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4.11.2
Tsunami Generated by volcanoes
Report , Establishment of PTWS team

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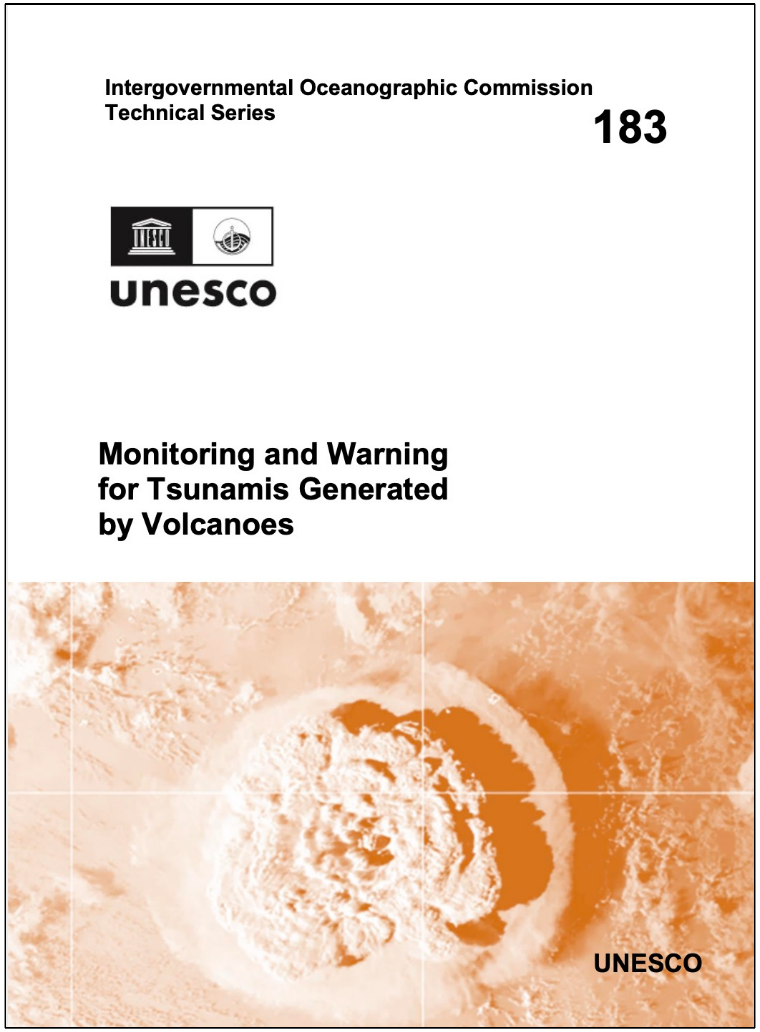

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A Review of Tsunamis Generated by Volcanoes (TGV)

Source Mechanism, Modelling, Monitoring and Warning Systems

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A Review of Tsunamis Generated by Volcanoes (TGV) Source Mechanism, Modelling, Monitoring and Warning Systems

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Abstract—Tsunamis generated by volcanic eruptions have risen to prominence since the December 2018 tsunami generated by the flank collapse of Anak Krakatau during a moderate eruption and then the global tsunami generated by the explosive eruption of the Hunga volcano in the Tongan Archipelago in January 2022. Both events cause fatalities and highlight the lack in tsunami warning systems to detect and warn for tsunamis induced by volcanic mechanisms. Following the Hunga Tonga—Hunga Ha'apai eruption and tsunami, an ad hoc working group on Tsunamis Generated by Volcanoes was formed by the Intergovernmental Oceanographic Commission of UNESCO. Volcanic tsunamis differ from seismic tsunamis in that there are a wide range of source mechanisms that can generate the tsunamis waves and this makes understanding, modelling and monitoring volcanic tsunamis much more difficult than seismic tsunamis. This paper provides a review of both the mechanisms behind volcanic tsunamis and the variety of modelling techniques that can be used to simulate their effects for tsunami hazard assessment and forecasting. It gives an example of a volcanic tsunami risk assessment undertaken for Stromboli, outlines the requirement of volcanic monitoring to warn for tsunami hazard and provides examples of volcanic tsunami warning systems in Italy, the Hawaiian Island (USA), Tonga and Indonesia. The paper finishes by highlighting the need for implementing monitoring and warning systems for volcanic tsunamis for locations with submarine volcanoes or near-shore volcanoes which could potentially generate tsunamis.

