

The Rare Volcano creating a Mega Tsunami out of the Wrath of Ruaumoko[@]

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Abstract: The Paper is divided into two parts A and B. Part A is general and in Part B is considered the Physics of eruption and the generation of tsunami. In part A the paper begins with a philosophical touch citing the historical part of the 1883 eruption of Anak Krakatau in Indonesia. Pictorial illustrations of damages created by the 23 December 2018 Indonesian tsunami. At many places in the paper, The God Ruaumoko is given importance and mentioned His wrath for the destruction. In Part B, the Physics of eruption and specially situations when a volcano explodes and bursting of magma chamber are dealt with. Discussion of an already published research paper on volcanic explosion with phreatomagmatic explosions. Volcanic explosivity with tsunami generation has been mathematically dealt with. Formation of Caldera; General treatment on Physics of tsunami. A list of about 30 volcanic tsunamis of the 20th century having the same or similar properties and effects as the Anak Krakatau is included in the paper. The paper ends with a Conclusion wherein the author has added some of his own ideas.

Keywords: Anak Krakatau Volcano, Caldera, Caldera subsidence, Eruption magnitude and Intensity, Magma chamber, Phreatomagmatic explosion. Ruaumoko, Size of tsunami, Tsunamis, Volcano, Volcano Explosive Index, Volcanic Tsunamis.

A GENERAL

I INTRODUCTION

1.Dedication: This Research Paper is dedicated to *Ruaumoko*[@] (Fig. 1) the Maori God of Earthquakes, Volcanoes and seasons. Maories, the island tribes of New Zealand believed and worshipped Ruaumoko so as to free themselves from natural calamities such as Earthquakes, Volcanoes, Tsunamis and Seasons. It is believed that the earthquakes created by Ruaumoko in turn are responsible for the change of seasons. According to a legend, Rūaumoko pulls on the ropes that control the land causing the shimmering effect of hot air, called haka of Tane-rore, and in some versions, earthquakes and tsunamis. Rūaumoko is also known as husband of his niece Hine-nui-te-pō, the goddess of death and a daughter of Tāne. The Maori mythology appears to be a cock and bull story for scientists specially physicists like me. But, however, I would like to give this paper a philosophical and a spiritual touch and say that it is the Nature that creates and also subsides calamities. Ruaumoko is a part of Nature. If Nature creates only calamities, we will not be alive today. It destroys, at least, in principle, subsides the calamities. Hence, I join the Maori tribes and am compelled to worship Ruamoko with folded hands.

[@]The God of Earthquakes, Volcanoes, Tsunamis, Winds and Seasons of the Maori tribes of New Zealand

1.1 The Rare Volcano: The geologic beast, under discussion, is the rare Indonesian Volcano, Anak Krakatau (Fig.2) meaning the “Child of Krakatau” is surrounded by a small group of islands in the Sunda



Fig.1 The Wrath of Ruaumoko in full vigor.[Inset (Right) Picture of the dreadful face of Ruaumoko, the Maori (New Zealand) God of Volcanoes, Earthquakes, Tsunamis and Seasons]

Strait between Java and Sumatra and which was stuttering eruption since June 2018, erupted vigorously and exploded creating a Tsunami in Lampung province of Indonesia on the night of 22 December 2018 at 9.30 PM local time. The author shall exclusively deal with tsunamis created by volcanoes specially the Anak Krakatau and not by any seismic causes.

1.1.1 Historical: We study History to interpret the future in terms of the past and hence, it is of interest to know the history of the rare volcano just mentioned. The 1883 eruption of Krakatoa in the Dutch East Indies (Fig.2) began in the afternoon of Sunday, 26 August 1883, and peaked in the late morning of Monday, 27 August 1883, when over 70% of the island and its surrounding archipelago were destroyed as it collapsed into a caldera.. The eruption generated a 3 m tsunami in the Sunda Strait which killed 36,000 people as it washed away 165 coastal villages on Java and Sumatra. The eruption (Fig.3 and 5) made the world's loudest sound. It was so loud that it ruptured eardrums of people some 40 miles away. A sound of 200 dB can even kill a person. The sound waves travelled round the world 4 times and was heard 3000 miles away.

As per a Book, Krakatoa the Day the world exploded, August 27, 1883 by Simon Winchester [15], an island volcano west of Java, exploded on August 23, 1883. The blast was equal to 3,000 Hiroshima-size atom bombs, 26 times more powerful than the strongest hydrogen bomb, and 18 times more powerful than the Mt. St. Helens blast. Tsunamis as high as 100 feet were created. Eleven cubic miles of debris was sent flying into the atmosphere.



Fig.2 Location map of Anak Krakatau (Picture re-drawn from Wikipedia) [20]



Fig.3 (Left): The 1883 eruption of Krakatoa and (Right): Krakatoa eruption as on today

The most powerful explosion was twice as strong as the largest nuclear blast. It hurled pumice 34 miles into the air that fell 3,313 miles away 10 days later. Winds from the blast circled the earth seven times before they died down and waves escaped from the Indian Ocean below Cape Horn in the Atlantic and radiated into the English Channel, 11,500 miles away.

The noise was the loudest in recorded history. It was heard distinctly in central Australia 3000 kilometers away. Five thousand kilometers on the small island of Rodriguez "the roar of heavy guns" was heard and a captain ordered his ship out to sea. By some estimated the blast could be heard over one thirtieth of earth's surface. Some people in Texas claim they heard the sound.

Five cubic miles of ash was thrust into the air. Ash fell as far away as New York, and humans bones were carried 4,500 miles across the Indian ocean to Zanzibar. So much ash was thrust into the stratosphere the color of the sun turned green and temperatures around the globe dropped several degrees, producing blizzards in the mid-western United States in July. On the positive side, brilliant sunsets lingered for years all around the world.

According to another report, The Krakatoa explosions and the tsunamis they generated killed 36,489 people, decimating 165 villages and nearly destroying 132 others. Most of those killed were carried away and drowned by tsunamis. Victims washed up months later as far away as the east coast of Africa.

The tsunamis reached the height of four storey buildings. They hit Java and Sumatra particularly hard and were felt as far away as California and England. These waves were generated by massive chunks of island that fell into the sea. At 10:32am a huge wave smashed into Tjaringin, 30 miles from Krakatoa, killing 10,000 people. The town of Penimbang, 10 miles inland, was submerged as were Tjeringr, Karang, Antoe, Telok Betong, Beneawany and Batavia.

Villages were swept off the face of the earth. A naval gunboat was heaved up to two miles inland by the awesome waves and deposited on a hill. Boats that cruised the waters around Krakatoa after the disaster found the corpses of humans and tigers floating in the sea. A Dutch administer in Sumatra saw a wave lap against his house and remove flower pots from his veranda and a town with 800 people below it. A fisherman on Java was swept inland several miles and kept himself from drowning by holding on to the back of a crocodile which he first thought was a log. A reminder of the destruction, which can be seen today, is a huge one-ton iron buoy that was thrust onto a hill a mile inland near the Sumatran town of Telukbetung

1.1.2 The state of affairs of 1883 Anak Krakatau eruption is graphically shown by Giachetti, et.al [6] in Fig.4. The landslide scar obtained by some Digital Elevation Model (DEM) is shown dotted. It is oriented southwards with a slope of 8.2° delimiting a collapsing volume of about 0.28 km^3

1.2 The Mega Tsunami: Maya Wei Haas [10] report published on 23 December 2018 reads: "A tsunami similar to the one of 1883 swept across Indonesia's Islands of Sumatra and Java on the night of 22 December 2018 just before 9.30 AM local time. There was no notice for the wall of water, which left devastation in its wake. Though casualties are likely to rise as missing people are located, at least 220 are confirmed dead and more than 800 are injured.

The reason behind the lack of warning is the surprise source of the waves. As there was no earthquake, the mega tsunami was most likely caused by the collapse of an offshore volcano."

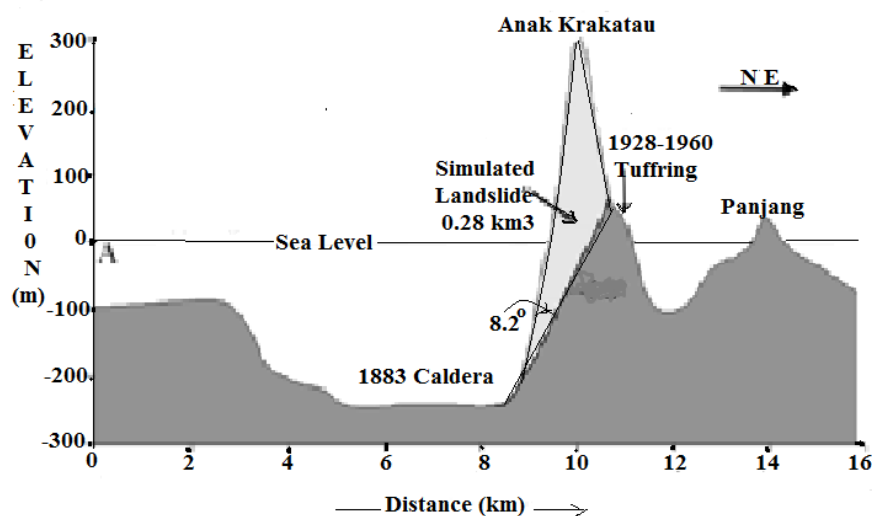


Fig.4 The 1883 Anak Krakatau eruption in a nutshell (Fig. suitably re-drawn by Author)

