Satellite Activity for the UN Ocean Decade Safe Ocean Laboratory

Further Challenges for Warnings of Tsunamis

SESSION B: What do we know and need to know to warn for tsunamis generated by non-seismic and complex sources?

4. The seven types of volcanic tsunami sources

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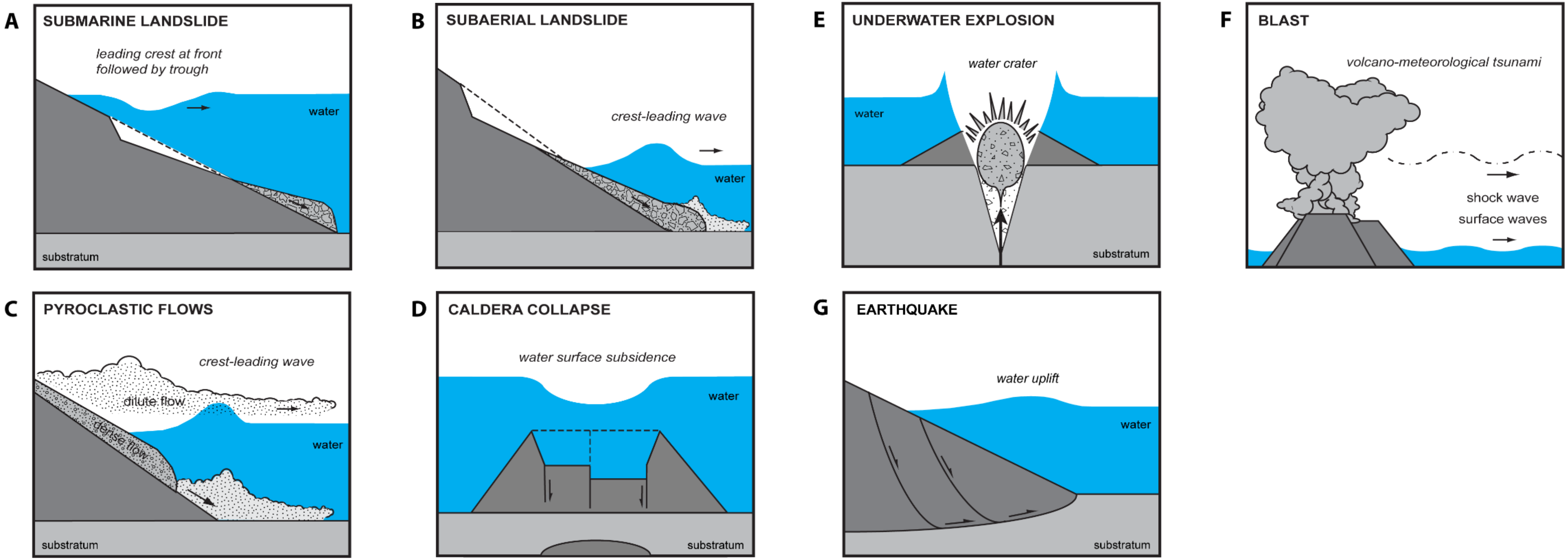
CNRS - Université Clermont Auvergne

FRANCE

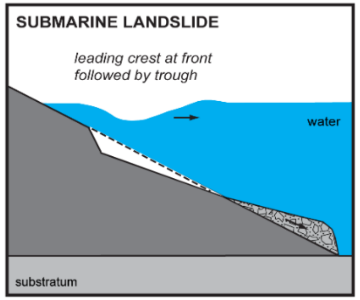
The activity and instability of volcanic edifices can produce tsunamis, so-called volcanic tsunamis or volcano-generated tsunamis.

Different types of source mechanisms were identified during past events.



Modified from Paris (2015)

A



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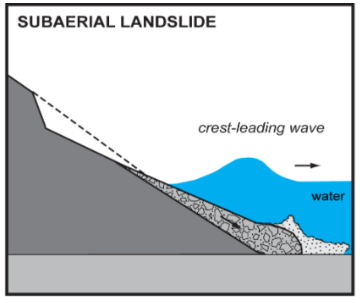

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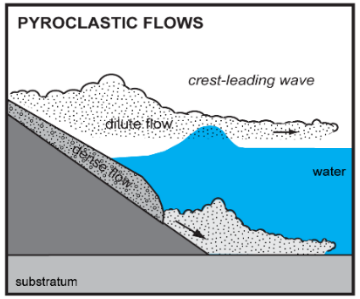

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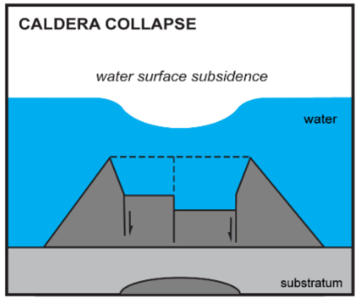

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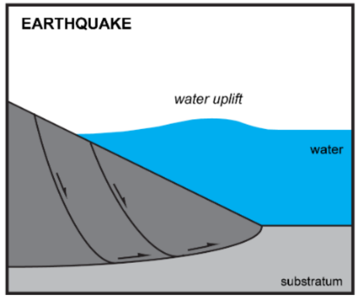


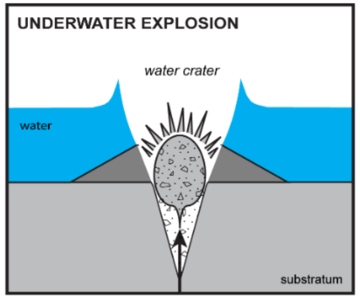
25 %
0.1 - 500 km³
10^5-10^6 m³/s
Anak Krakatau 2018

20 %
0.1 - 100 km³
10^5-10^8 m³/s
Montserrat 1997-2003

10 %
1 - 100 km³
10^4-10^6 m³/s
?

15 %
0.1 - 10 km³
10^6-10^9 m³/s
Kalapana 1975

E



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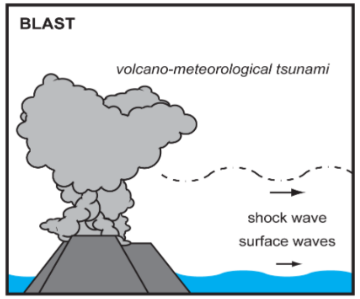


25 %
< 1 km³
10^8 - 10^9 m³/s
Karymskoye 1996

5 %

Tonga 2022

Volcanic tsunami are often considered as « point » source generating local tsunami only.

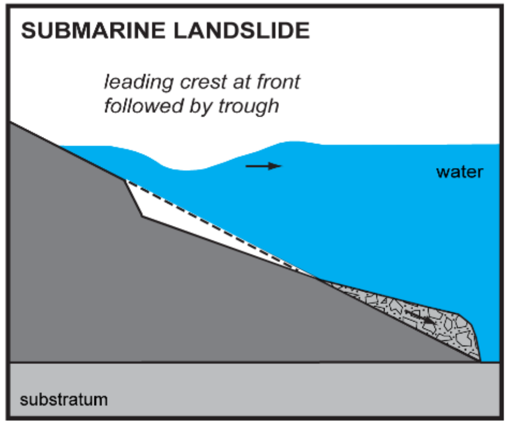
However, the different types of source mechanisms vary in terms of frequency, volume, and flux.

-> different wave patterns from one case to another.

Learning from past examples of volcanic tsunamis

Type of eruption	Type event	Earth-quake	Underwater explosion	Caldera subsidence	Pyroclastic flow	Flank failure
Phreatomagmatic explosions in shallow waters	Myojin-Sho 1952 Karymsky Lake 1996					
Plinian eruption forming a submarine caldera	Krakatau 1883 Santorini LBA 3.6 ka					
Plinian eruption forming a subaerial caldera	Tambora 1815 Aniakchak 3.5 ka					
Explosive eruption with dome growth and collapse	Montserrat 2003 Paluweh 1928					
Explosive paroxysm of strombolian cone	Stromboli 2002 Tinakula 1971					
Massive flank failure	Ritter 1888 Oshima-Oshima 1741	?				

- The great majority of volcanic eruptions do not generate tsunami.
- A single eruption might generate different types of tsunamis.
- Source of tsunami observed during an eruption is often difficult to identify.
- It is extremely difficult to anticipate a volcanic tsunami.
- Hazard assesment is complex and requires a double volcano-tsunami expertise.
- Risk assement is thus challenging but not impossible if an adequate monitoring is combined with early warning system and population preparedness.

