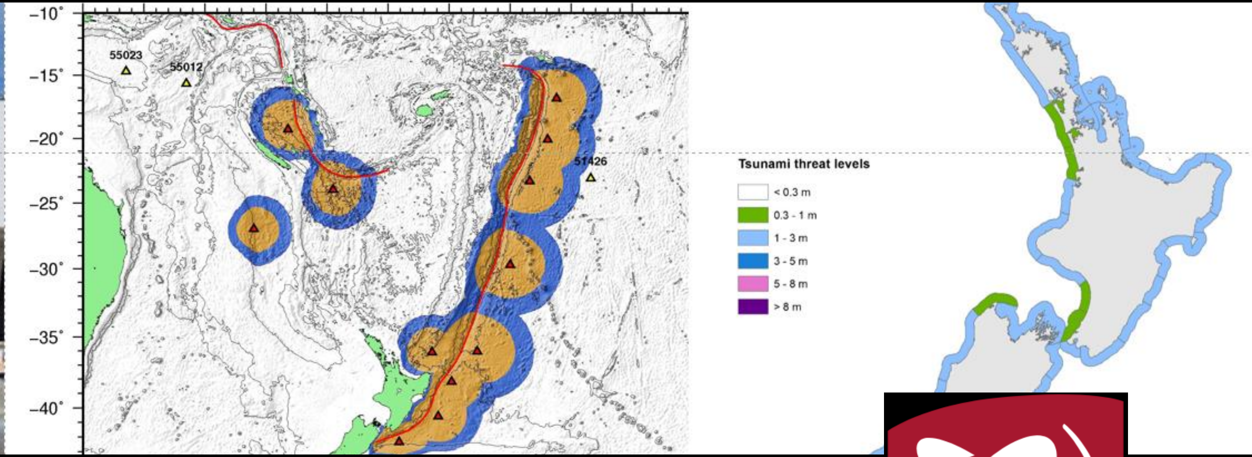
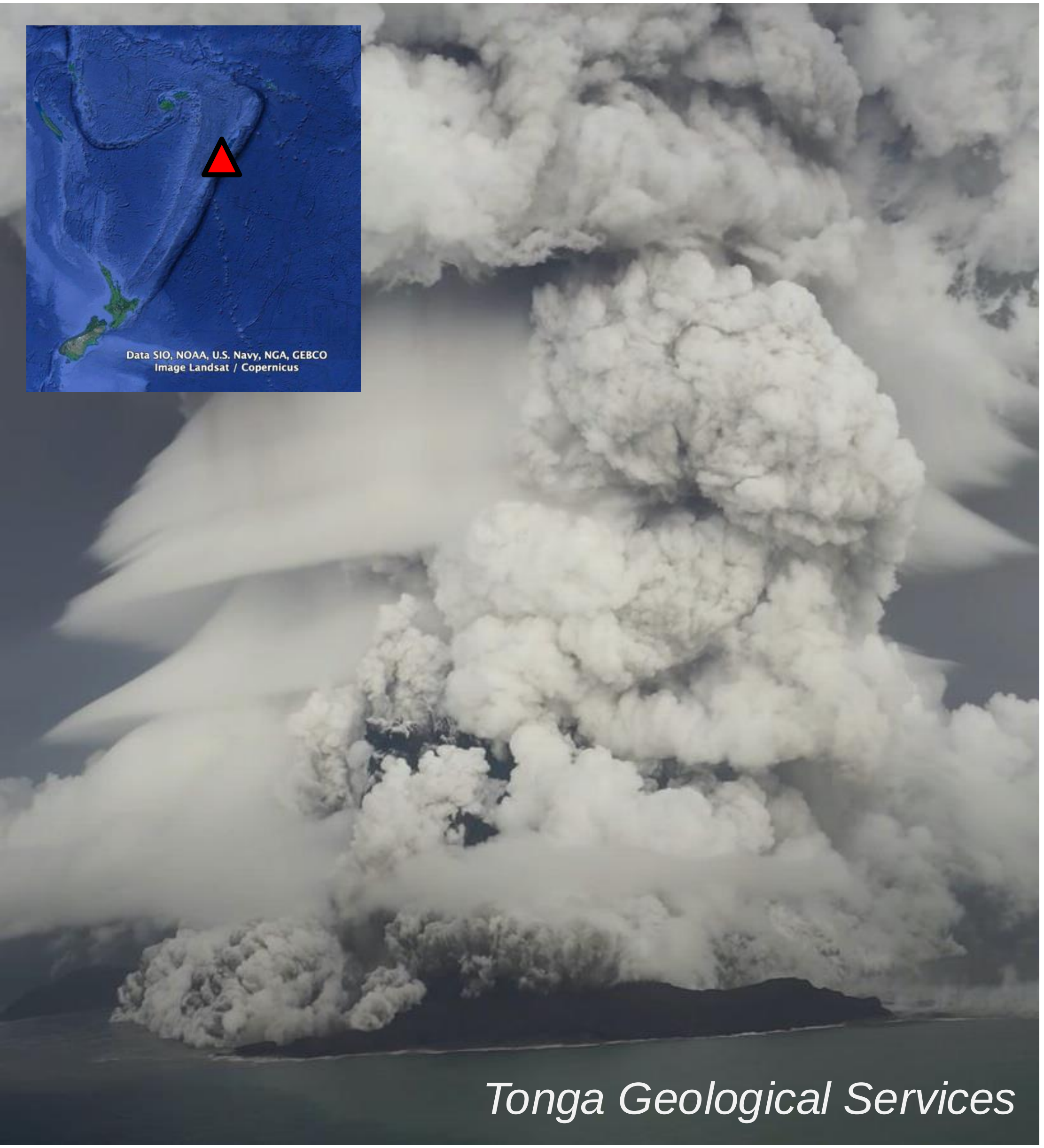
Volcanic Tsunami Modelling



Aditya Gusman, Xiaoming Wang, and Jean Roger
a.gusman@gns.cri.nz
Earth Structure and Processes, GNS Science, New Zealand

Introduction

The 2022 HTHH tsunami

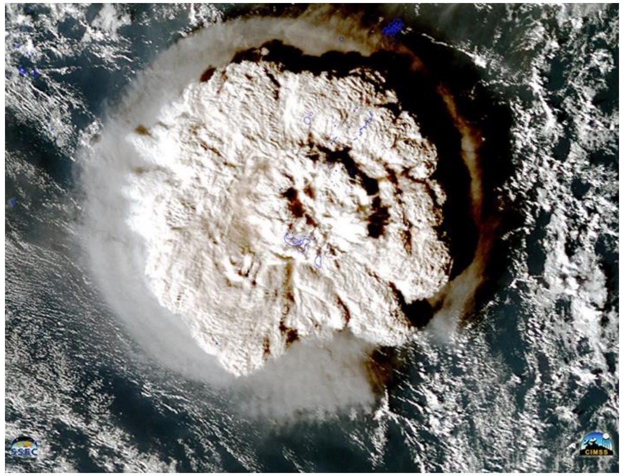


Tonga Geological Services

After the 14 January 2022 eruption

HIMAWARI-8

15 January 2022 eruption



After the 15 January 2022 eruption

Planet Labs, Inc.

Tsunami Inundation Observations

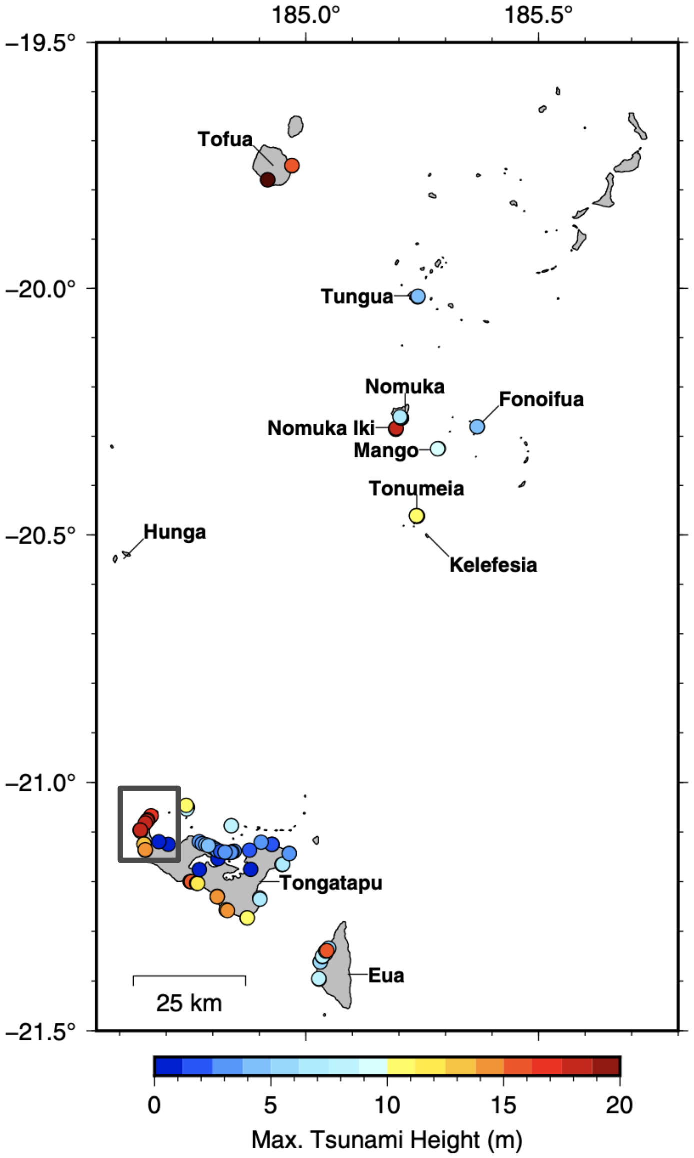
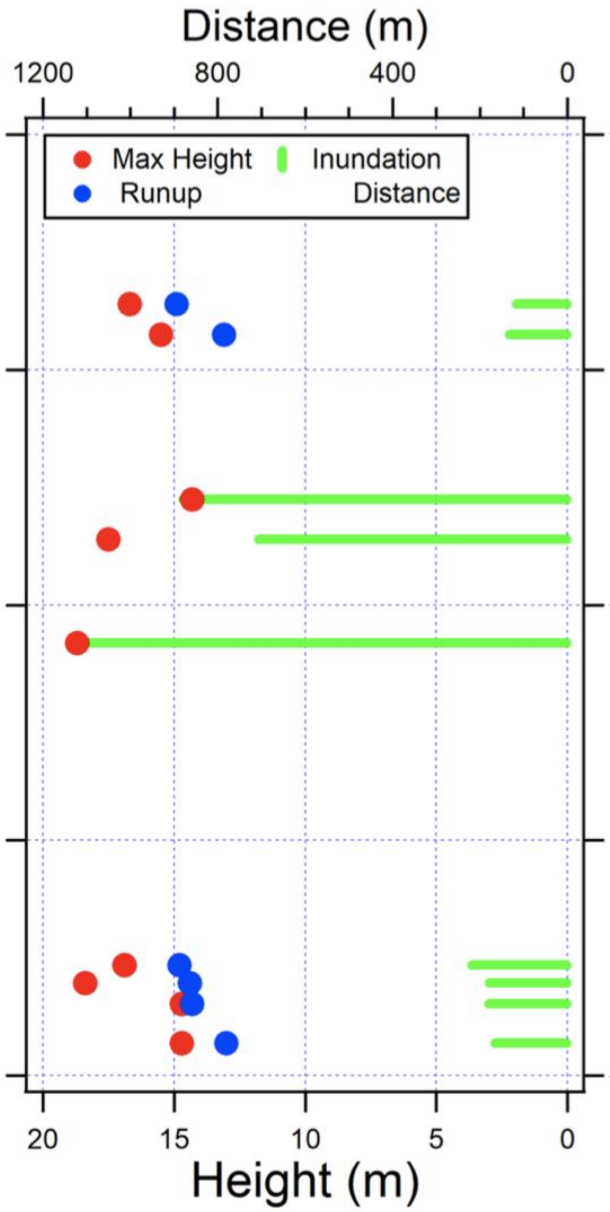
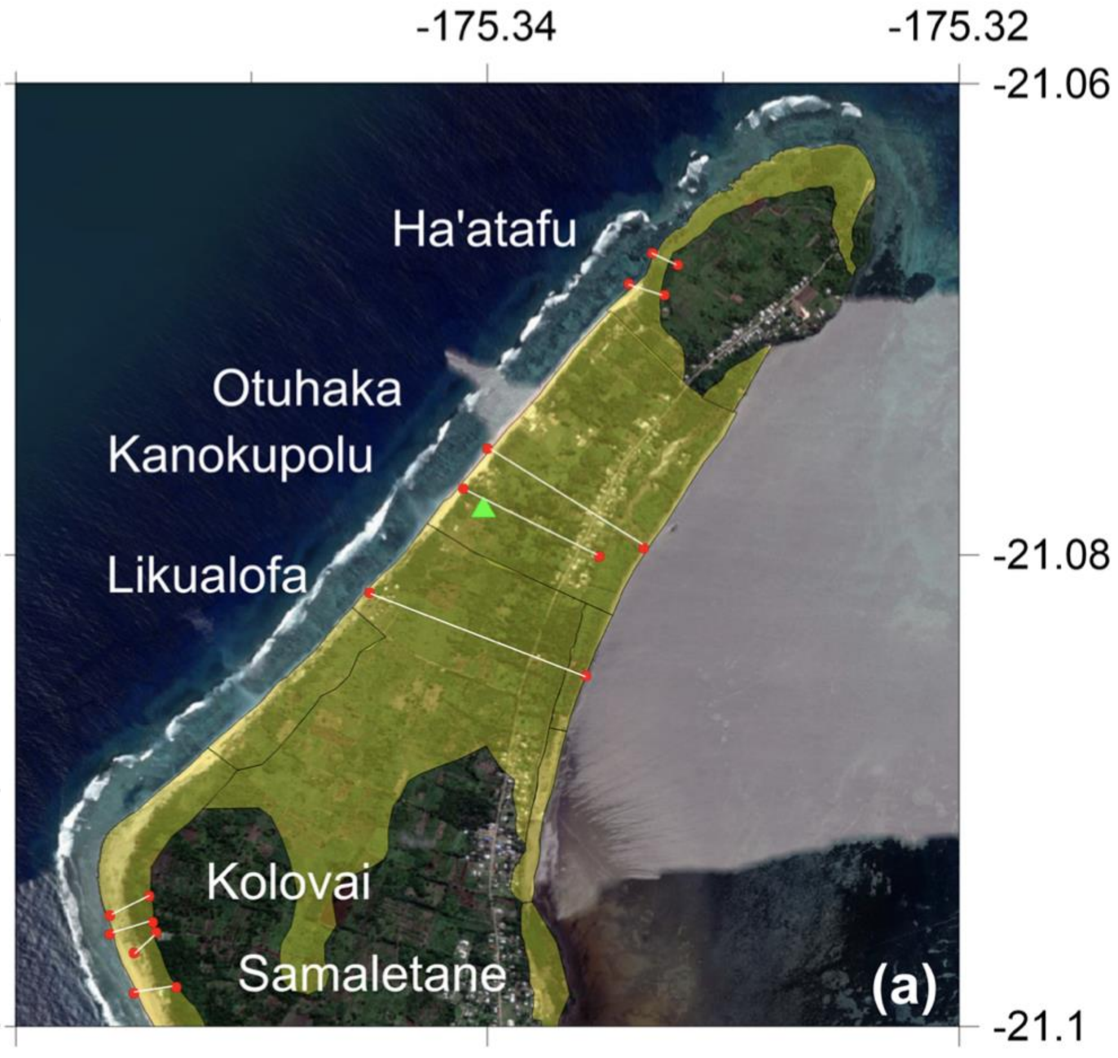


Figure 6
Summary data plots of maximum measured tsunami heights





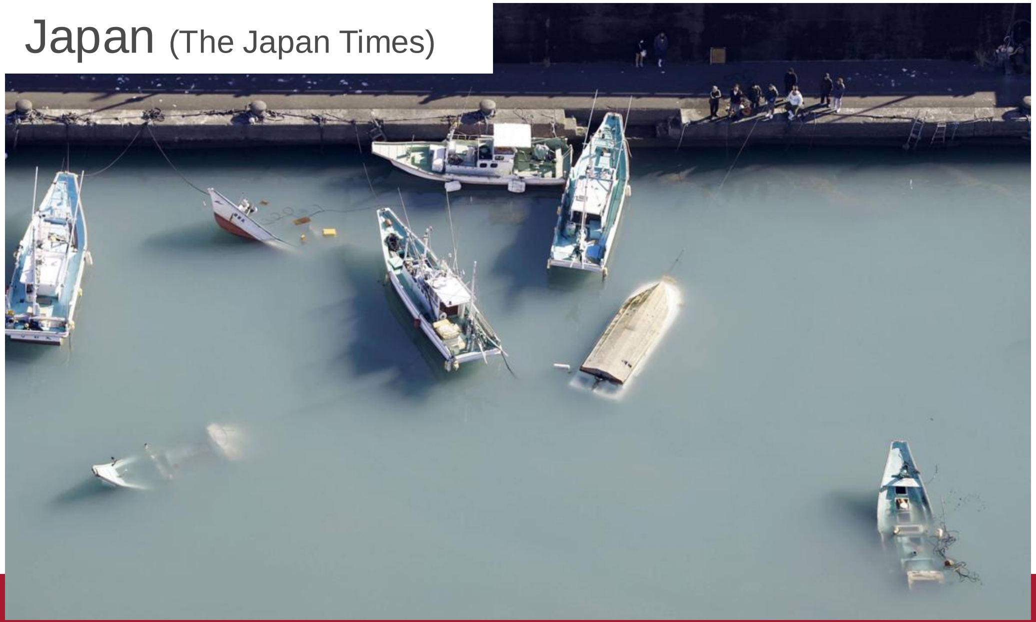
Borrero et al. (2023)

Tsunami Damages

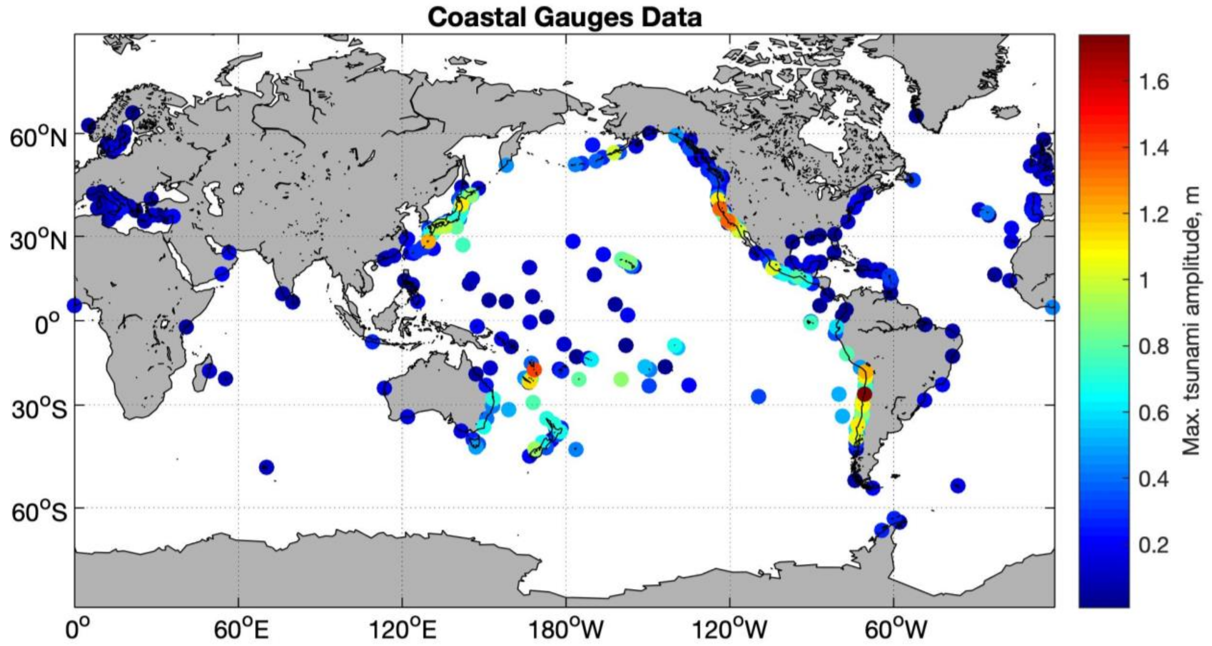

Tonga (Borrero et al., 2022)

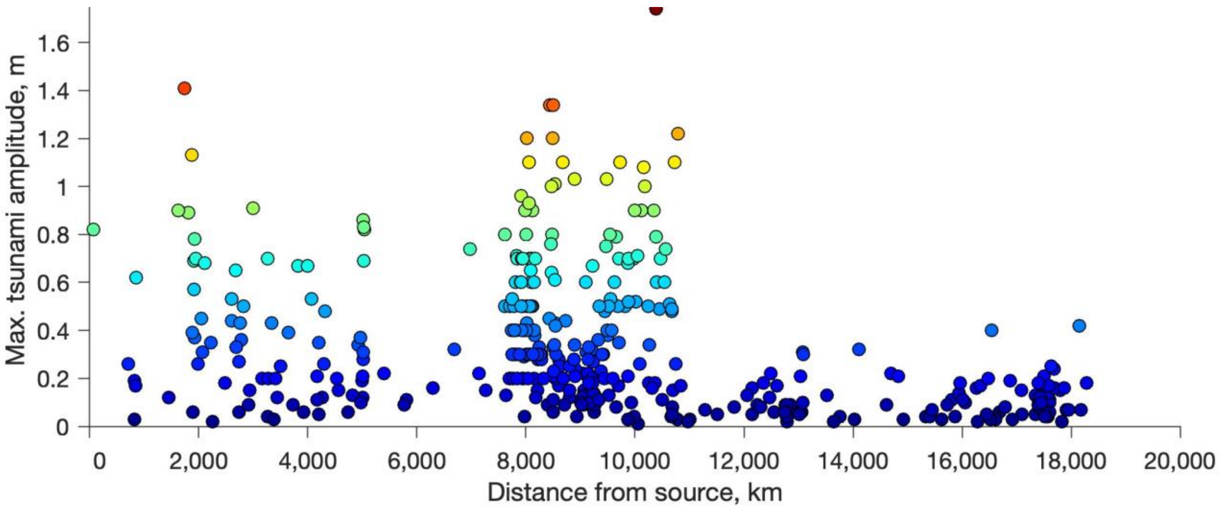

New Zealand (Stuff)

