Tsunami Generated by Volcanoes ad Hoc Team Report

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TGV activities

- MEETINGS
  The TGV team met 6 times by video-conference, from April 2022 to February 2023.

- SURVEY :
  The TGV team at his first meeting identified that to get as much information as possible related to the volcano observatories activities on tsunami monitoring and warning systems, on volcanic tsunami hazard assessment.
  The TGV ad hoc team decided to perform a survey.

- QUESTIONNAIRES
  A specific questionnaire would be prepared sent to a set of Volcano observatories and institutes in charge of volcano monitoring with identified contact people.

- VOLCANO OBSERVATORIES

Establishment of a list of Volcano observatories located close to sea or oceans with identified contact to send the questionnaire.

TGV Report

- 0 Introduction and background
- 1 Tsunami generated by volcanic activity
- 2 Numerical modeling of volcanic tsunamis
- 3 Volcanic tsunami hazard assessment (Stromboli)
- 4 Volcano monitoring requirements for tsunami warning (Stromboli)
- 5 Volcanic tsunami warning systems and SOPs (Stromboli, Anak Krakatau)
- 6 Recommendations

- Appendix 1 questionnaire and summary results/responses?
- Appendix 2 : list of tsunamigenic volcanoes

Chapter 1 – Tsunamis generated by volcano activity and instability

-> background information on the physical phenomena associated with each identified possible tsunami source in a volcanic setting

-> references on historical and recent case-studies.

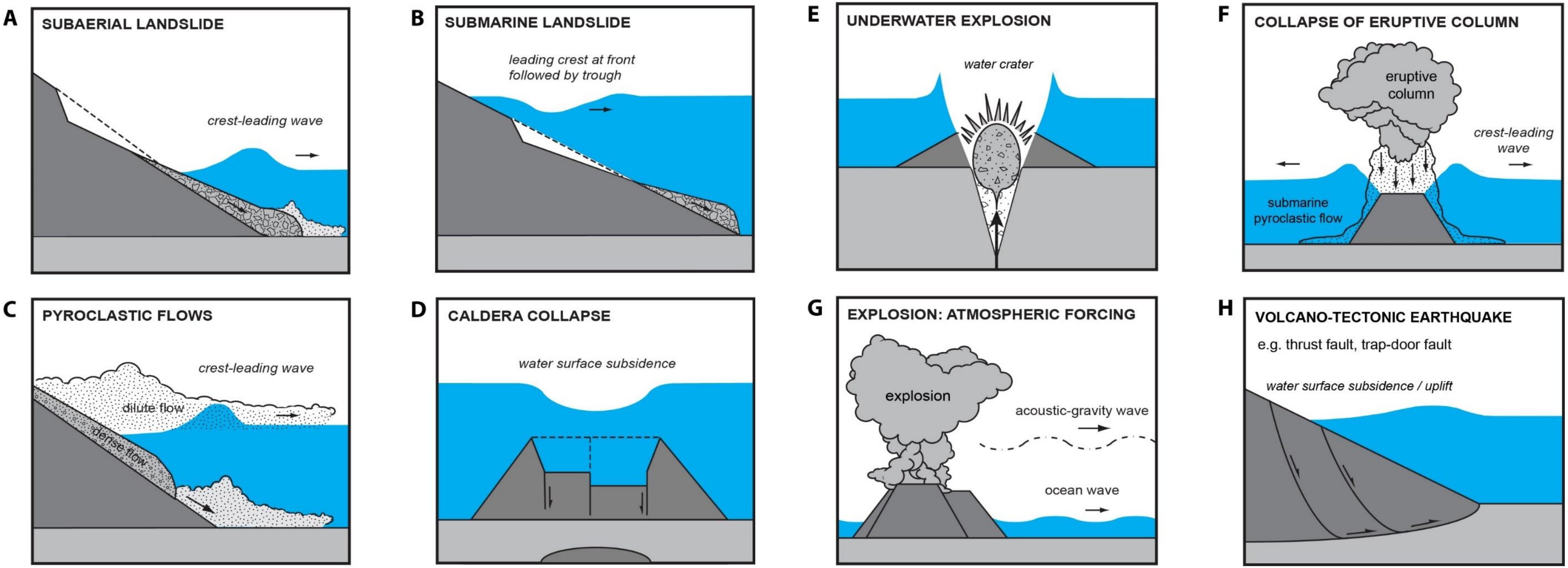


Table 1 – Examples of tsunami generated by volcano flank instability.

Volcano	**Location**	**Year**	**Landslide volume**	**Max tsunami runup (dist. from source)**	**Reference**
Anak Krakatau	Sunda Strait, Indonesia	2018	210×10^{6} m^{3}	85 m (4 km)	Muhari et al. (2019), Walter et al. (2019), Borrero et al. (2020), Perttu et al. (2020), Putra et al. (2020), Hunt et al. (2021)
Stromboli	Aeolian Islands, Italy	2002	17×10^{6} m^{3} and 5×10^{6} m^{3}	11 m (1.5 km)	Bonaccorso et al. (2003), Maramai et al. (2005)
Kilauea	Hawaï, USA	1994	~10^{5} m^{3}	15 m (50 m)	Mattox and Mangan (1997)
Iliwerung	Lembata, Indonesia	1979	50×10^{6} m^{3}	9 m (18 km)	Lassa (2009), Yudhicara et al. (2015)
Ritter Island	Papua New Guinea	1888	5 km^{3}	15 m (9 km)	Johnson (1987), Ward and Day (2003), Kartens et al. (2019)
Unzen-Mayuyama	Kyushu, Japan	1792	340×10^{6} m^{3}	57 m (7 km)	Tsuji and Hino (1993), Inoue (2000)
Oshima-Oshima	Japan Sea, Japan	1741	2.4 km^{3}	13 m (50 km)	Satake & Kato (2001), Satake (2007)

Nb – similar tables are provided for pyroclastic flows, underwater explosions, and atmospheric forcing (HTHH-type).

Table 6 – Types of potentially tsunamigenic volcanoes and associated source mechanisms of tsunamis (updated from Paris et al., 2014a).

		Volcano type			
		Coastal / island stratovolcano	Submarine stratovolcano	Shallow-water caldera	Oceanic shield volcano
Tsunami source	Subaerial landslide	▨		▨	▨
	Submarine landslide		▨	▨	▨
	Underwater explosion		▨	▨	
	Caldera collapse		▨	▨	
	Column collapse		▨	▨	
	Pyroclastic flow	▨	▨	▨	
	Volcano-tectonic earthquake				▨
	Atmospheric forcing	▨	▨	▨	
Examples		Stromboli, Italy	HTHH, Tonga	Taal, Philippines	Kilauea, Hawaii
		Soufriere Hills, Montserrat	Kick'em Jenny, Grenada	Rabaul, Papua New Guinea	Fournaise, Reunion Island
		Unzen, Japan	Kolumbo, Greece	Krakatau, Indonesia	Fogo, Cape Verde

Conclusion

The great majority of volcanic eruptions do not generate tsunami, but a single eruption might combine different sources of tsunamis (Table 6). Thus, the source of a tsunami observed during an eruption is often difficult to characterize. All source mechanisms listed here have different characteristics in terms of location, duration, volume, mass flux, and energy, which have consequences on the waves generated. Landslides are the most frequent sources of volcanic tsunamis. From all points of view, volcanic islands (arcs) are the most exposed to volcanic tsunamis.

List of 89 potentially tsunamigenic volcanoes established upon precise criteria.

