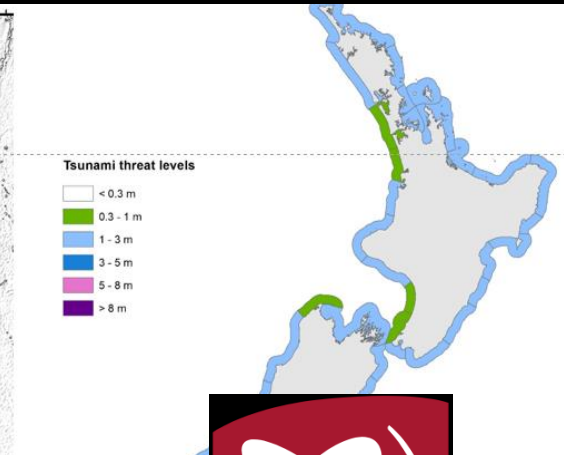
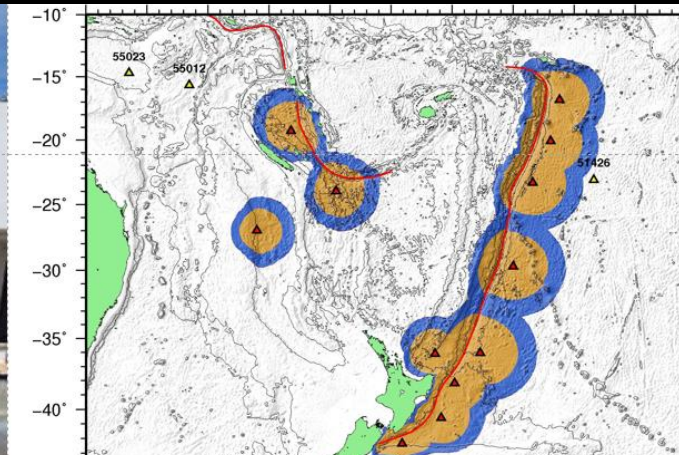


# Volcanic Tsunami Modelling



Aditya Gusman, Xiaoming Wang, and Jean Roger

[a.gusman@gns.cri.nz](mailto:a.gusman@gns.cri.nz)

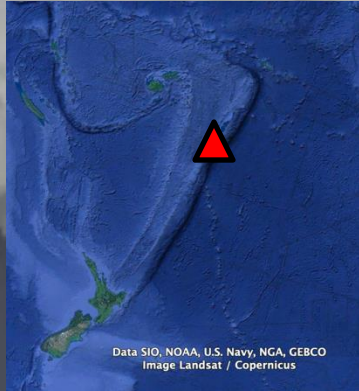
Earth Structure and Processes, GNS Science, New Zealand





# Introduction

## The 2022 HTHH tsunami

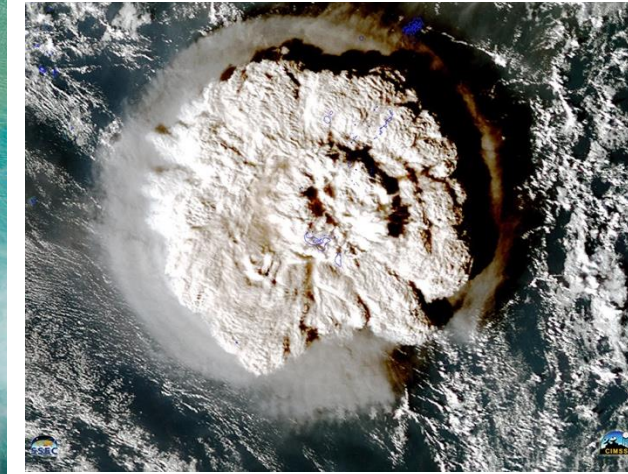


## After the 14 January 2022 eruption



## HIMAWARI-8

## 15 January 2022 eruption



## After the 15 January 2022 eruption





# Tsunami Inundation Observations

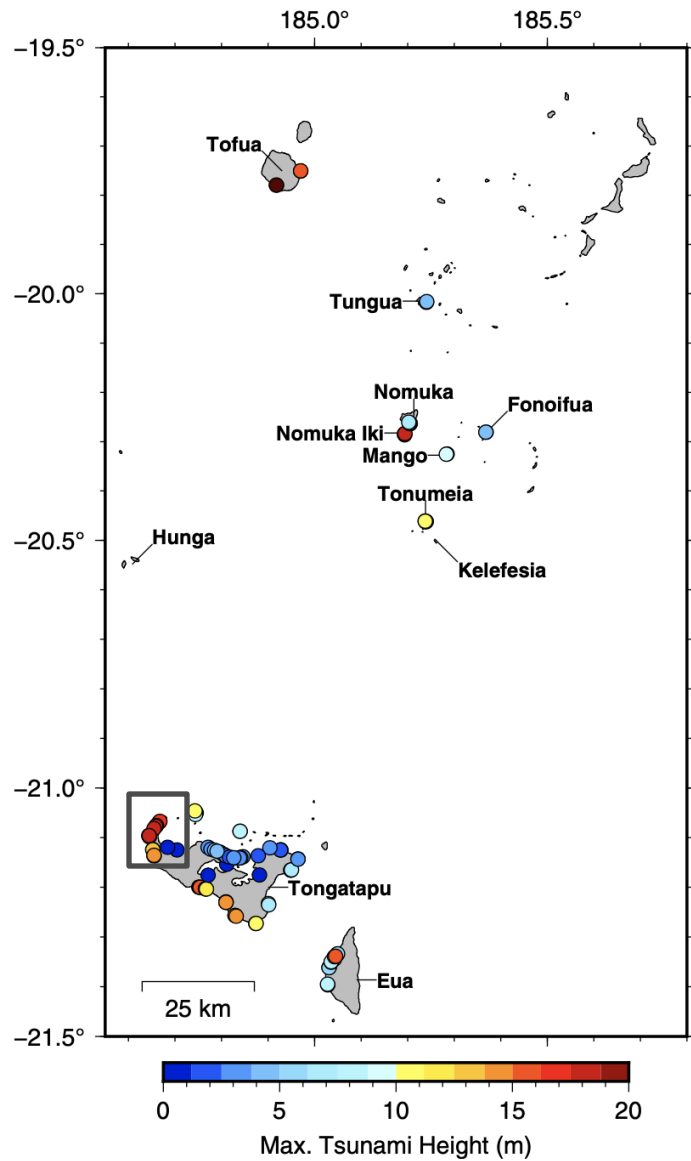
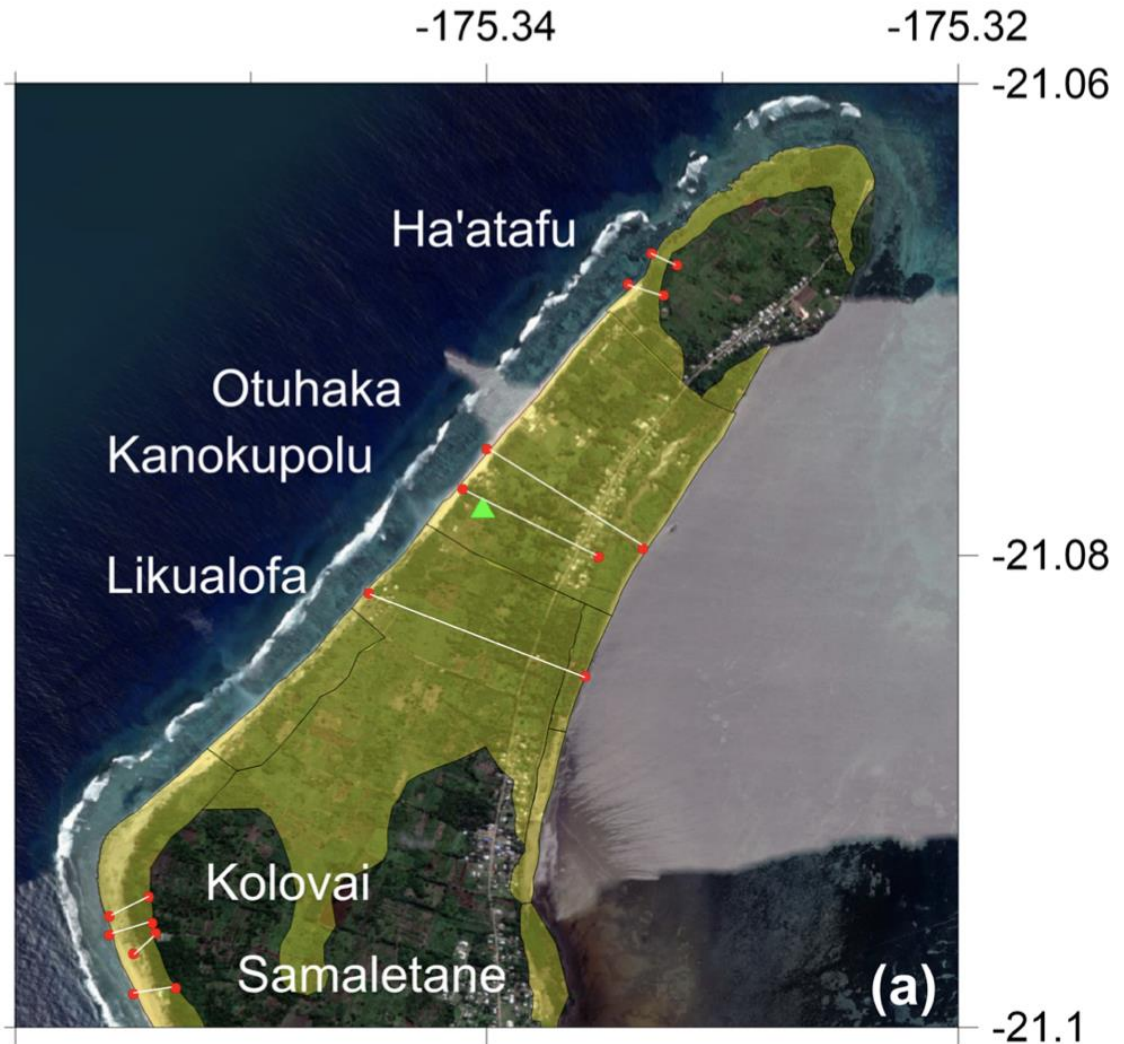
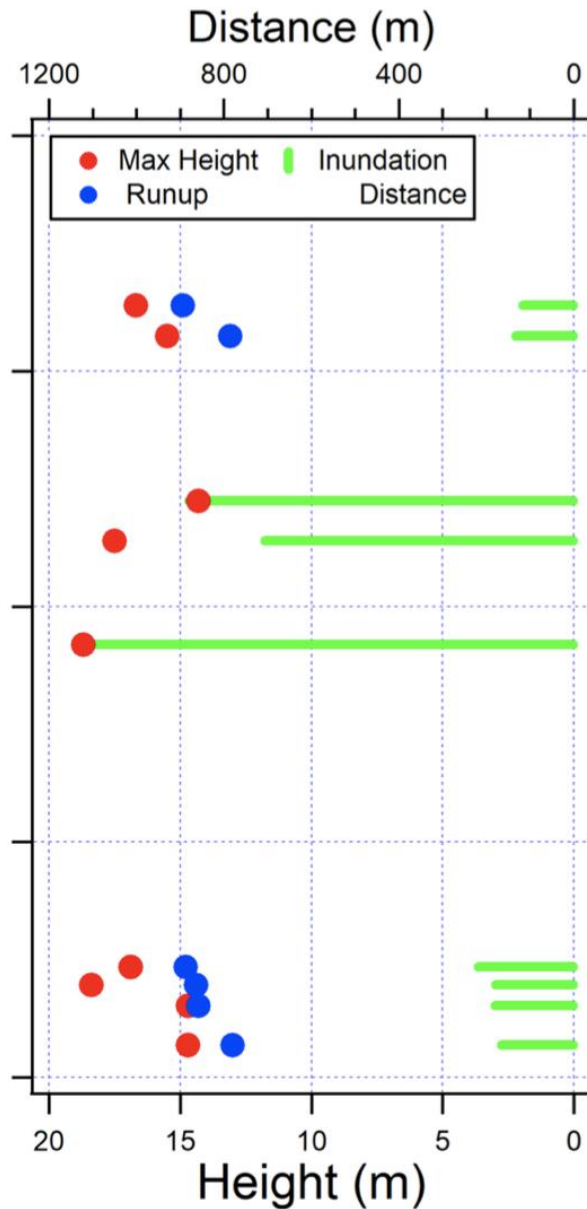


Figure 6  
Summary data plots of maximum measured tsunami heights

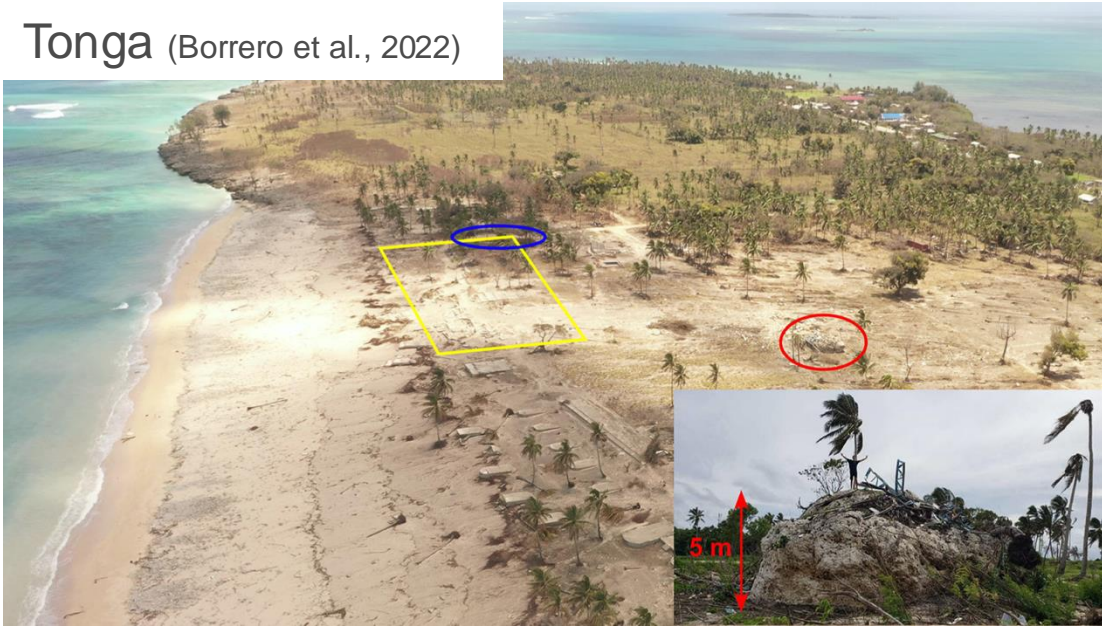


Borrero et al. (2023)



# Tsunami Damages

Tonga (Borrero et al., 2022)



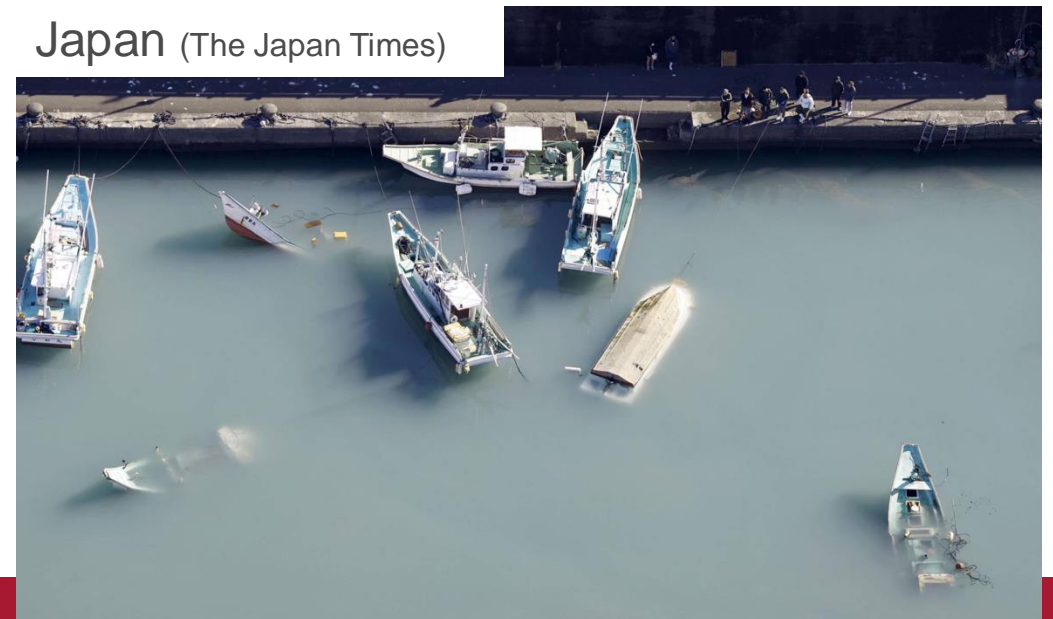
New Zealand (Stuff)



Peru (Merco Press)

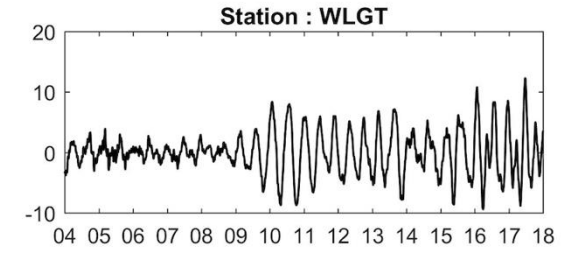
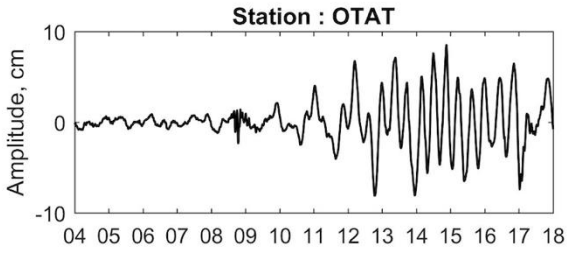
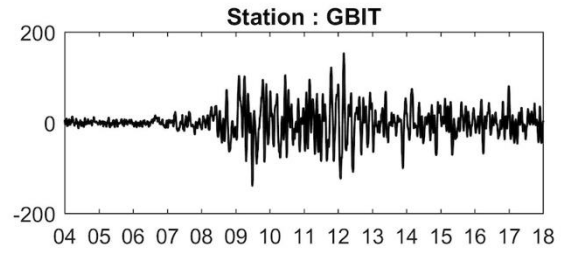
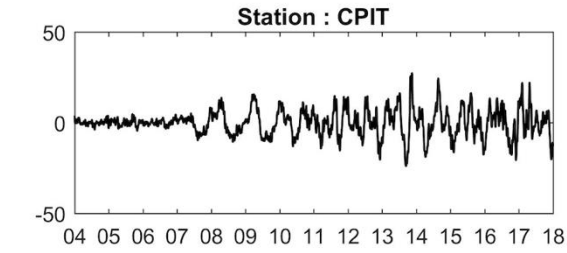
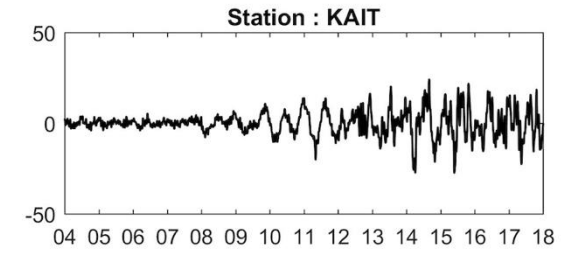
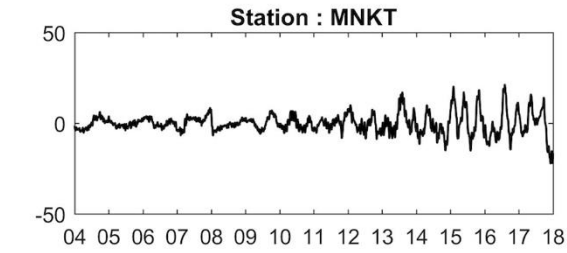
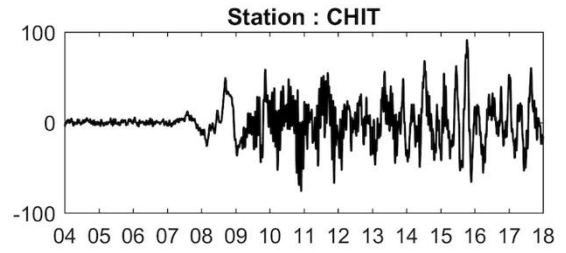
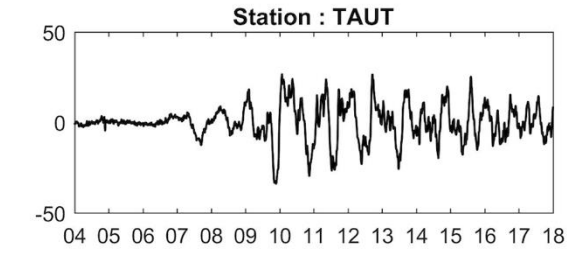
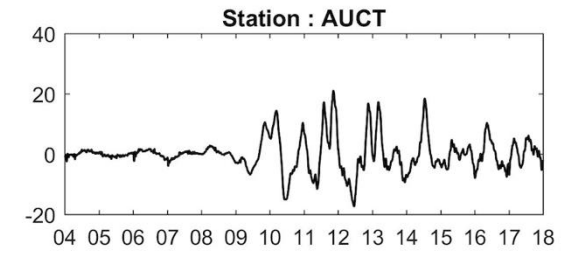
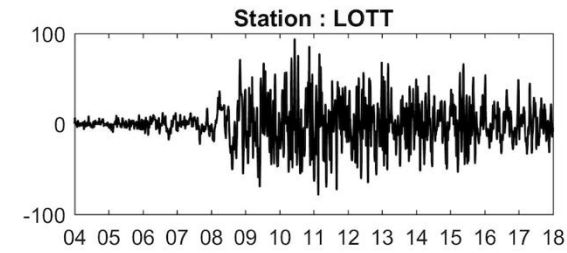
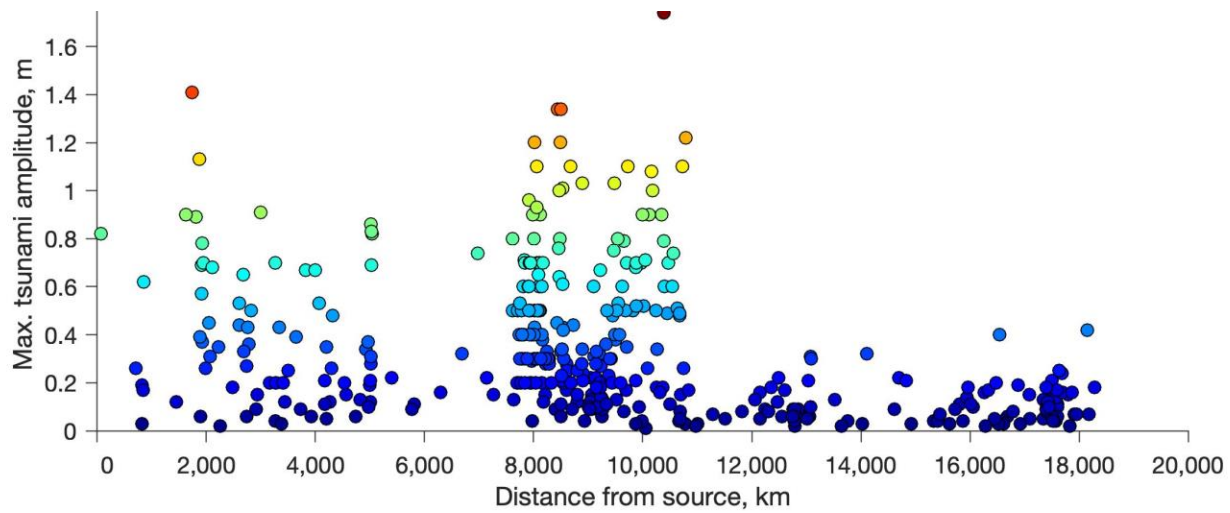
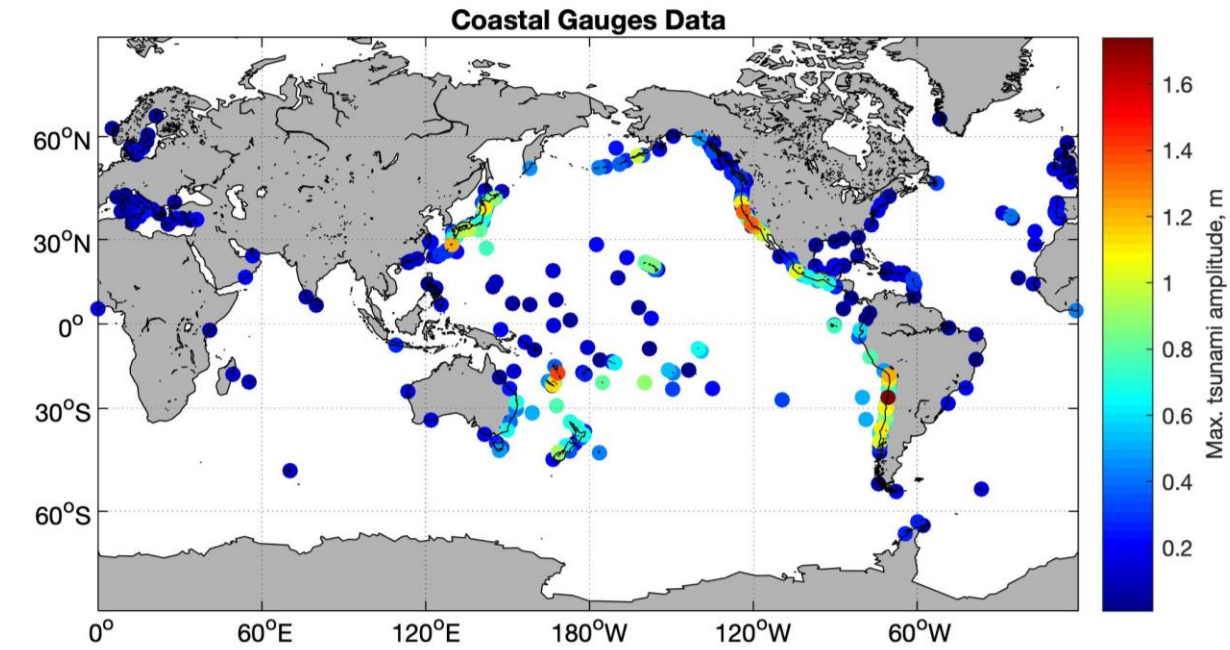