1.3 The Wrath of Ruaumoko: The result of the wrath of Ruaumoko is the Indonesian Mega Tsunami the sign board indication of which is displayed in Fig.6



Fig.5 An aerial view of Anak Krakatau volcano during an eruption at Sunda strait in South LampungLampung, Indonesia, Dec 23, 2018



Fig.6 Result of Wrath of Ruaumoko

II THE DESTRUCTION AND DAMAGE

2 Photos taken and published by China Daily.com

2.1.1 An areal view of the damage: This is shown in Fig.7



Fig.7 An aerial view of an affected area after a tsunami hit the coast of Pandeglang, Banten Province, Indonesia – Dec. 24 2018

2.1.2 Damage created in the Banten Province: This is shown in Fig.8



Fig.8 A destroyed boat is seen after a tsunami hit an area near Carita in Pandeglang, Banten province, Indonesia, Dec 24, 2018. [Photo/Agencies]

2.1.3 It is all in shambles: Another photo in the Banten Province is shown in Fig.9



Fig.9 A local walks near her damaged house hit by tsunami at Tanjung Lesung district in Pandeglang, Banten province, Indonesia, Dec 23, 2018 in this photo taken by Antara Foto. [Photo/Agencies]

2.1.4 The vehicles are ruined: An up-dated photo of the damage to vehicles and houses is shown in Fig.10



Fig.10 An Indonesian man looks at ruined vehicles after a tsunami hit Sunda Strait in Anyer, Banten, Indonesia

2.1.5 The Damage created at Rajabasa District in South Lampung of Indonesia: This is shown in Fig. 11 where a man is searching for his items in the debris.



Fig.11 A man inspects his house which was damaged by a tsunami, in Carita, Indonesia

2.1.6 The Damage created in Carita, Indonesia: This is shown in Fig.12



Fig.12 The entire house is broken down

The Ruaumoko has subsided creating the above damages, even though the volcano continues to rumble. The following are the outcry and reports

2.2 The Outcry and Reports: The Foreign Staff of the Telegraph News [17] stationed at Indonesia reported at 12.03 PM on 29 December 2018.

- *Anak Krakatau has lost two-thirds of its height. The volcano which used to stand at 338 meters high is now just 110 meters tall after the deadly tsunami
 - *The crater's status has been raised to high alert, the second-highest warning on Indonesia four-point danger scale.
 - *The exclusion zone has been extended from two to five kilometres (1.2 to three miles).
 - *A week after the tsunami, thousands of Indonesian Muslims attended a mass prayer on Saturday to remember the victims and pray for the safety of their tsunami-prone hometown.
 - *Residents of Pandeglang regency, which was hit the hardest by the disaster, gathered in the early morning, some in tears as they chanted their prayers.
 - *"I prayed for the victims and I also pray for the safety of the people who live in the tsunami affected area," Dadan Suryana, a tsunami survivor, told AFP.
 - *"My prayer is for the victims to get help and be granted patience and I also pray the government will immediately help us to rebuild, to provide clothes and food, or at least to give us moral support," fellow congregant Dian Rosdiana said.
 - *Authorities said at least 426 people were killed and 23 missing in the disaster.
- Some 7,202 people suffered injuries and nearly 1,300 homes were destroyed after the waves crashed into the coastlines of western Java island and south Sumatra.
- *More than 40,000 people have been evacuated for fear of another tsunami as Anak Krakatoa continues to rumble.

B THE PHYSICS OF ERUPTION AND GENERATION OF TSUNAMI

III THE VOLCANO AND THE PHYSICS OF ERUPTION

3. The Volcano: Following the concept of 'Cause' and 'Effect' Formalism, 'Eruption of Volcano' is the cause for the 'Generation of Tsunami' which is the effect. A general knowledge on the part of the reader regarding a volcano and its structure is assumed. Philosophically, I might say that the Maori God, Ruaumoko, with his uncontrollable wrath and fury, works in conjunction with 'Vulcan' the blacksmith of Mars, the God of wars in preparing weapons for Jupiter, the king of Gods, Volcano is believed to be the chimney of the forge of Vulcan. On orders from Ruaumoko, Vulcan explodes both the forge and the chimney. This is actually what is seen as a result by Geologists and specially the volcanologists.

3.1 Types of Volcanic Eruptions:- Each volcano is different from the other one from the point of view of the type of eruption. Each one shows a distinctive pattern of behavior. Some erupts mildly simply discharge steam and other gases whereas others extrude molten lava. The most spectacular one consists of violent explosion that blast great clouds of gas-laden debris into the air. Any volcano erupting anywhere is compared with the one already taken place elsewhere and the names are given accordingly. For example, "Strombolian", "Vulcanian", "Vesuvian", "Pelean", "Hawaiian", etc. The most powerful eruption is called "Plinian" and is really a dangerous one because of the pyroclastic flows from the vent.

3.1.1 Measure of Volcanic Eruptions (Eruption Scale):[11]

In the year 1982, Stephen Self and Chris Newhall of the University of Hawaii [11] devised a quantity known as the Volcano Explosivity Index (VEI) which is a measure of volcanic eruptions. This is different from Volcanicity which is the level of power of a volcano. The tremor signal and properties vary with the intensity of explosive eruptions. The VEI is usually represented in terms of a scale of 8 and is shown in Table. The VEI is further categorized into two. That is the low intensity events where $VEI < 3$ and high intensity events where $VEI > 3$.

Table Source: **Volcano World**, (an educational site at the University of North Dakota)

VEI	Description	Plume*Height	Volume	Classification	How often	Example
0	non-explosive	< 100 m	1000s m ³	Hawaiian	daily	Kilauea
1	gentle	100-1000 m	10 000sm ³	Haw/Strombolian	daily	Stromboli
2	explosive	1-5 km	1 000 000s m ³	Strom/Vulcanian	weekly	Galeras, 1992
3	Severe	3-15 km	10 000000 s m ³	Vulcanian	yearly	Ruiz, 1985
4	cataclysmic	10-25 km	100 000 000s m ³	Vulc/Plinian	10s of years	Galunggung, 1982
5	paroxysmal	> 25 km	1 km ³	Plinian	100s of years	St. Helens, 1981
6	Colossal	> 25 km	10s km ³	Plin/Ultra-Plinian	100s of years	Krakatau, 1883
7	super-colossal	> 25 km	100s km ³	Ultra-Plinian	1000s of years	Tambora, 1815
8	mega-colossal	> 25 km	1 000s km ³	Ultra-Plinian	10 000s of years	Yellowstone, 2 Ma

[*A volcanic plume is a mixture of particles and gas emitted by an eruption. Plumes may reach heights of 80 km in large eruptions. The plume is generated by fragmentation of magma. The plume has 3 phases. Jet Phase is dominated by upward momentum. Convective Phase is where the plume rises by buoyant convection. Umbrella Phase is where the plume spreads out.]

3.1.2 Eruption Magnitude and Intensity

The size of eruptions is usually described in terms of total erupted mass (or volume), often referred to as magnitude, and mass eruption rate, often referred to as intensity. David M Pyle (2015) [5] quantified magnitude and eruption intensity as follows:

$$\begin{aligned}\text{magnitude} &= \log_{10}(\text{mass, in kg}) - 7, \text{ and} \\ \text{intensity} &= \log_{10}(\text{mass eruption rate, in kg/s}) + 3.\end{aligned}$$

The Volcano Explosivity Index (VEI) assigns eruptions to a VEI class based primarily on measures of either magnitude (erupted mass or volume) or intensity (mass eruption rate and/or eruption plume height), with more weight given to magnitude

3.2 The Magma and Lava: Magma and Lava are different. ‘Magma’ comes from the Greek word, “*Kneaded Mixture*”. Magma is a complex high temperature fluid substance formed out of molten rock material that commonly contains solids and gases. Magma and lava are different in the sense that magma is turned into lava after it gets cooled and loses its dissolved gases on coming out of the vent. Thus, Lava is the extrusive equivalent of magma which over a period of time becomes an igneous rock. The terms, magma and lava are synonymously used. The temperature ranges for different types of magma are shown below:

Basaltic Magma

1000 °C - 1200 °C

Andesitic Magma

800 °C - 1000 °C

Rhyolitic Magma

650 °C - 800 °C

3.3 The Magma Chamber/Reservoir: I have written an oblique after the word, ‘chamber’ because authors use them synonymously even though they are actually different. The following information [1] will make things clear. Both the reservoir and chamber lie between the crust and the mantle as shown in the Fig.13. Reservoirs are situated in the upper parts of the mantle. Magma is stored in the magma chambers flown from the reservoirs. In some cases, magma flows directly from the reservoirs to the volcano in which case the chamber is the reservoir itself. In this case the dike and conduit are same. The chambers get continuously filled in and any thermal imbalance triggers an eruption.

In order to envisage the size of a magma chamber of a volcano of VEI- 8, have a look at Fig.14. It’s hard to imagine the massive size and volume, but the following image puts it into some perspective while visualizing the San Francisco Bay Area with Sacramento, San Jose, and the Sierra’s in the background. The magma chamber of the Yellow stone Volcano is 17 km beneath the surface, 90 km long and 40 km wide. So, one can imagine the state of affairs when a magma chamber of such size explodes as it happened in the case of Anak Krakatau.