1. Volcano was active during the XXth or XXIst centuries.

2. It belongs to one of the following types of volcanoes:

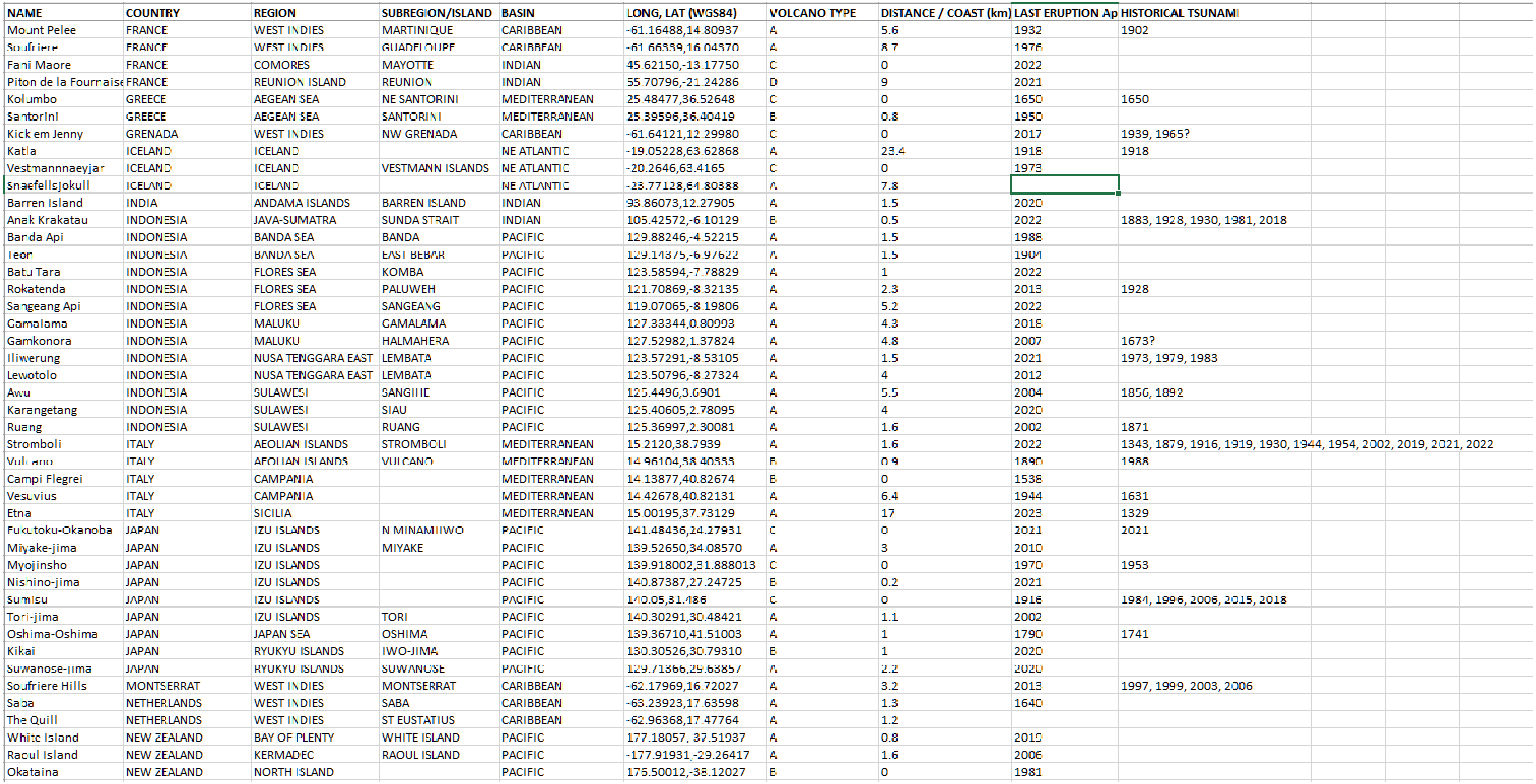
A- It is a steep-flanked stratovolcano whose main eruptive centre is located less than 7 km from the coast (sea or lake). Typical examples: Stromboli, Soufrière Hills.

B- The volcano belongs to a complex of eruptive centres in a partly submerged caldera. A distinction can be made between caldera lakes (e.g. Taal, Philippines), calderas opened to the sea (e.g. Rabaul, PNG) and submerged calderas with emerged eruptive centres (e.g. Krakatau, Indonesia).

C- It is a submarine volcano with shallow-water vents, whose activity and flank instability are clearly potential sources of tsunamis, as demonstrated by the HTHH eruption in 2022.

D- It is a shield volcano (ocean island) showing evidence of flank deformation, such as Kilauea volcano in Hawaii, and Piton de la Fournaise in Reunion Island.

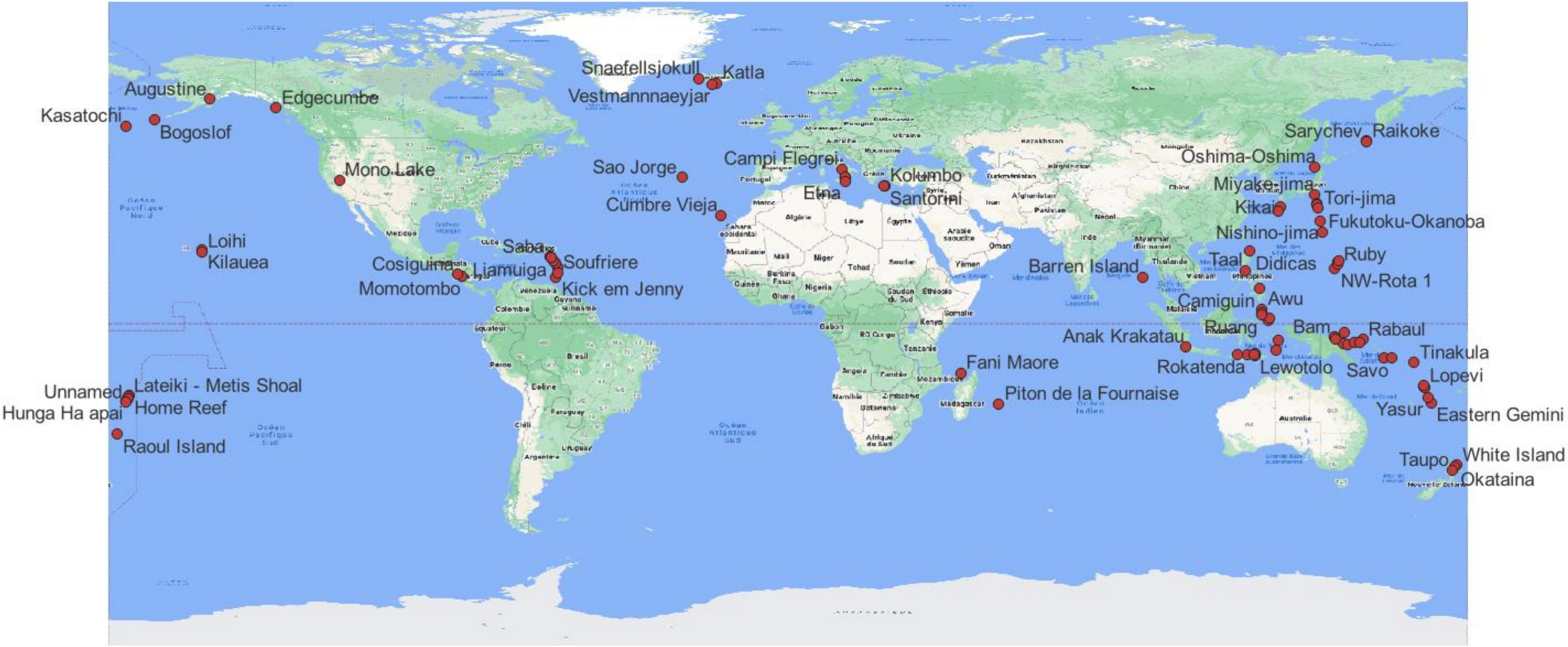
3. Additional volcanoes were added to the list, based on suggestions found in the questionnaires sent to volcano observatories.