Japan (The Japan Times)





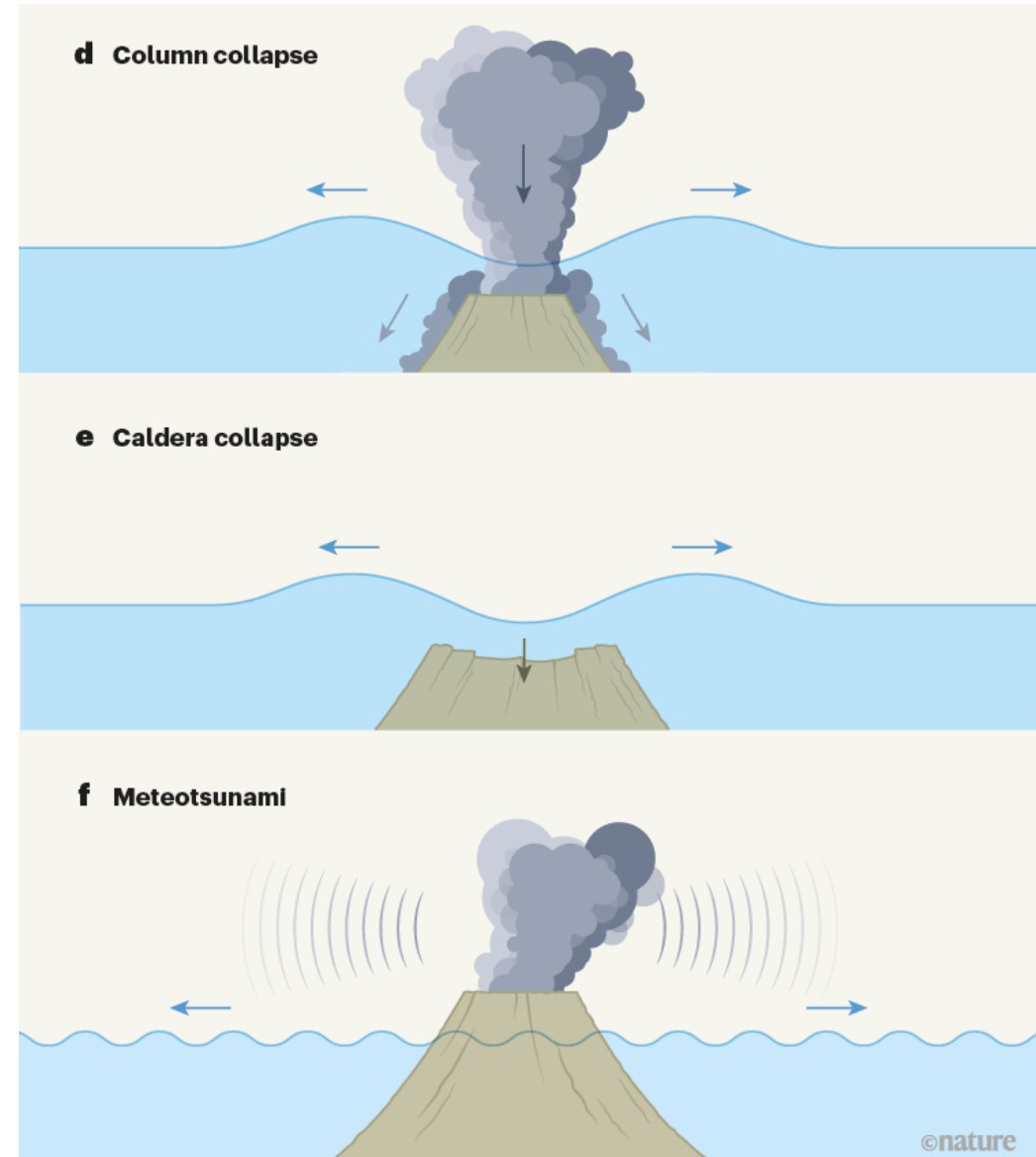
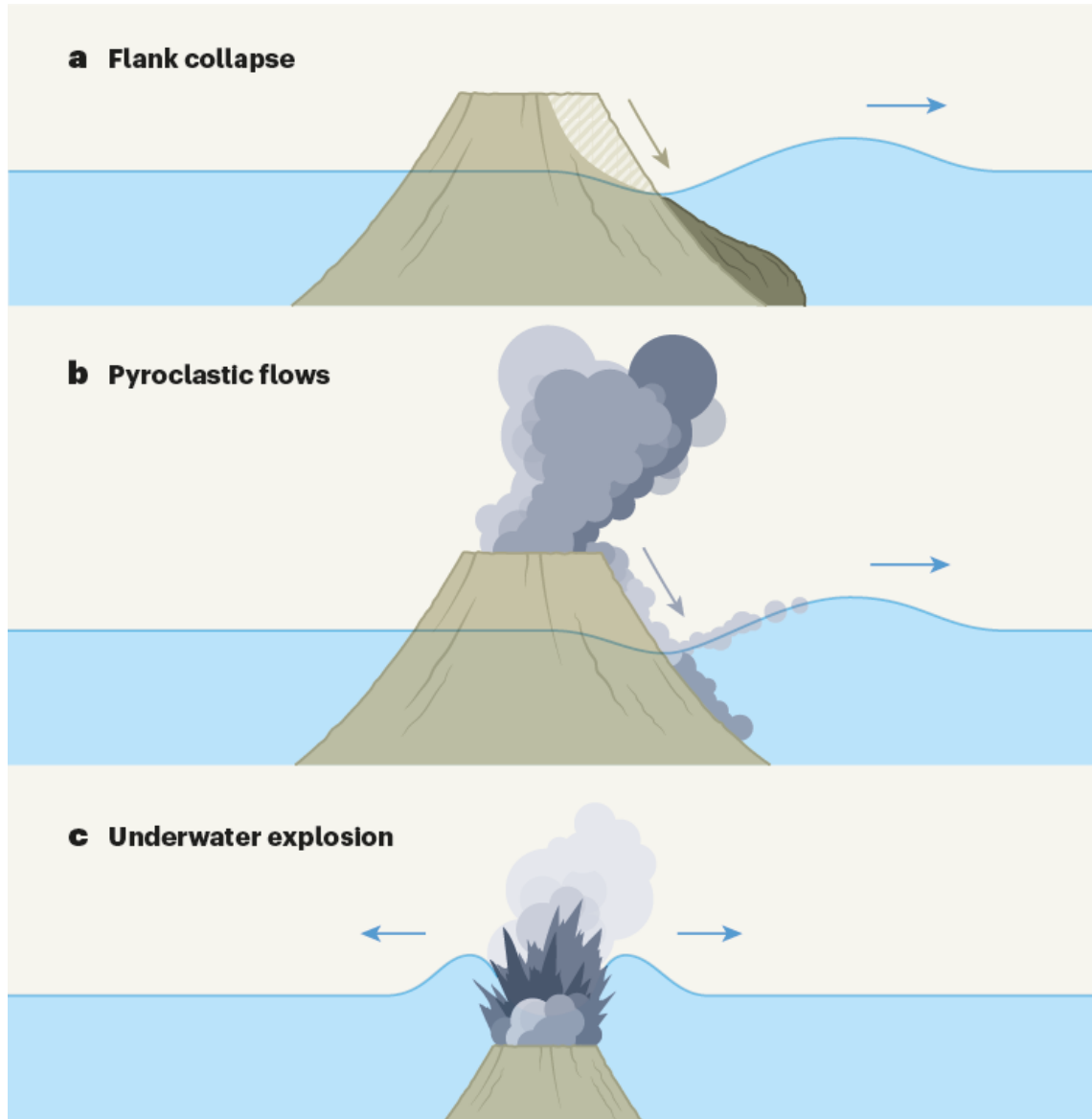
# Coastal Gauges Data



Data source: Global Historical Tsunami Database (NOAA - NCEI)



# Volcanic Tsunami Source Mechanisms



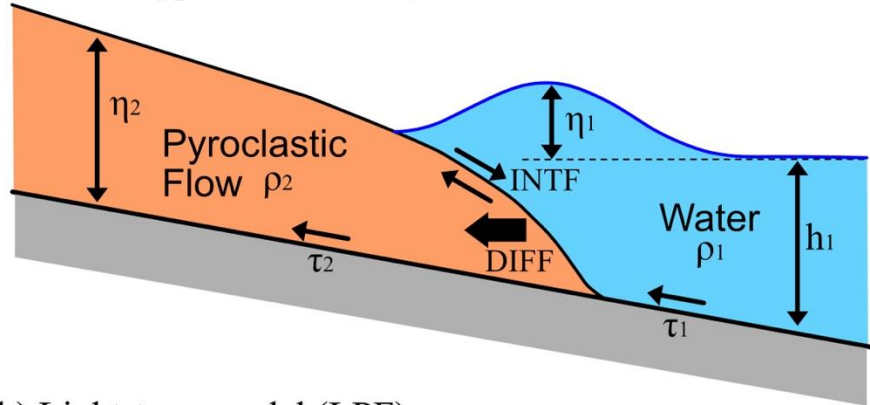
Lane et al. (2022)

©nature

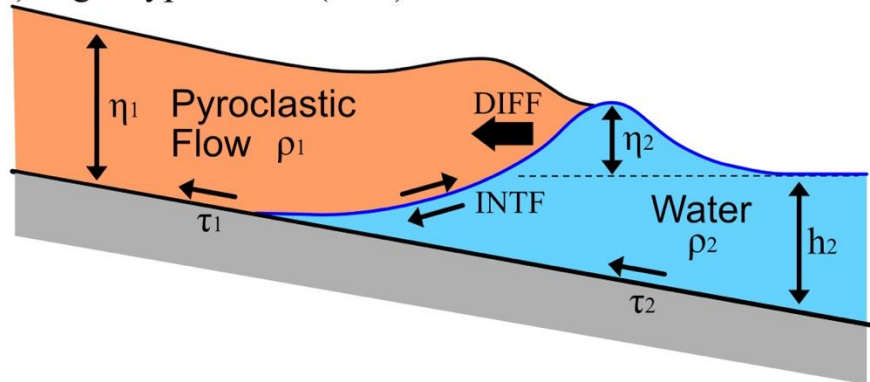


# Pyroclastic Flow and Landslide Generated Tsunami

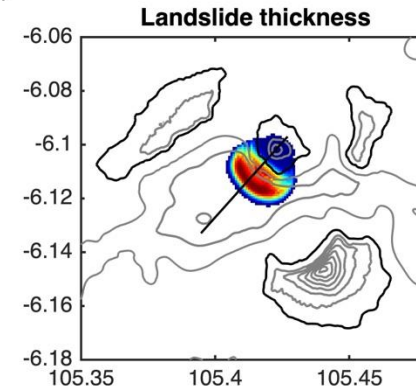
a) Dense-type model (DPF)



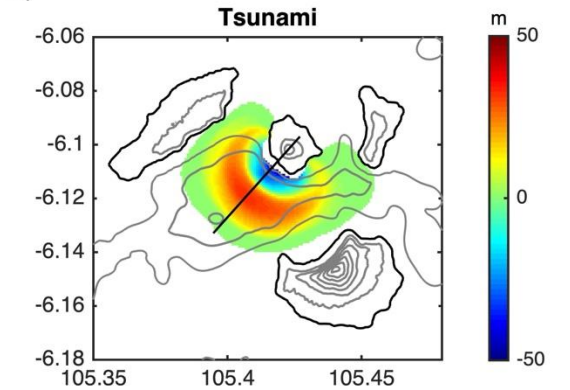
b) Light-type model (LPF)



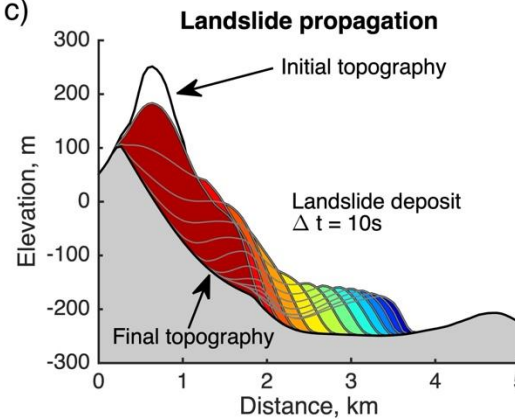
a)



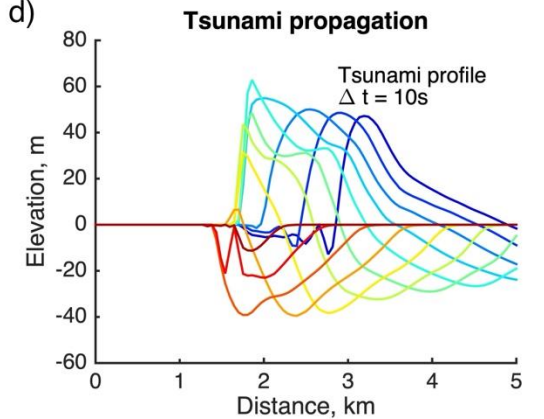
b)



c)



d)

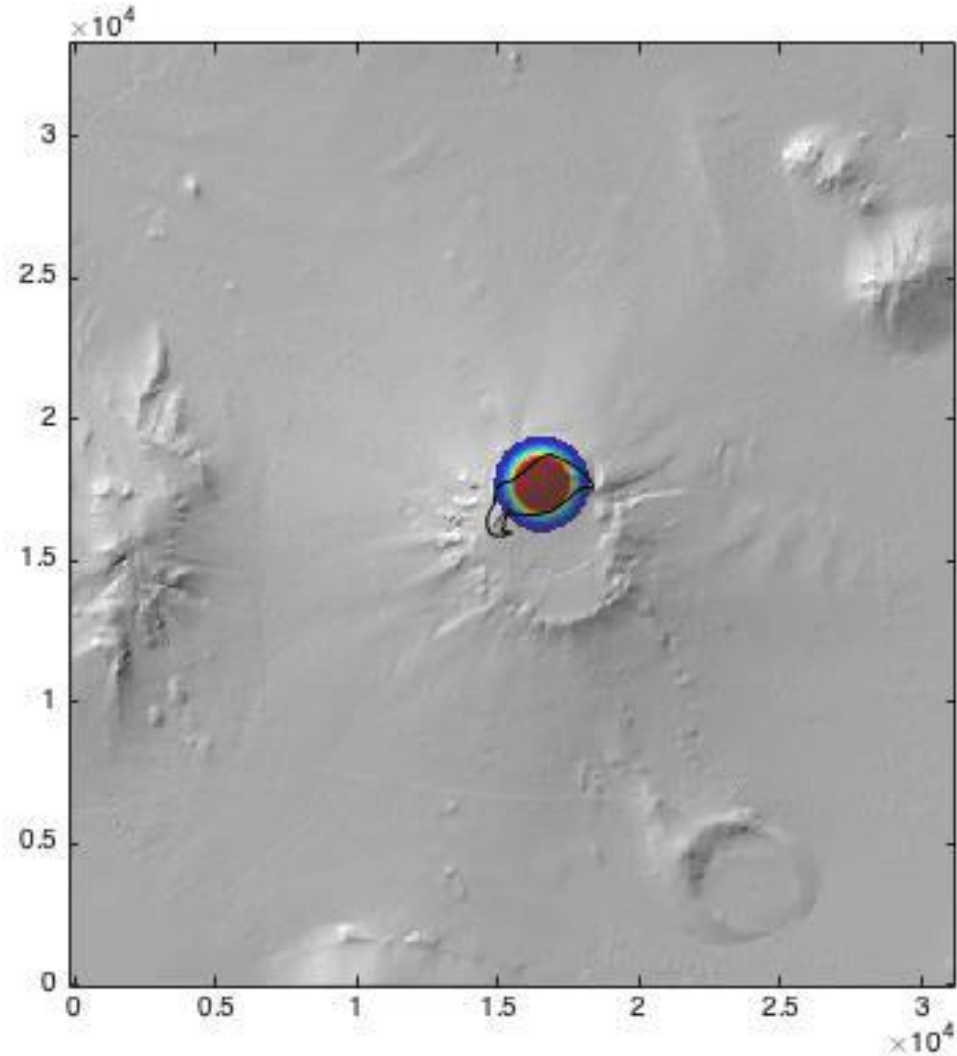


To calculate pyroclastic flows and tsunamis simultaneously, two types of two-layer shallow water models, a dense-type (DPF) model and a light-type (LPF) model were developed by Maeno and Imamura (2011).

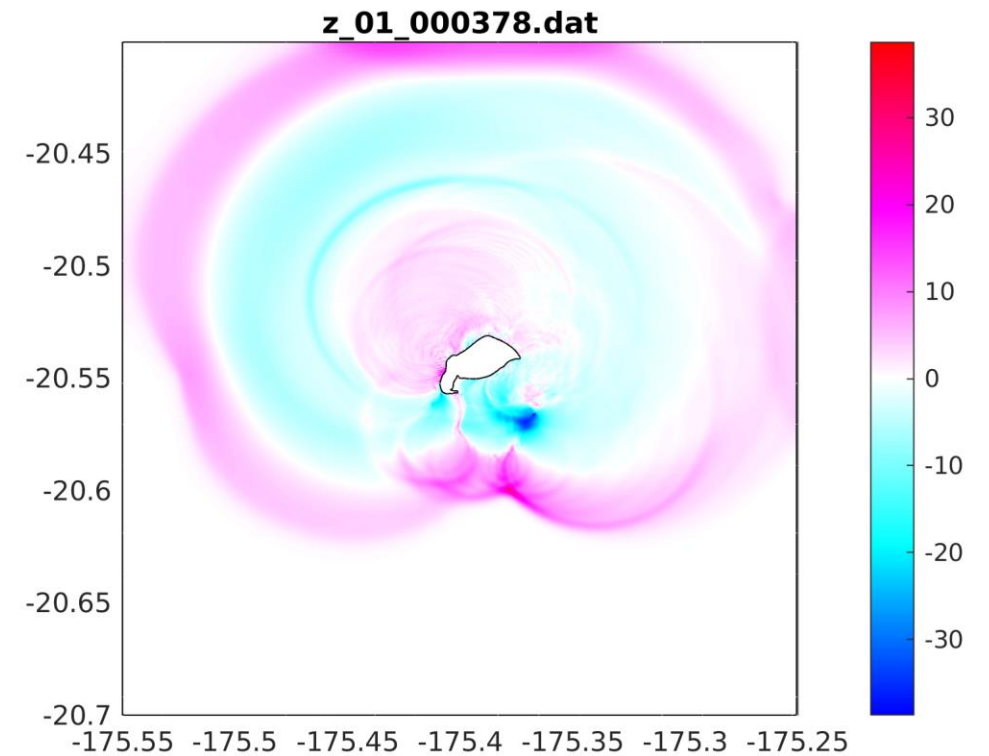
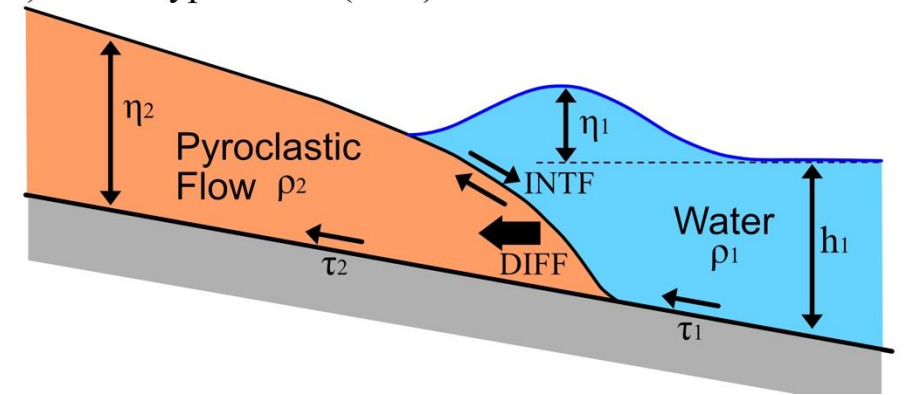
The flank collapse model of the Anak Krakatau Volcano, which occurred during the eruption in 2018



# The 2022 HTHH Eruption: Pyroclastic Flow Tsunami Modeling



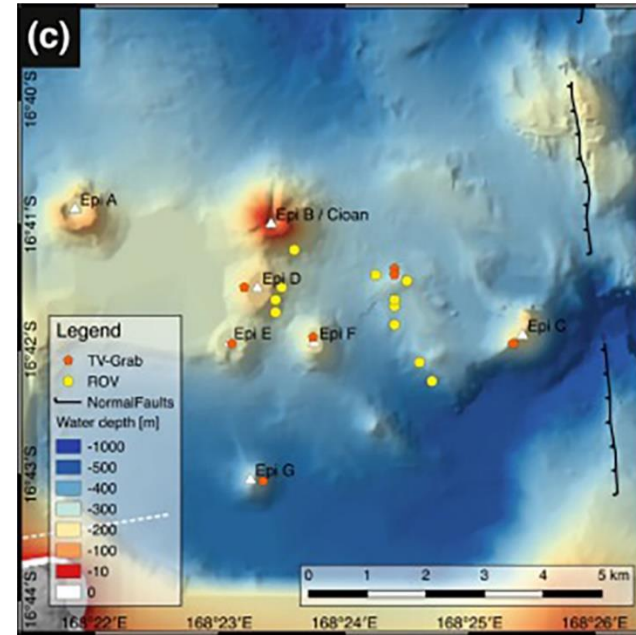
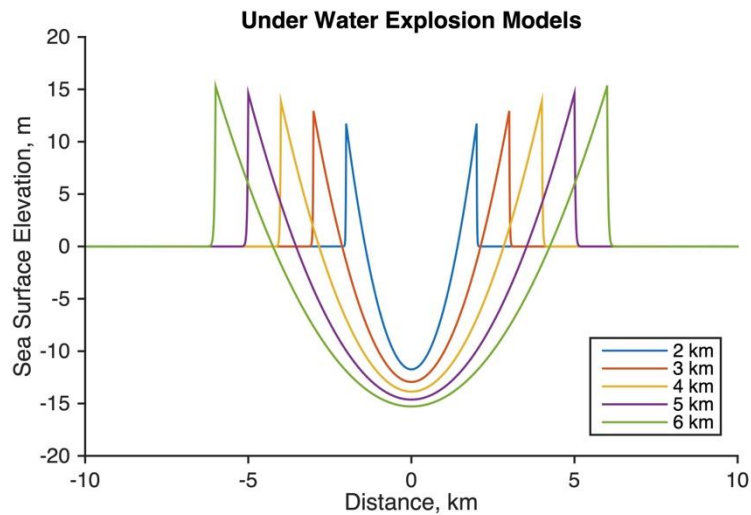
a) Dense-type model (DPF)



# Under Water Explosion Model

A formula to estimate the initial water displacement model for underwater explosions has been proposed by [Le Méhauté \(1971\)](#). Some modification were made after ward ([Torsvik et al., 2010](#)).

