bathystrophic Storm Surge Model. U.S. Army, Corps of Engineers Coastal Engineering Research Center, Washington, D.C., Technical Memorandum No. 50, May 1975. http://www.drgeorgepc.com/HurricaneBathystrophicSurgeModel.pdf
Pararas-Carayannis, G, (1983). Tsunami Effects from the Krakatau Eruption. Unpublishrd review of the Smithsonian Institution's book Krakatau 1883: The volcanic eruption and its effects: by Simkin, T., and Fiske, R.S., published in 1983 by the Smithsonian Institution Press: Washington, D.C., 464 p.
Pararas-Carayannis, G.: 1988, The tsunami generated from the eruption of the volcano of Santorin in the Bronze Age, *Sci. Tsunami Hazard* **6** (1), 23–30.
Pararas-Carayannis, 1989, 2003). Rakata
Pararas-Carayannis, G. (1992). The Tsunami Generated from the Eruption of the Volcano of Santorin in the Bronze Age.Natural Hazards 5:115-123, Kluwer Academic Publishers. Printed in the Netherlands
Pararas-Carayannis, G. (1999). The Tsunami Generated by the August 26, 1883 Explosion of the Krakatau Volcano, The Tsunami Page of Dr. George PC. http://drgeorgepc.com/Tsunami1883Krakatoa.html
Pararas-Carayannis, G. 2002. Evaluation of the threat of mega tsunami generation from postulated massive slope failures of island stratovolcanoes on La Palma, Canary Islands, and on the Island of Hawaii, Science of Tsunami Hazards, Vol. 20, 5, 251;277
Pararas-Carayannis, G., 2002a. Volcanically Generated Tsunamis, 2nd Symposium of the Tsunami Society, Honolulu, Hawaii, May 25-29, 2002.

Pararas-Carayannis, G. (2002b). Evaluation of the threat of mega tsunami generation from postulated massive slope failures of island stratovolcanoes on La Palma, Canary Islands, and on the island of Hawaii. *Science of Tsunami Hazards*, *20*(5), 251-277.

Pararas-Carayannis, G., (2003). Near and far-field effects of tsunamis generated by the paroxysmal eruptions, explosions, and massive slope failures of the Krakatau volcano in Indonesia on August 26-27,1883. Science of Tsunami Hazards, January 2003, 21 (4), 191-201. See also http://www.drgeorgepc.com/Tsunami1883Krakatau.html

Pararas-Carayannis, G. (2004). Volcanic tsunami generating source mechanisms in the Eastern Caribbean Region. *Science of Tsunami Hazards*, Vol *22*(2), 74-114.

Pararas-Carayannis G. 2004a, RISK ASSESSMENT OF TSUNAMI GENERATION FROM ACTIVE VOLCANIC SOURCES IN THE EASTERN CARIBBEAN REGION. NSF Caribbean Tsunami Workshop, Puerto Rico March 30-31.

Pararas-Carayannis, G. (2006). Risk Assessment of Tsunami Generation from Active Volcanic Sources in the Eastern Caribbean Region. Caribbean Tsunami Hazard, pp. 91-137. https://doi.org/10.1142/9789812774613_0005

Pararas-Carayannis, G. 2019. Meteotsunami of 29 August 1916 at Santo Domingo, Dominican Republic — Analysis of the destruction of the USS Memphis, Russian Academy of Sciences, Вычислительные технологии, Том 24, No 2, 2019, pp 16-36. https://resolver.caltech.edu/CaltechAUTHORS:20150928-113055558

Press F. & Harkrider D., 1966, Air-Sea Waves from the Explosion of Krakatoa. ***SCIENCE*** 9 Dec 1966 Vol 154, Issue 3754 pp. 1325-1327 DOI: 10.1126/science.154.3754.1325

Proudman J., 1929. The Effects on the Sea of Changes in Atmospheric Pressure. Geophysical Journal International: October 1929 https://doi.org/10.1111/j.1365-246X.1929.tb05408.x