Becky Oskin [2] of the Live Science reports in the Scientific American on 6 March 2015 that the Kilauea volcano of Hawaii is fed by more than one magma chamber.

The approximate volumes of magma chambers of VEI 4 to 8 are shown below:

Volcanic Explosive Index (VEI)	Volume
4	1 Billion cubic meters
5	10 Billion cubic meters
6	100 Billion cubic meters
7	1 Trillion cubic meters
8	10 Trillion cubic meters

3.4 The 23 December 2018 Eruption of Anak Krakatau Volcano: Keeping in letter and spirit of the title of this paper, we shall strictly stick on to the physical processes that led to the explosion of the Anak Krakatau and the ensuing mega tsunami. Report from International Tsunami Information Center (ITIC) [8] and published by Geoscience,[7], Australia has diagrammatically (Fig.15) mentioned 7 things as shown below:

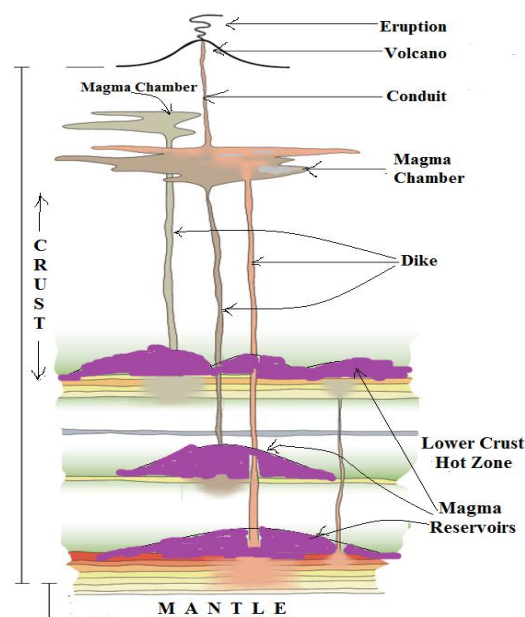


Fig. 13. The location of Magma Reservoir and Magma Chamber (Figure modified from the original by Author to bring out the distinction between Magma Reservoir and Magma Chamber. See text)

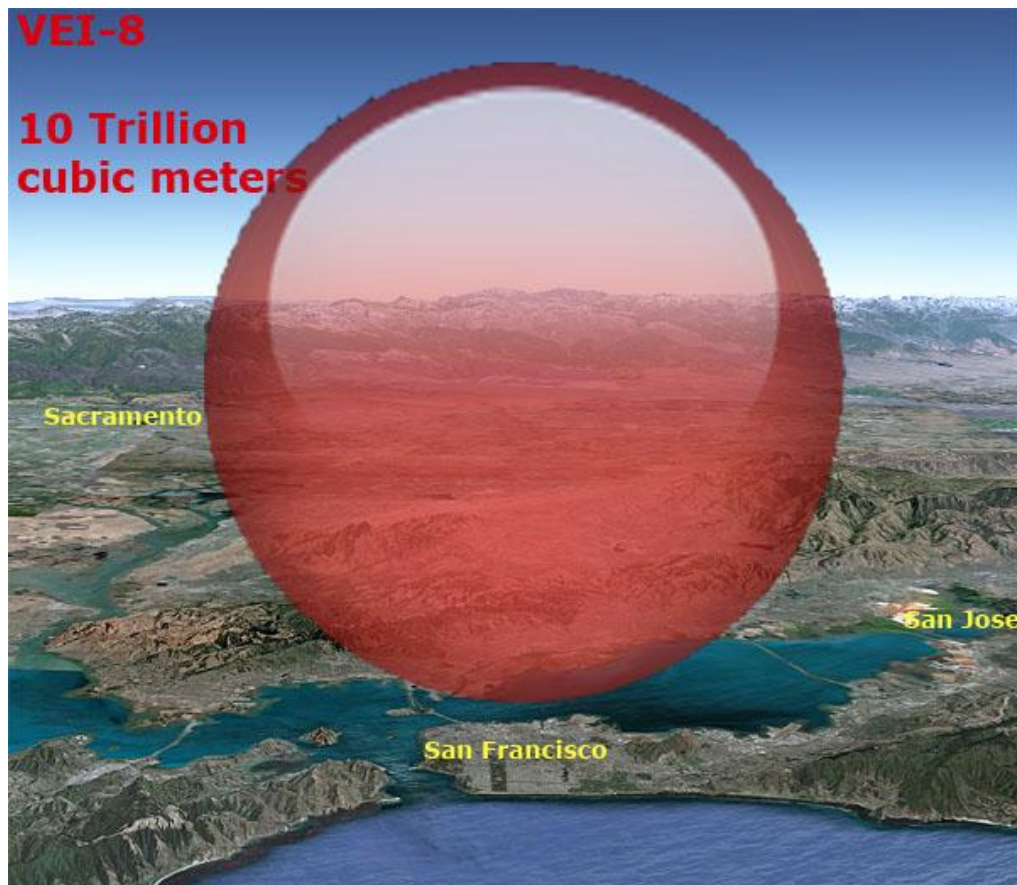


Fig.14 Comparison of size of a Magma Chamber

Although relatively infrequent, violent volcanic eruptions represent also impulsive disturbances, which can displace a great volume of water and generate extremely destructive tsunami waves in the immediate source area. According to this mechanism, waves may be generated by the sudden displacement of water caused by a volcanic explosion, by a volcano's slope failure, or more likely by a phreatomagmatic explosion and **collapse/engulfment** of the volcanic magmatic chambers. One of the largest and most destructive tsunamis ever recorded was generated in August 26, 1883 after the explosion and collapse of the volcano of Krakatoa (Krakatau), in Indonesia. This explosion generated waves that reached 135 feet, destroyed coastal towns and villages along the Sunda Strait in both the islands of Java and Sumatra, killing 36, 417 people. It is also believed that the destruction of the Minoan civilization in Greece was caused in 1490 B.C. by the explosion/collapse of the volcano of Santorin in the Aegean Sea.

As far as the volcano is concerned, what is of importance is the explosion and collapse of the volcano with many flank eruptions and the entire magma getting dumped into the sea and the summit getting almost immersed in water and forming a caldera. There are 7 stages or processes that take place before a caldera is formed as illustrated in Fig.15.

1. Original summit of volcano is ruptured.
2. The volcano collapses
3. Magma body is up-rooted
4. The lateral blast starts
5. Fast moving debris avalanche crashes into the sea
6. Tsunami forms and
7. Waves travel to distant coast lines

The Images captured by the European Space Agency's Sentinel-1 satellite showed a large portion of the southern flank of the volcano had slid off into the ocean, scientists said.

What really happened in the Anak Krakatau is that due to some obstruction in the vent and summit, there was explosion in the magma chamber even. Taking the lower temperatures of magma as, say 600°C , the situation becomes dangerous when magma flows into sea water and gets mixed with it. A research paper Titled, "Tsunami Generation due to Submarine Volcanic Eruptions with Phreatomagmatic Explosion or Caldera Subsidence" by Taro Kakinuma, et.al [16] have dealt with the situation of magma getting mixed

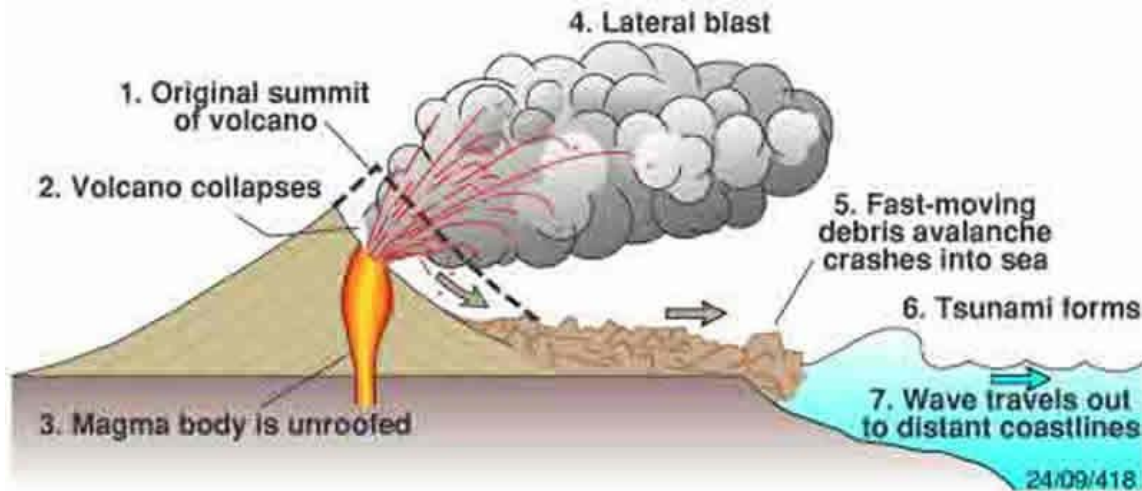


Fig. 15 The state of affairs when a volcano explodes (Diagram source: Geoscience Australia)

with water and finally leading to generation of tsunamis. Before I take it up, I would like to show the photograph (Fig.16) of lava flowing into the sea on the southeastern edge of the island of Hawaii. The mixture produces a noxious haze when it hits the seawater made out of hydrochloric acid, steam, and shards of volcanic glass, the gas is hazardous to anyone who breathes it. We now come to Tar Kakinuma's paper [16]

Submarine explosive eruption causes not only a blow out of volcanic products but also phreatomagmatic explosions resulting in the generation of tsunamis. The author has used simple gas laws of Thermal Physics such as the Charle's Law and has mathematically obtained the index of submarine volcanic explosivity regarding tsunami generation. The following data will be required.

