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ENGINEERING

Volcanic tsunamis: From generation mechanisms to inundation

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20 November 2023

Outline

- “Volcanoes can make waves too”
- Eruptions in the laboratory
- Pyroclastic density current tsunami generation
- Modelling from source to shore
- Lake Taupō
- Hunga Tonga-Hunga Ha’apai
- Tsunami inundation and infrastructure
- Outlook

Bisnis, 2018

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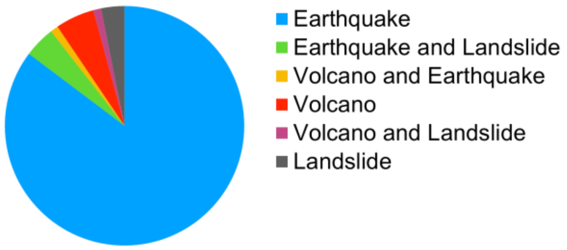
Volcanic tsunamis



(NGDC/NOAA, 2013)

- Impulsively generated water wave
- Properties determined by generation mechanism
    - Earthquake
    - Submarine or subaerial landslide
    - **Volcanic eruption**
    - Meteorite
- Dispersive waves, near-source hazards
- Expanding the destructive radius: Responsible for ~5% of tsunamis, but 20-25% of fatalities from volcanic activity
- Hazard assessments and warning systems previously skewed towards seismic sources

https://greece.greekreporter.com/files/santorini-volcano.jpg

Domcar C Lagto/PACIFIC P/SIPA/Shutterstock

Maritime Safety Agency - Japanese book "The Fifty Years of Postwar Japan"

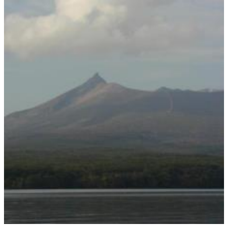
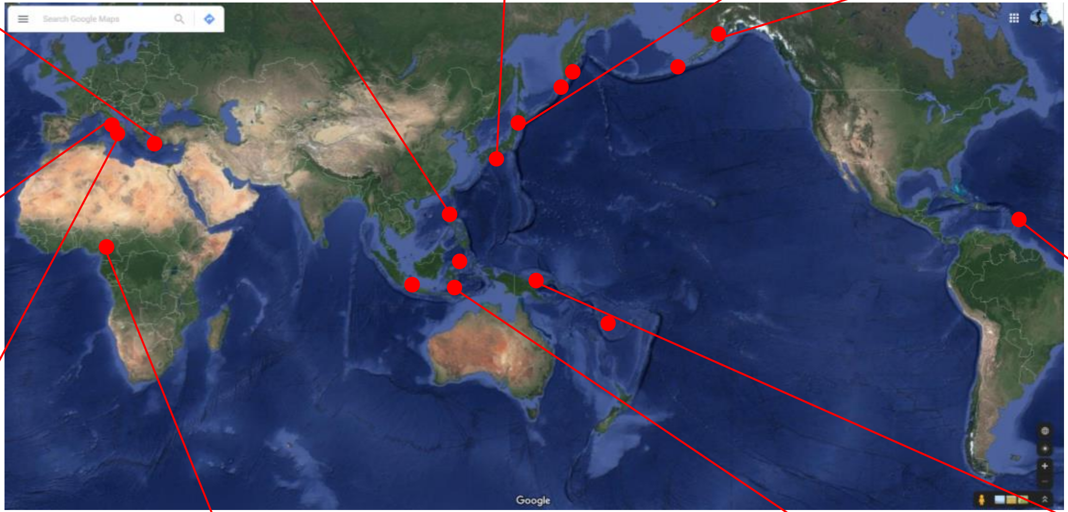
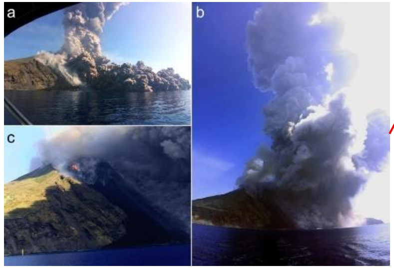