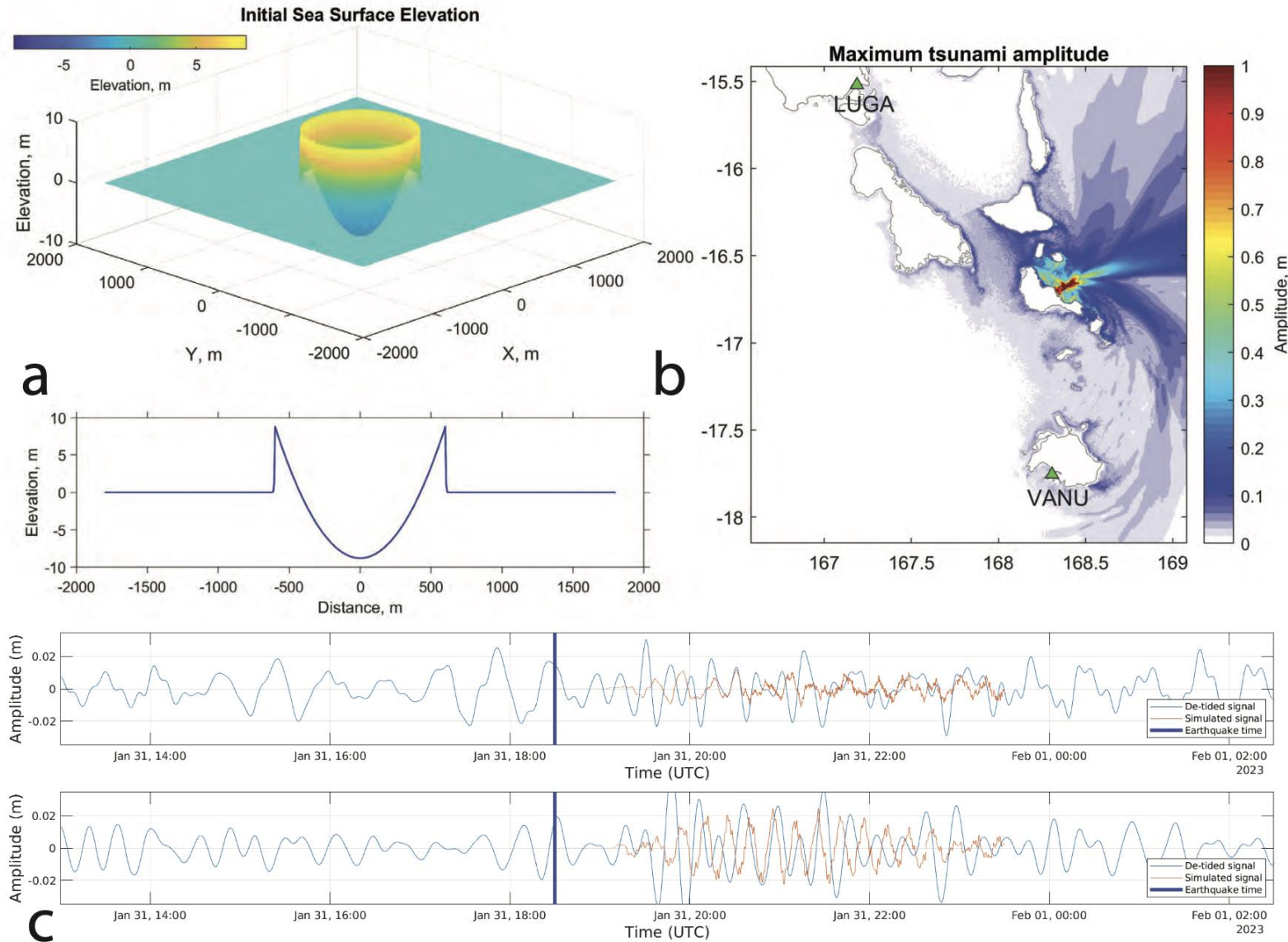
$$\eta(r) = \begin{cases} \eta_0 \left[ 2 \left( \frac{r}{R} \right)^2 - 1 \right], & \text{if } r \leq R \\ \eta_0 \left[ 2 \left( \frac{r}{R} \right)^2 - 1 \right] e^{Pr(1-r/R)}, & \text{if } R < r \leq 2R \\ 0, & \text{if } r > 2R \end{cases}$$



Epi Volcano eruption in December 2023 generated a small tsunami. The tsunami was simulated using an underwater explosion mode (Roger et al., under preparation) (Photo from: Vanuatu Meteorology and Geohazards Department)



# Epi Volcano Tsunami



AGU Fall meeting 2023 Poster (Roger et al., 2023)

Tsunami simulation: (a) Initial sea-surface deformation model (in meters); (b) Maximum wave amplitude map after 5 hours of tsunami propagation on a  $\sim 450$ -arcmin resolution grid; (c) Comparison of the simulated waveforms (red curve) to the de-tided real recorded data (blue curve) at Lugan ville (LUGA) and Port-Vila (VANU) coastal gauges; the data were filtered using a passband filter to remove both tide signal and high-frequency background noise from the 1-minute sampling rate dataset (VLIZ/IOC, 2023).

# The 1883 Krakatau Tsunami

Largest eruption 27 August 1883 3:02 UTC

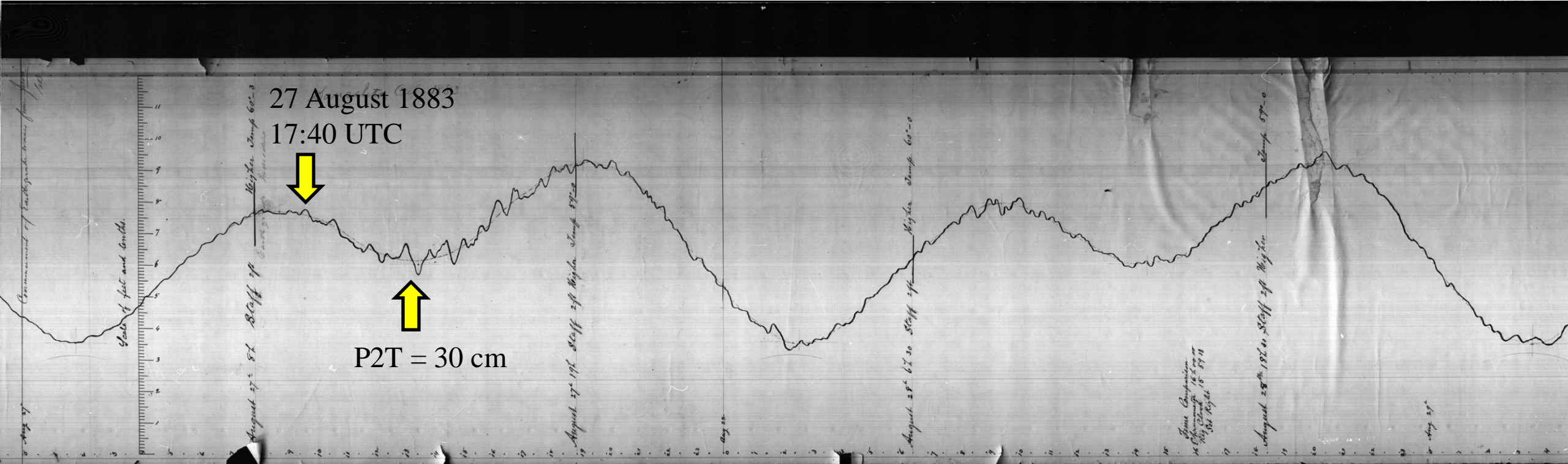
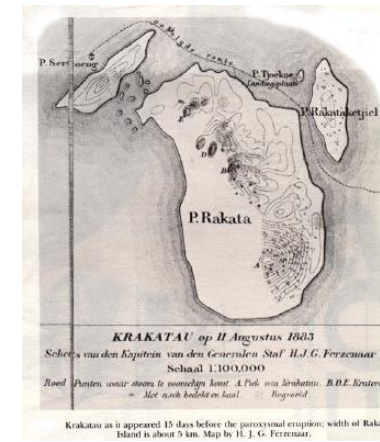
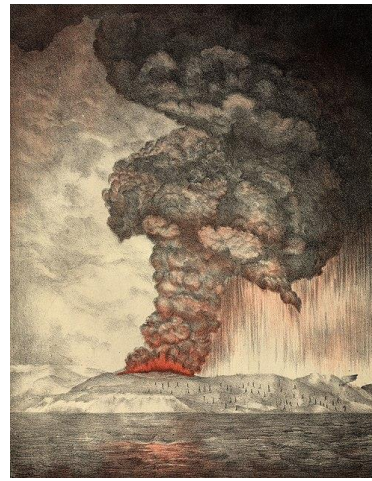
Distance from Krakatau to San Francisco 14,000 km

Arrival time: 27 August 1883 17:40 UTC

Wave speed: 266 m/s

Tsunami speed at 4 km water depth:  $\sqrt{gd} = 200$  m/s

Tsunami speed at 1 km water depth:  $\sqrt{gd} = 100$  m/s





# Lamb Wave Generated Tsunami Simulation

The long wave theory can be used to simulate the behavior of air pressure waves in the atmosphere. The equations take into account factors such as atmospheric temperature, gravity, and air density.

$$\frac{\partial p}{\partial t} + \frac{\rho_a g}{R \sin \theta} \left[ \frac{\partial [u_p H_p]}{\partial \varphi} + \frac{\partial [v_p H_p \sin \theta]}{\partial \theta} \right] = 0$$

$$\frac{\partial u_p}{\partial t} + \frac{1}{\rho_a R \sin \theta} \left[ \frac{\partial p}{\partial \varphi} \right] + f v = 0$$

$$\frac{\partial v_p}{\partial t} + \frac{1}{\rho_a R} \left[ \frac{\partial p}{\partial \theta} \right] - f u = 0$$

$$H_p = \frac{\gamma R T}{g M}$$

$\gamma = 1.4$ ; % ratio of specific heat of air

$T = 288$  % K

$R = 8314.36$ ; % J Kmol<sup>-1</sup> K<sup>-1</sup> universal gas constant

$M = 28.966$ ; % kg Kmol<sup>-1</sup> Molecular mass for dry air

$g = 9.81$ ; % gravity acceleration m s<sup>-2</sup>

$\rho_a = 1.225$ ; % air density in 15C in kg m<sup>-3</sup> (Amores et al., 2022)

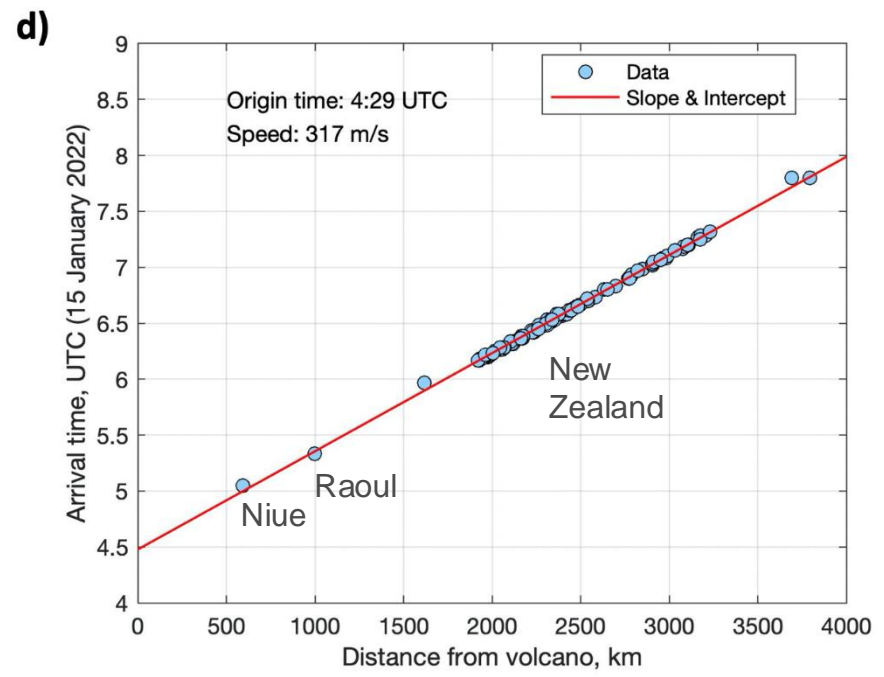
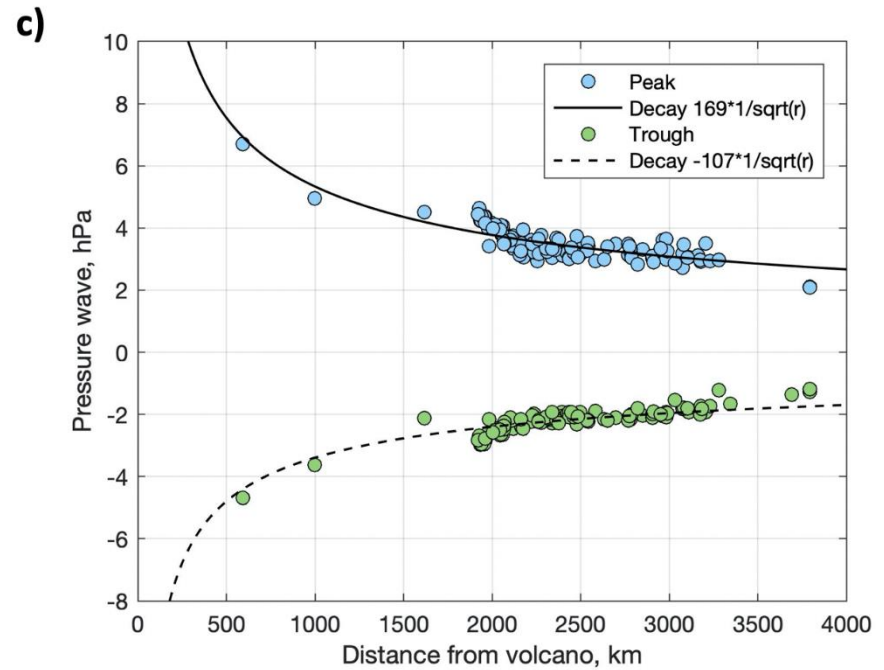
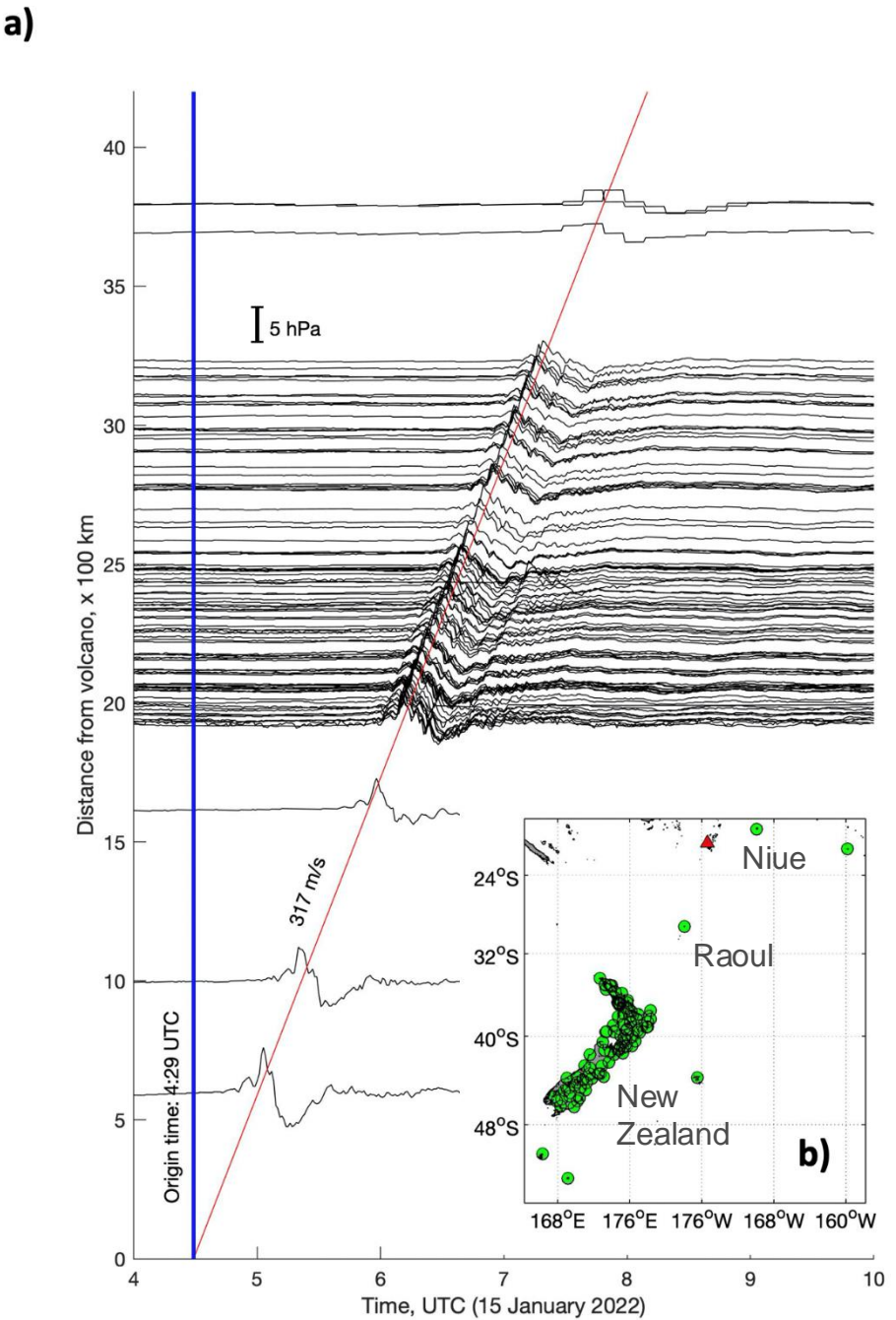
To simulate the tsunami generated by the air wave we used a linear shallow water wave model with the atmospheric pressure term in spherical coordinates

$$\frac{\partial h}{\partial t} + \frac{1}{R \sin \theta} \left[ \frac{\partial [ud]}{\partial \varphi} + \frac{\partial [v d \sin \theta]}{\partial \theta} \right] = 0$$

$$\frac{\partial u}{\partial t} + \frac{1}{R \sin \theta} \left[ g \frac{\partial h}{\partial \varphi} + \frac{1}{\rho} \frac{\partial p}{\partial \varphi} \right] + f v = 0$$

$$\frac{\partial v}{\partial t} + \frac{1}{R} \left[ g \frac{\partial h}{\partial \theta} + \frac{1}{\rho} \frac{\partial p}{\partial \theta} \right] - f u = 0$$

$$p_{obs} = p_{atm} + p_{\eta}$$



# Air pressure observations

- Air pressure data at 94 stations (600 – 4000 km from HTHH volcano) were provided by MetService.
- Air-wave amplitude decays proportionately to  $1/\sqrt{r}$ .
- Estimated wave speed: **317 m/s**.
- Effective origin time: **4:29 UTC**.
- We used the above information to make a simple air pressure wave model.