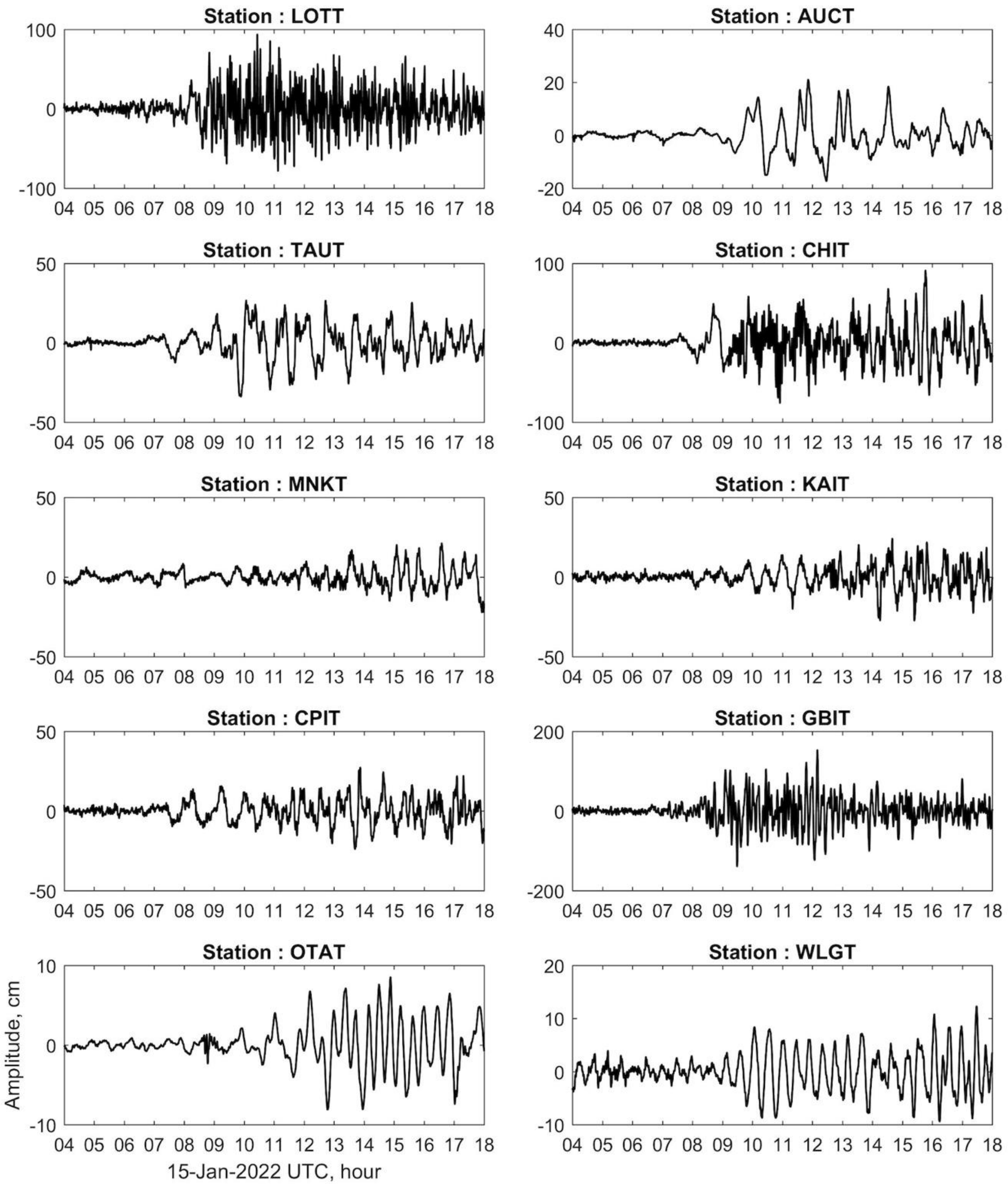

Peru (Merco Press)


Japan (The Japan Times)

Coastal Gauges Data

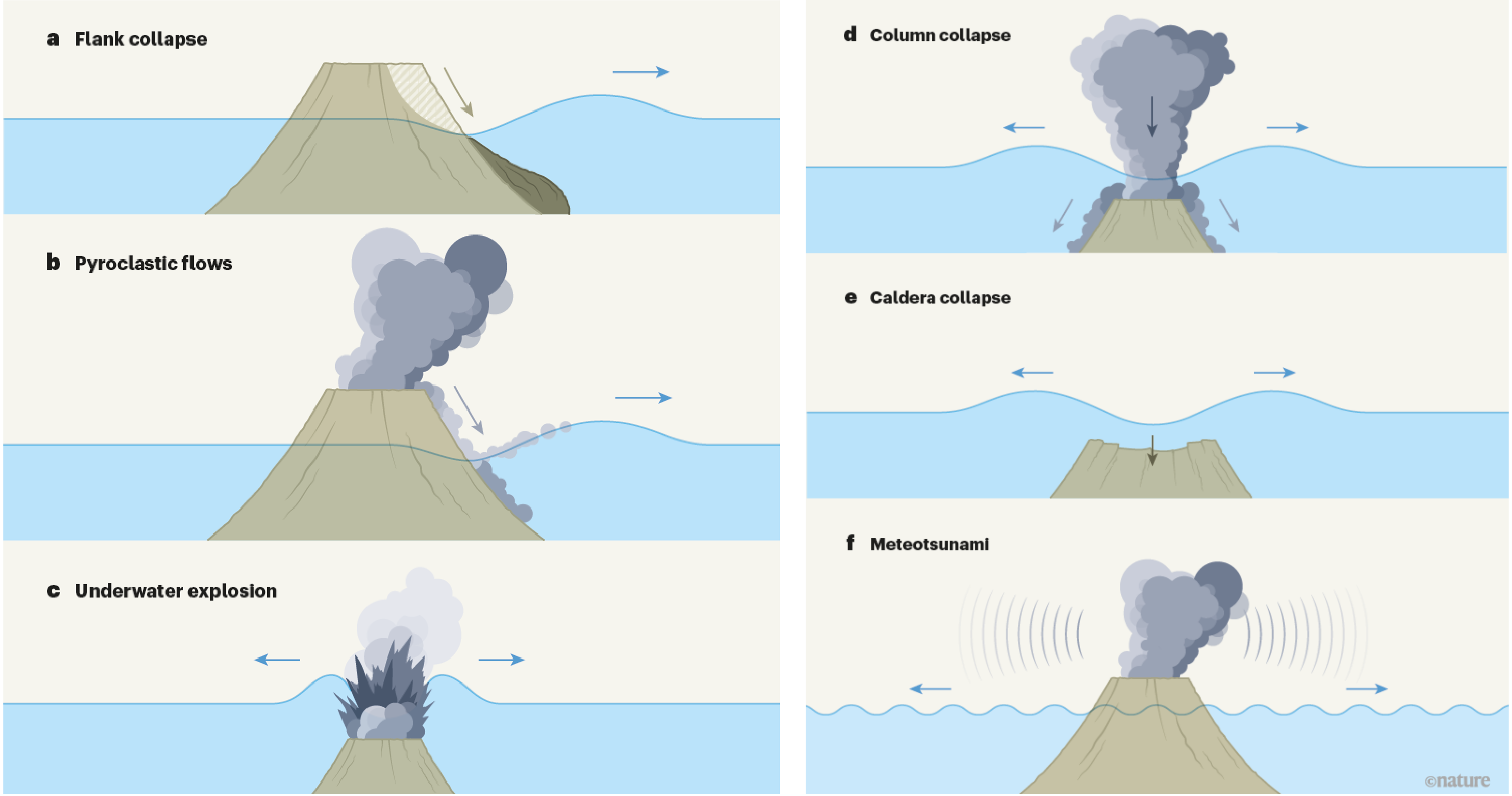






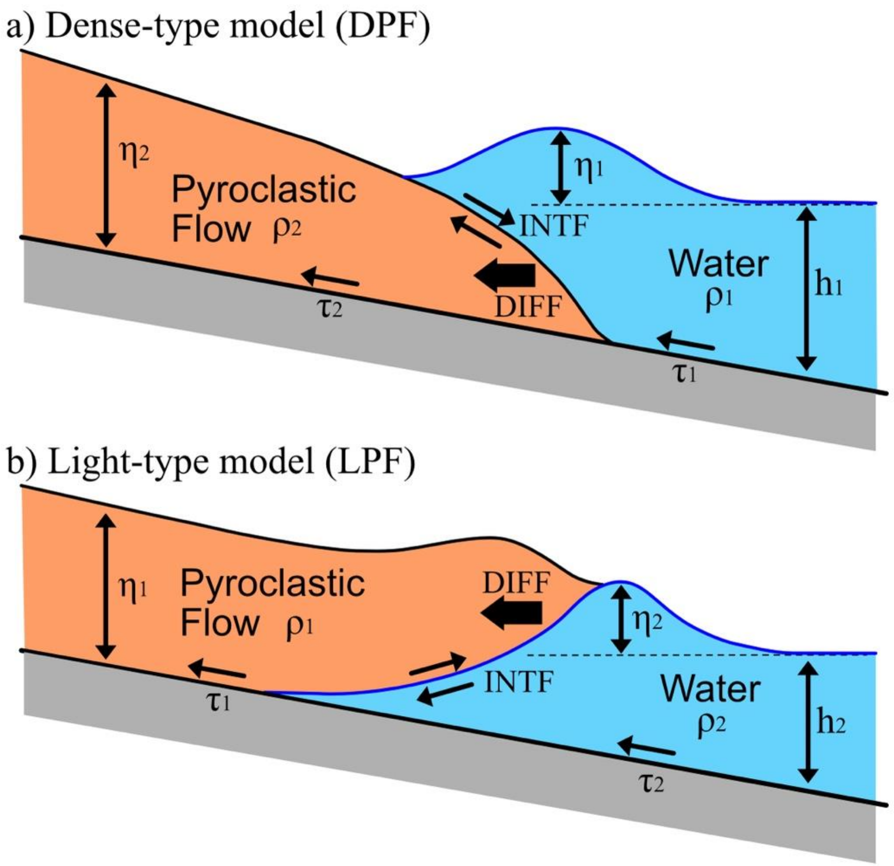
Data source: Global Historical Tsunami Database (NOAA - NCEI)

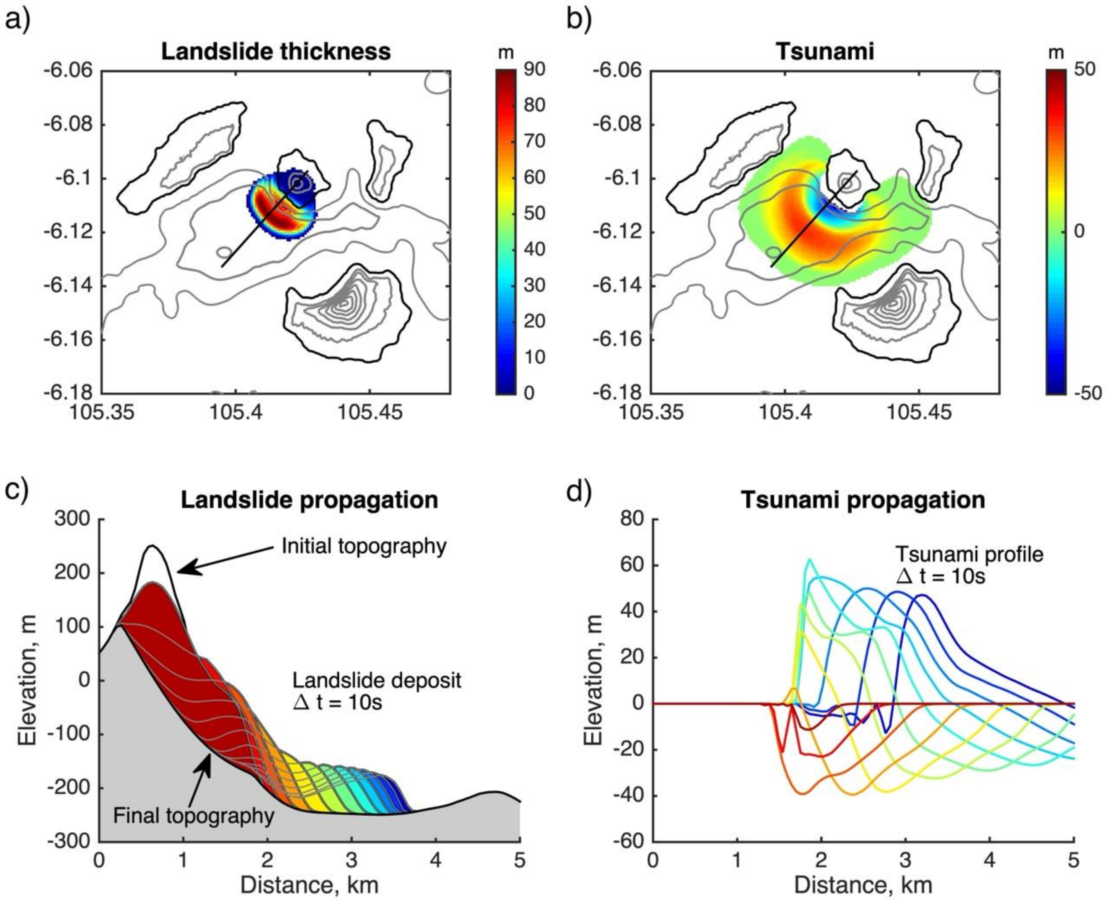
Volcanic Tsunami Source Mechanisms



Lane et al. (2022)

Pyroclastic Flow and Landslide Generated Tsunami

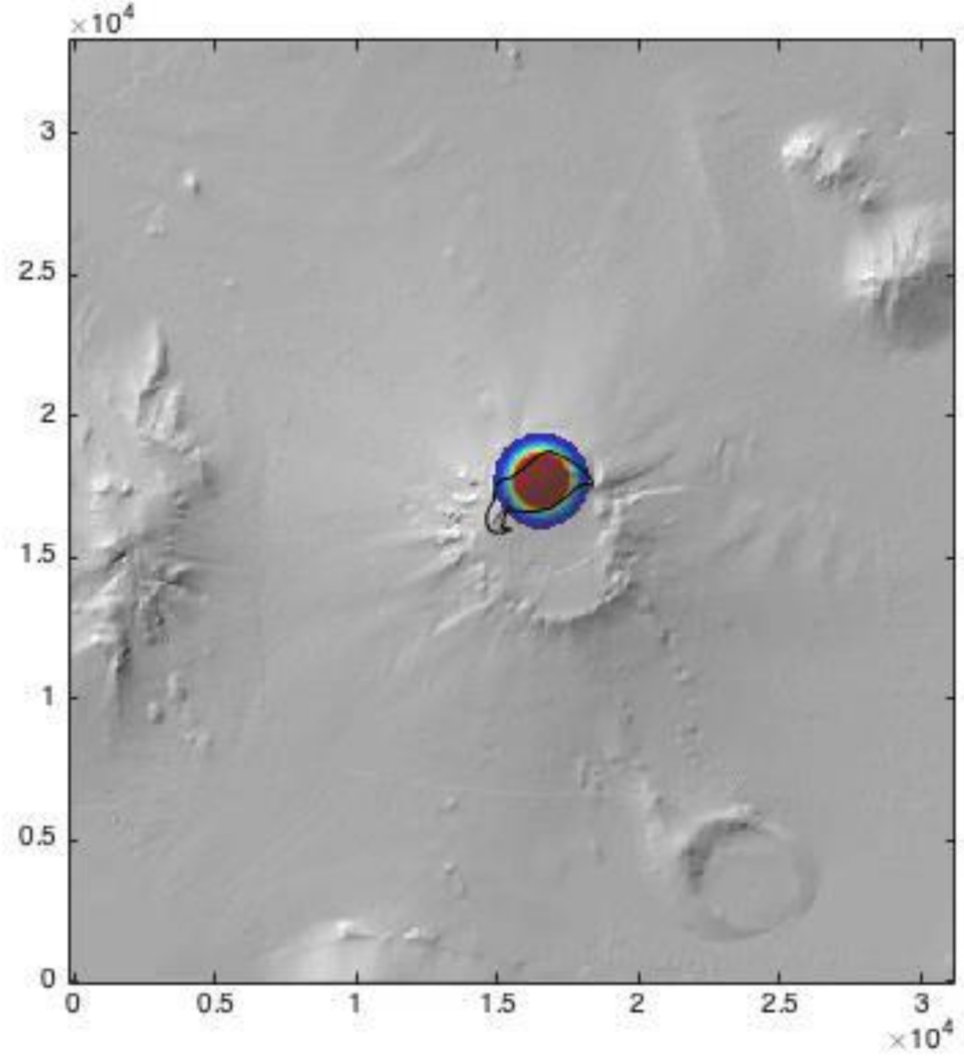


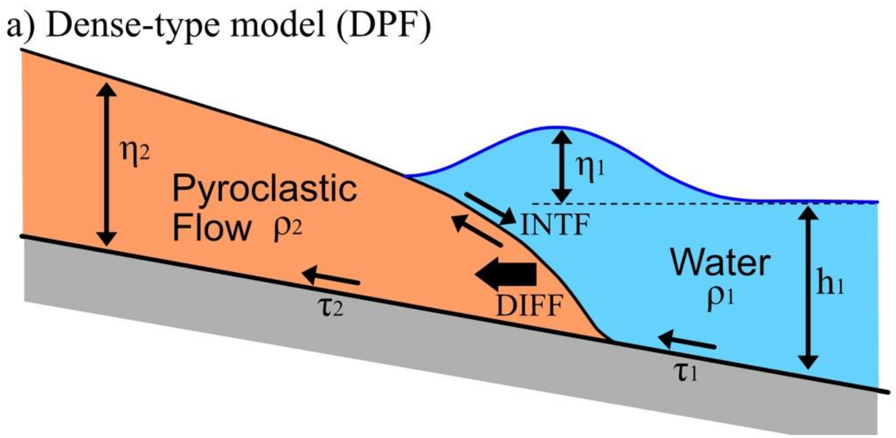


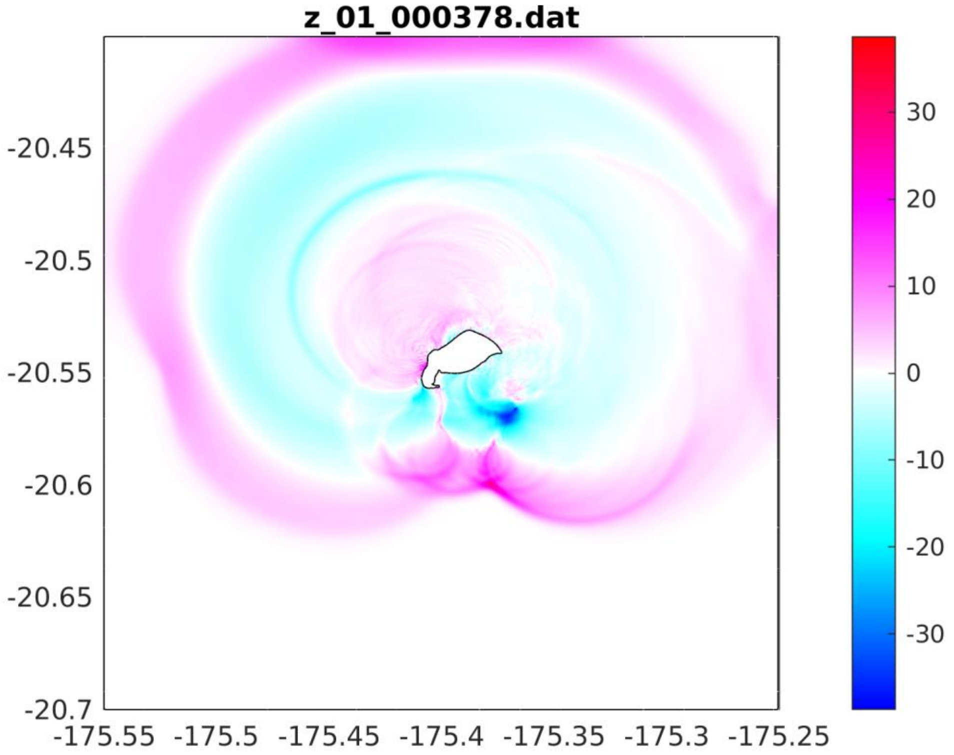
To calculate pyroclastic flows and tsunamis simultaneously, two types of two-layer shallow water models, a dense-type (DPF) model and a light-type (LPF) model were developed by Maeno and Imamura (2011).

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

The 2022 HTHH Eruption:
Pyroclastic Flow Tsunami Modeling



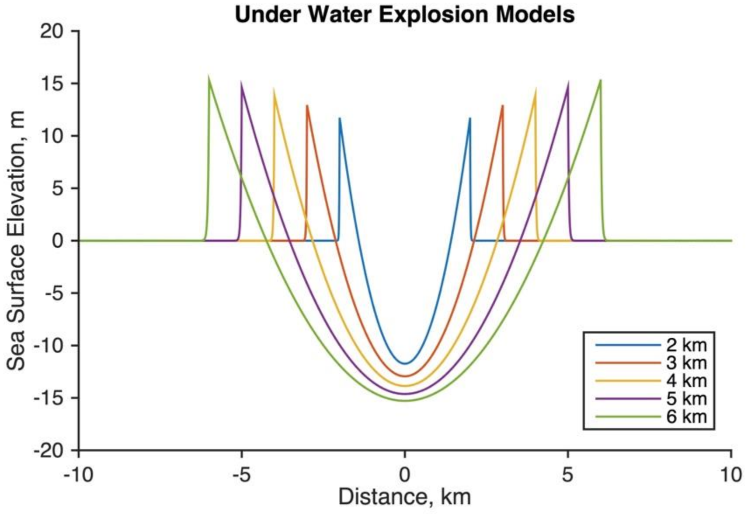


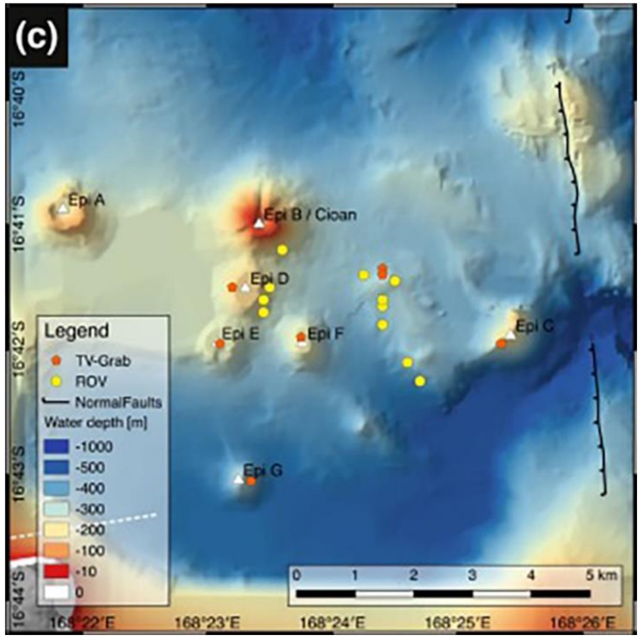


Under Water Explosion Model

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).