Photo Courtesy: Jani Patokallio

https://www.usgs.gov/atom/15347



BBC



https://volcano.si.edu/images/bulletin/211040/211040_BGVN_150.jpg

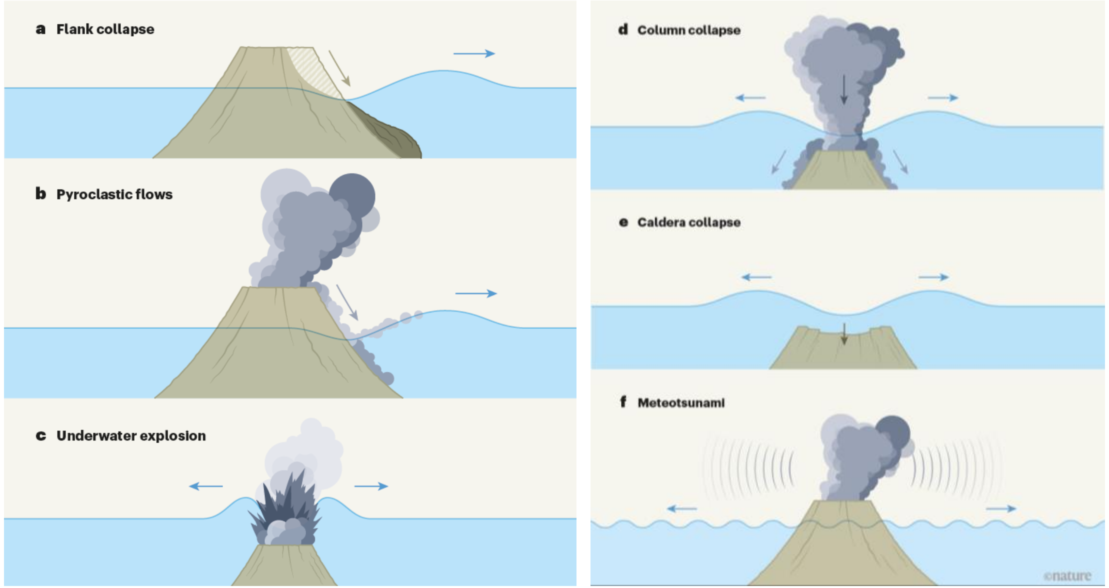
United States Geological Survey

British Geological Survey,

Photo Courtesy: www.deyave.com

Photo Courtesy: NASA

Source mechanisms



Lane, E. M. (2022). Atmospheric waves reinforced tsunami after Tongan eruption.
https://www.nature.com/articles/d41586-022-01855-0

British Geological Survey, https://www.bgs.ac.uk/discovering Geology/hazards/volcanoes/montserrat/home.html

Greek Reporter, https://greekreporter.com/2015/05/03/santorini-volcano-returns-to-dormant-state/

Global Volcanism Programme, Ryohei Morimoto, 1952.

Planet Labs PBC/EYEPRESS/Shutterstock

Library of Congress, https://allthatsinteresting.com/krakatoa-eruption

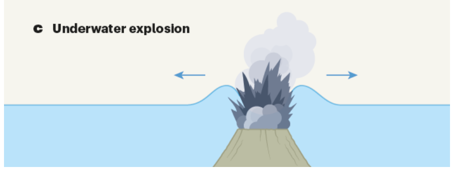
We make waves

- **Volcanoes make waves too: a new understanding of tsunamis generated by volcanic eruptions.**
- Marsden Grant from the Royal Society of New Zealand, 2018-2022
- Led by Dr Emily Lane (NIWA) and Dr William Power (GNS)
- Investigating volcanic tsunami generation using physical experiments and numerical modelling
- “Start simple and build up complexity”
- Fundamental knowledge underpinning future hazard assessment

The New Zealand contingent of the “We make waves” team.

From left to right: Yaxiong Shen (PhD student), Dr Colin Whittaker (University of Auckland), Dr Emily Lane (NIWA), Lily Battershill (PhD student), Dr William Power (GNS), Natalia Lipiejko (PhD student), James White (University of Otago), and Matty Hayward (PhD student).

International team members: Paraskevi Nomikou (University of Athens), Stéphane Popinet (Université Pierre et Marie Curie)



Eruptions in the laboratory

- Complex volcanic eruptions idealised as explosions, jets or sudden uplifts
- Eruptive activities driven by expansion of magmatic gases, strongly directional
- Idealised submerged jet experiments in the University of Auckland Fluid Mechanics Laboratory
- Varied source strength and water depth
- Compressed air and steam sources, varying ambient water temperature to investigate condensation effects
- Small tank experiments to investigate fountains on free surface, larger tank experiments for generated waves
- Fountain regimes: Undisturbed, domes to fingers