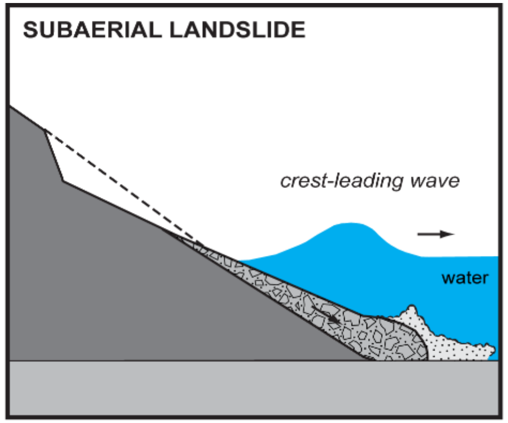


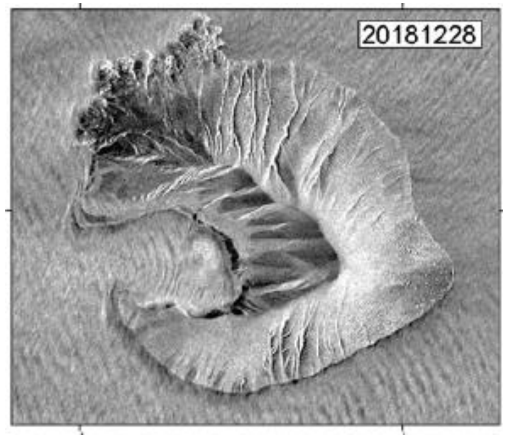
Main parameters:

- volume of the sliding mass
- its initial acceleration
- its maximum velocity

Three successive waves:

1. a first crest ahead of the slide front (energy transfer from the slide)
2. a large trough propagating at the speed of the slide front
3. a final crest (often the highest) = main cause of inundation



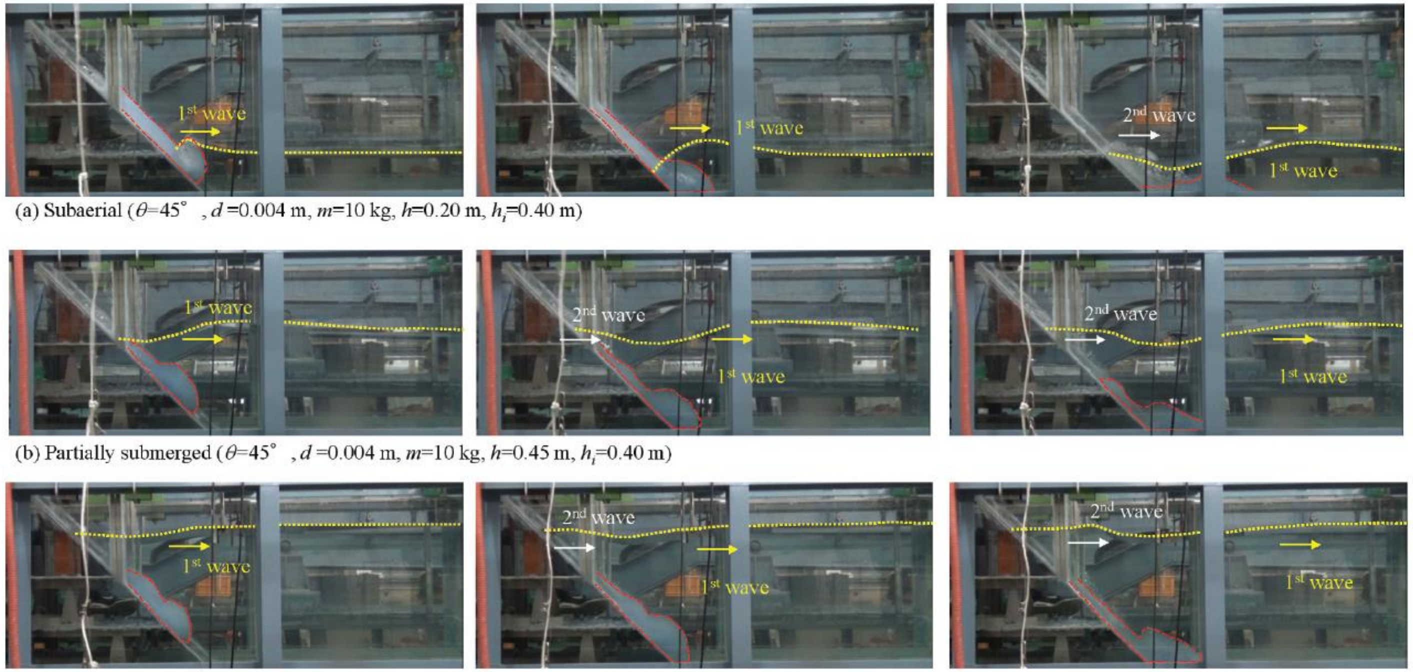


Subaerial landslides characterized by complex interactions flow/air/water at the impact -> more challenging to simulate.

- Water above the flow pushed upward, and water in front pushed forward.
- Impulse (forced) wave first travels at the speed of the slide front, and then becomes a free wave
- Followed by trailing waves

- Near-field, this leading wave is usually the largest one (efficient energy transfer). Its height increases with increasing slide Froude number, relative thickness, mass flux and volume
- Far-field: propagation influenced by frequency dispersion

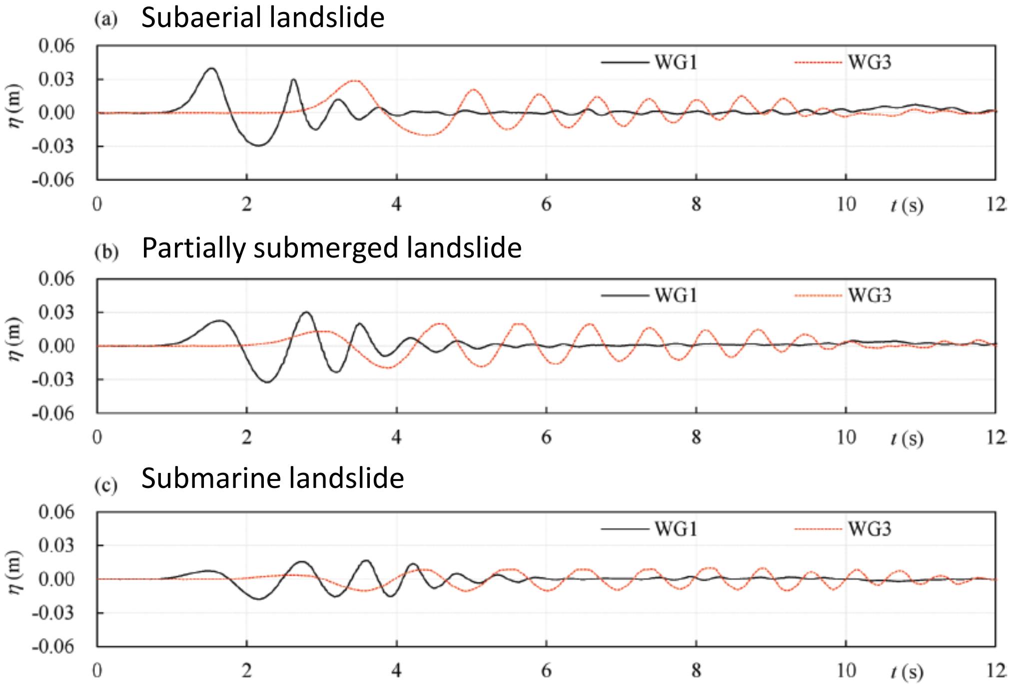
Numerical models are benchmarked using laboratory experiments



(a) Subaerial (θ=45°, d =0.004 m, m=10 kg, h=0.20 m, h_i=0.40 m)

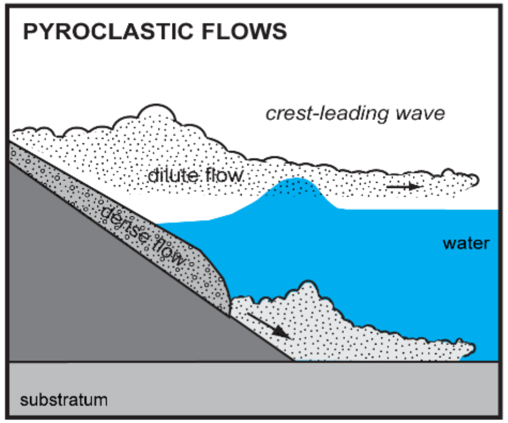
(b) Partially submerged (θ=45°, d =0.004 m, m=10 kg, h=0.45 m, h_i=0.40 m)

(c) Submarine (θ=45°, d =0.004 m, m=10 kg, h=0.60 m, h_i=0.40 m)



Takabatake et al. 2020

- Understanding the physics of wave generation and wave propagation
- Influence of each parameter
- Propose equations that predict the wave amplitude
- Provide guidance for the parameterization of the numerical models