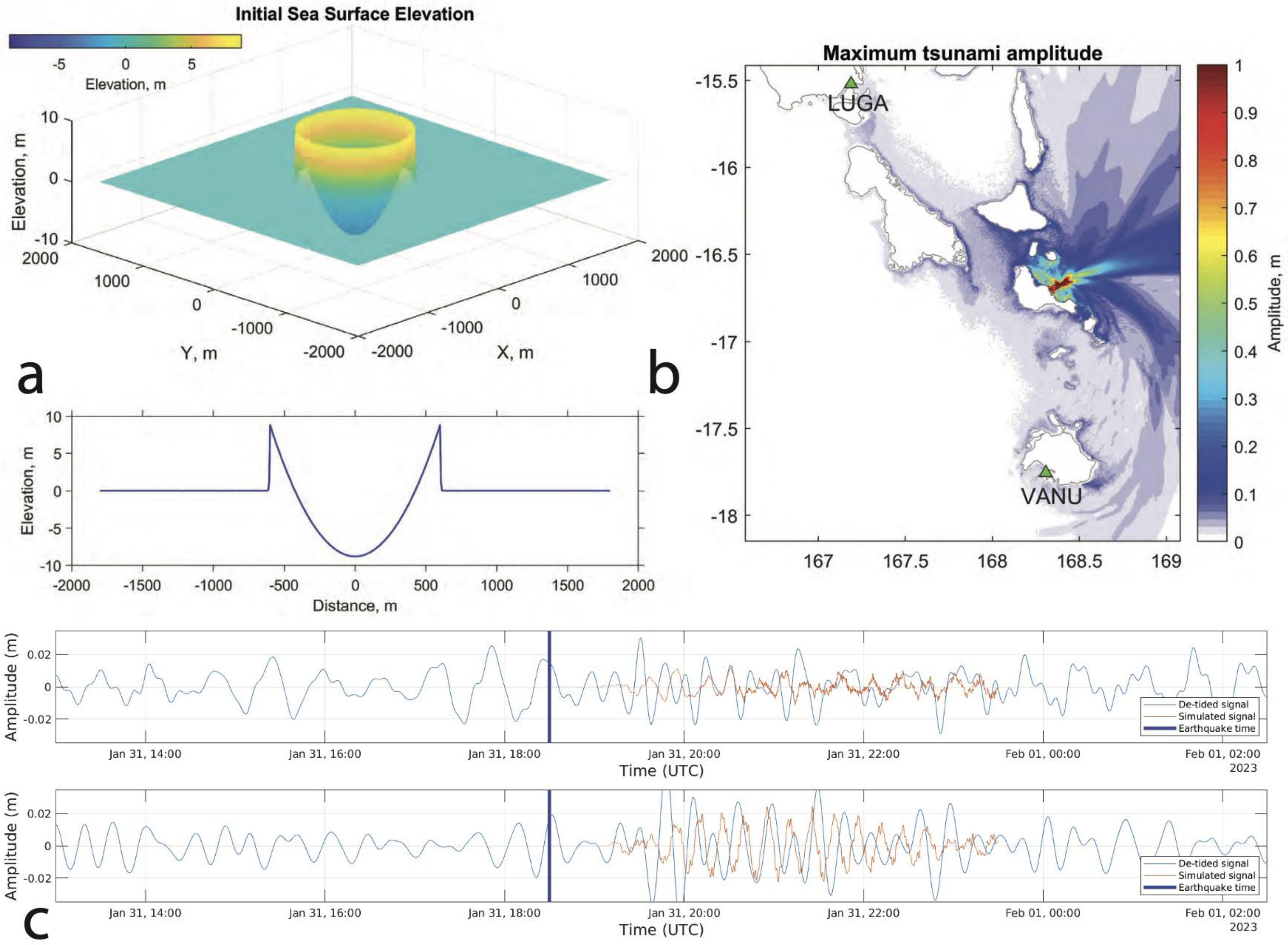
$$\eta(r) = \begin{cases} \eta_0\left[2\left(\frac{r}{R}\right)^2 - 1\right], & if\ r \le R \\ \eta_0\left[2\left(\frac{r}{R}\right)^2 - 1\right] e^{P_r(1-r/R)}, & if\ R < r \le 2R \\ 0, & if\ r > 2R \end{cases}$$





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

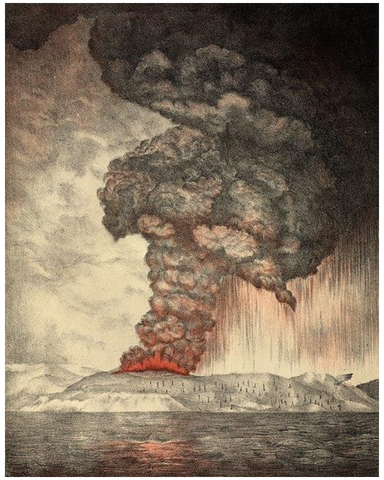


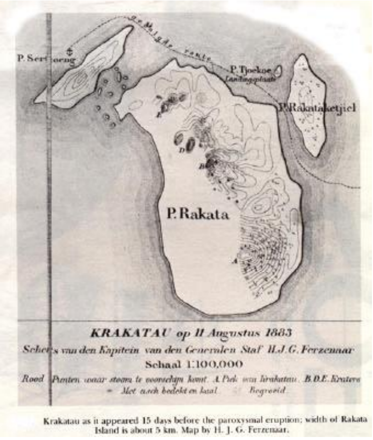
AGU Fall meeting 2023 Poster (Roger et al., 2023)

Tsunami simulation: (a) Initial sea-surface deformation model (in meters); (b) Maximum wave amplitude map after 5 hours of tsunami propagation on a ~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 filterred 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

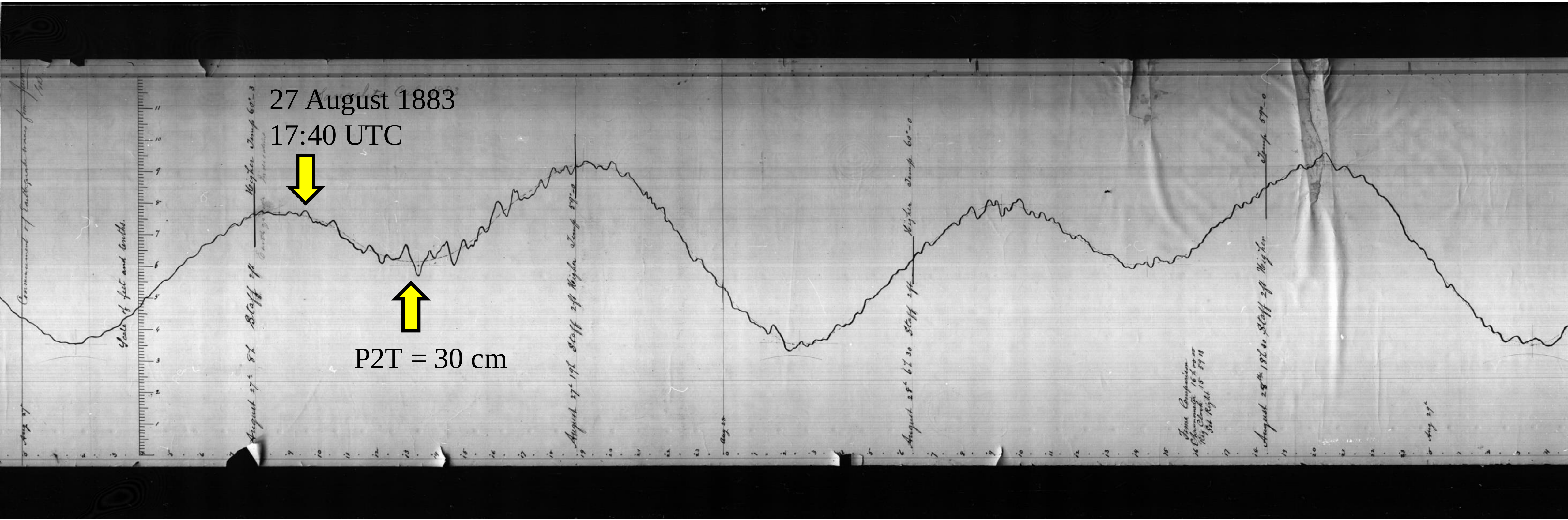
Largest eruption 27 August 1883 3:02 UTC
Distance from Krakatau to San Francisco 14,000 km
Arrival time: 27 August 1883 17:40 UTC
Wave speed: 266 m/s
Tsunami speed at 4 km water depth: $\sqrt{gd} = 200$ m/s
Tsunami speed at 1 km water depth: $\sqrt{gd} = 100$ m/s





Krakatau as it appeared 15 days before the paroxysmal eruption; width of Rakata Island is about 5 km. Map by H. J. G. Ferzenaar.


Krakatau to San Francisco
14,000 km


27 August 1883
17:40 UTC

P2T = 30 cm

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.

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

$$\frac{\partial u_p}{\partial t}+\frac{1}{\rho_a Rsin\theta}\left[\frac{\partial p}{\partial\varphi}\right]+fv=0$$

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

$$H_p=\frac{\gamma RT}{gM}$$

γ = 1.4; % ratio of specific heat of air
T = 288 % K
R = 8314.36; % J Kmol^-1 K^-1 universal gas constant
M = 28.966; % kg Kmol^-1 Molecular mass for dry air
g = 9.81; % gravity acceleration m s^-2
ρ_a = 1.225; % air density in 15C in kg m^-3

(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

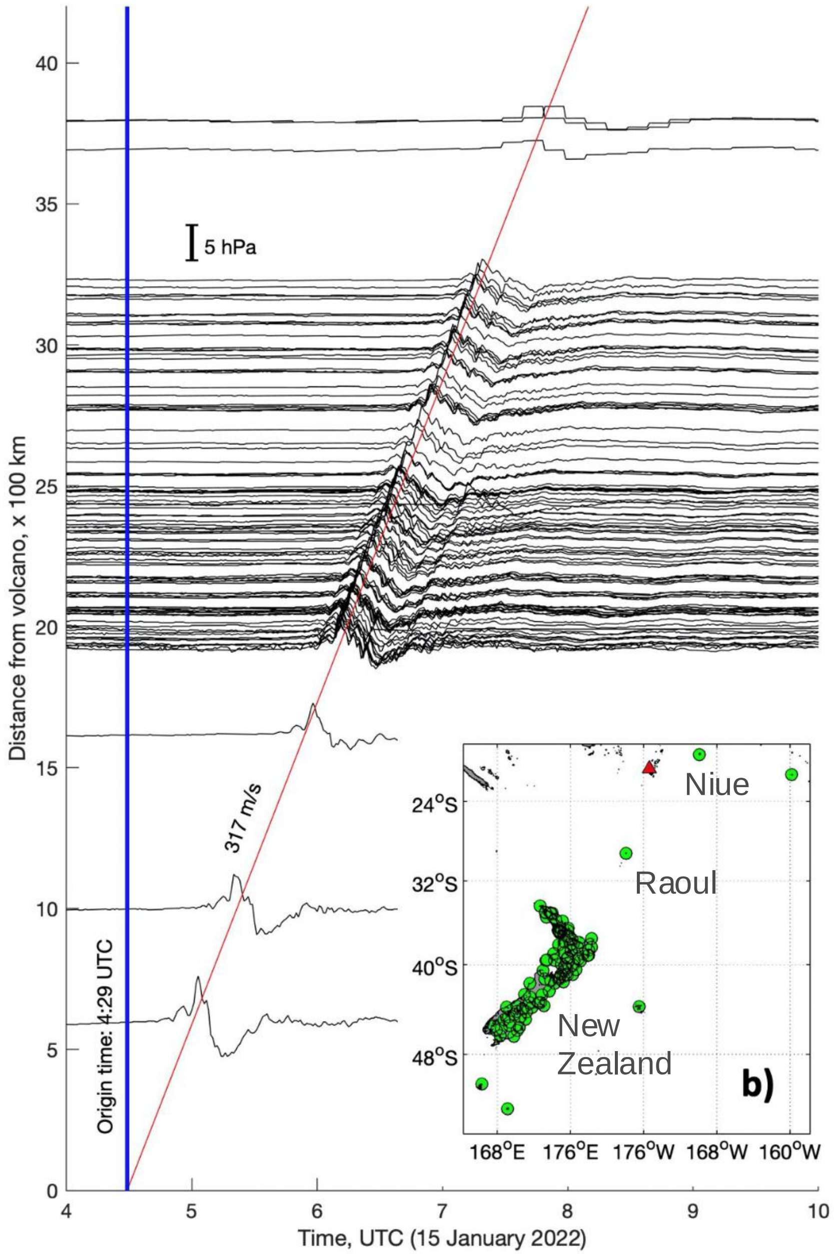
$$\frac{\partial h}{\partial t}+\frac{1}{Rsin\theta}\left[\frac{\partial[ud]}{\partial\varphi}+\frac{\partial[vdsin\theta]}{\partial\theta}\right]=0$$

$$\frac{\partial u}{\partial t}+\frac{1}{Rsin\theta}\left[g\frac{\partial h}{\partial\varphi}+\frac{1}{\rho}\frac{\partial p}{\partial\varphi}\right]+fv=0$$

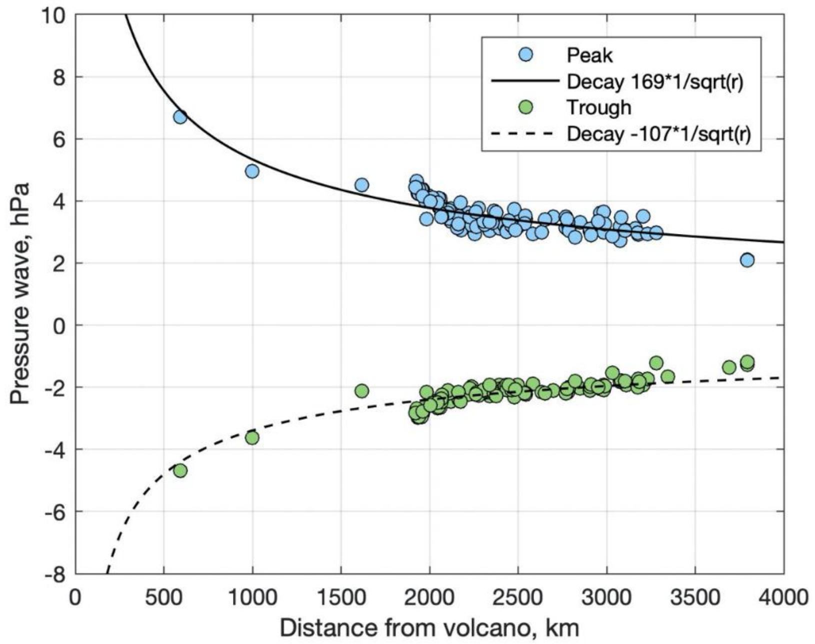
$$\frac{\partial v}{\partial t}+\frac{1}{R}\left[g\frac{\partial h}{\partial\theta}+\frac{1}{\rho}\frac{\partial p}{\partial\theta}\right]-fu=0$$

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

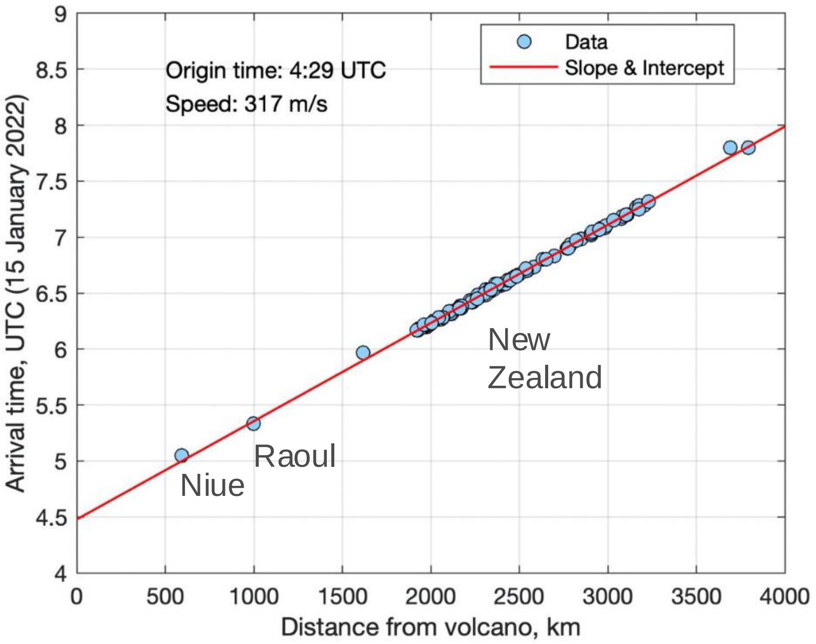
a)



c)



d)



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

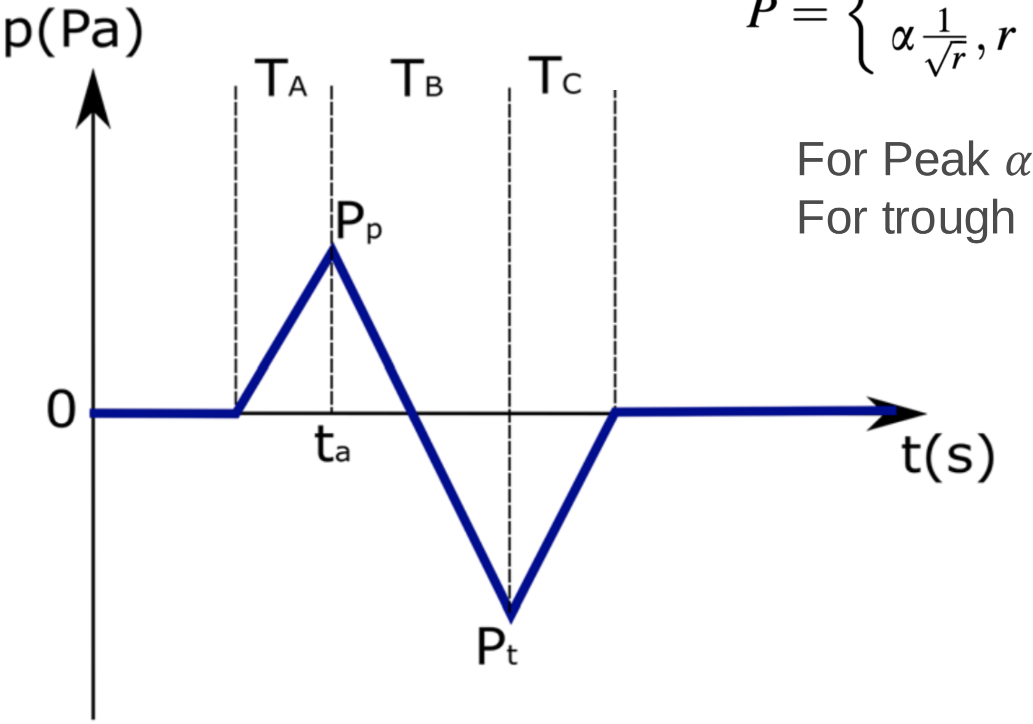
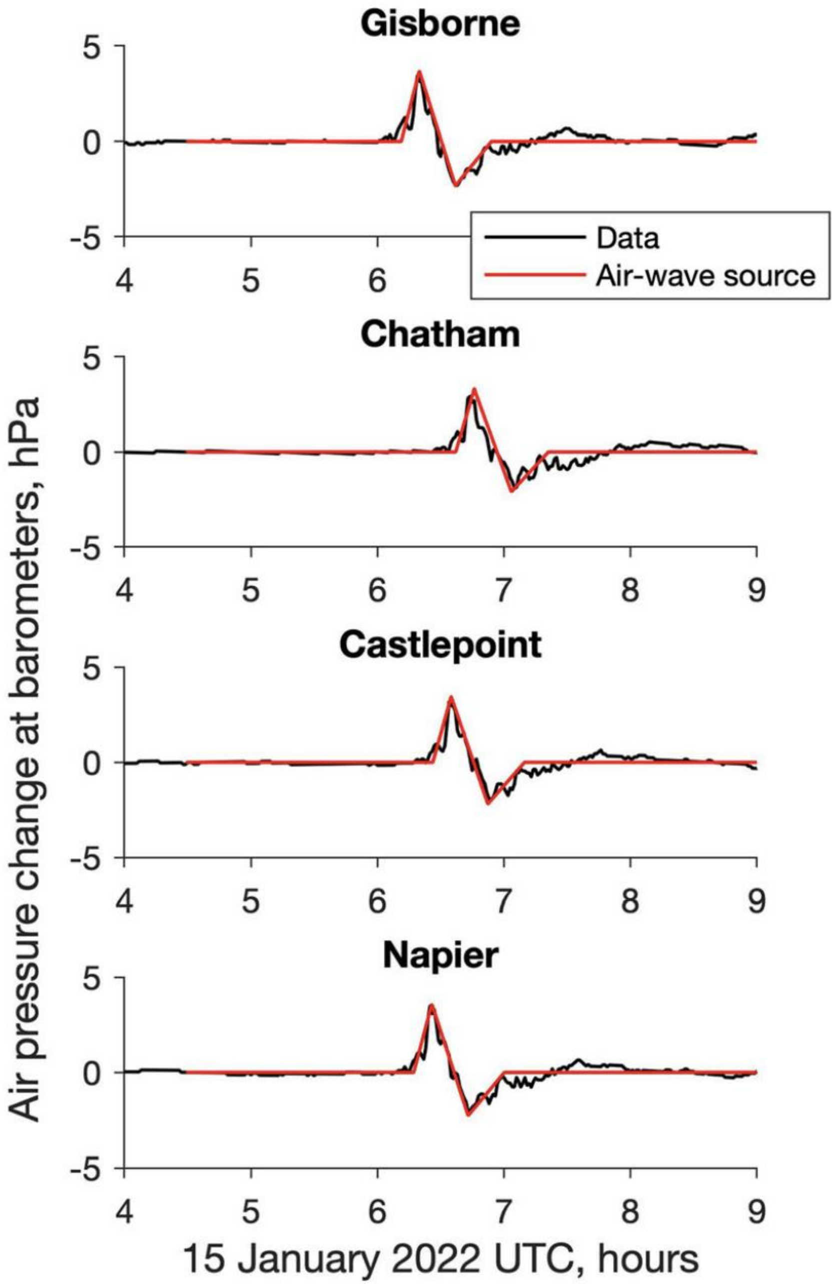