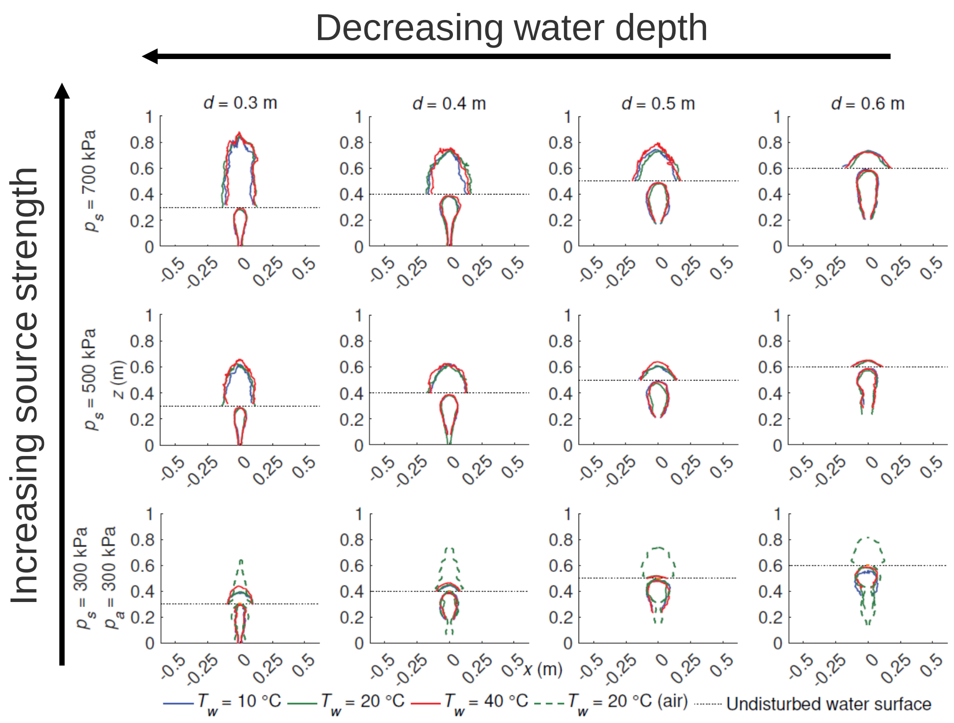
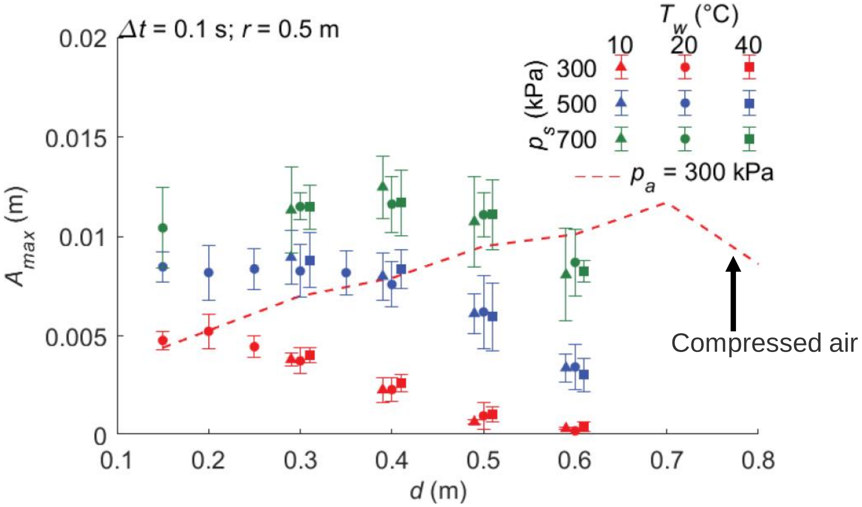


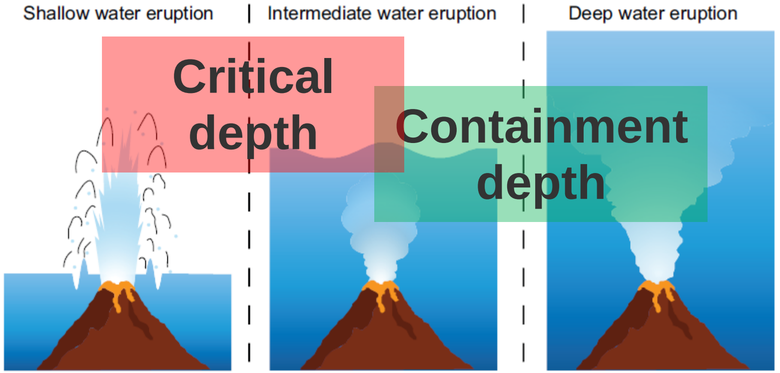
Figure from Shen et al. (N.D.) “Physical experiments of waves generated by submerged steam eruptions with applications to volcanic tsunamis”. Currently under review

Generated waves

- Radiating waves generated by the collapse of the fountain back onto the free surface
- Cavity collapse mechanism from large explosive event neglected in these tests
- Steam jet generated evanescent waves in shallow water
- Amplitudes first increase then decrease with increasing water depth (constant pressure)
- Negligible waves generated for weakest source, deepest depth
- Amplitudes increase with the source strength (jet pressure)
- Condensation effects minimal in these tests
- Amplitudes initially increase then remain approximately constant with jet duration