Mass of 1 mole of water (H_2O) $\rightarrow 18 \text{ g}$

Density of Sea water $\rightarrow 1.03 \approx 1 \frac{\text{g}}{\text{cc}}$

\therefore Volume of 1 mole of water $\rightarrow 18 \text{ ml}$

But, assuming water vapor to be a perfect gas, 1 mole of vapor occupies 22400^* ml of volume at NTP (Normal Temperature and Pressure) where the temperature is $0^{\circ}\text{C} = 273^{\circ}\text{K}$ and normal pressure is 1 Atmosphere which is 10^5 Pa .

Now, when molten magma falls into seawater, the volume of the vapor becomes $\left(\frac{22400}{18}\right) = 1244$ times as much as that of water. If p is the pressure, then the volume of the gas at temperature, $t^{\circ}\text{C}$ as per Charle's Law is

$$V = V_0 \left(\frac{10^5}{p}\right) \left(1 + \frac{t}{273}\right)$$

Where V_0 is the volume of the gas at 0°C .

Consequently, when the water occupying volume V_0 at NTP changes to vapor of volume V at $t^{\circ}\text{C}$ and pressure, p . Thus, the cubical expansion ratio is

$$\gamma = \left(\frac{V}{V_w}\right) = 1244 \times 10^5 \left[\frac{(1 + \frac{t}{273})}{p}\right] \dots \dots (1)$$

*In the original paper, the author, Taro Kakinuma has used the figure as 22700 which I very much feel is not correct. In fact, in the study of Heat, the burden of the song is, 1 ml of any ideal gas at NTP occupies 22.4 liters. My statement is open to readers for correction and in this paper I have gone with my correction.



Fig.16 Lava spilling off the southern edge of the island of Hawaii

The moment the magma touches the water, the following equation is satisfied on their interface

$$\frac{(t_m - t_i)}{(t_i - t_w)} = \left[\frac{\rho_w (c_p)_w k_w}{(\rho_m (c_p)_m k_m)} \right]^{\frac{1}{2}} \dots \dots \dots (2)$$

Where the symbols t , ρ , c and k are respectively the temperature, density, specific heat and thermal conductivity. The subscripts, i , m and w stand for interface, magma and water respectively. The author has given general values for the parameters as shown in the Table below: [Note that c_p is actually the specific heat at constant pressure.]

Table

For Magma			For Water		
Physical Quantity	Symbol	Value	Physical Quantity	Symbol	Value
Density	ρ_m	$2400 \frac{\text{kg}}{\text{m}^3}$	Density	ρ_w	$1000 \frac{\text{kg}}{\text{m}^3}$
Temperature	t_m	$\sim 700^\circ\text{C} = 973^\circ\text{K}$	Temperature	t_w	273°K
Specific Heat	$(c_p)_m$	$1.3 \times 10^3 \frac{\text{J}}{\text{kg}^\circ\text{K}}$	Specific Heat	$(c_p)_w$	$4.2 \times 10^3 \frac{\text{J}}{\text{kg}^\circ\text{K}}$
Thermal Conductivity	k_m	$1.2 \frac{\text{W}}{\text{m}^\circ\text{K}}$	Thermal Conductivity	k_w	$0.61 \frac{\text{W}}{\text{m}^\circ\text{K}}$

Now substitute these values in equation (2) to get the temperature, t_i at the interface as

$$t_i = 649^\circ\text{K} = 376^\circ\text{C} \dots\dots\dots (3)$$

This is, however larger than the spontaneous nuclear generation temperature of water which is 583°K at 1 atmosphere. The author has worked out the relationship between cubical expansion ratio of sea water near the sea bed and still water depth.

The water pressure, p at a submarine crater in still water is given by

$$p = \rho_w g h = 1000 \times 9.8 h = 9800 h \dots\dots\dots (4)$$

where h is the still water depth at the location of crater and g is the acceleration due to gravity. On substituting the value of t_i given in equation (3) and pressure p by equation (4) into t and p in equation (1) respectively, we get

$$\gamma = \frac{V}{V_w} = (1244 \times 10^5) \left[\frac{(1 + \frac{649}{273})}{9800 h} \right] = \left(\frac{1244 \times 10^5}{9800 h} \right) (1 + 2.38) = \left(\frac{1244 \times 10^5}{9800 h} \right) (3.38)$$

$$\therefore \gamma = \frac{(0.43 \times 10^5)}{h} = \frac{43000}{h} \dots\dots\dots (5)$$

where the water surface displacement is assumed to be much smaller than the still water depth. Equation (5) expresses the relationship between the cubical expansion ratio of water over the crater and the still water depth at the location of the crater, for instance, if $h = 3 \text{ km} = 3000 \text{ m}$, $\gamma = 14.3$ while if $h = 50 \text{ m}$, $\gamma = 860$. The author has worked out the relationship between submarine volcanic explosivity and the initial tsunami profile as follows:

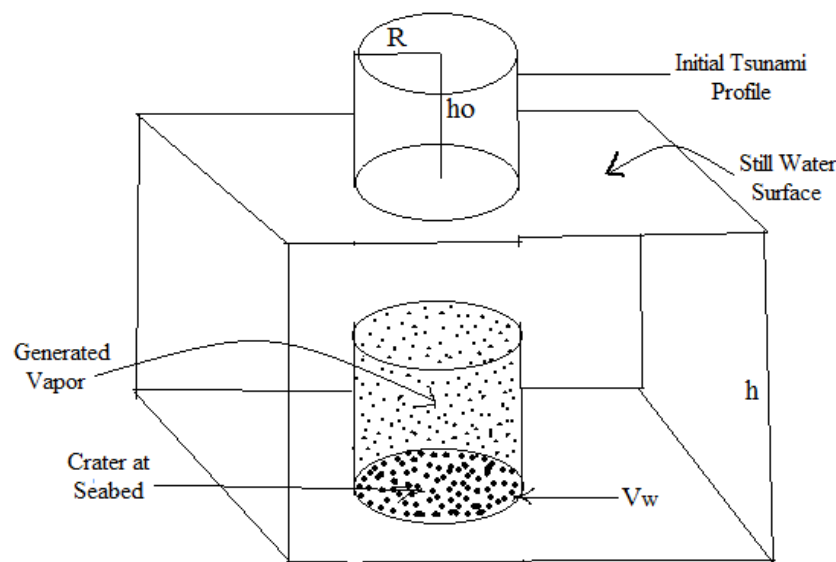


Fig.17 Illustration of Tsunami generation

Let us assume that a circular crater of radius R appears at the horizontal seabed with the sea water over the crater being vaporized to form a sort of cylinder forming a tsunami profile as shown in Fig.17. The original volume of water V_m before generation of tsunami is, however, neglected for simplicity and the volume of the cylinder, $V = \pi R^2 h_0$, where h_0 is the height of the cylinder which is the height of initial tsunami. Thus, according to equation (5), h_0 can be evaluated by

$$V_w = \frac{V}{\gamma} = \frac{\pi R^2 h_0 h}{43000} = 0.0000 \pi R^2 h_0 h$$

$$\therefore V_w = 2.326 \times 10^{-5} \pi R^2 h_0 h \dots\dots\dots(6)$$

Thus, the original volume of sea water which changes to vapor through phreatomagmatic explosion V_w is the new index of submarine volcanic explosivity regarding tsunami generation. To find out the values, we may proceed as follows:

The radius R of the crater is given by a formula,

$$R = 0.97 (V_c)^{0.36} \dots\dots\dots (7)$$

where V_c is the volume or quantity of eruption. The author has worked out the volume V_c for a volcano of VEI, 3 and taking the highest value for V_c as 10^8 m^3 , the radius of the crater works out to be

$$R = 0.97 (10^8)^{0.36} = 0.97 \times 758.6$$

$$\therefore R = 735.8 \approx 736 \text{ m} \dots\dots\dots (8)$$

meaning thereby that the diameter of the crater can be $\sim 1.5 \text{ km}$

IV CALDERA

4.1 Caldera: is a volcanic feature formed by the collapse of a volcano into itself, making it a large, special form of volcanic crater. A **caldera** collapse is usually triggered by the emptying of the magma chamber beneath the volcano, as the result of a large volcanic eruption. It is a large cauldron-like hollow that forms following the evacuation of a magma chamber/reservoir. When large volumes of magma are erupted over a short time, structural support for the crust above the magma chamber is lost. The ground surface then collapses downward into the partially emptied magma chamber, leaving a massive depression at the surface (from one to dozens of kilometers in diameter). Although sometimes described as a crater, the feature is actually a type of sinkhole, as it is formed through subsidence and collapse rather than an explosion or impact.