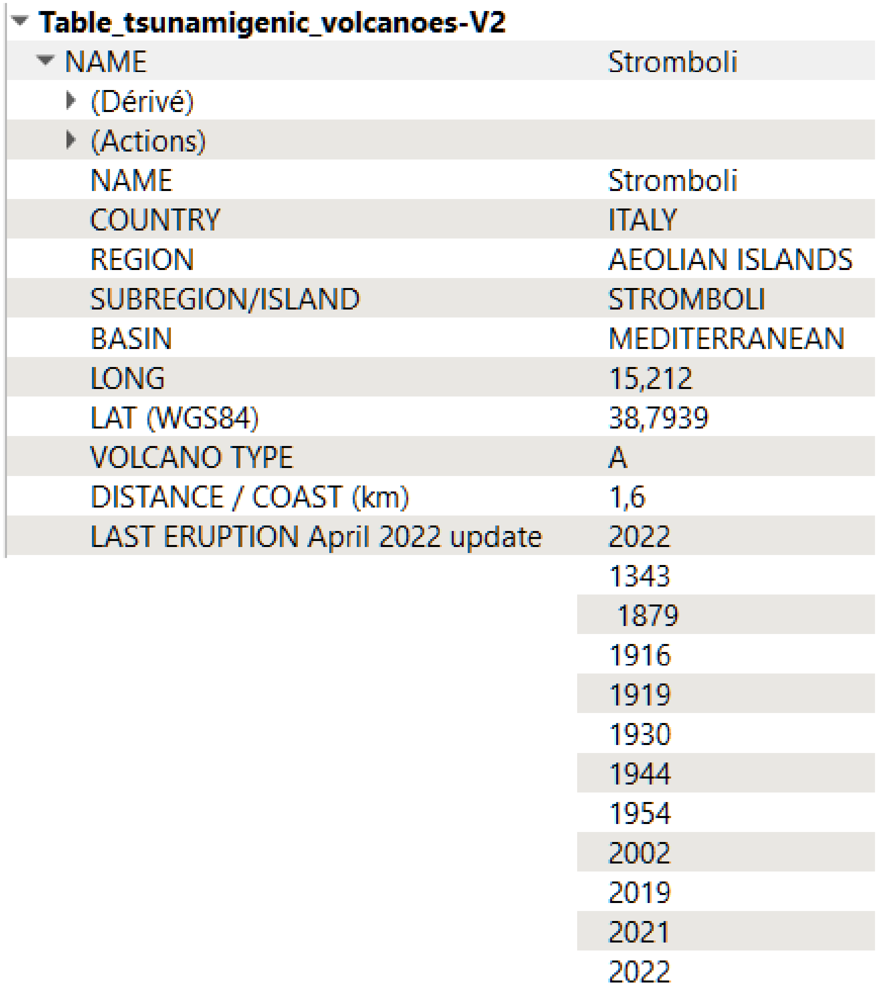


NAME	COUNTRY	REGION	SUBREGION/ISLAND	BASIN	LONG, LAT (WGS84)	VOLCANO TYPE	DISTANCE / COAST (km)	LAST ERUPTION Ap	HISTORICAL TSUNAMI
Mount Pelee	FRANCE	WEST INDIES	MARTINIQUE	CARIBBEAN	-61.16488,14.80937	A	5.6	1932	1902
Soufriere	FRANCE	WEST INDIES	GUADELOUPE	CARIBBEAN	-61.66339,16.04370	A	8.7	1976	
Fani Maore	FRANCE	COMORES	MAYOTTE	INDIAN	45.62150,-13.17750	C	0	2022	
Piton de la Fournaise	FRANCE	REUNION ISLAND	REUNION	INDIAN	55.70796,-21.24286	D	9	2021	
Kolumbo	GREECE	AEGEAN SEA	NE SANTORINI	MEDITERRANEAN	25.48477,36.52648	C	0	1650	1650
Santorini	GREECE	AEGEAN SEA	SANTORINI	MEDITERRANEAN	25.39596,36.40419	B	0.8	1950	
Kick em Jenny	GRENADA	WEST INDIES	NW GRENADA	CARIBBEAN	-61.64121,12.29980	C	0	2017	1939, 1965?
Katla	ICELAND	ICELAND		NE ATLANTIC	-19.05228,63.62868	A	23.4	1918	1918
Vestmannnaeyjar	ICELAND	ICELAND	VESTMANN ISLANDS	NE ATLANTIC	-20.2646,63.4165	C	0	1973	
Snaefellsjokull	ICELAND	ICELAND		NE ATLANTIC	-23.77128,64.80388	A	7.8		
Barren Island	INDIA	ANDAMA ISLANDS	BARREN ISLAND	INDIAN	93.86073,12.27905	A	1.5	2020	
Anak Krakatau	INDONESIA	JAVA-SUMATRA	SUNDA STRAIT	INDIAN	105.42572,-6.10129	B	0.5	2022	1883, 1928, 1930, 1981, 2018
Banda Api	INDONESIA	BANDA SEA	BANDA	PACIFIC	129.88246,-4.52215	A	1.5	1988	
Teon	INDONESIA	BANDA SEA	EAST BEBAR	PACIFIC	129.14375,-6.97622	A	1.5	1904	
Batu Tara	INDONESIA	FLORES SEA	KOMBA	PACIFIC	123.58594,-7.78829	A	1	2022	
Rokatenda	INDONESIA	FLORES SEA	PALUWEH	PACIFIC	121.70869,-8.32135	A	2.3	2013	1928
Sangeang Api	INDONESIA	FLORES SEA	SANGEANG	PACIFIC	119.07065,-8.19806	A	5.2	2022	
Gamalama	INDONESIA	MALUKU	GAMALAMA	PACIFIC	127.33344,0.80993	A	4.3	2018	
Gamkonora	INDONESIA	MALUKU	HALMAHERA	PACIFIC	127.52982,1.37824	A	4.8	2007	1673?
Iliwerung	INDONESIA	NUSA TENGGARA EAST	LEMBATA	PACIFIC	123.57291,-8.53105	A	1.5	2021	1973, 1979, 1983
Lewotolo	INDONESIA	NUSA TENGGARA EAST	LEMBATA	PACIFIC	123.50796,-8.27324	A	4	2012	
Awu	INDONESIA	SULAWESI	SANGIHE	PACIFIC	125.4496,3.6901	A	5.5	2004	1856, 1892
Karangetang	INDONESIA	SULAWESI	SIAU	PACIFIC	125.40605,2.78095	A	4	2020	
Ruang	INDONESIA	SULAWESI	RUANG	PACIFIC	125.36997,2.30081	A	1.6	2002	1871
Stromboli	ITALY	AEOLIAN ISLANDS	STROMBOLI	MEDITERRANEAN	15.2120,38.7939	A	1.6	2022	1343, 1879, 1916, 1919, 1930, 1944, 1954, 2002, 2019, 2021, 2022
Vulcano	ITALY	AEOLIAN ISLANDS	VULCANO	MEDITERRANEAN	14.96104,38.40333	B	0.9	1890	1988
Campi Flegrei	ITALY	CAMPANIA		MEDITERRANEAN	14.13877,40.82674	B	0	1538	
Vesuvius	ITALY	CAMPANIA		MEDITERRANEAN	14.42678,40.82131	A	6.4	1944	1631
Etna	ITALY	SICILIA		MEDITERRANEAN	15.00195,37.73129	A	17	2023	1329
Fukutoku-Okanoba	JAPAN	IZU ISLANDS	N MINAMIIWO	PACIFIC	141.48436,24.27931	C	0	2021	2021
Miyake-jima	JAPAN	IZU ISLANDS	MIYAKE	PACIFIC	139.52650,34.08570	A	3	2010	
Myojinsho	JAPAN	IZU ISLANDS		PACIFIC	139.918002,31.888013	C	0	1970	1953
Nishino-jima	JAPAN	IZU ISLANDS		PACIFIC	140.87387,27.24725	B	0.2	2021	
Sumisu	JAPAN	IZU ISLANDS		PACIFIC	140.05,31.486	C	0	1916	1984, 1996, 2006, 2015, 2018
Tori-jima	JAPAN	IZU ISLANDS	TORI	PACIFIC	140.30291,30.48421	A	1.1	2002	
Oshima-Oshima	JAPAN	JAPAN SEA	OSHIMA	PACIFIC	139.36710,41.51003	A	1	1790	1741
Kikai	JAPAN	RYUKYU ISLANDS	IWO-JIMA	PACIFIC	130.30526,30.79310	B	1	2020	
Suwanose-jima	JAPAN	RYUKYU ISLANDS	SUWANOSE	PACIFIC	129.71366,29.63857	A	2.2	2020	
Soufriere Hills	MONTSERRAT	WEST INDIES	MONTSERRAT	CARIBBEAN	-62.17969,16.72027	A	3.2	2013	1997, 1999, 2003, 2006
Saba	NETHERLANDS	WEST INDIES	SABA	CARIBBEAN	-63.23923,17.63598	A	1.3	1640	
The Quill	NETHERLANDS	WEST INDIES	ST EUSTATIUS	CARIBBEAN	-62.96368,17.47764	A	1.2		
White Island	NEW ZEALAND	BAY OF PLENTY	WHITE ISLAND	PACIFIC	177.18057,-37.51937	A	0.8	2019	
Raoul Island	NEW ZEALAND	KERMADEC	RAOUL ISLAND	PACIFIC	-177.91931,-29.26417	A	1.6	2006	
Okataina	NEW ZEALAND	NORTH ISLAND		PACIFIC	176.50012,-38.12027	B	0	1981	