Saturation duration

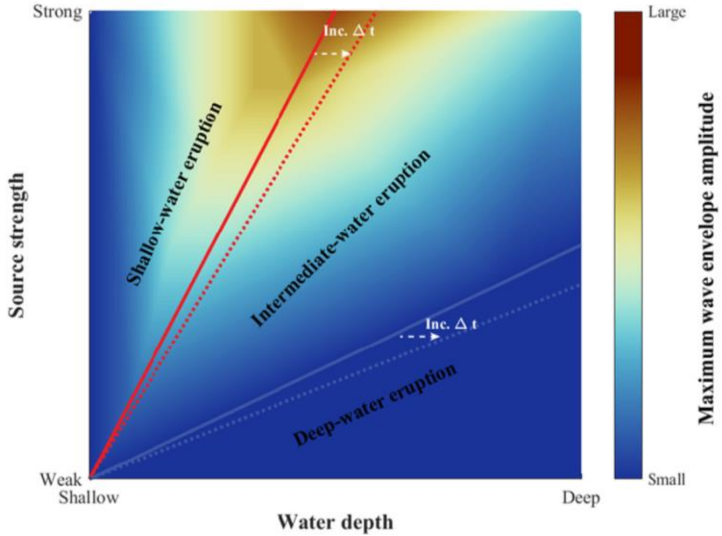




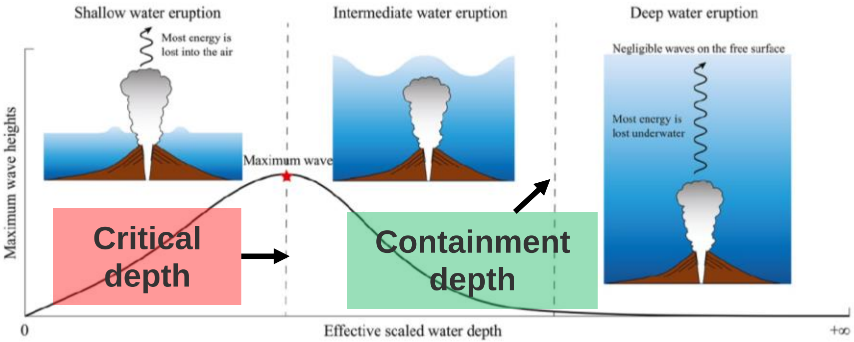
Figures from Shen et al. (N.D.) “Physical experiments of waves generated by submerged steam eruptions with applications to volcanic tsunamis”. Currently under review

Wave regimes

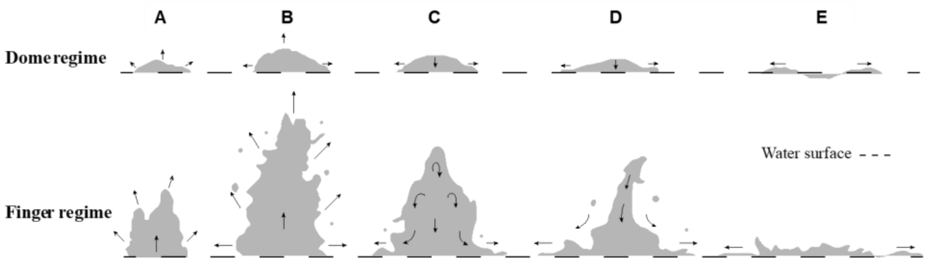
- Critical depth and containment depth both increase with source strength (jet pressure)
- Critical depth also increases slightly with jet duration
- Implications for hazard assessment:
  - Largest waves generated in critical depth conditions ("Goldilocks" zone)
  - Containment depth (anecdotally 500 m) will depend on strength of volcanic source



Shen, Y., Whittaker, C. N., Lane, E. M., White, J. D., Power, W., & Melville, B. W. (2021). Waves generated by discrete and sustained gas eruptions with implications for submarine volcanic tsunamis. Geophysical Research Letters, 48(21), e2021GL094539.

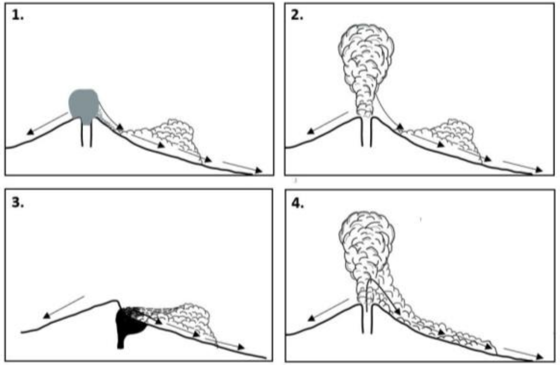


Shen, Y., Whittaker, C. N., Lane, E. M., White, J. D., Power, W., & Nomikou, P. (2021). Laboratory experiments on tsunamigenic discrete subaqueous volcanic eruptions. Part 2: Properties of generated waves. Journal of Geophysical Research: Oceans, 126(5), e2020JC016587.

