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2021 United Nations Decade
2030 of Ocean Science
for Sustainable Development

**UNESCO Intergovernmental Oceanographic Commission
(UNESCO-IOC)**

**NEAM Regional Online Webinars on Tsunamis Generated by
Non-Seismic Sources**

27 November 2025



Moderator

- **Dr Denis Chang Seng**
- Programme Specialist and Technical Secretary(ICG/NEAMTWS) UNESCO-IOC

Panelist

- **Mr Bernardo Aliaga** is Head of Tsunami Resilience Section, UNESCO-IOC.



Panelist

- **Dr Roger Urgeles** is a senior scientist at the Department of Marine Geosciences of the Institute of Marine Sciences (Spanish Research Council) based in Barcelona, Spain



Frequency, magnitude and mobility of submarine landslides in the NEAM region: towards probabilistic tsunami hazard assessment



United Nations
Educational, Scientific and
Cultural Organization



Intergovernmental
Oceanographic
Commission

Roger Urgeles

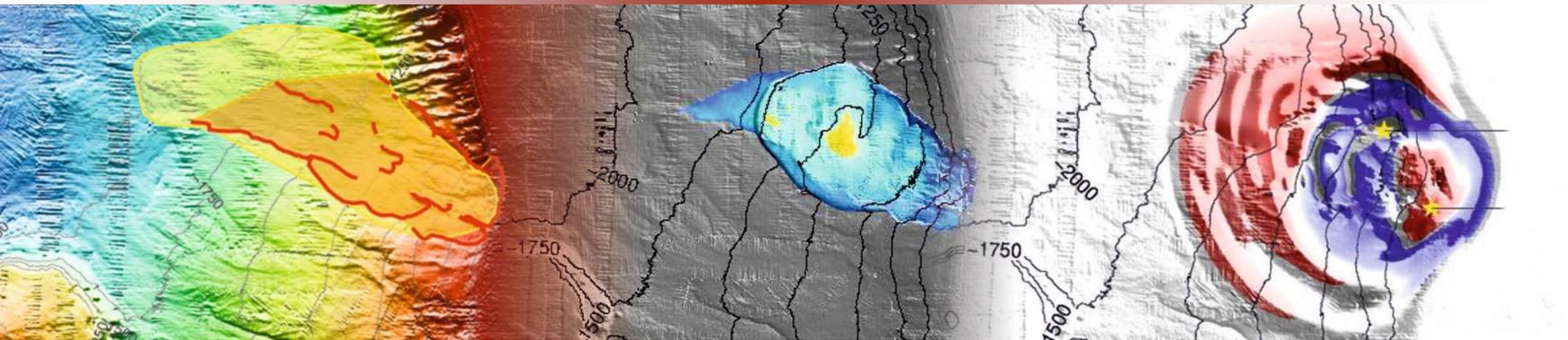


CSIC

CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS



Institut
de Ciències
del Mar



With contributions from: Finn Løvholt

and developers of the EMSS25 (Davide Gamboa, Carla Vila, Ricardo León, Sjur Beyer, Maarten Vanneste, Carl Frederich Forsberg, Angelo Camerlenghi, Denise C. Ruther, Rachid Omira, Laura Fantoni Nils W. Brückner, Yolanda De Pro)



Introduction

- ✓ Earthquake tsunami
 - ✓ Frequent events
 - ✓ Occur along well defined zones (faults)
 - ✓ Well established PTHA methods
- ✓ Submarine landslide tsunamis
 - ✓ Not so frequent events (2nd most frequent tsunami source, likely underreported) → better evaluated on the long term, in periods not covered by tsunami DB.
 - ✓ Do not tend to occur where they did in the past / they are more spatially random
 - ✓ Not accounted in current PTHA methodologies
- ✓ Critical infrastructure → $P_f \sim 10^{-4} - 10^{-6}$ → events with return periods of 10 kyrs - 1 Myrs.
 - ✓ The US Nuclear Regulatory Commission considers submarine landslides as the most probable tsunami source to the US east coast.

Introduction & aim

✓ Landslide location & geomorphology →

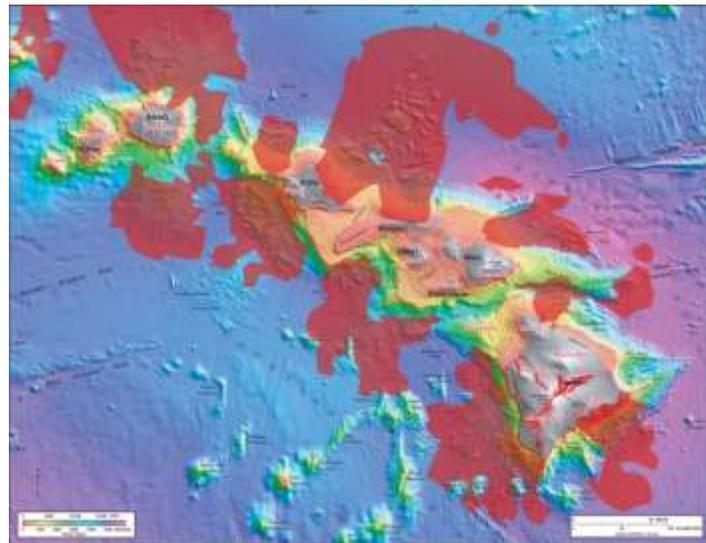
- ✓ Trigger mechanisms
- ✓ Strength characteristics
- ✓ Landslide dynamics
- ✓ Tsunamigenic potential

✓ Landslide catalogues →

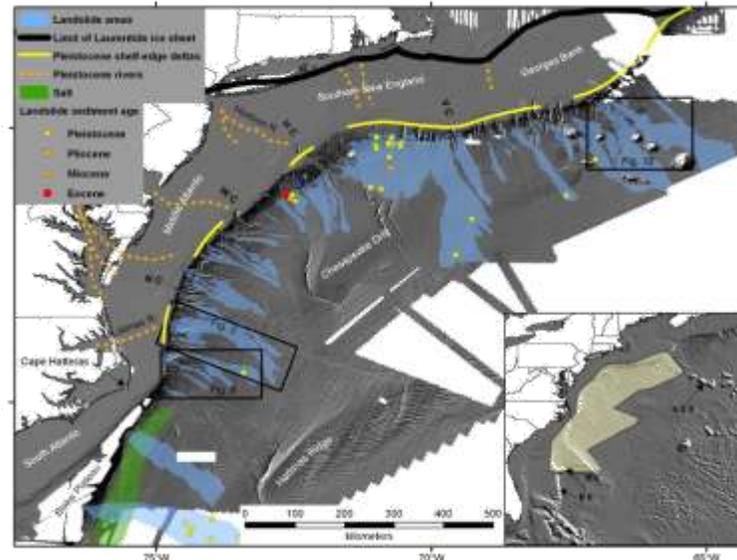
- ✓ PLHA
- ✓ PTHA



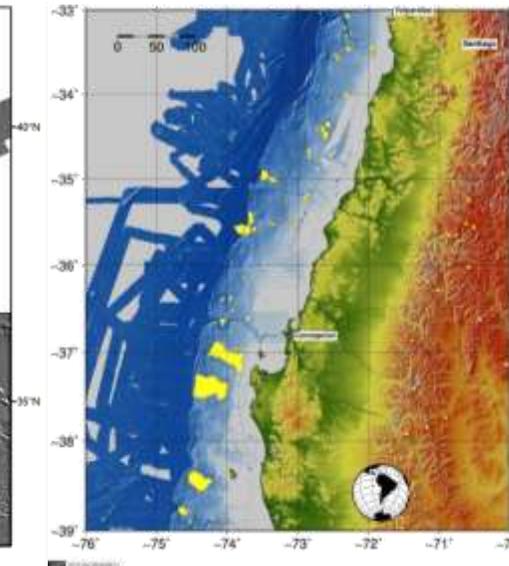
Urgeles et al., 2013, JGRES



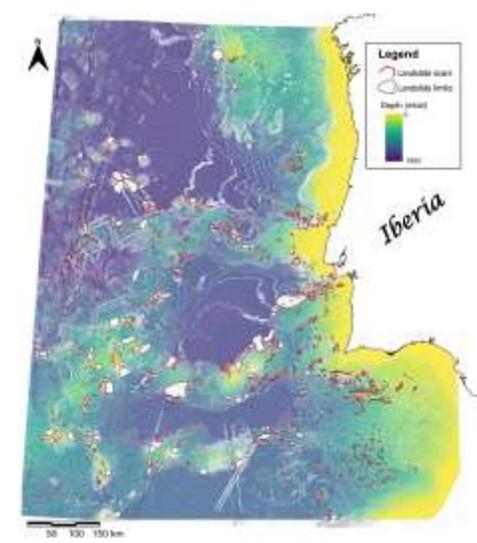
Moore et al., 1994, Ann. Rev. EPS



Twichell et al., 2009 Mar.Geol.



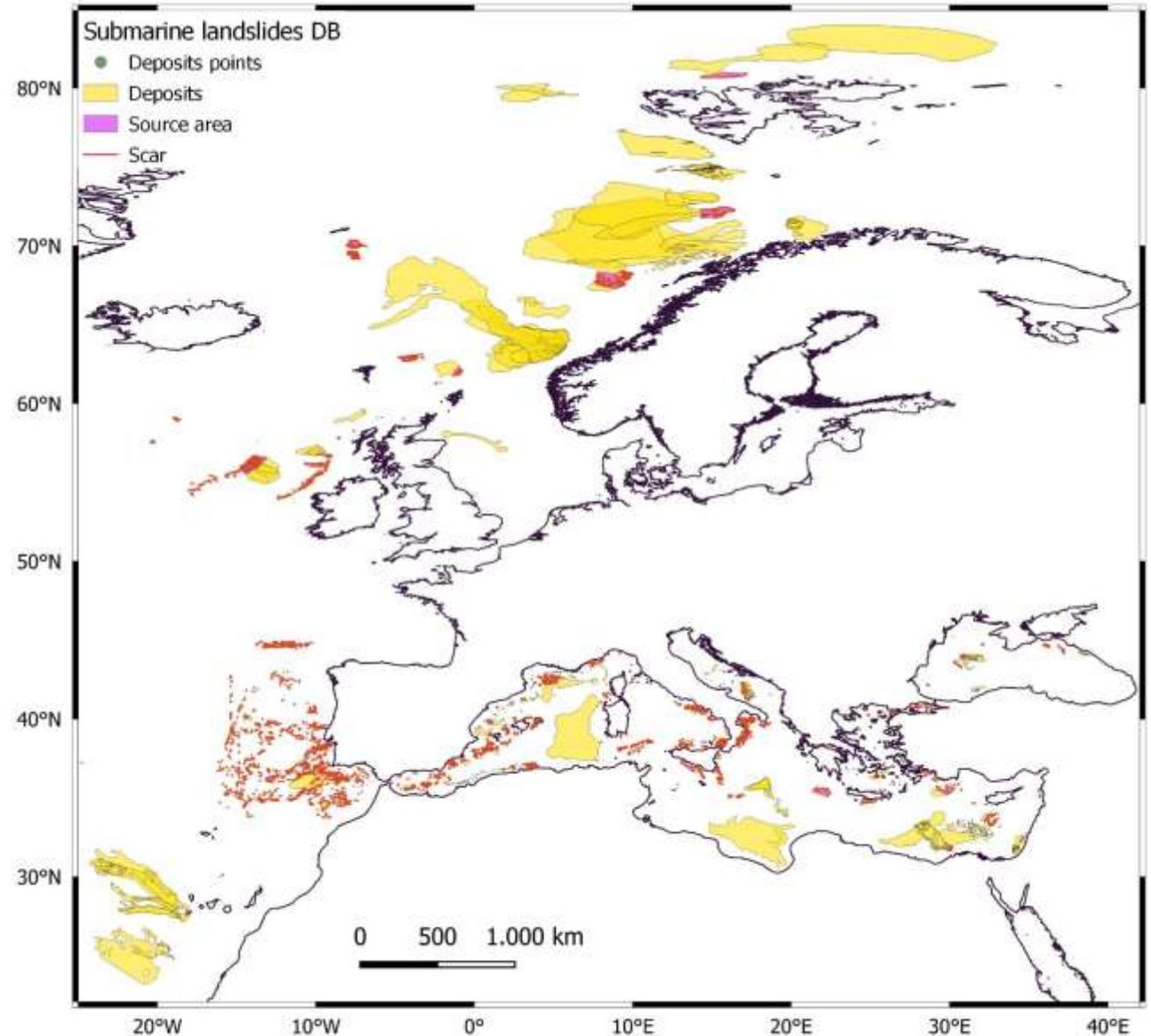
Völker et al., 2011, SMMTC



Gamboa et al., 2021, Sci.Data

EMSS25

- ✓ Increased coverage
- ✓ More events
 - ✓ 6954 Scars
 - ✓ 6945 Source areas
 - ✓ 2191 Deposits
- ✓ More features & information
- ✓ Seed for the world ocean submarine landslide database



Landslide Tsunami Hazard

Landslide hazard – H_L (Guzzetti et al., 2006; NHESS):

$H_L = P(M_L \geq m_L) \times P(N_L) \times P(S)$ expresses landslide hazard H_L as the conditional probability of

- ✓ $P(M_L \geq m_L)$ landslide size, the magnitude (A|V) of a landslide greater or equal than a minimum magnitude, m_L .
- ✓ $P(N_L)$ landslide occurrence in a given region in an established period
- ✓ $P(S)$ landslide spatial occurrence given the local environmental setting.

For H_T , H_L needs to be propagated for

- ✓ Landslide runout
 - ✓ Tsunami generation
 - ✓ Tsunami propagation
 - ✓ Tsunami runup
- $P(H_T \geq h_T); P(R_T \geq r_T)$

What matters?

DB driven

- ✓ Where? How deep? $\rightarrow P(S)$
- ✓ How large? $\rightarrow P(M_L)$
- ✓ How often? How many? $\rightarrow P(N_L)$
- ✓ Which runout?

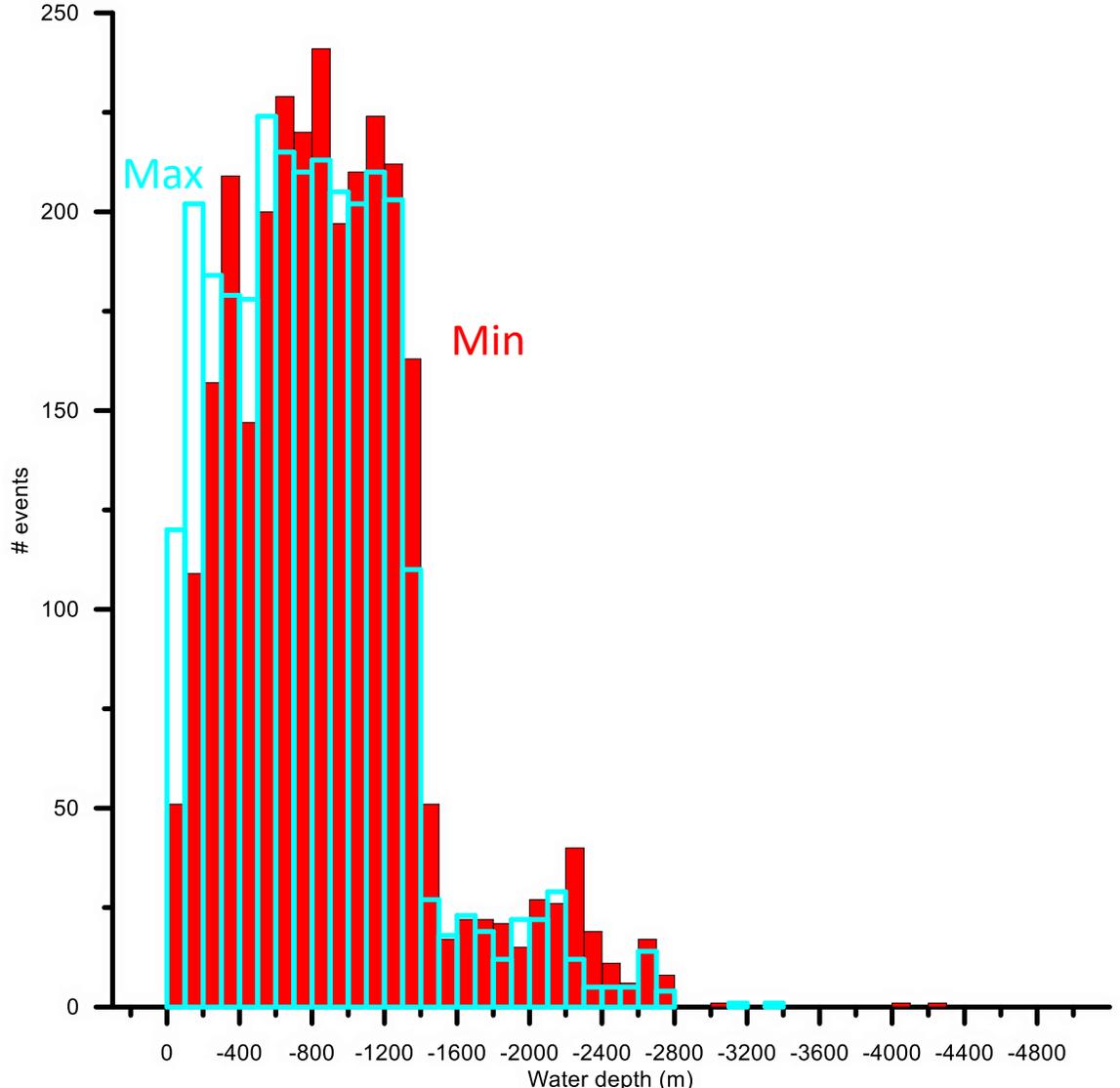
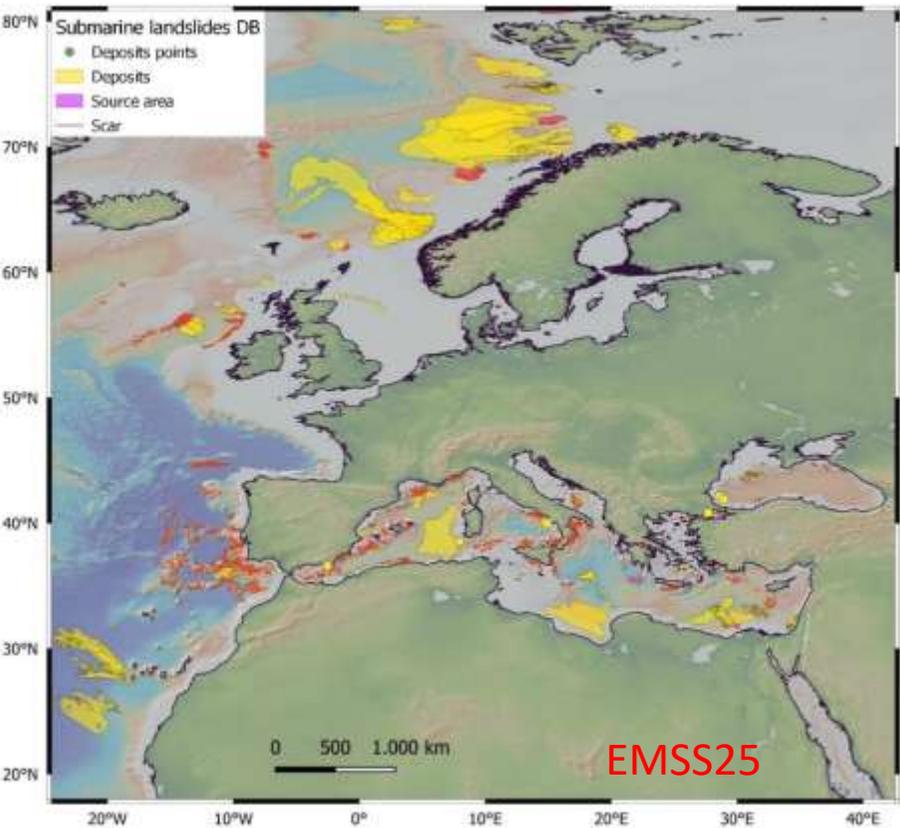
Model driven

- ✓ Which runout?
- ✓ How fast? (landslide dynamics)
- ✓ How tsunamigenic?
 $P(H_T \geq h_T); P(R_T \geq r_T)$



Where? How deep? → P(S)

✓ Most landslides occur in between 100-1500 mbsl → continental slope



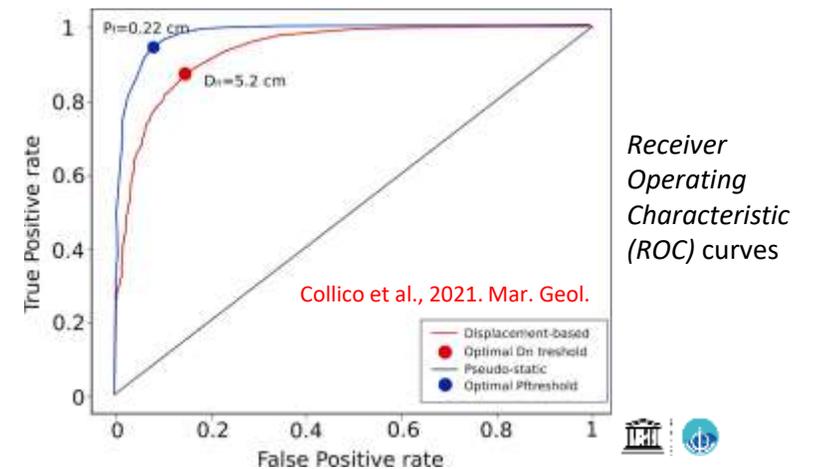
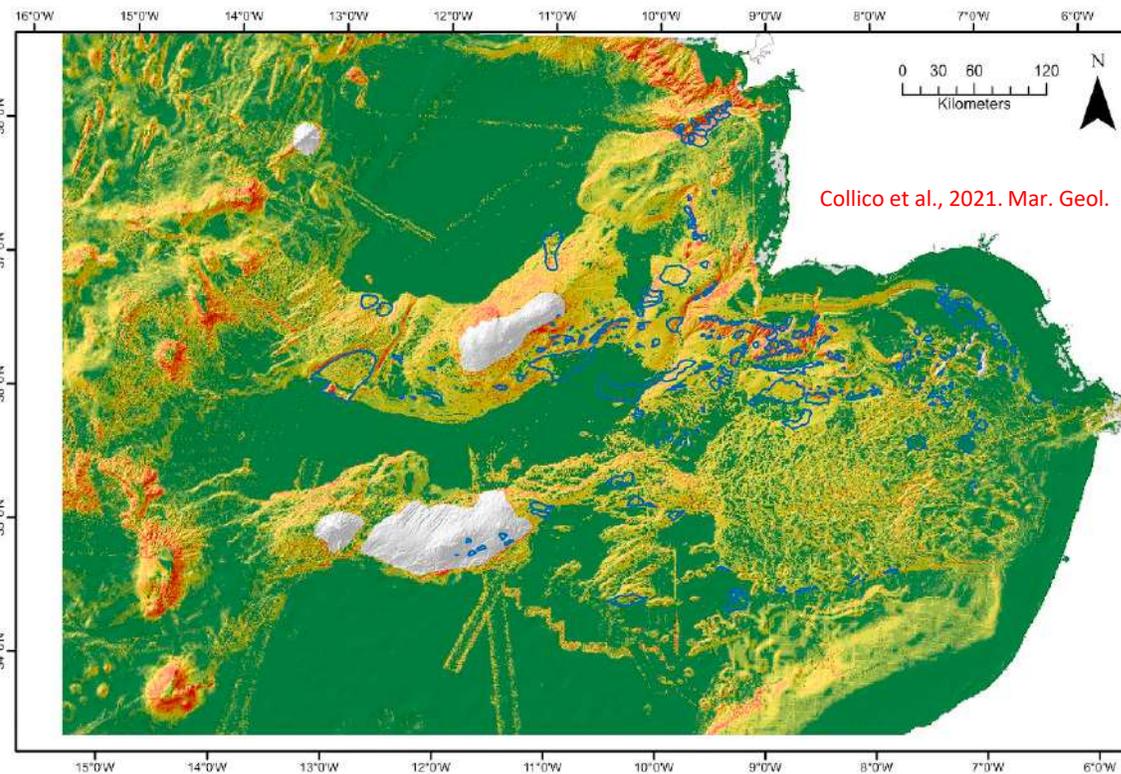
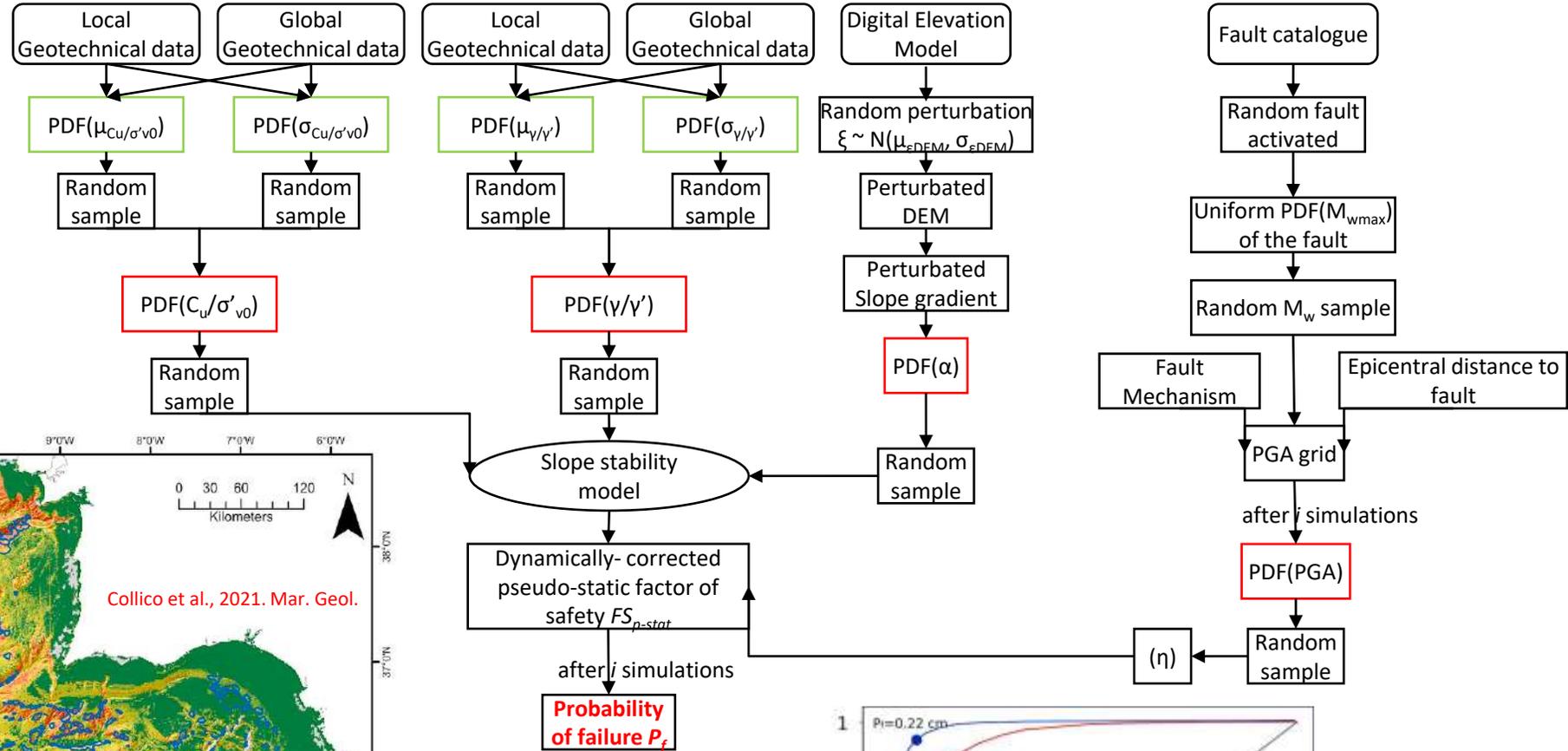
Where? How deep? → P(S)