NAME	COUNTRY	REGION	SUBREGION/ISLAND	BASIN	LONG, LAT (WGS84)	VOLCANO TYPE	DISTANCE / COAST (km)	LAST ERUPTION Ap	HISTORICAL TSUNAMI
Taupo	NEW ZEALAND	NORTH ISLAND		PACIFIC	175.91988,-38.80097	B	0	260	
Momotombo	NICARAGUA	LAKE MANAGUA		PACIFIC	-86.53808,12.42113	A	3.5	2016	
Cosiguina	NICARAGUA	PACIFIC COAST		PACIFIC	-87.57093,12.98246	A	6.1	1859	1835?
Bam	PAPUA - NEW GUINEA	BISMARCK SEA	BAM	PACIFIC	144.81801,-3.61275	A	1.1	1960	
Kadovar	PAPUA - NEW GUINEA	BISMARCK SEA	KADOVAR	PACIFIC	144.58806,-3.60754	A	0.5	2020	2018
Long Island	PAPUA - NEW GUINEA	BISMARCK SEA	LONG ISLAND	PACIFIC	147.11783,-5.35215	A	7	1993	
Manam	PAPUA - NEW GUINEA	BISMARCK SEA	MANAM	PACIFIC	145.03743,-4.07896	A	5	2020	
Ritter Island	PAPUA - NEW GUINEA	BISMARCK SEA	RITTER ISLAND	PACIFIC	148.11472,-5.51957	C	0	2007	1888, 1972, 1974, 2007
Dakataua	PAPUA - NEW GUINEA	NEW BRITAIN		PACIFIC	150.10607,-5.05447	B	5.5	1895	
Rabaul	PAPUA - NEW GUINEA	NEW BRITAIN		PACIFIC	152.20300,-4.27081	B	0.6	2014	1878, 1937, 1994
Tuluman	PAPUA - NEW GUINEA	NEW BRITAIN	SOUTH MANUS	PACIFIC	147.30293,-2.45519	C	0	1957	
Ulawun	PAPUA - NEW GUINEA	NEW BRITAIN		PACIFIC	151.32889,-5.05038	A	10.5	2022	
Didicas	PHILIPPINES	BABUYAN ISLANDS	NE CAMIGUIN	PACIFIC	122.20254,19.07709	B	0.2	1978	1969?
Camiguin	PHILIPPINES	BOHOL SEA	CAMIGUIN	PACIFIC	124.7201,9.1754	B	4	1953	1871
Taal	PHILIPPINES	LUZON		PACIFIC	120.9930,14.0070	B	2.2	2021	1716, 1749, 1754, 1911, 1965
Sao Jorge	PORTUGAL	AZORES ISLANDS	SAO JORGE	ATLANTIC	-28.07764,38.65153	D	1.5	1902	
Raikoke	RUSSIA	KURIL ISLANDS	RAIKOKE	PACIFIC	153.24978,48.29220	A	0.7	2019	
Sarychev	RUSSIA	KURIL ISLANDS	SARYCHEV	PACIFIC	153.20003,48.09158	A	2.8	2021	
Tinakula	SOLOMON ISLANDS	EAST SOLOMON	TINAKULA	PACIFIC	165.80392,-10.38640	A	1.1	2020	1897, 1966
Kavachi	SOLOMON ISLANDS	WEST SOLOMON	SOUTH VANGUNU	PACIFIC	157.97888,-8.99099	C	0	2021	1951
Savo	SOLOMON ISLANDS	WEST SOLOMON	NORTH GUADALCANAI	PACIFIC	159.80749,-9.13400	A	2.3	1847?	
Cumbre Vieja	SPAIN	CANARY ISLANDS	LA PALMA	ATLANTIC	-17.83715,28.56832	D	1.2	2021	
Liamuiga	ST KITTS & NEVIS	WEST INDIES	ST KITTS	CARIBBEAN	-62.80896,17.37007	A	4.4	1843?	
Soufriere	ST VINCENT	WEST INDIES	ST VINCENT	CARIBBEAN	-61.18092,13.33104	A	3.5	2020	1902, 2020
Home Reef	TONGA	TONGA	WEST NEIAFU	PACIFIC	-174.77517,-18.99183	C	0	2006	
Hunga Ha apai	TONGA	TONGA	NORTH TONGATAPU	PACIFIC	-175.39068,-20.54491	B	0.1	2022	2015, 2021, 2022
Lateiki - Metis Shoal	TONGA	TONGA	WEST NEIAFU	PACIFIC	-174.86999,-19.18002	C	0	2019	
Tofua	TONGA	TONGA	TOFUA	PACIFIC	-175.07002,-19.75023	A	3	2014	1892
Unnamed	TONGA	TONGA	WEST TONGATAPU	PACIFIC	-175.55041,-20.85174	C	0	2017	
Augustine	USA	ALASKA	AUGUSTINE	PACIFIC	-153.43023,59.36302	A	4	2006	1883
Bogoslof	USA	ALEUTIAN ISLANDS	BOGOSLOF	PACIFIC	-168.03530,53.93010	A	0.2	2017	
Kasatochi	USA	ALEUTIAN ISLANDS	KASATOCHI	PACIFIC	-175.50881,52.17454	A	0.4	2008	2008
Mono Lake	USA	CALIFORNIA		PACIFIC	-119.02835,38.00242	B	0.6	1790	
Kilauea	USA	HAWAII	BIG ISLAND	PACIFIC	-155.2889,19.4202	D	14	2022	1975
Loihi	USA	HAWAII	SOUTH BIG ISLAND	PACIFIC	-155.2681,18.9262	D	0	1996	
Anatahan	USA	MARIANA ISLANDS	ANATAHAN	PACIFIC	145.67389,16.35038	A	1.5	2008	
NW-Rota 1	USA	MARIANA ISLANDS	WEST SINAPALU	PACIFIC	144.77496,14.60064	C	0	2010	
Ruby	USA	MARIANA ISLANDS	NORTH SAIPAN	PACIFIC	145.56974,15.61975	C	0	1995	
South Sarigan	USA	MARIANA ISLANDS	SARIGAN	PACIFIC	145.77989,16.57998	C	0	2010	2010
Edgecumbe	USA	ALASKA	EASTERN ALASKA	PACIFIC	-135.75289,57.05220	A	5.1	2080 BCE	
East Epi	VANUATU	VANUATU	EAST EPI	PACIFIC	168.37002,-16.68009	C	0	2023	
Eastern Gemini	VANUATU	VANUATU	SOUTH ANATOM	PACIFIC	170.28844,-20.98807	C	0	1996	
Kuwae	VANUATU	VANUATU	SOUTH EPI	PACIFIC	168.53500,-16.83028	C	0	1974	
Lopevi	VANUATU	VANUATU	SE AMBRYM	PACIFIC	168.34504,-16.50700	A	2.2	2007	