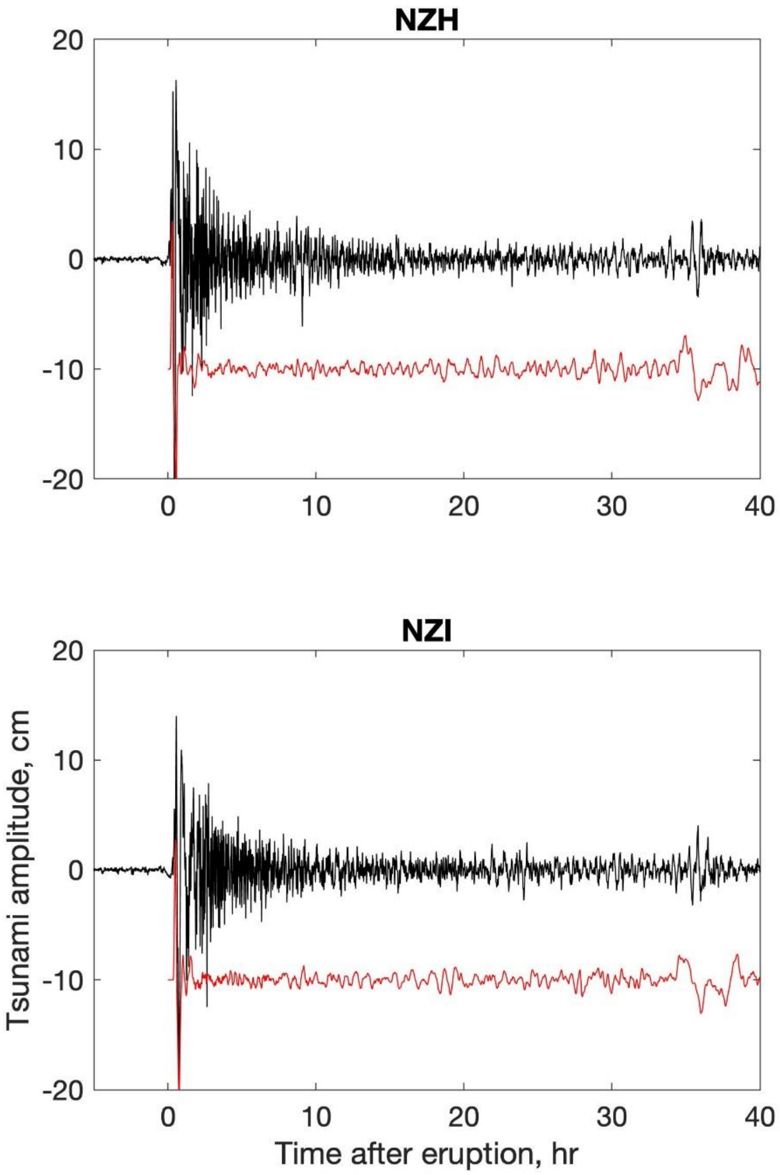
Figure 4
Illustration of air pressure wave model parameters used in this study

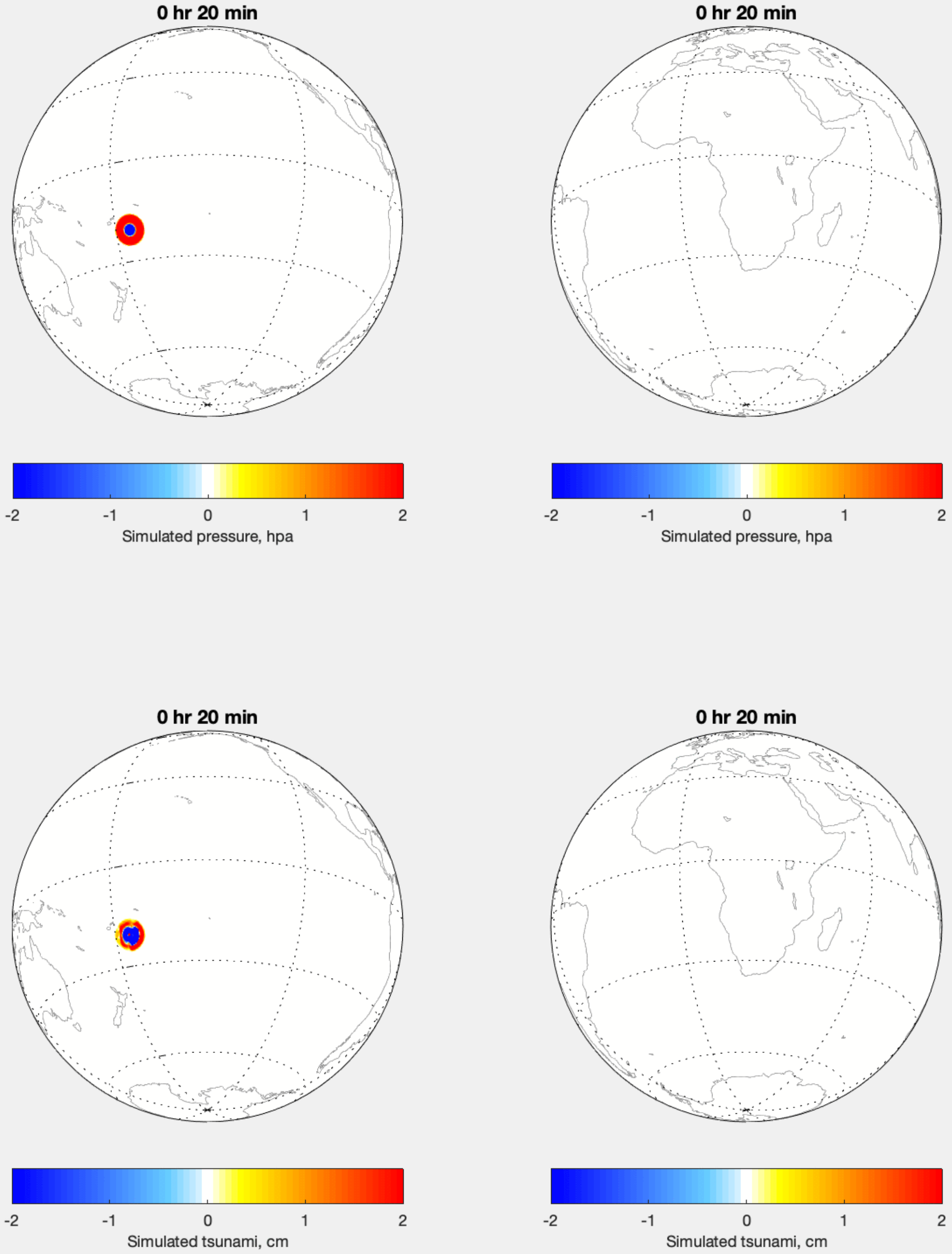
$$P = \begin{cases} \alpha, 0 < r \leq 1\ km \\ \alpha \frac{1}{\sqrt{r}}, r > 1\ km \end{cases}$$

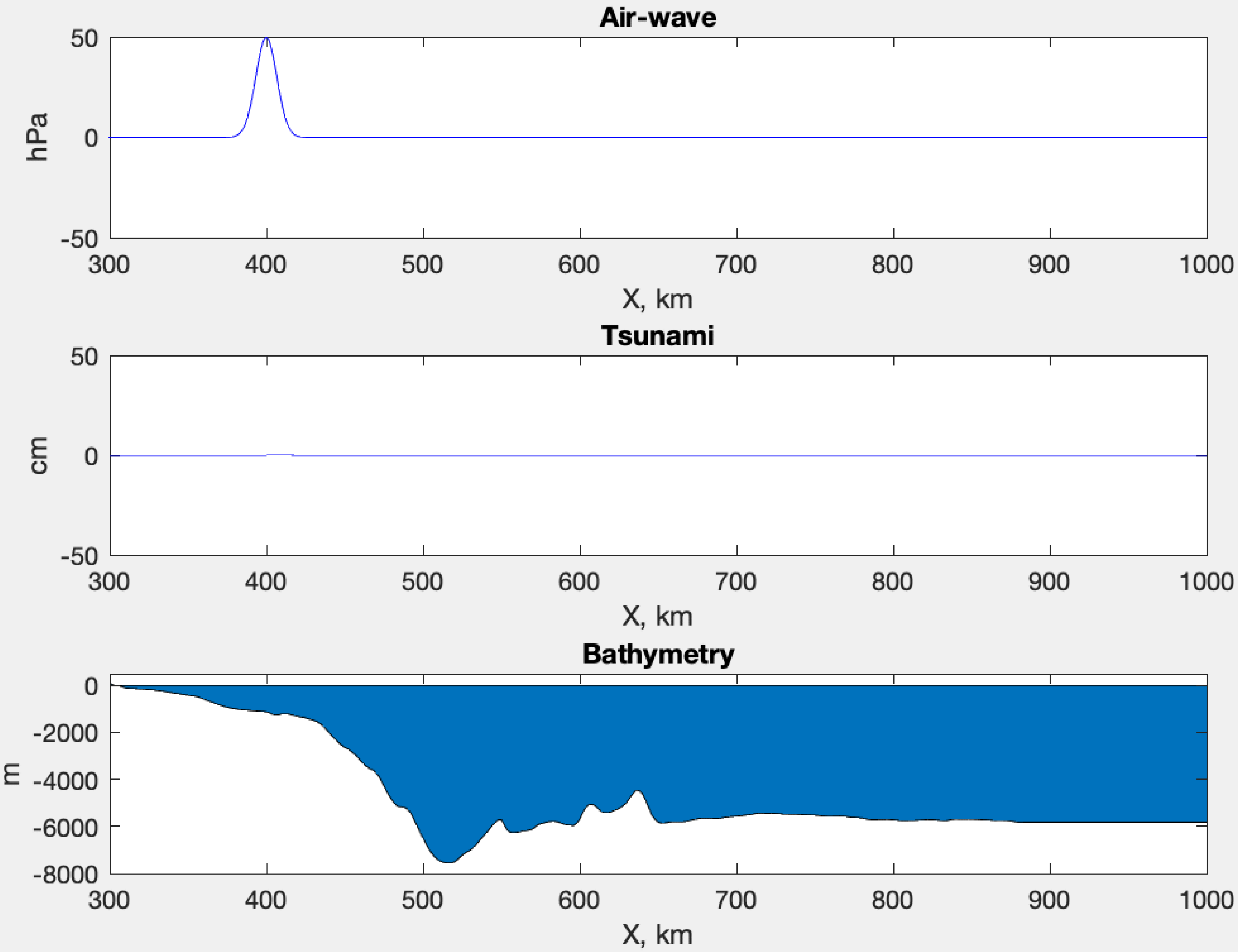
For Peak $\alpha = 169$
For trough $\alpha = -107$

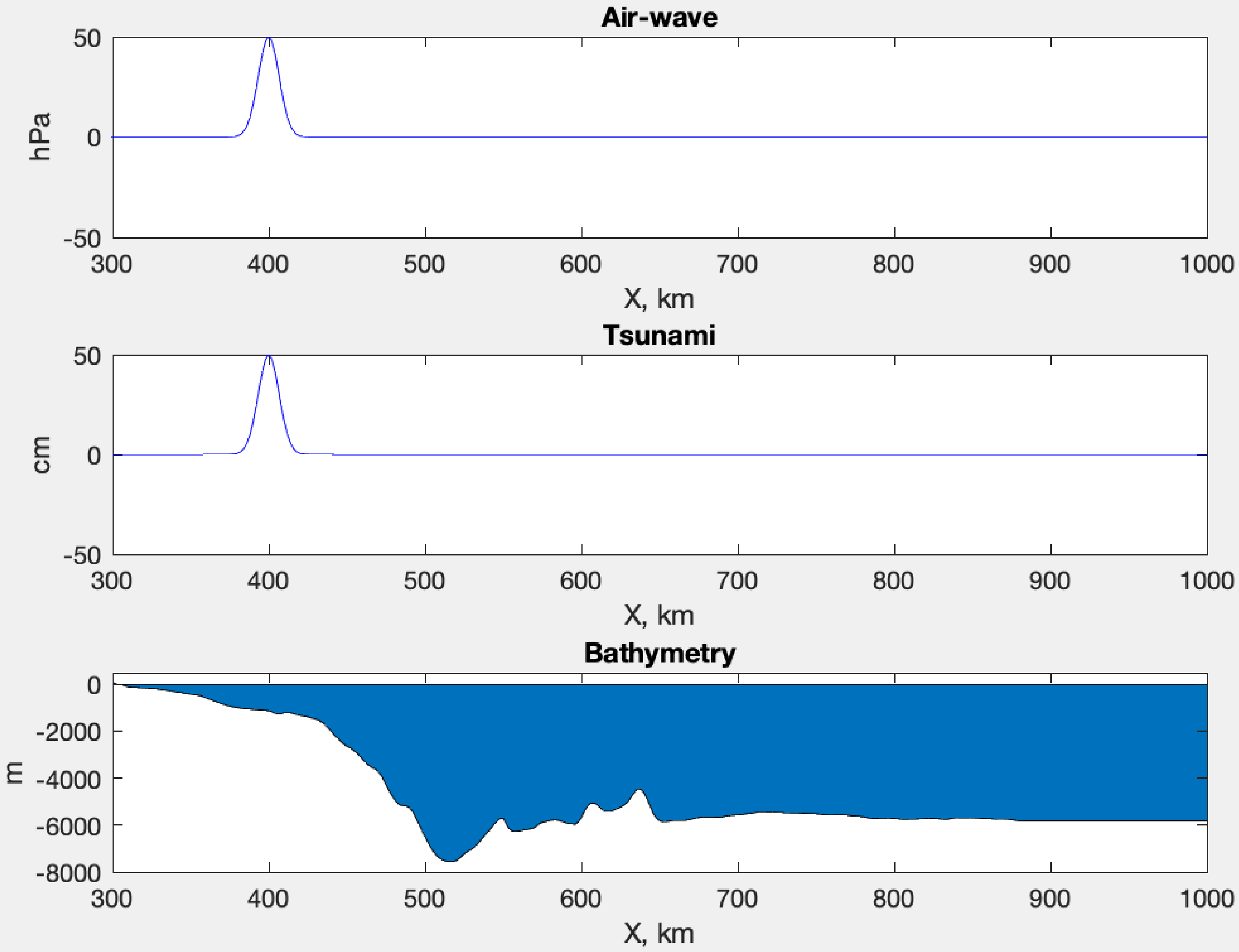


Global Tsunami Propagation (Lamb wave generated)

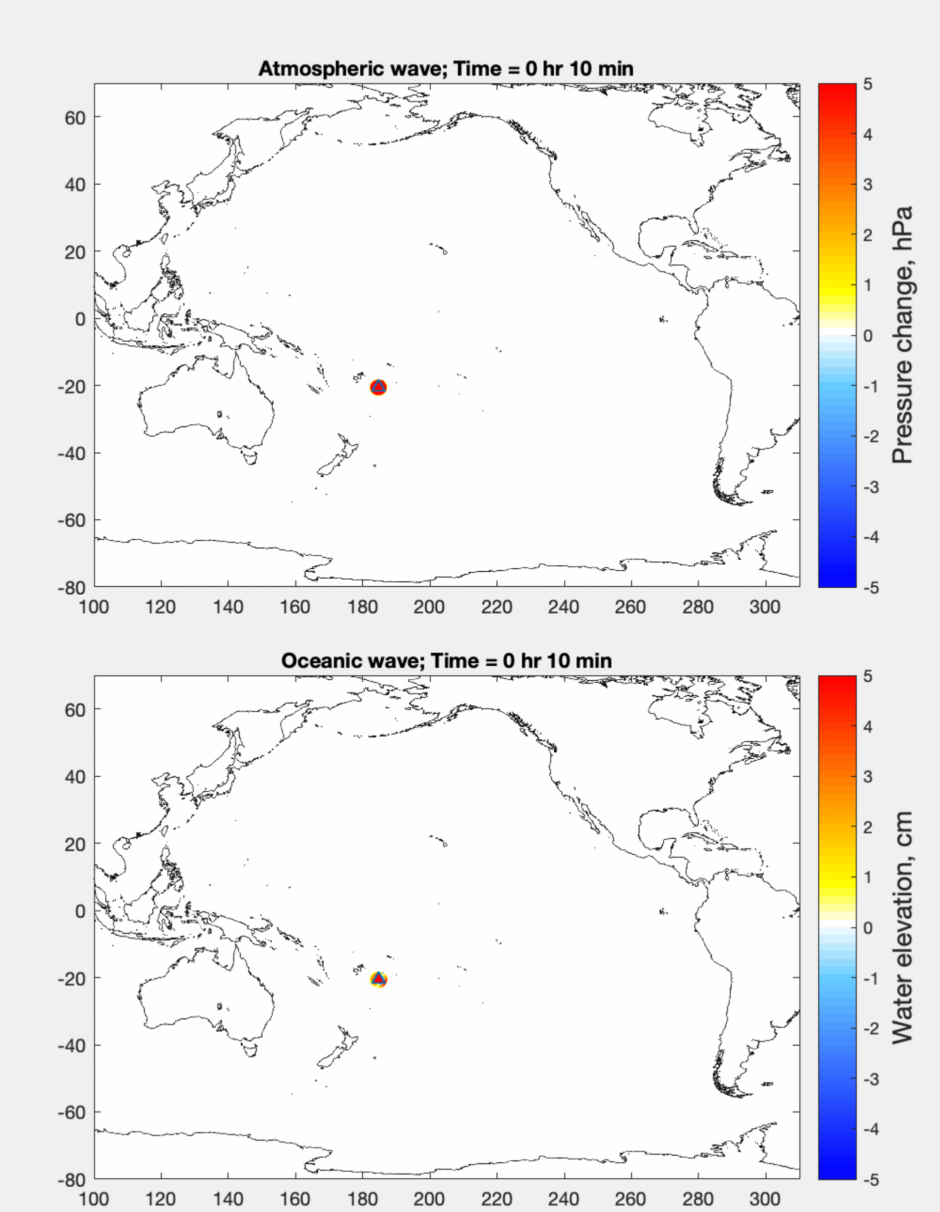


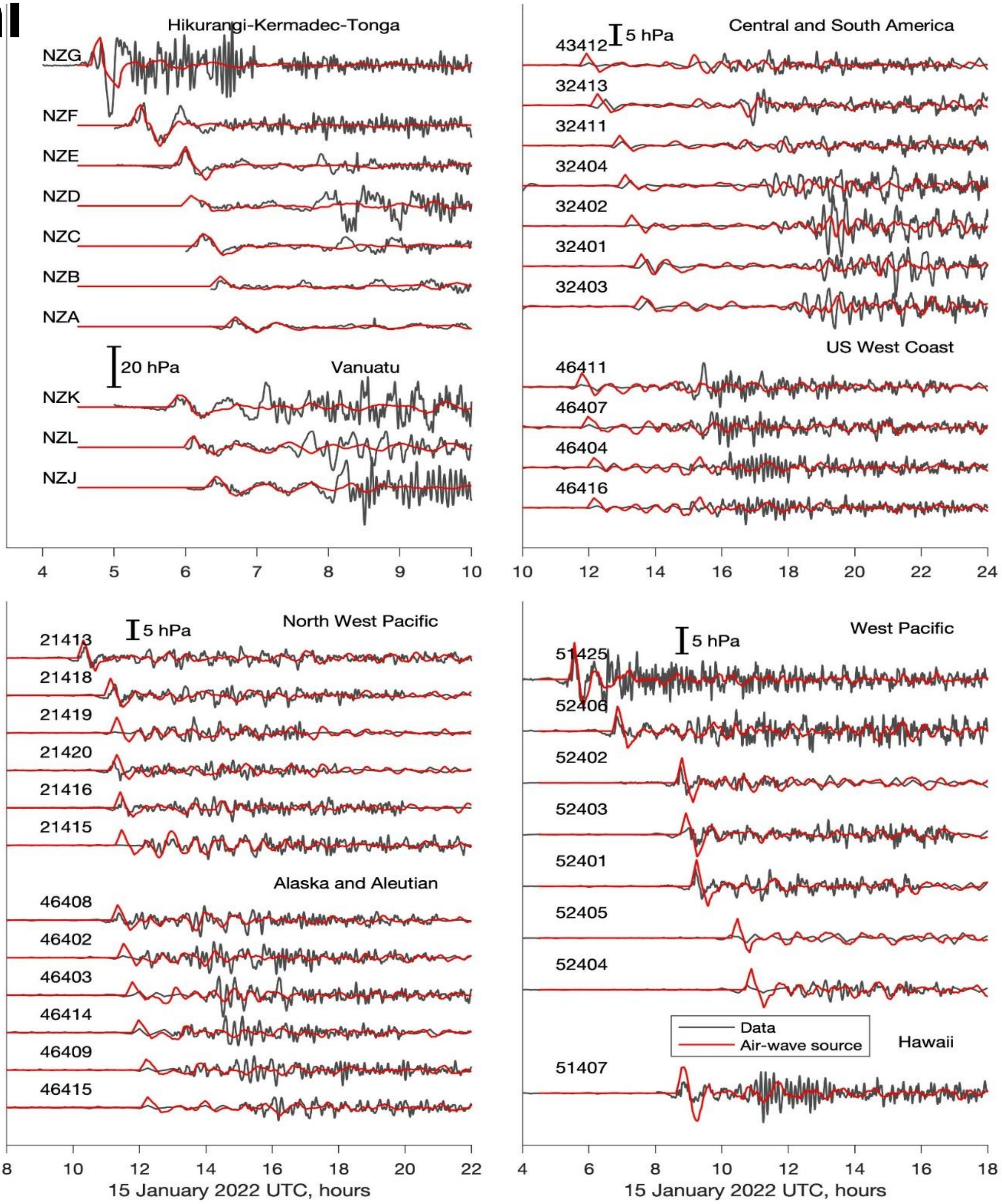



Air-wave
50
0
-50
hPa
300
400
500
600
700
800
900
1000
X, km
Tsunami
50
0
-50
cm
300
400
500
600
700
800
900
1000
X, km
Bathymetry
0
-2000
-4000
-6000
-8000
m
300
400
500
600
700
800
900
1000
X, km