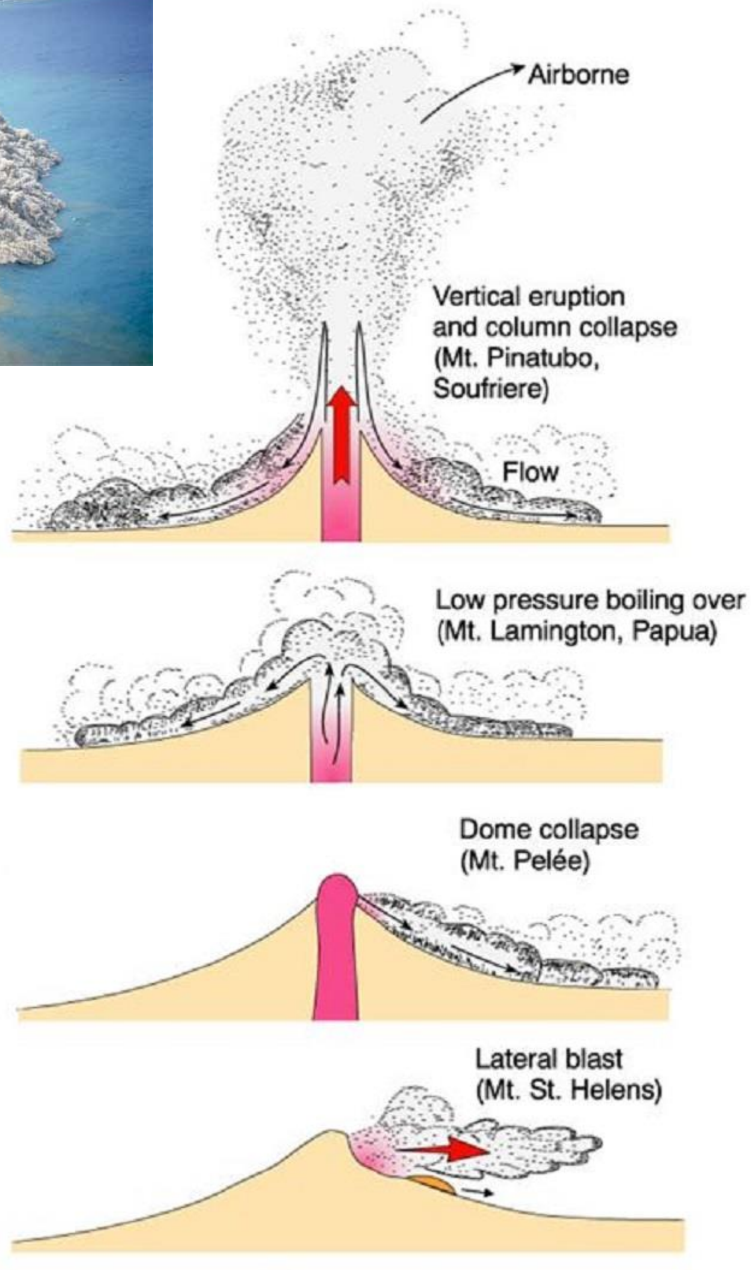


Pyroclastic flows are highly-mobile hot mixtures of gas and particles generated by volcanic eruptions, particularly in case of a volcano dome collapse or a plume (column) collapse

-> add a degree of complexity compared to other landslides

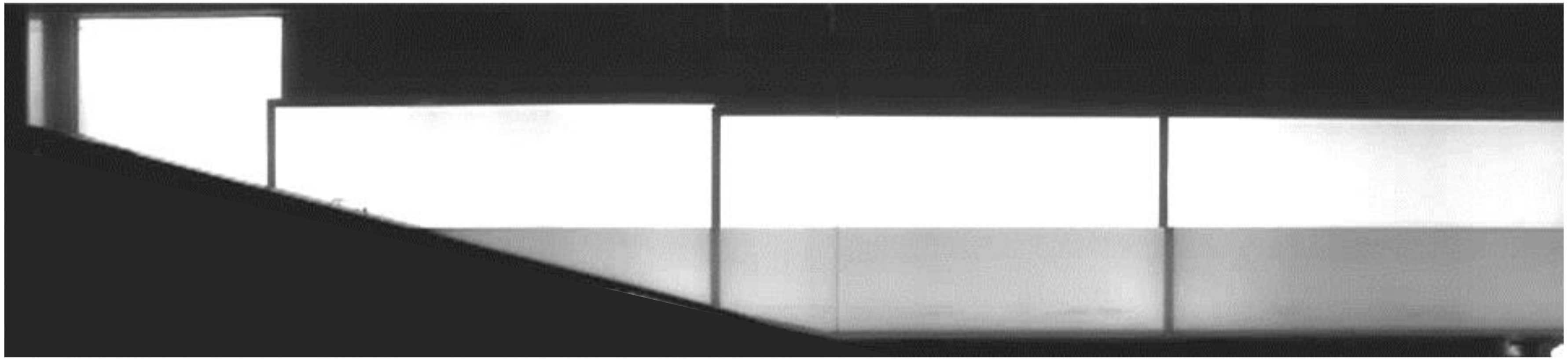
Important parameters controlling the interactions between pyroclastic flows and water bodies:

- flow bulk density
- flow permeability (i.e., its grain size distribution)
- mass flux at the impact with water
- angle of incidence (slope) at the impact with water
- distance from the eruptive vent to the shoreline

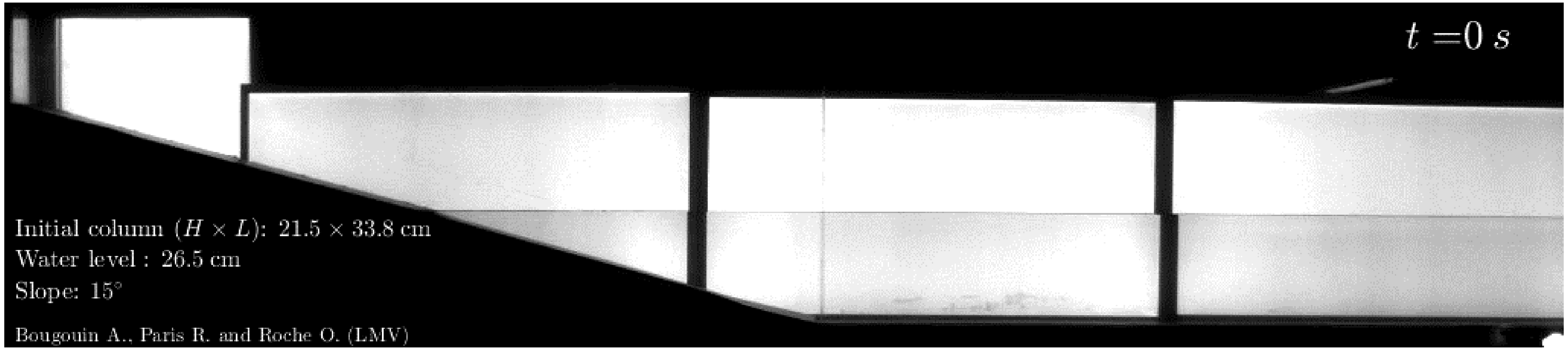


McDonald 1972

Laboratory experiments on tsunami generated by pyroclastic flows



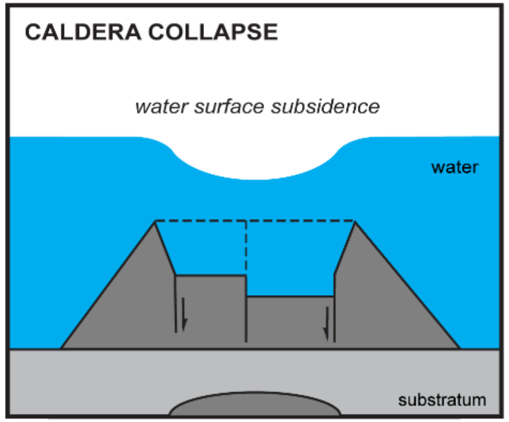
Non-fluidized

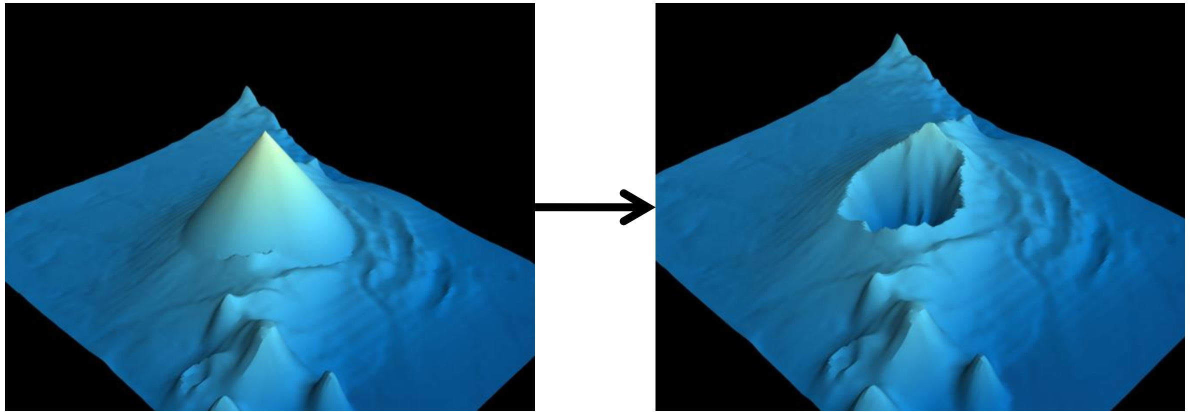


Fluidized

Highly mobile flow
E.g. pyroclastic flow

-> higher flow velocity and mass flux
-> very efficient energy transfer from flow to water
-> steeper and higher wave