List of potentially tsunamigenic volcanoes -> GIS database





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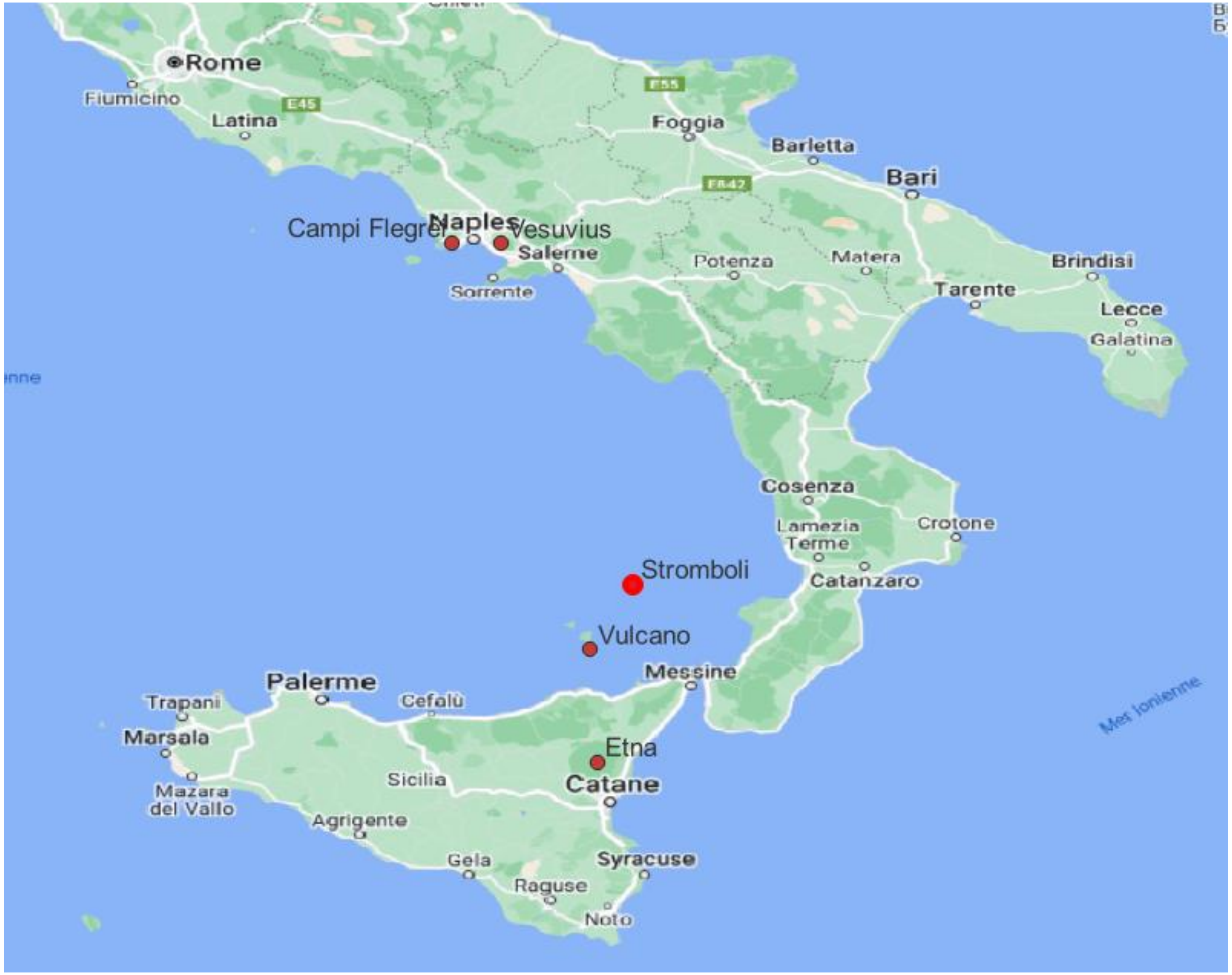
NAME	Stromboli
(Dérivé)	
(Actions)	
NAME	Stromboli
COUNTRY	ITALY
REGION	AEOLIAN ISLANDS
SUBREGION/ISLAND	STROMBOLI
BASIN	MEDITERRANEAN
LONG	15,212
LAT (WGS84)	38,7939
VOLCANO TYPE	A
DISTANCE / COAST (km)	1,6
LAST ERUPTION April 2022 update	2022
	1343
	1879
	1916
	1919
	1930
	1944
	1954
	2002
	2019
	2021
	2022



Next step to be completed soon: adding possible source (e.g. landslide, explosion) of tsunami for each volcano (from table 6).

Chapter 2 – Numerical modeling of volcanic tsunamis

1. General consideration of model applications for volcanic tsunamis

- Complex sources (different fluids, fast processes, phase-shifts) = sophisticated models = high computational cost
- Shorter wave length compared to earthquake-induced tsunamis -> faster attenuation -> local tsunamis
- Short time to forecast -> real-time applications are thus challenging
- How far can we go in the approximation in order to save time?

2. Tsunami generation and initialization modeling: *the most challenging phase*

☐ Instantaneous initialization : tsunami happens rapidly compared to the shallow water wave speed
E.g. underwater explosions, ~~caldera collapse~~ (not realistic)

☐ Finite time initialization : forcing happens over a specified time at the start of the modelling
- Ground deformation : sea floor motion as a forcing term. *E.g. submarine landslide, caldera collapse.*
- Multi-layer models : all fluids are modelled as separated layers + interactions. *E.g. subaerial landslides, pyroclastic flows.*
- Ongoing forcing by a pressure anomaly, such as Lamb waves produced by *large explosions in the atmosphere*.

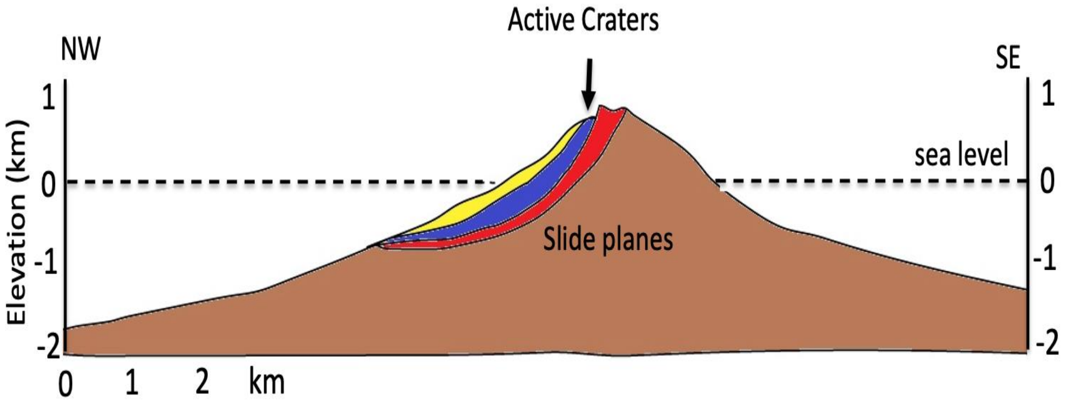
3. Tsunami propagation modeling

Most propagation models are suitable, but dispersive effects are important -> Boussinesq approximation often required.

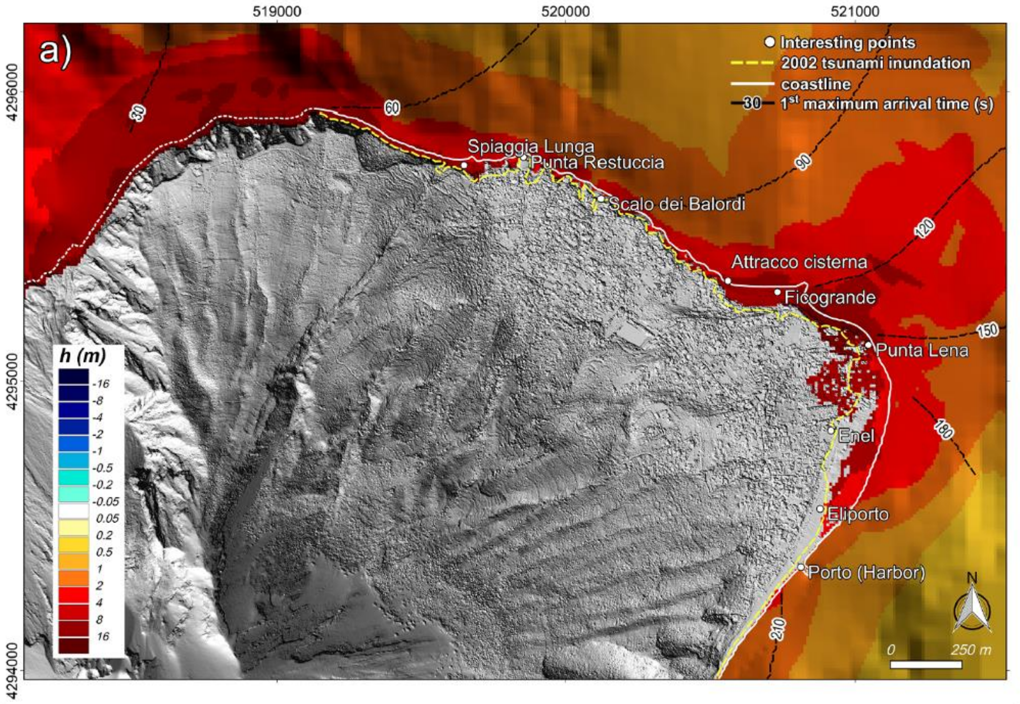
4. Tsunami inundation modeling

Similar to any long wave inundation, but distribution of wave runups is similar to landslide (local) tsunamis (except HTHH-type)