Air-wave
hPa
50
0
-50
300
400
500
600
700
800
900
1000
X, km
Tsunami
cm
50
0
-50
300
400
500
600
700
800
900
1000
X, km
Bathymetry
m
0
-2000
-4000
-6000
-8000
300
400
500
600
700
800
900
1000
X, km

The 2022 HTHH Eruption Tsunami





Gusman et al. (2022)

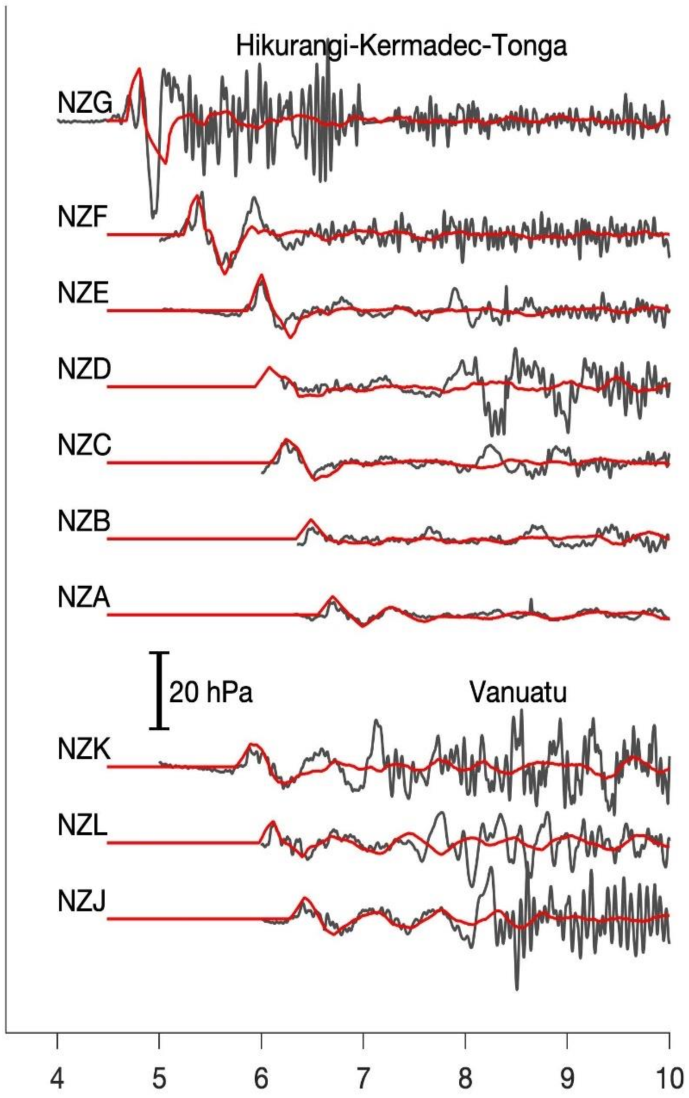
The 2022 HTHH Eruption Tsunami

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

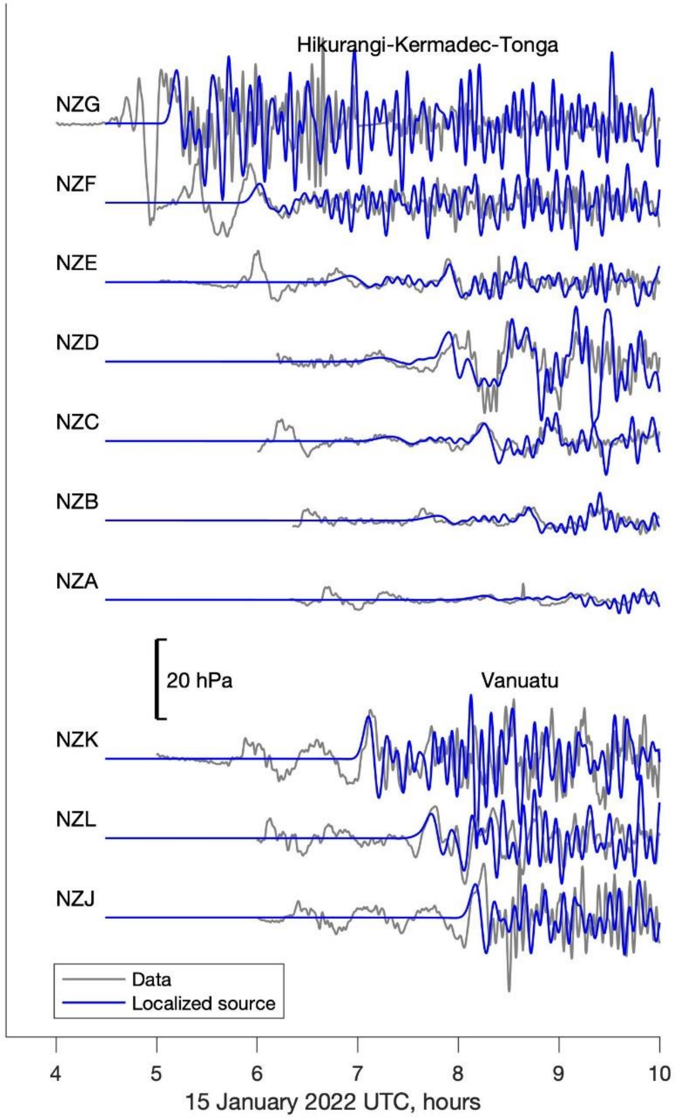
1. **Underwater explosion**
2. **Air wave**
3. **Pyroclastic flow**
4. **Flank Failure**
5. **Caldera subsidence**
6. **Lahar**
7. **Earthquake**

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



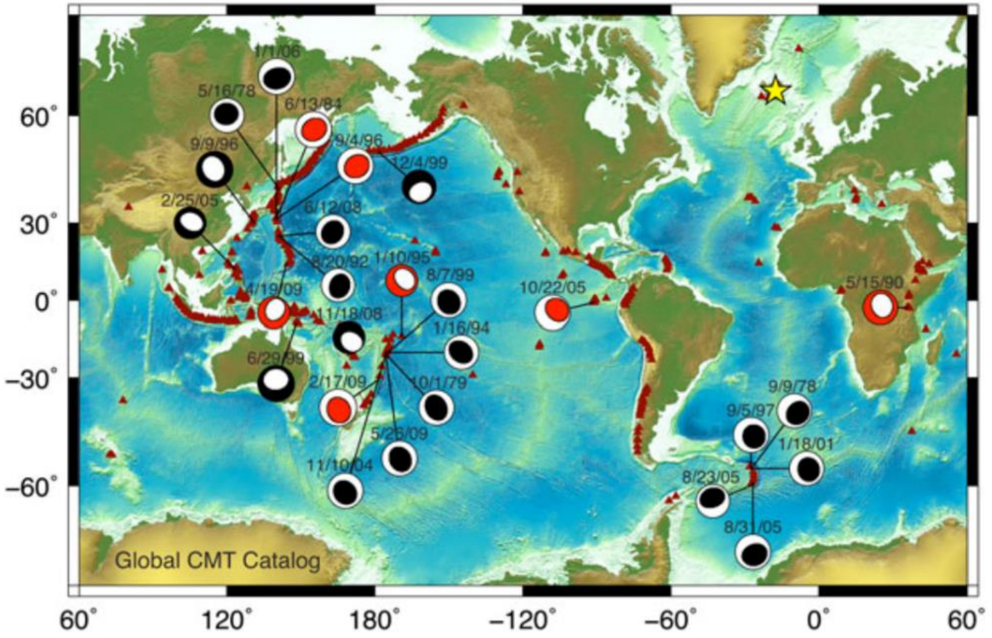
Water displacement
Localized source



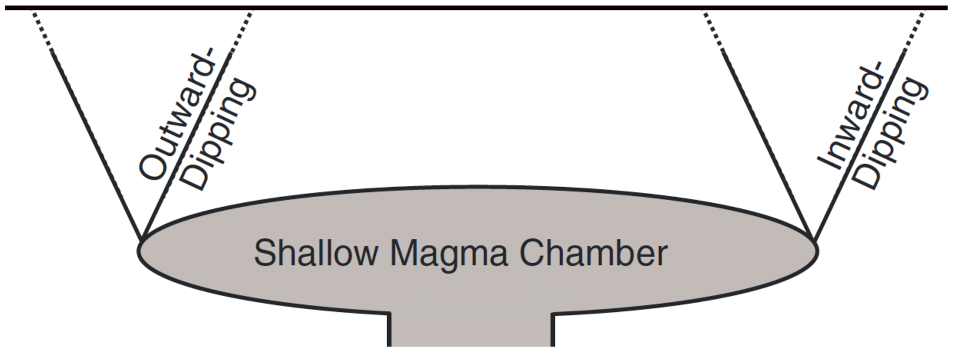
Gusman et al. (2022)

Vertical CLVD Earthquakes

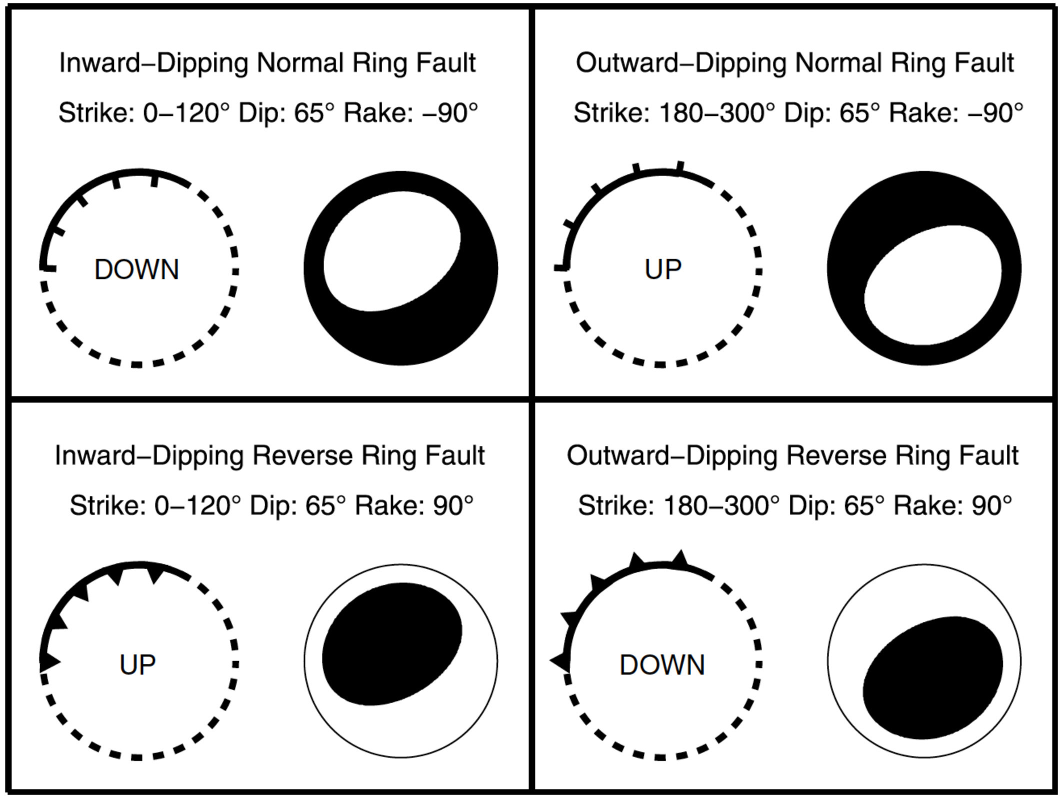
CLVD: Compensated Linear Vector Dipole



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).



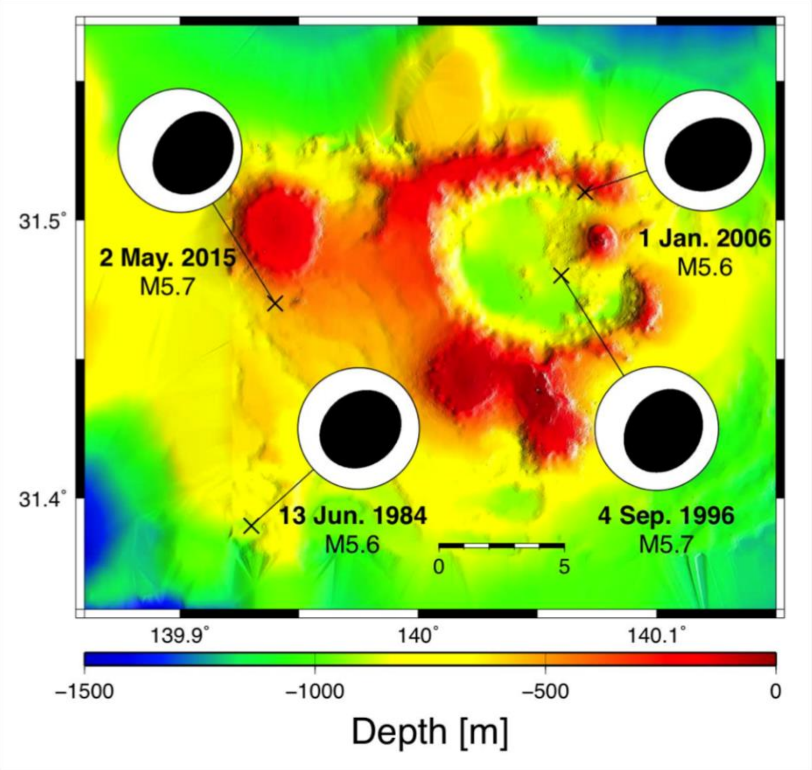
Schematic diagram for inward- and outward- dipping ring faults located above a shallow magma chamber



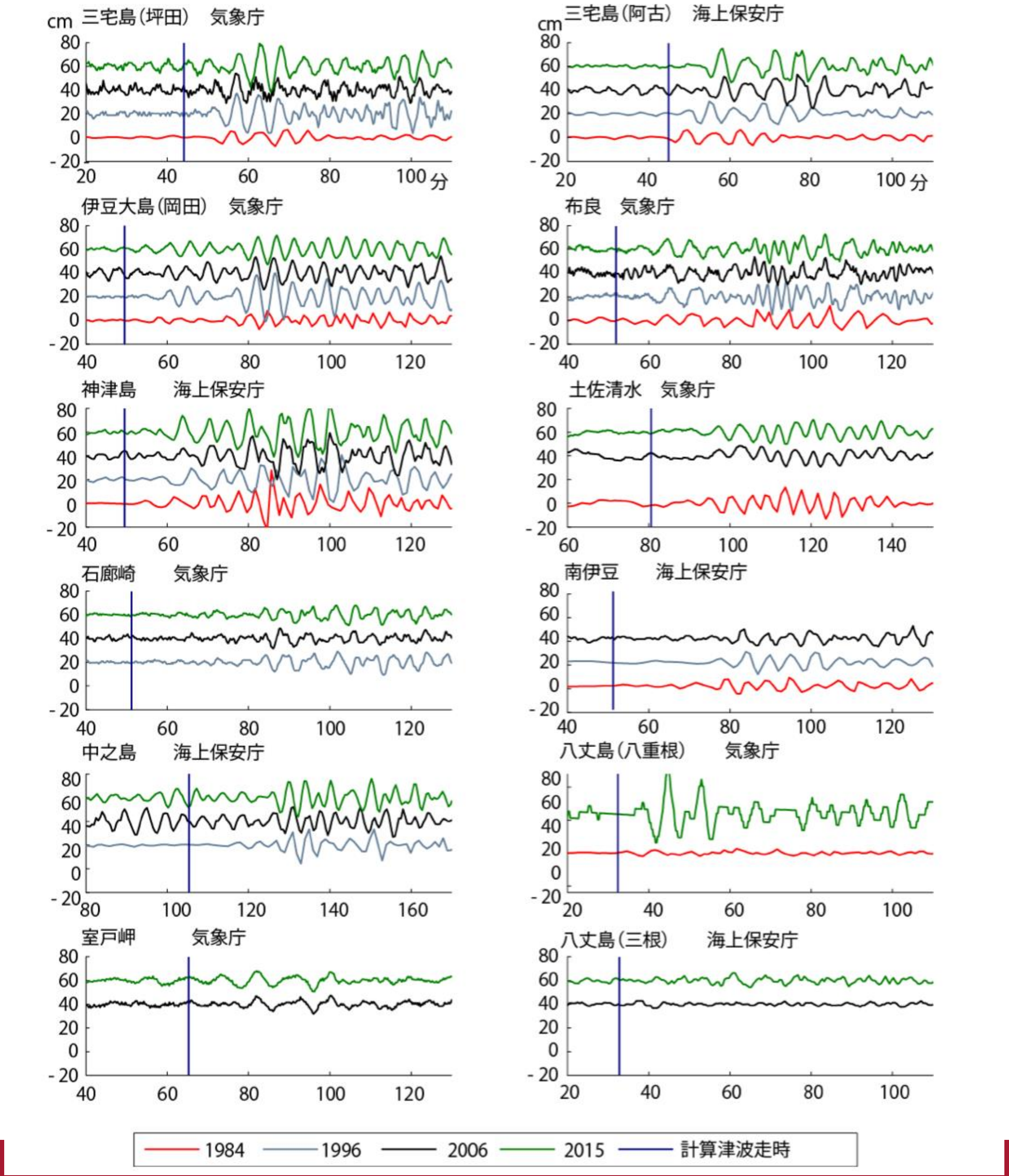
(Shuler et al., 2013)

The Torishima Tsunami Earthquakes

13 June 1984 (M5.9)
5 September 1996 (M5.6)
1 January 2006 (M5.9)
3 May 2015 (M5.9)



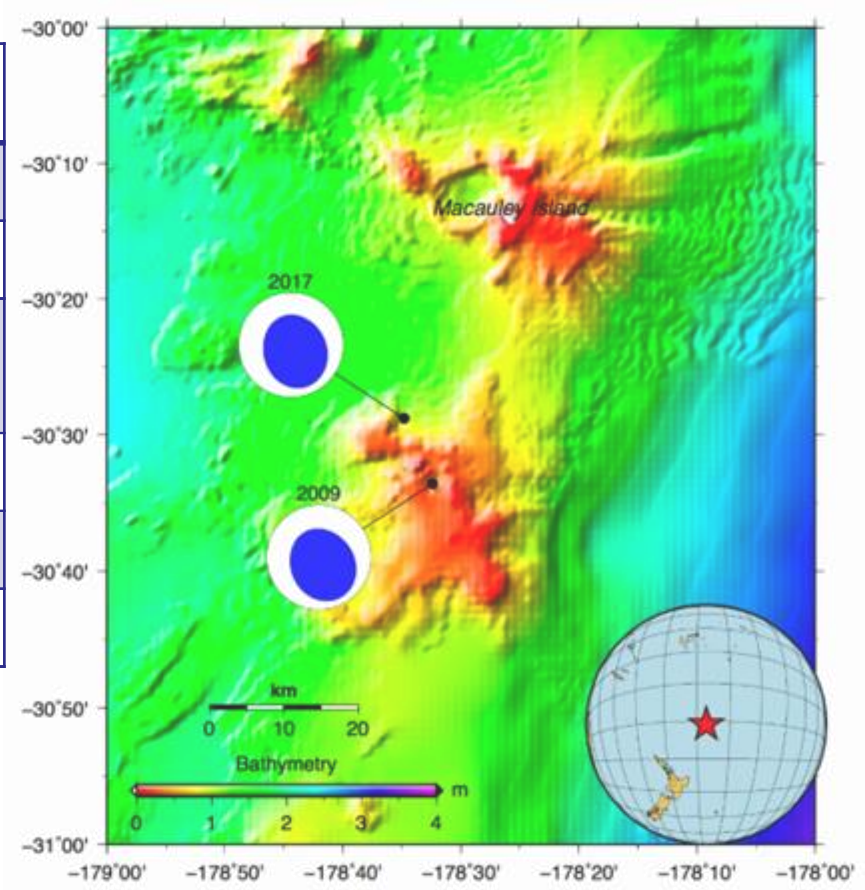
(Satake and Gusman, 2015)