Keywords: Volcanic tsunami, tsunami source mechanisms, modelling, hazard assessment, monitoring, warning system.

1. Introduction

Six percent of all tsunamis over the last four centuries have been generated by volcanoes (NCEI database, US NOAA, 2023). Most volcanic tsunamis have their greatest impact in the region near the volcano, and they can cause many casualties. In some rare cases (e.g. Krakatau, 1883; Hunga, 2022), volcanic tsunamis can have global impacts. Recent events such as the Anak Krakatau 2018 and Hunga 2022 tsunamis are a reminder that such volcanic tsunamis can occur at any time. Worldwide there are over a hundred currently active volcanoes, many located under or near water.

The Anak Krakatau tsunami (2018) inundated western Java and southern Sumatra in Indonesia and caused 432 fatalities. While the tsunami generated by the Hunga eruption only caused six fatalities (four in Tonga and two in Peru), it caused measurable waves worldwide. The event also highlighted deficiencies in our tsunami warning systems with regards to tsunamis generated by sources other than earthquakes.

Following the Hunga eruption and tsunami, an ad hoc working group on Tsunamis Generated by Volcanoes (TGV) was formed by the Tsunamis and Other Hazards related to Sea Level Warning and Mitigation Systems Working Group (TOWS-WG) of the Intergovernmental Oceanographic Commisssion (IOC) of UNESCO. This ad hoc group took stock of different volcanic tsunami mechanisms, assessed the simulation methods and codes best used to model these events for hazard assessments and real-time tsunami forecasting studies and undertook a survey of current volcanic tsunami monitoring and warning practices globally.

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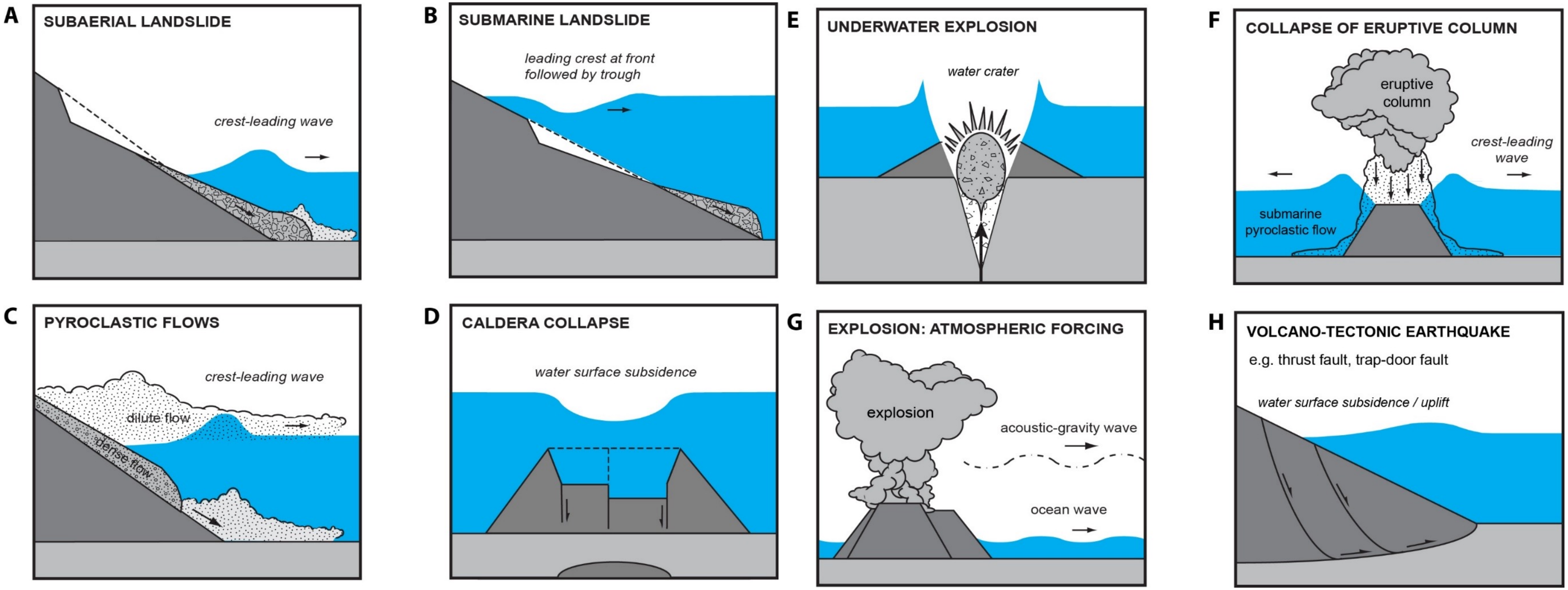
1 – Tsunamis generated by volcano activity and instability