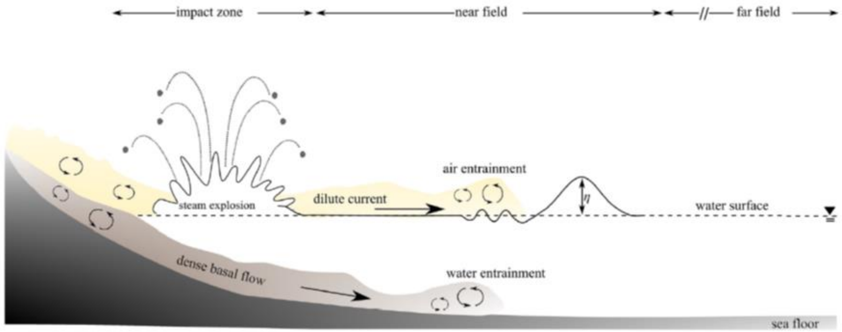


PDC tsunami generation

- **Pyroclastic density currents (PDCs):** Highly mobile, denser-than-air mixtures of volcanic particles, heated air and volcanic gases generated during volcanic eruptions
- Entry into water can generate tsunamis by **impulsive displacement of water by the basal particle-rich flow**, dilute ash cloud (cloud pressure and associated shearing), steam explosions, and pressure impulse
- Dilute current travels along water surface
- Underwater PDC may interact with generated waves and may propagate long distances with the potential to damage underwater infrastructure



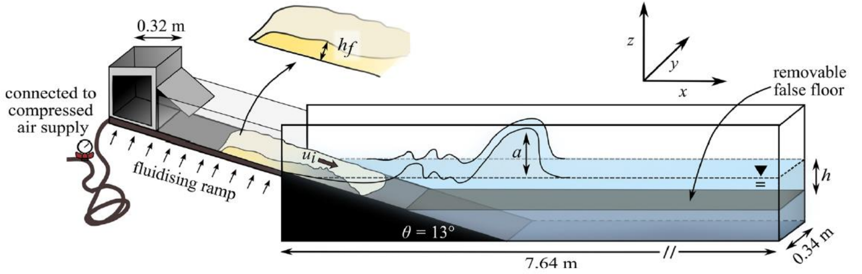
Battershill, L. (2022). Numerical modelling of tsunamis generated by pyroclastic density currents (Doctoral dissertation, ResearchSpace@ Auckland).

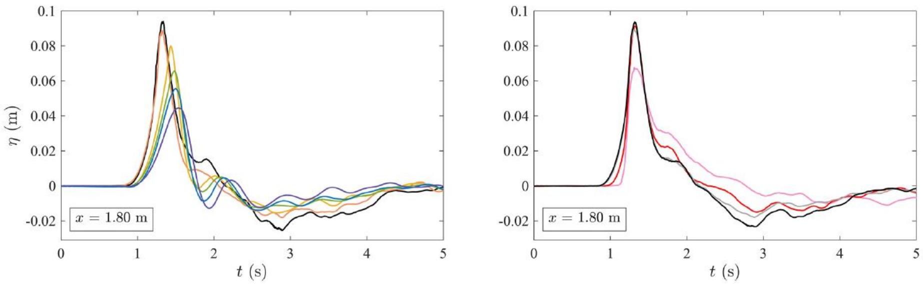


Lipiejko, N., Whittaker, C. N., Lane, E. M., White, J. D., & Power, W. L. (2022). Experimental Modeling of Tsunamis Generated by Pyroclastic Density Currents: The Effects of Particle Size Distribution on Wave Generation. Journal of Geophysical Research: Solid Earth, 127(11), e2022JB024847.

PDC experiments

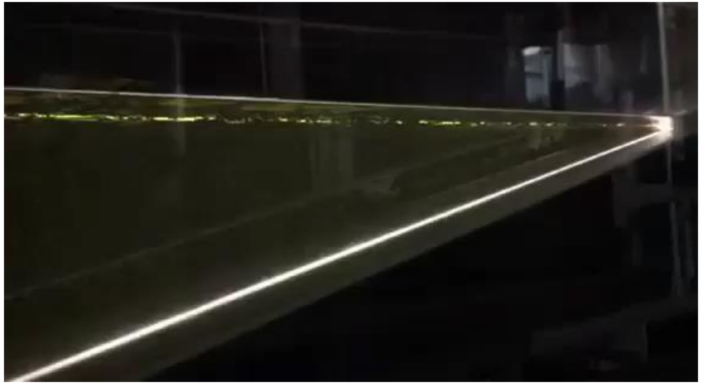
- Physical experiments to investigate wave generation by fluidised flows representing the dense portion of a PDC
- Small glass beads and real volcanic material were fluidised using air flow through a porous plate
- Temperature effects neglected
- Maximum wave amplitude increased with PDC mass
- Not all volcanic material entered the water, gravity current much slower
- Dimensional wave amplitude almost independent of water depth, apart from the shallowest depths
- Further experiments and simulations planned to investigate depth and slope angle dependence, reconsidering the role of the Froude number in wave generation