PTWC (2022). Message: American Samoa Warn/Adv./Watch #1 Issued Sat Jan 15 05:52:38 UTC 2022. https://tsunami.gov/?p=PHEB/2022/01/15/22015050/1/WEZS40

Science.org (2022). Tonga shock wave created tsunamis in two different oceans https://www.science.org/content/article/tonga-shock-wave-created-tsunamis-two different oceans

Sekizawa S, and Kohyama T., 2022. Meteotsunami observed in Japan following the Hunga Tonga eruption in 2022 investigated using a one-dimensional shallow-water model, SOLA, 2022, Vol.18, pp.129-134. doi:10.2151/sola.2022-021

Seno T. and Yamanaka Y.,1998. Arc stresses determined by slabs: Implications for back-arc spreading, Earthquake Research Institute, University of Tokyo, Geopys. Res. Lett., 3227-3230 .

TelesurTV (2022). Perú cierra 80 puertos tras erupción de volcán en Tonga. https://www.telesurtv.net/news/peru-cierra-puertos-erupcion--volcan-tonga-20220117-0025.html

Terry, J.P., Goff, J., Winspear, N. *et al.* 2022. Tonga volcanic eruption and tsunami, January 2022: globally the most significant opportunity to observe an explosive and tsunamigenic submarine eruption since AD 1883 Krakatau. *Geosci. Lett.* **9,** 24 (2022). https://doi.org/10.1186/s40562-022-00232-z

The Conversation (2022). Why the volcanic eruption in Tonga was so violent, and what to expect next. https://theconversation.com/why-the-volcanic-eruption-in-tonga-was-soviolent-and-what-to-expect-next-175035

Timm C., Davy, B., Haase, K., Hoernle, K. A., Graham, I. J., De Ronde, C. E., ... & Gamble, J. A. (2014). Subduction of the oceanic Hikurangi Plateau and its impact on the Kermadec arc. *Nature Communications*, *5*(1), 1-9.

Toulkeridis T., Martinez N., Barrantes G., Rentería W., Barragan-Aroca G., Simón-Baile D., Palacios I., Salazar R., Salcedo-Hurtado E. , & Pararas-Carayannis G., 2022 IMPACT AND RESPONSE IN CENTRAL AND SOUTH AMERICA DUE TO THE TSUNAMI GENERATED BY THE SUBMARINE ERUPTION OF HUNGA TONGA-HUNGA HA'APAI VOLCANO. Science of Tsunami Hazards Vol 41. N 1 Y 2022. pp 1-38

Watada, S., 2022. (Earthquake Research Institute, University of Tokyo) (2022). Theory of tsunami generation. Reported by Koji Matsumoto, NHK. https://www.nhk.or.jp/kaisetsu-blog/100/459802.html

Worthington, T. J., Gregory, M. R., & Bondarenko, V. (1999). The Denham caldera on Raoul Volcano: dacitic volcanism in the Tonga–Kermadec arc. *Journal of Volcanology and Geothermal Research*, *90*(1-2), 29-48.

Woulff, G., McGetchin, T. R. (1976) Acoustic Noise from Volcanoes: Theory and Experiment. *Geophysical Journal International*, 45 (3). 601-616 doi:10.1111/j.1365-246x.1976.tb06913.x

Young R.  S., 2004. Small scale edifice collapse and tsunami generation at eastern Caribbean volcanoes; a standard phase of the volcanic cycle. NSF Caribbean Tsunami Workshop, Puerto Rico March  30-31.

Zahibo,  N. and Pelinovsky, E. 2001. Evaluation of tsunami risk in the Lesser Antilles, Natural Hazard and Earth Sciences, 3, 221&;231.

Zengaffinen, T., Løvholt, F., Pedersen, G. K., & Muhari, A. (2020). Modelling 2018 Anak Krakatoa Flank Collapse and Tsunami: effect of landslide failure mechanism and dynamics on tsunami generation. *Pure and Applied Geophysics*, *177*(6), 2493-2516.