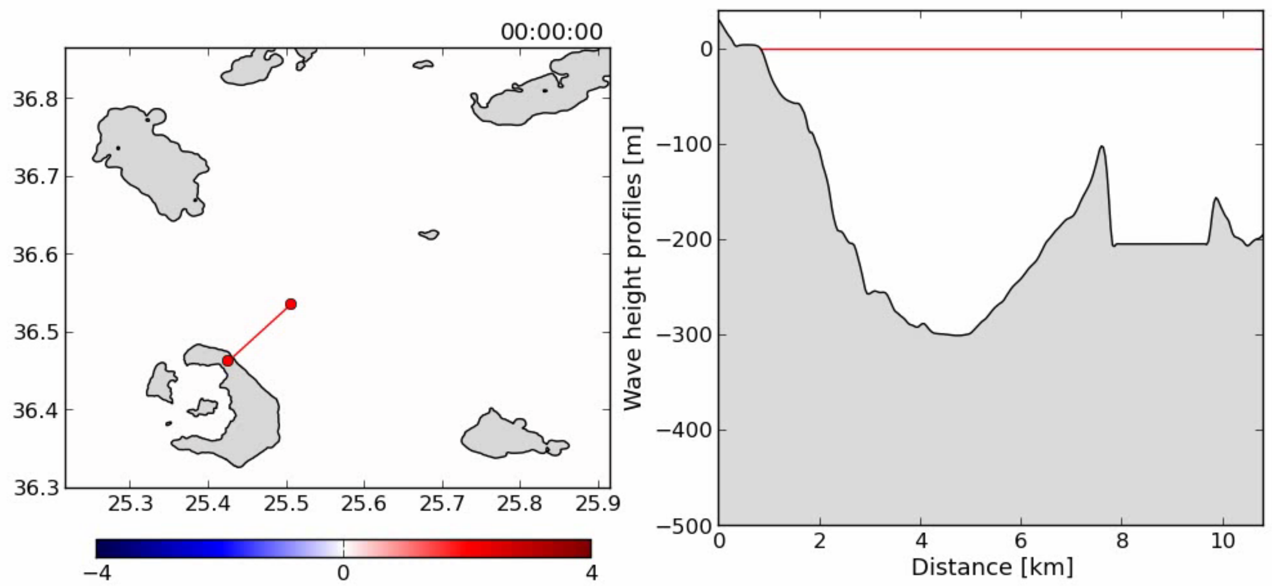
Large explosive eruptions may result in the collapse of the central part of the edifice
-> large depression, so-called caldera, with diameter typically hundreds of metres to tens of kilometres.

Sources of uncertainty:

- Duration of a caldera collapse: poorly constrained (from minutes to hours)
- Geometry: from a single block to multi-stage subsidence of sub- blocks.

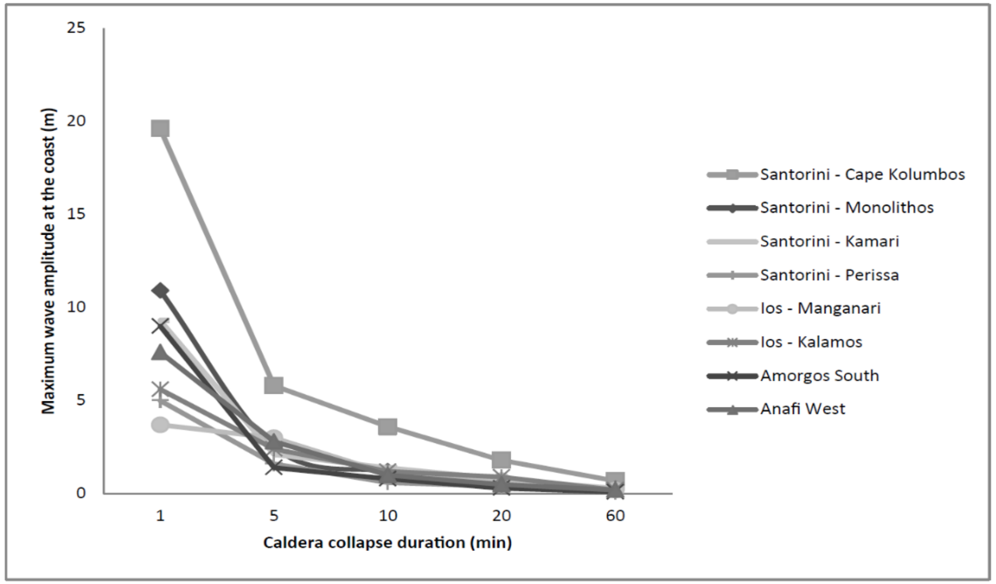
In theory, submarine caldera collapse generates:

- An initial subsidence of the water surface -> leading trough (negative wave), whose size depends on the collapse geometry and duration.
- Followed by a dome of water that collapse -> secondary crests (positive waves)



Kolumbo submarine volcano (Aegean Sea)

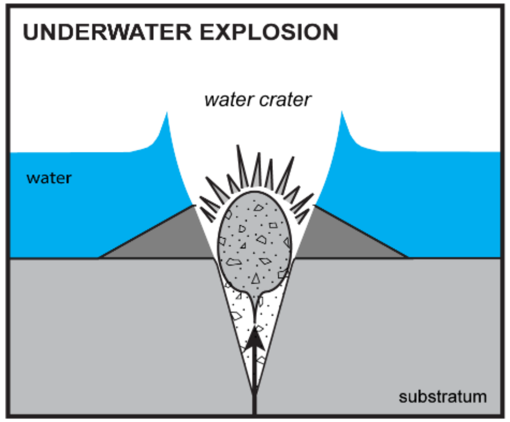
Ulvrova et al. 2016



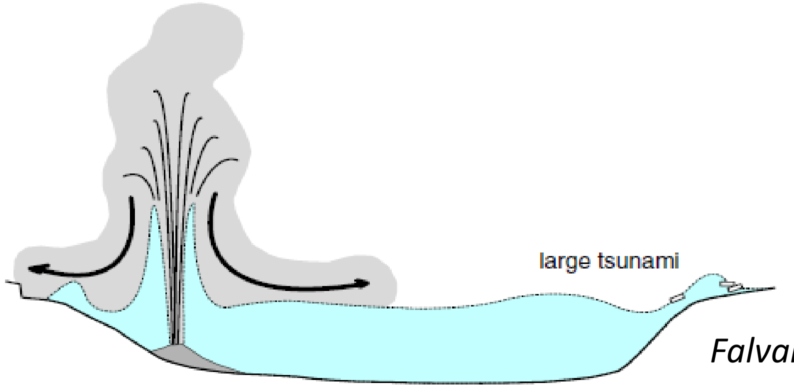
Only fast caldera collapses (<5 minutes) are efficient in terms of tsunami generation. Unrealistic?

Real-case caldera collapses usually last from ~30 minutes (e.g., Pinatubo 1991, Philippines) to 12 days (e.g., Fernandina 1968, Galapagos).

Tonga 2022 caldera collapse?



Underwater explosion may generate tsunami under specific conditions of explosion depth, duration, and energy.

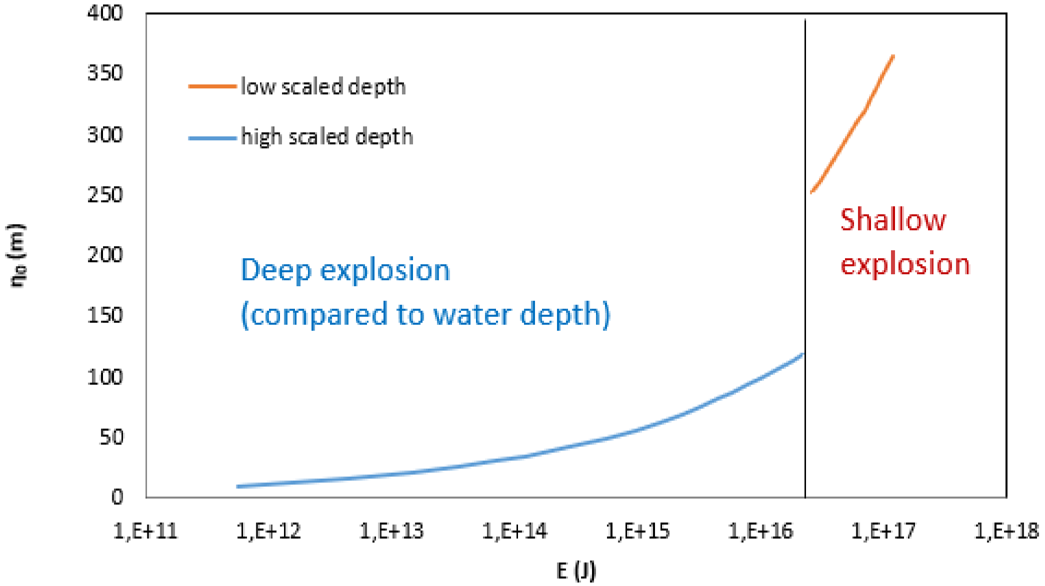


Falvard et al. 2017

1. Water is initially pushed upward -> water crater
2. Water crater collapses -> dome of water
3. Water dome then turns to a cylindrical bore that expands radially to form the leading wave