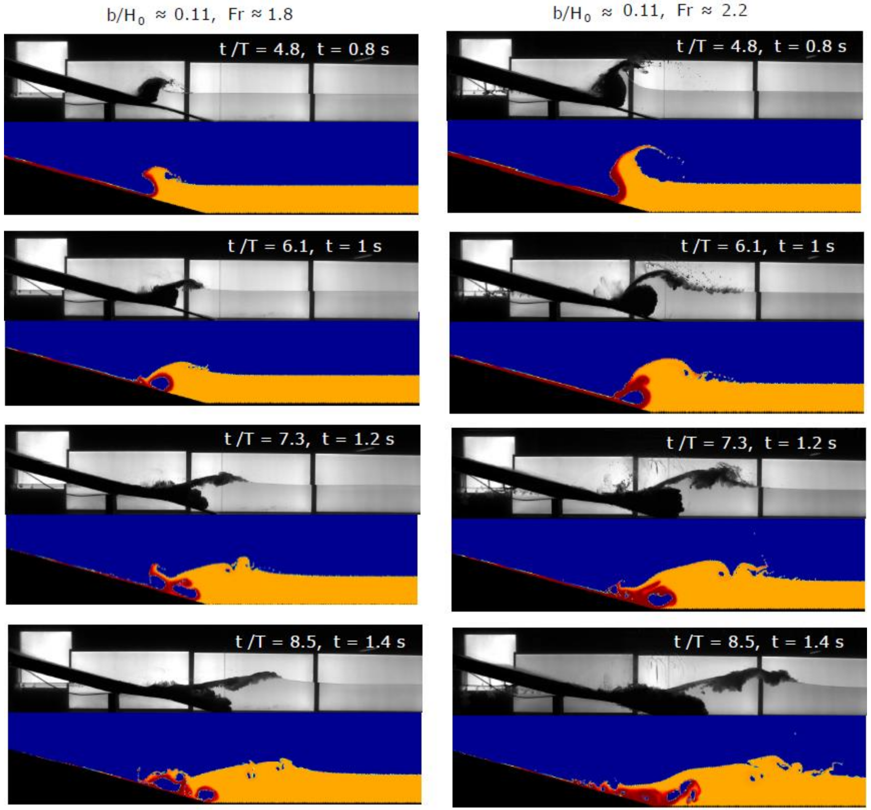
Lipiejko, N., Whittaker, C. N., Lane, E. M., & Power, W. L. (2023). Wave Generation by Fluidized Granular Flows: Experimental Insights Into the Maximum Near-Field Wave Amplitude. *Journal of Geophysical Research: Oceans*, *128*(6), e2022JC019583.

$$Fr = \frac{u}{\sqrt{gh}}$$



PDC simulations

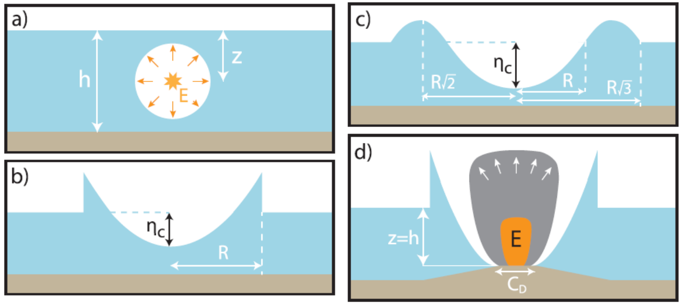
- Simulating the dense part of a PDC as the flow of a Newtonian fluid, again neglecting temperature effects
- Two-dimensional Navier-Stokes simulations using the Basilisk Solver (developed by Stéphane Popinet)
- Comparison with experimental results of Bougouin, Paris, and Roche (2020)
  - Red = PDC
  - Yellow = Ambient fluid
  - Blue = Air
  - Monochrome images from experiments
- Excellent agreement, model subsequently applied to broader parameter space
- Results very sensitive to boundary condition on slope (partial slip best)



Battershill, L., Whittaker, C. N., Lane, E. M., Popinet, S., White, J. D., Power, W. L., & Nomikou, P. (2021). Numerical simulations of a fluidized granular flow entry into water: insights into modeling tsunami generation by pyroclastic density currents. *Journal of Geophysical Research: Solid Earth*, *126*(11), e2021JB022855.