John Browning, et.al [3] have given the following equation dealing with the rupture of the roof of magma chamber:

$$p_l + p_e = \sigma + T \dots\dots\dots(9)$$

where p_l is the lithostatic overburden pressure (due to the weight of the overlying rocks), p_e is the magmatic excess pressure within the chamber, σ is the local minimum compressive principal stress and T is the local tensile strength of the host rock. Since σ is the local stress, at the margins of the chamber, stress concentration effects due to magma chamber shape and loading, the authors say, are automatically taken into account in the equation (9).

4.2 Stages of Formation of Caldera: Wikipedia [20] has diagrammatically given various stages of Caldera formation pertaining to Mount Mazama's eruption. In Fig.18 is shown various stages of formation of a caldera. The duration of a caldera collapse is purely constrained from minutes to hours. In Fig.19 is shown by Raphael Paris [12] a typical caldera collapse for North-East Santojini Volcano. It is seen that within a minute to 5 minutes the collapse was abrupt from an amplitude of 20 meters coming down to 5 meters and within an hour the amplitude declined considerably.

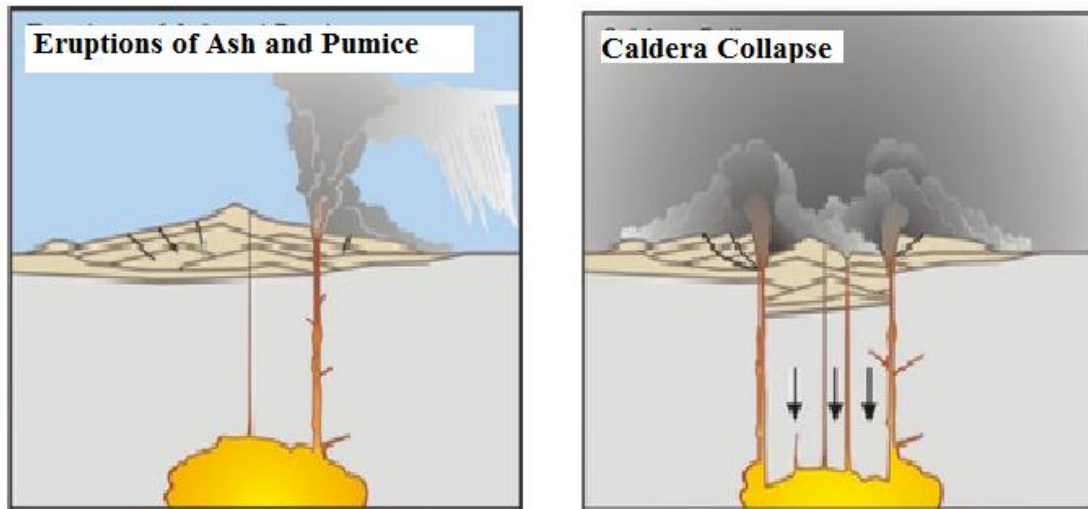


Fig.18 Illustration of Mount Mazama's eruption time-line, an example of caldera formation [20]

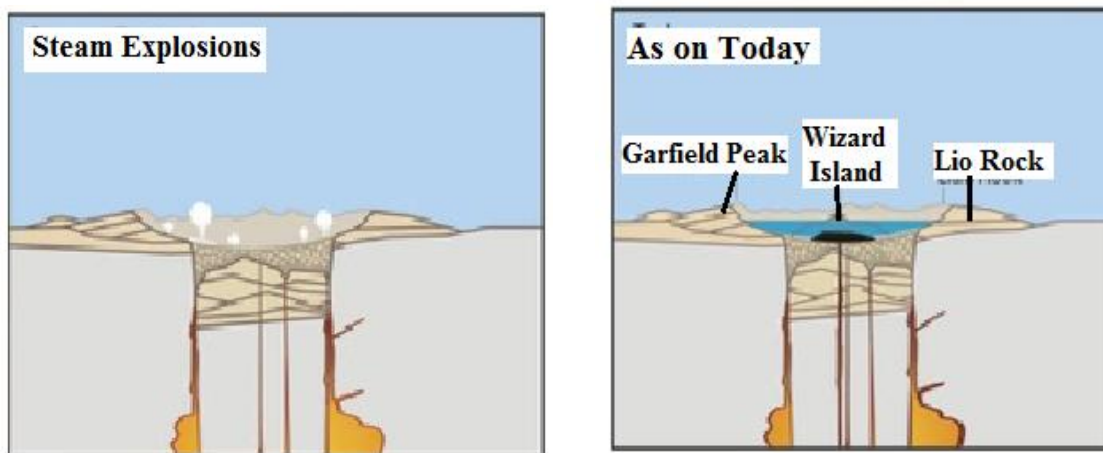


Fig.18 (Contd.)

In Fig. 20 is shown the picture of Crater Lake, Oregon, formed around 5,680 BC

Reynolds James [13], a journalist visited the Anak Krakatau on Sunday, 13 January 2019 and reported that the crater area has become a lake and still steaming.

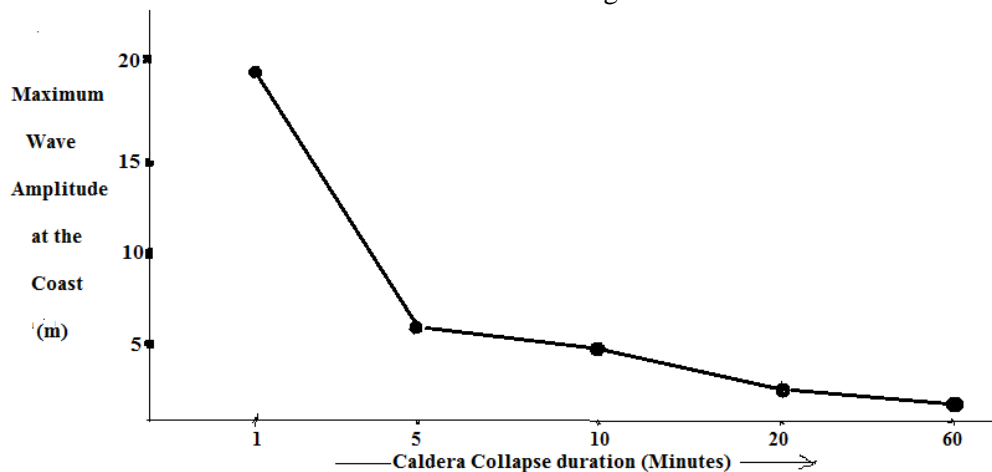


Fig. 19 Duration of Caldera Collapse [12]



Fig.20 Crater Lake, Oregon, formed around 5,680 BC

V PHYSICS OF THE MEGA TSUNAMI, THE RESULT OF WRATH OF RUAUMOKO

5. General: On orders from Ruaumoko, Vulcan blew up the chimney of the forge thereby completely destroying both the duct and the vent of the volcano and even emptying the magma chamber with the entire tons of debris falling into the ocean. The wrath of Ruaumoko then fell on the ocean in creating gigantic waves called ‘Tsunamis’ which ultimately destroyed property and population of the coastal areas. I hereby join the Maoris of New Zealand and also the people of Indonesia and pray Ruaumoko to calm down and reduce the damage to life and property of mankind in days to come.

5.1 The Peculiar Wave: Samir G. Khoury [14] in his article on “Tsunami”- Basic Principles. ‘Tsunami’ is a Japanese word represented by two characters, ‘tsu’ meaning ‘harbor’ and ‘nami’ meaning ‘wave’. Hence, in Japanese, ‘Tsunami’ means ‘Harbor wave’. A tsunami wave is different from an ordinary water wave from the points of view of their difference in their characteristics. Both the waves are transverse waves having both crests and troughs. The essential differences are shown in the following Table:

Table:

Characteristics	Ordinary water waves	Tsunamis
Wave Velocity, V	8 to 100 km/hr	500 to 1000 km/hr
Wave Period, T (Time required for two consecutive crests or troughs to pass a reference point)	5 to 20 seconds	10 minutes to 2 hours

Wavelength, λ Distance between two consecutive crests or troughs	100 to 200 meters	100 to 500 kms
Amplitude, H or A Height from mean sea level	Few cms to $\frac{1}{2}$ meter	Few meters to even 50 meters

Samir G. Khoury [14] at the Appendix adds the following:

Velocity of Ideal Waves in Open Water

The wave velocity (V) is the velocity of the wave form, not that of the water itself. A particle on the surface of the water moves in a vertical plane and describes in time (T) a circle with a diameter that is equal to the wave height (H). Although the generating forces for tsunamis and wind-generated waves are different, the restoring force for both is gravity.

Terence Tao [18] has dealt with the Mathematics of Tsunami and has given the wave velocity of a tsunami wave as related to the square root of the wavelength (λ) and water depth (D) as follows:

$$V = \sqrt{\frac{g \lambda}{2 \pi} \tanh \frac{(2 \pi D)}{\lambda}} \dots \dots \dots (10)$$

where g is the acceleration due to gravity (9.81 meters/second²).