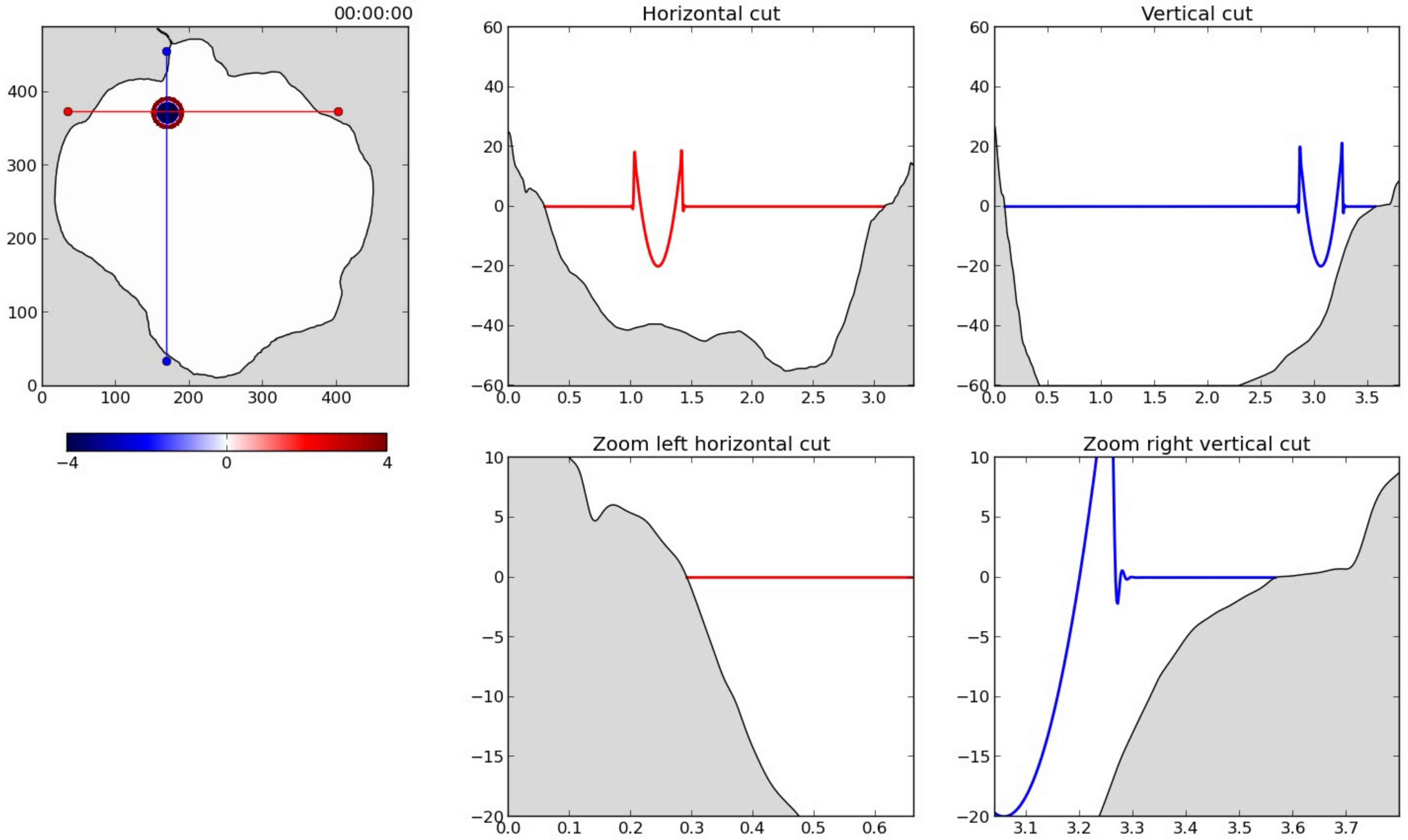
The leading wave (crest) is followed by a trough and a secondary crest. Short-period waves, frequency dispersion

Initial water surface uplift η_0 can be estimated as a function of explosion energy E.

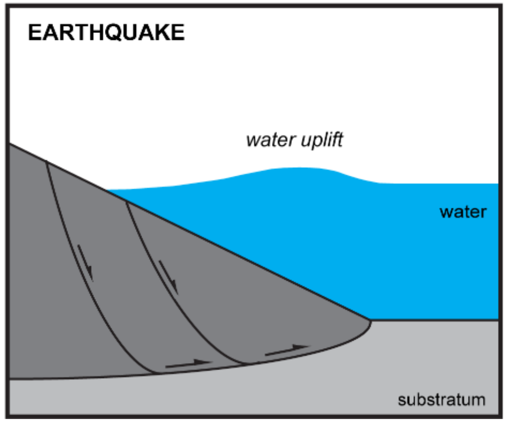


Adapted from Le Méhauté & Wang 1971 & 1996

Numerical simulation of the 1996 tsunami in Karymskoye Lake (Kamchatka)



Ulvrova et al. 2014



In theory, volcano-tectonic earthquakes (VT) with a magnitude $M_s > 6$ resulting from the accumulation of stress induced by magma ascent may involve ground deformation large enough to generate local tsunami.

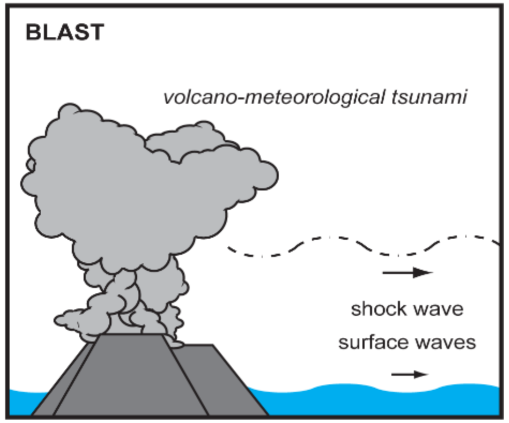
However, it is often difficult to distinguishing between the tsunamigenic nature of the VT earthquake itself and its secondary effects such as landslides.

Another scenario :

$M_s > 7$ on large thrust faults at the base of ocean shield volcanoes can generate local tsunami with significant wave amplitude

e.g. 1975 Kalapana $M_s = 7.2$ earthquake in Hawaii
-> large-scale slumping/faulting (still debated) of the SE submarine flank of Kilauea volcano
-> 1 m subsidence onshore and 1 m uplift offshore = 2.5 km³ of water displaced *(Ma et al. 1999)*
-> tsunami runup up to 14 m on SE Hawaii

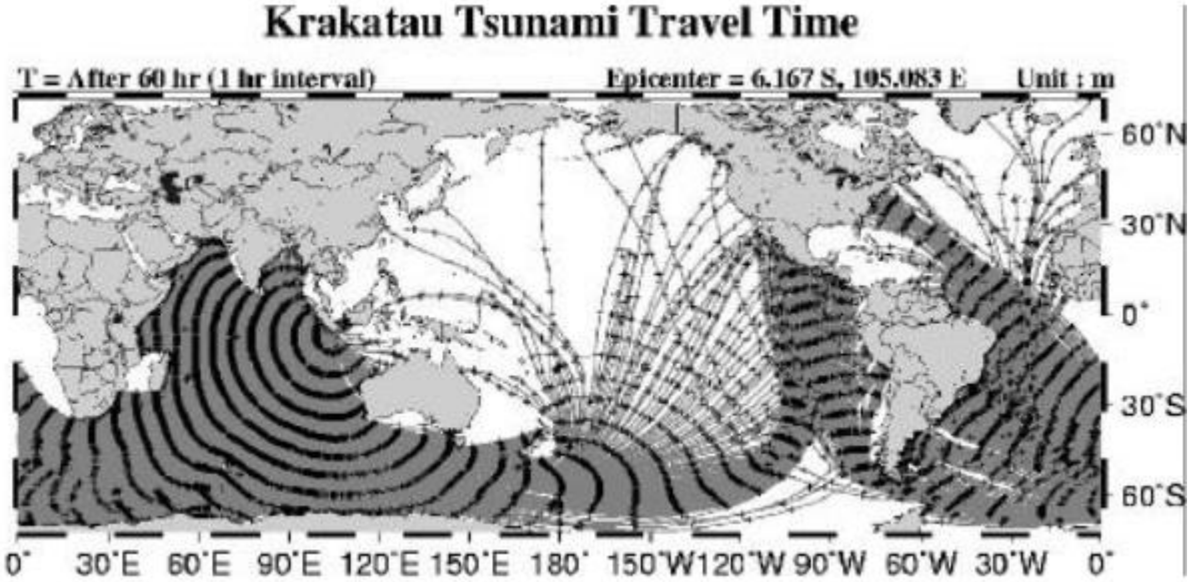
Hawaii National Park Service



Large explosion -> volcano-meteorological tsunami

Lamb-type atmospheric pressure-forcing (moving source) generates basin-wide tsunamis that jumps over land and travels faster (~310 m/s) than usual earthquake-induced tsunamis.