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

-> references on historical and recent case-studies.



modified from Paris et al., 2013

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)

List of 89 potentially tsunamigenic volcanoes (57 in Pacific Ocean)

1. **Volcano was active during the XXth or XXIst centuries.**
2. **Belongs to one of following types of volcanoes:**

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 - Volcano belongs to complex of eruptive centres in partly submerged caldera. Distinction can be made between caldera lakes (e.g. Taal, Philippines), calderas opened to sea (e.g. Rabaul, PNG) and submerged calderas with emerged eruptive centres (e.g. Krakatau, Indonesia).

C - Submarine volcano with shallow-water vents, whose activity and flank instability are clearly potential sources of tsunamis, as in HTHH eruption 2022

D - 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 list, based on suggestions found in questionnaires sent to volcano observatories.**


Snaefellsjokull
Katla
Vestmannnaeyjar
Augustine
Edgecumbe
Kasatochi
Bogoslof
Mono Lake
Sao Jorge
Cumbre Vieja
Campi Flegrei
Etna
Kolumbo
Santorini
Sarychev
Raikoke
Oshima-Oshima
Miyake-jima
Tori-jima
Kikai
Fukutoku-Okanoba
Nishino-jima
Loihi
Kilauea
Cosiguina
Momotombo
Saba
Soufriere
Liamuiga
Kick em Jenny
Barren Island
Taal
Didicas
Ruby
NW-Rota 1
Camiguin
Awu
Ruang
Bam
Rabaul
Anak Krakatau
Fani Maore
Rokatenda
Lewotolo
Savo
Tinakula
Lopevi
Piton de la Fournaise
Yasur
Eastern Gemini
Unnamed
Lateiki - Metis Shoal
Hunga Ha apai
Home Reef
Raoul Island
Taupo
White Island
Okataina