Using this equation (10), the author has calculated the wave velocities, V at different ocean depths, D for a particular wavelength, λ , equal to 100 km = 100,000 meters. Starting from a water depth, D = 7000 m (7 km), a standard value for the Atlantic or the Pacific Ocean and down to the coast of depth, say, 10 m, the tsunami velocities are tabulated below:

Table:

Wavelength. $\lambda = 100,000$ m

Water Depth, D	Wave Velocity, $V = \sqrt{\frac{g \lambda}{2 \pi} \tanh \frac{(2 \pi D)}{\lambda}}$
7000 m	253.957 m/s = 943 km/hr
5000 m	217.829 m/s = 784 km/hr
2000 m	139.633 m/s = 504 km/hr
1000 m	98.930 m/s = 356 km/hr
500 m	69.988 m/s = 252 km/hr
100 m	31.305 m/s = 11.3 km/hr
10 m	9.899 m/s = 36 km/hr

It is seen that as the depth of the ocean decreases, the height of the wave increases and the wavelength of the tsunami decreases as shown in Fig. 21. As a result, the front of the leading wave becomes significantly steeper because of the pile-up effect of the succeeding waves and the same is called as the 'Run-up' effect which is an important factor that controls the ensuing wave run-up at the coast. The speed greater than 900 km/hr for an ocean depth of 7000 m is something like the speed of a jet aircraft. At such high speeds, a tsunami generated in Aleutian Islands may reach Hawaii in less than four and a half hours. In 1960, great

tsunami waves generated in Chile reached Japan, more than 16,800 km away in less than 24 hours, killing hundreds of people.

5.2 The Size of a Tsunami: According to The Australian Geological Survey Organization, the size of a tsunami is measured by the 'Run-up' height, i.e the maximum height above sea level of a tsunami. The size of the tsunami is shown in the following Table:

Table:

Tsunami Magnitude (Size)	0	1	2	3	4	5
Run-up Height (Meters)	1 to 1.5	2 to 3	4 to 7	8 to 15	16 to 31	32 and greater

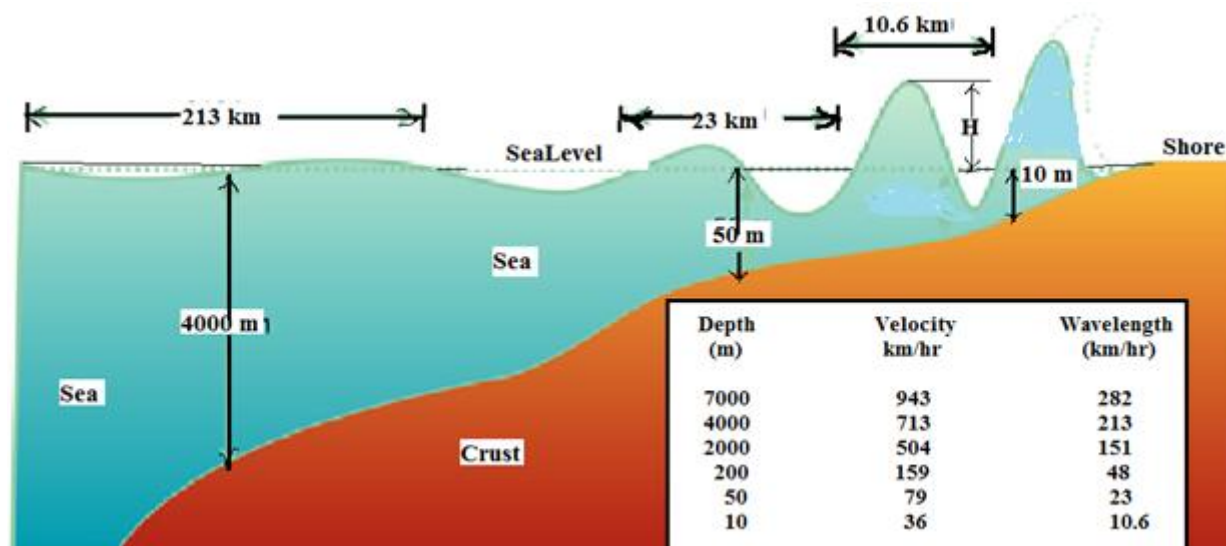


Fig.21 Propagation of shoaling long waves, showing the variation of wavelength and wave height with decreasing water depth.

Let us come back to the equation, (10) and from simple Trigonometry of hyperbolic functions,

Tanh θ approaches θ for small θ and
Tanh θ approaches 1 for large θ

Consequently, in parts of the ocean where water depth (D) is say less than one twentieth of the wavelength (λ), the equation reduces to:

$$V = \sqrt{g D} \dots\dots\dots (11)$$

This is the Limit wave velocity equation in water depth that is less than about 1/20th of the wavelength

Alternatively, in parts of the ocean where water depth (D) is say greater than one half of the wavelength (λ), the equation reduces to:

$$V = \sqrt{\frac{g \lambda}{2 \pi}} \dots\dots\dots (12)$$

This is the Limit wave velocity equation in water depth that is greater than $\frac{1}{2}$ of the wavelength λ

Terence Tao [] adds further: and says that:

The equation (10) viz. $V = \sqrt{g D}$ is the standard equation governing the dynamics of a tsunami

As the tsunami approaches shore, the depth D of course decreases, causing the tsunami to slow down, at a rate proportional to the square root of the depth, as per equation (10). Unfortunately, wave shoaling then forces the amplitude A to increase at an inverse rate governed by *Green's law*, that is,

$$A \propto \frac{1}{D^{\frac{1}{4}}} \dots\dots\dots (13)$$

at least until the amplitude becomes comparable to the water depth (at which point the assumptions that underlie the above approximate results break down; also, in two (horizontal) spatial dimensions there will be some decay of amplitude as the tsunami spreads outwards). If one starts with a tsunami whose initial amplitude was A_0 at depth D_0 and computes the point at which the amplitude A and depth D become comparable using the proportionality relationship (13), and with the help of some simple algebra then reveals that at this point, amplitude of a tsunami (and the depth of the water) is about $[(A_0)^{\frac{4}{5}}][(D_0)^{\frac{1}{5}}]$

Thus, for instance, a tsunami with initial amplitude of one metre at a depth of 2 kilometres can end up with a final amplitude of about 5 metres near shore, while still traveling at about ten metres per second (35 kilometres per hour, or 22 miles per hour), and the impact will be terrible when it hits shore.

As the Anak Krakatau eruption and the ensuing tsunami was on 23 December 2018, just 3 months have passed as on today (April 2019), enough literature has not been published by researchers and hence for a review of literature one has to depend on some similar past events by Raphael Paris [12] who have shown the waveforms of the 1883 Krakatau tsunami recorded by the Tandjung Prioktide gauge at Batav. 3 scenarios are tested. (Fig.22). Pyroclastic Flow (PF) with a 10 km^3 and a volume flux of $1 \times 10^3 \text{ m}^3 \text{ s}^{-1}$. The Caldera Collapse (CC) lasted half an hour (30 minutes). The Under Water Explosion (UWE) generated 10^{17} Joules of heat corresponding to an initial displacement of 290 m.

A massive tsunami generated by the volcano Flank failure is shown in Fig.23. In less than 200 seconds (~ 3 minutes) the thrust created a wave-height of over 300 meters.

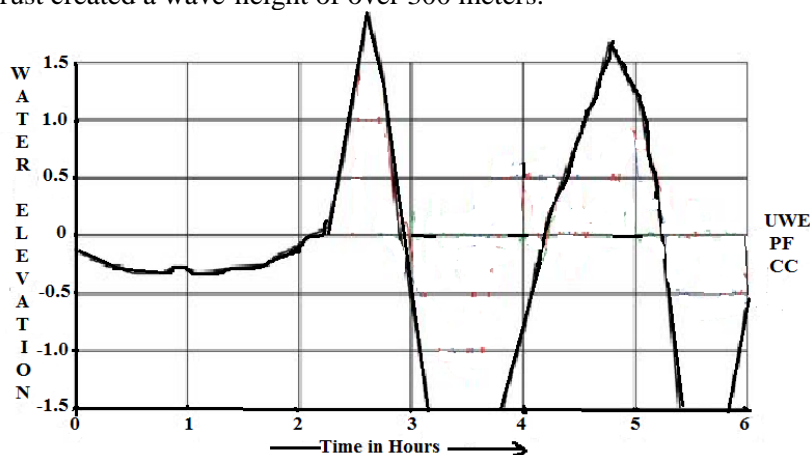


Fig.22 Tsunami Wave Forms of the 1883 Krakatau eruption (Graph re-drawn by author. Graph Credit: Raphael Paris)

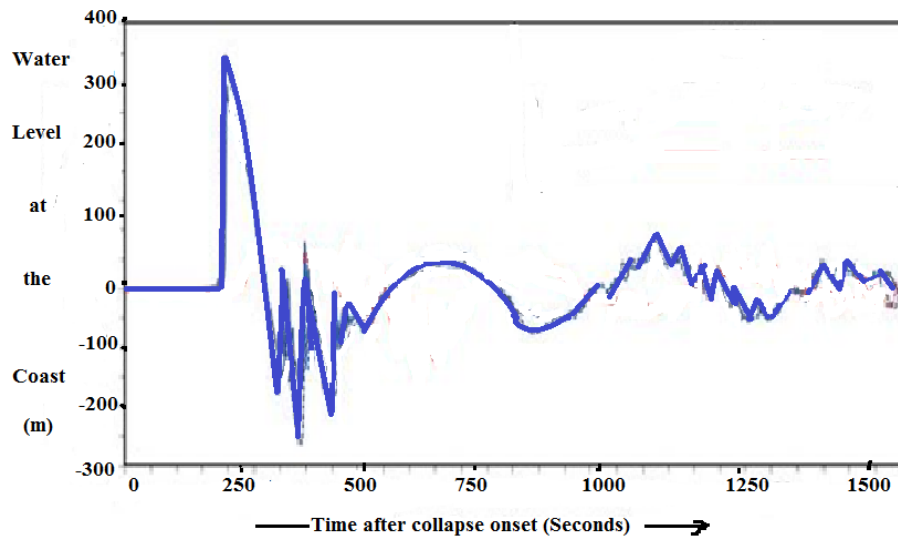


Fig.23 Simulated wave profiles of a massive tsunami generated by Volcano Flank Failure.
(Graph re-drawn by author. Graph Credit:Raphael Paris)

VI LIST OF VOLCANIC TSUNAMIS

John Seach [9] has given a list of volcanic tsunamis in the 20th century starting with the year 1902 and ending with the year 2002 and the same is shown in Table No.