Source to shore

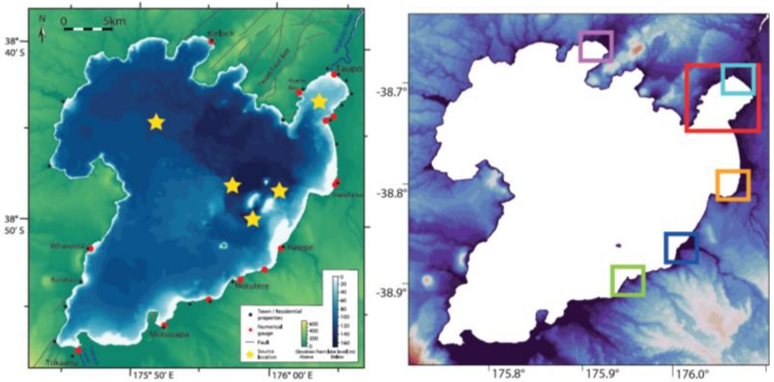
- Simulations using an efficient multi-layer non-hydrostatic solver for volcanic tsunami wave propagation and inundation
- Validated against flume experiments of Prins (1958) and Barranco and Liu (2021) and field-scale underwater explosions undertaken at Mono Lake in 1965
- Model applied to Lake Taupō in a scenario-based assessment using multiple source locations and magnitudes

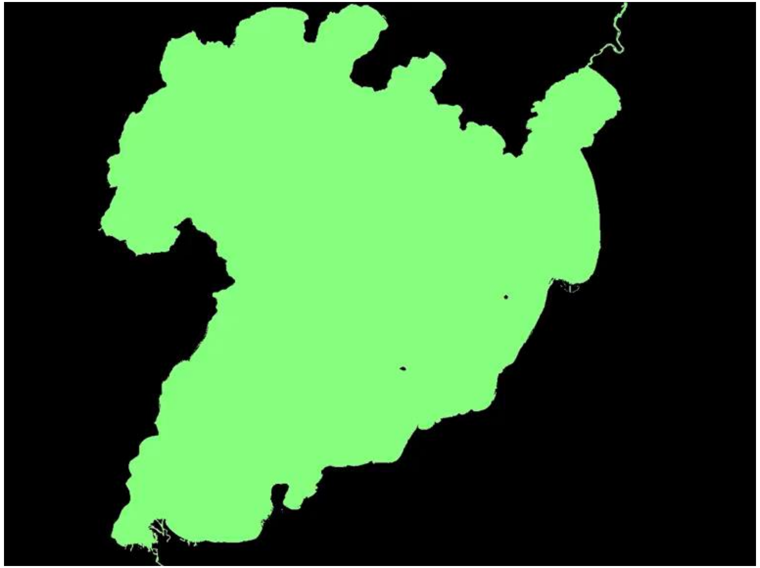


$$\eta_c = aE^{\frac{6}{25}}$$

$$R = bE^{\frac{3}{10}}$$

Hayward, M. W., Whittaker, C. N., Lane, E. M., Power, W. L., Popinet, S., & White, J. D. (2022). Multilayer modelling of waves generated by explosive subaqueous volcanism. Natural Hazards and Earth System Sciences, 22(2), 617-637.