3 Volcanic tsunami hazard assessment

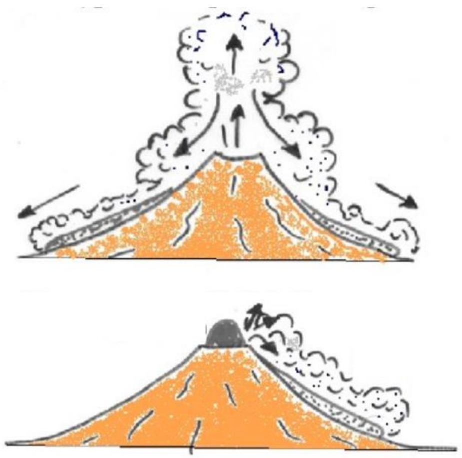


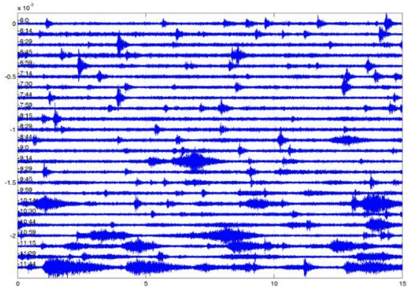
Position of the sliding planes of the 3 main collapses (from Tibaldi, 2001) of Vancori (in red), NeoStromboli (in blue) and Pizzo (in yellow).

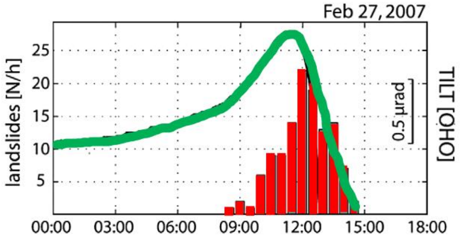


. Observed and simulated tsunami wave heights (December 2002) and runups on Stromboli

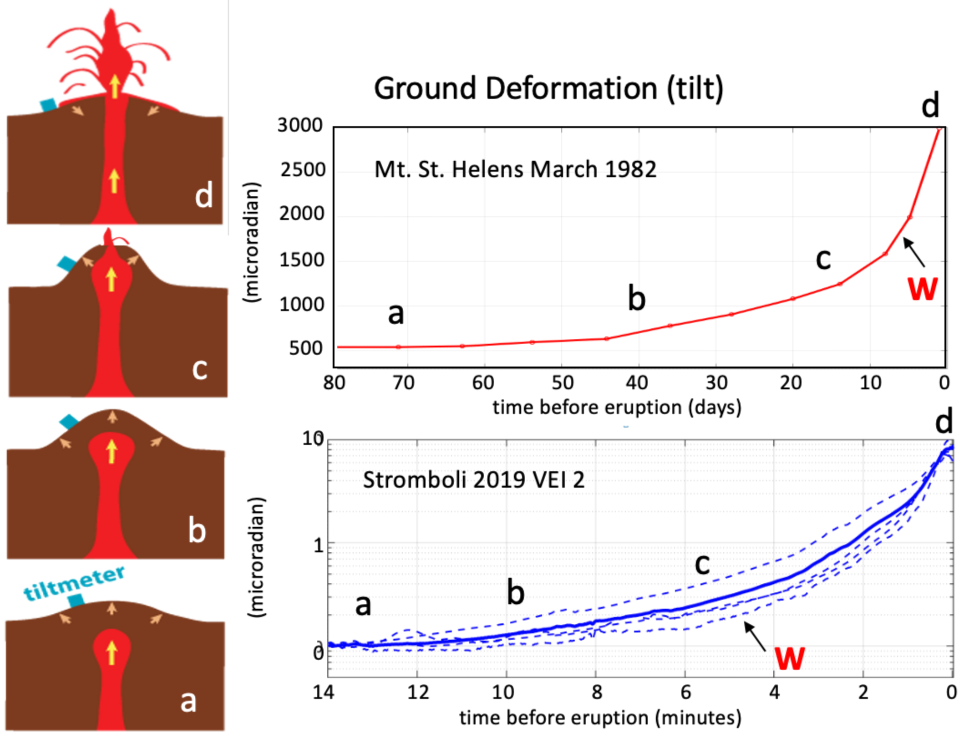
4 Volcano monitoring requirements for tsunami warning





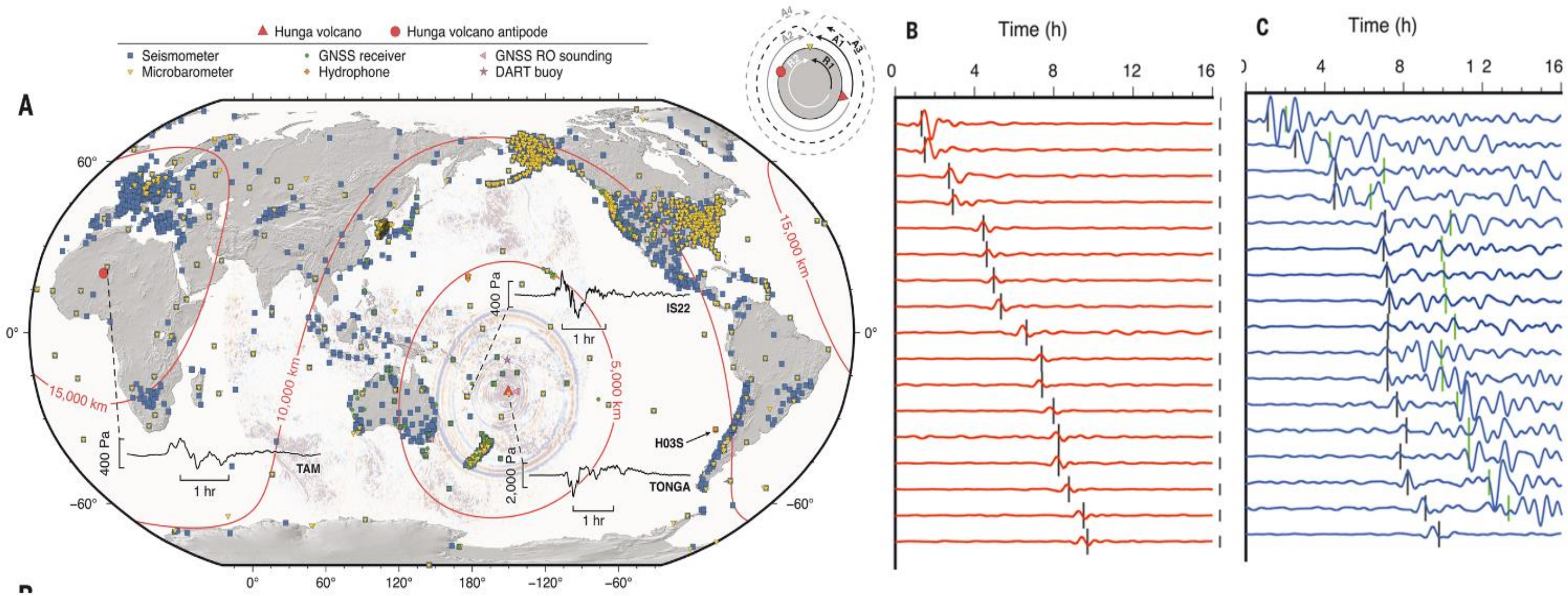


Collapse of the eruptive plume and/or crater rim/dome generates pyroclastic flows and rock avalanches along the steep volcano slope (from Francis, 1993).