Table

No.	Year	Name of Volcano	Type of Eruption/Generation of Tsunami, etc
1	1902	St Vincent (Caribbean)	Pyroclastic flow generated tsunami.
2	1902	Pelee (Caribbean)	Pyroclastic flow generated tsunami.
3	1906-07	Savai'i (Samoa)	Tsunamis caused by lava entering the sea.
4	1911	Taal (Philippines)	Tsunami caused by base surge.
5	1913	Ambrym (Vanuatu)	Underwater eruption.
6	1913	Taal (Philippines)	Unknown wave height.
7	1915	Bayonnaise Rocks (Myojin Reef) Japan	Unknown wave height.
8	1928	Paluweh (Indonesia)	Waves 10 m. Caused by avalanche. 150 killed.
9	1929	Anak Krakatau (Indonesia)	Wave 4 m.
10	1930	Stromboli (Italy)	Wave 2 m. Caused by volcanic earthquake and landslide.
11	1933	Severgin (Kurile Islands)	Waves 10 m. Caused by volcanic earthquakes.
12	1937	Rabaul (Papua New Guinea)	Wave over 4 m, caused by volcanic earthquake.
13	1951	Kavachi (Solomon Islands)	Unknown wave height.

14	1952	Bayonnaise Rocks (Myojin Reef) Japan	Submarine eruption. Wave 2 m.
15	1953	Tuluman (Papua New Guinea)	Small wave.
16	1956	Bezymianny (Russia)	Tsunami caused by shockwave.
17	1965	Taal (Philippines)	Tsunami caused by base surge.
18	1969	Didicas (Philippines)	Three killed.
19	1971	Tinakula (Solomon Islands)	Unknown wave height.
20	1972	Ritter (Papua New Guinea)	Subsidence. Small tsunamis.
21	1974	Ritter (Papua New Guinea)	Subsidence. Small tsunamis.
22	1979	Illiwering (Indonesia)	Waves 9 m. Caused by avalanche. Over 500 killed.
23	1980's	Ruapehu (New Zealand)	Wave < 2 m.
24	1980	St Helens (USA)	Waves 260 m. Caused by avalanche into lake.
25	1983	Illiwering (Indonesia)	Submarine eruption. Some deaths.
26	1986	Nyos (Cameroon)	Waves 75 m. Caused by underwater eruption of CO ₂ .
27	1988	Vulcano (Italy)	Waves 5.5 m. Caused by avalanche.
28	1994	Rabaul (Papua New Guinea)	Wave 1.2 m. Caused by pyroclastic flow.
29	1996	Karymsky (Russia)	Waves 30 m. Caused by phreatomagmatic eruption.
30	1997	Soufriere Hills (Montserrat)	Waves 3 m. Caused by volcanic debris slide.
31	2002	Stromboli (Italy)	Landslide.

VII CONCLUSION

Thus, the wrath of Ruauumoko created lot of damage and destruction to lives and property. But, at the same time engaged a large number of scientists particularly geophysicists and volcanologists in the research regarding the scientific aspects and the Physics of both the eruption and the tsunami.

In the Conclusion, I would like to add some of my own ideas and hence for this there is no reference. Any research Paper is just a collection of ideas published by others and reviewed to look different. Nobody can create new things something like the 'Principle of Conservation of Matter and Energy' where both have the same identity and when they are annihilated appear in different forms. I have certainly tried my best to make the paper look different if not unique.

Most of the volcanic tsunamis occur due to eruption of volcanoes situated in islands. In fact some of the islands are volcanic islands such as Iceland and Hawaii. In the case of Anak Krakatau eruption of

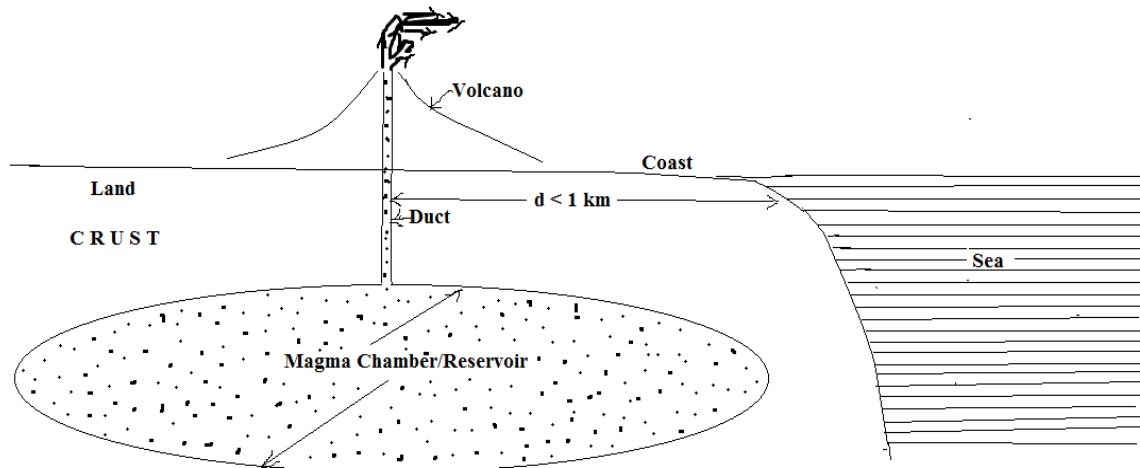


Fig.24 Volcanic eruption near shore (less than a km from the volcano)[Freehand diagram by author]

23 December 2018, the eruption was vigorous and erratic with the flank of the volcano right away falling into the sea. Further explosion of the magma chamber added insult to injury. In Fig.24 I have drawn and shown the positions of the volcano and the magma chamber with respect to the sea. The volcano is shown hardly a kilometer away from the sea. The overall effect here was both the explosion of the volcano along with the magma chamber.

In Fig.25 I have shown the situation where the sea is far away from the volcano. In such a case the effects, damage and hazards due to the volcano still remain in areas near the volcano. But, due to the large size of the magma chamber, there is no excuse for the generation of tsunami. In the figure, the size of the chamber is purposely drawn larger as already mentioned somewhere in the literature of this paper regarding the size of the chamber. A tsunami to generate requires just a trigger such as the molten magma flowing into the sea more faster from the explosion of the chamber rather than from the vent of the volcano.

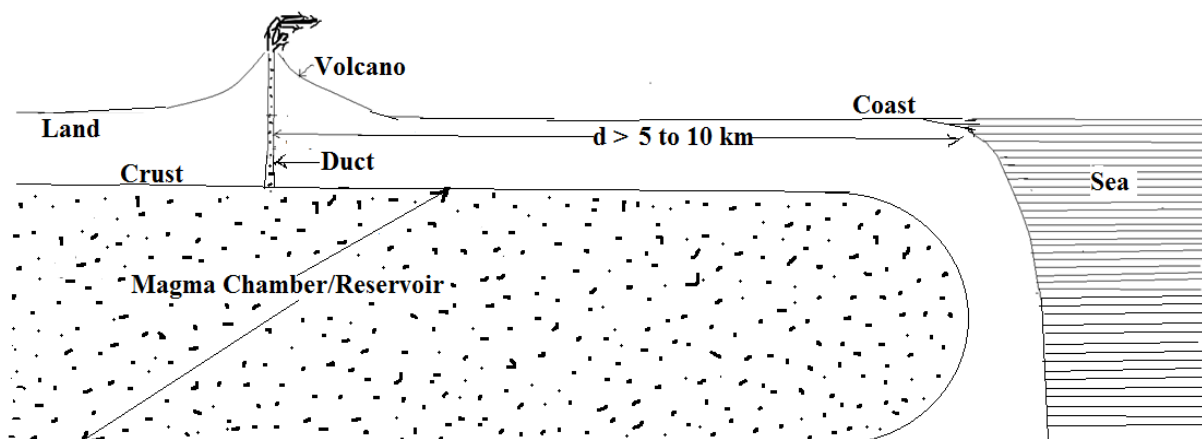


Fig.25 An erupting volcano far away from the sea) [Freehand diagram by author]

Before I conclude, it is of interest to know the extent of damage at a place created by an erupting volcano. In Fig26 is shown a bar graph giving a brief idea about the damage at a place and certain time and distance from the volcano such that with the volcano at the center, the damage created in a circle of say radius 10 km can be worked out. On the x-axis is shown the distance in kilometers. There is no unit for the damage and destruction. As and when the eruption is on, the molten lava continues to flow. The dangerous volcanic ash is thrown out of the vent and reaches kilometers above. They get spread in the atmosphere by blow of winds and also due to rotation of the Earth. There are possibilities of seismic tremors as well. In general, the area

around the volcano is a dangerous zone. I have assigned some arbitrary units from 1 to 10 along the y-axis. Thus, coming to the figure, we find that at a distance of and up to 1 km, the damage is maximum shown by the shaded area ABCD in pink color. Now, at a distance of 2 km, the damage is shown by the shaded area in green which is less than the previous one. But, the total damage at 2 km distance is area of rectangle ABCD plus the green shaded area on the right and so on.