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 × 10^{17} Nm

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

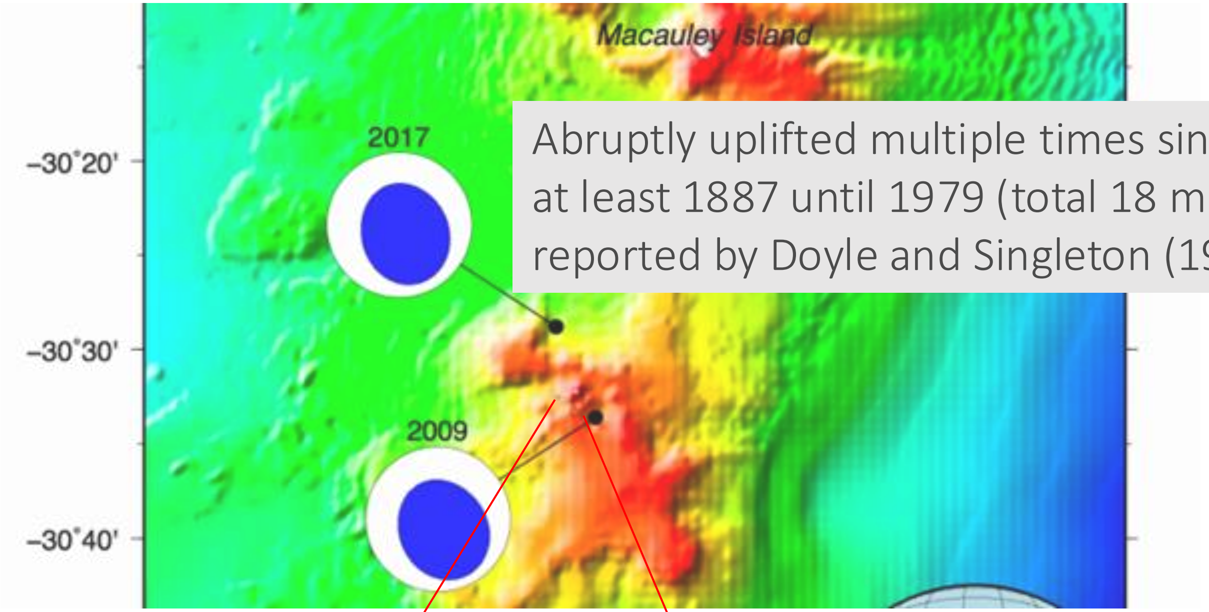


Epicenter: USGS
Focal mechanism: Global CMT

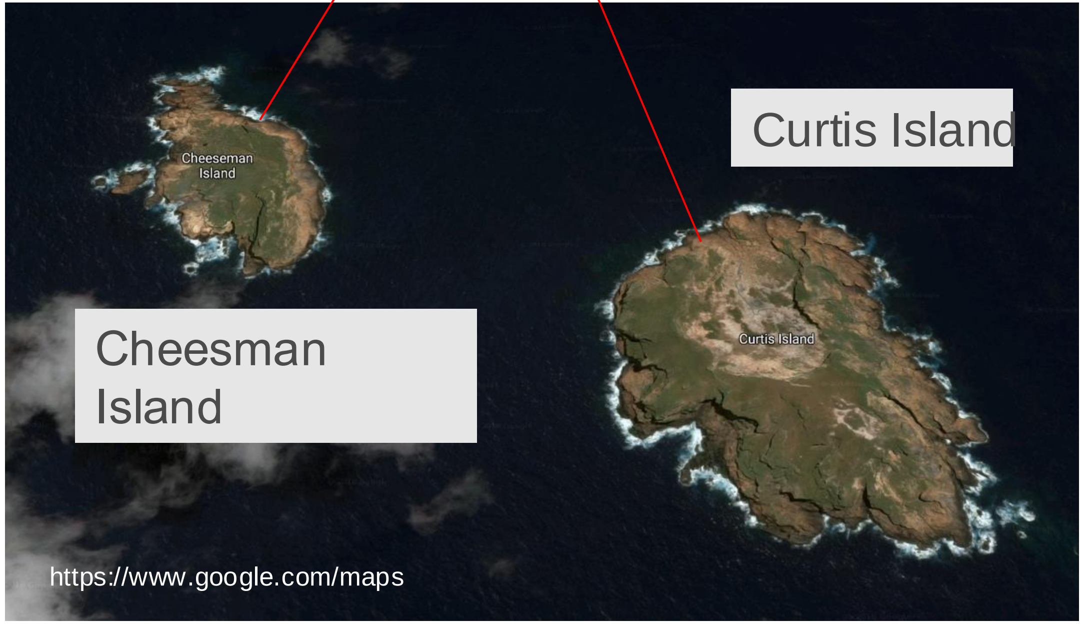
The 2017 Earthquake	
Date	2017-12-08
Time	02:09:57 UTC
Epicenter	30.555°S 178.492° W
Depth	12 km
Mw	5.8
Moment	6.44 × 10^{17} Nm

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

The Kermadec CLVD Earthquakes



Abruptly uplifted multiple times since at least 1887 until 1979 (total 18 m) as reported by Doyle and Singleton (1979)

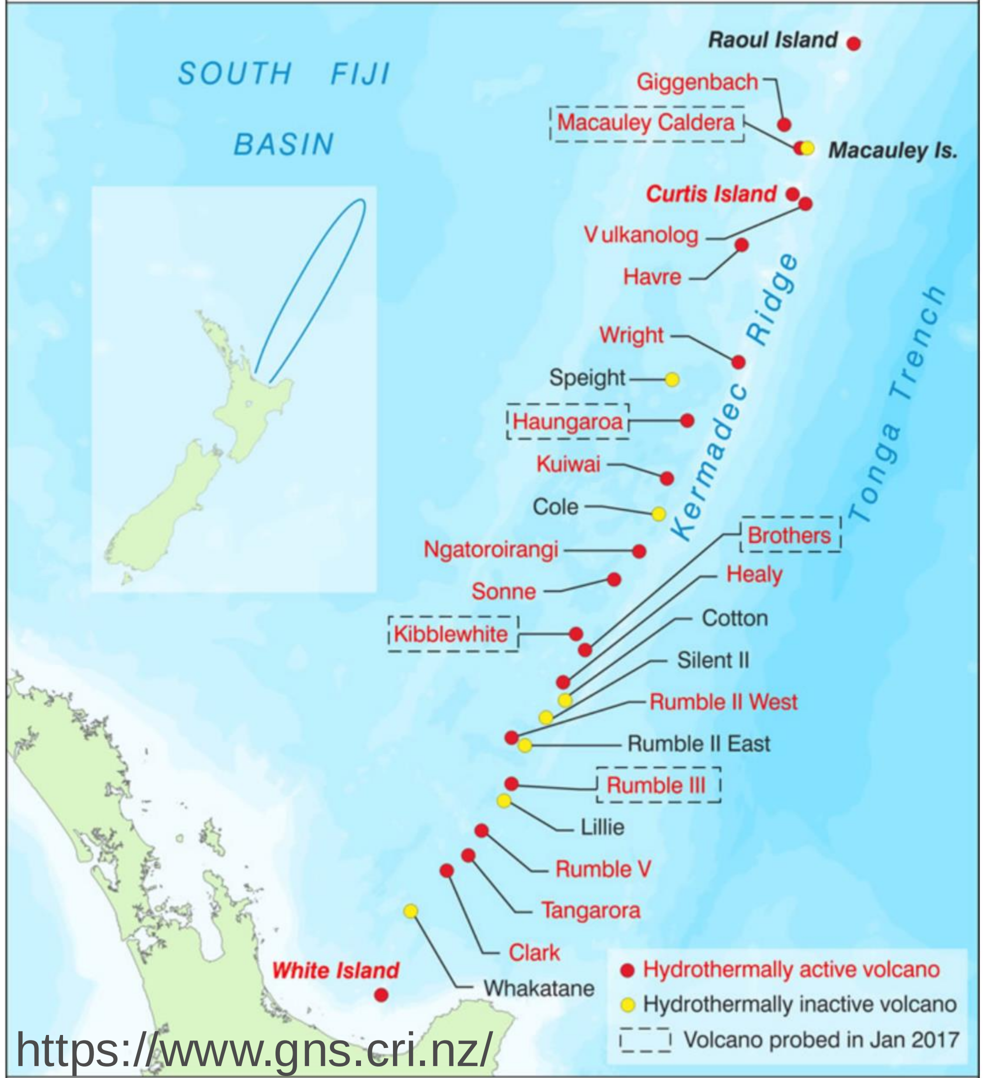


Curtis Island

Cheesman Island

https://www.google.com/maps

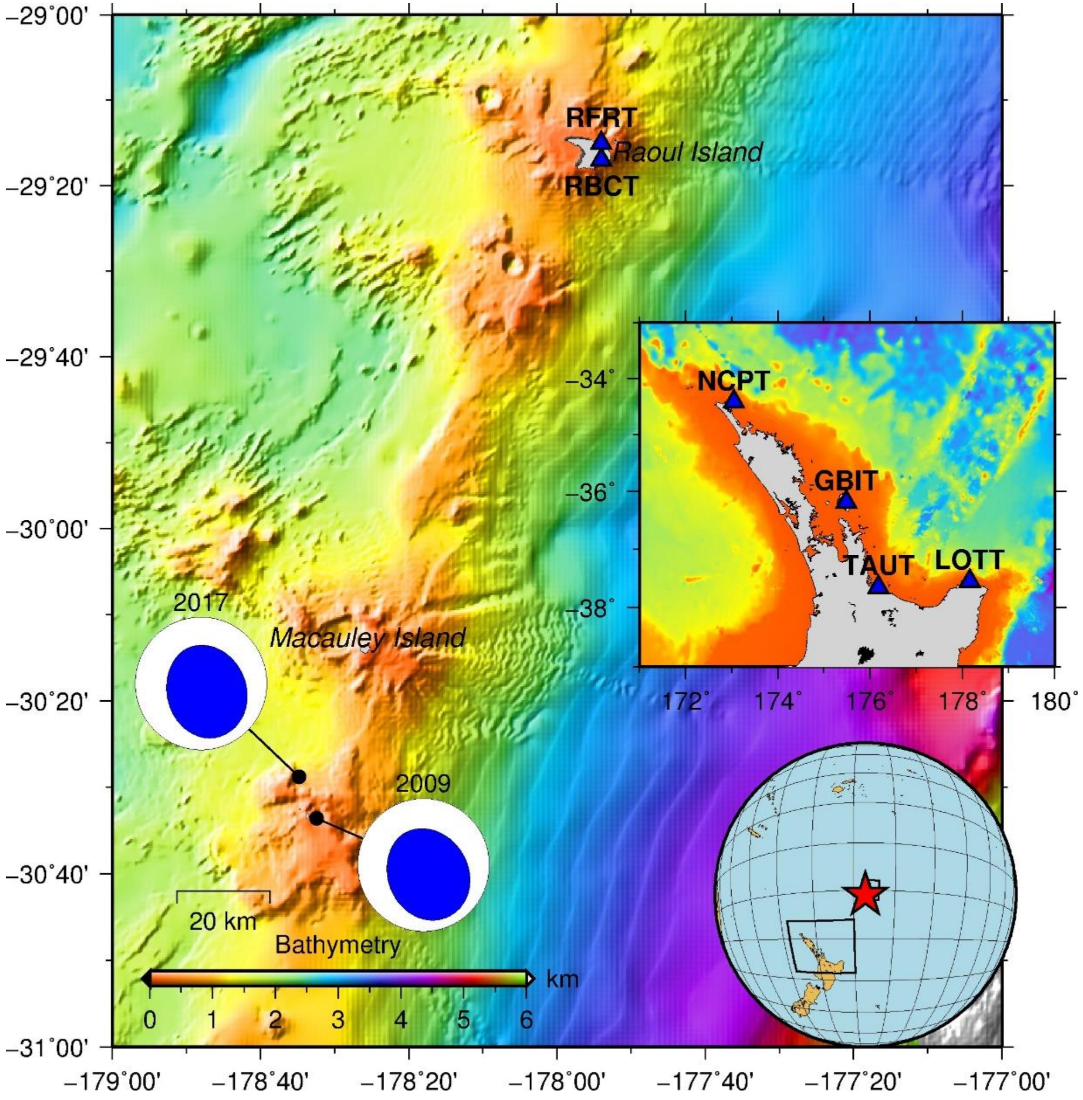
Kermadec arc-trench system

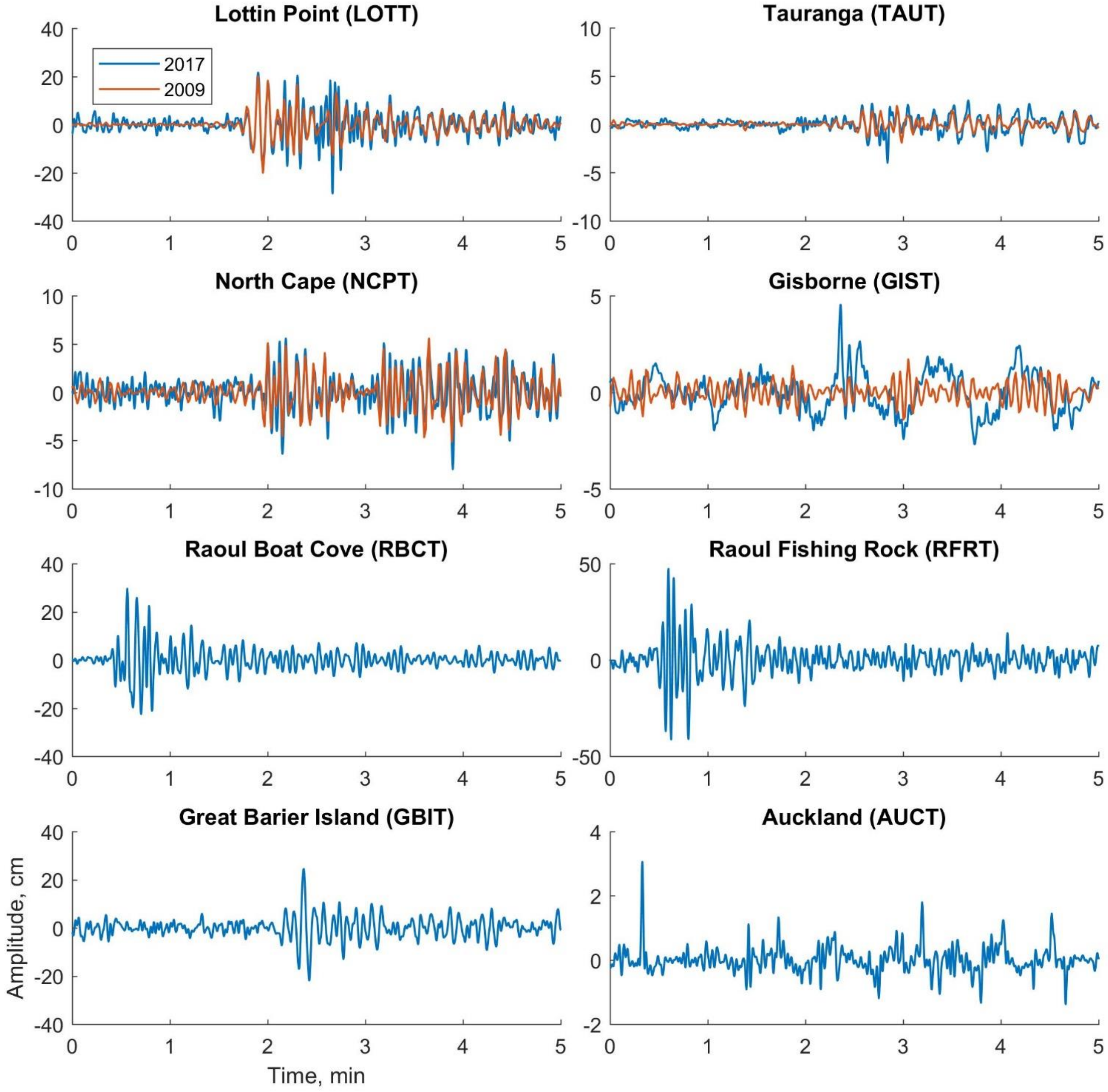


https://www.gns.cri.nz/

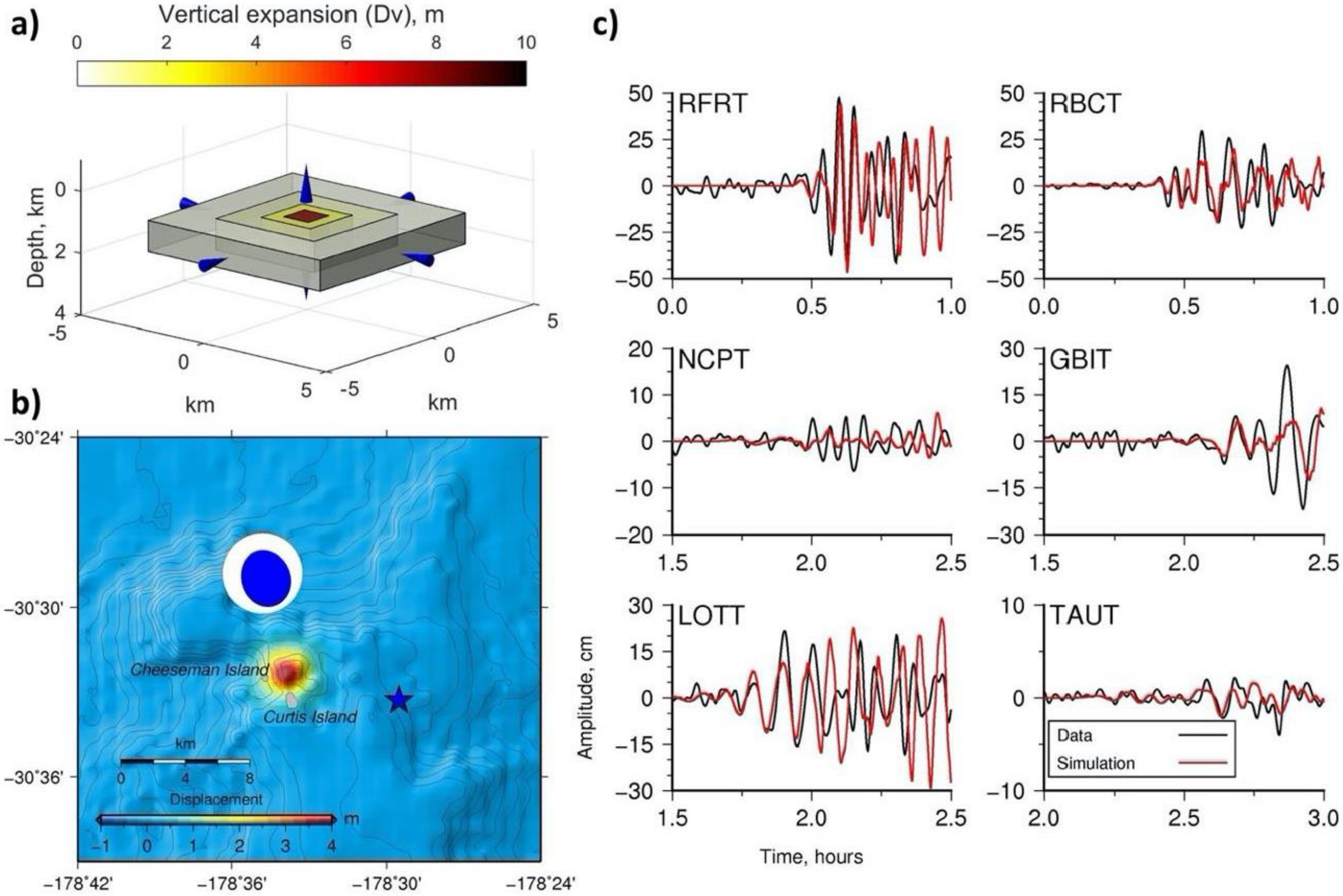
The Kermadec arc-trench system features a chain of about 80 predominantly submarine volcanoes stretching from White Island up through Tonga and beyond – a continuous volcanic front of about 2500km. About 80 percent of the volcanoes in this chain are hydrothermally active. That is, they have multiple vents on the seafloor where hot mineral-rich fluids and gases discharge into the ocean. When the hot fluids meet cold seawater, metals precipitate out and form mineral deposits on the seafloor. The submarine volcanoes also host vibrant ecosystems that feature and range of marine life specially adapted to these conditions.

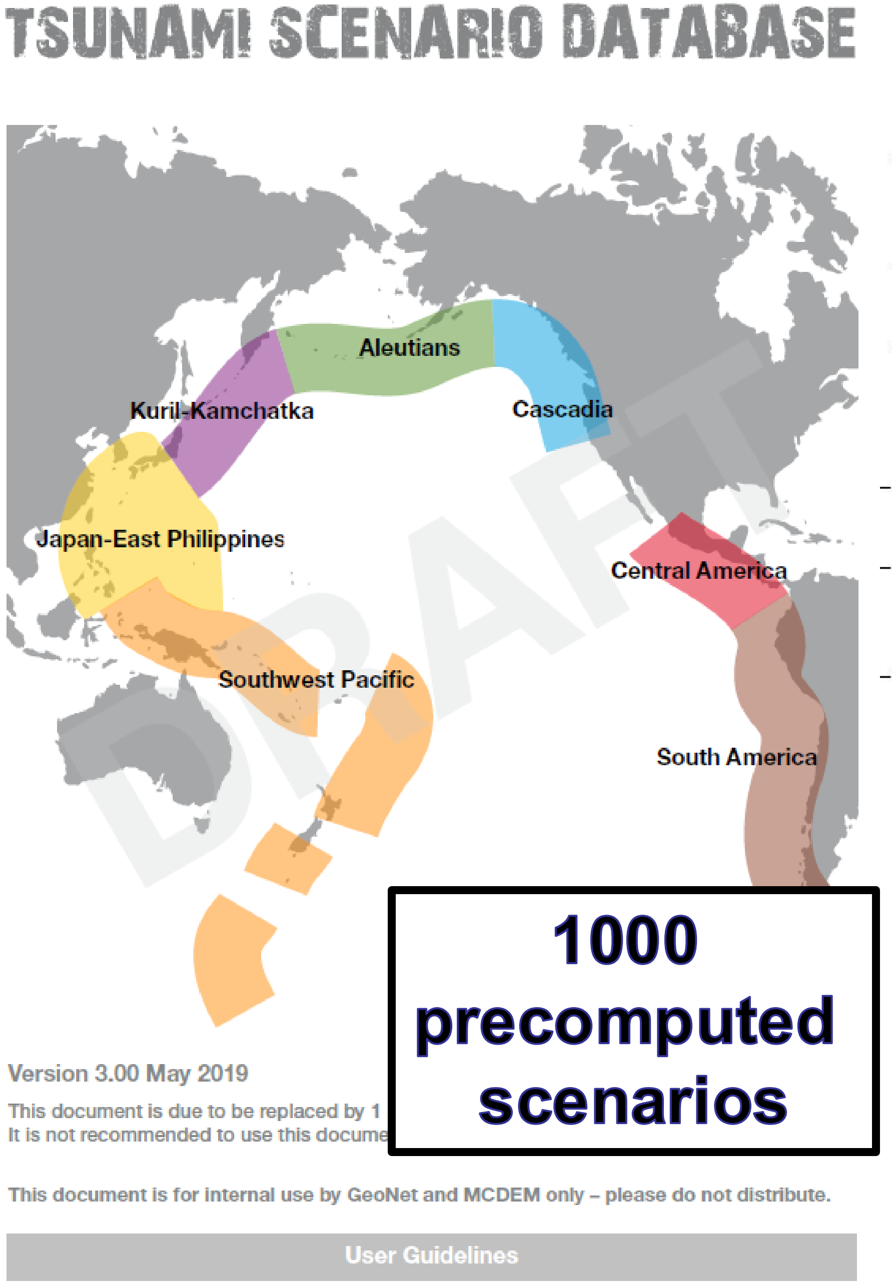
Tide gauge data





Source model for the CLVD earthquake and tsunami





TSUNAMI SCENARIO DATABASE

Version 3.00 May 2019

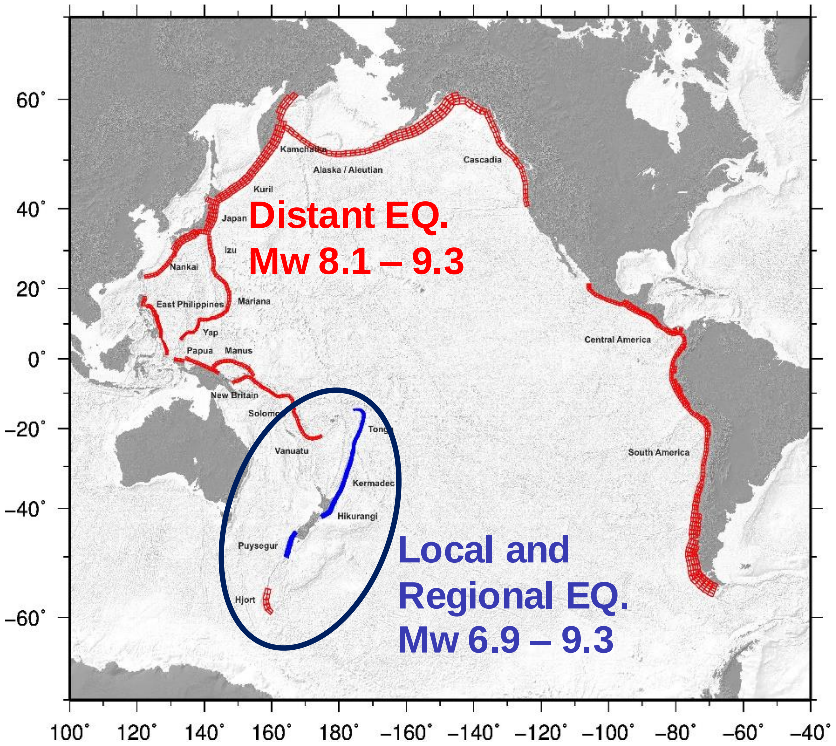
This document is due to be replaced by 1
It is not recommended to use this docume

This document is for internal use by GeoNet and MCDEM only – please do not distribute.