Hazard models cannot predict when a landslide will occur based on where landslides have occurred in the past (Guzzetti, 2003)

Model performance quantification

Receiver Operating Characteristic (ROC) curves compare

1. model outputs (probabilistic susceptibility maps)
2. observations (i.e. grid cells with mapped landslide)



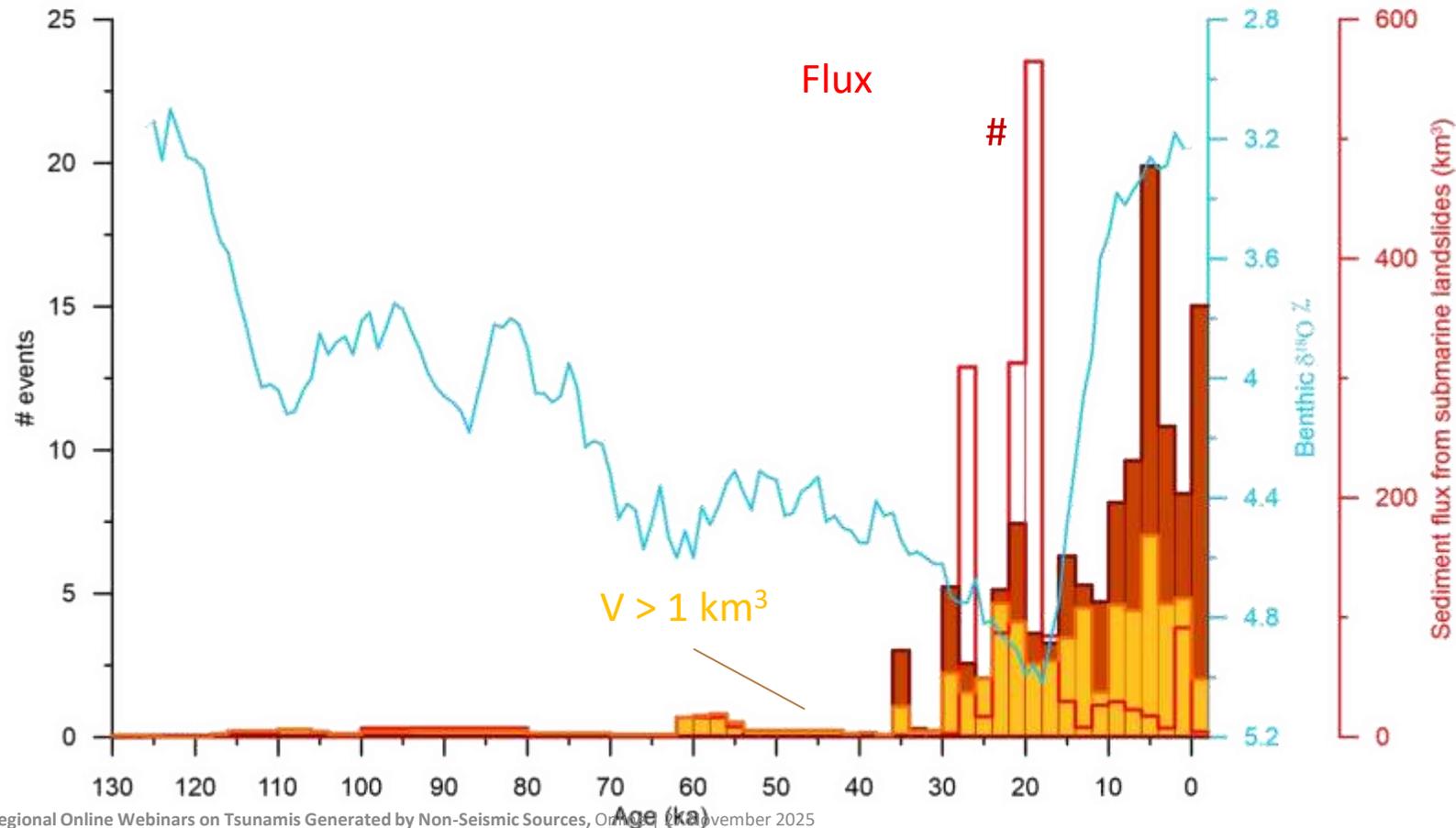
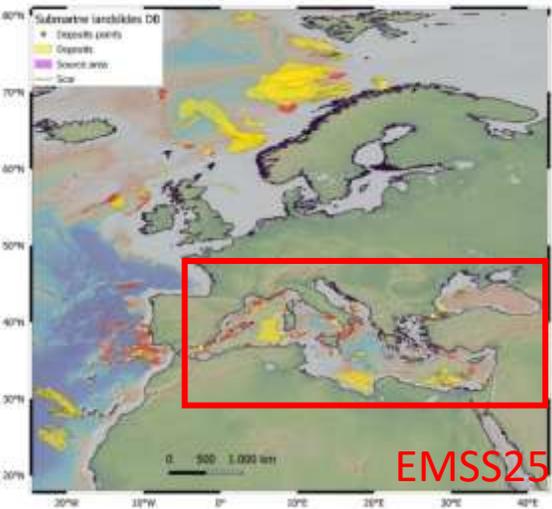
How often?



Accounting for age uncertainty

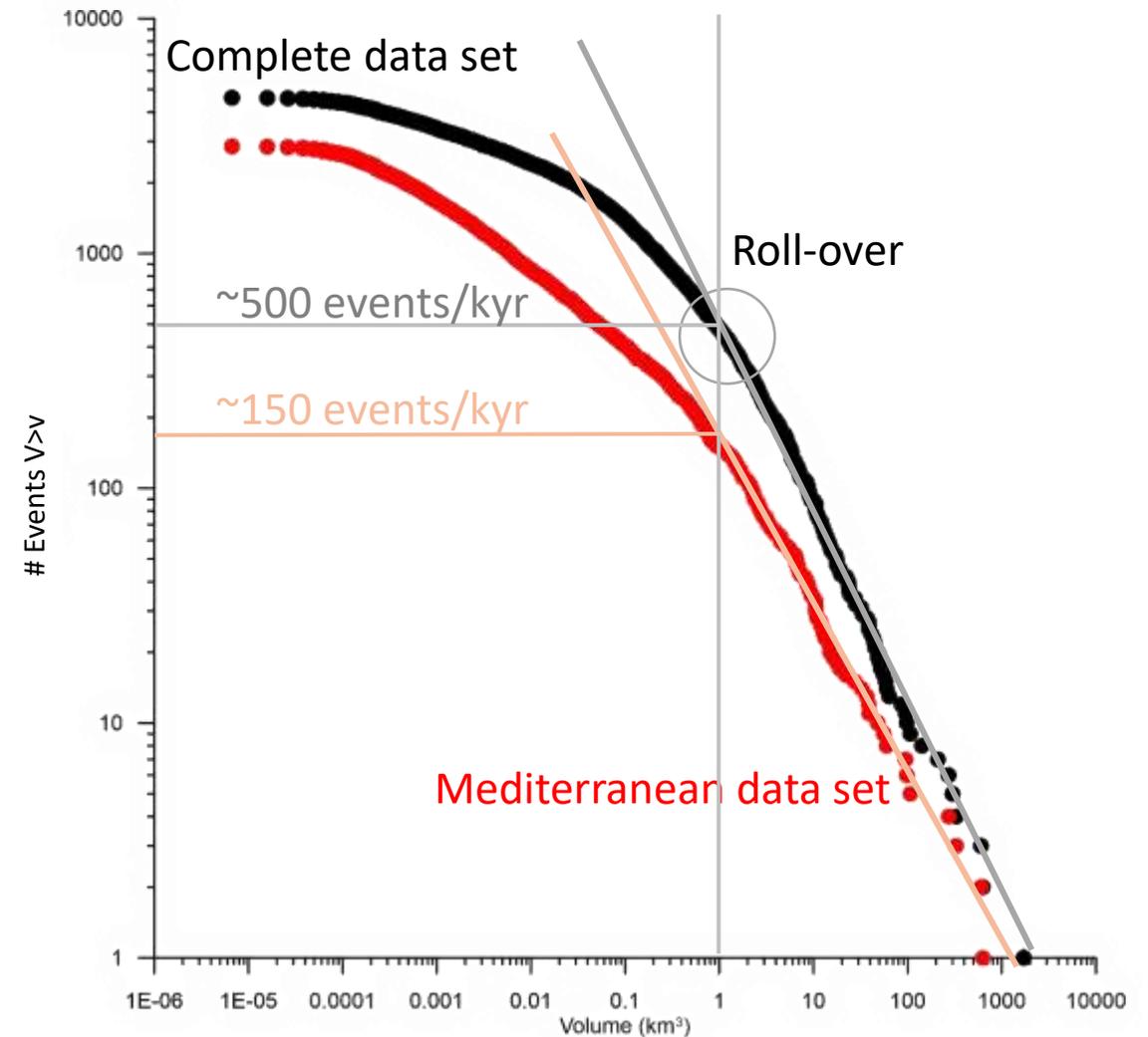
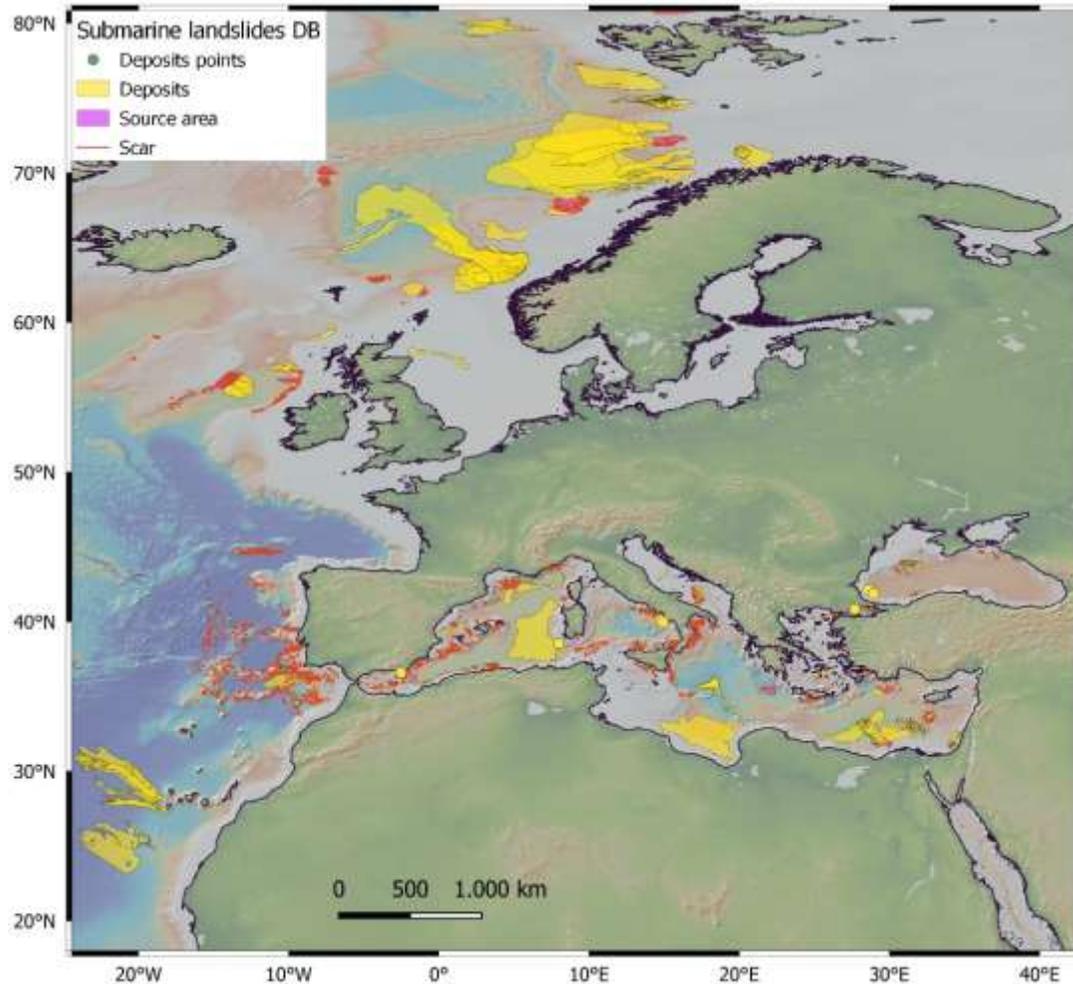
Mediterranean subset (n=141)

Age → not so important if we can put an overall time frame and assume equal probability in time



How large? $\rightarrow P(M_L)$; How many? $\rightarrow P(N_L)$

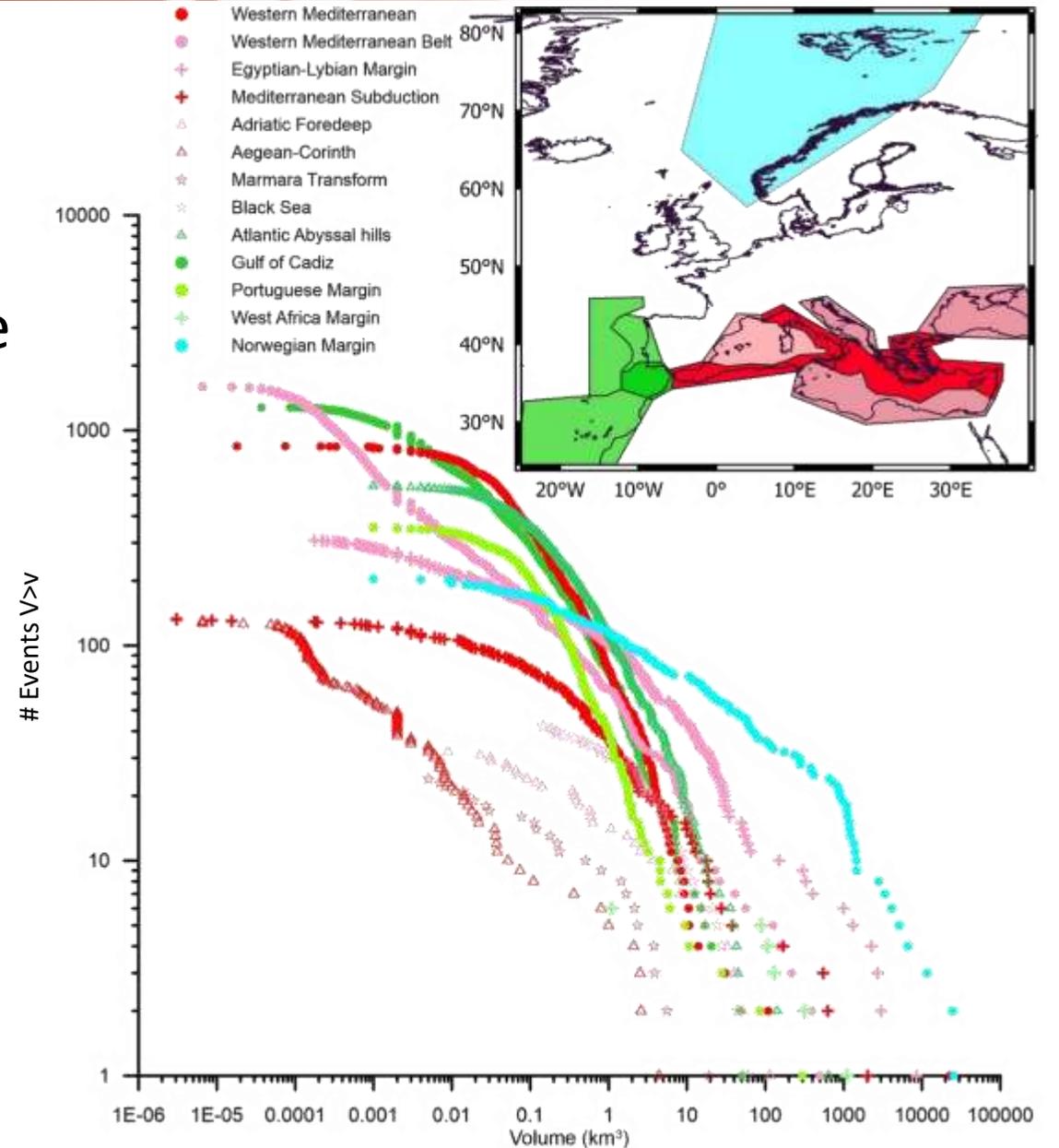
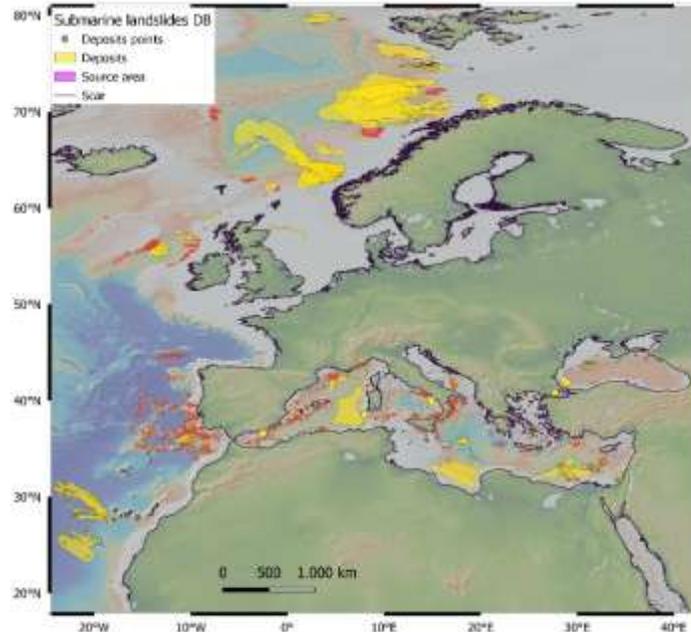
✓ Frequency/magnitude distribution



How large? $\rightarrow P(M_L)$; How many? $\rightarrow P(N_L)$

Poisson process?

- ✓ Active/passive margins have different slopes of the F/M relationship
- ✓ The larger failure volumes dominate the flux, even for active margins



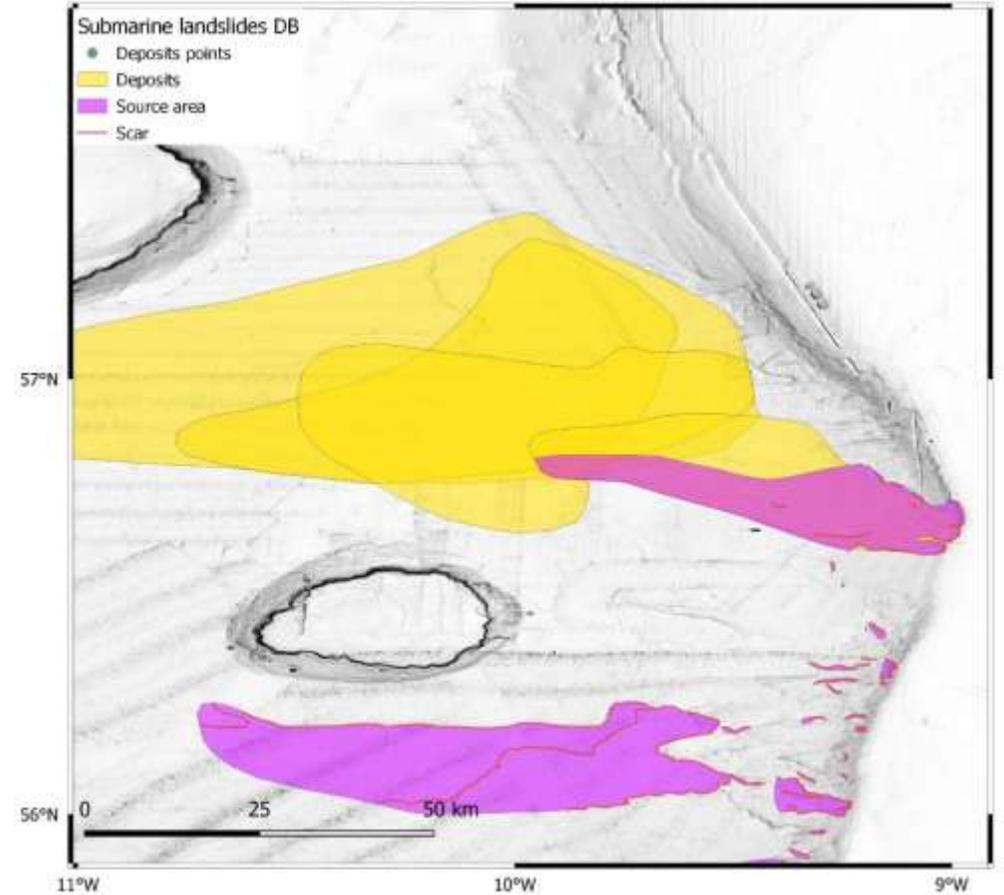
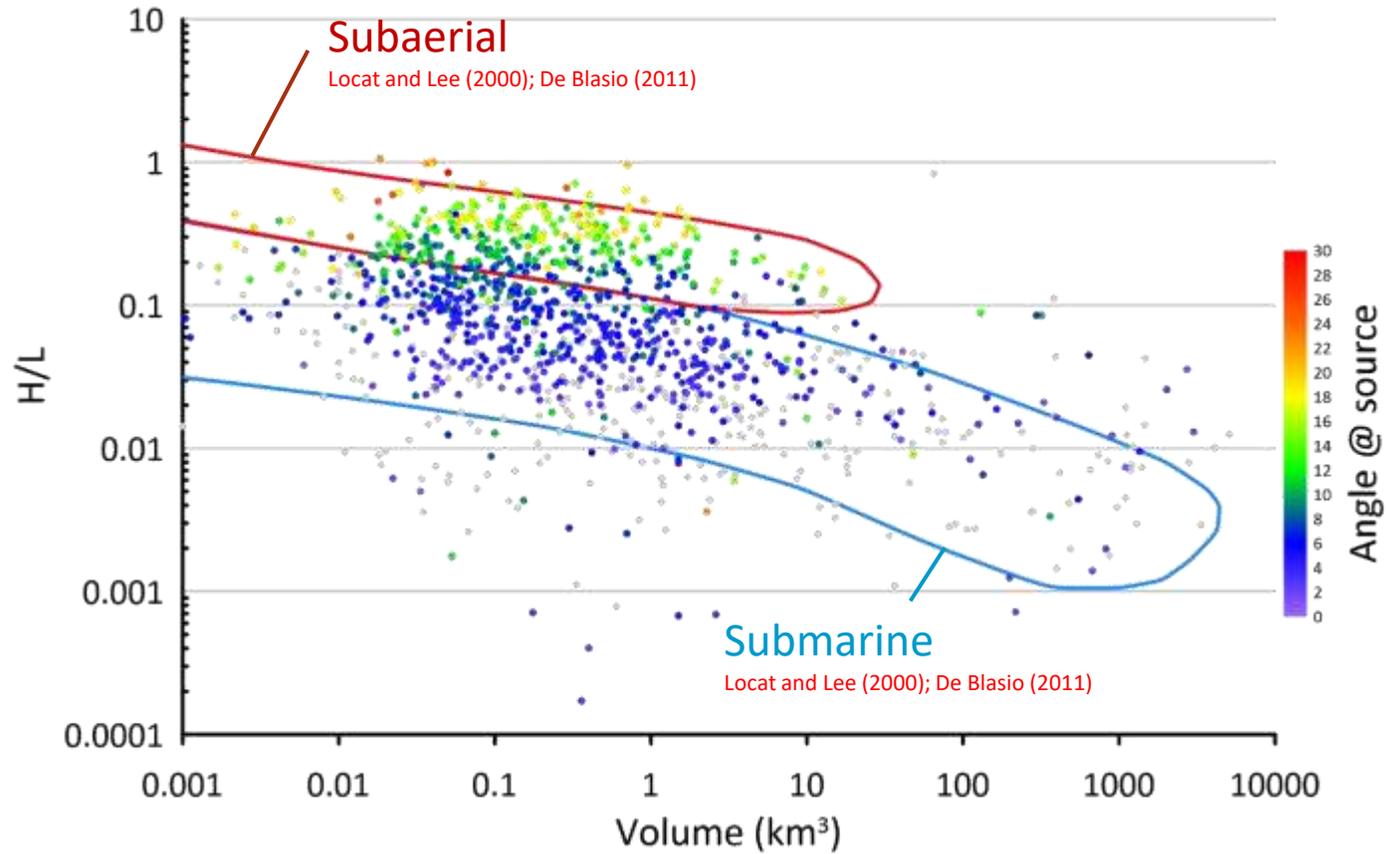
How fast?