Gusman et al. (2022)



# Simple Lamb wave Model

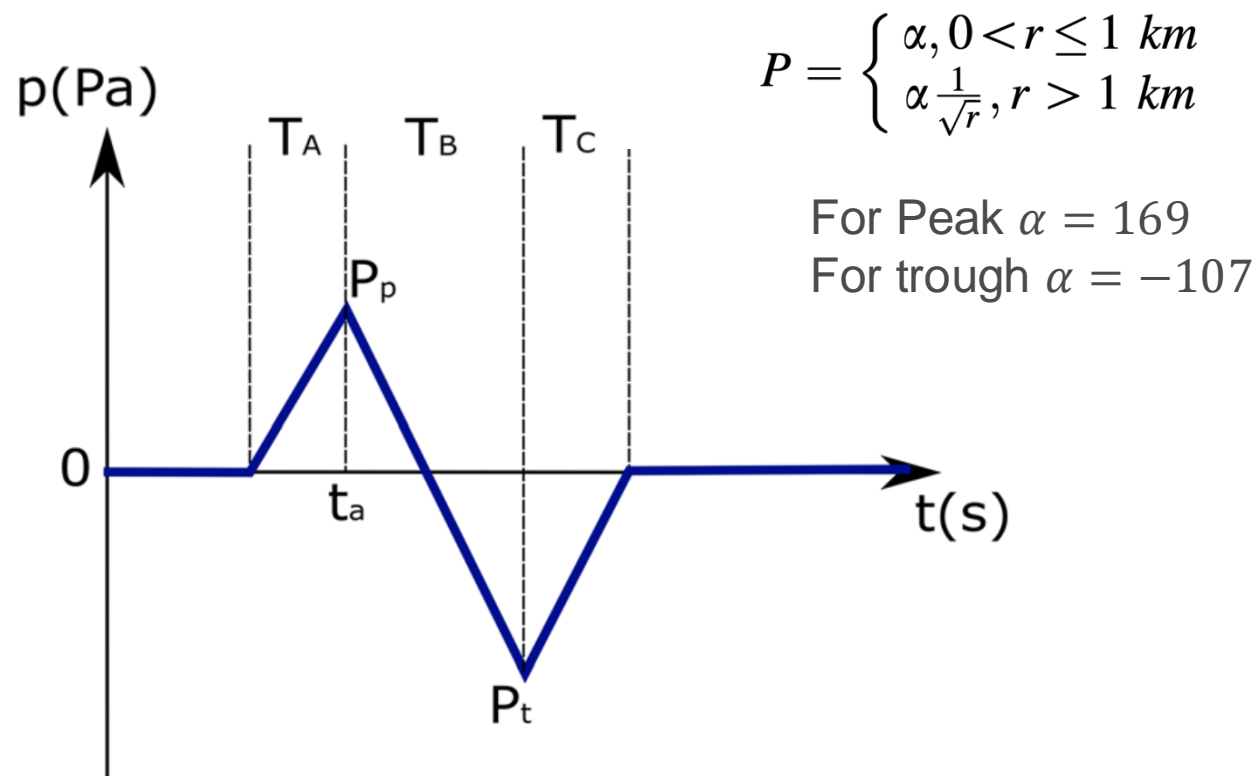
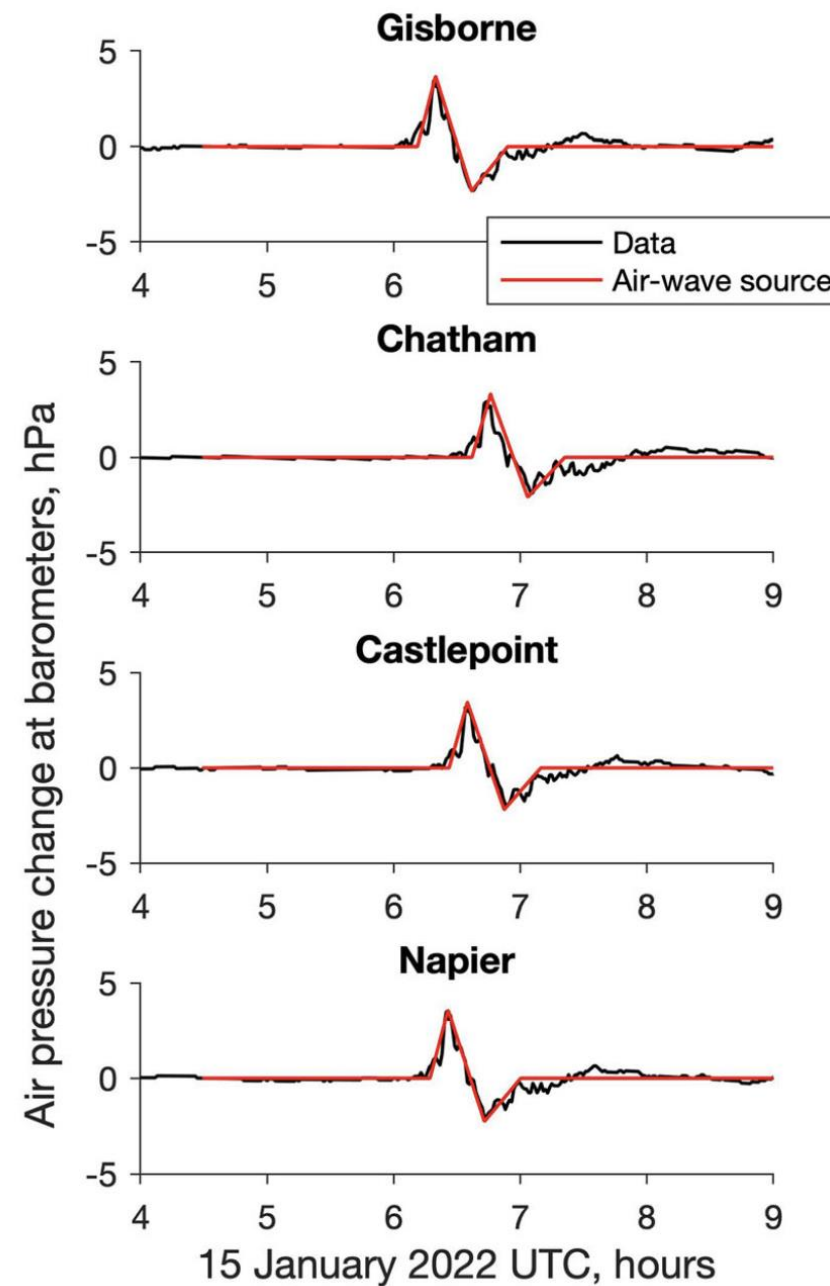
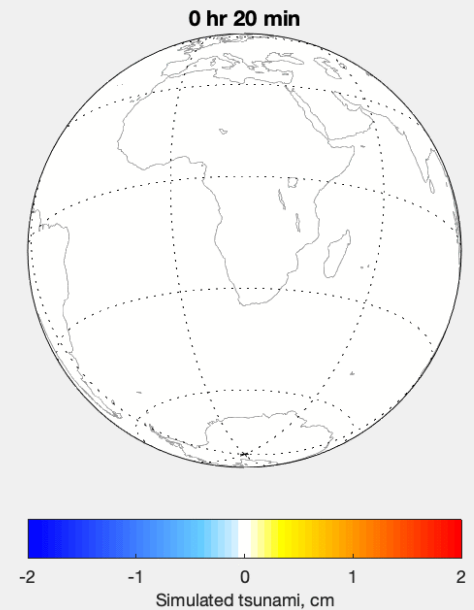
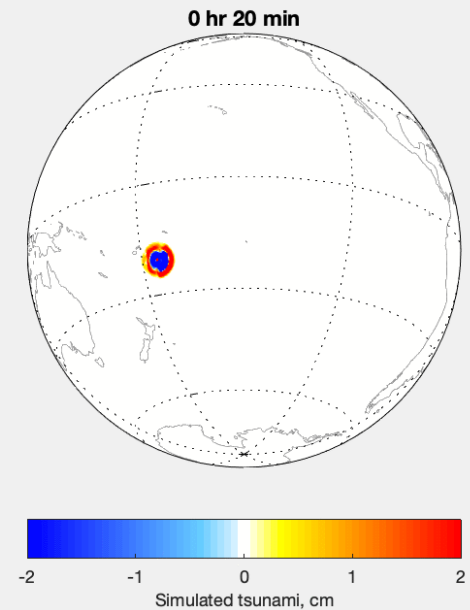
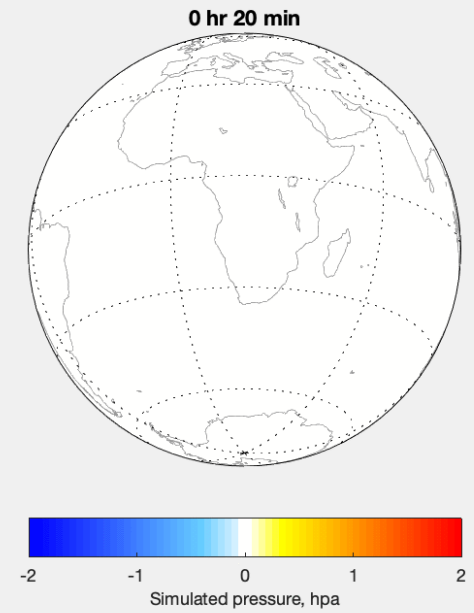
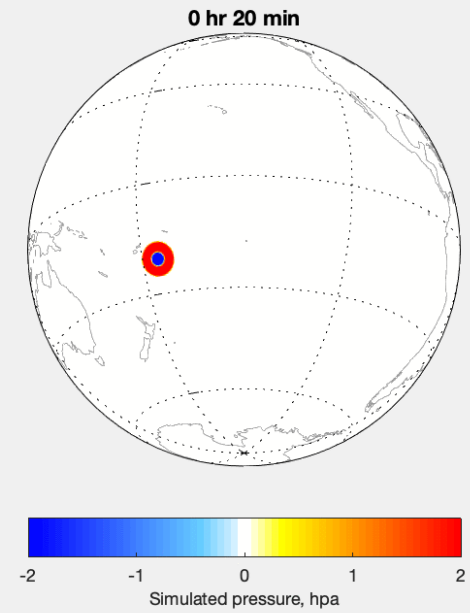
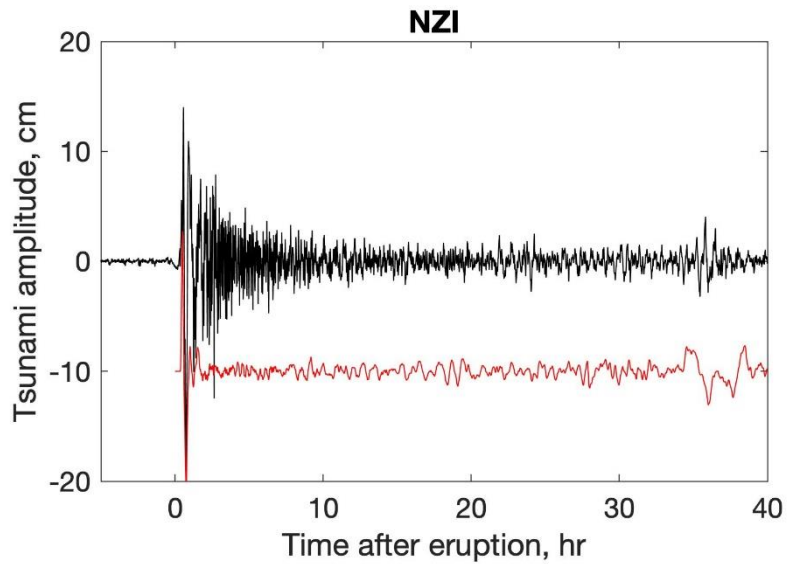
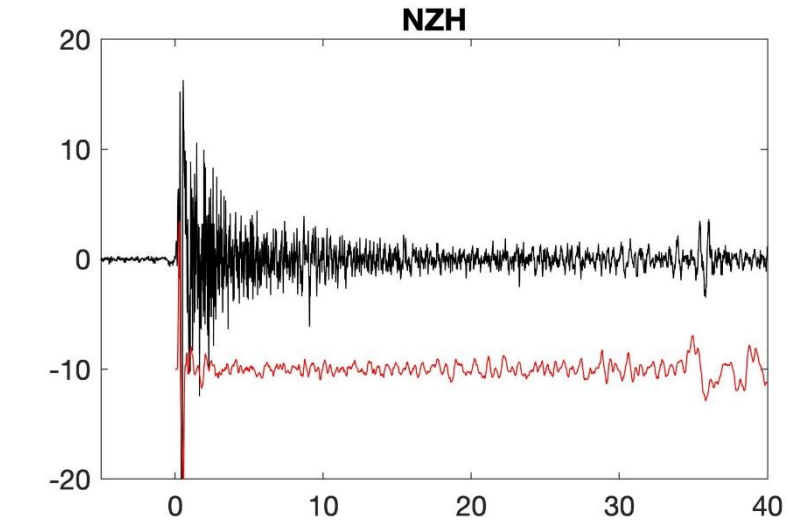


Figure 4

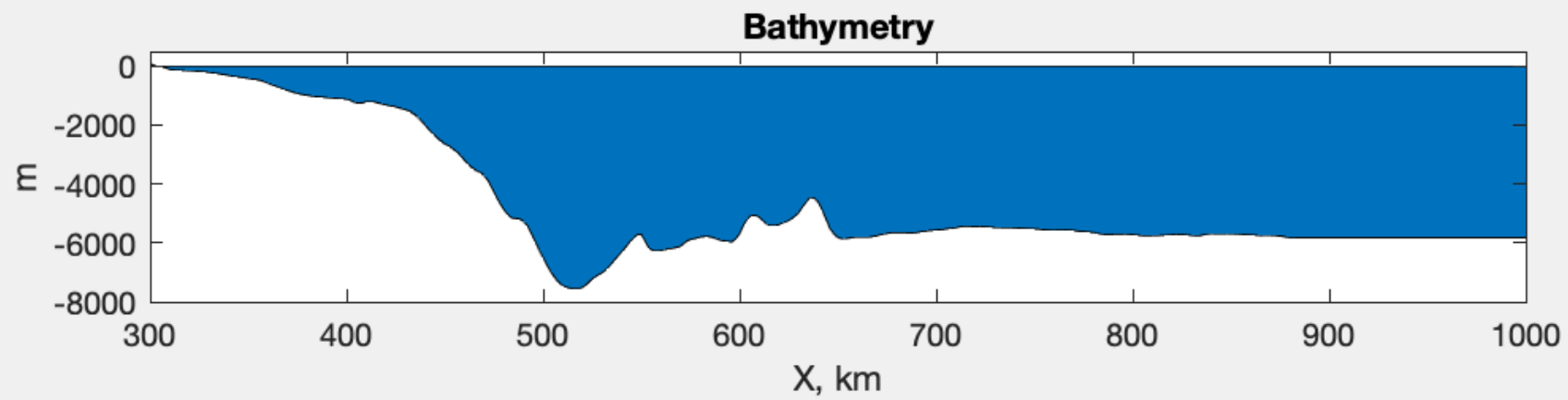
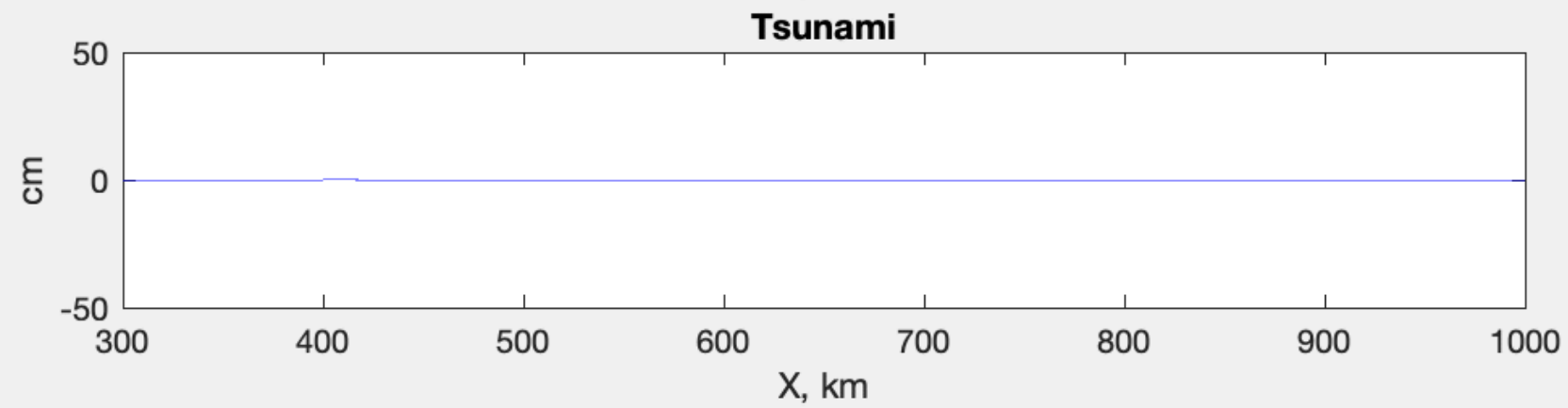
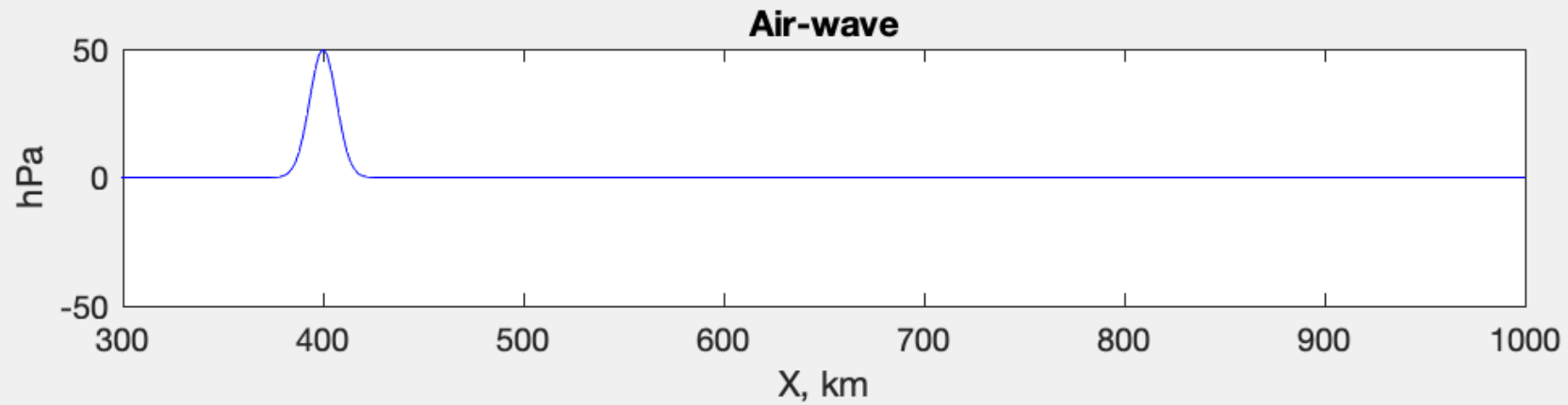
Illustration of air pressure wave model parameters used in this study

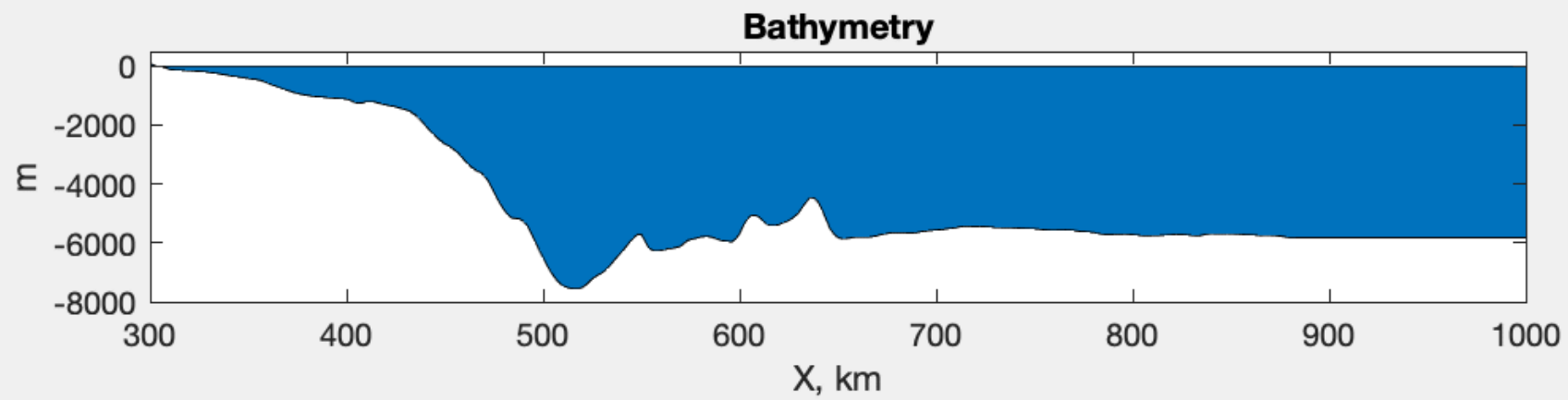
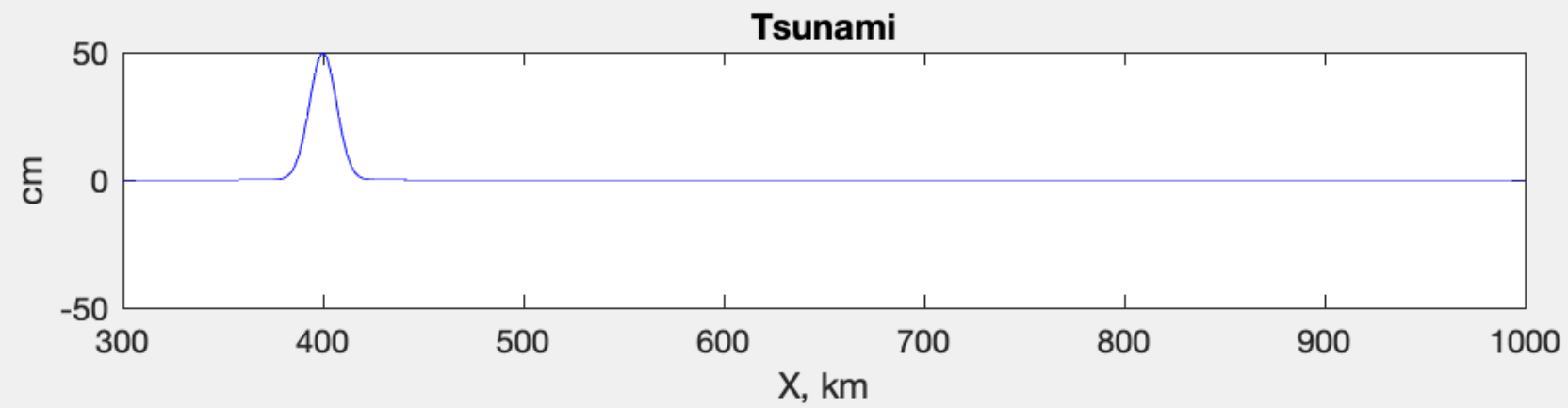
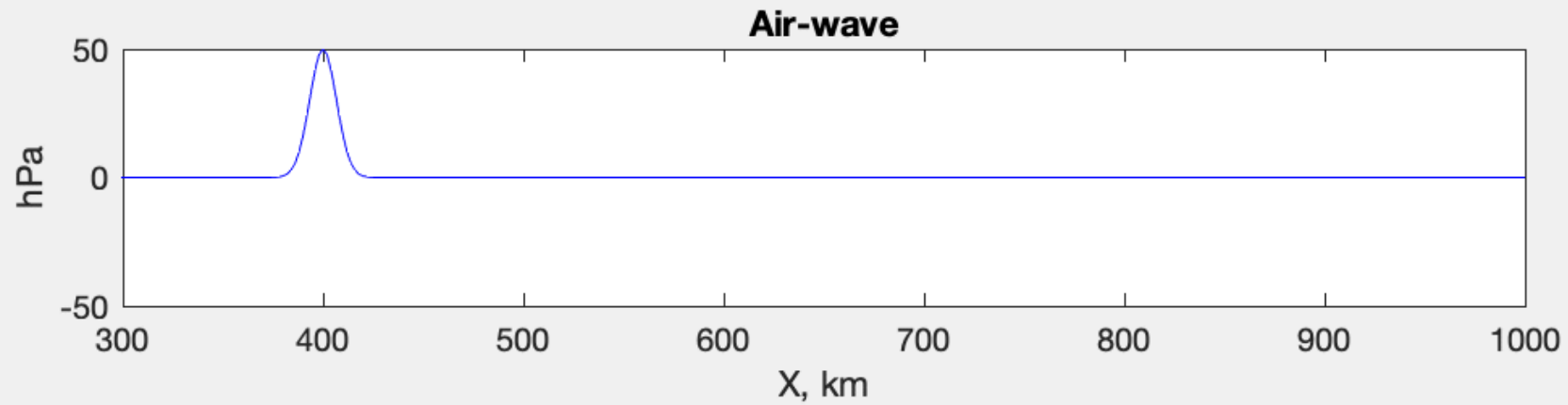