2 – Numerical modeling of volcanic tsunamis

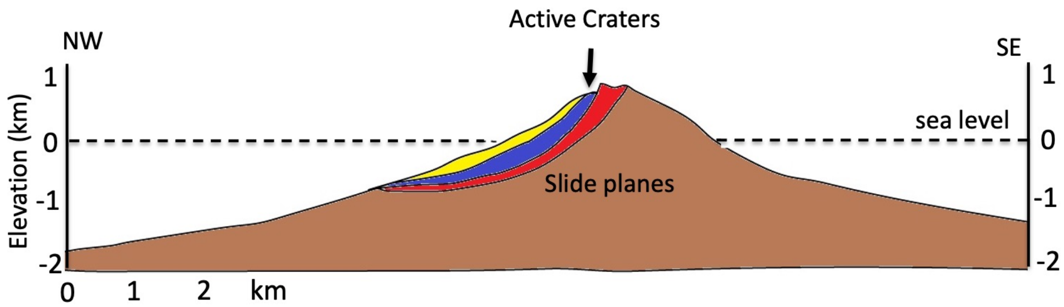
1. General consideration of model applications for volcanic tsunamis
   - Complex sources (different fluids, fast processes, phase-shifts) = sophisticated models = high computational cost
   - Shorter wave length compared to EQ-induced tsunamis -> faster attenuation -> local tsunamis
   - Short time 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 shallow water wave speed, *e.g. underwater explosions, volcano tectonic earthquake*
   - ❑ Finite time initialization : forcing happens over a specified time at start of modelling
     - Ground deformation : sea floor motion as a forcing term. *e.g. submarine landslide, caldera collapse*.
     - Multi-layer models : all fluids modelled as separated layers + interactions. *e.g. subaerial landslides, pyroclastic flows*.
     - Ongoing forcing by pressure anomaly, such as Lamb waves produced by *large explosions in atmosphere*.

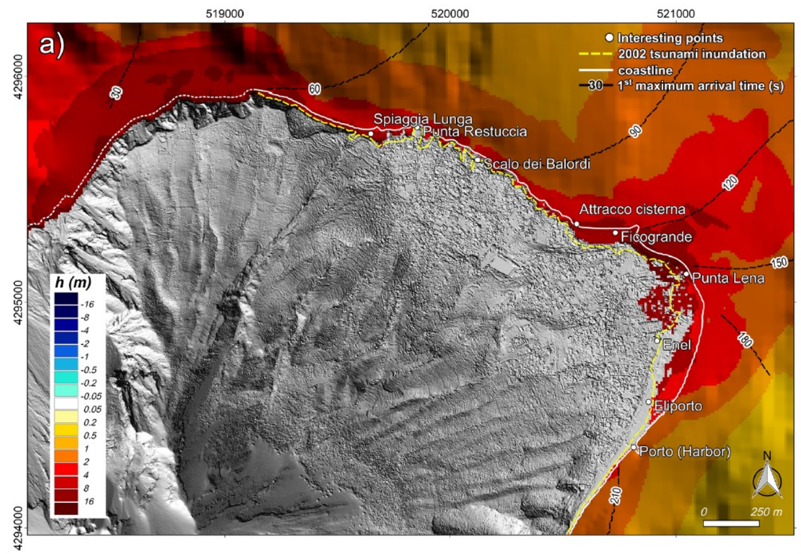
3. Tsunami propagation modeling. Most propagation models are suitable, but dispersive effects are important -> Boussinesq approximation often required.

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 (Stromboli)

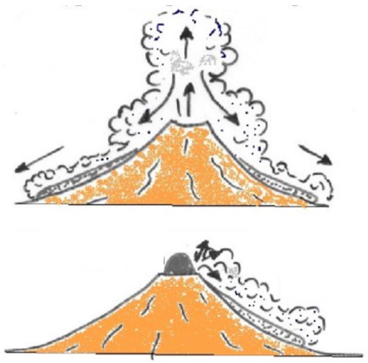


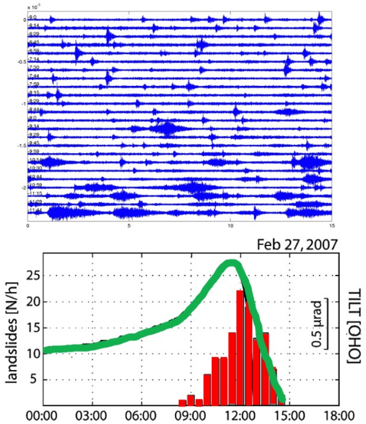
Position of the sliding planes of the 3 main collapses on Stromboli (from Tibaldi , 2001).