✓ Structured in:

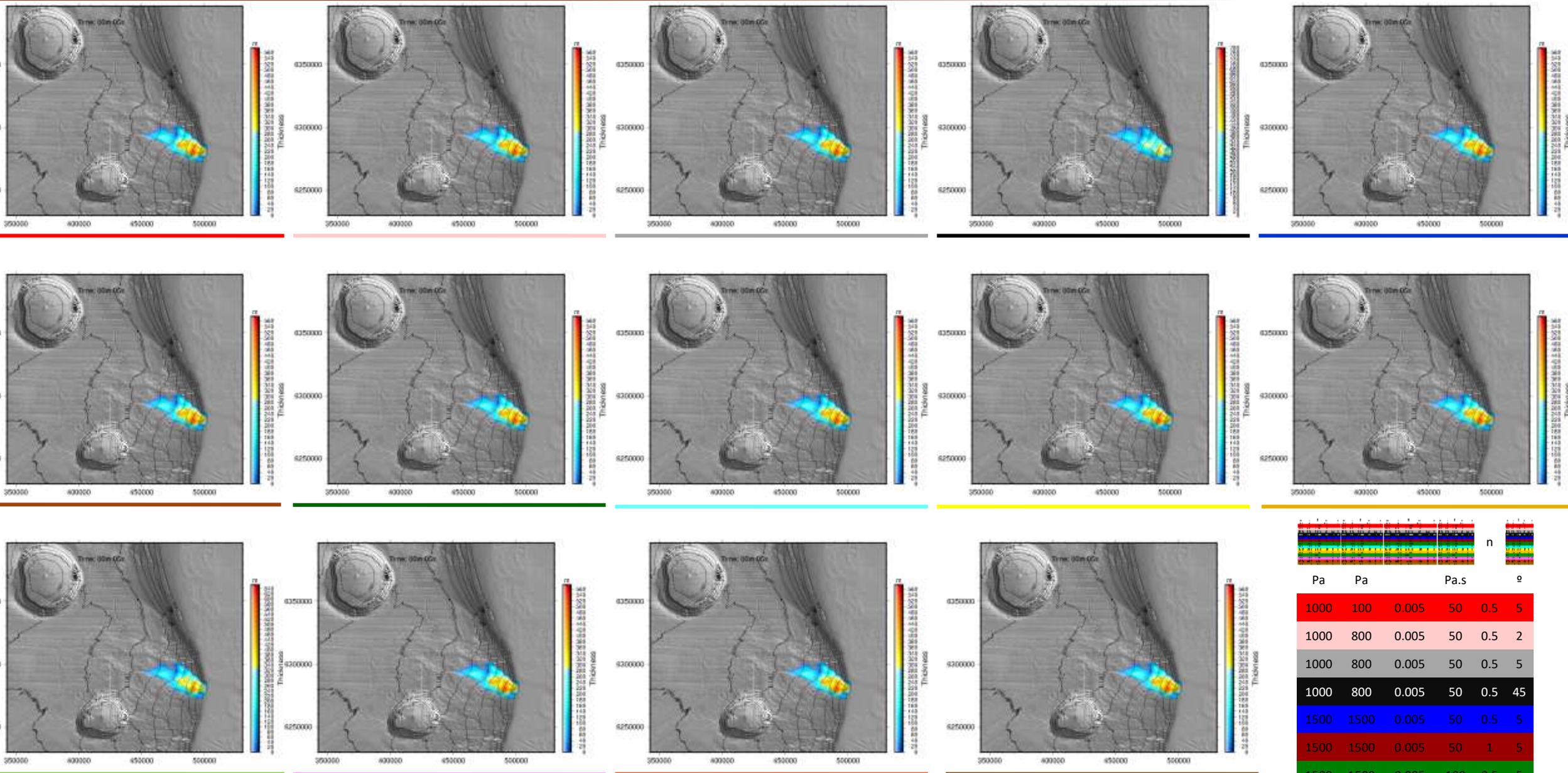
- ✓ Source areas
- ✓ Deposits

✓ Implications for:

- ✓ Initial tsunami source
- ✓ Landslide rheology
- ✓ Acceleration history
- ✓ Tsunami build-up



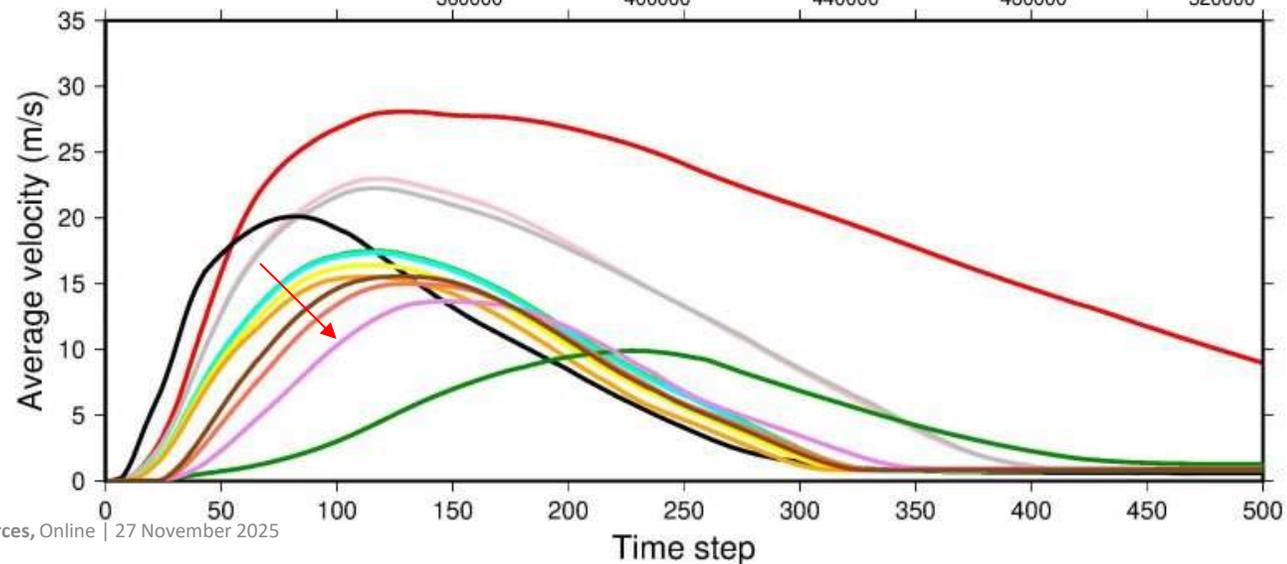
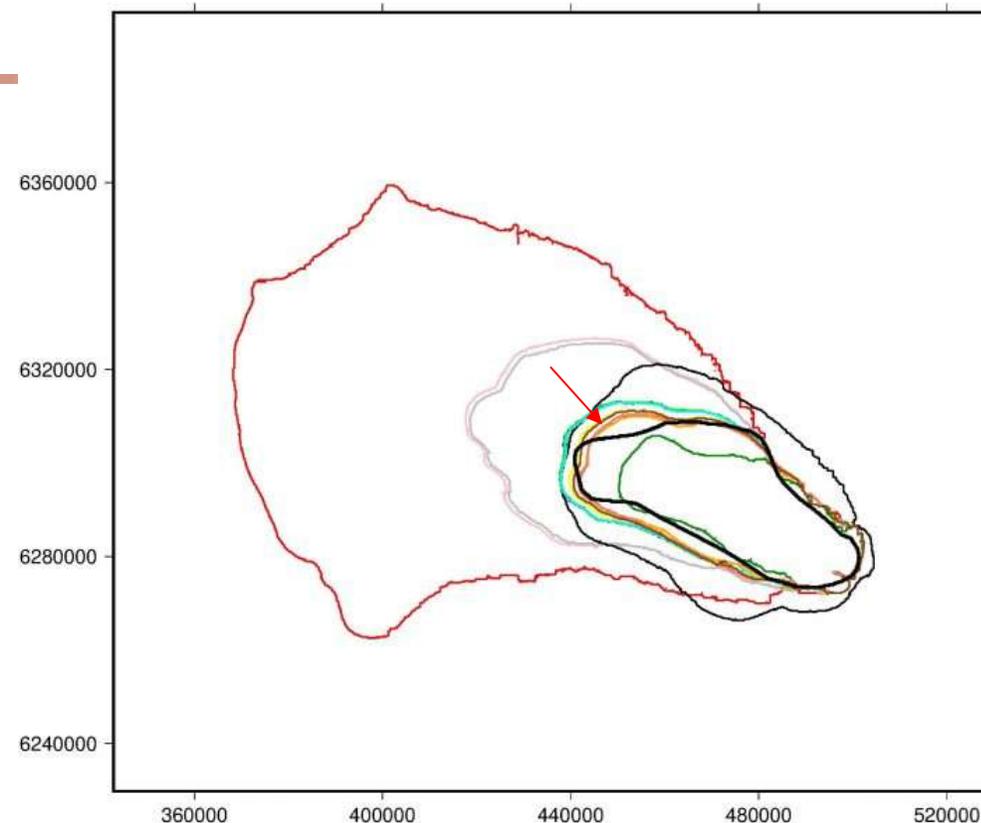
How fast?



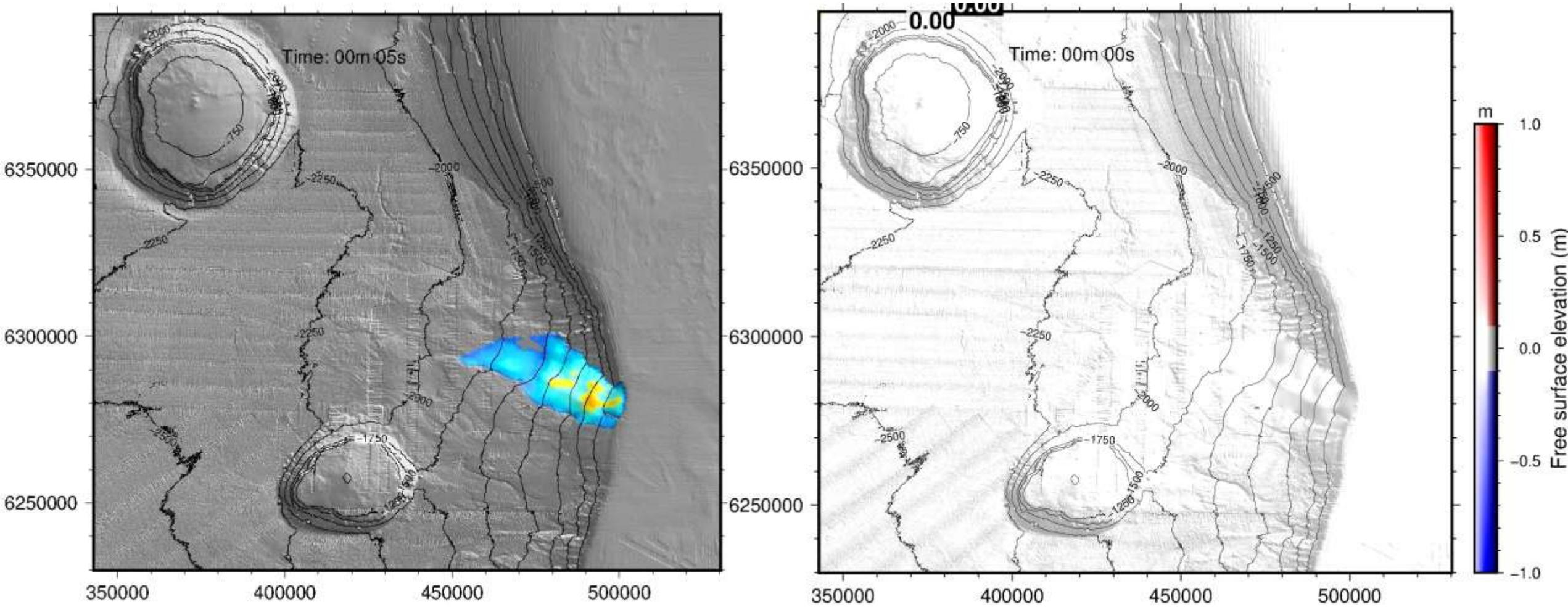
Pa	Pa	Pa.s	ρ	η	
1000	100	0.005	50	0.5	5
1000	800	0.005	50	0.5	2
1000	800	0.005	50	0.5	5
1000	800	0.005	50	0.5	45
1500	1500	0.005	50	0.5	5
1500	1500	0.005	50	1	5
1500	1500	0.005	100	0.5	5
1500	1500	0.005	400	0.5	5

How fast?

Initial Yield Stress	Min Yield Stress	Wetting efficiency	Viscosity	HB Exp	Int Friction
Pa	Pa		Pa.s		ρ
1000	100	0.005	50	0.5	5
1000	800	0.005	50	0.5	2
1000	800	0.005	50	0.5	5
1000	800	0.005	50	0.5	45
1500	1500	0.005	50	0.5	5
1500	1500	0.005	50	1	5
1500	1500	0.005	100	0.5	5
1500	1500	0.005	400	0.5	5
1650	1650	0.005	100	1	5
1800	1800	0.005	100	1	5
8000	1650	0.0005	100	1	5
8000	1650	0.005	100	1	5
8000	1650	0.05	100	1	5
8000	1650	0.5	100	1	5
Actual observation					



How fast?

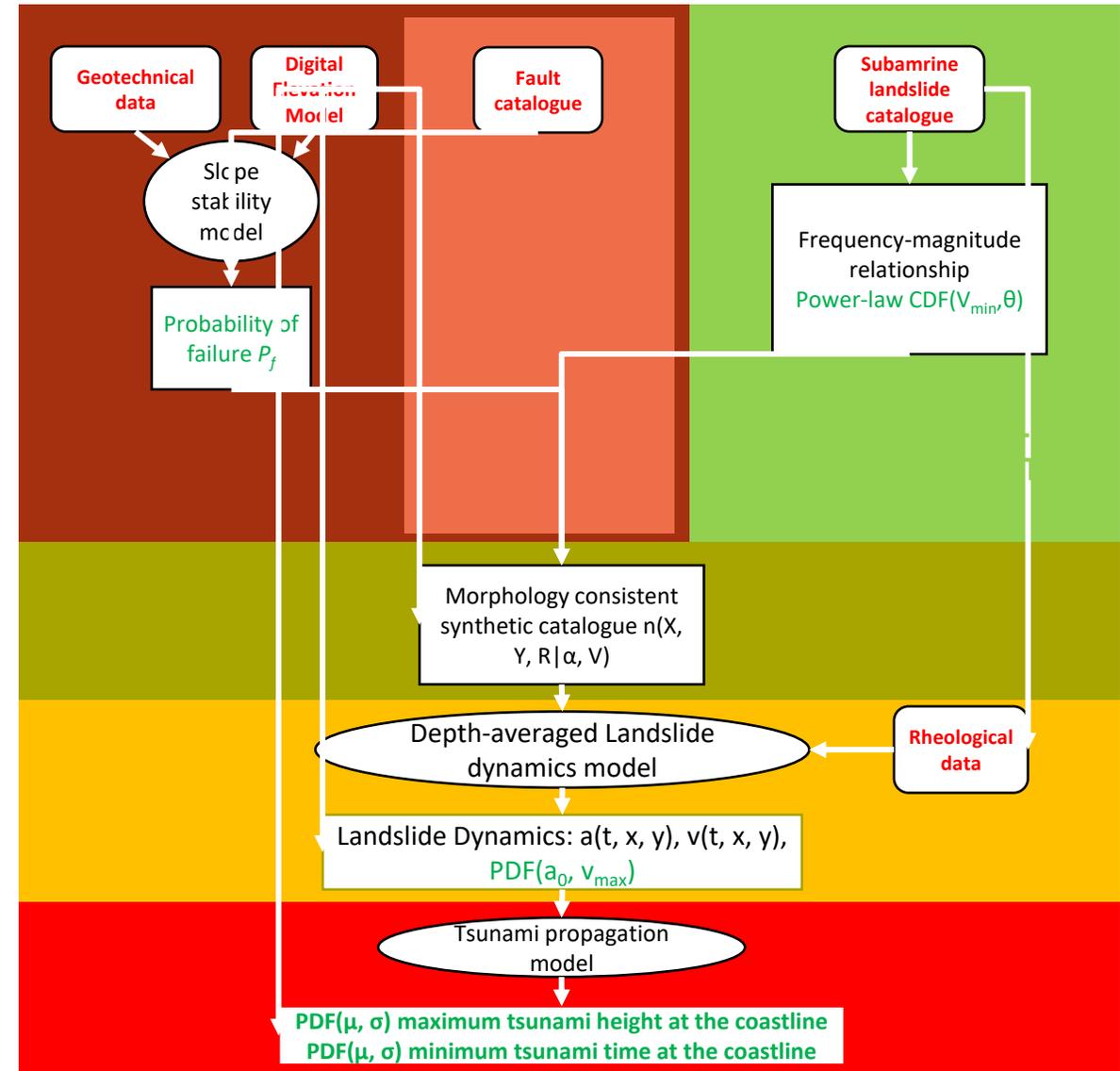


Conclusions

- ✓ Despite size and time biases, landslide catalogs offer adequate data for assessing landslide tsunami hazard
 - ✓ Where → Susceptibility mapping
 - ✓ When and how large → Frequency/magnitude relationships
 - ✓ Dynamics → Runout

$H_L \rightarrow H_T$

- ✓ Hazard models cannot predict when a landslide will occur based on where landslides have occurred in the past
- ✓ Synthetic submarine landslide catalogue consistent with:
 - ✓ DB ground-truthed landslide susceptibility
 - ✓ Frequency/Magnitude relationship
 - ✓ Aspect ratio
 - ✓ Slope/size relationship
- ✓ Propagated into
 - ✓ Landslide dynamics (consistent with DB runout statistics)
 - ✓ Tsunami genesis & propagation
- ✓ Offer potential approaches to characterize H_T





Burning Question(s)

Panelist

- **Dr Carl Bonnevie Harbitz** is an Expert Adviser at NGI Oslo, Norway, Division of Natural Hazards.



Landslide tsunamis

Carl Harbitz^{1,2,3} Finn Løvholt^{1,2,3} Sylfest Glimsdal^{1,2,3}

1 - Global Tsunami Model (GTM)

2 - Norwegian Geotechnical Institute (NGI)

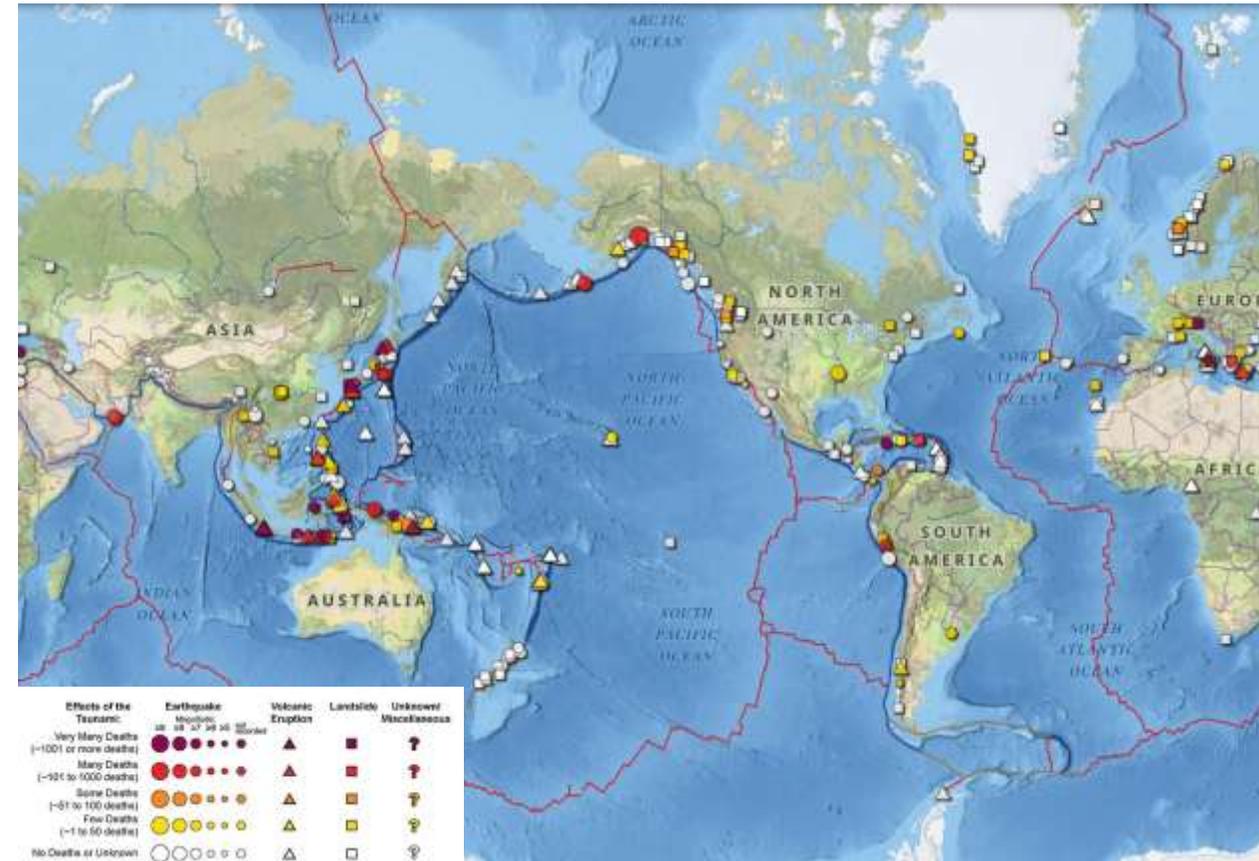
3 – International Centre for Geohazards (ICG)

Landslide tsunamis



- Tectonics
 - Subduction zones → earthquake tsunamis
 - Margins and slopes, materials, mass flows → landslide tsunamis
- Two main classes of landslides
 - Submarine landslides
 - Subaerial landslides, including volcano flank collapses; roughly 10-15% of the reported tsunami sources globally (Harbitz et al., 2014, Nat Haz)
- Can in principle occur on any slope
 - Seismically passive or active margins
 - Frequent violent earthquakes induce frequent smaller landslides
 - Larger landslides along passive continental margins
 - Large sediment transport from rivers and glaciers
- More local character than earthquake tsunamis, with potentially severe impact → might dominate the local risk
- More complex generation and propagation process than earthquake tsunamis

Map showing landslide tsunamis, volcanic tsunamis, and joint earthquake/landslide tsunami events Source, NCEI, NGDC, NOAA



Submarine landslides and tsunamis around the globe

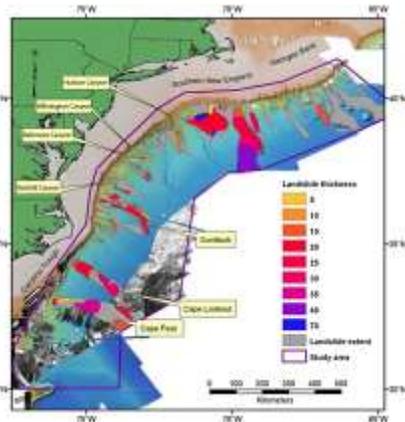


Hühnerbach et al., (2004), Mar Geol

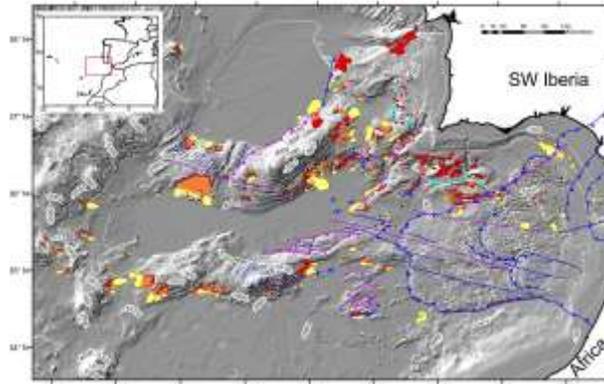


- The landslides are non-uniformly mapped globally
- Many events date way back in time, dating is often uncertain
 - Most major landslides pre-historical
- A very small fraction of the mapped events are known to be tsunamigenic
- → much data, still large uncertainties

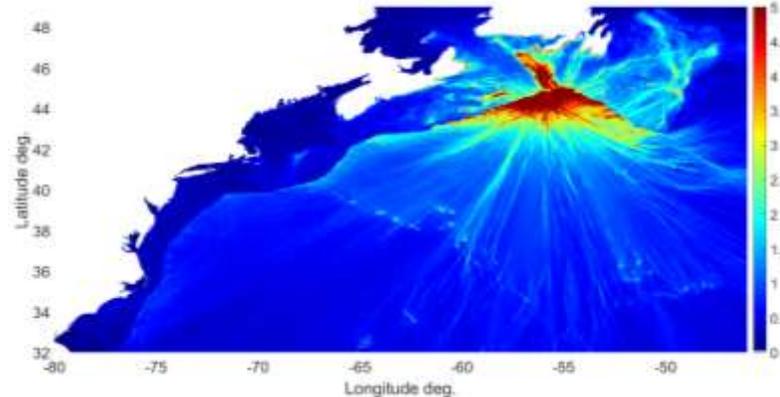
US East Coast database
Lee (2009), Mar Geol