# Global Tsunami Propagation (Lamb wave generated)



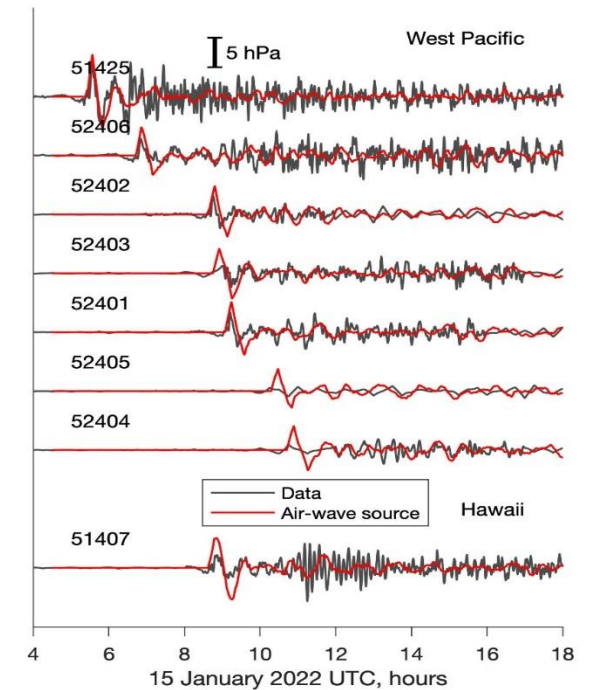
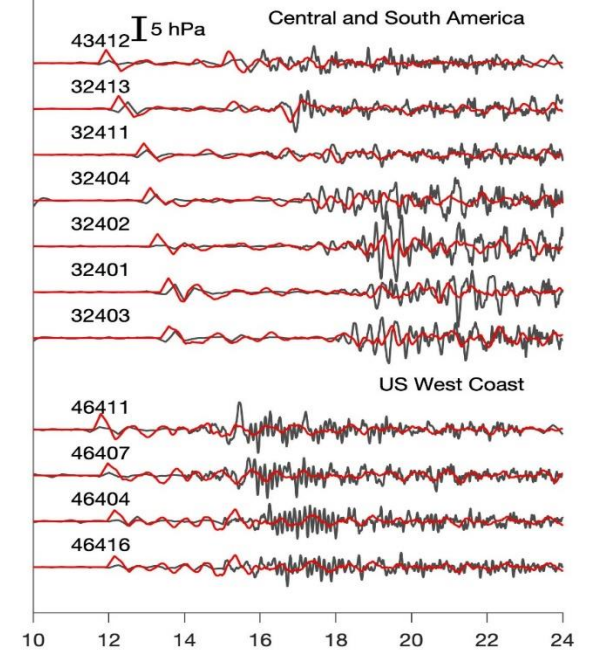
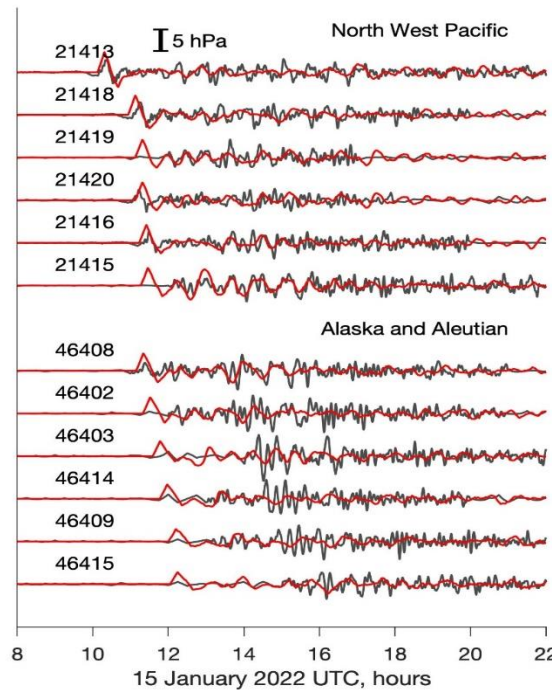
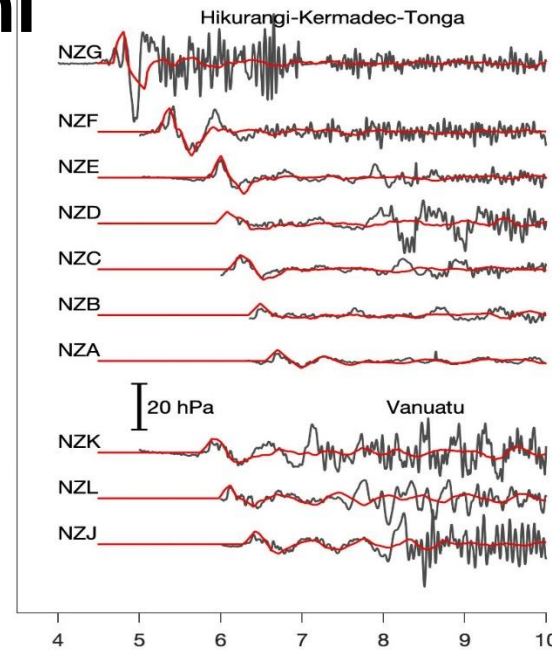
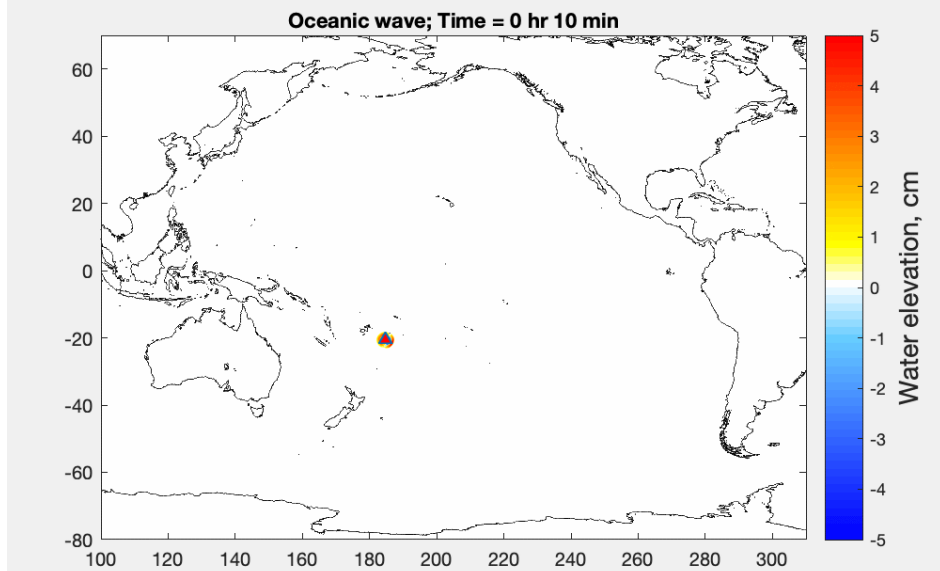
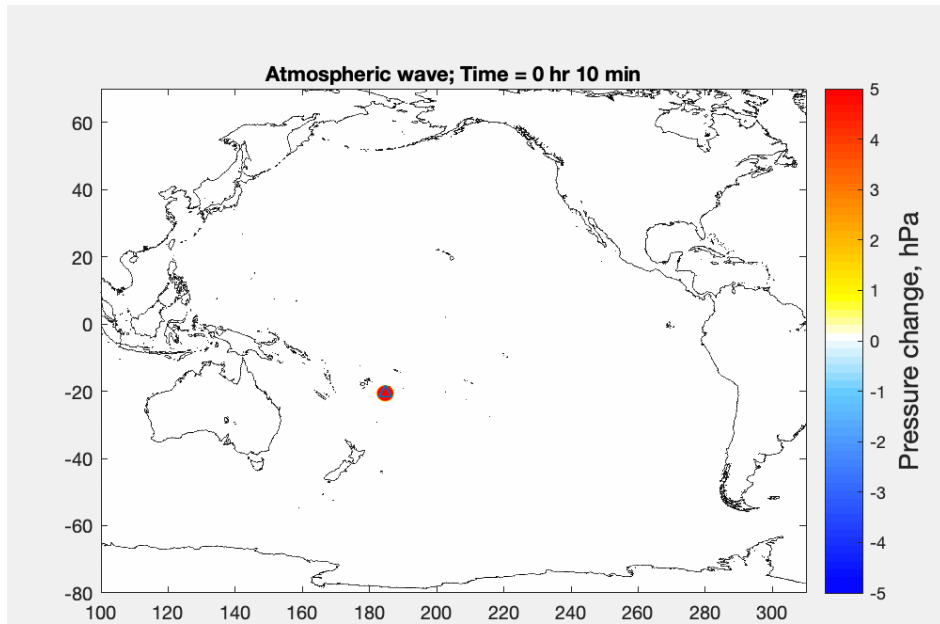








# The 2022 HTHH Eruption Tsunami



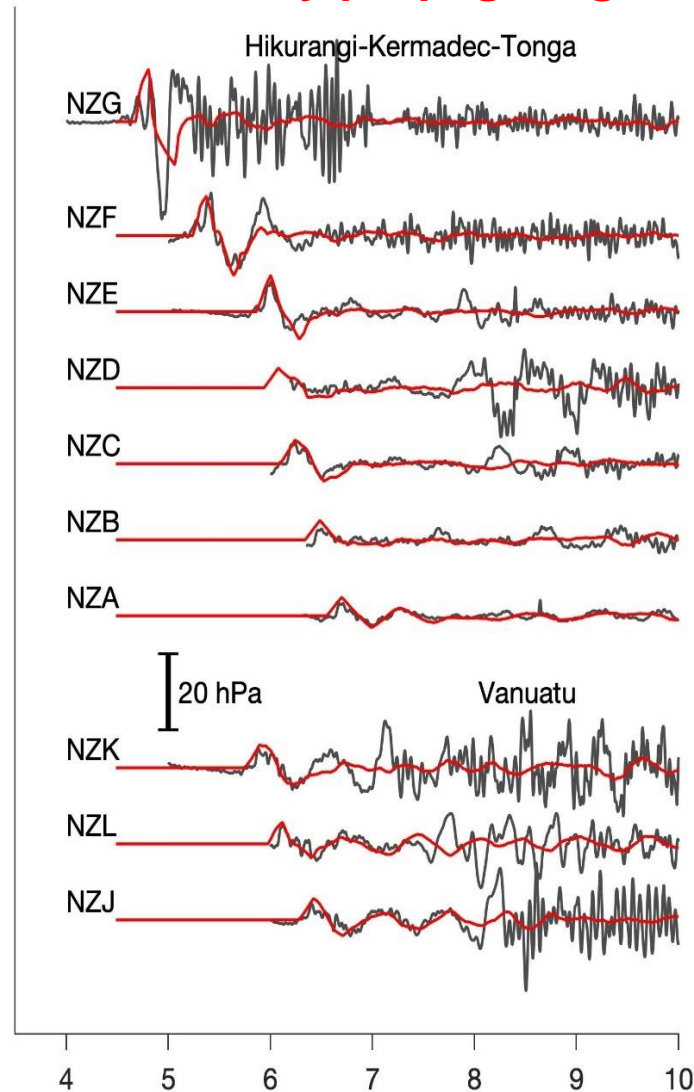
# The 2022 HTHH Eruption Tsunami

Volcanic tsunami source mechanisms according to Paris et al. (2014):

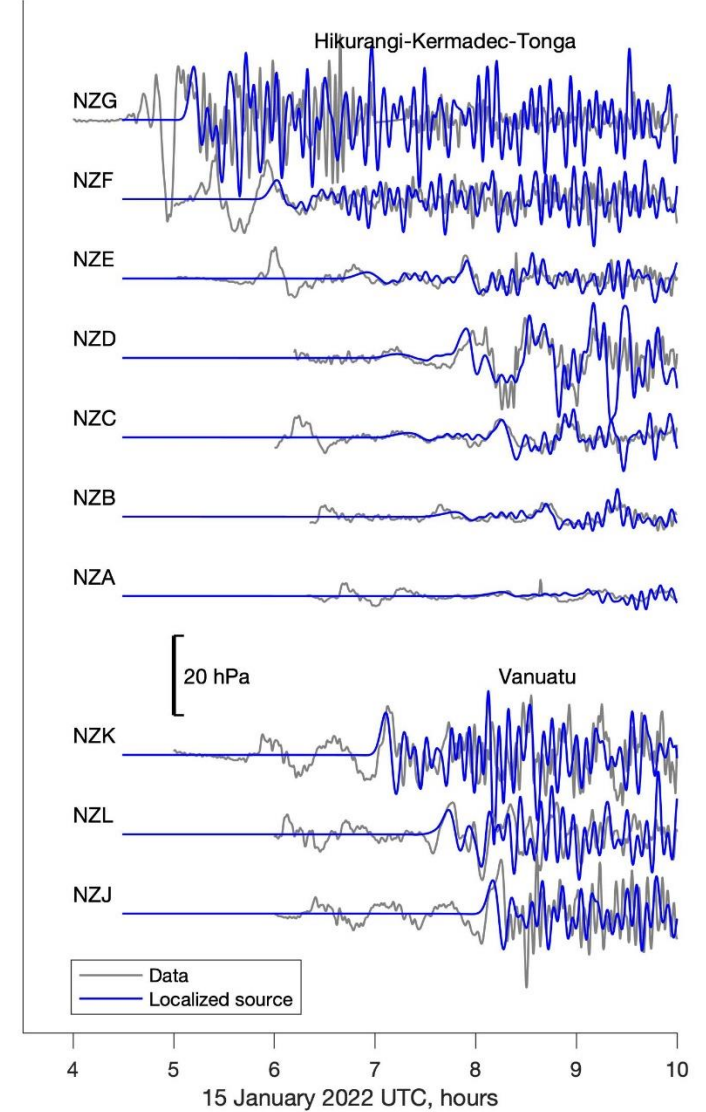
1. Underwater explosion
2. Air wave
3. Pyroclastic flow
4. Flank Failure
5. Caldera subsidence
6. Lahar
7. Earthquake

**Localized source:** A circular water uplift at the volcano with a characteristic diameter of 10 km and the same origin time as the air-wave

## Air wave Continuously propagating source



## Water displacement Localized source

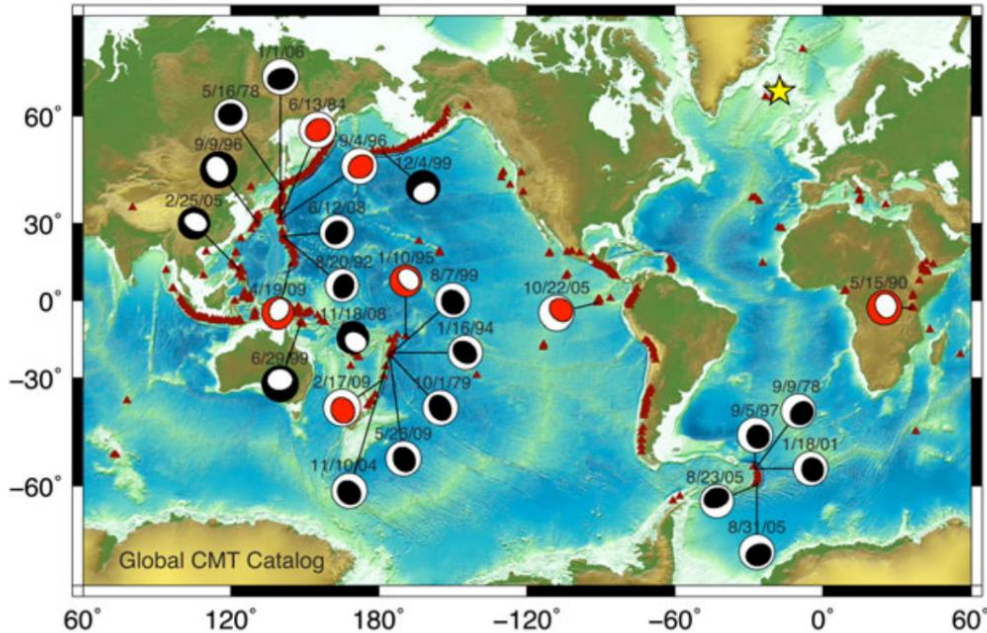


Gusman et al. (2022)

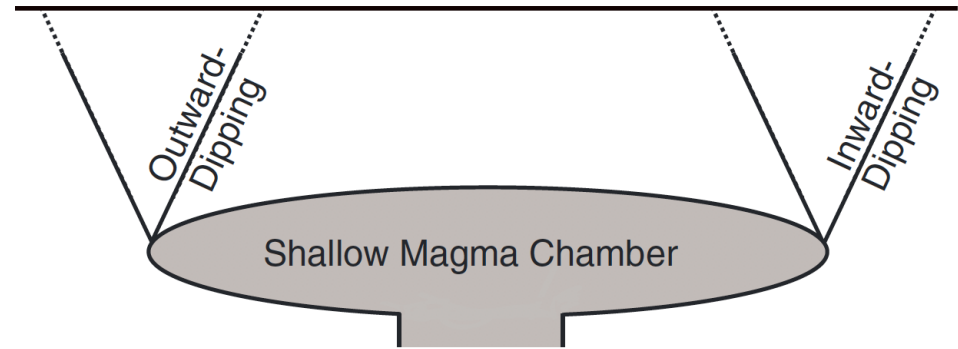


# Vertical CLVD Earthquakes

CLVD: Compensated Linear Vector Dipole



Vertical-CLVD earthquakes are predominantly associated with volcanic activities with most common source volcanoes are strato-volcanoes and submarine volcanoes with caldera structures (Shuler et al., 2013).



Schematic diagram for inward- and outward- dipping ring faults located above a shallow magma chamber

<p>Inward-Dipping Normal Ring Fault Strike: 0–120° Dip: 65° Rake: –90°</p>	<p>Outward-Dipping Normal Ring Fault Strike: 180–300° Dip: 65° Rake: –90°</p>
<p>Inward-Dipping Reverse Ring Fault Strike: 0–120° Dip: 65° Rake: 90°</p>	<p>Outward-Dipping Reverse Ring Fault Strike: 180–300° Dip: 65° Rake: 90°</p>

(Shuler et al., 2013)

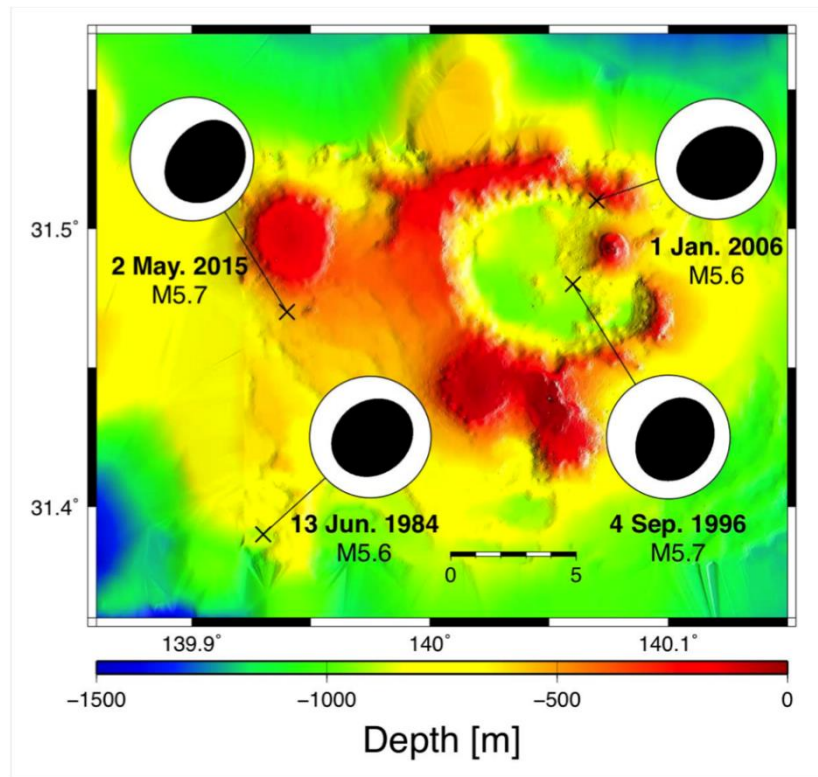
# The Torishima Tsunami Earthquakes

13 June 1984 (M5.9)

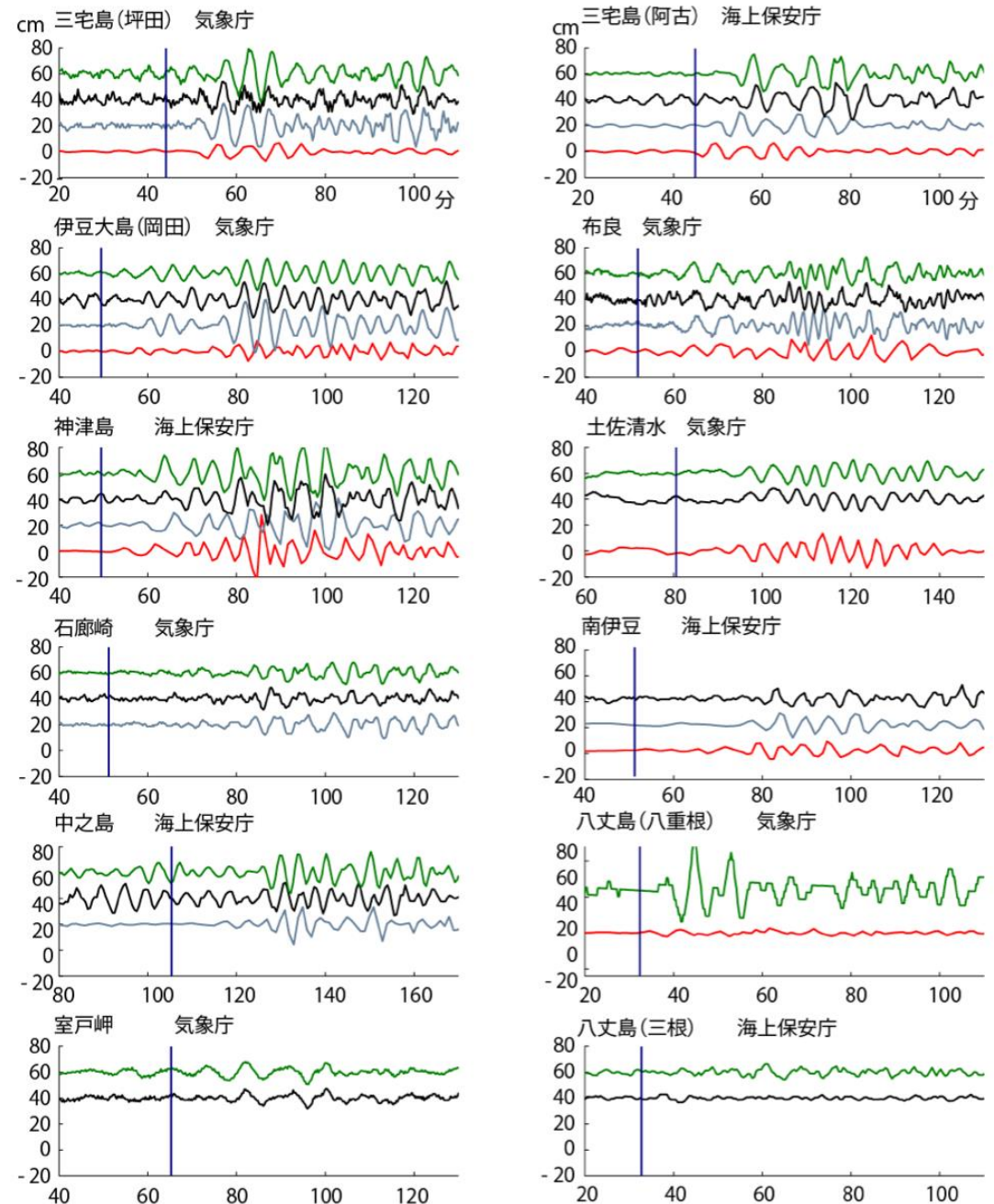
5 September 1996 (M5.6)