User Guidelines

1000 precomputed scenarios

Fault patches used for the scenarios



Pre-computed scenarios

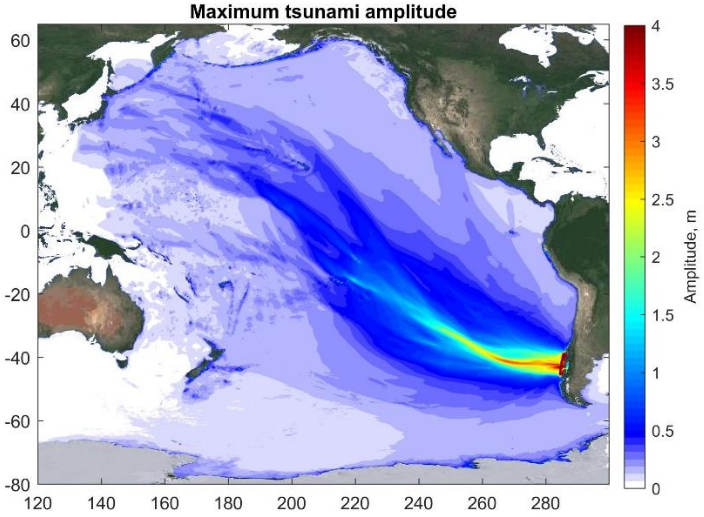
Distant sources

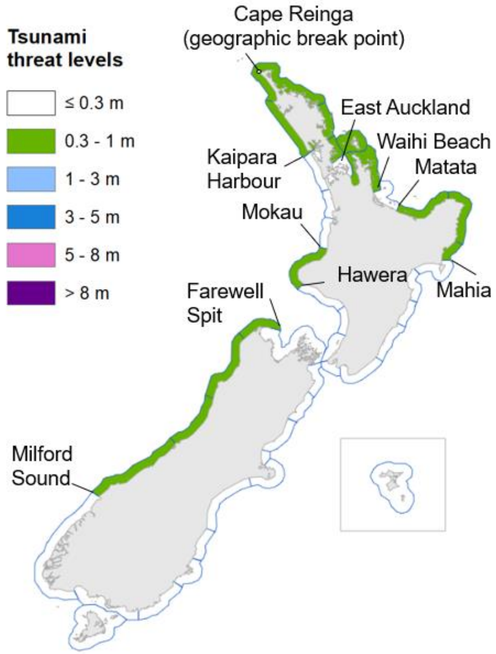
- The fault size is 100 km x 50 km.
- Earthquake magnitudes: 8.1 – 9.3 (interval of 0.2)
- Space: 300 km

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

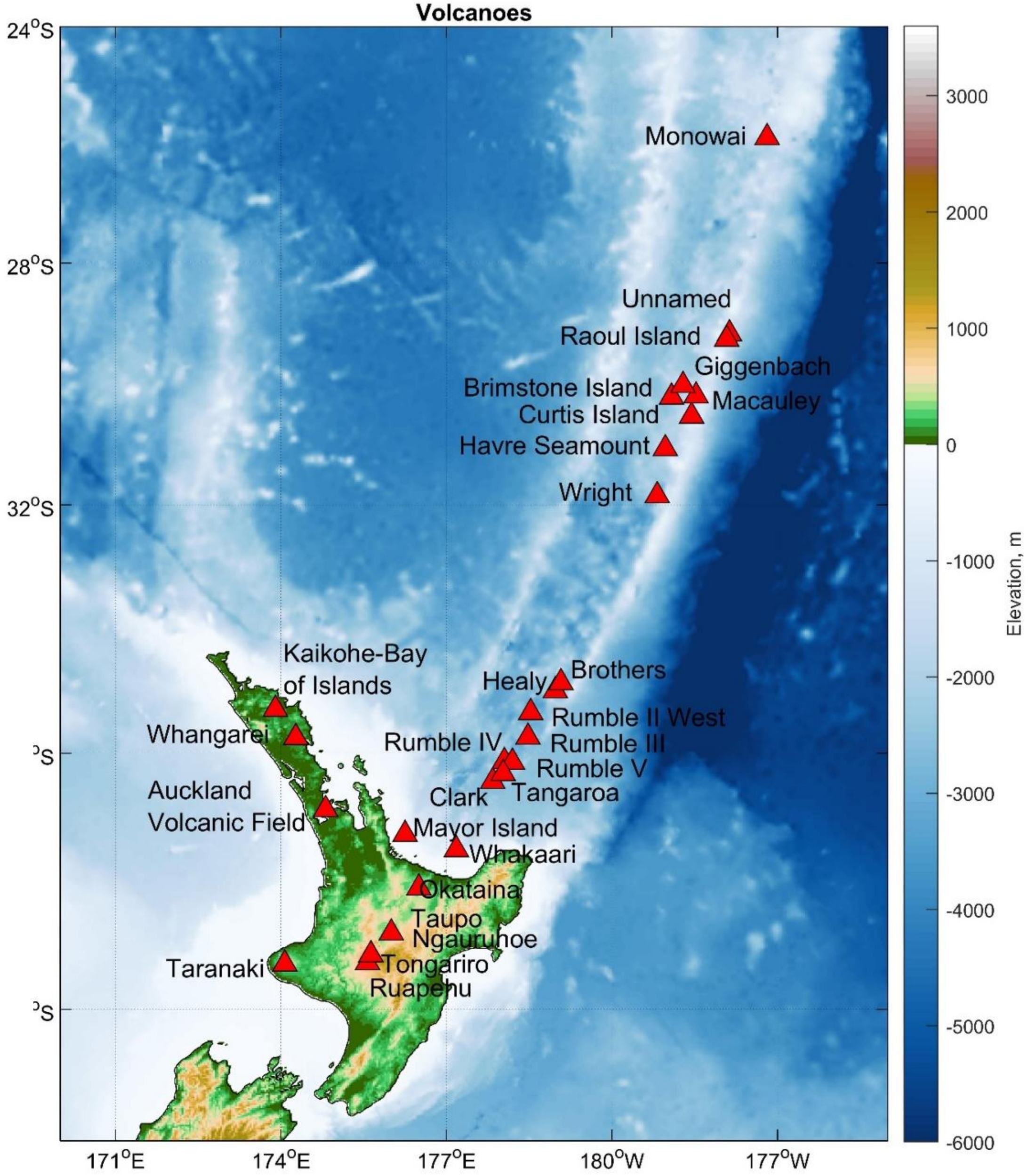




Volcanic Tsunami Threat Level Database

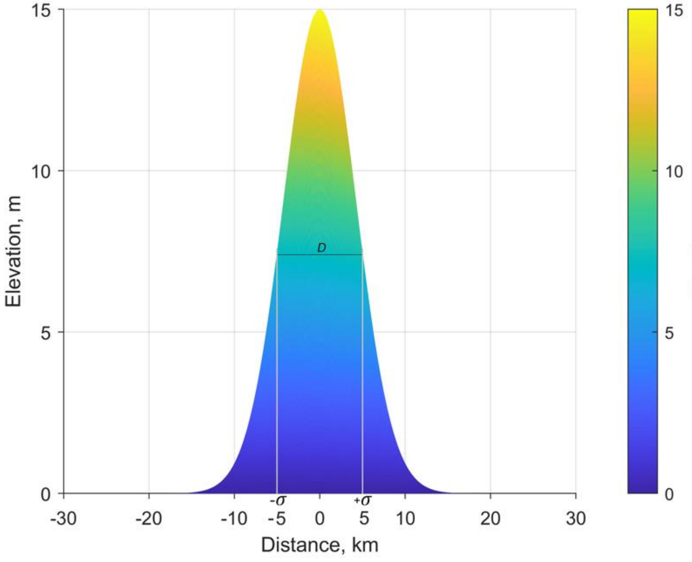
Selected Volcanoes

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.

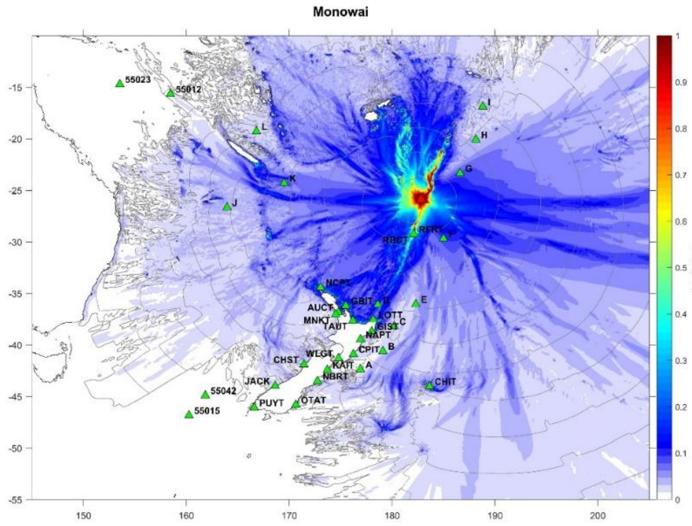


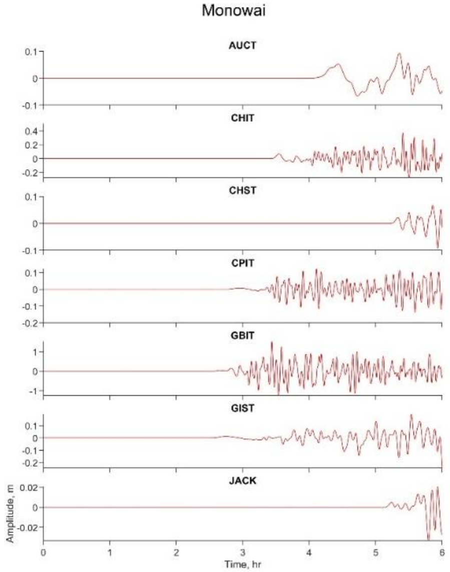
Source Model

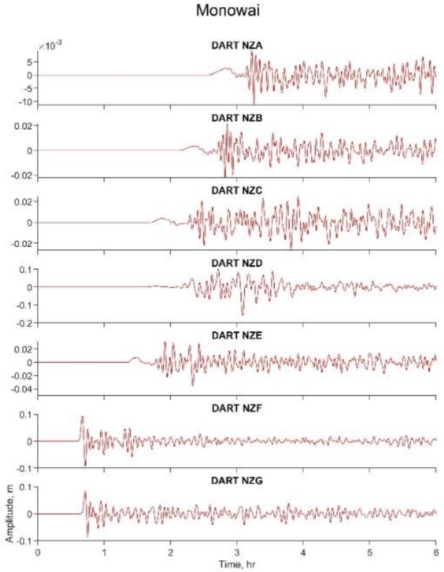
We use a simple localized source model in which tsunami generation is approximated by an initial static sea surface displacement. The shape of the initial sea surface displacement is represented in simplified form by a three-dimensional Gaussian function with a characteristic diameter (D) of 10 km and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

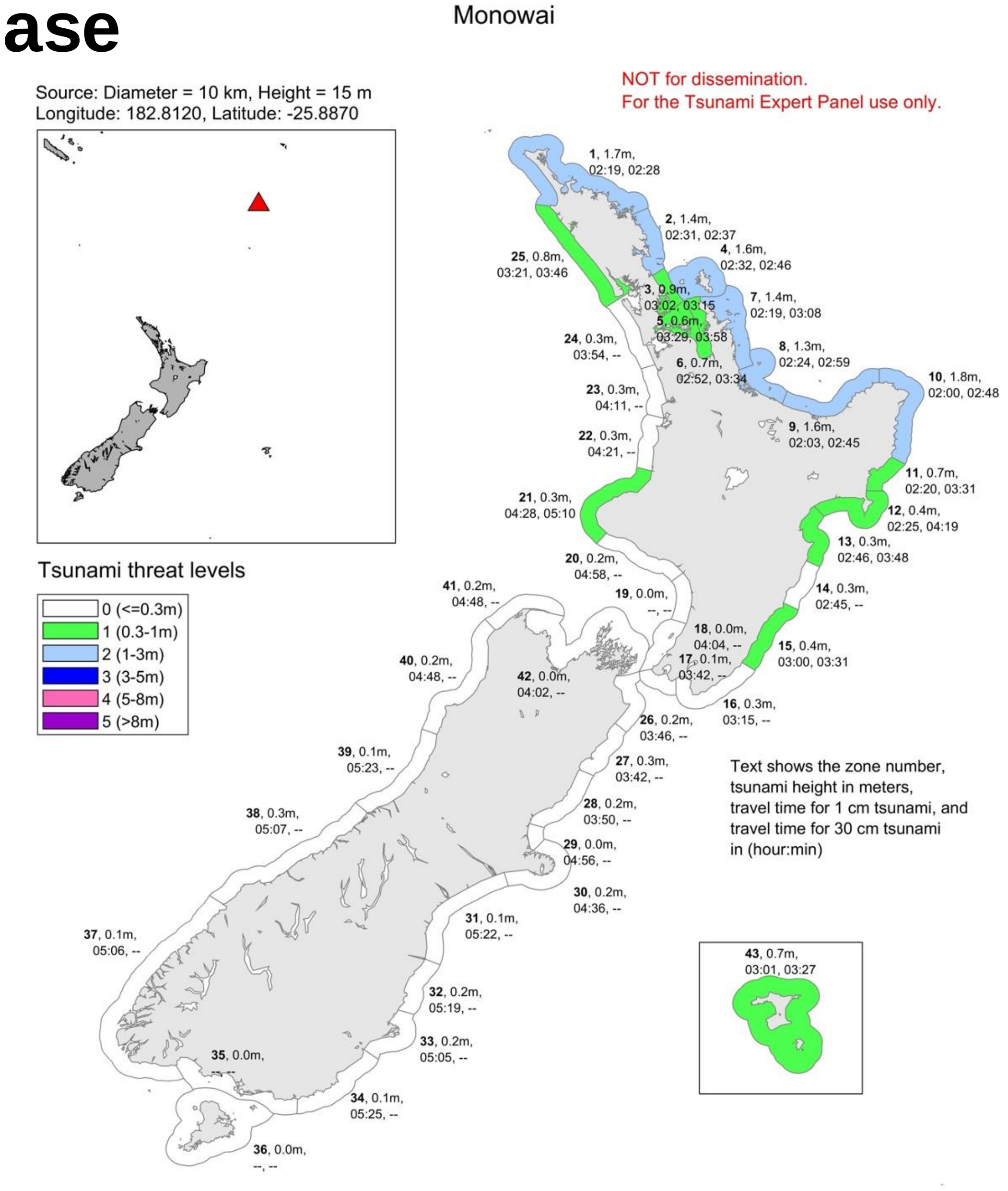


Volcanic Tsunami Threat Level Database








Monowai

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

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

Tsunami threat levels

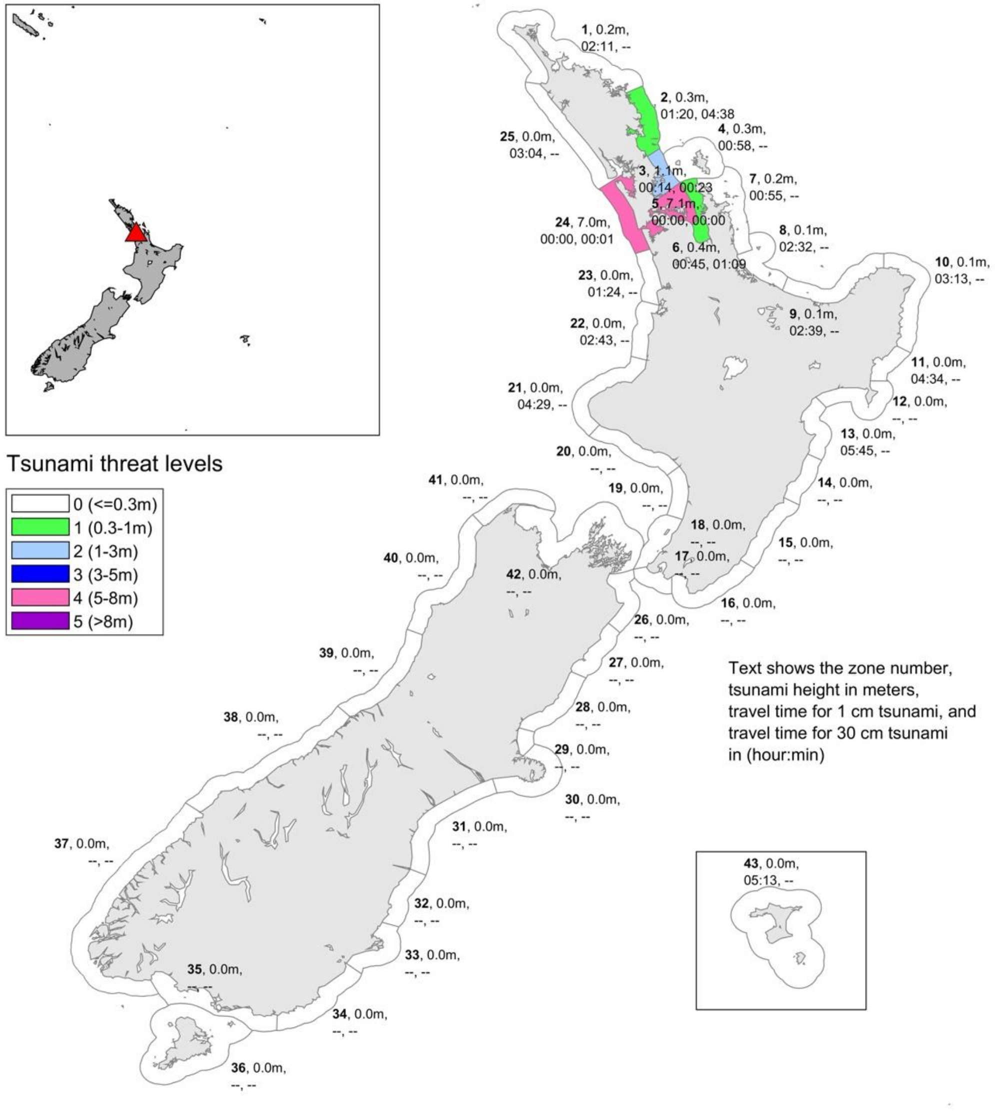
- ☐ 0 (<=0.3m)
- 🟩 1 (0.3-1m)
- 🟦 2 (1-3m)
- 🟦 3 (3-5m)
- 🟪 4 (5-8m)
- 🟪 5 (>8m)

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

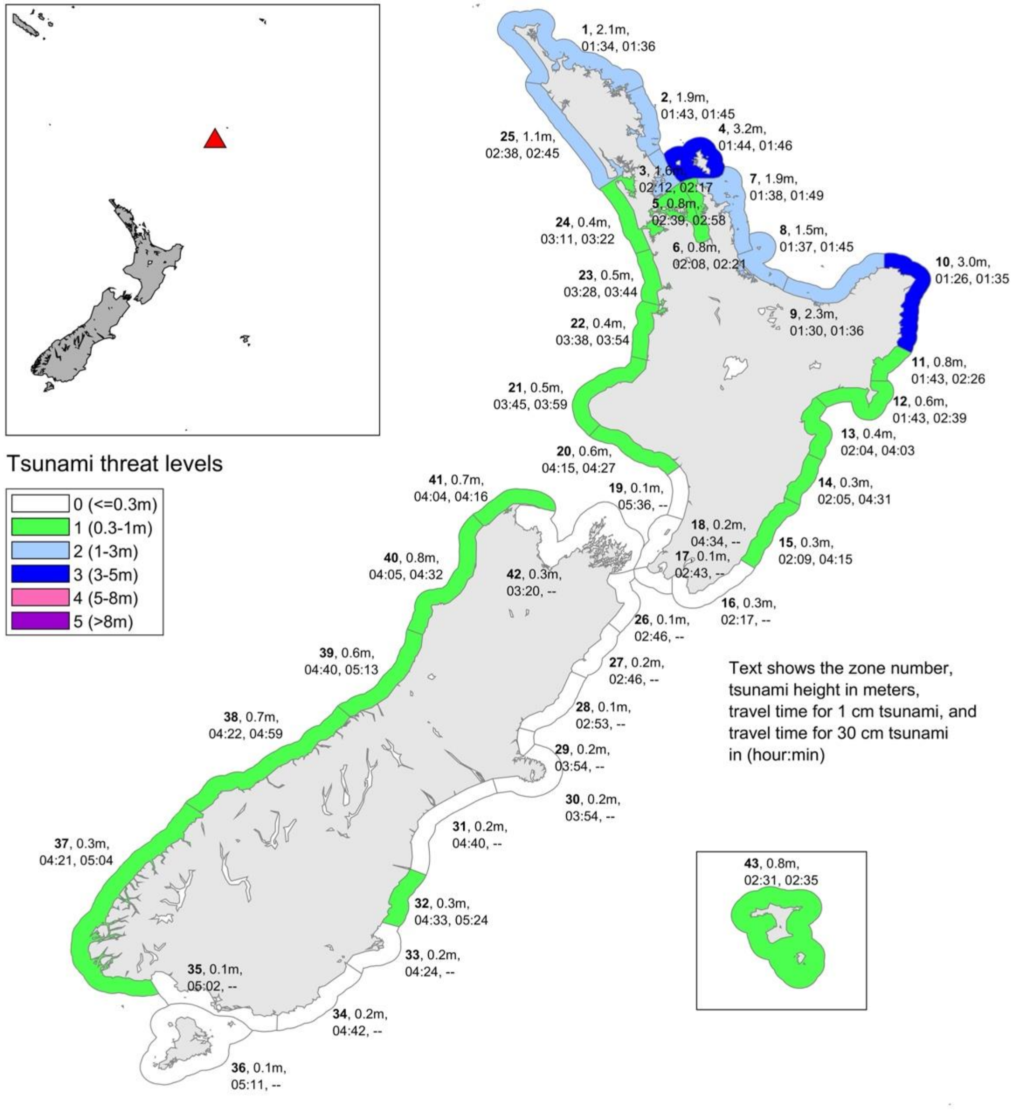
- ⬜ 0 (<=0.3m)
- 🟩 1 (0.3-1m)
- 🟦 2 (1-3m)
- 🟦 3 (3-5m)
- 🟥 4 (5-8m)
- 🟪 5 (>8m)

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)

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.