Gulf of Cadiz database,
Zengaffinen-Morris et al., (2022), JGR



1929 Grand banks tsunami
> 300 km³ – 27 fatalities in Newfoundland
Løvholt et al., (2019), GSL



1998 PNG tsunami > 2 000 fatalities
Image courtesy of Jose Borrero

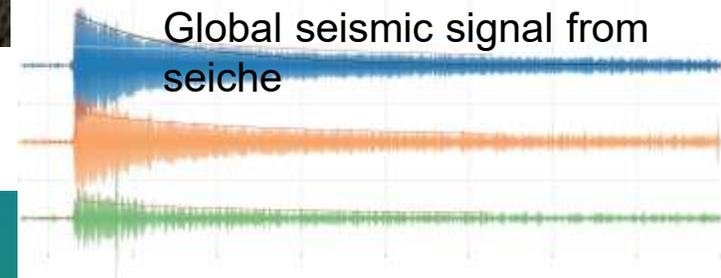
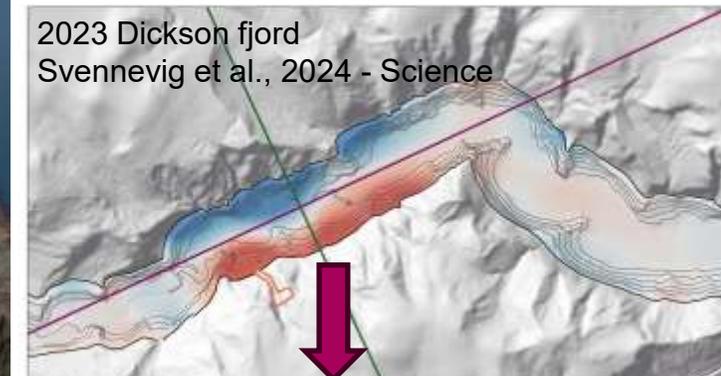
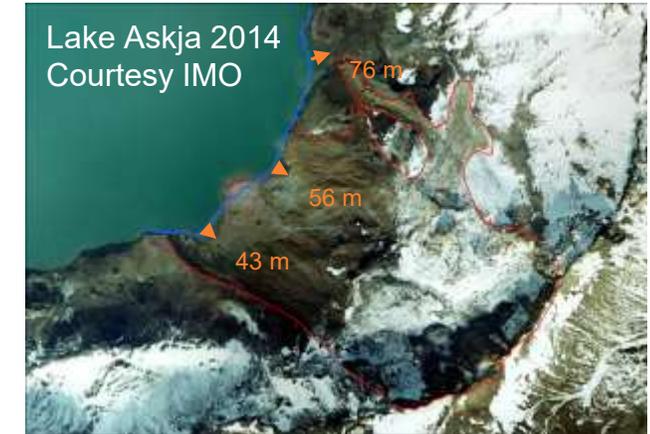


Subaerial landslides tsunamis – More frequent, high local impact



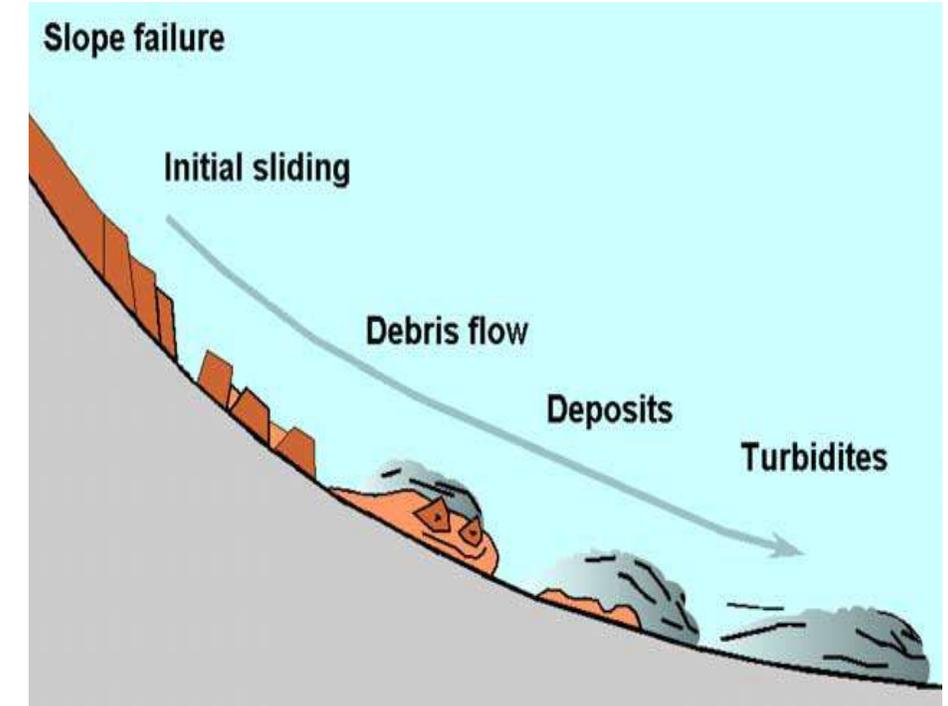
Selected events since year 2000

Year	Event	Country	Volume	Max run-up
2000	Paatuut	Greenland	~50 Mm ³	> 50 m
2002	Stromboli (two slides)	Italy	4-9 Mm ³ and 20 Mm ³	> 10 m
2003	Qianjiang ping	China	24 Mm ³	39 m
2007	Dayantan g	China	3Mm ³	~50 m
2007	Aysen fjord	Chile	High number of slides	~50 m
2008	Chehalis Lake	Canada	3Mm ³	38 m
2008	Three Gauges	China	0.38 Mm ³	13 m
2014	Lake Askja	Iceland	~20 Mm ³	80 m
2015	Icy Bay	USA	76 Mm ³	193 m
2017	Karrat fjord	Greenland	~40 Mm ³	90 m
2018	Bureya	Russia	25 Mm ³	90 m
2018	Baige	China	>10 Mm ³	54 m
2018	Anak Krakatau	Indonesia	~210 Mm ³	85 m
2020	Elliot Creek	Canada	13.5 Mm ³	120 m
2023	Dickson fjord	Greenland	25 Mm ³	200 m
2025	Tracy Arm	Alaska	~100 Mm ³	500 m



Landslide dynamics

- The high mobility of submarine landslides may partly be explained by the large volumes involved and the landslide/water interaction
- Material properties, including clay rheology, are of great importance for the dynamics of most events
- The quantification of the landslide parameters is complicated by the transformation of the landslide from a huge slab to smaller blocks, then to a highly viscous fluid and – in many cases – to a turbidity current

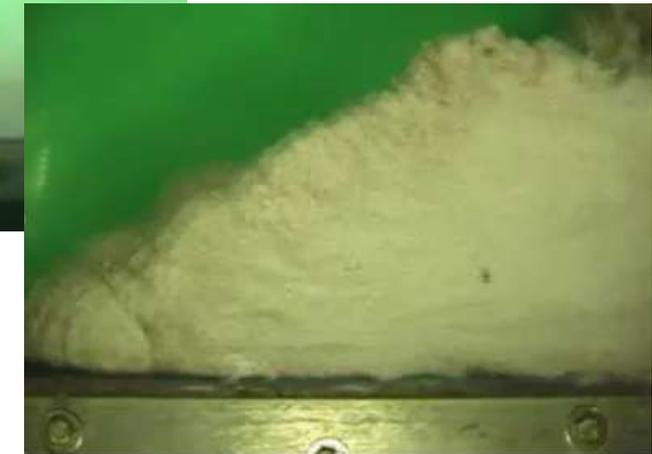
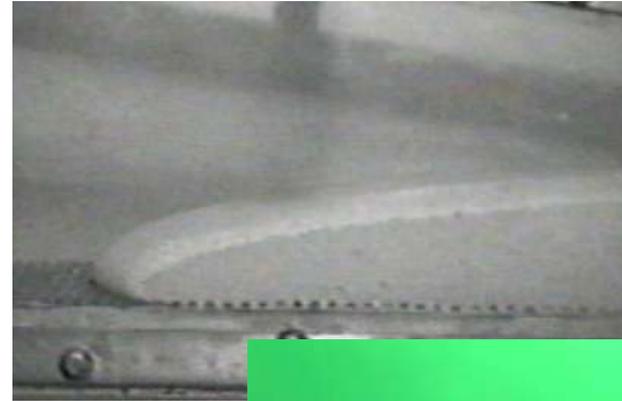


From Bryn et al. 2005

1990s laboratory tests @ SAFL



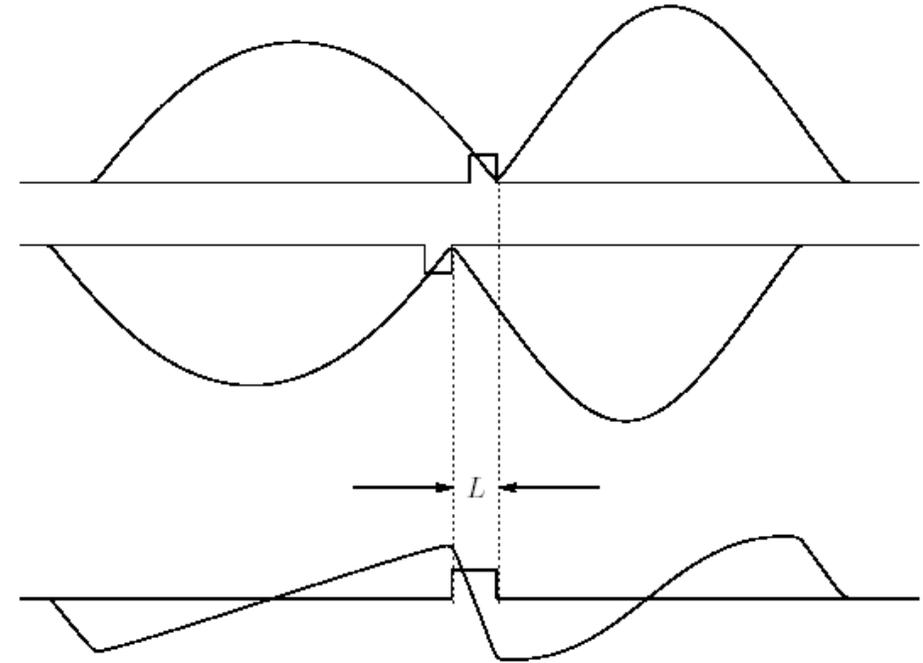
- Subaerial – high clay
- Subaqueous – high clay
- Subaqueous – low clay



Elverhøi et al. (2010) Ocean Dynamics Special Issue

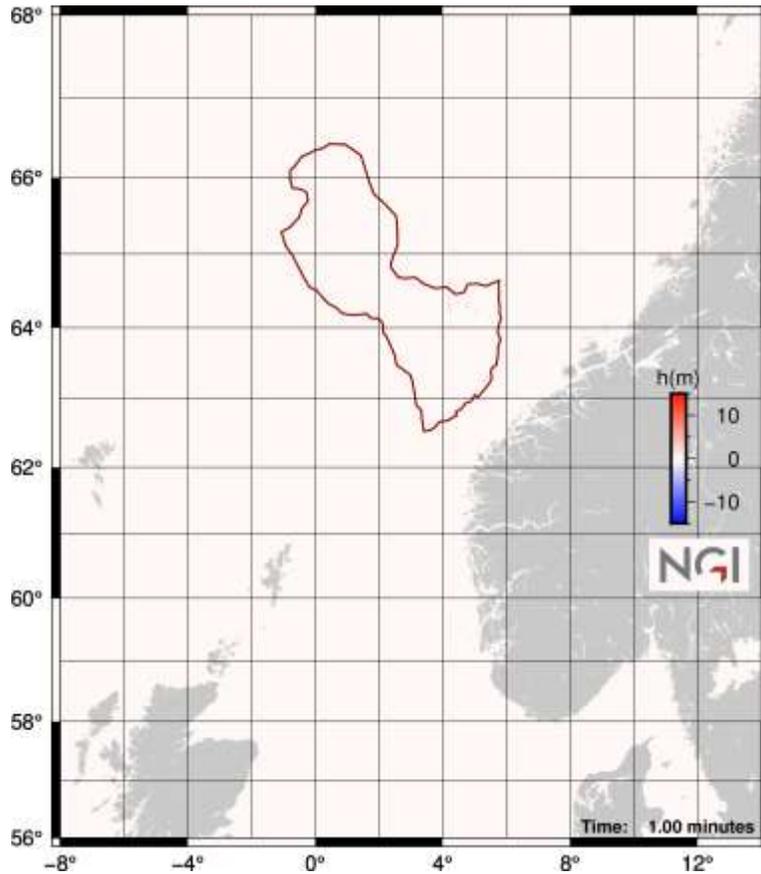
Importance of landslide parameters

- Submarine landslides are most often sub-critical; $Fr=U/c < 1$
- Wavelength depends on landslide length
- Wave height depends on
 - landslide length!
 - wave speed (water depth)
 - landslide height
 - initial acceleration (importance of slope and viscosity)

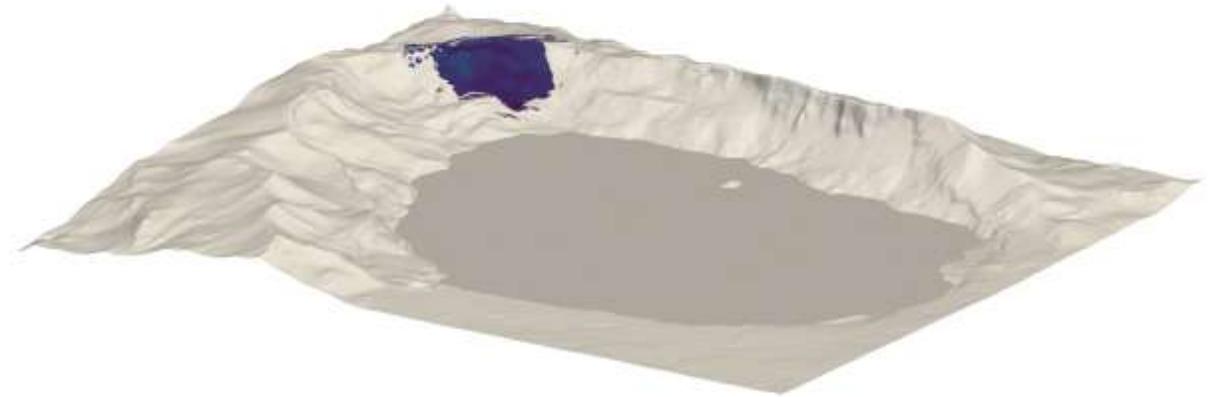


Generation mechanisms

8000 BP Storegga slide and tsunami
(Courtesy, S. Gibbons, NGI)



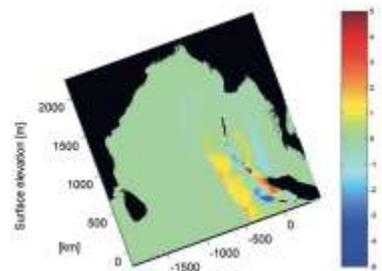
2014 Lake Askja slide and tsunami
(Courtesy, M. Rauter)



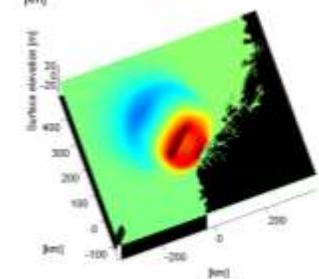
Landslide tsunami characteristics and modelling needs



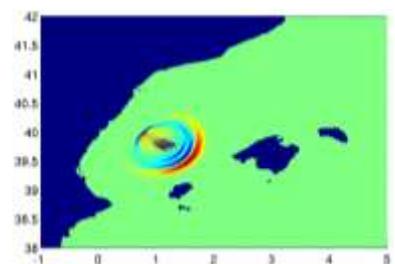
- Main factors of importance for the generation
 - Submarine landslides: volume, water depth, slope, rheology
 - Subaerial landslides: impact area and velocity
- Models need to provide time-dependent landslide motion
 - Capture rheological properties of the landslide
 - Include effect of ambient water
 - Link landslide and tsunami models
- Wave characteristics and propagation differ from earthquake tsunamis
 - Higher amplitudes, shorter wavelength, and stronger radial damping, frequency dispersion
 - Needs more sophisticated models than SWE, e.g.: Boussinesq, layered models, CFD



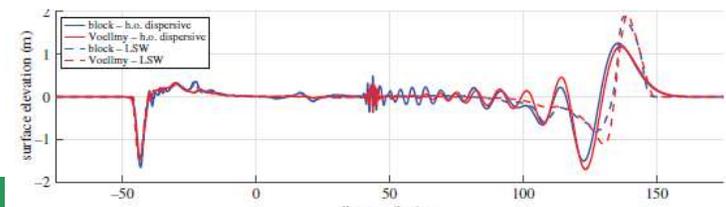
The 2004 Indian Ocean tsunami after 20 minutes Harbitz et al. 2006, NGT



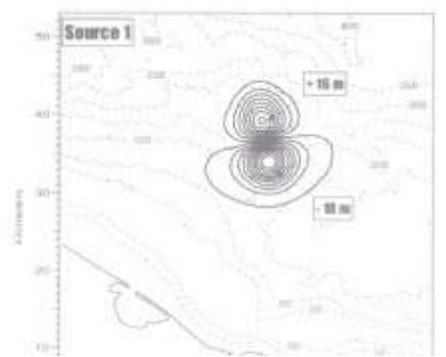
The 8100 BP Storegga Slide tsunami after 30 minutes



The BIG '95 landslide Løvholt et al. 2013, SMMTC



Løvholt et al., 2015, Royal Soc



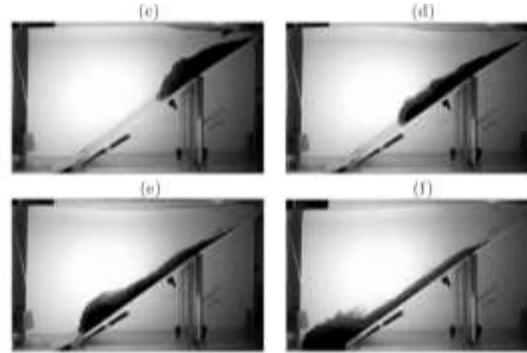
PNG - slump - dipole Lynett et al., 2003, PAGEOPH

Still a need to advance the way we test and improve our prediction models

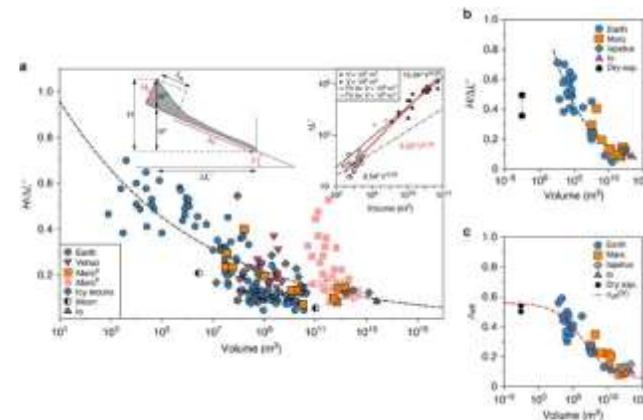


- Calibration of prediction models
- For idealized studies, physics, model consistency
 - US-NTHMP benchmark tests
 - Mainly laboratory tests
 - <https://www1.udel.edu/kirby/landslide/>
 - Kirby et al. 2022, Ocean modelling
- Testing towards field events
 - Tsunami generation does not scale from lab to field; Lucas et al. 2014
 - Calibration of hazard models
 - USGS/USC led initiative – validation towards Taan fjord – revealed need for improvement
 - A range of the most recent well-documented events can be also used (e.g. Greenland, Alaska, Norway, Iceland)

NTMHP Benchmark tests - examples



Friction depends on the volume,
Lucas et al., 2014, Nature Comm



Landslide Probabilistic Tsunami Hazard Assessment – LPTHA

Estimating tsunami probability of occurrence

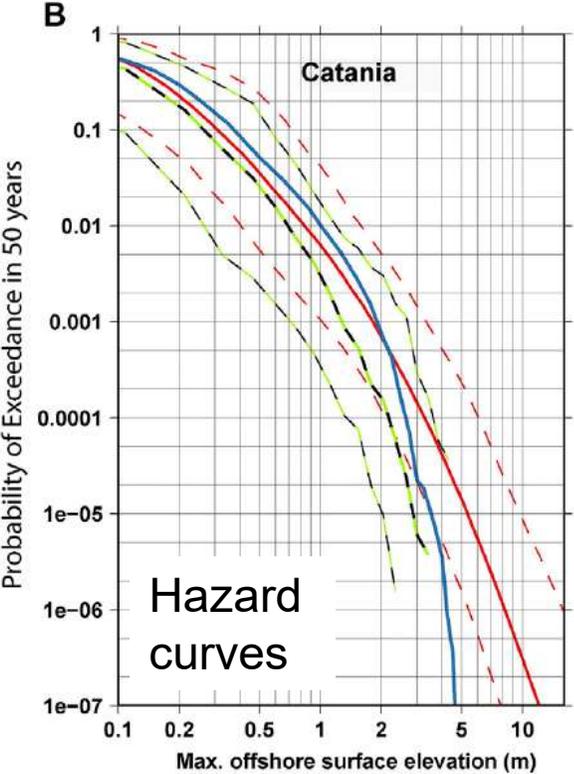
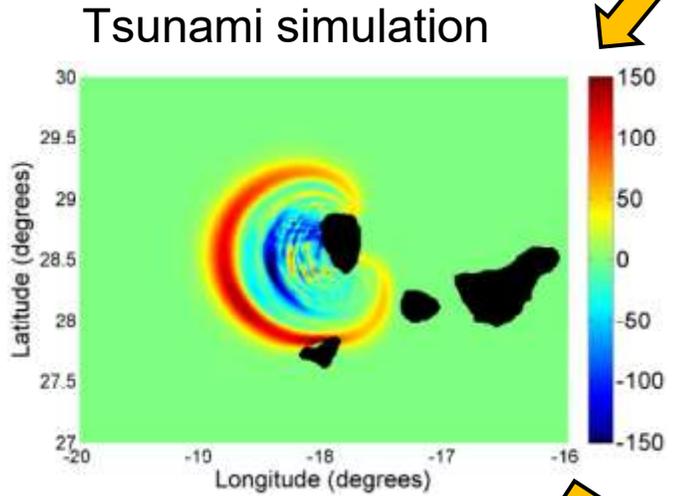
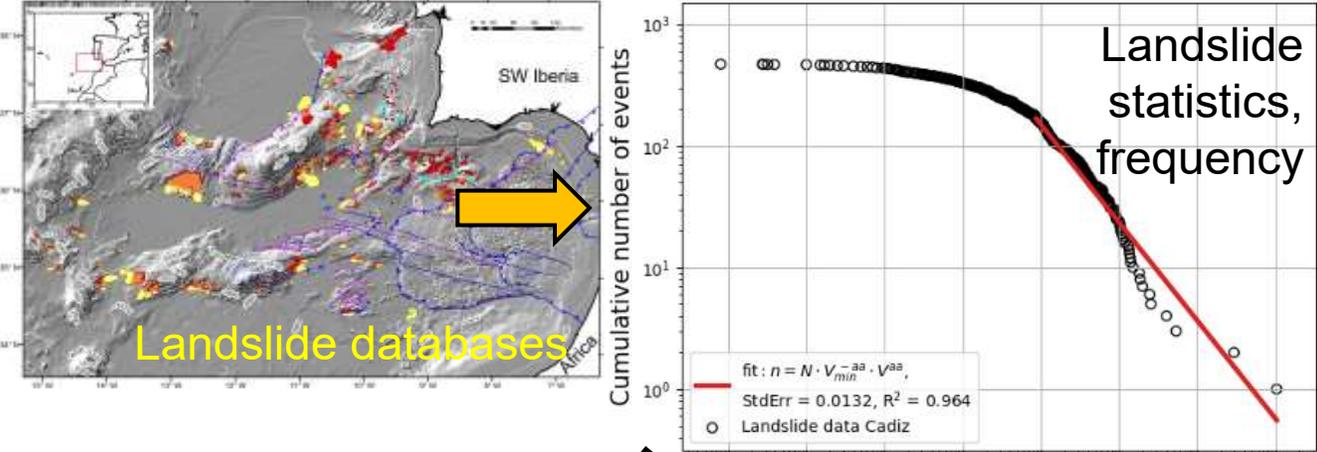
Two alternative pathways to anchor probabilities

- Based on past landslide data
- Based on slope stability

LPTHA can largely mimic PTHA for earthquakes

1. Generate a synthetic set of landslide sources
2. Define annual source probabilities
3. Simulate the wave propagation for each landslide source
4. Aggregate probabilities from all simulations to hazard curves

Challenge: Lack of landslide data



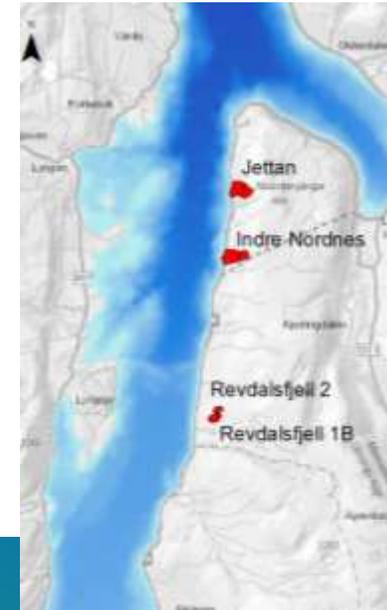
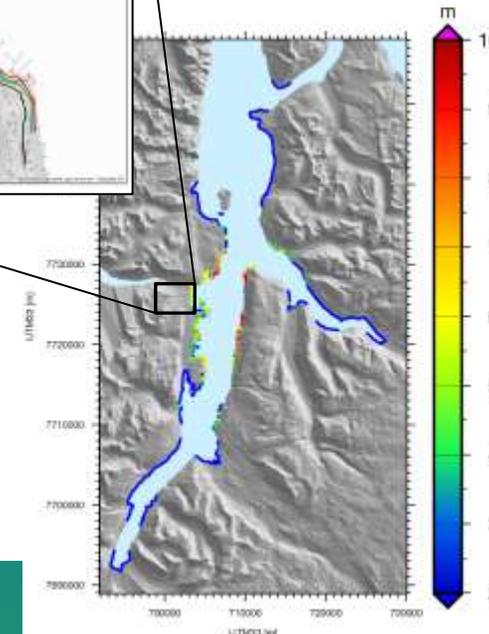
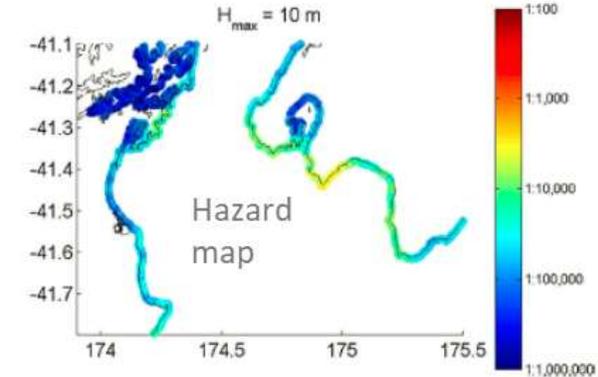
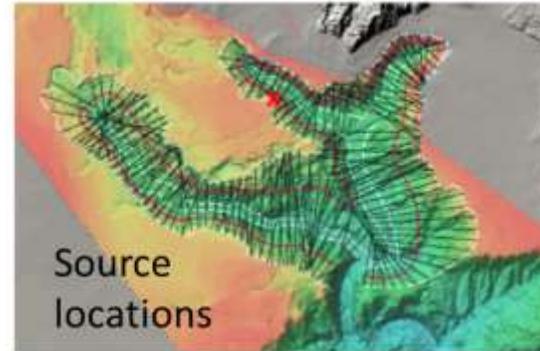
We have only a few extensive hazard applications