World-wide tsunami following the 1883 August 27 explosion of Krakatau:
a predecessor of the 2022 January 15 Tonga tsunami



Pelinovsky et al. 2005

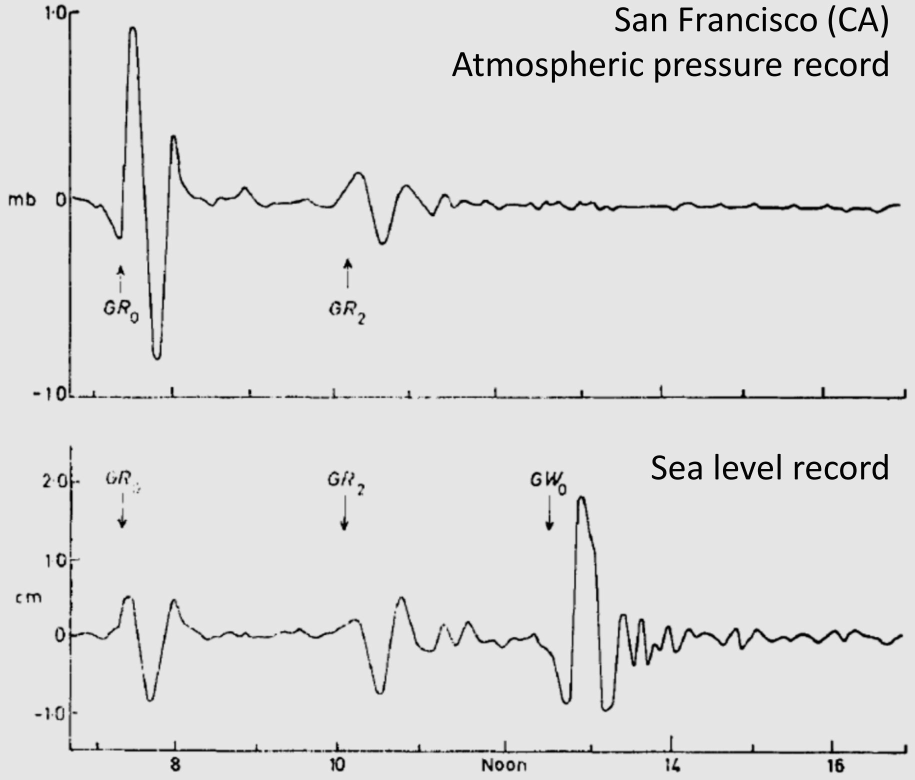


FIG. 8. Synthetic barogram (upper) and marigram (lower) for San Francisco. Source time function is a single-cycle sine wave of 40 minute period. Time is local time, 1883 August 27.

Harkrider & Press 1967

Annex

Other examples of volcanic tsunamis

La catastrophe de 1792, Japon, Kyushu

Tokiwa Museum of Historical Materials, Honkoji Temple, Kyushu

Tsunami in Ariake Bay generated by the collapse of the Mayuyama peripheral dome during the eruption of Unzen volcano

Precursors: strong sismicity
Aggravating factor: hydrothermal alteration

Volume of collapse:
340×10^{6} m^3
(Michiue et al., 1999)

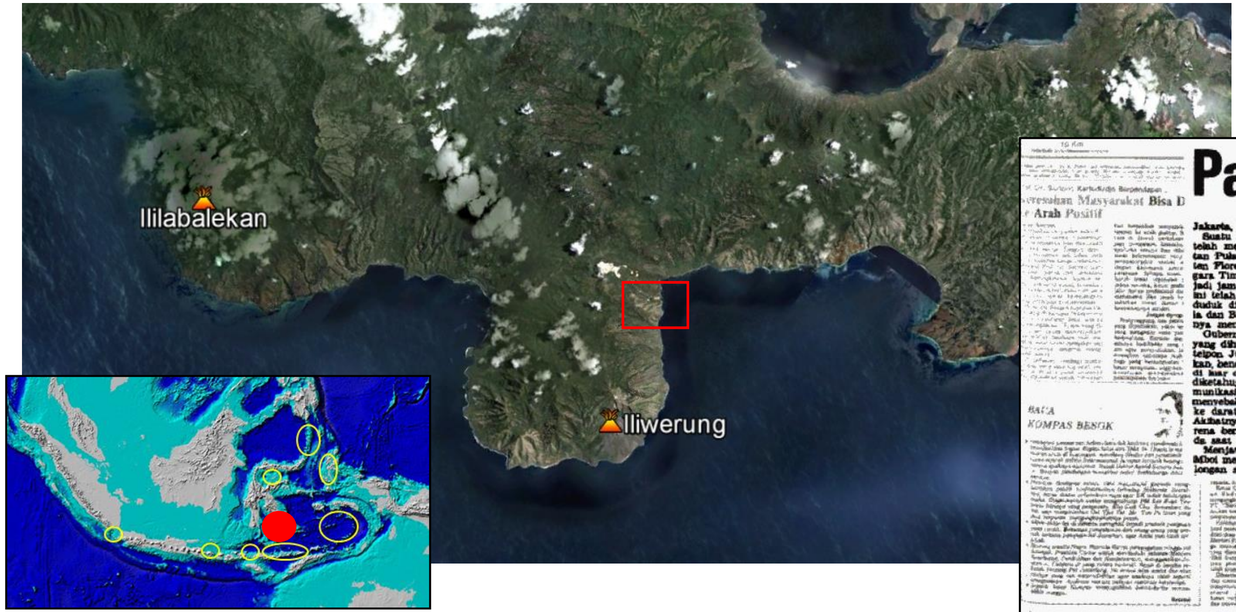
~3 times Krakatau 2018

Tsunami > 10000 fatalities

2nd deadliest natural disaster in Japan with the 2011 Tohoku-oki earthquake and tsunami

Tsunami inundation map (the first one?) made by Japanese engineers after the disaster

Iliwerung 1979 (Flores)



Pantai Selatan Lomblen

* 154 Penduduk Tewas

Jakarta, Kompas.

Suatu gelombang rakasasa telah menyerang pantai selatan Pulau Lomblen, Kabupaten Flores Timur, Nusa Tenggara Timur. Bencana yang terjadi jam 01.00 tanggal 18 Juli ini telah menewaskan 154 penduduk di Desa Waitebe, Lebala dan Bala, sedangkan 23 lainnya menderita luka berat.

Gubernur NTT dr Ben Mboi yang dihubungi Kompas lewat telpon Jumat malam mengatakan, bencana tersebut sungguh di luar dugaan dan terlambat diketahui karena sulitnya komunikasi. Gelombang tersebut menyebabkan air laut masuk ke daratan sejauh 150 meter. Akibatnya semakin fatal karena bencana itu muncul pada saat penduduk tidur lelap.

Menjawab pertanyaan, Ben Mboi mengatakan, usaha pertolongan seperti pengiriman bahan pangan, obat-obatan dan sebagainya sedang dilakukan. Ia sendiri baru dapat ke tempat bencana Sabtu pagi ini dengan helikopter. Penduduk lainnya yang masih selamat telah diungsikan ke Desa Loang yang terletak di pantai barat-laut pulau tersebut.

Ben Mboi selanjutnya mengatakan, belum mengetahui persis penyebab bencana tersebut. Saat ini memang ombak cukup ganas di sana. Namun ia menambahkan pula bahwa bukan mustahil gelombang tersebut muncul akibat kegiatan gunung api di sekitar tempat bencana.

Bencana itu juga telah dilaporkan ke Markas Besar Kepolisian RI di Jakarta oleh Kodak XV Nusra tanggal 20 Juli. Dikatakan, Team Siaga dari kabupaten setempat telah dibentuk. Team bertugas memberi bantuan obat-obatan, beras, pakaian, susu dan sebagainya.

Sebuah sumber Kompas di Jakarta mengatakan, masuk akal bila berita tersebut terlambat diketahui orang luar. Sebab komunikasi di pulau itu sangat minim. Tidak ada jalan raya yang menghubungkan desa-desa di sana. Bahkan hubungan telpon-pun tidak ada.

Gelombang tsunami?

Sampai Jumat malam belum bisa diperoleh keterangan pasti, apa yang sebenarnya telah terjadi sehingga menimbulkan mala petaka tersebut. Tetapi dari ceritera yang kami peroleh tentang gelombang pasang yang datangnya tiba-tiba tersebut, dapat dipastikan bahwa gelombang tsunami telah melanda desa-desa di pantai selatan pulau Lomblen tersebut.