1 January 2006 (M5.9)

3 May 2015 (M5.9)



(Satake and Gusman, 2015)



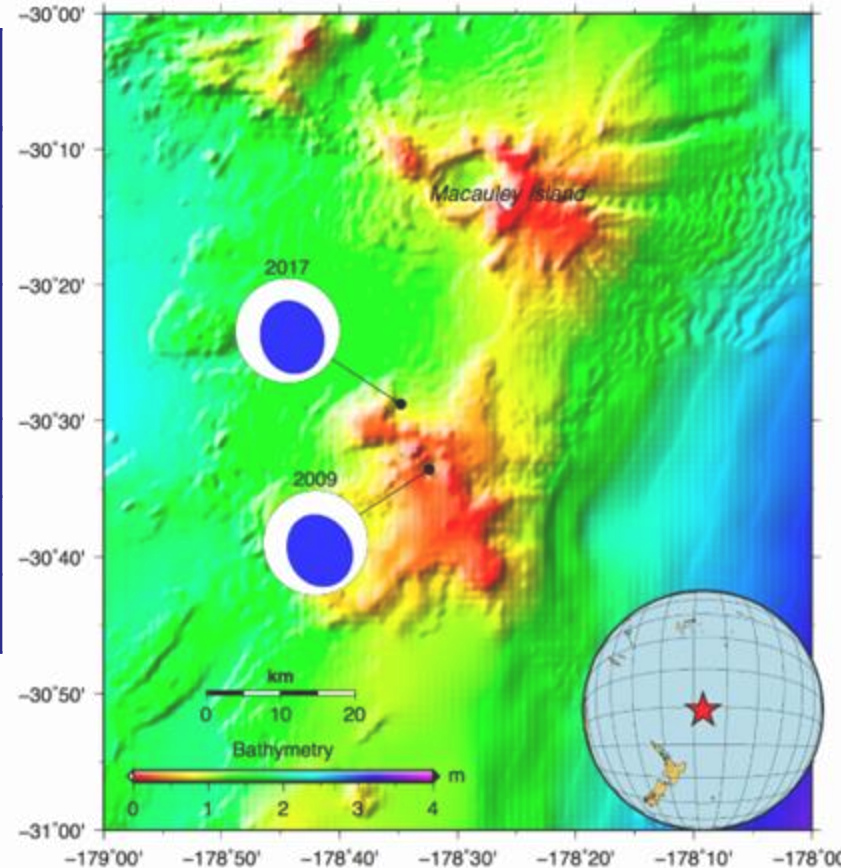
— 1984 — 1996 — 2006 — 2015 — 計算津波走時



# The Kermadec CLVD Earthquakes

## The 2009 Earthquake

Date	2009-02-17
Time	03:30:53 UTC
Epicenter	30.724°S 178.617°W
Depth	13 km
Mw	5.8
Moment	$7.29 \times 10^{17}$ Nm



Epicenter: USGS  
Focal mechanism: Global CMT

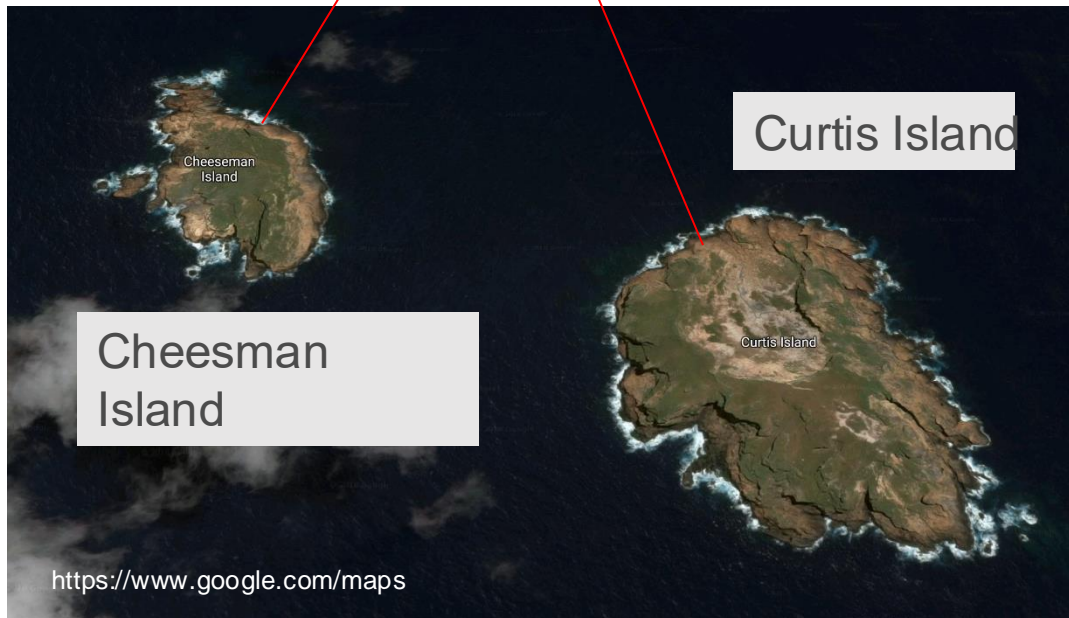
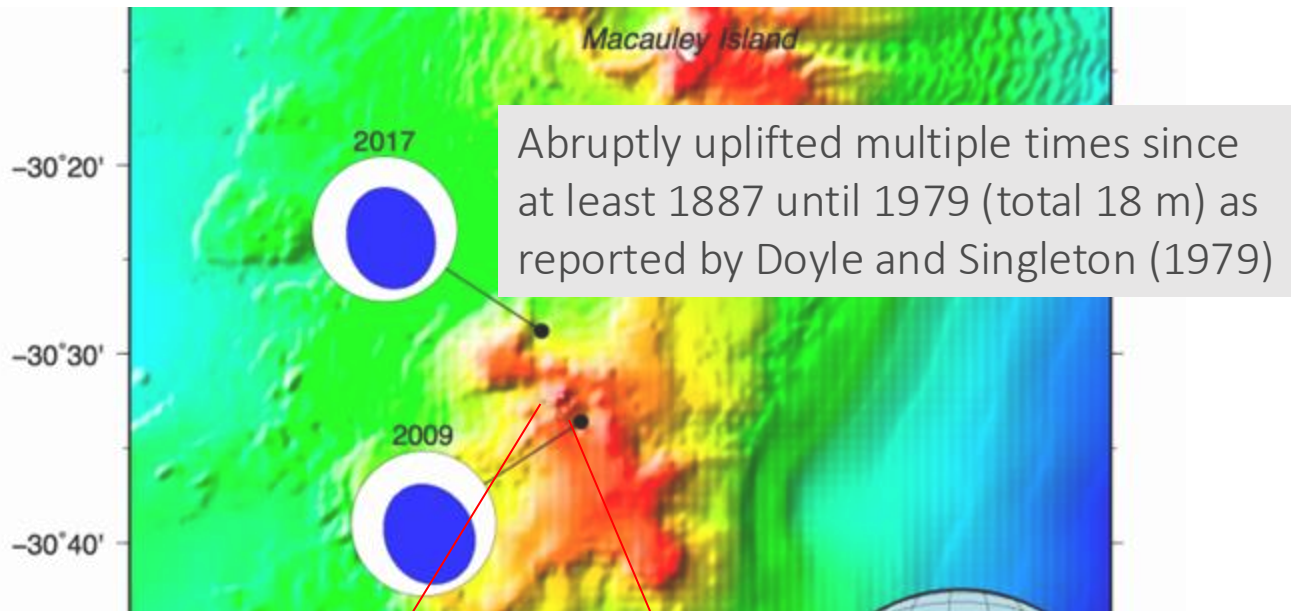
## The 2017 Earthquake

Date	2017-12-08
Time	02:09:57 UTC
Epicenter	30.555°S 178.492°W
Depth	12 km
Mw	5.8
Moment	$6.44 \times 10^{17}$ Nm

	NP 1	NP 2
Strike	319°	167°
Dip	47°	70°
Rake	46°	110°

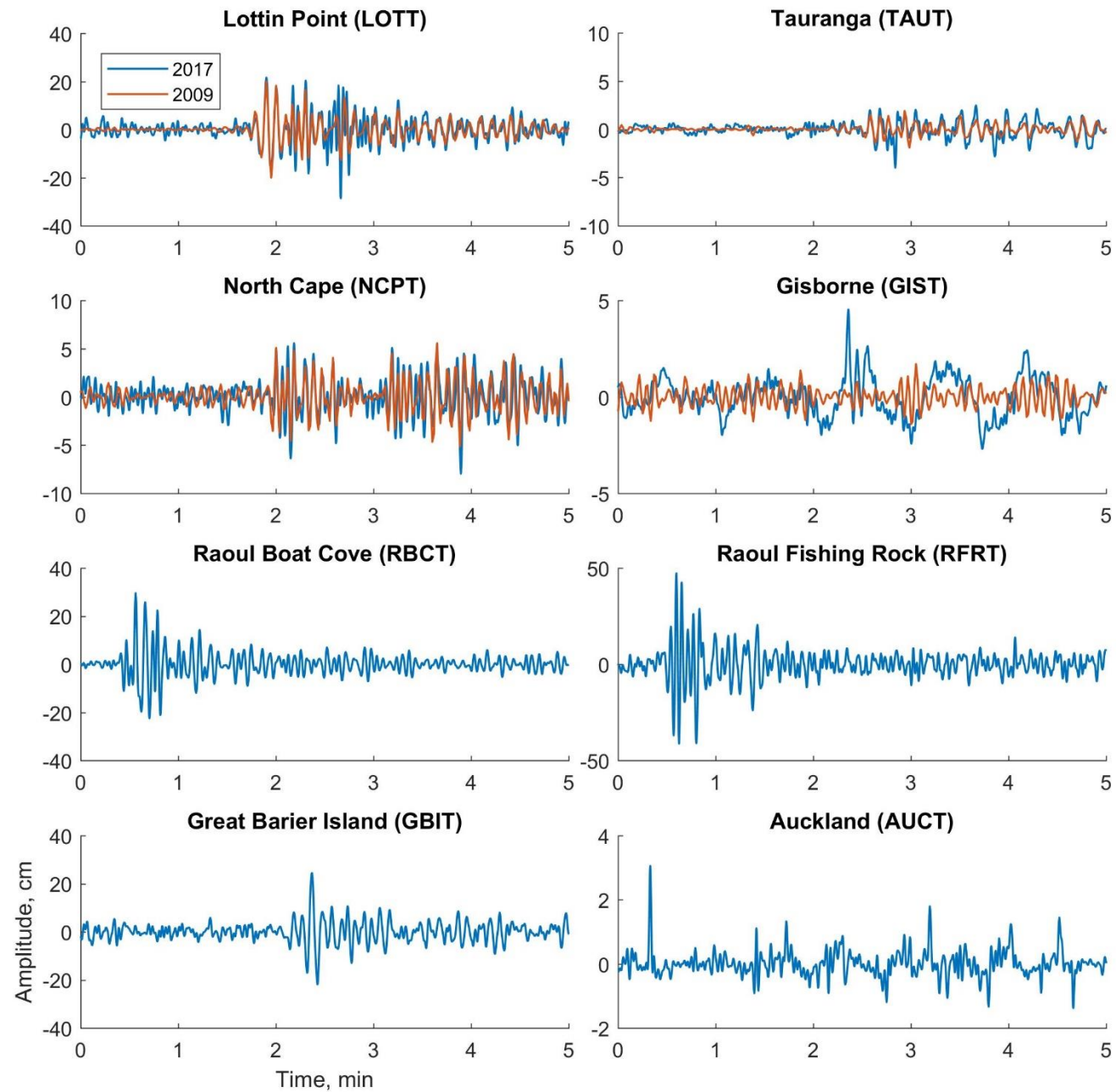
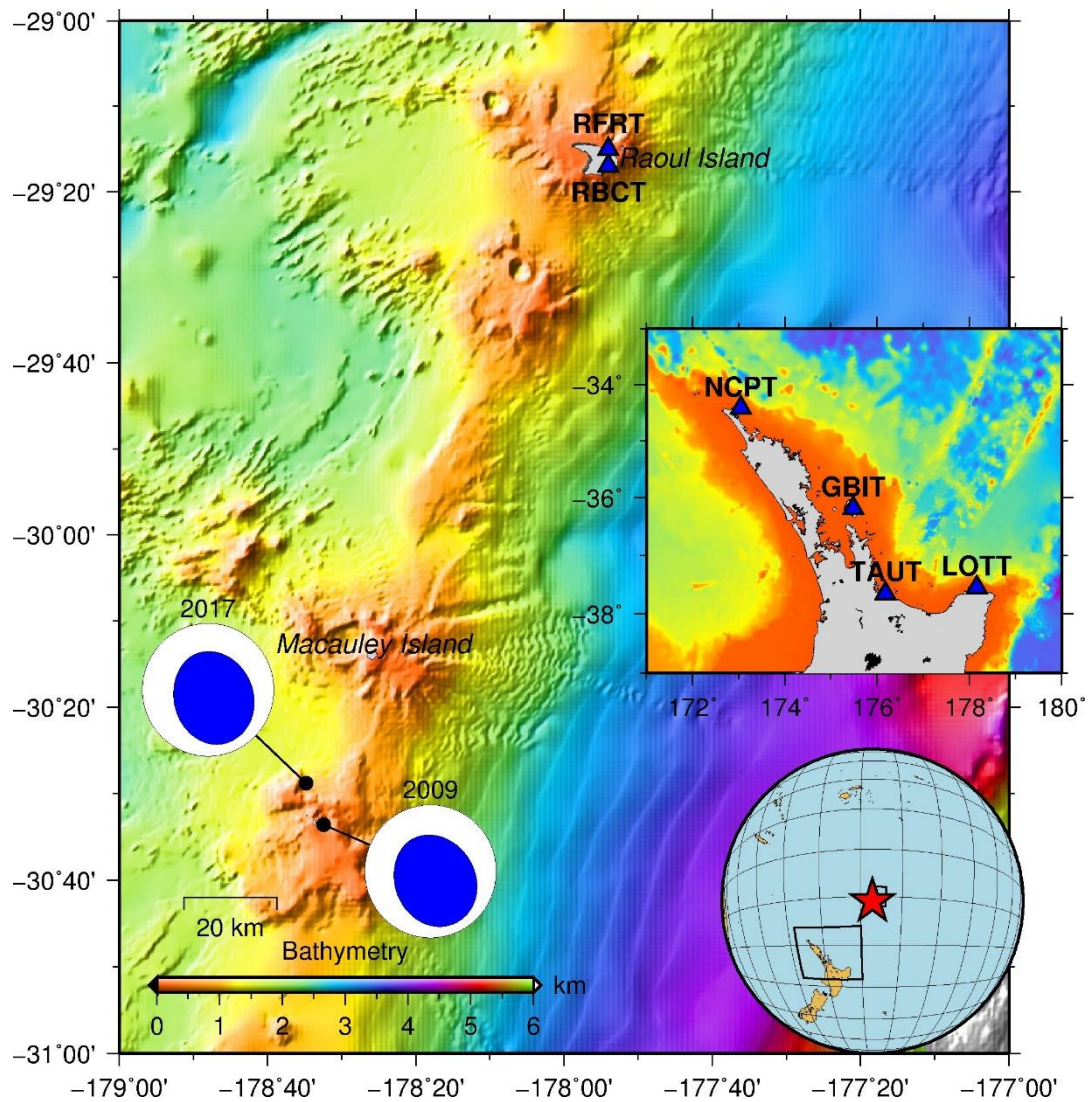
	NP 1	NP 2
Strike	327°	173°
Dip	43°	50°
Rake	70°	107°

# The Kermadec CLVD Earthquakes



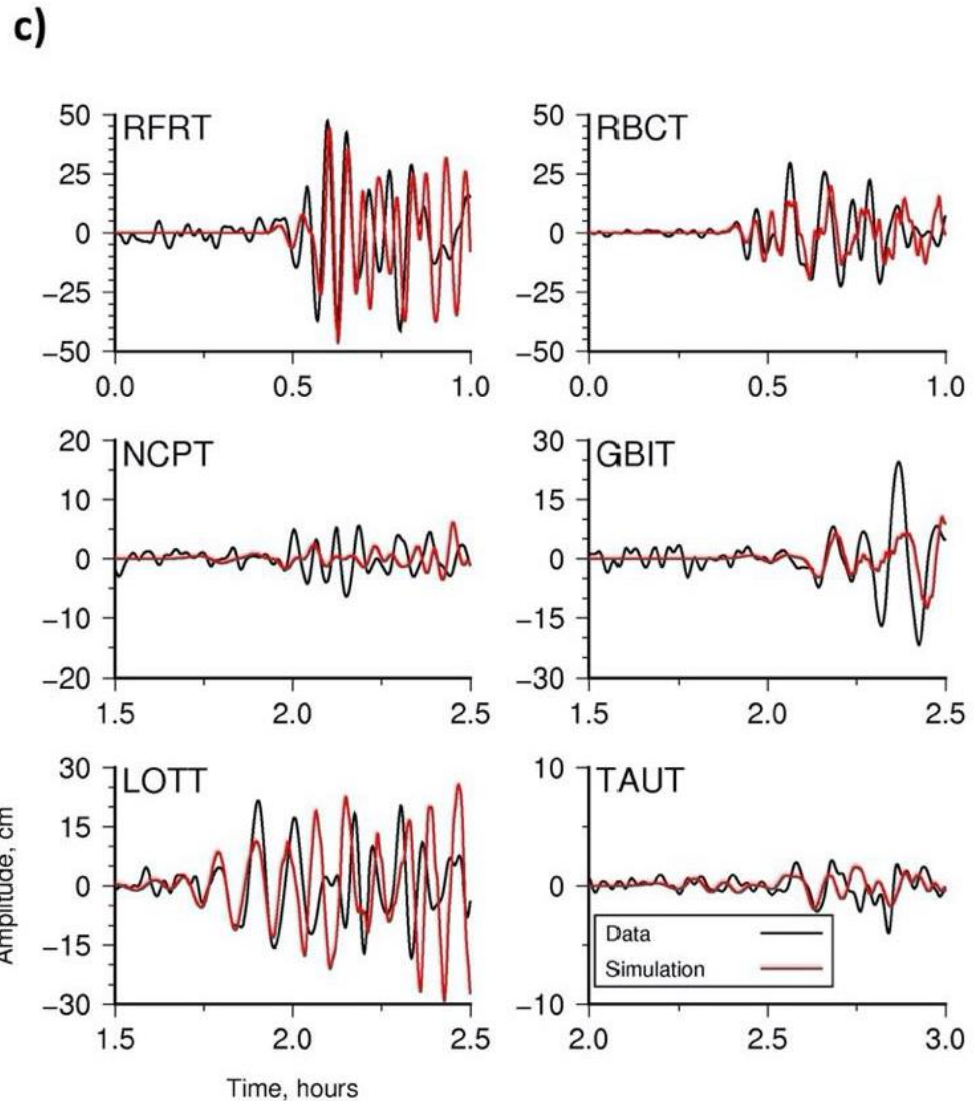
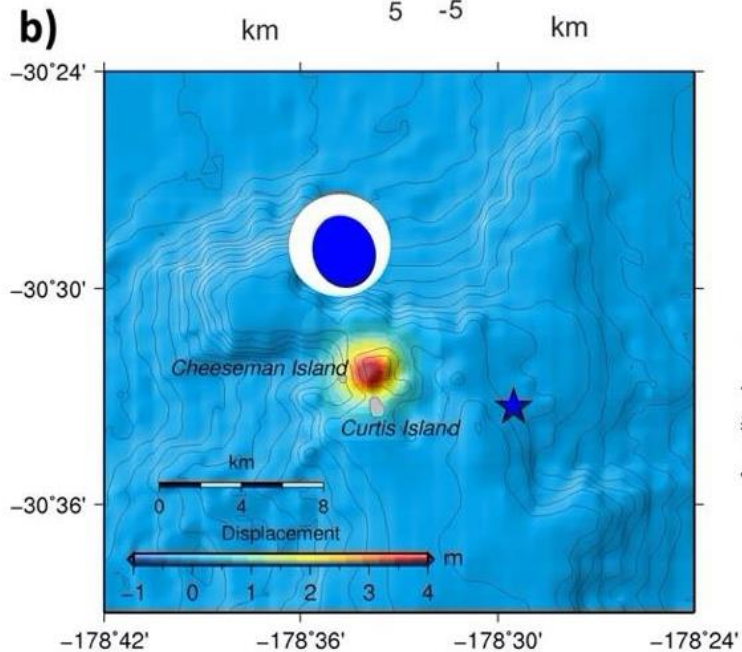
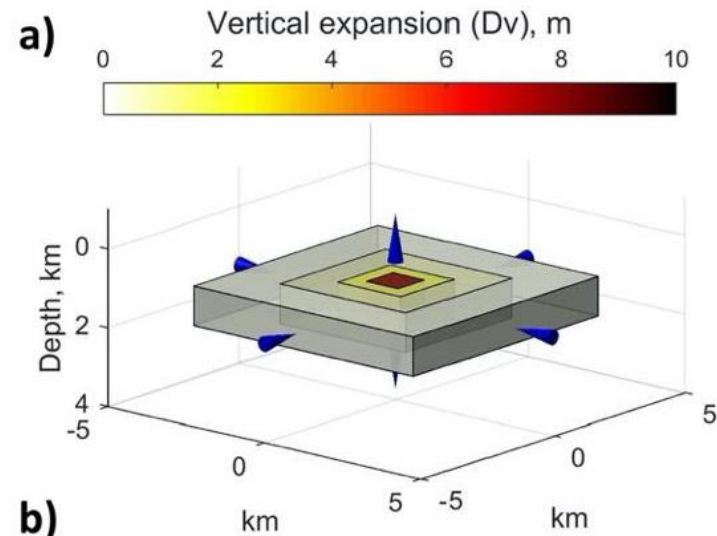