ICG 2.0
INTERNATIONAL
CENTRE FOR
GEOHAZARDS



- **Cook Strait Canyon, NZ** ([Lane et al. 2016, PAGEOPH](#))
 - Submarine landslides
 - Simplified landslide dynamics
 - Well constrained geological setting and timing
- **Lyngen fjord Northern Norway** ([Løvholt et al. 2020, Landslides](#))
 - Subaerial landslides
 - Four unstable slopes
 - Probabilities from rock slope stability analysis (subjectively established)
 - Uncertainty treatment of generation mechanisms (impact area and velocity, run-out distance)
- **In both cases, model calibration is needed**



Early warning and hazard analysis for local communities – example from Norwegian fjords

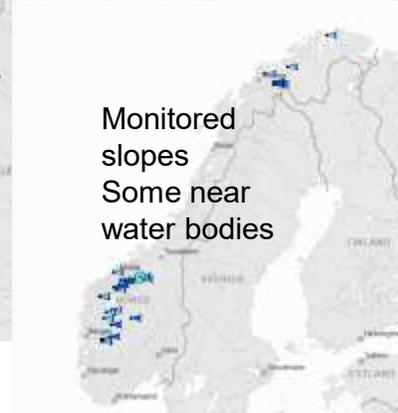


- Inter-municipal preparedness center
- Rock slope monitoring using a variety of fit-for-purpose instrumentation systems, e.g.
 - Boreholes, extensometers, weather stations
 - InSAR, laser, total stations, GPS
 - Seismic network of geophones
- Slope motion mirrored into regional tsunami hazard models
 - Preparedness and early warning systems based on defined rockslide scenarios
- Early warning issued a minimum of 72 hours in advance of rockslide release (large rockslides give pre-failure signals)

Identified slopes



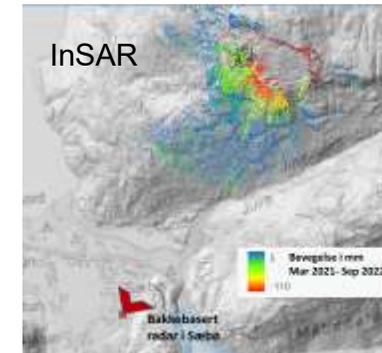
Monitored slopes
Some near water bodies



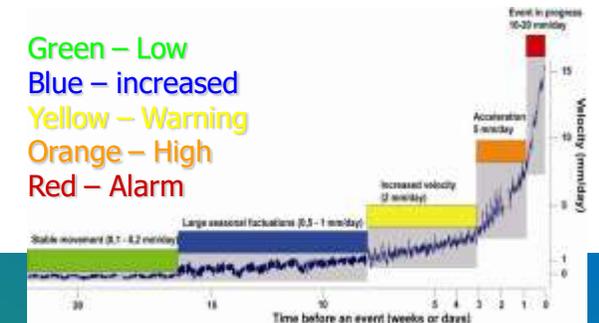
Borehole measurements



GPS station



Courtesy:
Lene Kristensen NVE

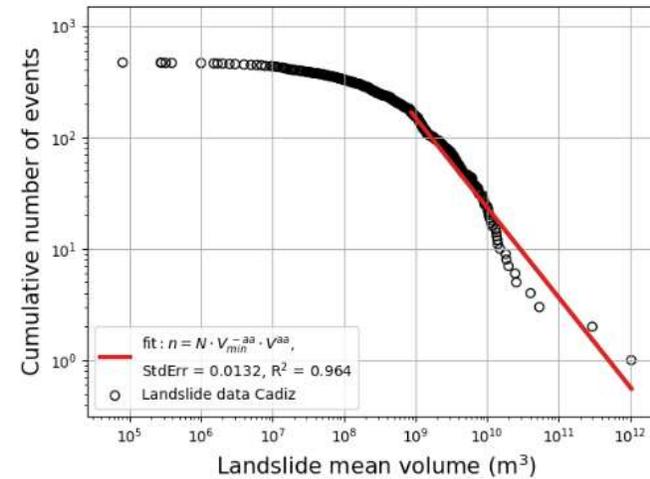


Scaling up: Challenges related to hazard, risk analysis, early warning

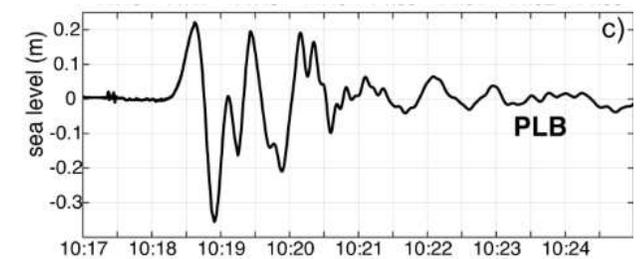


- Statistical background often lacking, limited, or without dating
 - Slope information limited or non-existing
 - Difficult to constrain volumes and probability
 - Acquiring data often expensive, and limited to local investigations
 - Local nature of landslides makes them more difficult to survey
 - They are not necessarily linked to triggers or precursors – and tsunami travel times can be short
- Warning times based on wave measurements may be too short

Zengaffinen-Morris et al. (2022), JGR Oceans



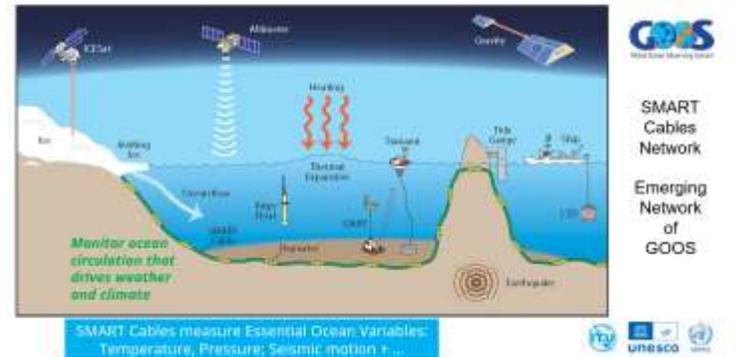
Stromboli wave recording Ripepe and Lacanna (2024), Nature Comm



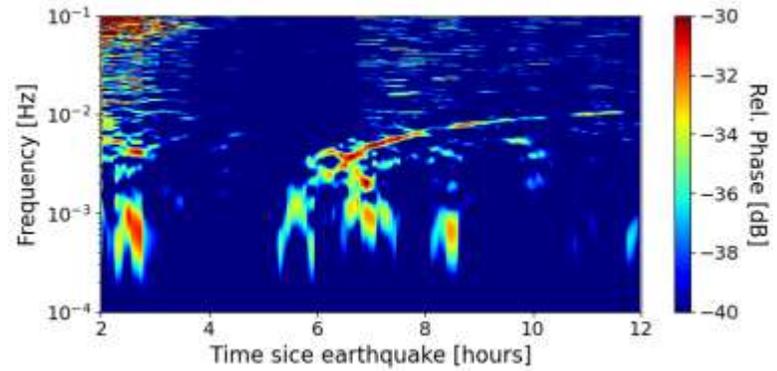
Other EW systems emerging – discussed at the First Ocean Decade Tsunami Programme Conference, Nov 2025



- **Global Navigation Satellite System (GNSS)**
 - Measure displacement of the Earth’s surface and the response of the ionosphere
- **Smart cables (sensor-equipped)**
 - Integrating SMART Capability into EWS, integrating scientific sensors into dual-purpose infrastructure
 - Global initiative supported by the International Telecommunication Unit (ITU), WMO and UNESCO-IOC; part of the global environmental monitoring system
- **Submarine fiber optic cables**
 - Based on existing and future telecom cables
 - Can be part of future SMART and dedicated cables
 - Use of existing networks of seismic monitoring units placed on the sea floor, change in water pressure changes cable length, distributed acoustic sensing (DAS) turn fiber optic cables into distributed strain sensors (detects acoustic frequency strain signals over large distances and in harsh environments), data delivered to shore stations at the speed of light
 - Enables deep-ocean tracking (DART buoys are closer to the shore)
- Cabled warning systems are expensive, and cannot be used (alone) in case of short tsunami travel distance / short warning time



From C R Cruz at the FIRST CONFERENCE OF THE OCEAN DECADE TSUNAMI PROGRAMME, (ODTP) 10-11 November 2025



July 29 2025 Kamchatka M8.8 mega-trust earthquake tsunami 500 km offshore Hawaii, >4000m depth
From M Mazur et al. at the ODTP, 10-11 November 2025

Some final reflections



- Landslide tsunamis recognized as an important source for tsunami hazards
- Landslide tsunami hazard models less developed, partly because of lack of data
- New hazard models will depend on data, either past landslide statistics or slope stability data and models – without it we cannot quantify return periods (only conditional hazard)
- With respect to early warning for all, landslide tsunamis constitute a major challenge:
 - There are few fully operational systems today (Norway and Stromboli perhaps the only ones)
 - Landslide tsunamis are highly local
 - Wave characteristics differ from earthquake tsunamis, and difficult to test as data are lacking
 - Need for extensive and expensive instrumentation
 - regional efforts might become infeasible at present
 - Most effective for areas with known hazard / slope instability
 - **Focus on the high-risk landslide prone areas, and expand later**
- Emerging technologies might provide additional probabilities, ML might accelerate forecasting



Thank you!



Burning Question(s)

Panelist

- **Dr Raphael Paris** is a researcher at the CNRS (French National Center for Scientific Research) at the Laboratoire Magmas & Volcans, University Clermont-Auvergne

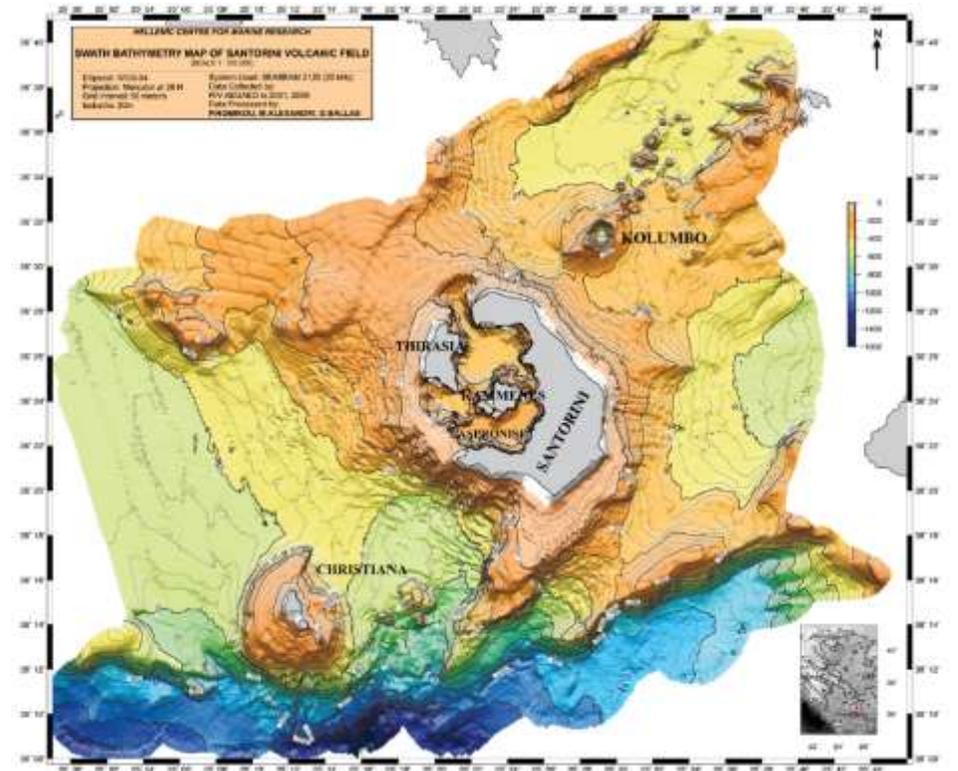


5. Volcanic sources in the NEAM region, eruption-linked wave generation, and lessons from historical events

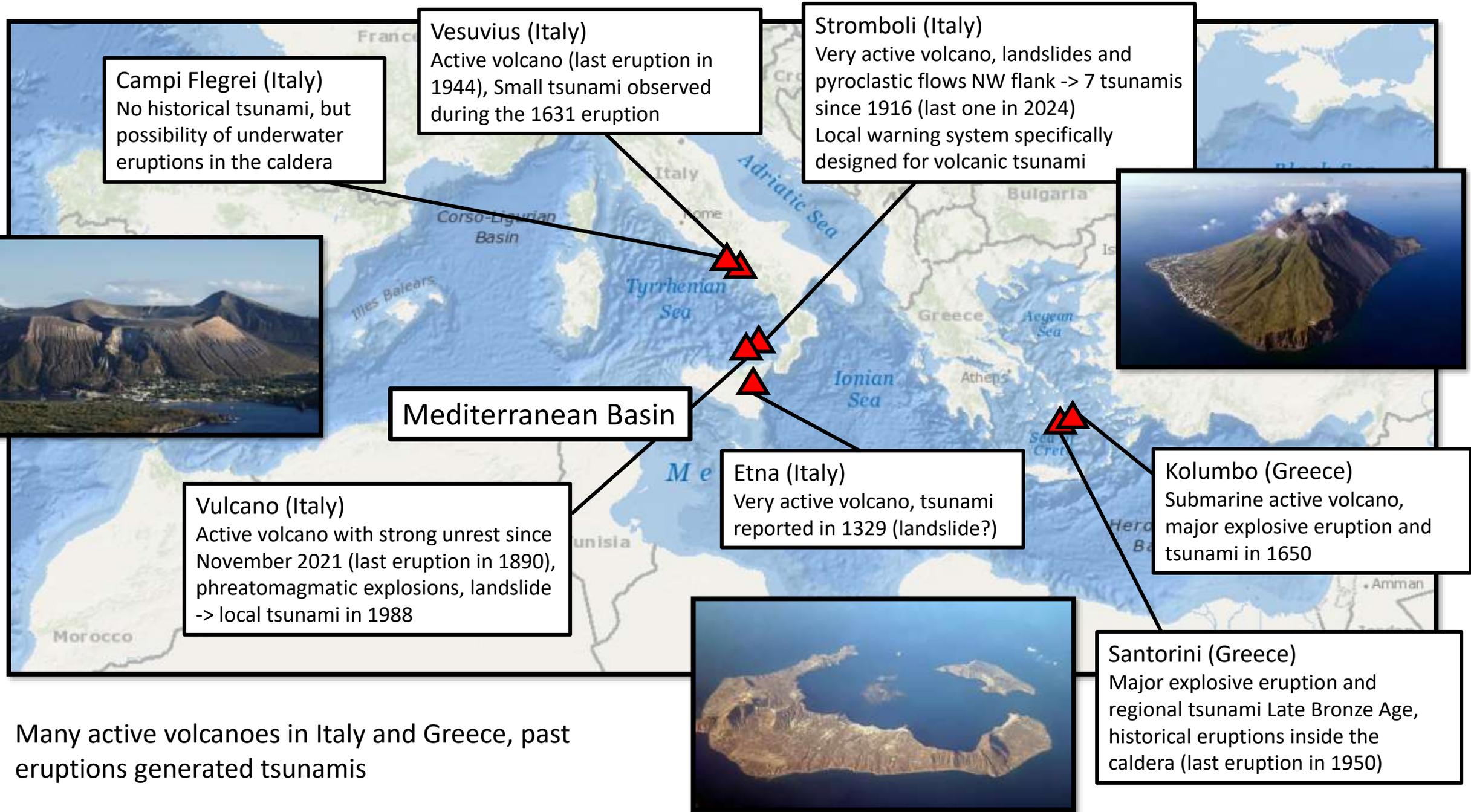
Raphaël Paris

Laboratoire Magmas & Volcans
CNRS - Université Clermont Auvergne
FRANCE

1. Brief presentation of volcanoes that might generated tsunamis in the NEAM region
2. Types of volcanoes and types of eruptions, and source mechanisms of tsunamis
3. Lessons learnt from past examples of tsunamigenic eruptions
4. Perspectives for volcanic tsunami hazard assesment



Stromboli 2002



Campi Flegrei (Italy)
 No historical tsunami, but possibility of underwater eruptions in the caldera



Vesuvius (Italy)
 Active volcano (last eruption in 1944), Small tsunami observed during the 1631 eruption

Stromboli (Italy)
 Very active volcano, landslides and pyroclastic flows NW flank -> 7 tsunamis since 1916 (last one in 2024)
 Local warning system specifically designed for volcanic tsunami



Mediterranean Basin

Vulcano (Italy)
 Active volcano with strong unrest since November 2021 (last eruption in 1890), phreatomagmatic explosions, landslide -> local tsunami in 1988

Etna (Italy)
 Very active volcano, tsunami reported in 1329 (landslide?)

Kolumbo (Greece)
 Submarine active volcano, major explosive eruption and tsunami in 1650



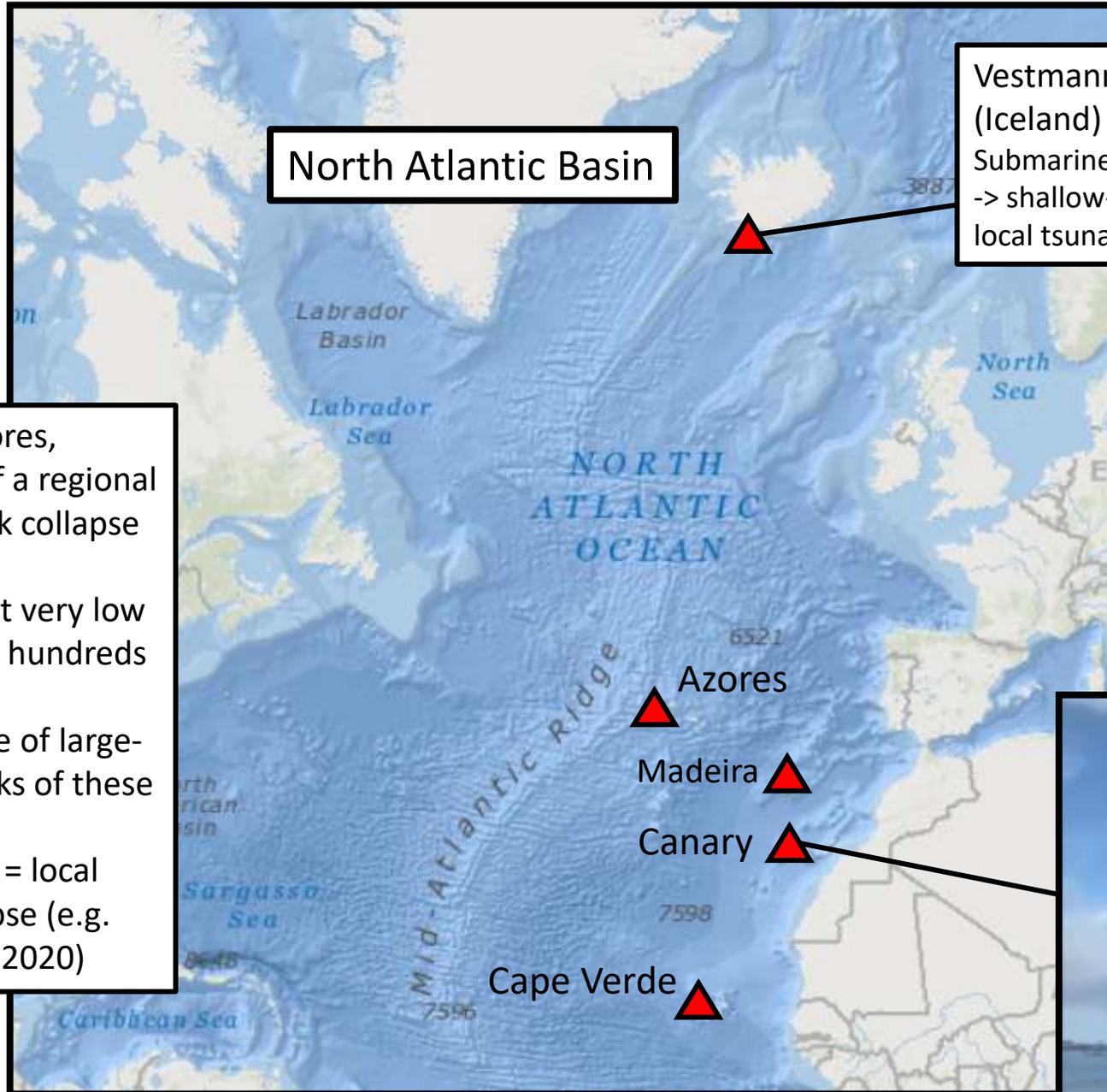
Santorini (Greece)
 Major explosive eruption and regional tsunami Late Bronze Age, historical eruptions inside the caldera (last eruption in 1950)

Many active volcanoes in Italy and Greece, past eruptions generated tsunamis

Probability for a volcanic tsunami in the North Atlantic Basin is low, but local tsunami sources should not be neglected

Ocean islands (Canary, Azores, Madeira) and the threat of a regional tsunami generated by flank collapse

- > very high-magnitude but very low recurrence events (tens to hundreds of thousands of years)
- > no present-day evidence of large-scale instability of the flanks of these islands
- > most probable scenario = local tsunamis due to cliff collapse (e.g. Madeira 1930, La Gomera 2020)



North Atlantic Basin

Vestmann Islands and Reykjanes ridge (Iceland)
Submarine eruptions along the Mid-Atlantic Ridge -> shallow-water phreatomagmatic explosions and local tsunamis.



Possible sources of tsunamis differ from one volcano to another

	Volcano type			
Tsunami source	Coastal / island stratovolcano	Submarine stratovolcano	Shallow-water caldera	Oceanic shield volcano
Subaerial landslide				
Submarine landslide				
Underwater explosion				
Column collapse				
Pyroclastic flow				
Atmospheric forcing				
Caldera collapse				
Volcano-tectonic earthquake				
<i>Examples</i>	<i>Stromboli, Unzen</i>	<i>HTHH, Kick'em Jenny</i>	<i>Rabaul, Krakatau</i>	<i>Kilauea, Fournaise</i>

Examples NEAM region

Stromboli
Vulcano

Kolumbo

Santorini

Canary Islands
Azores

-> All types of volcanoes are represented in the NEAM region

Possible sources of tsunamis differ from one type of eruption to another

		Source mechanisms of volcanic tsunamis							
		Gravitational		Eruptive				Tectonic	
Type of eruption	Example	Subaerial landslide	Submarine landslide	Underwater explosion	Column collapse	Pyroclastic flow	Atmospheric forcing	Caldera collapse	Volcano-tectonic earthquake
Phreatomagmatic eruption in shallow waters	<i>Iceland, Azores, Campi Flegrei</i>		■	■		■			
Explosive paroxysm of a coastal stratovolcano	<i>Stromboli Vulcano</i>	■	■			■			
Explosive eruption with dome growth and collapse	<i>no example?</i>	■	■			■			
Plinia eruption forming a subaerial caldera	<i>Santorini</i>	■				■	■		
Plinian eruption forming a submarine caldera	<i>Kolumbo</i>		■		■	■	■	■	■

-> All types of source mechanisms of volcanic tsunamis should be considered in the NEAM region

Volcanic tsunamis ~5% of all listed tsunamis

~20 volcanic tsunamis since the XVIIth century in the NEAM region

-> few damages, very few fatalities

BUT

Recent events such as the 2002 Stromboli tsunami could have been deadly if occurring in summer

Past (prehistorical) eruptions generated larger-intensity tsunamis, as compared to the historical ones:

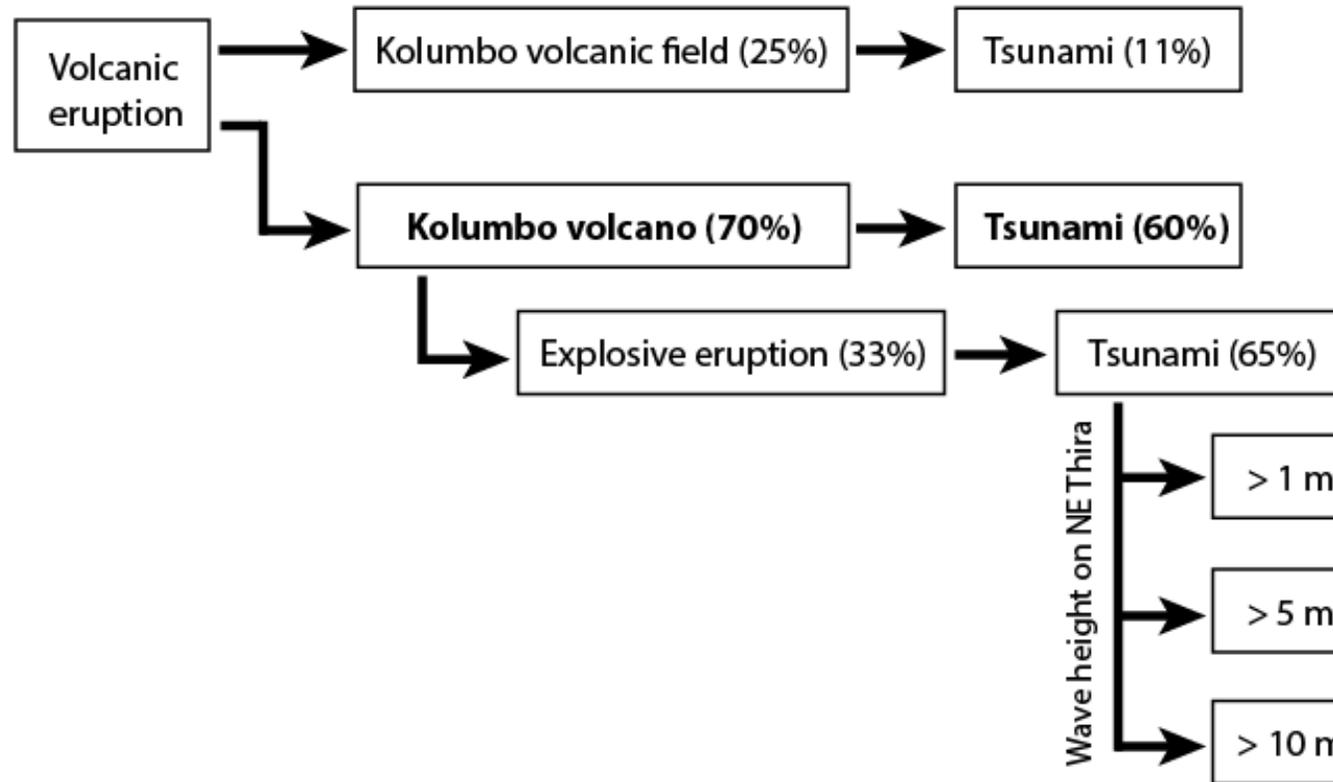
- Minoan (Late Bronze Age) eruption of Santorini
- Collapse of the Sciara del Fuco in Stromboli ~5 kyrs ago

Volcanic tsunami hazard assesment in the NEAM region is challenging because:

- There are no standard operating procedures between volcano observatories and tsunami warning centers
- No adequate monitoring, with the exception of Stromboli
- The diversity of volcanoes and eruptions -> diversity of source mechanisms and possible scenarios

Expert elicitation organized in 2023

What would be the probability to have a tsunami and which magnitude of tsunami in the case of a future eruptions at Kolombo submarine volcano?