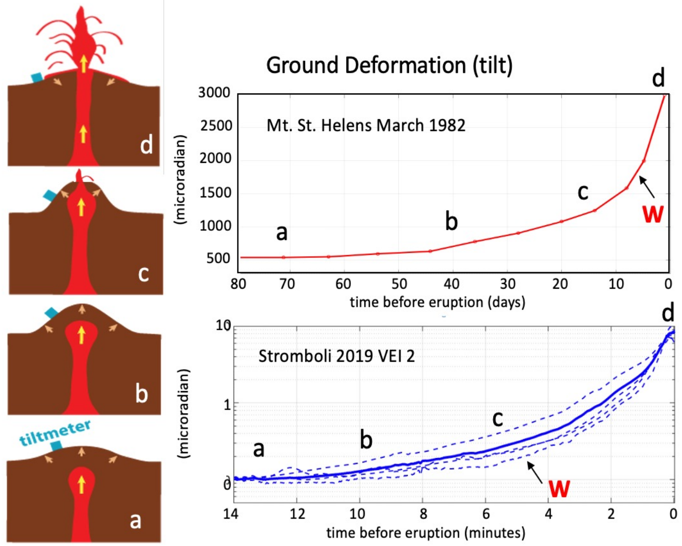


Observed and simulated tsunami wave heights (December 2002) and runups on Stromboli (Fornaciai , 2019).

4 – Volcano monitoring requirements for tsunami warning







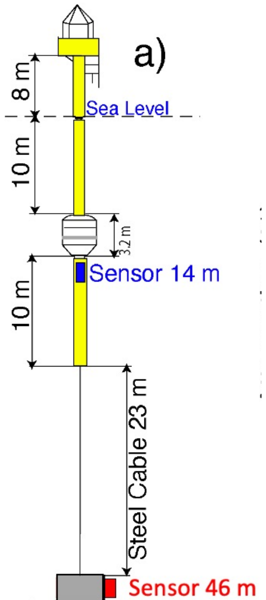
Collapse of the eruptive plume and/or crater rim/dome generates pyroclastic flows and rock avalanches along the steep volcano slope (from Francis, 1993).

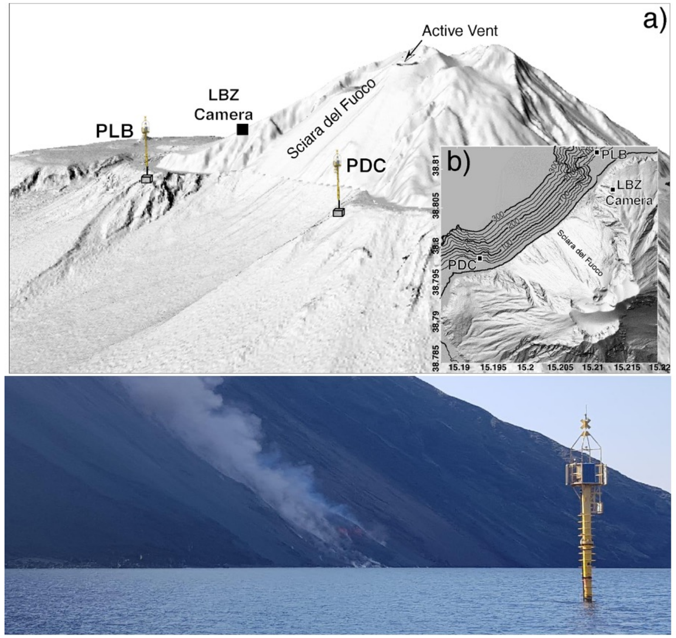
Magma intrusion inflates the volcano edifice (green line in D) which makes the flank unstable, generating rockfalls and pyroclastic flows. Tilt amplitude recorded by the radial component of tiltmeter (green line) and number of rockfalls per hour as recorded by seismic station (from Marchetti et al.,2009).