# Tide gauge data

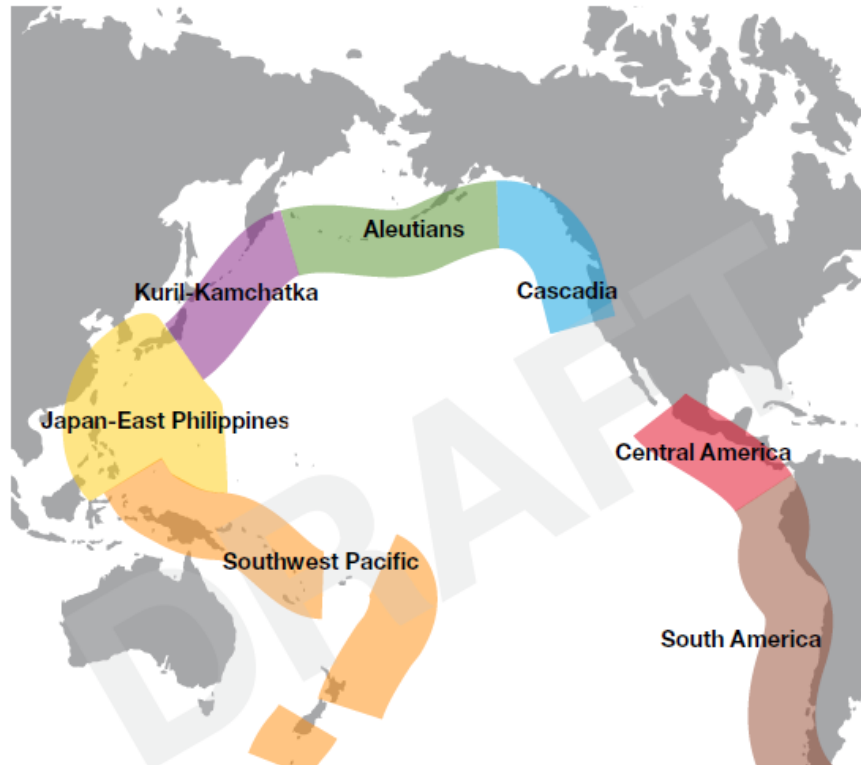




# Source model for the CLVD earthquake and tsunami



# TSUNAMI SCENARIO DATABASE



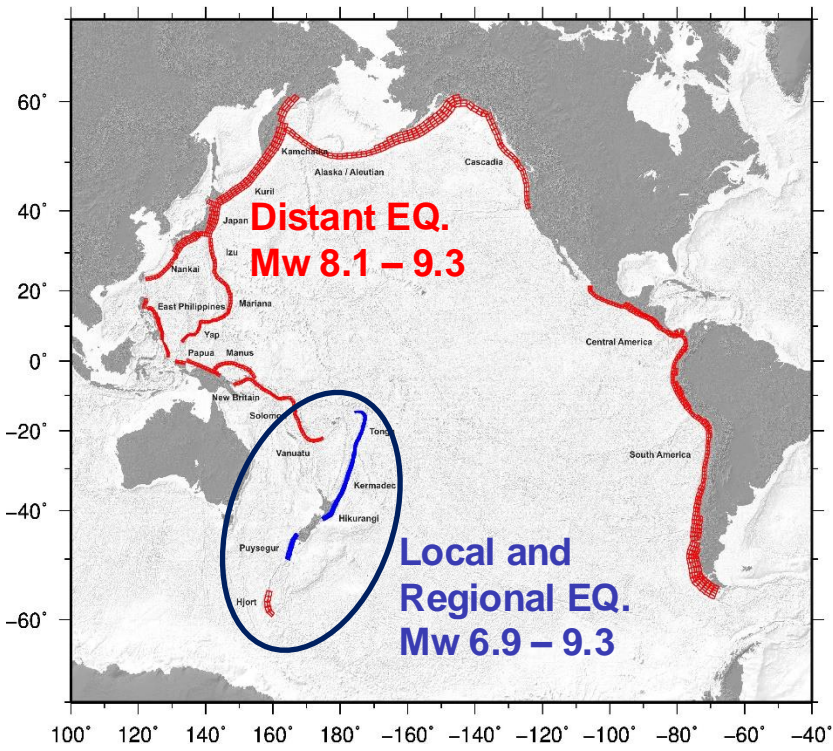
**1000  
precomputed  
scenarios**

Version 3.00 May 2019  
This document is due to be replaced by 1  
It is not recommended to use this document

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User Guidelines

## Fault patches used for the scenarios



### Pre-computed scenarios

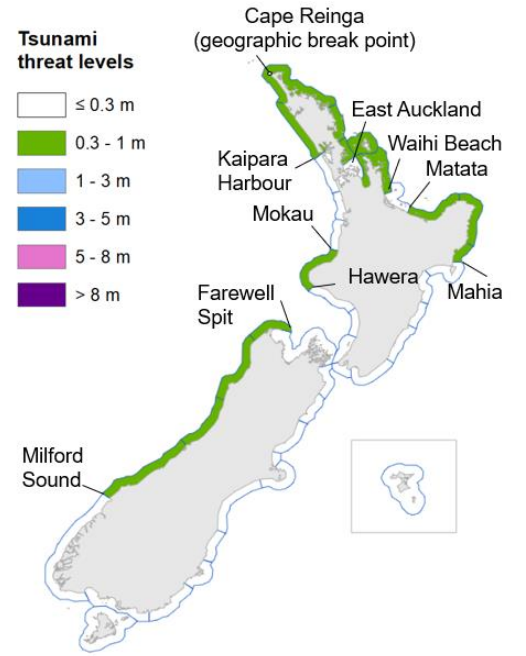
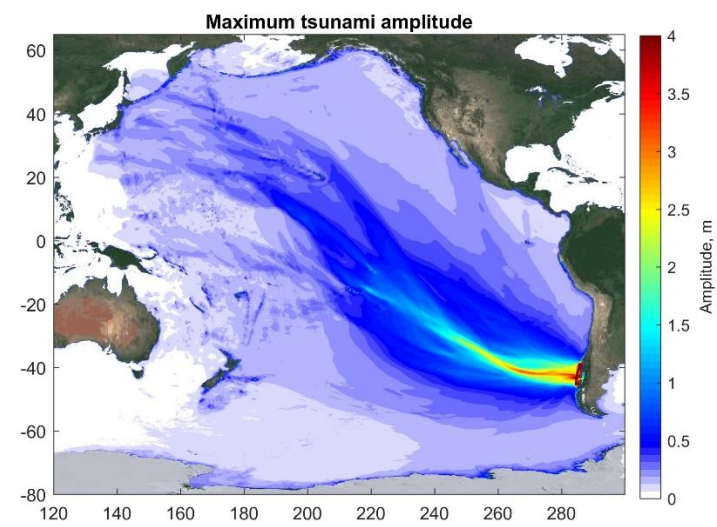
#### Distant sources

- The fault size is 100 km x 50 km.
- Earthquake magnitudes: 8.1 – 9.3 (interval of 0.2)
- Space: 300 km

#### Regional sources

- The fault size is 50 km x 25 km.
- Earthquake magnitudes: 6.9 – 9.3 (interval of 0.2)
- Space: 100-150km

## Tsunami Threat Level





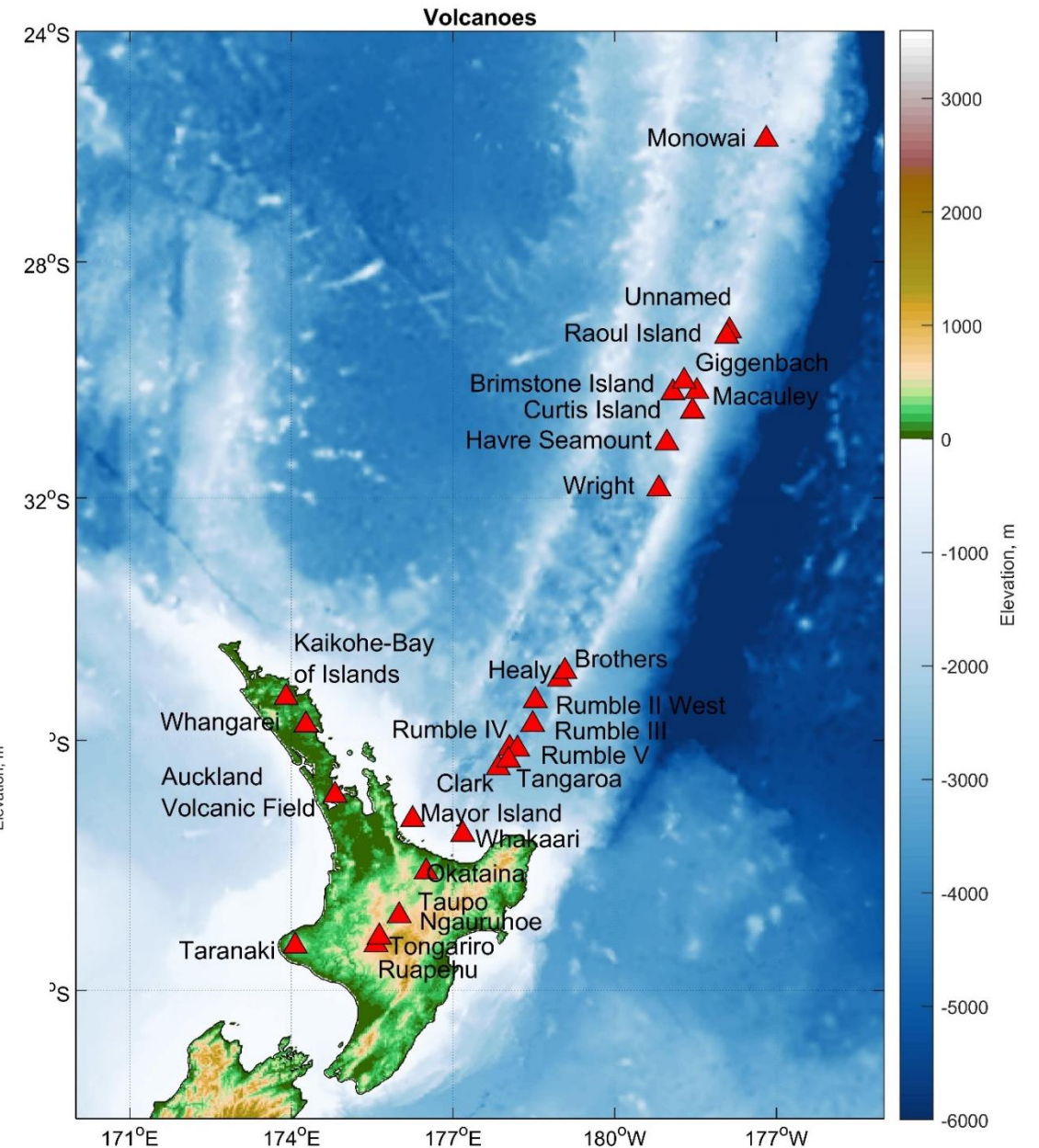
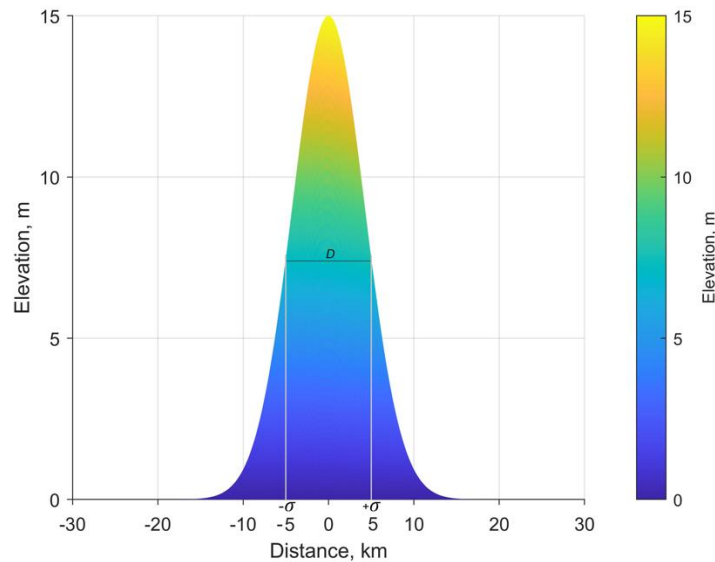
# Volcanic Tsunami Threat Level Database

## Selected Volcanoes

For this work, we selected 28 volcanoes located in New Zealand and the Kermadec ridge south of 25° S. These volcanoes include submarine volcanoes and volcanic islands from Monowai, a submarine volcano in Kermadec, to Whakaari/White Island, a volcanic island in the Bay of Plenty. Inland volcanoes are also evaluated, especially those located near the coast.

## Source Model

We use a simple localized source model in which tsunami generation is approximated by an initial static sea surface displacement. The shape of the initial sea surface displacement is represented in simplified form by a three-dimensional Gaussian function with a characteristic diameter (D) of 10 km and maximum height (H) of 15.

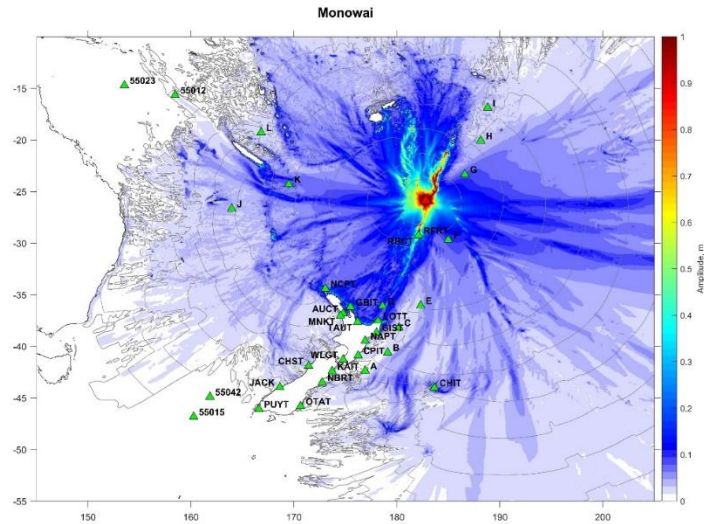




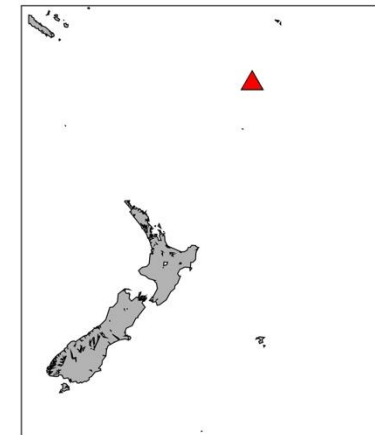
# Volcanic Tsunami Threat Level Database

Monowai

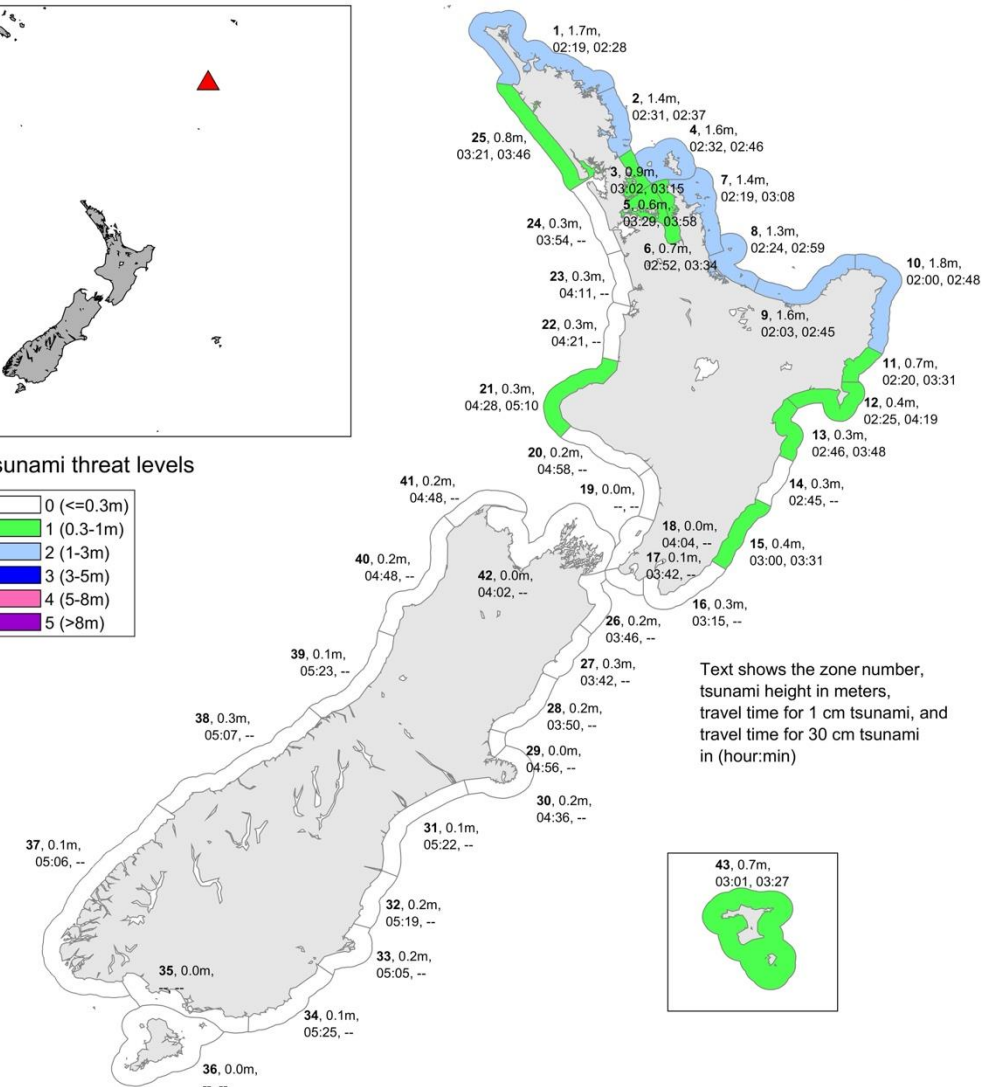
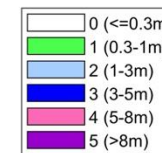
NOT for dissemination.  
For the Tsunami Expert Panel use only.



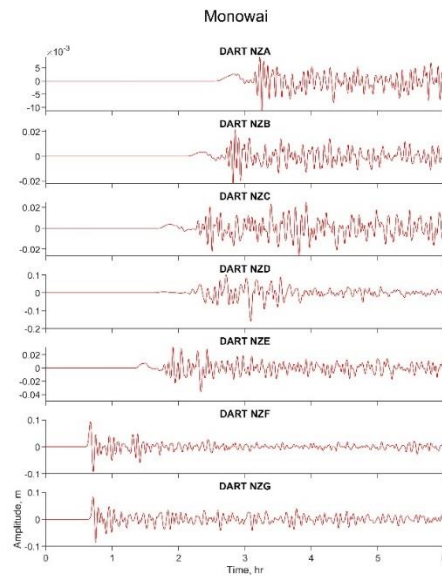
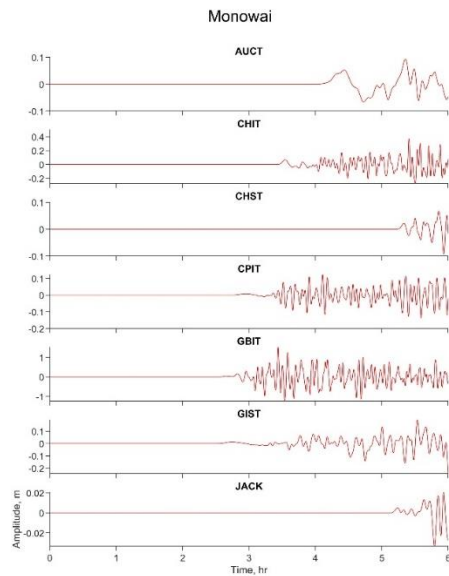
Source: Diameter = 10 km, Height = 15 m  
Longitude: 182.8120, Latitude: -25.8870



Tsunami threat levels



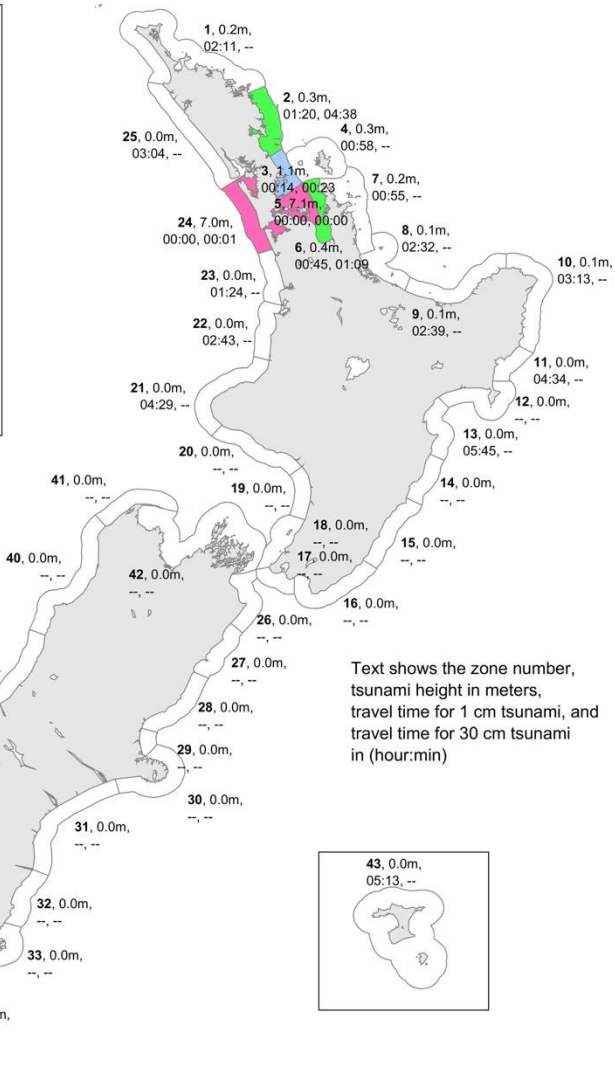
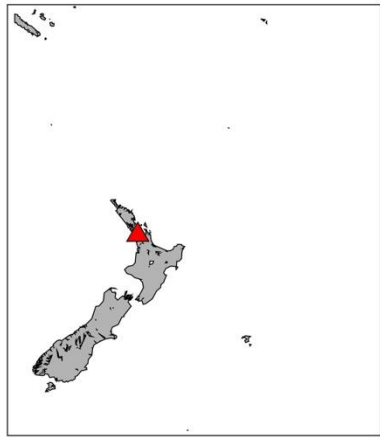
Text shows the zone number,  
tsunami height in meters,  
travel time for 1 cm tsunami, and  
travel time for 30 cm tsunami  
in (hour:min)



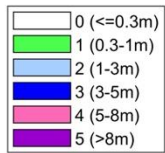
## Auckland Volcanic Field

Source: Diameter = 10 km, Height = 15 m  
Longitude: 174.8100, Latitude: -36.8900

NOT for dissemination.  
For the Tsunami Expert Panel use only.