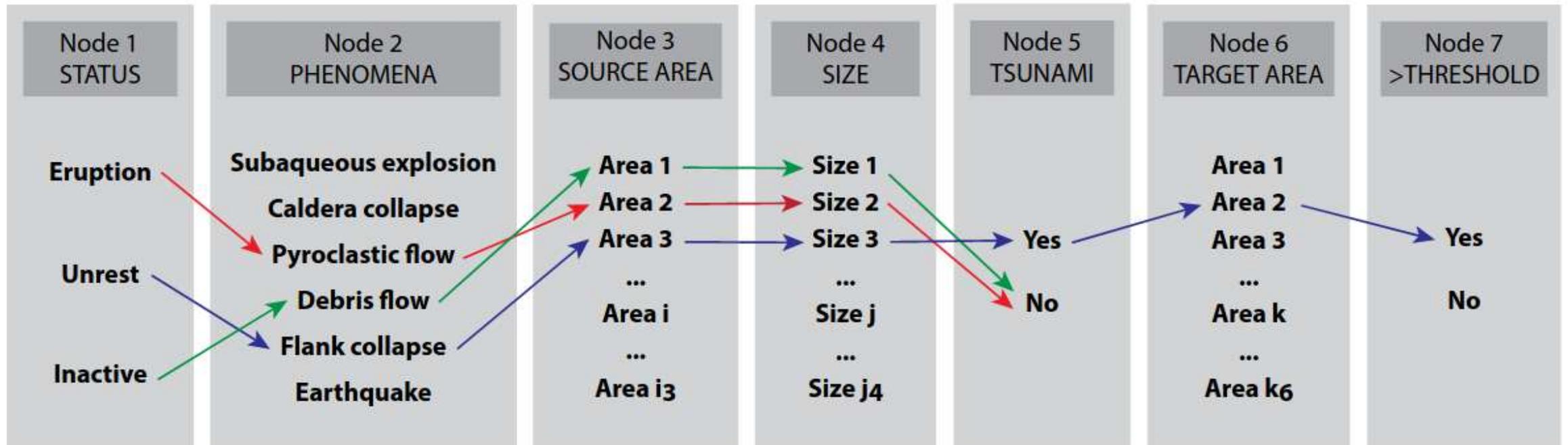
Tadini et al, submitted

Submarine explosion energy	Pyroclastic flow volume flux	Landslide volume crater - flanks	Caldera collapse duration
> 3×10^{14} J	> 10^5 m ³ /s	> 0.002 km ³	< 20 min
> 5.6×10^{14} J	> 10^6 m ³ /s	> 1.2 km ³	< 5 min
> 2.6×10^{16} J	> 10^7 m ³ /s	> 0.15 km ³	< 1 min

Moving from a deterministic to a probabilistic approach

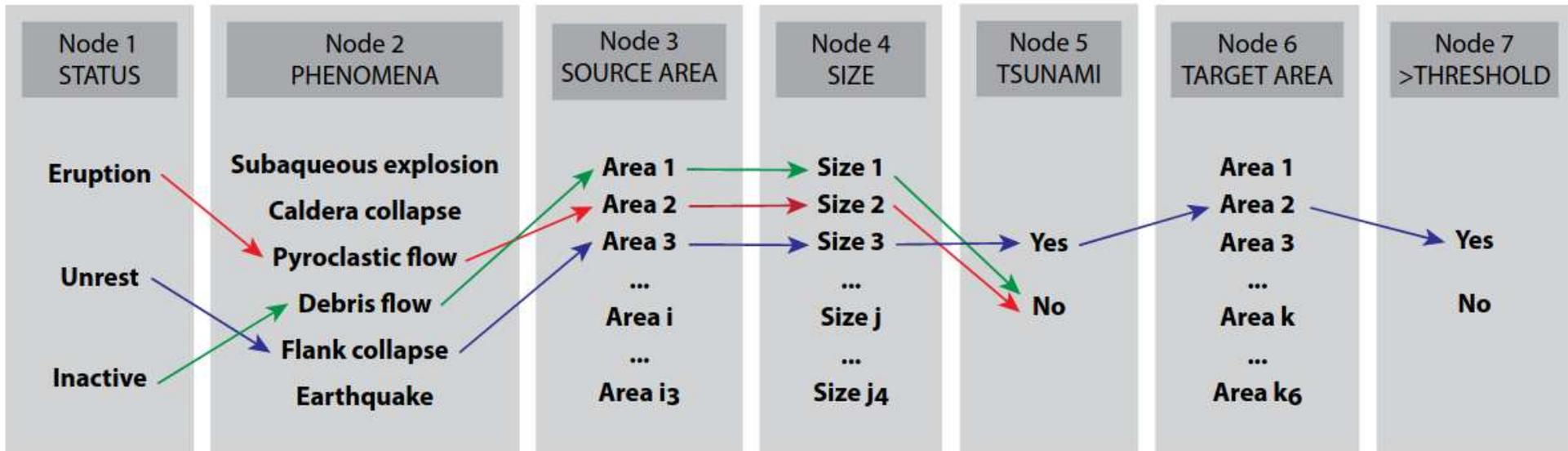
Database of numerical simulations

Introducing a bayesian Event Tree for Volcanic Tsunami Hazard Assessment (PVTHA)

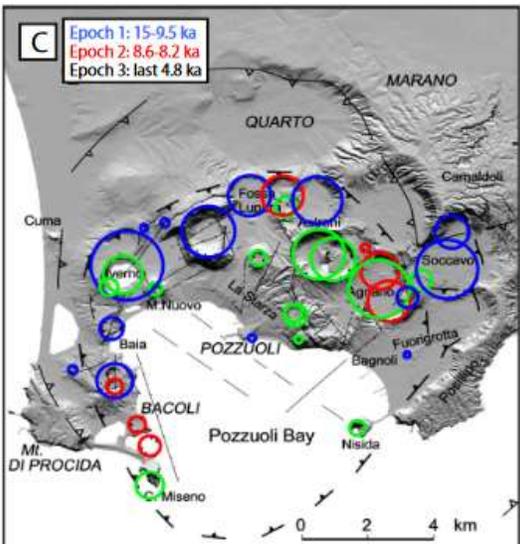


Arrows indicate potential paths which involve different volcanic states (node 1), phenomena (node 2), source position and size (nodes 3 and 4), and tsunami generation (node 5).

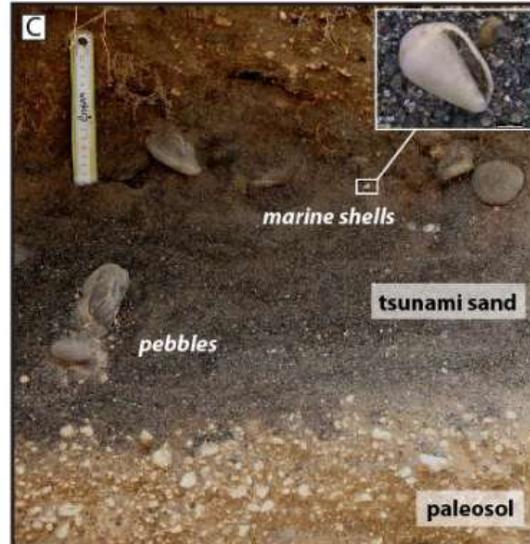
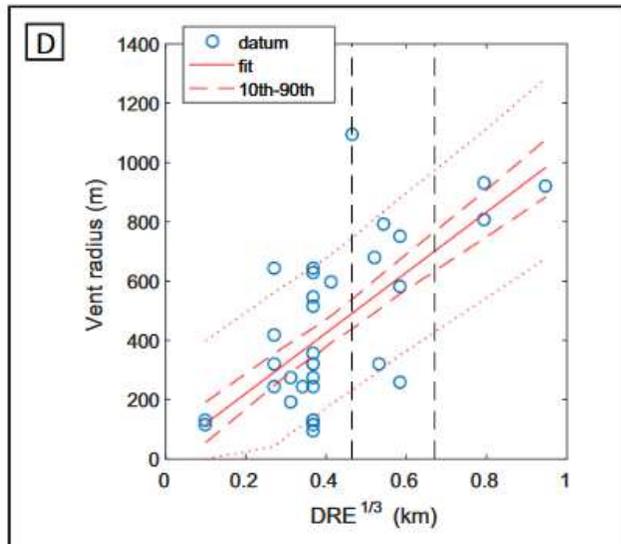
Blue arrows indicate a possible scenario (among others) generating a tsunami (node 5) and leading to the evaluation of hazard at a given location (nodes 6) and exceeding a certain threshold of wave height at the shoreline (7).



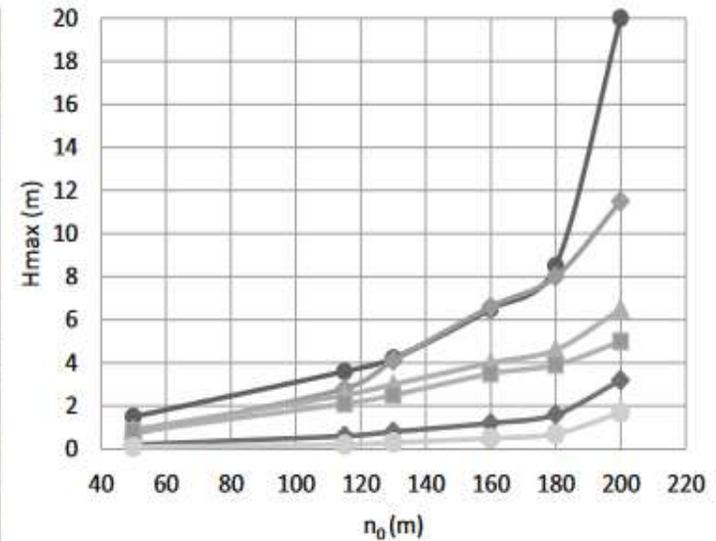
GEOLOGY **PHYSICS** **MODELING**



Paris et al. 2019a (Campi Flegrei)



Ulvrova et al. 2016 (Kolumbo)



Paris et al. 2019b (Lake Taal)



Burning Question(s)

- **Mr Domenico Mangione** is a volcanic risk management specialist employed in the Volcanic Risk Unit of the Italian National Civil Protection Department since 2007.



The tsunami early-warning system at Stromboli

Dr. Domenico Mangione
National Civil Protection Department
Volcanic Risk Unit



PROTEZIONE CIVILE
Presidenza del Consiglio dei Ministri
Dipartimento della Protezione Civile

Stromboli volcano

ISOLE EOLIE



Activity type: persistent strombolian

Location: Sicilia – Tyrrhenian Sea

Height: 924 m s.l.m.

Area: 12 km²

Activity onset: 200.000 years ago

Last event: 2024, effusive/explosive

Current volcanic alert level: YELLOW

Population: from 400 up to > 5.000



HAZARD ANALYSIS AND EARLY DETECTION



ISTITUTO NAZIONALE DI GEOFISICA E VULCANOLOGIA



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SCIENZE DELLA TERRA

PREVENTION, ALARM AND RESPONSE



PROTEZIONE CIVILE
Presidenza del Consiglio dei Ministri
Dipartimento della Protezione Civile



Tsunami hazard volcanic sources



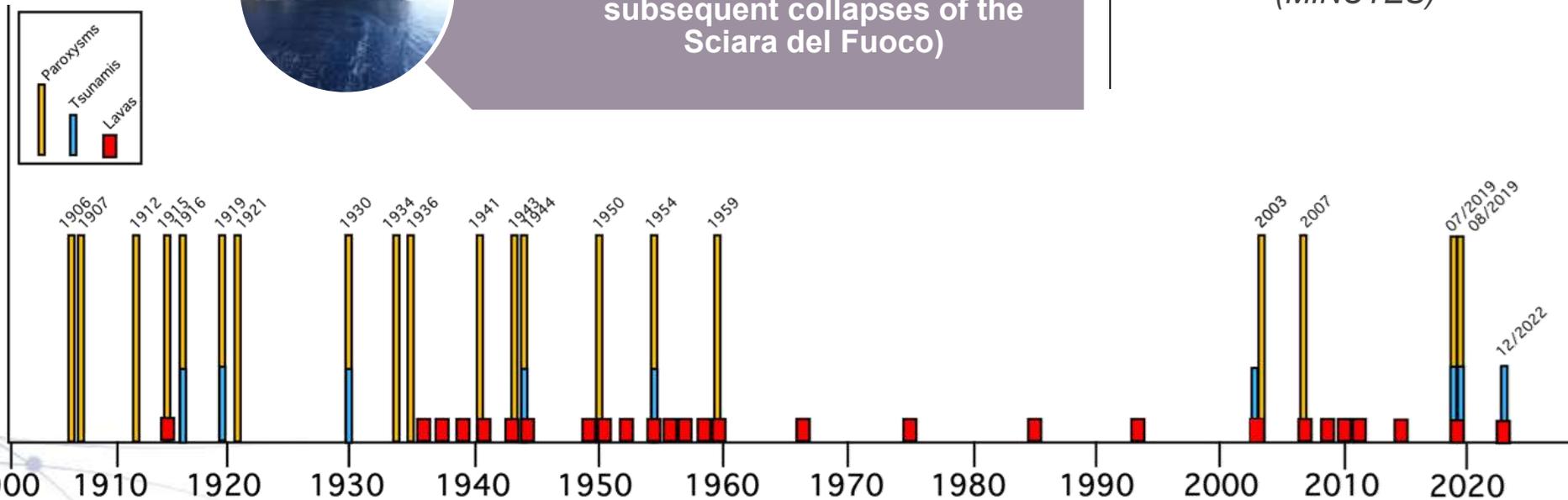
Partial collapses of the
 Sciara del Fuoco
 (magmatic intrusions)

*SLOW VOLCANIC DYNAMIC
 (DAYS)*



Paroxysmal explosions
 (pyroclastic flows and/or
 subsequent collapses of the
 Sciara del Fuoco)

*FAST VOLCANIC DYNAMIC
 (MINUTES)*



Medium-short term volcanic early-warning system



Partial collapses of the
 Sciara del Fuoco
 (magmatic intrusions)

SLOW VOLCANIC DYNAMIC
 (DAYS)

STROMBOLI - VOLCANIC ALERT LEVEL SYSTEM

ALERT LEVEL	VOLCANIC ACTIVITY STATUS	ONGOING OR EXPECTED HAZARDS	POSSIBLE IMPACT SCENARIOS
 GREEN	QUIESCENT	No eruptive activity and normal degassing from the summit craters.	Toxic gas emissions may reach downwind sectors
 YELLOW	LOW TO MEDIUM ERUPTIVE ACTIVITY Monitoring parameters from low to medium values	LOW OR MEDIUM STROMBOLIAN EXPLOSIVE ACTIVITY, EVENTUALLY ASSOCIATED WITH: • Short-lived (hours) lava overflows along the Sciara del Fuoco • Displacements of the crater area and/or of the Sciara del Fuoco involving small or medium volumes.	<ul style="list-style-type: none"> • Tephra fallout (ranging from centimeters to decimeters) in the crater area and, eventually, up to Pizzo sopra La Fossa. • Rock falls or debris slides along the Sciara del Fuoco, propagating tens of meters into the sea.
		HIGH STROMBOLIAN ERUPTIVE ACTIVITY	<ul style="list-style-type: none"> • Tephra fallout (ranging from centimeters to decimeters in size) in the summit area, eventually affecting the hiking trails • Rock falls or debris avalanches along the Sciara del Fuoco, propagating tens of meters into the sea. • Hydro-magmatic explosions along the Sciara del Fuoco coastline caused by lava-sea interaction. Fallout of big sized ballistics may reach several hundred meters from the coast. • Wildfires could propagate very quickly towards populated areas • Emission of toxic gases from the lava sea-entry.
		VERY HIGH STROMBOLIAN EXPLOSIVE ACTIVITY	<ul style="list-style-type: none"> • Tephra fallout (ranging from centimeters to meters in size) in the summit area, eventually affecting the hiking trails • Ash fallout affecting the downwind sectors with disruptions to the populated areas, streets and infrastructures • Rock falls or debris avalanches along the Sciara del Fuoco, propagating hundreds of meters into the sea. • Tsunami waves affecting island's coastal populated areas and infrastructures. Other Aeolian Islands and coastal areas of the Southern Tyrrhenian might be affected as well, depending on the size of the tsunami • Hydro-magmatic explosions along the Sciara del Fuoco coastline caused by lava-sea interaction. Fallout of big sized ballistics may reach several hundred meters from the coast • Emission of toxic gases from the lava sea-entry • In case of magma intrusions outside of the Sciara del Fuoco, lava flows could affect populated areas, streets and infrastructures • Extensive wildfires could propagate very quickly towards populated areas.



VERY HIGH ERUPTIVE ACTIVITY

Monitoring parameters on very high values

VERY HIGH STROMBOLIAN EXPLOSIVE ACTIVITY, ASSOCIATED WITH:

- Effusive vents opening along the Sciara del Fuoco feeding lava flows
- Displacement of emerged and submerged sectors of the Sciara del Fuoco flank involving very large volumes³, caused by magma intrusion
- Magma intrusion outside of the Sciara del Fuoco, eventually followed by the opening of eruptive vents.

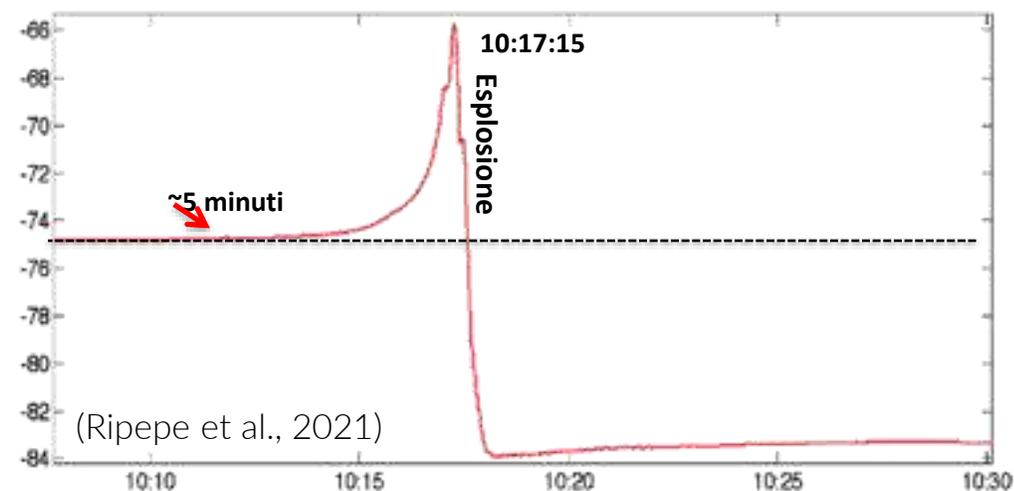
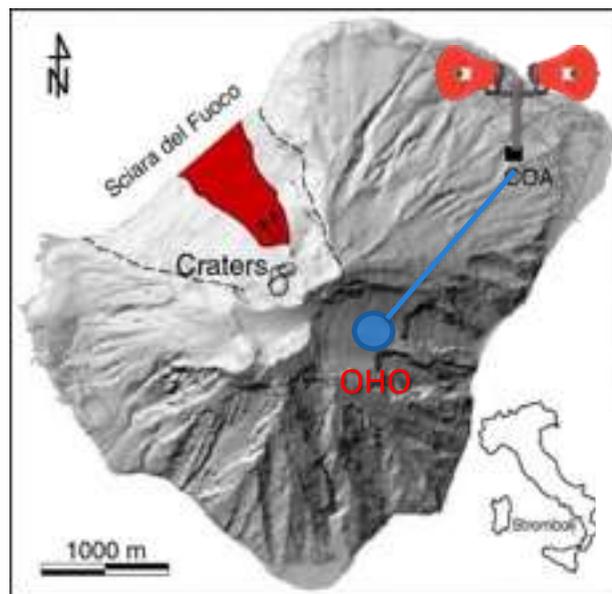
Very short-term volcanic early-warning system



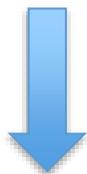
Paroxysmal explosions
(pyroclastic flows and/or
subsequent collapses of the
Sciara del Fuoco)

FAST VOLCANIC DYNAMIC
(MINUTES)

- Based on one tiltmeter managed by Università di Firenze
- Forecast: between 1 and 5 minute, based on the size of event
- Sirens automatically activated: Stromboli and Ginostra
- Sound followed by a message in Italian/English (2 m 30 sec.)