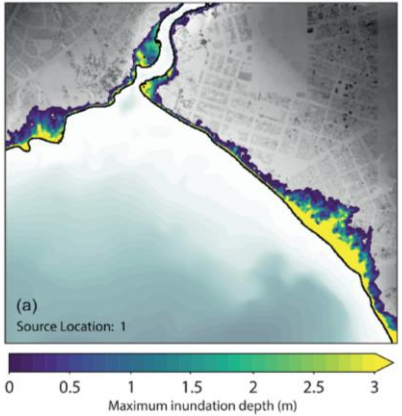


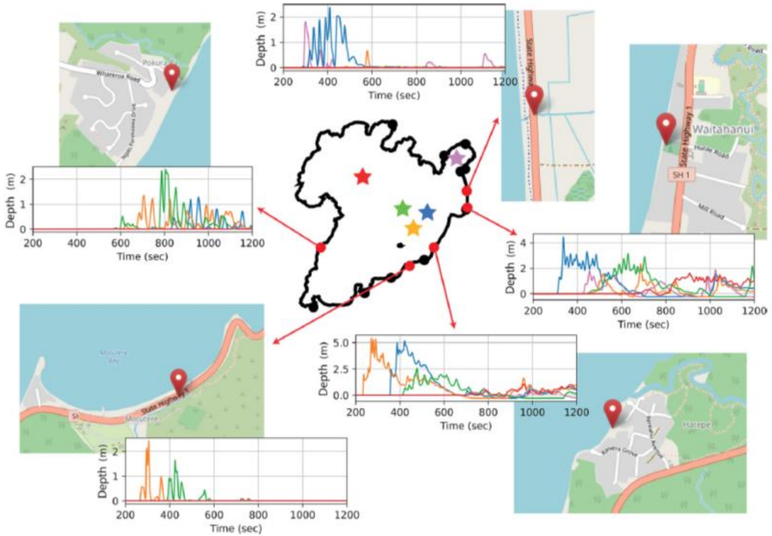


Hayward, M. W., Lane, E. M., Whittaker, C. N., Leonard, G. S., & Power, W. L. (2023). Scenario-based modelling of waves generated by sublacustrine explosive eruptions at Lake Taupō, New Zealand. Natural Hazards and Earth System Sciences, 23(2), 955-971.

Lake Taupō

- Simulations used dynamic adaptive refinement with a maximum horizontal grid resolution of 8 m
- Simulated time of 1400 s, average computation time 18.7 h (0.5 h to 53.3 h)
- Nearshore wave heights exhibited a strong dependence on source size and location
- Waves were highly dispersive and propagated throughout the entire lake within 15 minutes
- Results provide inundation extents and maximum depths within Taupō township and at critical points in the road network
- Some increased discharge down Waikato River, but not hazardous to hydro-electric power schemes





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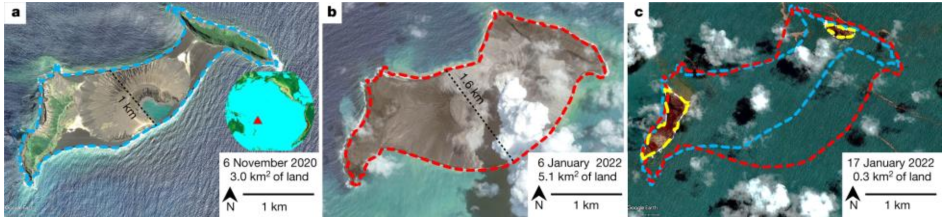
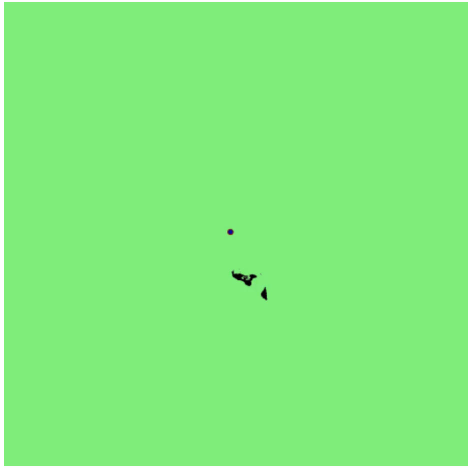
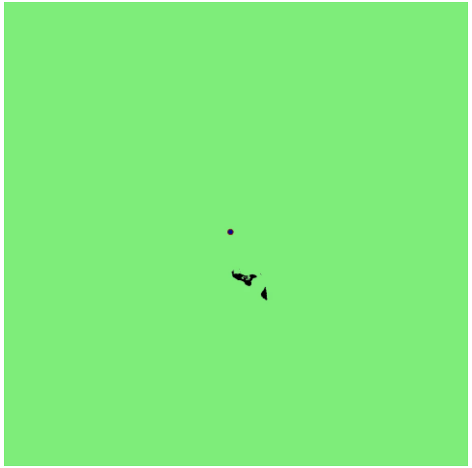
Hunga Tonga-Hunga Ha'apai

- First volcanic tsunami with global reach since Krakatau in 1883, thankfully with significantly lower loss of life
- Multiple source mechanisms, with atmospheric pressure wave responsible for meteotsunami in the far field (Lynett et al., 2022)
- Local source simulations to date have tended to focus only on explosive wave generation (e.g. Purkis et al., 2023, Pakoksung et al., 2022)
- Basilisk simulations demonstrate importance of dispersion in near-field
- PDCs observed at source, also evidence from ruptured communications cables
- Need for model initialisations that capture complex multiple sources



Lynett, P., McCann, M., Zhou, Z. et al. Diverse tsunamigenesis triggered by the Hunga Tonga-Hunga Ha'apai eruption. Nature 609, 728–733 (2022)





Outlook

- Combining physical experiments and numerical simulations provides insights and informs hazard and risk assessment
- Need for improved volcanic tsunami source characterisations for model initialisation
- Multiple source mechanisms remain challenging and more efforts are needed in this area
- Most volcanic tsunamis will be local hazards with limited warning time
- Community education and engagement will be crucial to improve readiness

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