Gelombang tsunami biasanya terjadi sebagai akibat dari gerakan tektonik pada kulit bumi, atau kegiatan suatu gunung berapi di bawah laut. Pada waktu terjadi gerakan pertama, biasanya air laut tersedot ke arah gunung tersebut, surut dari pantai-pantai yang ada di dekatnya. Air laut kemudian menghempas kembali, dan hempasan hebat itulah yang mendorong permukaan air dalam gelombang raksasa, yang dapat merambat sampai ribuan kilometer. Bila terhadang oleh pantai, gelombang besar itu mampu menyapu bersih semua yang ada, seperti malapetaka di pantai Labuhan, ketika gunung Krakatau meletus tahun 1884. Peristiwa serupa juga terjadi di pantai Lombok selatan tanggal 19 Agustus tahun lalu, ketika terjadi gempa laut kira-kira di sebelah selatan pulau Sumba.

Yang jelas di pulau Lomblen ini memang ada banyak gunung api. Akan tetapi menurut ingatan penduduk, yang selalu „mengganggu" mereka adalah gunung (Ili) Werung. Dan gunung ini memang mempunyai catatan panjang kegiatan. Gunung ini sebenarnya merupakan bagian dari kaldera besar gunung Lerek, yang membentuk patahan-patahan arah utara-selatan. Dan patahan-patahan itu mewujud dalam bentuk gunung-gunung api.

Kawah Ili Werung sebenarnya baru muncul tahun 1870, ketika gunung yang lebih tua, Ado Wajung, meletus. Ketika itu muncul dua gunung baru, Ili Monyet dan Ili Werung. Ke utara dan ke selatan gunung Ili Werung yang sekarang juga masih terdapat kawah-kawah, Lusitobe dan Ili Perumtan.

Tahun 1948, muncul lagi kerucut-kerucut baru, Ili Gripe

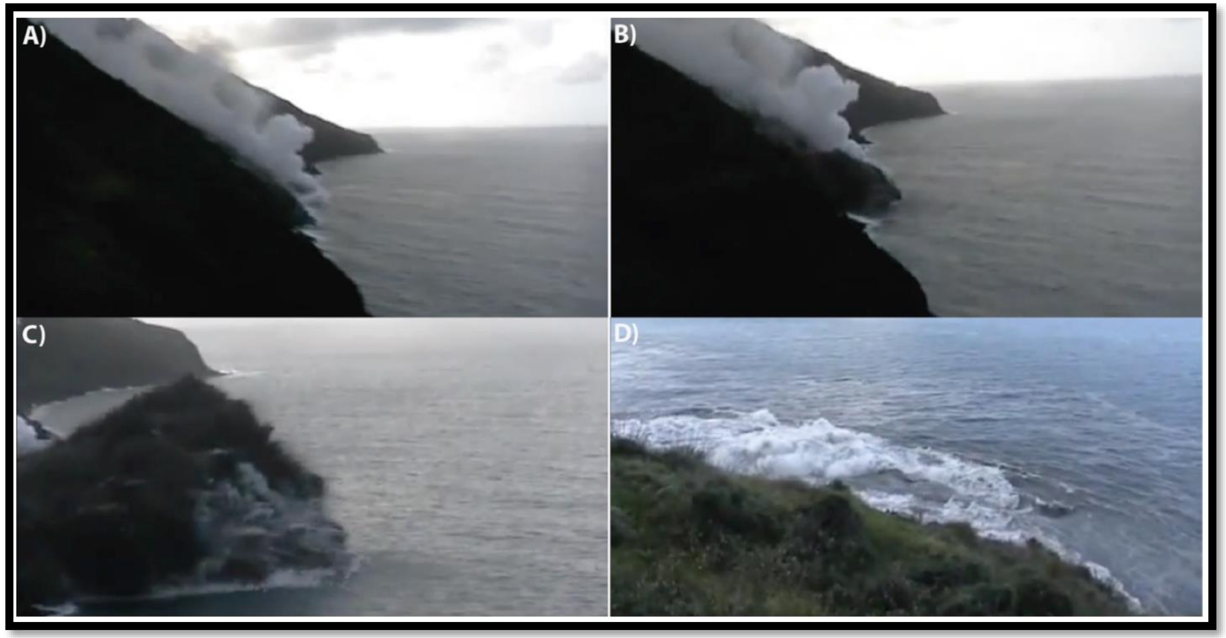
(Bersamb kehal XVI kol 8-9)

July 1979: 50 x 10^6 m^3 landslide (30% volume offshore)
on the NE flank of Iliwerung volcano
no on-going eruption, no earthquake recorded or felt

-> 4 villages buried
(364 killed)

-> tsunami waves 8 m
(539 killed).

Stromboli volcano (Aeolian Islands, Italy),
December 2002



Unusual explosive activity

17×10^6 m^3 landslide on the northern flank
(Tinti et al. 2006).

-> tsunami runup 8 m on the coasts of Stromboli, but no fatalities (winter time).

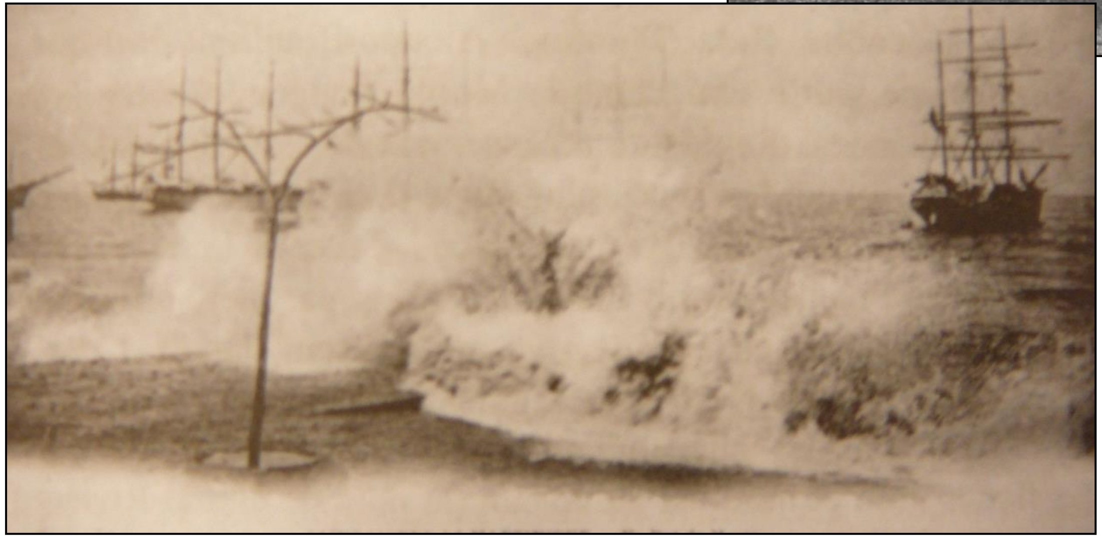
NB- short-period tsunami had a limited impact in the near-field (> 200 km)
(Maramai et al. 2005).

Mount Pelée, Martinique, May 1902

Debris flow on May 5, 1902 in the Rivière Blanche, 3 days before the destruction of St Pierre city by a large pyroclastic flow

-> Tsunami waves observed during 15 minutes

- sea retreat 10-30 m
- 15 successive oscillations
- wave amplitude 2-3 m



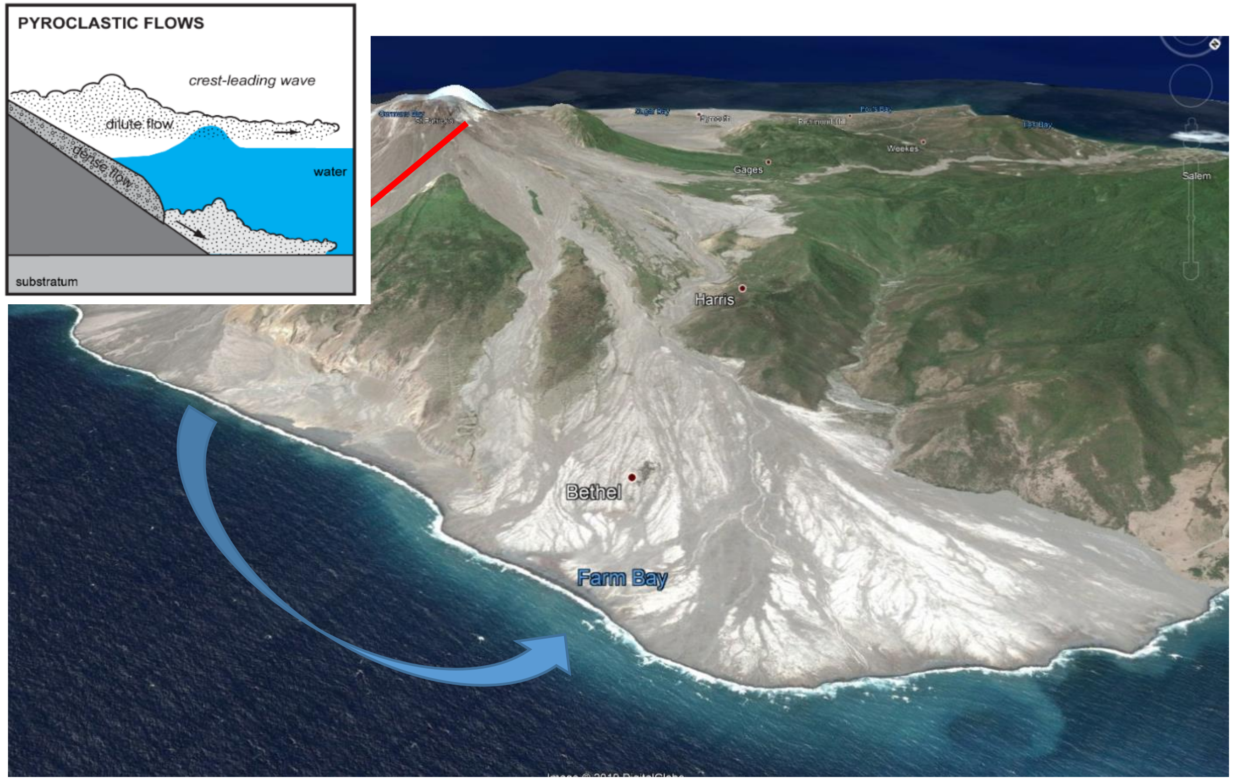
A unique example of tsunami generated by debris flow.