Volcanic tsunamis early-warning system



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EARLY DETECTION



- 8 sirens in Stromboli
- 2 in Panarea



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Dipartimento della Protezione Civile



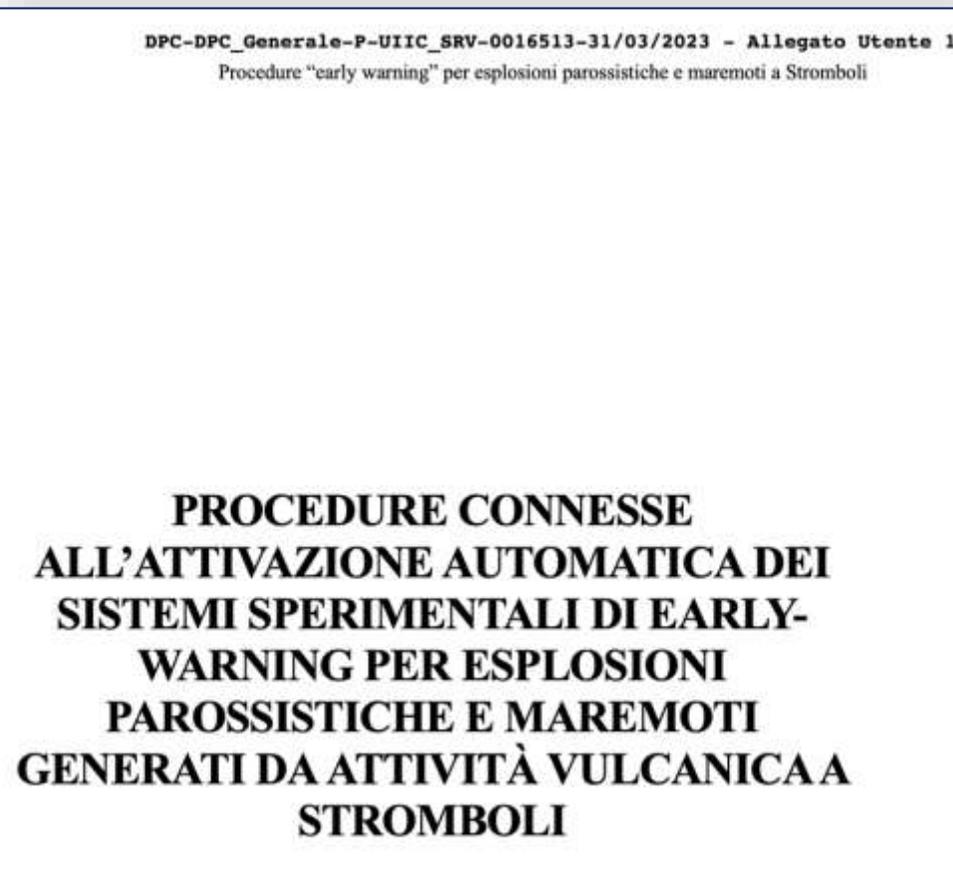
**SMS
e-mails**

- ING V
- Regional civil protection
- Messina Prefecture
- Municipality
- Coast guard

ALERTING

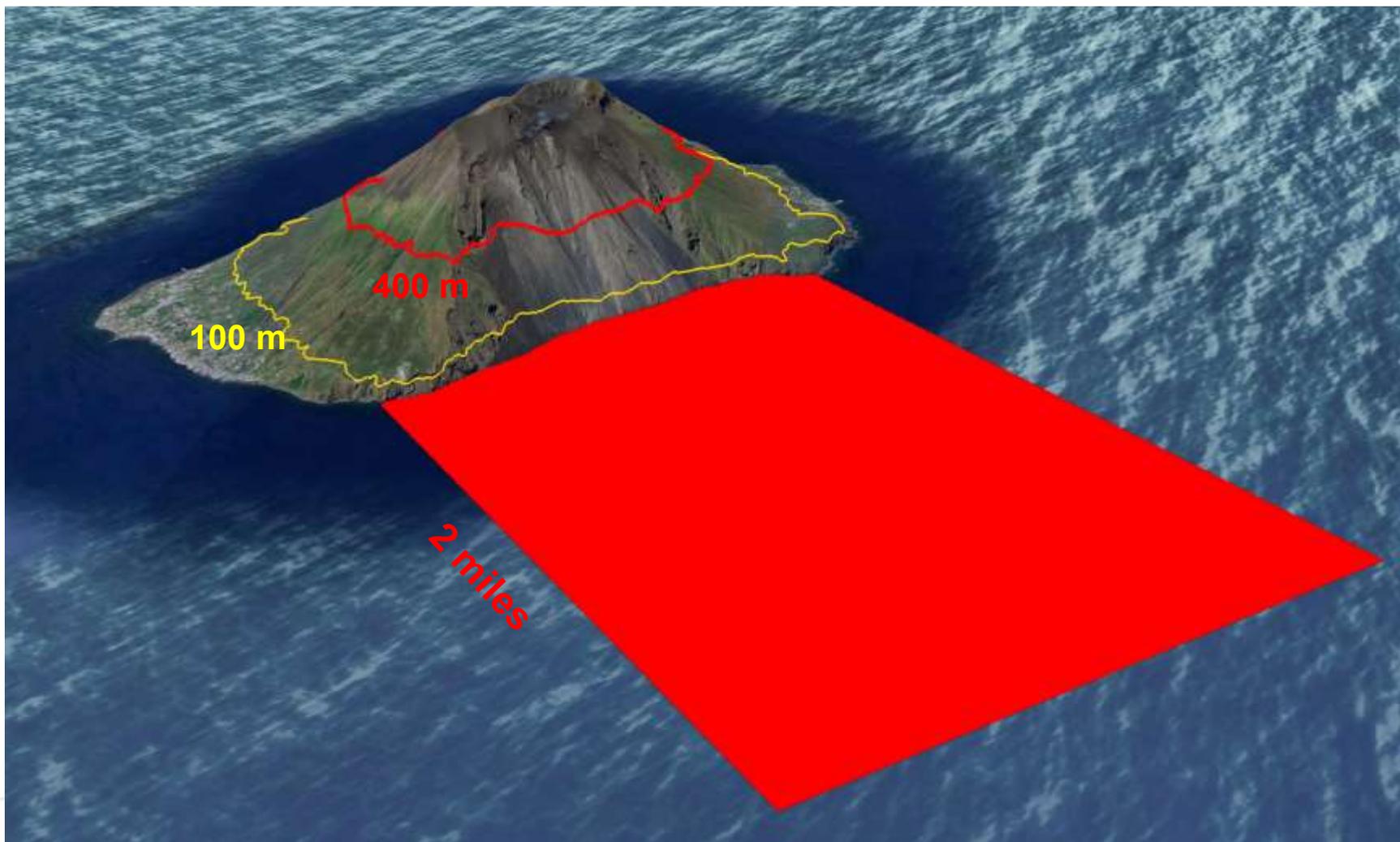


National civil protection plan



Standard operating procedures

Risk mitigation



**PERICOLO MAREMOTO
TSUNAMI HAZARD**

IN CASO DI:

- Tsunami
- Forza improvvisa del vento
- Maree più inalte della norma
- Scossa della terra

ALLONTANATI IMMEDIATAMENTE DALLA COSTA

IN CASO DI:

- Partecipare
- Stare vicino agli edifici
- Abbandonare il via
- Stare al sicuro

LEAVE THE COASTAL AREA IMMEDIATELY

**RISCHIO VULCANICO
VOLCANIC RISK**

**PERICOLO ESPLOSIONE PAROSSISTICA
PAROXYSMAL EXPLOSION HAZARD**

IN CASO DI:

- Forza improvvisa del vulcano
- Forza del vento

ALLONTANATI IMMEDIATAMENTE DA QUEST'AREA E RAGGIUNGI IL CENTRO ABITATO

IN CASO DI:

- Stare vicino agli edifici
- Stare al sicuro

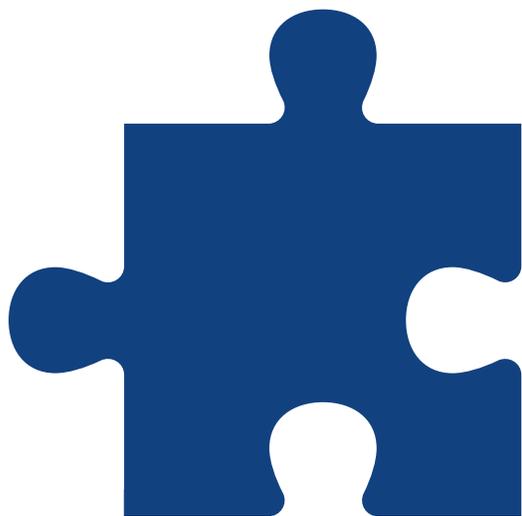
LEAVE THIS AREA IMMEDIATELY AND REACH THE VILLAGE

**VIA DI ALLONTANAMENTO
ESCAPE ROUTE**

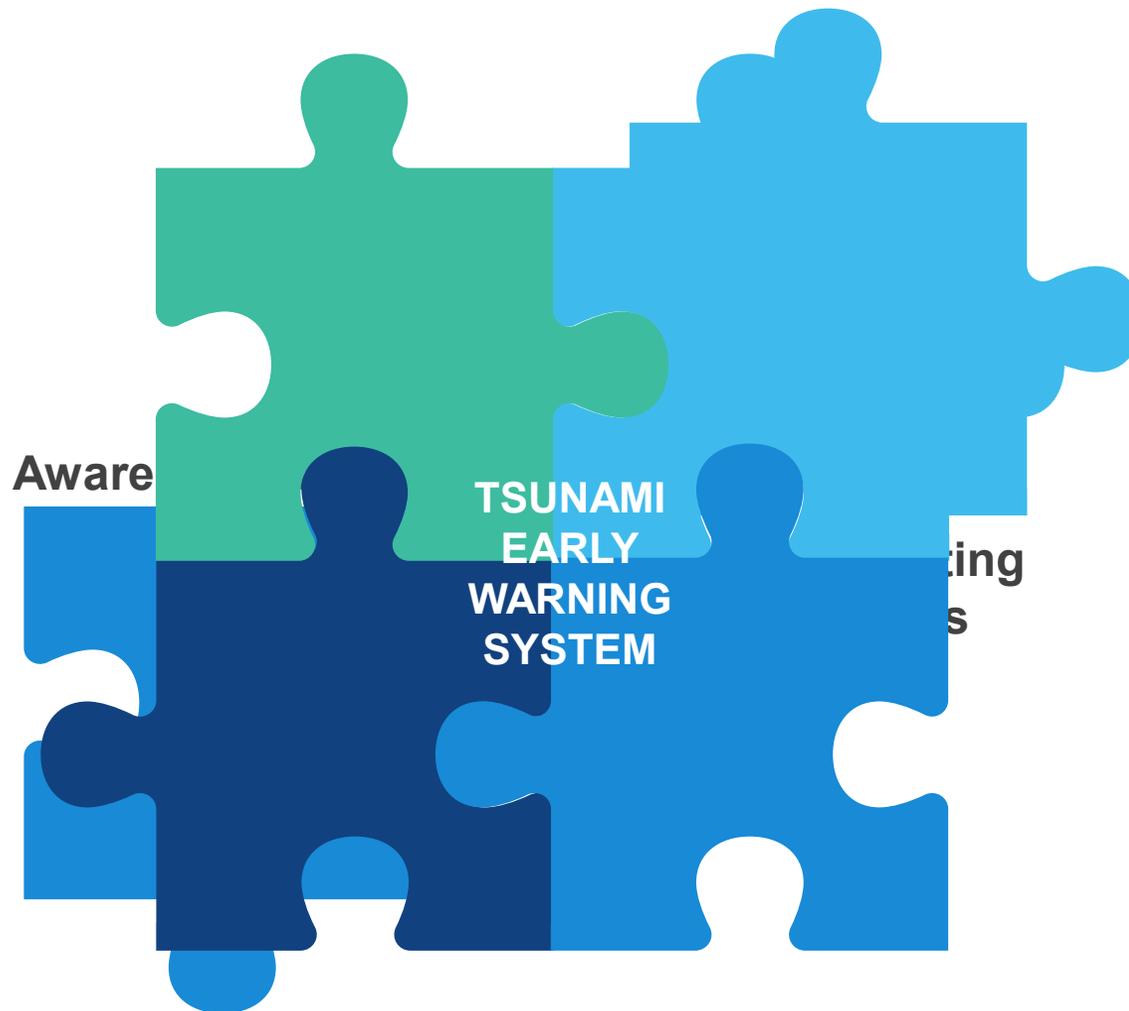
AREA DI ATTESA WAITING AREA

**AREA DI ATTESA
WAITING AREA**

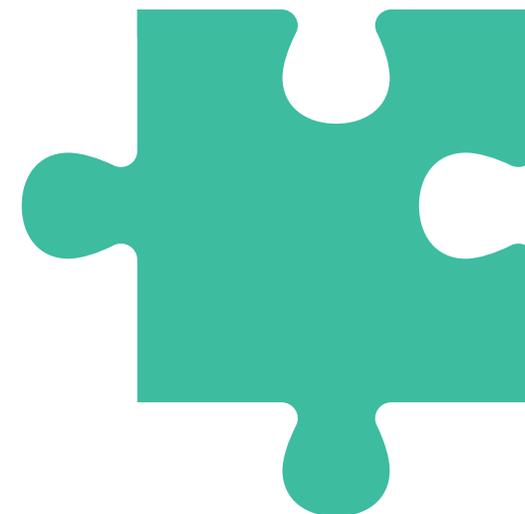
Key priorities



High performance monitoring and early detection, data transmission, infrastructure and cybersecurity



Update of the civil protection plan





Generated with AI



THANK YOU

domenico.mangione@protezionecivile.it



Burning Question(s)

Panelist

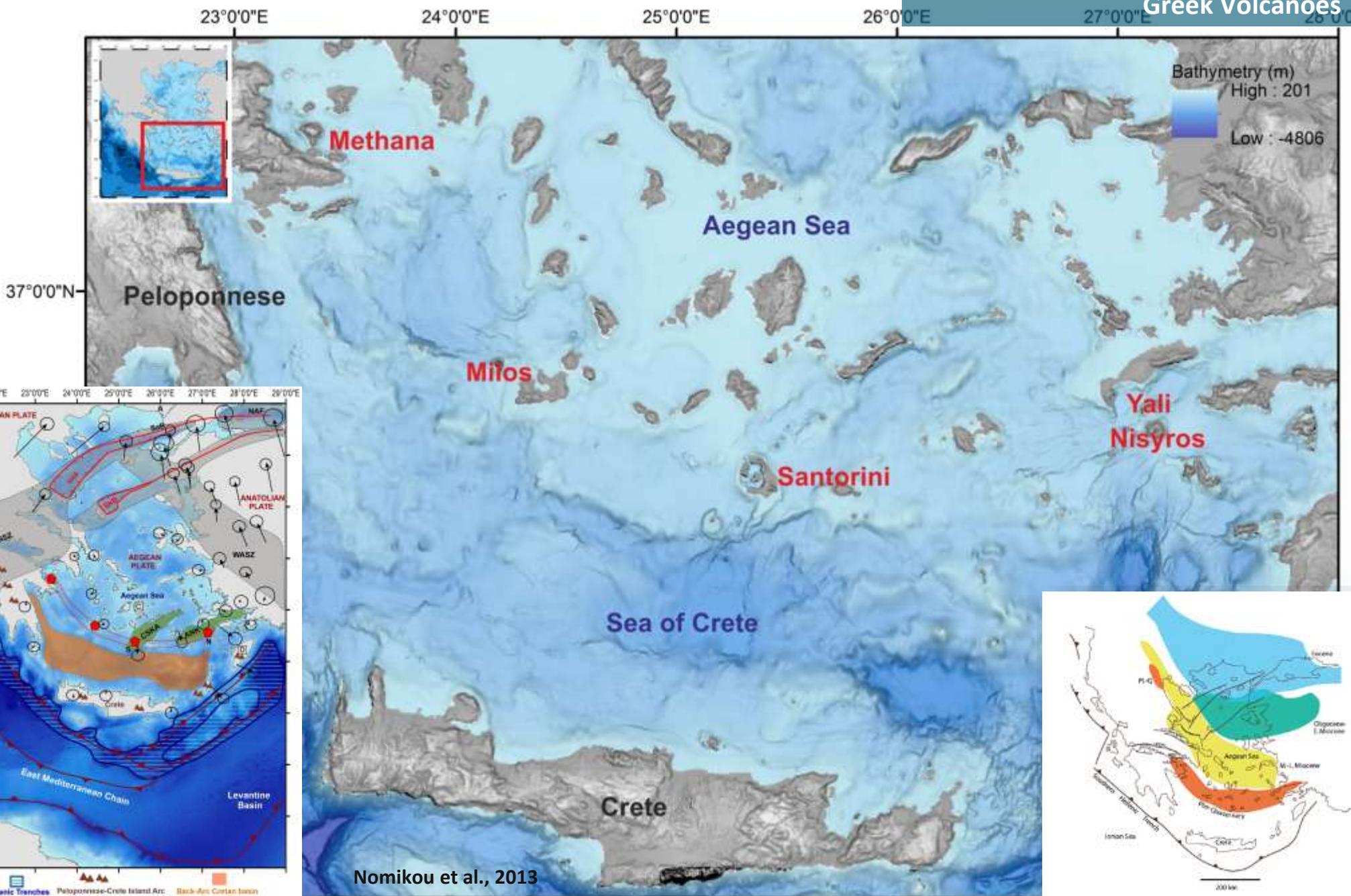
Prof. Paraskevi Nomikou,
National and Kapodistrian
University of Athens,
Greece



NEAM Regional Online Webinars on Tsunamis Generated by Non-Seismic Sources

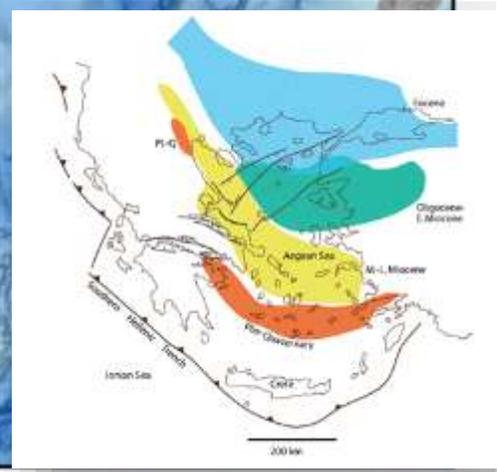
New findings on the Kolumbo system near Santorini and its implications for hazard assesment

Nomikou Paraskevi



The **four active volcanic centres** of the Aegean arc and another ten inactive volcanic centres activated during Oligocene – Middle Pleistocene following its southward migration across the Aegean Sea are described with emphasis on their tectonic signature. They are all localized within neotectonic and active tectonic grabens, resulting from the back-arc extension of the Hellenic arc and trench system throughout its Late Eocene – Present evolution.

Nomikou et al., 2013

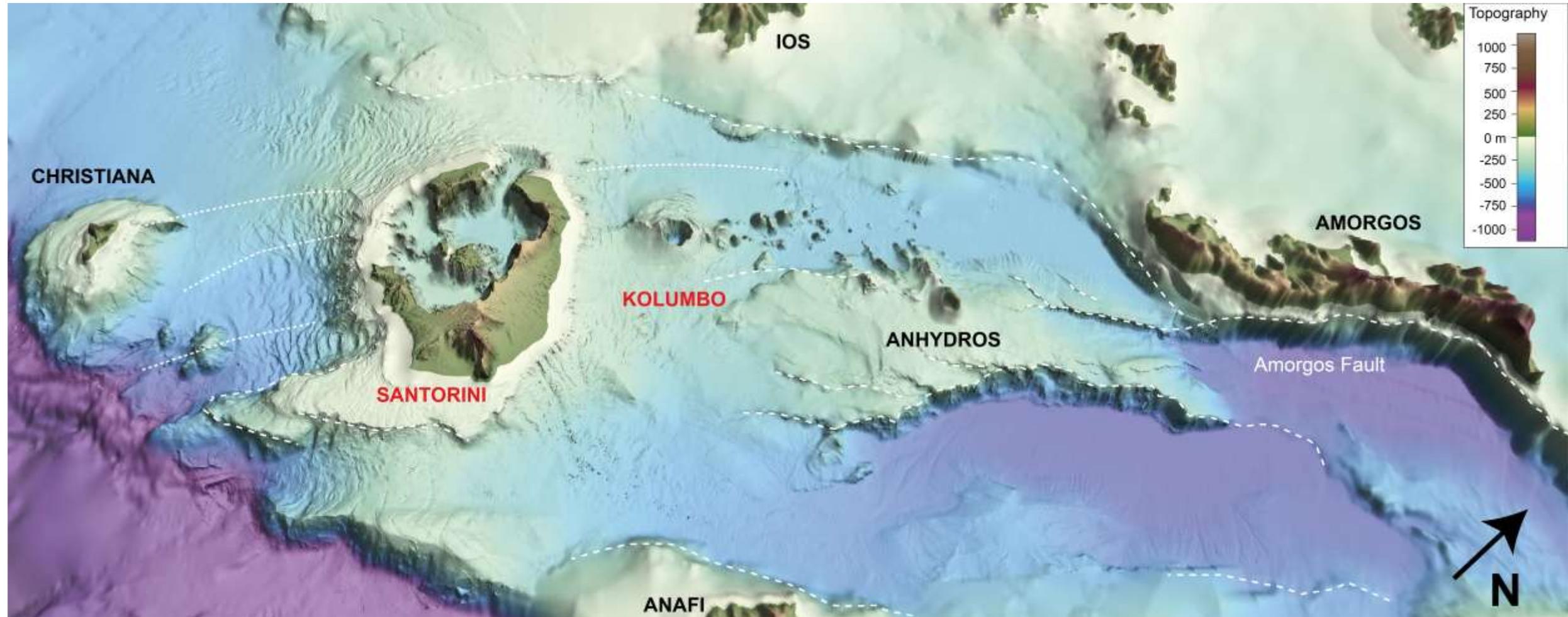


Royden & Papanikolaou (2011)



R/V AEGEAO: 2001, 2006, 2012, 2013, 2014, 2023
R/V ENDEAVOR: 2015
E/V NAUTILUS: 2010, 2011
R/V MARCUS LANGSETH: 2015
R/V POSEIDON: 2006, 2017, 2019
YPAPANTI shuttle boat: 2015
OCEAN LINK: 2019
R/V EUROPE: 2022, 2023, 2025
E/V FILIA: 2022, 2023
JOIDES Resolution: Dec 2022-Feb 2023
MARIA MERIAN: Dec 2024, April 2025
DISCOVERY: March 2025



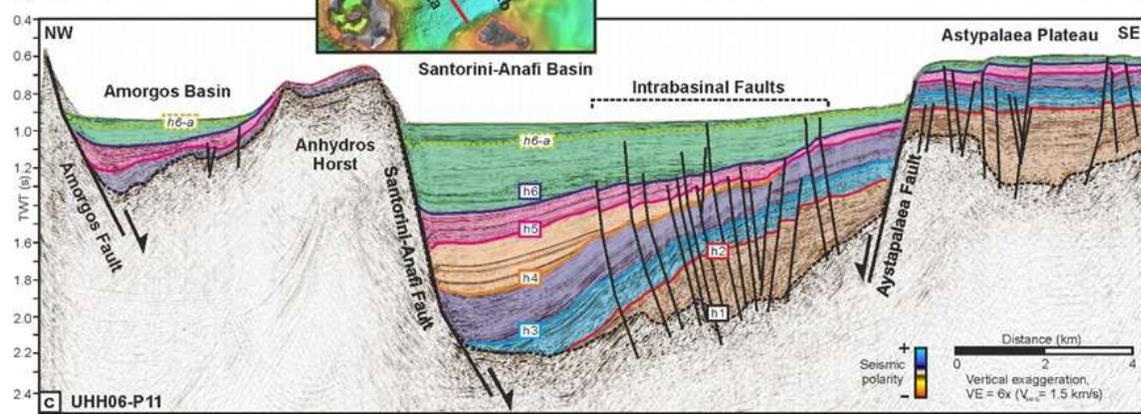
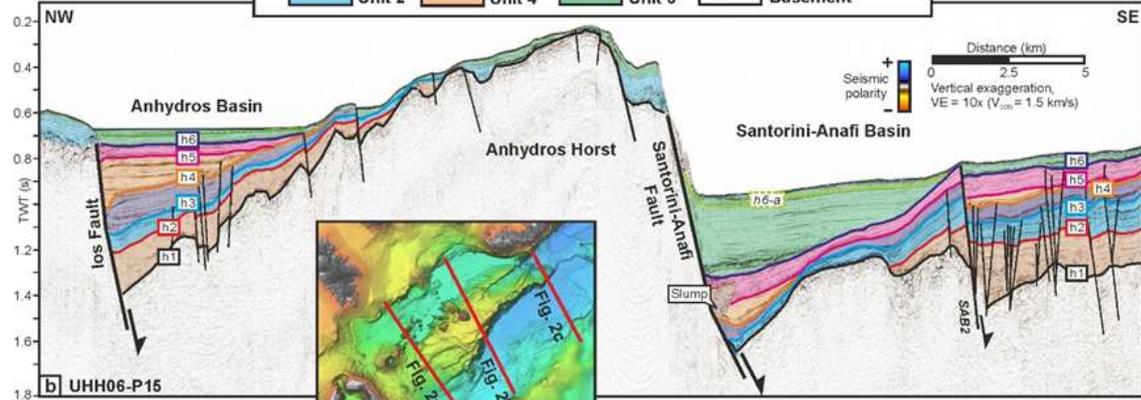
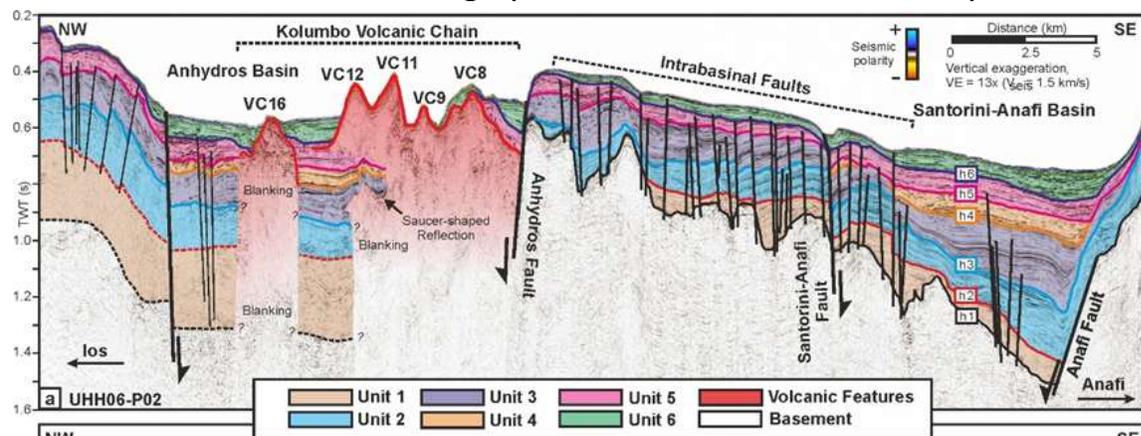


(Nomikou et al., 2019; Preine et al., 2022 and MSM132 scientific party)

Most cones of the Kolumbo Volcanic Chain are monogenetic eruptive centres, generally associated with the rapid ascent of small batches of relatively primitive magma with bulk volumes of less than 0.2 km^3 dense-rock equivalent (Nomikou et al., 2012). The cones' lack of pronounced summit craters suggests only mildly explosive formation, and the absence of slope failure scars indicate minor tsunamigenic potential (Schindel , F. et al. 2024).