Finally, at a distance of 10 km, the damage is only area of the rectangle PQRS. But, total damage due to eruption is the areas of all the shaded rectangles put together.

In order to justify my graph, I may give an illustrative example. Let us take death due to inhalation of volcanic ash as a damage. Assume that 12 people die within a radius of 1 km from the volcano; Some 10 people die at 2 km radius; 1 die at 3 km radius; Nobody dies at 4 km radius; Some 3 die at 5 km radius; Nobody dies at 6 km radius; 2 die at 7 km radius; 1 dies at 8 km radius; 1 dies at 9 km radius and nobody dies at 10 km radius. Thus, the total number of deaths within a radius of 10 km from the volcano is:

$$12 + 10 + 01 + 00 + 03 + 00 + 02 + 01 + 01 + 00 = 30$$

According to this, wherever there is no death, the bar graph has to be zero. But, it is not zero because we have taken death as a damage. There can be other damages such as sickness due to skin eruption, loss

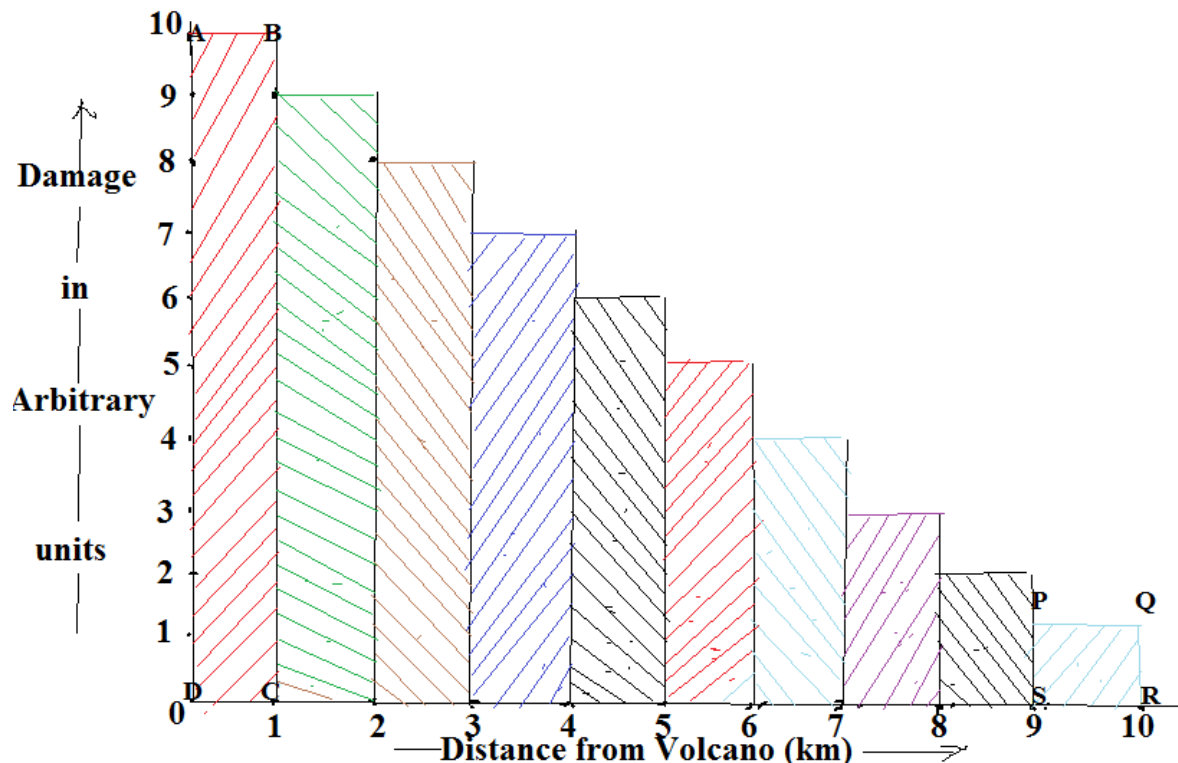


Fig.26 Bar graph showing the extent of damage and destruction created by a volcano

of life of cattle, damage caused to vegetation, etc. Thus, the bar graph is justified. Finally what I conclude is that the graph is a proportionality graph where the damage is inversely proportional to the distance. That is,

$$(\text{Damage}) \propto \left(\frac{1}{\text{Distance}} \right) \dots \dots \dots (14)$$

This is the reason why the State Departments advice an evacuation of population in the region.

I would like to invite comments from readers in this regard on my e-mail.

REFERENCES

- [1] C. Annen., J.D. Blundy and RSJ Sparks: Reproduced with permission from C Annen et.al "The Genesis of Intermediate of Silicic Magmas in Deep Crustal Hot Zones. Journal of Petrology, Pub. Online by Oxford Univ. Press (2006) 47(3), p.505-539.
- [2] Becky Oskin of Live Science reports in the Scientific American: 6 March 2015
- [3] Browning John, Kyriaki Drymoni and August Gudmudsson: Forecasting Magma-chamber rupture at Santorini volcano, Greece. Scientific Reports, 28 Oct. 2015.
- [4] China Daily.com, Antara Photo, 28 Dec. 2018.
- [5] David M. Pyle, Prof. of Earth Sc. UK
- [6] T. Giachetti . R Paris K. Kelfoun and B. Ontowirjo. Tsunami Hazard related to flank collapse of Anak Krakatao volcano, Sunda Strait, Indonesia, Geological Society Publications, London, Jan.2012, p.79-90
- [7] Geoscience, Australia based at Canberra, Australia carrying Geoscientific Research.
- [8] International Tsunami Information Center (ITIC) based at Honolulu, Hawaii, US
- [9] John Seach, Volcanic Tsunamis, Volcanolive.com
- [10] Maya Wei Haas, a Science writer for National Geographic
- [11]Newhall C.G. and S. Self. The Volcano Explosive Index (VEI). An estimate of explosive magnitude for historical volcanism, Journal of Geophysical Research, 87.C2, p.1231-1238.
- [12]Raphael Paris, Source Mechanisms of Volcanic Tsunamis, Philosophical Transactions of the Royal Society-A Mathematical, Physical and Engineering Sciences. 28 Oct. 2015. p.1-15
- [13]Reynold James. A Journalist visited the place on Sunday, 13 Jan.2019 reporting that the crater area has become a lake and steaming.
- [14]Samir G. Khouri – Tsunami Basic Principles
- [15]Simon Winchester. A British- American author and journalist-The Day World Exploded (on the 1883 eruption of Krakatau). Harper Collins Publishing Co.
- [16]Taro Kakinuma, Hiroshi Matsumoto, Kei Yamashita and Yudai Yanagi of Graduate School of Science and Engineering, Kogashima Univ., Japan. Tsunami Generation due to Submarine Volcanic Eruptions with Phreatomagmatic Explosion or Caldera Subsidence. Jan.2014.
- [17]Telegraph News, Jakarta, Indonesia.
- [18]Terence Tao. The Shallow Water Wave Equation and Tsunami Propagation-Updates on my research and expository papers, discussion of open problems and other math- related topics, published under title, "What's New?"
- [19]Volcano World, an educational site at the Univ. of North Dakota.
- [20]Wikipedia
- [21] **Important Note:** Readers are advised to extensively go through the following two Research Papers by the same author in the same publication:
 1. "A Colossal Tsunami, an Offspring of a Gigantic Under-Water Earthquake" by Dr.(Prof) V.C.A. Nair, International Advanced Research Journal in Science, Engineering and Technology, Vol.5, Issue-1, Jan. 2018, p.77-89.
 2. "Volcanoes, an Excellent Indicator of Heat within the Earth" by Dr.(Prof.) V.C.A. Nair, International Advanced Research Journal in Science, Engineering and Technology, Vol.5, Issue-5, May 2018. P.110-133

BIOGRAPHY



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his e-mail is typed in that style. He is a Life Member of Indian Society for Technical Education which is an all India body. He had been to USA a number of times and visited eminent Universities such as Stanford, Harvard, MIT, 3 Universities of California at Berkeley, Los Angeles and also at Davis, University of Princeton at New Jersey, University of Chicago, Roosevelt University at Chicago and University of San Francisco. At present Dr. Nair is a Research Guide for Physics at Shri JNT University, Rajasthan-333001, India. He is member of the Editorial Board of this Journal. His Ph.D. Thesis is in Geophysics and he is working on topics such as Tides, Clouds, Global Warming and Climate Change. – *Editor*.

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