Before explosive eruptions, upward magma migration progressively inflates the ground. This inflation could 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 and allowed a warning (W) to be given a few days before the explosion (from USGS report).

At Stromboli, ground inflation follows a regular pattern which is used to automatically issue alerts 4-5 minutes before violent explosive events (Ripepe et al., 2021).

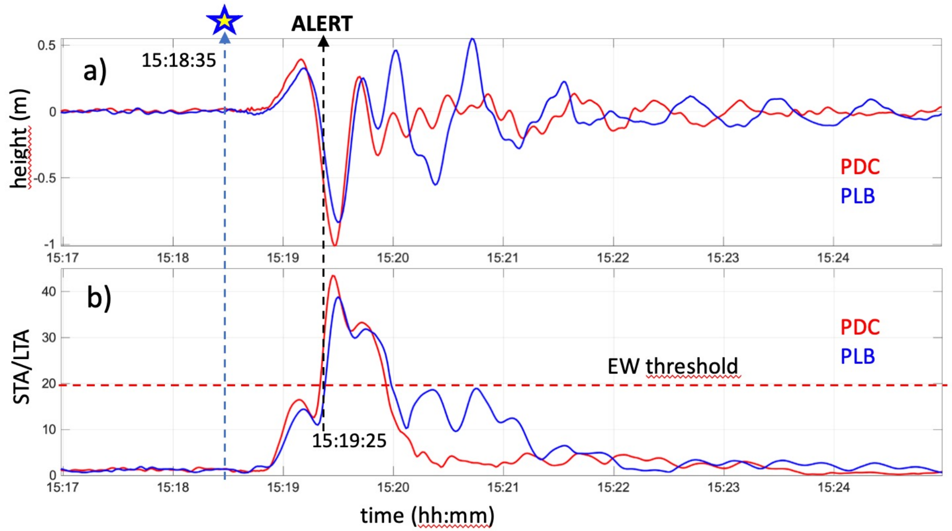
5– Volcanic tsunami warning system (Stromboli)





Schematic technical illustration of the main components of the elastic beacon.

Position of 2 elastic beacons (PLB and PDC)



a) Tsunami record generated by impact of pyroclastic density current occurred at Stromboli on December 4, 2022 and recorded at two elastic beacons (PDC and PLB).

b) The STA/LTA ratio increased above the fixed warning threshold.

5– Volcanic tsunami warning system (Stromboli)

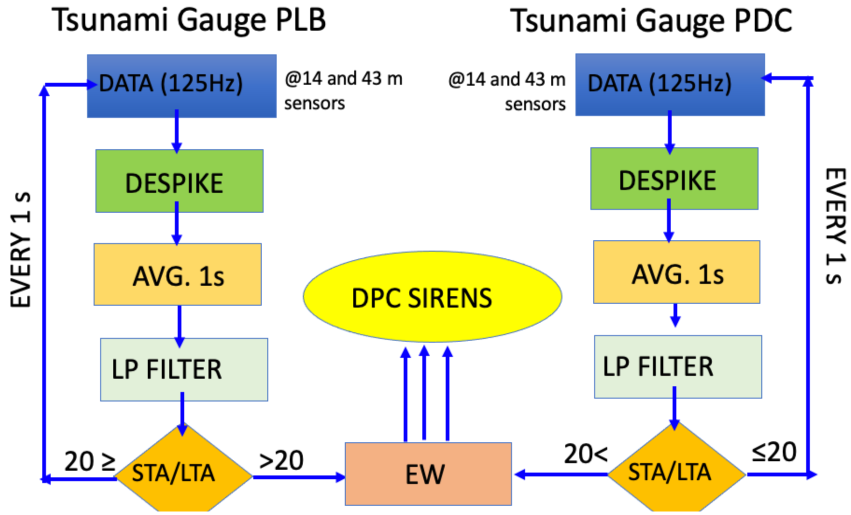


Chart flow of automatic tsunami detection algorithm operating at Stromboli

Sequence of frames of the December 4, 2022, pyroclastic flow which moving downslope generated a small tsunami visible in lower right corner frame.