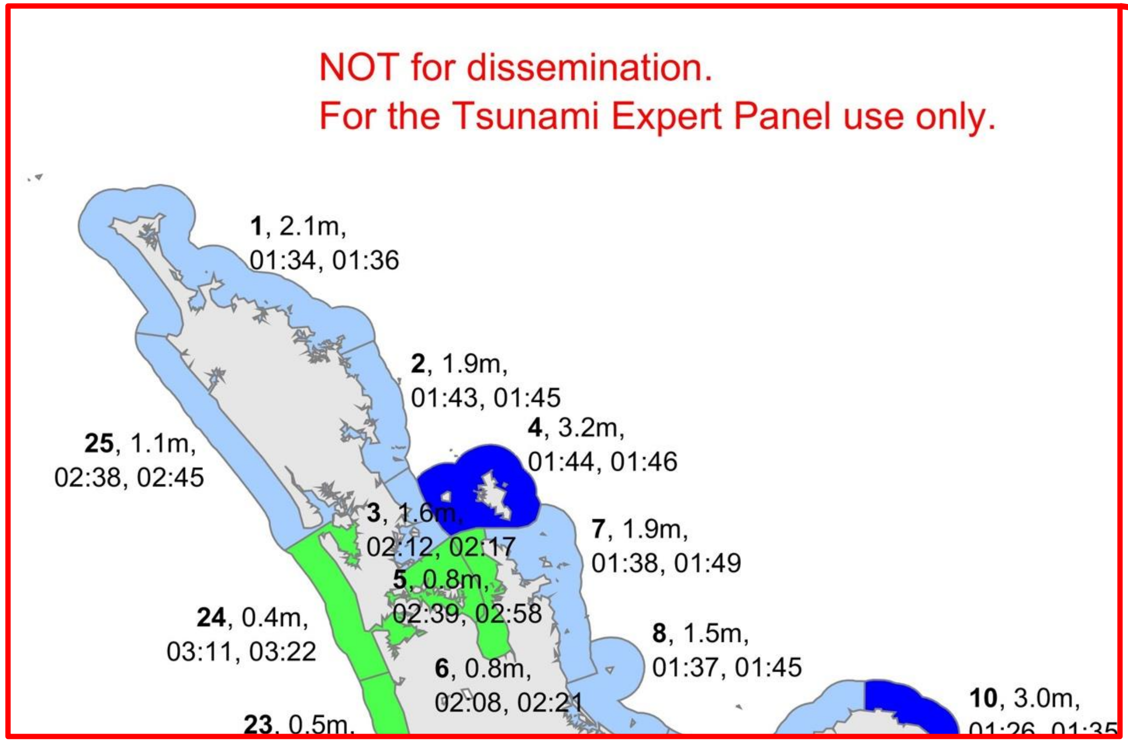


Tsunami threat levels

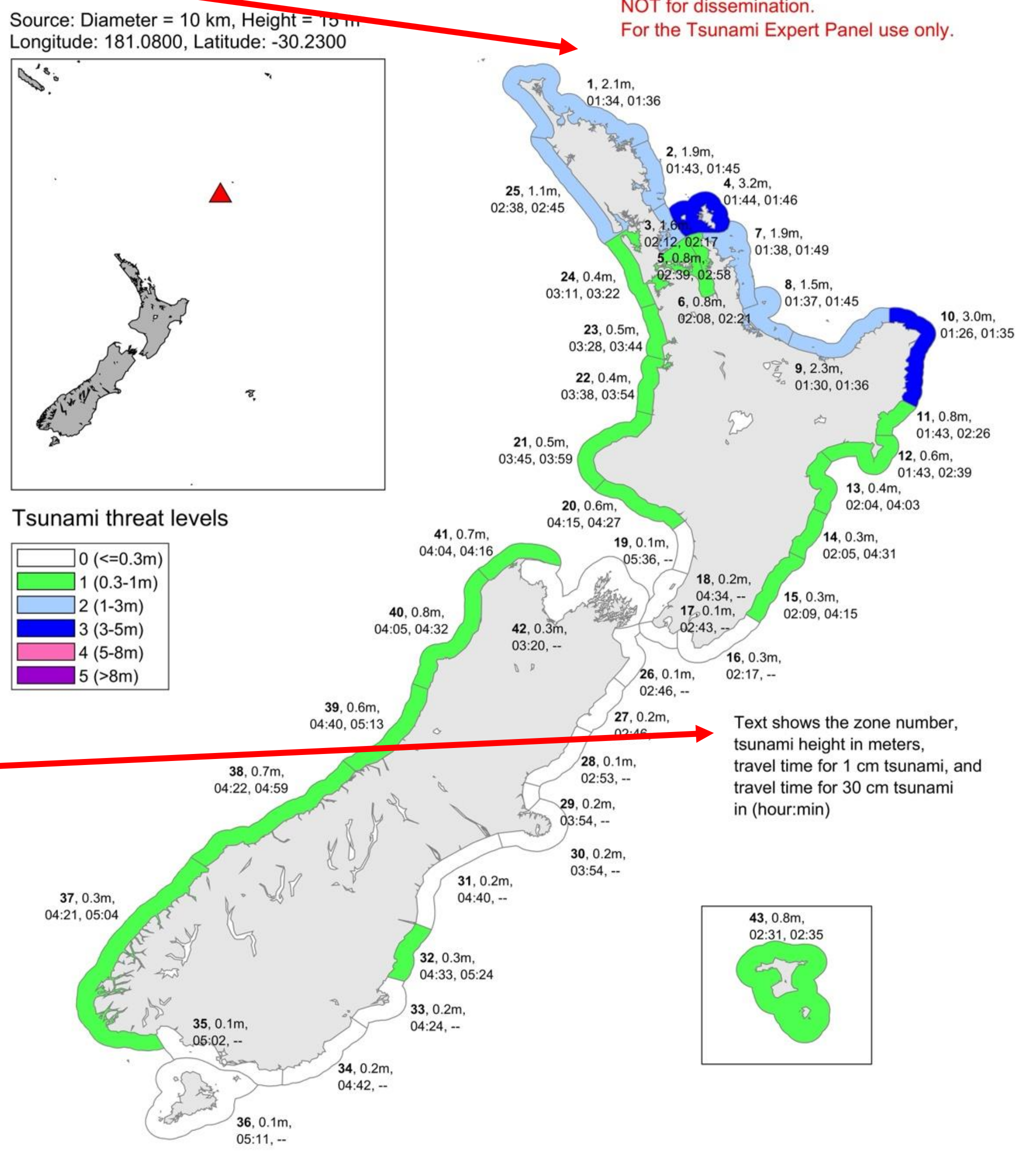
- ⬜ 0 (<=0.3m)
- 🟩 1 (0.3-1m)
- 🟦 2 (1-3m)
- 🟦 3 (3-5m)
- 🟥 4 (5-8m)
- 🟪 5 (>8m)

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)

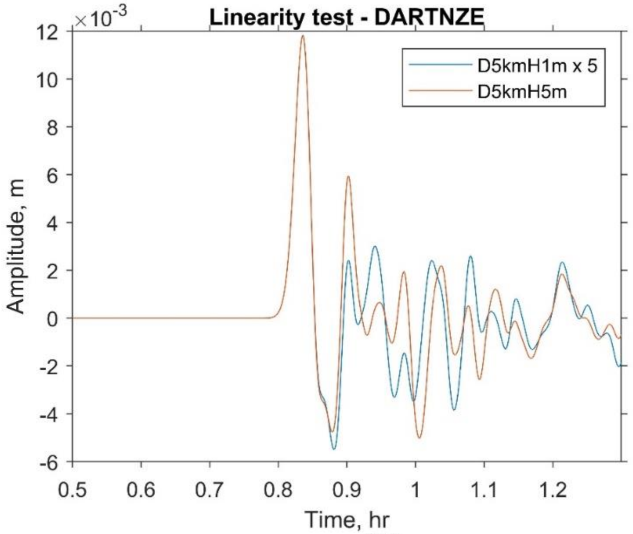
Brimstone Island

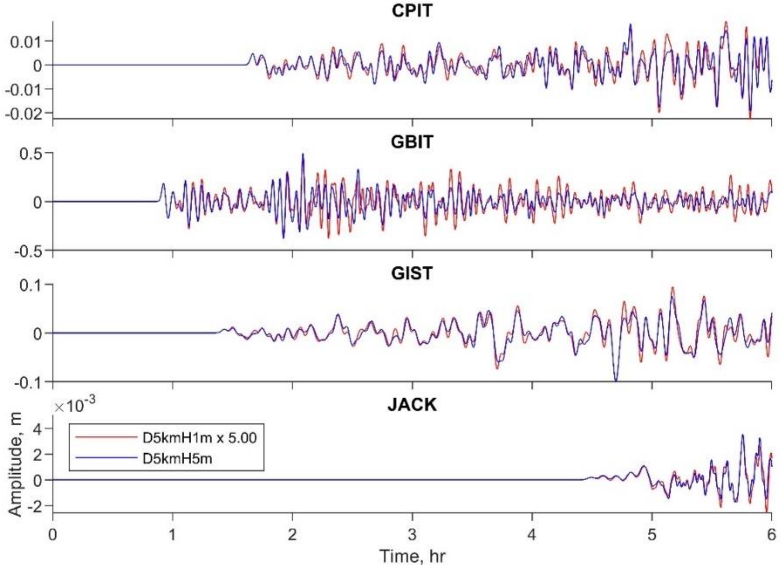


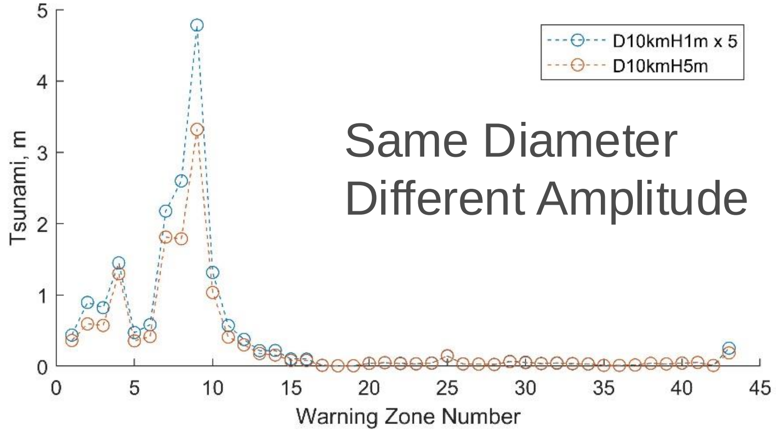
Text shows the zone number,
tsunami height in meters,
travel time for 1 cm tsunami, and
travel time for 30 cm tsunami
in (hour:min)



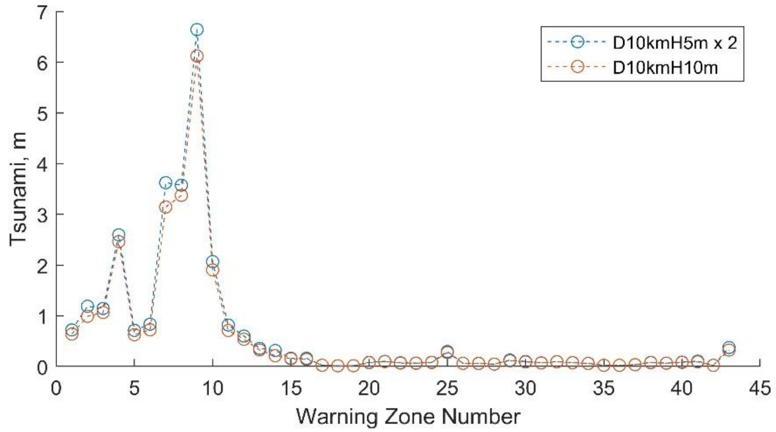
Is it possible to adjust/scaling the scenarios using the peak amplitudes recorded by DART?

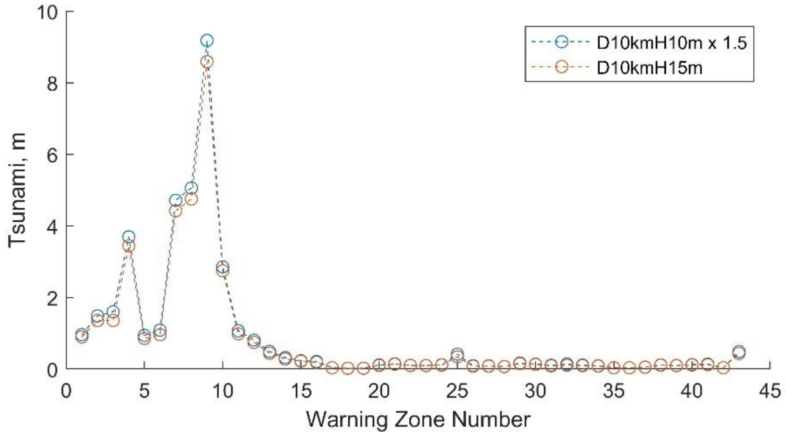






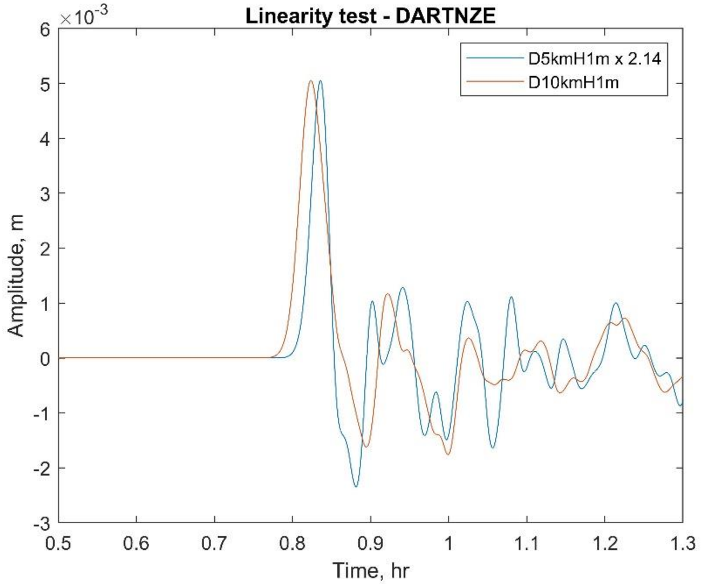
Same Diameter
Different Amplitude

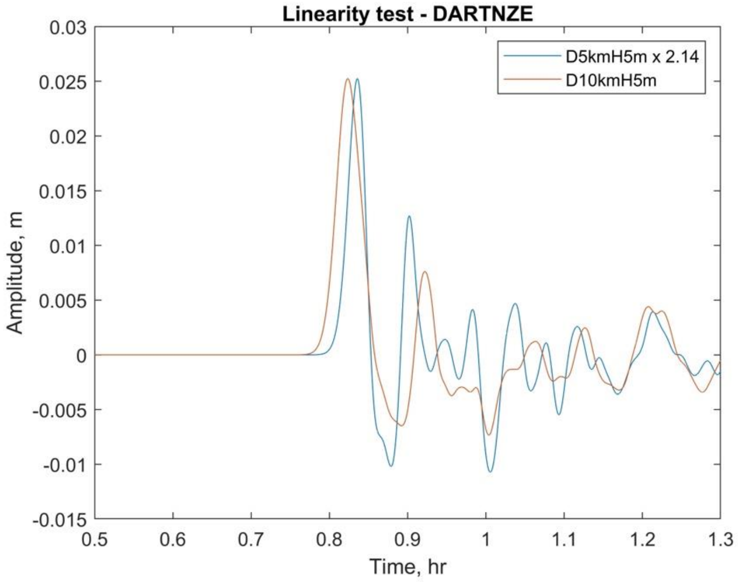


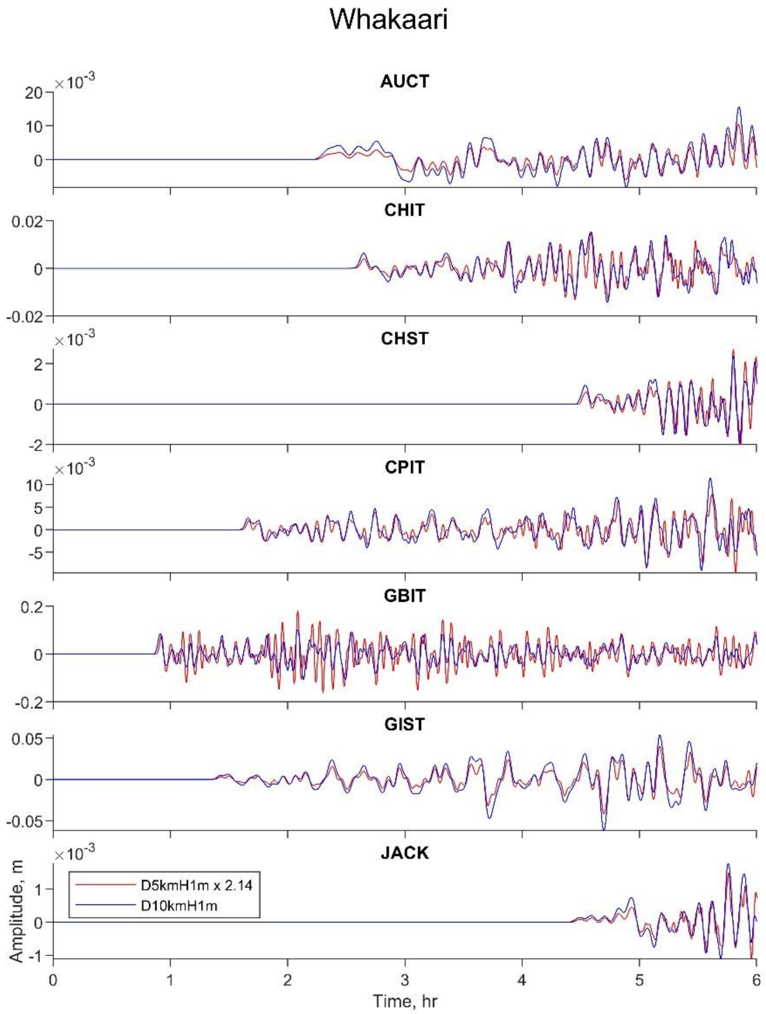


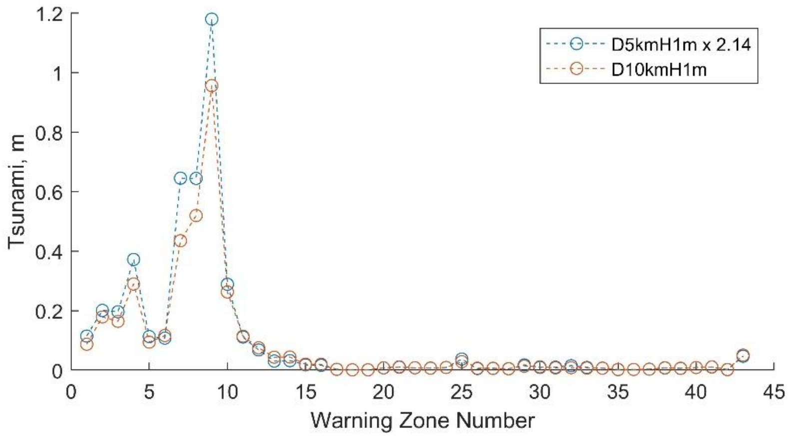
Is it possible to adjust/scaling the scenarios using the peak amplitudes recorded by DART?

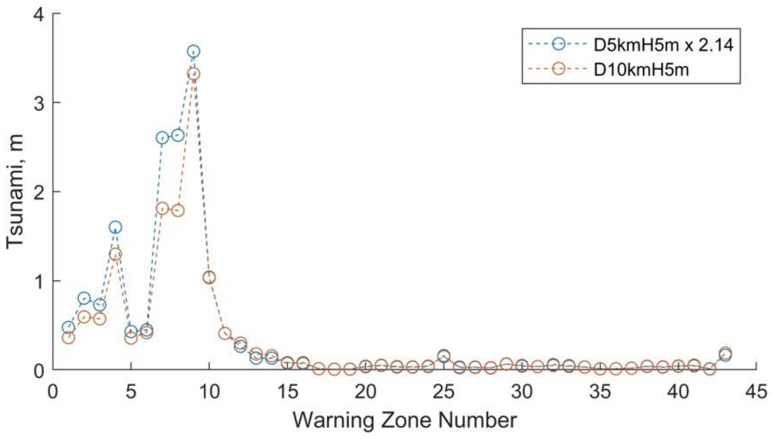
Same Amplitude
Different Diameter



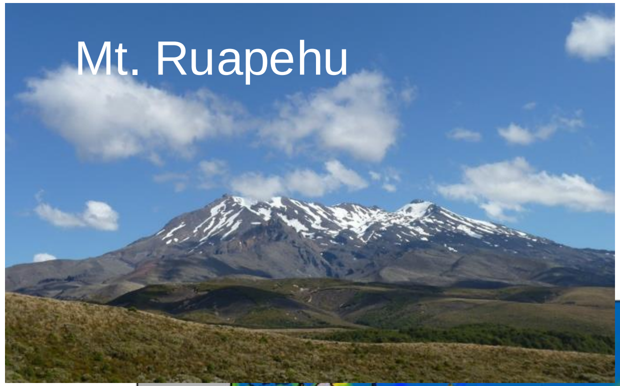








Inland Volcano Eruption Scenario



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