Montserrat, 1997

On the night of the Boxing Day eruption (December 26, 1997) waves inundated the Old Road Bay area.

- Initial sea retreat observed
- Tsunami runup 3 m
- Inundation distance 80 m
- No strong evidence for wave inundation elsewhere

c



Montserrat, 2003

Major collapse of lava dome on July 12, 2003

-> tsunami 4 m on Montserrat Island at up to 4 km from the source area (Farm Bay)

-> tsunami <1 m on NW coast of Guadeloupe Island (50 km away from the volcano)

Pelinovsky et al. (2004)

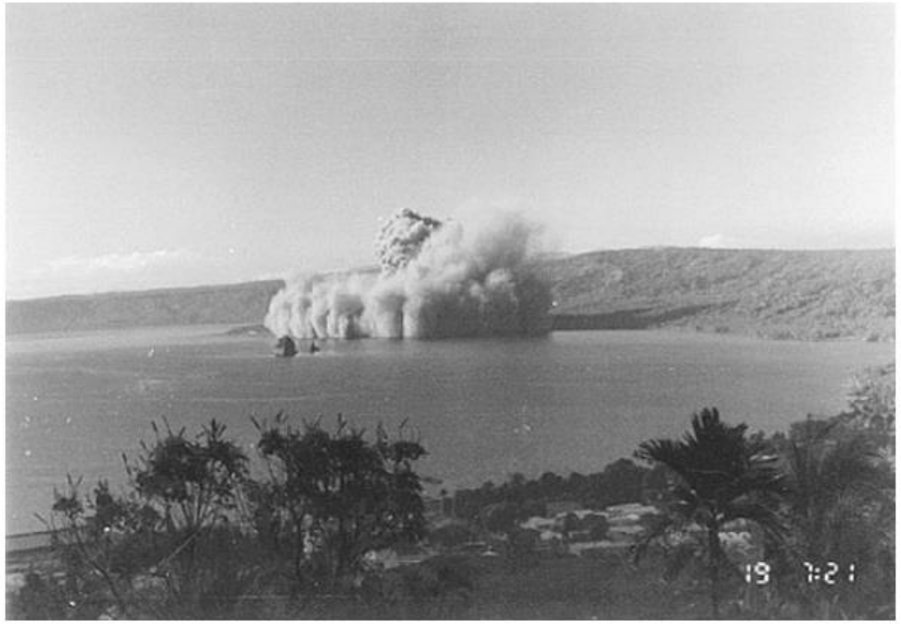


Fig. 7 19 September 1994 pyroclastic flow entering seawater on the northern flank of Vulcan (photograph taken from the Rabaul Volcano Observatory). Note that no water disturbance is apparent yet

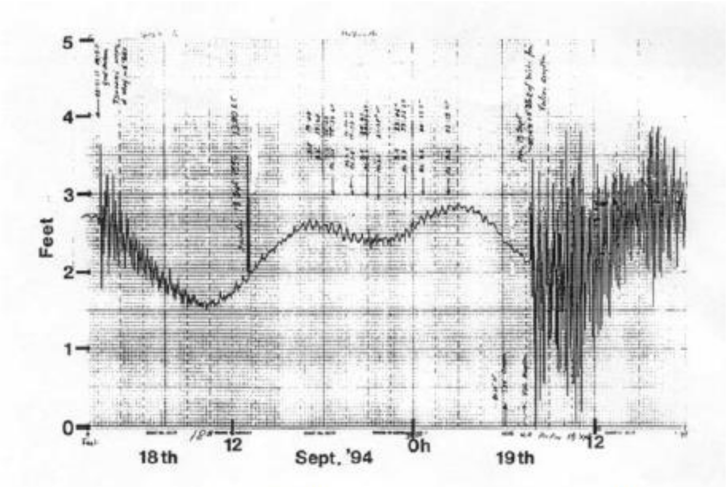


Fig. 2. Tide gauge record at Rabaul, registering two tsunamis. The tsunami that occurred on the morning of September 18th, 1994, was caused by earthquake, and that of September 19th was associated with the eruptive activity of Vulcan volcano. The tide gauge is operated by the Rabaul Volcanological Observatory.

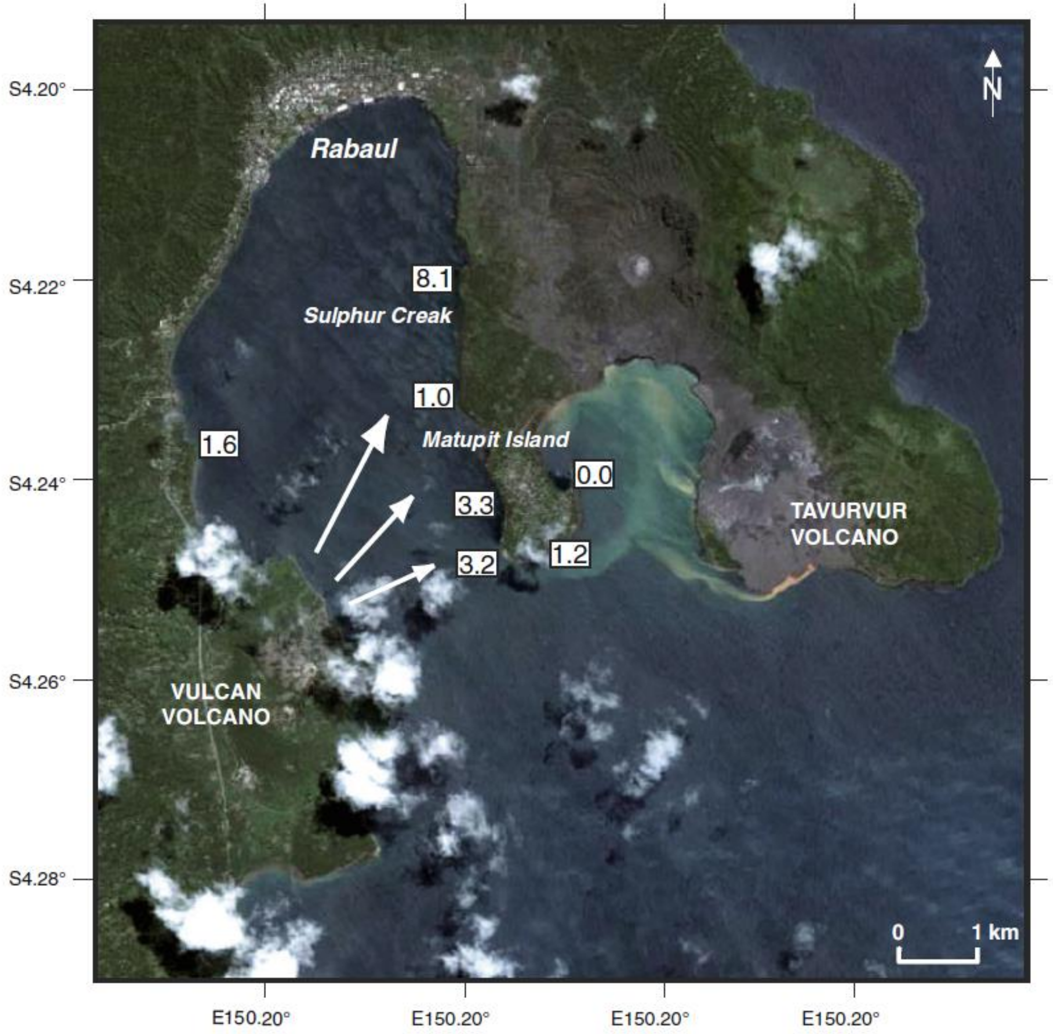


Fig. 6 September 2006 satellite imagery showing the maximum tsunami run-up heights (m a.s.l.) generated by the 1994 Rabaul eruption, Papua New Guinea (modified after Nishimura et al. 2005)