Before explosive eruptions, upward magma migration progressively inflates the ground. This inflation can be used to deliver a warning days or minutes before eruption. Inflation at Mt. St. Helens (upper panel) started several days before the 19 March 1982 eruption. At Stromboli (lower panel), ground inflation is smaller but follows a regular pattern which is used to automatically issue alerts 4-5 minutes before violent explosive events (Ripepe et al., 2021).

4 Volcano monitoring requirements for tsunami warning



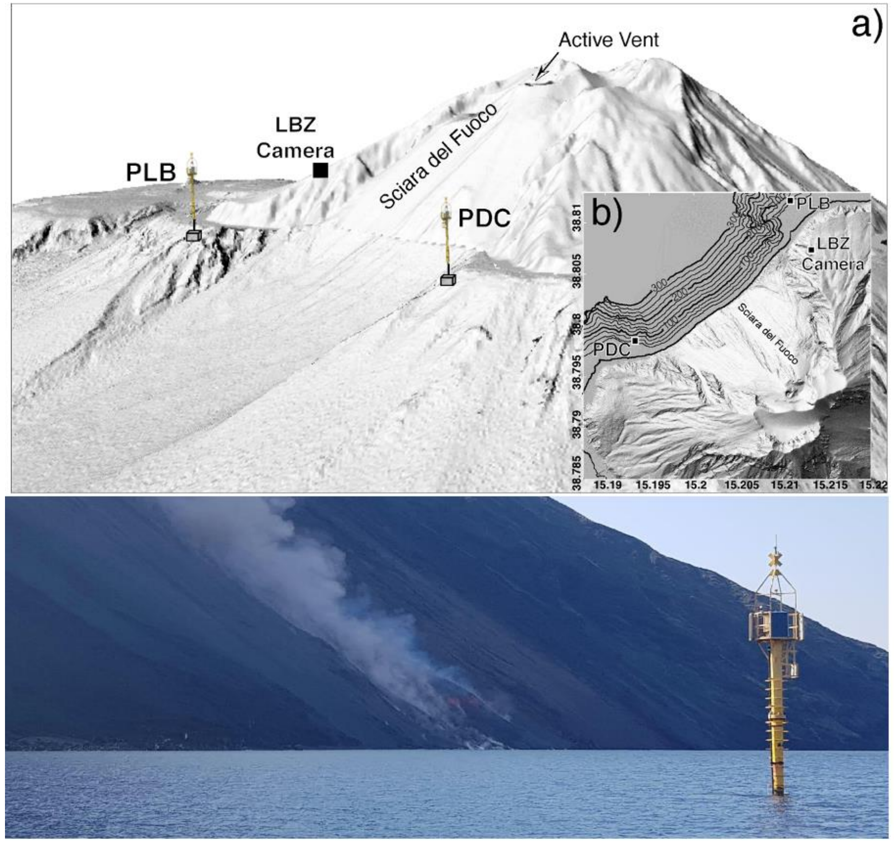
(A) Global distribution of recording geophysical sensors Background image is brightness temperature difference (Himawari-8) at 07:10 UTC on 15 January 2022. Selected 4-hour pressure waveforms are filtered from 10,000 to 100 s. Upper-right inset shows Hunga wave paths around Earth. (B) Observed barograms. (C) Observed ocean bottom pressure gauge waveform (Matoza et al., 2022; Kubota et al., 2022).

4 Volcano monitoring requirements for tsunami warning

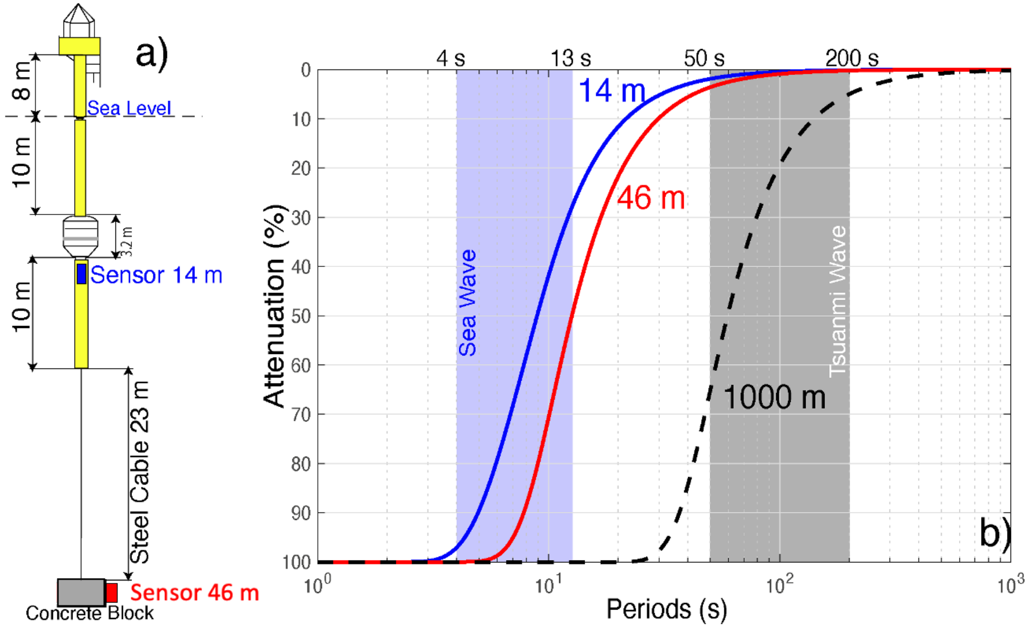
Alert Level	Meaning
GREEN/NORMAL.	Background
YELLOW/ADVISORY	Above Background
ORANGE/WATCH	Escalation of Parameters
RED/ALERT	Eruption imminent/Ongoing

. **Color code representing the Volcano Alert levels (VAL)** used by many Volcano Observatories to issue alerts, which could be integrated in the Tsunami Warning Systems to actuate pre-warning procedures..

5 Volcanic Tsunami warning System : Stromboli (1/3)

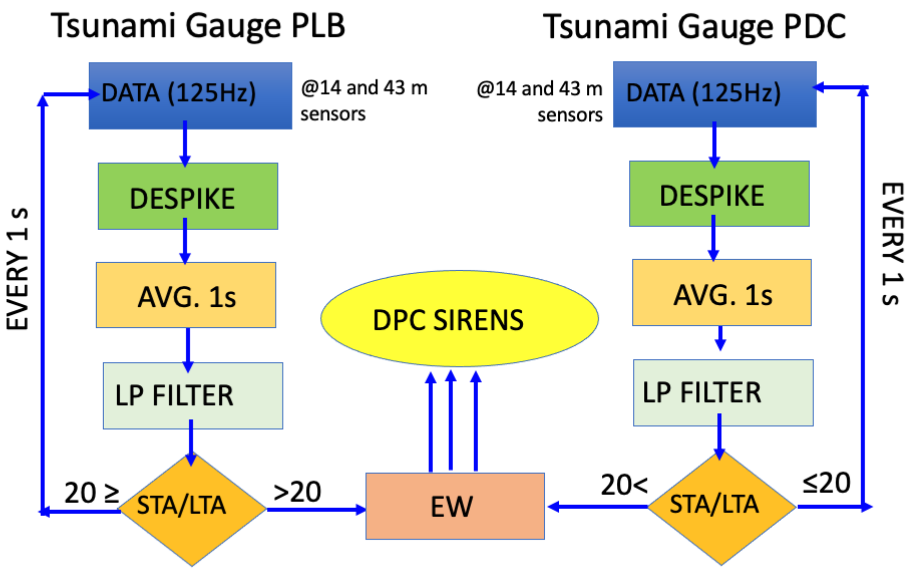


Position of the two elastic beacons (PLB and PDC)



Schematic technical illustration of the main components of the elastic beacon

5 Volcanic Tsunami warning System : Stromboli (2/3)



Tsunami Gauge PLB

Tsunami Gauge PDC

DATA (125Hz)