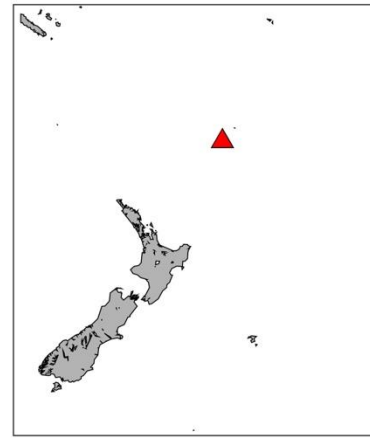
### Tsunami threat levels



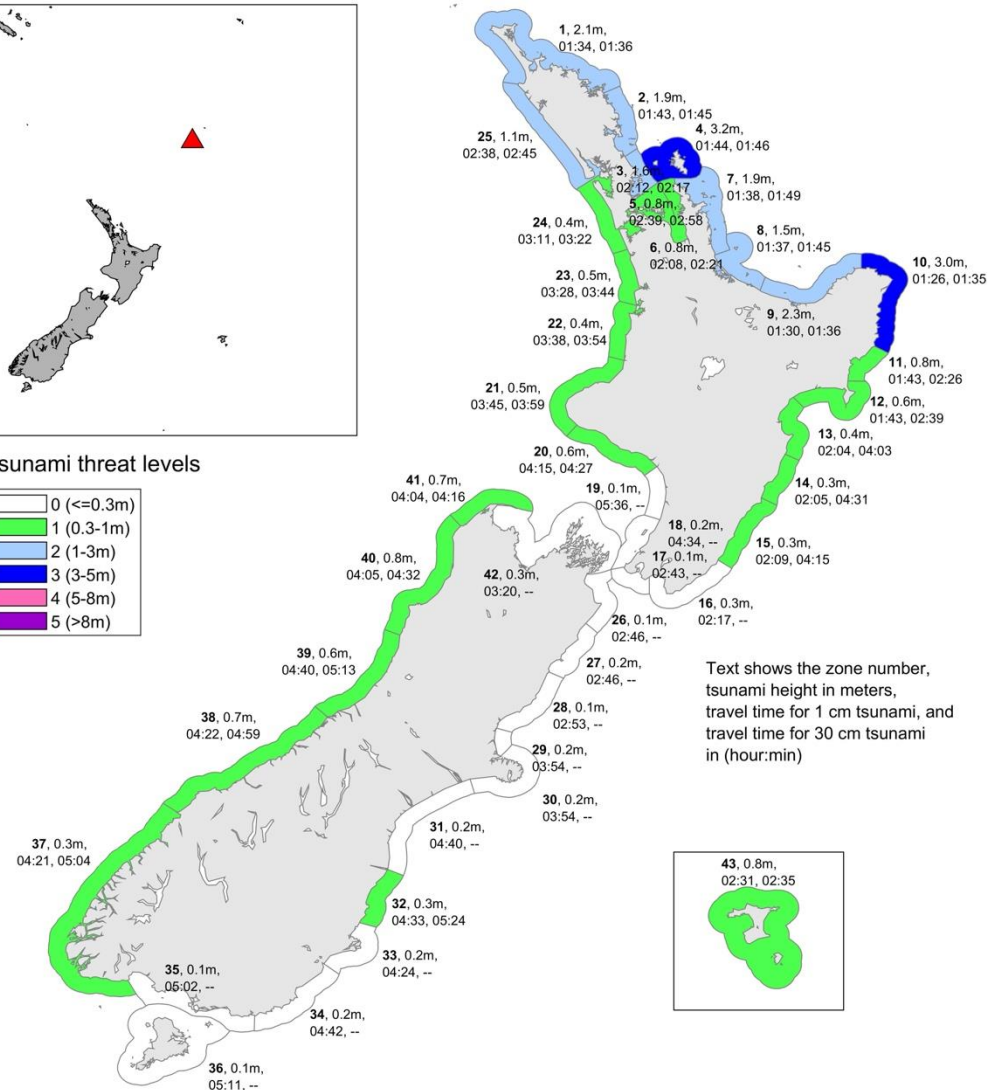
## Brimstone Island

Source: Diameter = 10 km, Height = 15 m  
Longitude: 181.0800, Latitude: -30.2300

NOT for dissemination.  
For the Tsunami Expert Panel use only.



### Tsunami threat levels

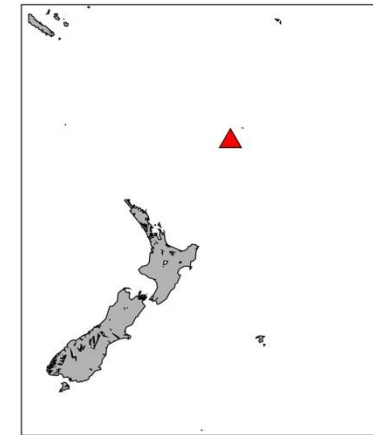
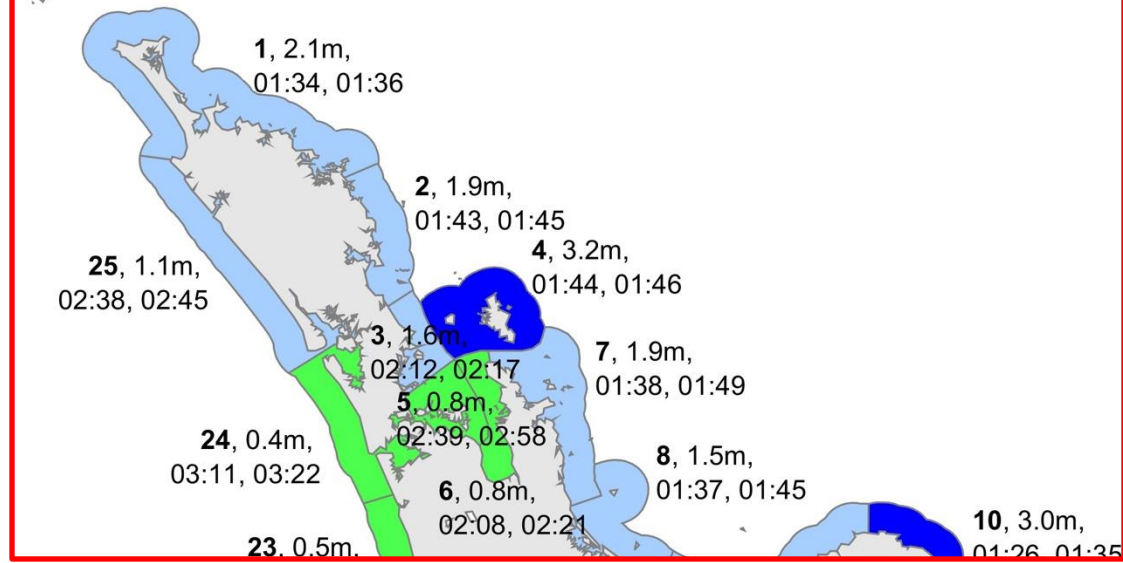


NOT for dissemination.  
For the Tsunami Expert Panel use only.

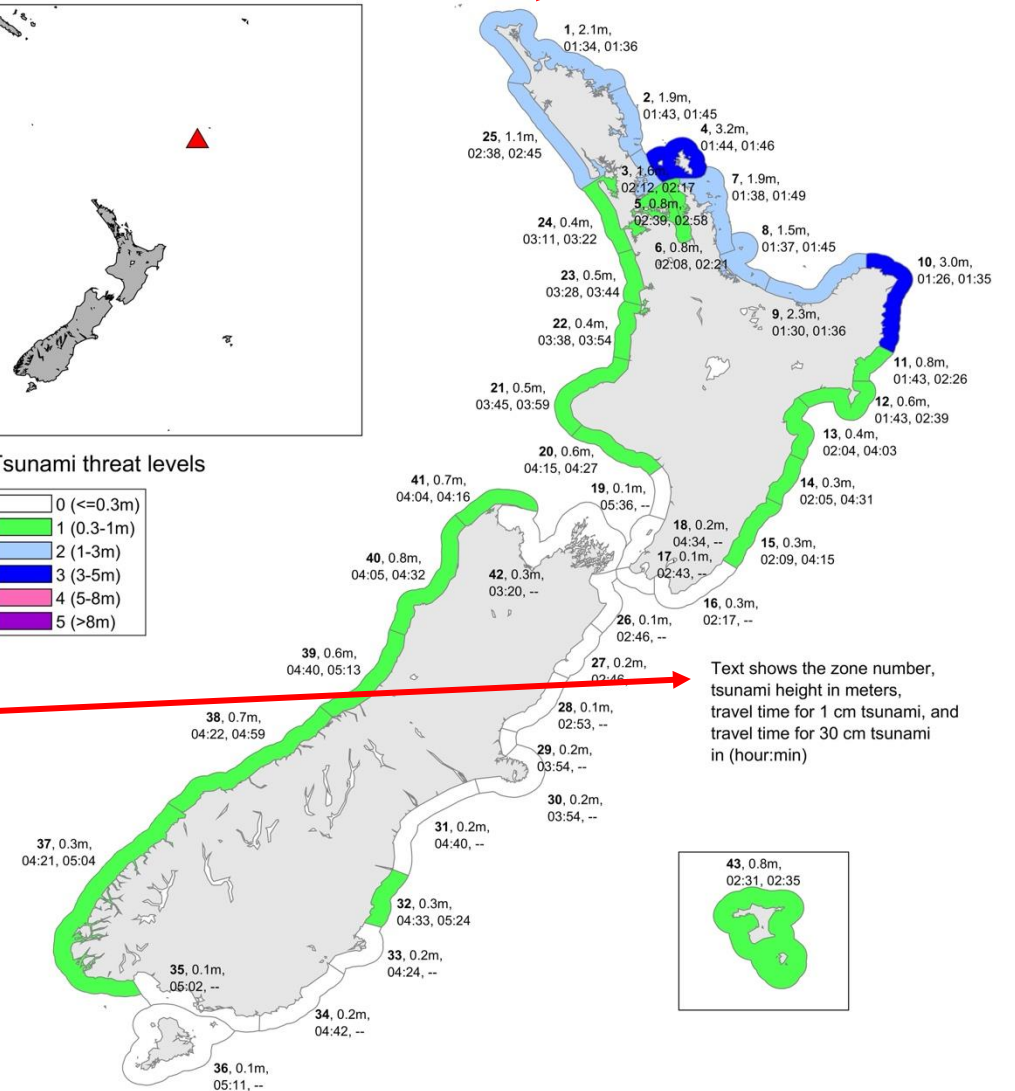
Brimstone Island

Source: Diameter = 10 km, Height = 15 m  
Longitude: 181.0800, Latitude: -30.2300

NOT for dissemination.  
For the Tsunami Expert Panel use only.



Tsunami threat levels

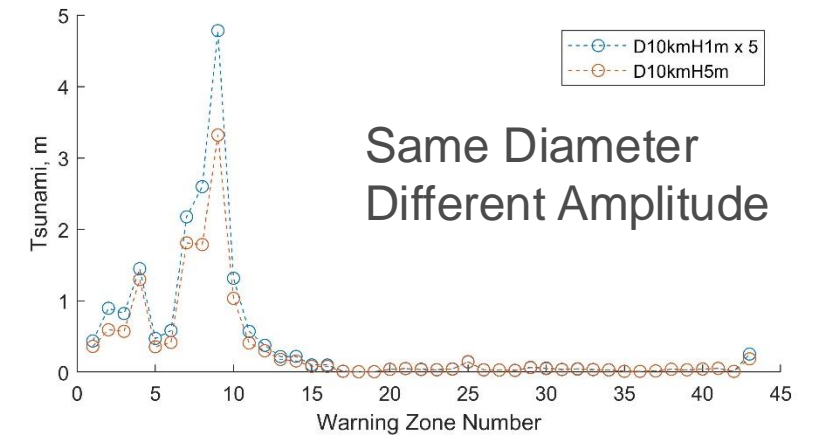
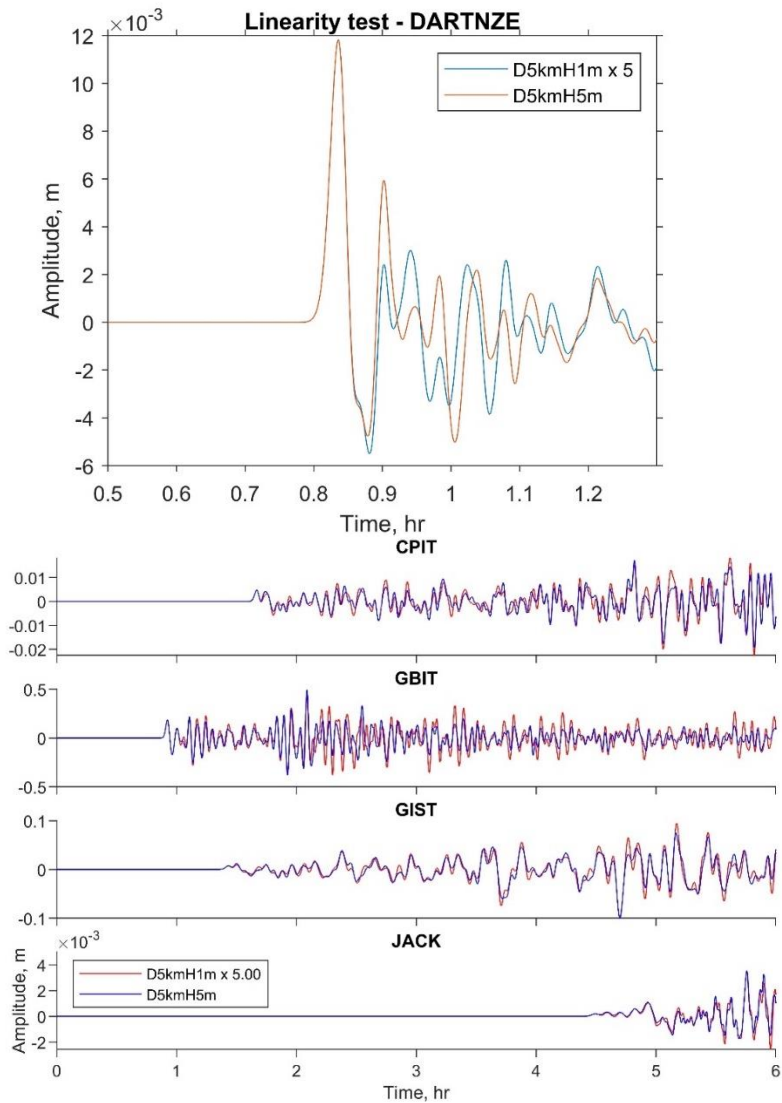


Text shows the zone number, tsunami height in meters, travel time for 1 cm tsunami, and travel time for 30 cm tsunami in (hour:min)

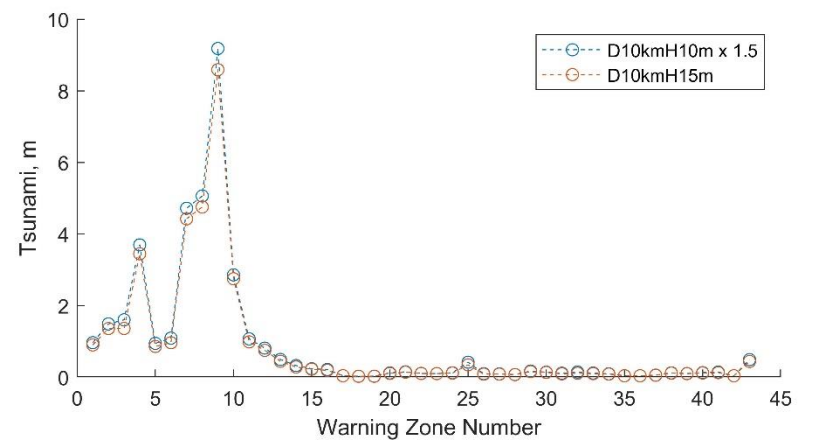
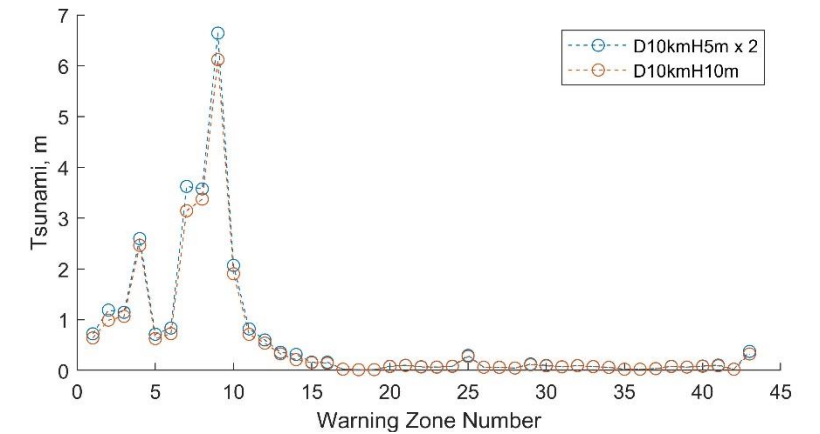
Text shows the zone number, tsunami height in meters, travel time for 1 cm tsunami, and travel time for 30 cm tsunami in (hour:min)



# Is it possible to adjust/scaling the scenarios using the peak amplitudes recorded by DART?

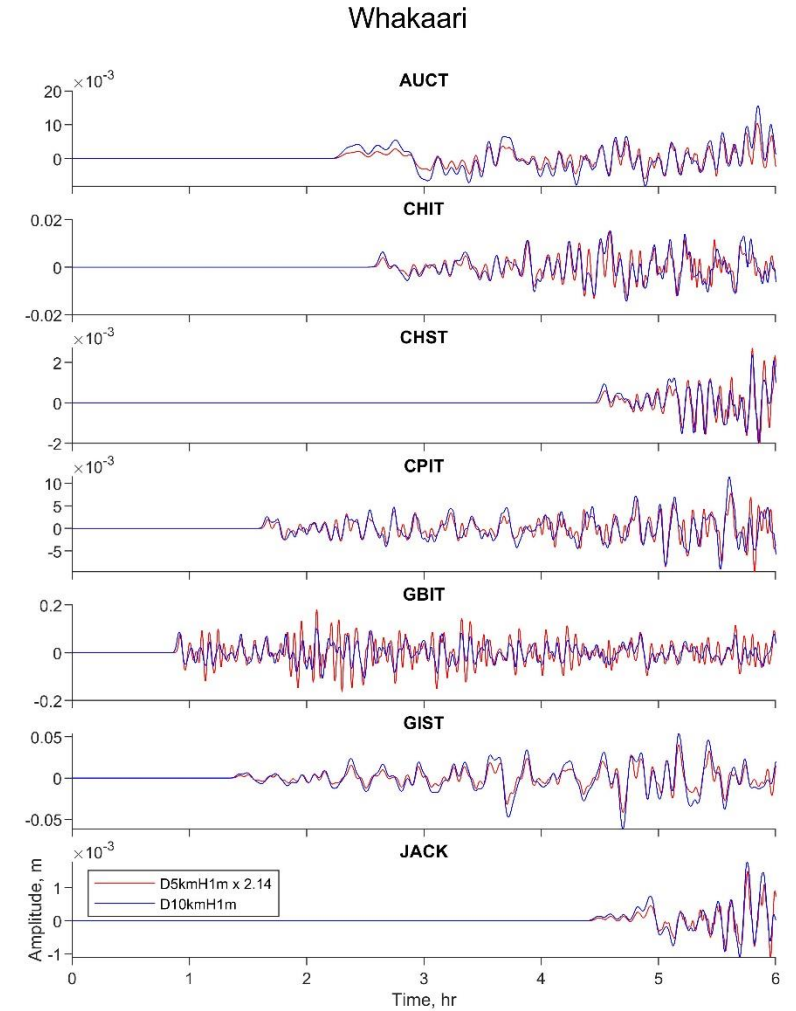
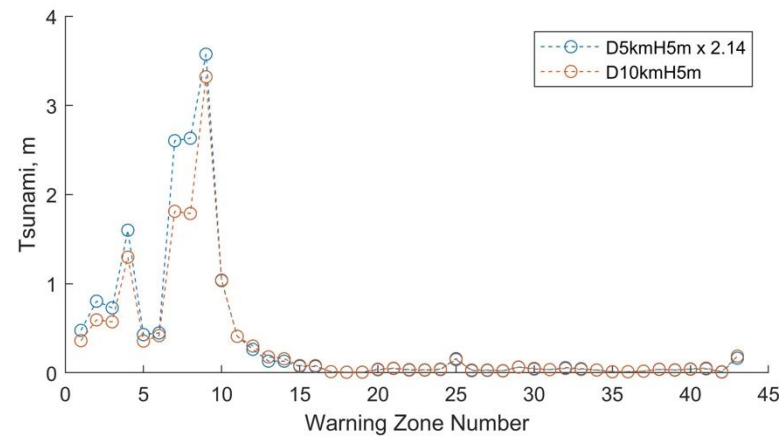
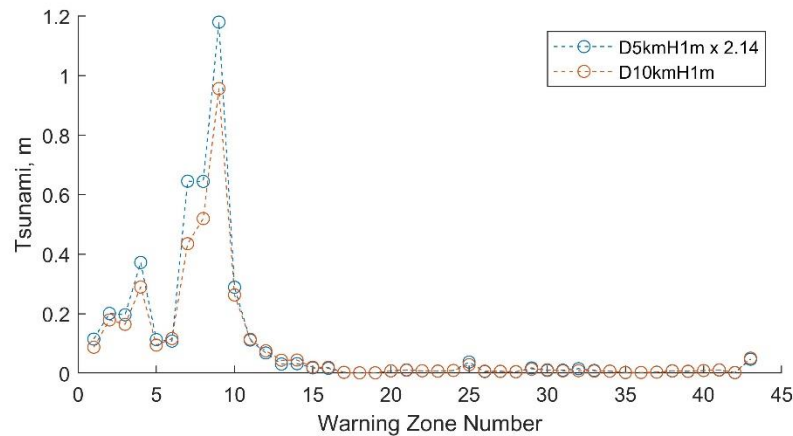
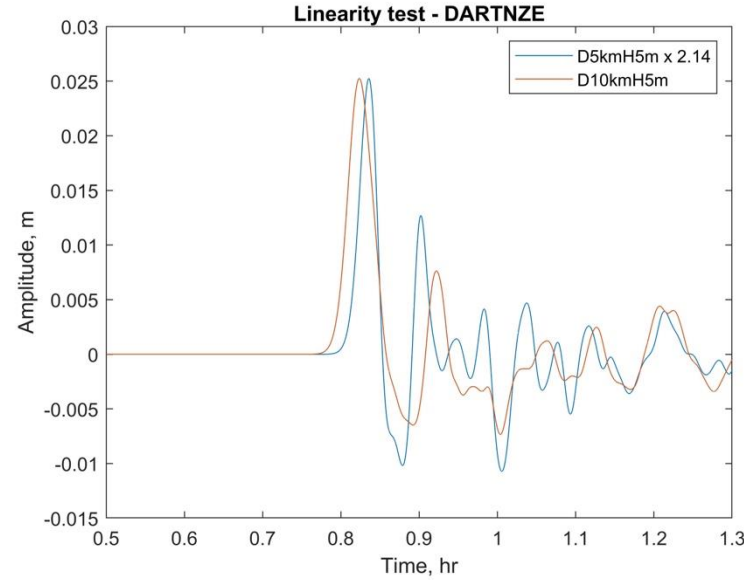
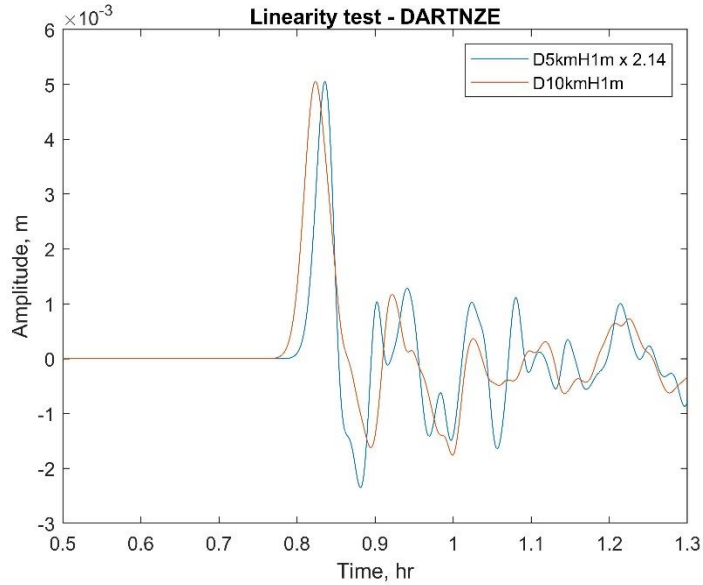


Same Diameter  
Different Amplitude



# Is it possible to adjust/scaling the scenarios using the peak amplitudes recorded by DART?

Same Amplitude  
Different Diameter



# Inland Volcano Eruption Scenario



Lamb wave generated tsunami simulation for a Mt. Ruapehu scenario  
Source parameters: same as the 2022 HTHH eruption