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

6– Volcanic 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?**

6– Volcanic observatory questionnaire (Summary)

Intergovernmental Oceanographic Commission

- **TGV tsunami warnings currently follow a 'Detect, then Warn' procedure only.** Requires detection and confirmation, 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 defined.**
- **Hazard Assessment (eruption history, numerical modelling of historical events or worst- case scenarios) - not been conducted for all potential volcanoes.**

6– Volcanic observatory questionnaire (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.

6– Volcanic observatory questionnaire - 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

6– Volcanic observatory questionnaire - TGV Procedures - National

- Stromboli (2018-2019) – **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 in development case-by-case basis

6– Volcanic observatory questionnaire - Warning Arrangements

Intergovernmental Oceanographic

- 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 very recently, Stromboli VO been working with Italian NTWC (INGV) for TGV monitoring and warning**

7– Recommendations (1/3)

Monitoring and Warning:

1. As a first step, **organisation(s) should be designated for monitoring and warning of Tsunamis Generated by Volcanoes (TGV). The second and third steps are to install monitoring instrumentation and develop Standard Operating Procedures (SOPs) to handle volcanic tsunamis.**

2. **TGV monitoring and warning system should be implemented by, or in cooperation with the National Tsunami Warning Centre (NTWC) and regional Tsunami Service Provider and national and regional Volcano Service Providers**, where such exist.

3. **All volcanoes mentioned in the TGV report should be monitored and have processes in place to warn for tsunamis**. Should other, potentially tsunamigenic volcanoes begin erupting, these should also be monitored and included within the tsunami warning process.

4. **Detect/warn geophysical (seismology, GNSS, tiltmeter, barometric and sea level data streams need to be available to the designated tsunami monitoring/warning agency (and possibly also to the volcano monitoring agency)**

7– Recommendations (2/3)

Intergovernmental Oceanographic Commission

Monitoring and Warning:

5. As well as monitoring systems for volcano activity and potential far-field propagation of sea level signal, a **sea level gauges network with real-time continuous data transmission should be deployed close to each identified volcano to verify risk and then ongoing monitoring and warning.** One second sampling with 1cm accuracy (< 1 mm sampling) is recommended sampling is recommended for recording and automatic detection. Data transmission through radio or microwave links, fiber optic, or dedicated telephone lines, or other modes should be implemented to ensure the data is transmitted and received and widely shared with international community in timely manner.

6. Methods to also specifically alert persons in remote areas (such as scientific teams in the field, or recreational hikers) should be considered.

7. TGV SOPs for tsunami warning should be linked with existing Volcano Alert Activity scales.

7– Recommendation (3/3)

Risk Assessment and Preparedness:

8. A TGV hazard and risk assessment should be undertaken **to determine vulnerable areas.**

9. For TGV, multi-stakeholder meetings should be convened that included science agencies, volcano and tsunami warning operations centres, and disaster management agencies. For each identified potential source, worst-case and credible scenario planning discussions should start as soon as possible.

10. During a period of heightened TGV hazard, consider **closing access to vulnerable areas**. When eruption is imminent and then tsunami hazard is high, consider **evacuating populations from vulnerable locations**.

11. Specific TGV signage and evacuation routes should be implemented in all areas that may be impacted by tsunamis generated by volcanoes.

12. TGV public awareness campaigns should be conducted regularly – the type and frequency of awareness activities may be different for the local population compared to transient populations such as tourists.

8– Establishment PTWS TGV Task team ToR

1. Confirm the list of potential threat volcanoes identified by the TGV in the Pacific (referred in annex 4 Technical Series 183)

2. For those volcano, identify what is currently implemented as tsunami hazard assessment, monitoring and warnings systems

3. Develop guidelines on SOPs to monitor, detect and warn for any the induced tsunami waves

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