@14 and 43 m sensors

@14 and 43 m sensors

DATA (125Hz)

DESPIKE

DESPIKE

AVG. 1s

AVG. 1s

DPC SIRENS

LP FILTER

LP FILTER

EVERY 1 s

EVERY 1 s

20 ≥

STA/LTA

>20

EW

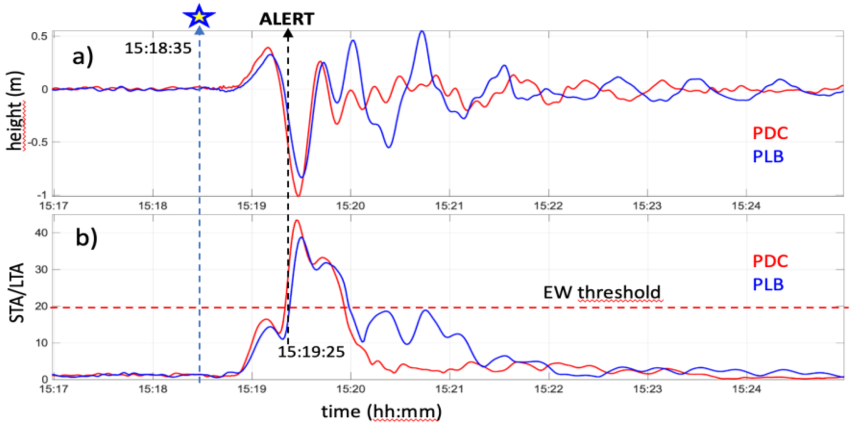
20<

STA/LTA

≤20

Chart flow of the automatic tsunami detection algorithm operating at Stromboli

Sequence of frames taken from the LBZ camera of the December 4, 2022, pyroclastic flow which moving downslope the Sciara del Fuoco



The tsunami generated by the impact of the pyroclastic density current occurred at Stromboli on December 4, 2022

5 Volcanic Tsunami warning System : Stromboli (3/3)

. Tsunami signage at Stromboli indicating a) the limit of the Tsunami Hazard zone, b) the direction of the safer "Escape route" and c) the direction to waiting areas (from Bonilauri et al., 2021).

Volcano Observatory Questionnaire

- **Sent to 25 Volcano Observatories (15 countries); 16 responded:** Australia, France, Greece, Iceland, Indonesia, Italy, Japan, Netherlands, New Zealand, Papua New Guinea, Solomon Islands, Spain, USA (Alaska Volcano Obs), Vanuatu, Trinidad & Tobago. **DNR**: Ecuador, Nicaragua, Philippines, Portugal, Russia, Tonga, USA (Hawaiian Volcano Obs)
- **Asked 14 questions and reference papers:**
  - Volcano: how many, name, tsunami possible?, discussed and addr volcano tsunami hazard?
  - Monitoring: networks, best way to monitor for early tsunami detection?, tsunami-specific monitoring instr?, implement TGV warning system?, any data shared with TWC / TSP, FDSN/IRIS DMC, any historical TGV?
  - Warning: TGV SOPs?, Any contact with a TWC? Procedures with VAAC?, Submarine Volcano monitoring and alerts?

VOQ Summary

- TGV tsunami warnings currently follow a **‘Detect, then Warn’** procedure only. Requires detection and confirmation ofwave, and may be too late to be useful unless there are many sensors between the volcano and coastal communities.
- For significant tsunami, **eruption or flank collapse needs be ‘massive,’ but not yet been quantitatively defin**ed.
- Hazard Assessment (eruption history, numerical modelling of historical events or worst- case scenarios) - **not been conducted for all potential volcanoes**.

VOQ Summary – Monitoring

- Volcano Observatories (VO) monitor seismicity, surface deformation (tilt, movement), and geochemistry as eruption indicators.
- Two types of triggers for tsunami:
  - **VAAC notice of activity.** VO-VAAC information exchange. Does not include tsunami hazard potential, nor confirm tsunami wave generated. Therefore,it is a **pre-alert – tsunami watch** .
  - **Wave detection** at coastal or in-water sensors. Confirms wave was generated, and if large enough results in Tsunami Warning. Instruments: coastal sea level gauges and in-water pressure sensors (Elastic beacon, DART or DART-like)
- **Most VO do not host sea level stations, and thus are not monitoring sea level for tsunamis.**

VOQ Summary – TGV Procedures - IOC

- **PTWS HTHH Interim (March 2022).** PTWC messages triggered by near-by gauge (Nuku’alofa, DART). Forecast scaled by 15 Jan 2022 observations.
- **CARIBE-EWS testing Volcano Observatory Notice for Tsunami Threat (VONUT)** in CARIBEWAVE 2023 (scenario Mt Pelée). Messages by countries and PTWC. Contain Volcanic Activity Summary and closest sea level gauge locations

VOQ Summary – TGV Procedures - National

- Stromboli (2018) – VO Elastic Beacons in ocean, trigger alerts Civil Protection and sounds sirens
- Anak Krakatau (2019) – Indonesia BMKG (NTWC) coastal sea level gauges
- Australia – BOM SOPs use VAAC notifications
- US, Hawaii Island – PTWC uses TIDS deployed on land. ‘Wet sensor’ detects tsunami inundation (from any source)
- Japan - SOPs developed case-by-case basis

VOQ Summary – Warning Arrangements

- Tsunami Warnings usually issued by Tsunami Warning Centres (TWC), which receive real-time sea level data for tsunami monitoring. **Since most Volcano Observatories (VO) do not have 24x7 operations, they cannot be TWCs**.
- To date, **VO mostly have not worked closely with TWCs**. When earthquake, tsunami, volcano monitoring are part of same agency (e.g. New Zealand), TGV SOPs can be coordinated (seamless) to enable efficient warnings. If not, then harder.
- Situation similar for science agencies and universities, who may not be aware of tsunami early warning process and SOPs.
- **Only recently, Stromboli VO been working with Italian NTWC (INGV) for TGV monitoring and warning**

Recommendations and Gaps (1)

1. **All volcanoes** mentioned in the questionnaire **should be monitored and have processes in place to warn for tsunamis**. Should other, potentially tsunamigenic volcanoes become erupting, these should also be monitored and included within the tsunami warning process.
2. **For these TGV**, **multi-stakeholder meetings should be convened that included science agencies, and volcano and tsunami warning operations centres.** For each identified potential source, Worst-case and credible scenario planning discussions should start as soon as possible.
3. **Detect/warn data streams need to be available** to designated tsunami monitoring/warning agency (and possibly also to volcano monitoring agency)

Recommendations and Gaps (2)

4. **Sea level gauges network with real-time continuous data transmission** should be deployed close to each identified volcano. **One second sampling** is recommended for record and automatic detection. Current satellite data transmission intervals of few minutes to 15 minutes used by the global tsunami warning system are inadequate for TGV warnings. Local transmission through radio link, fiber optic, or telephone lines, or other modes should be implemented.
5. **As a first step**, the **national organization for TGV should be designated for monitoring and warning**. The second and third steps are to install **monitoring instrumentation** and develop **SOPs** to handle volcanic tsunamis.

Recommendations and Gaps (3)

6. **TGV warning notification systems** should be considered, and when possible, be **part of a multi-hazard alert system**. Methods to alert persons in remote areas should be considered (such as scientific teams in the field, or recreational hikers)
7. During period of **heightened TGV hazard, consider closing access to vulnerable areas**, and when the eruption is imminent and then tsunami hazard high, **evacuating populations** from specific locations.
8. **Specific TGV signage and evacuation routes** should be implemented in all areas that may be impacted by tsunamis generated by volcanoes.

Recommendations and Gaps (4)

9. **TGV public awareness campaigns** should be conducted regularly – the type of awareness activity or pamphlet/flyer and frequency of the activities may be different for the local population compared to transient populations such as tourists.
10. **TGV monitoring and warning system** should be implemented in relationship **with the NTWC**, where such exist.
11. **TGV SOPs** for tsunami warning should be **linked with the existing Volcano Alert Activity scales**.

Recommendation to IOC

☐ IOC should publish the report in an IOC publication in 2023.

Recommendation by TOWS

☐ Ad hoc TGV team should finalize the report mid 2023