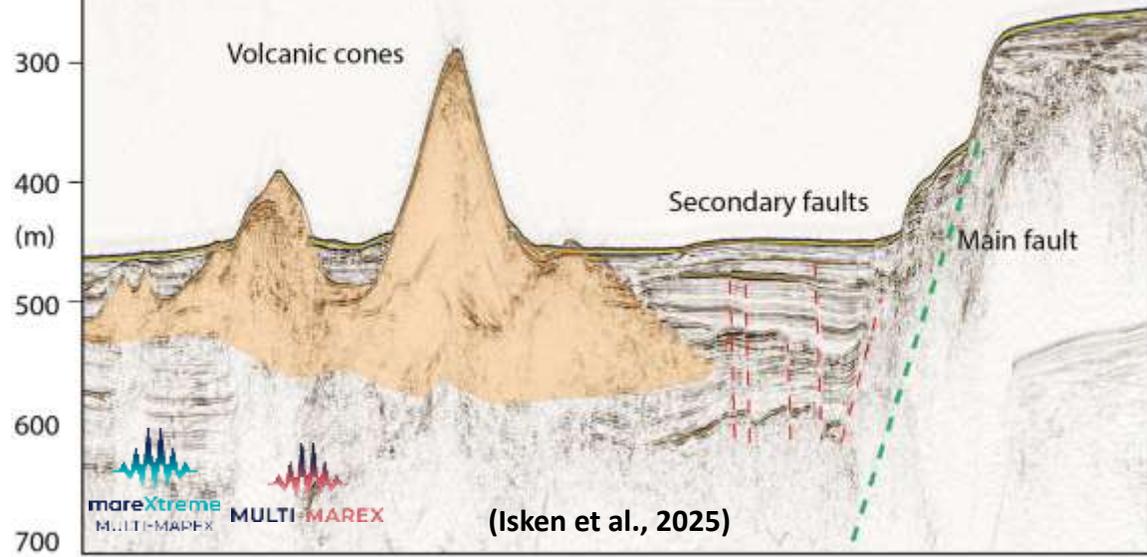
Multi-channel reflection seismic profiles

Highly faulted basement of the Anhydros block

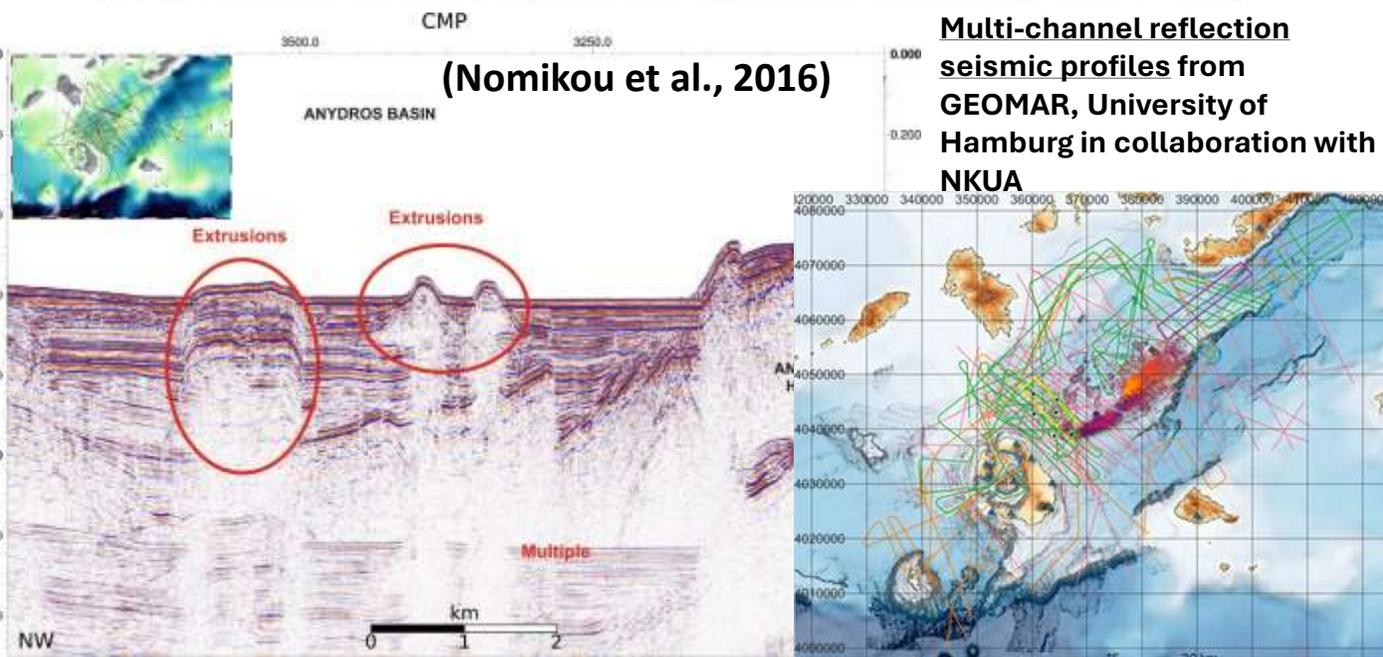


(Preine et al., 2022)

D) The shallow subsurface is disrupted by various sub-kilometre-scale fault zones that control the location of fluid escape structures on the seafloor, evidenced by the linear alignment of volcanic centres of the KVC, both of which form on southeast-dipping faults.



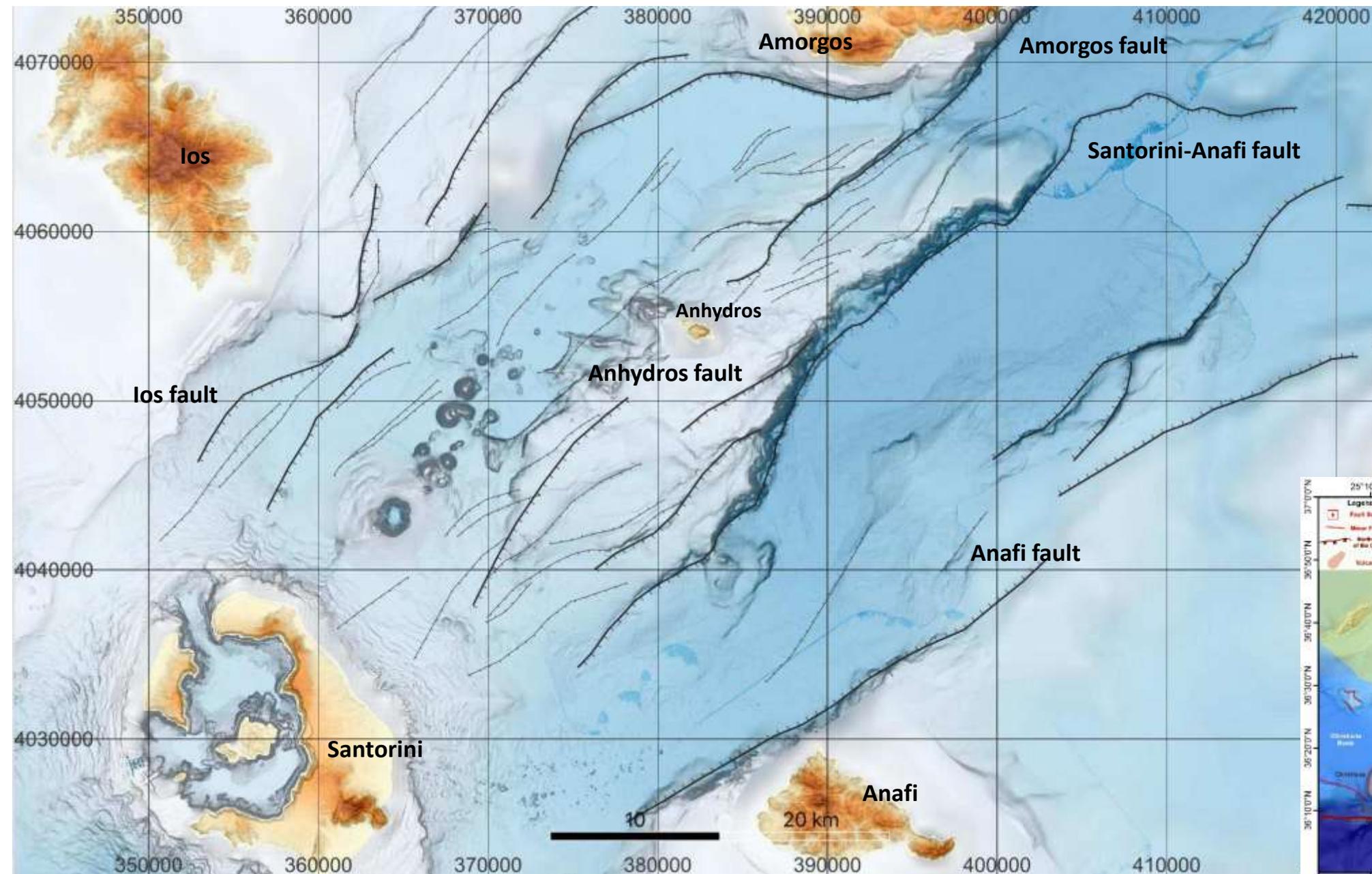
(Isken et al., 2025)



(Nomikou et al., 2016)

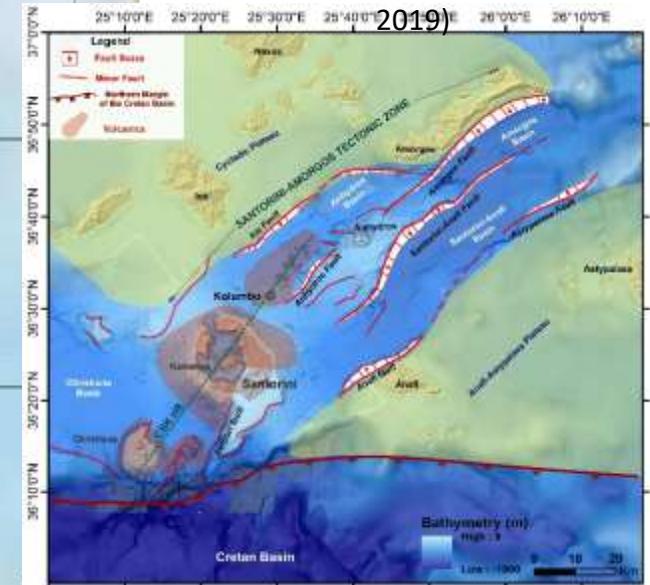
Multi-channel reflection seismic profiles from GEOMAR, University of Hamburg in collaboration with NKUA

Tectonic Map (based on Multi-channel reflection seismic profiles, C. Berndt and MSM132 scientific party, Isken et al., 2025)



The **Anhydros block** is a tilted block that likely represents a large relay ramp structure between the bounding Amorgos and Santorini-Anafi faults (Crutchley, et al. 2023)

(Nomikou et al., 2019)



1956 Amorgos Earthquakes

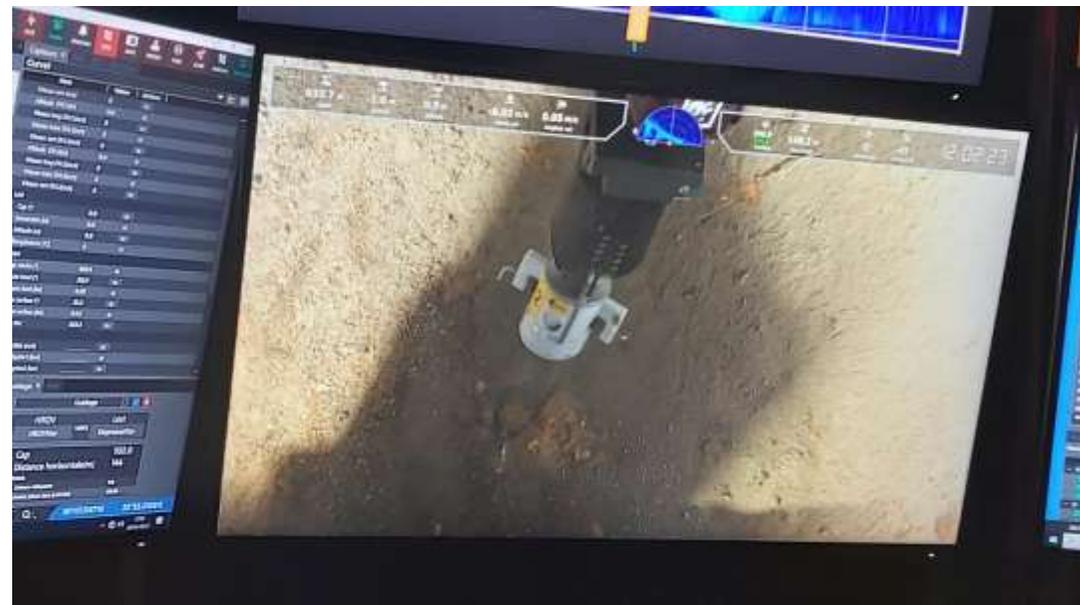


The exceptional event of the 1956 twin Amorgos earthquakes of magnitude 7.5 and 7.2 affected the wider area and produced a large tsunami.

ΠΡΟΕΛΑΜΒΑΝΕΙ ΔΙΑΣΤΑΣΕΙΣ Η ΤΡΑΓΩΔΙΑ ΤΗΣ ΠΛΗΓΙΣΘΗΣΗΣ ΝΗΣΟΥ
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 ΤΗΣ ΣΑΚΤΟΡΗΣ ΜΕΝΕΙ ΑΓΩΣΤΟΣ ΚΑΙ ΠΟΛΥ ΜΕΓΑΛΥΤΕΡΟΣ ΤΟΥ ΑΡΧΙΣΤΟΣ ΥΠΟΛΟΓΙΣΤΕΥΣ
 ΕΠΙΣΤΑΛΑΜΕΝΟΣ ΜΑΣ Κ. Θ. ΔΡΑΚΟΣ ΜΑΣ ΠΕΡΩΡΑΦΕΙ ΤΗΝ ΕΙΚΟΝΑ ΤΗΣ ΚΑΤΑΣΤΡΟΦΗΣ ΜΑΙ 17 2006
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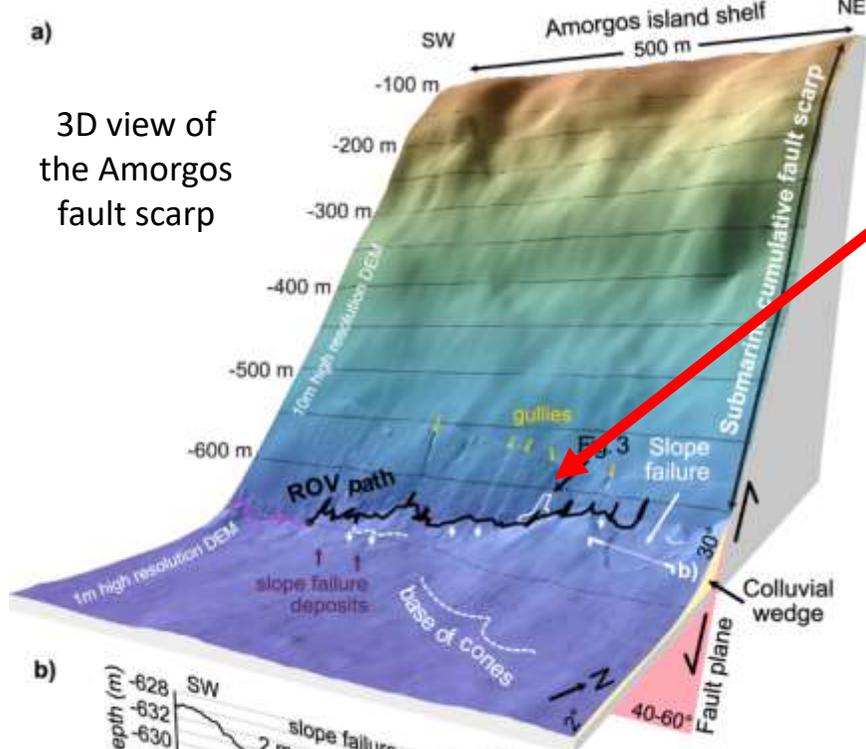
ΜΝΗΜΕΙΟ
ΘΥΜΑΤΩΝ ΣΕΙΣΜΟΥ ΔΕΥΤΕΡΑ 9 ΙΟΥΛΙΟΥ 1956

ΦΗΡΑ	ΗΜΕΡΟΒΙΓΓΙ	ΘΙΑ
ΔΡΟΣΟΥ ΕΥΔΟΚΙΑ	ΒΑΣΙΜΑΚΗ ΑΙΚΑΤΕΡΙΝΗ	ΑΝΑΠΛΩΤΗΣ ΙΑΚΩΒΟΣ
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ΜΥΤΙΛΗΝΑΙΟΥ ΜΑΡΙΑ	ΓΑΒΡΙΛΗ ΜΑΡΟΥΛΙΑ	ΚΑΙ ΔΥΟ ΤΕΚΝΑ
ΣΙΓΑΛΑ ΑΙΚΑΤΕΡΙΝΗ	ΔΑΜΙΓΟΥ ΕΙΡΗΝΗ	ΝΟΜΙΚΟΣ ΝΙΚΟΛΑΟΣ
ΚΑΙ ΠΕΝΤΕ ΤΕΚΝΑ	ΚΑΡΒΟΥΝΗΣ ΜΑΡΚΟΣ	ΝΟΜΙΚΟΥ ΝΙΚΟΛΕΤΤΑ
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ΣΙΓΑΛΑΣ ΜΑΡΚΟΣ	ΣΠΗΛΩΤΗ ΚΑΛΛΙΟΠΗ	ΣΟΡΩΤΟΥ ΕΙΡΗΝΗ
ΠΥΡΓΟΣ	ΑΚΡΩΤΗΡΙ	ΣΟΡΩΤΟΥ ΜΑΡΓΑΡΙΤΑ
ΚΑΜΠΙΤΣΗ ΜΑΡΙΑ	ΒΛΑΧΟΥ ΚΟΥΛΑ	ΚΑΙ ΔΥΟ ΤΕΚΝΑ
ΚΑΡΑΜΟΛΕΤΚΟΣ ΔΗΜΗΤΡΙΟΣ	ΒΛΑΧΟΥ ΜΑΡΓΑΡΙΤΑ	ΣΥΡΙΓΟΣ ΑΠ.
ΦΥΤΡΟΣ ΗΛΙΑΣ	ΣΥΡΙΓΟΥ ΡΟΩΤΟΥ	ΜΕΙΣΑΡΙΑ
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		ΤΕΣΣΕΡΑ ΤΕΚΝΑ



a)

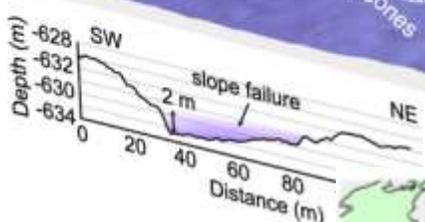
3D view of the Amorgos fault scarp



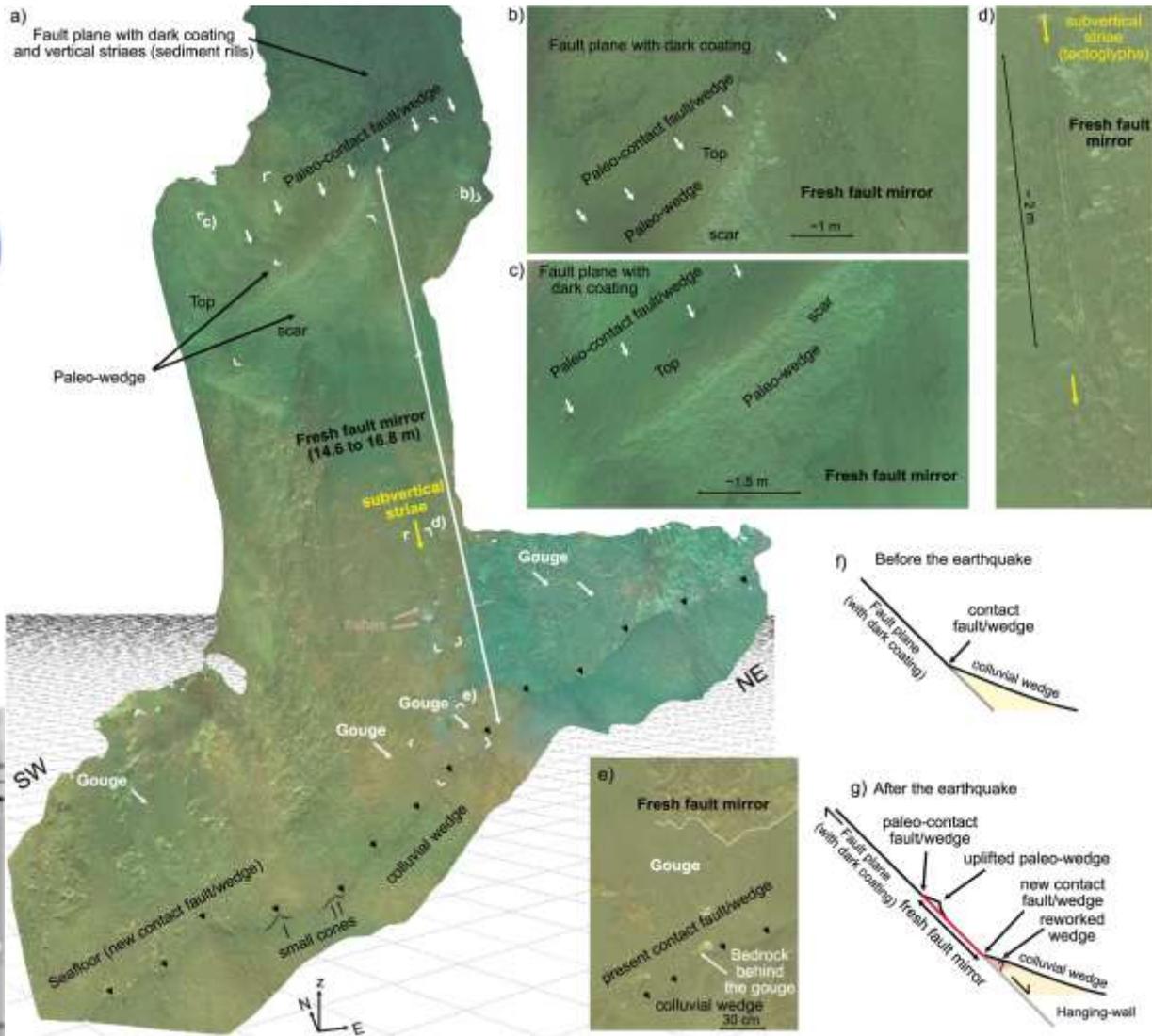
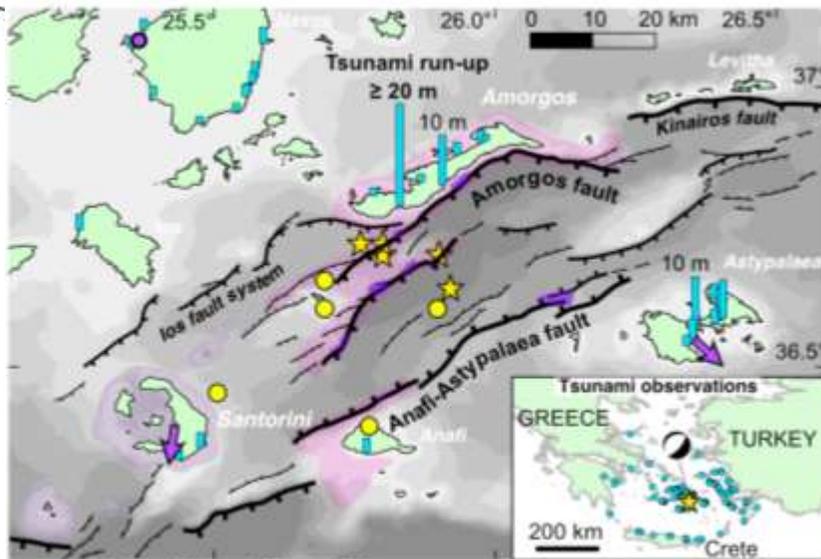
Video

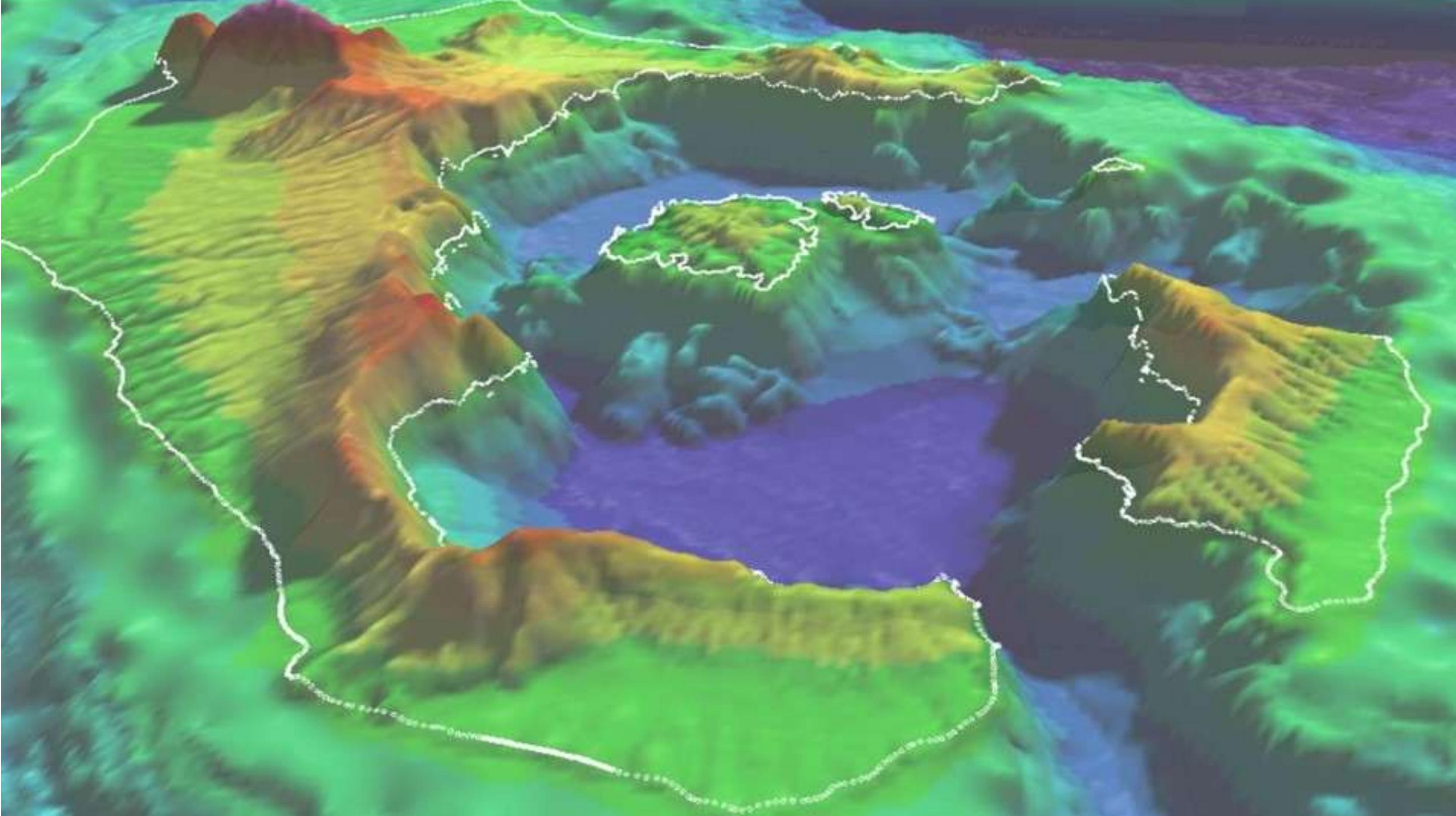


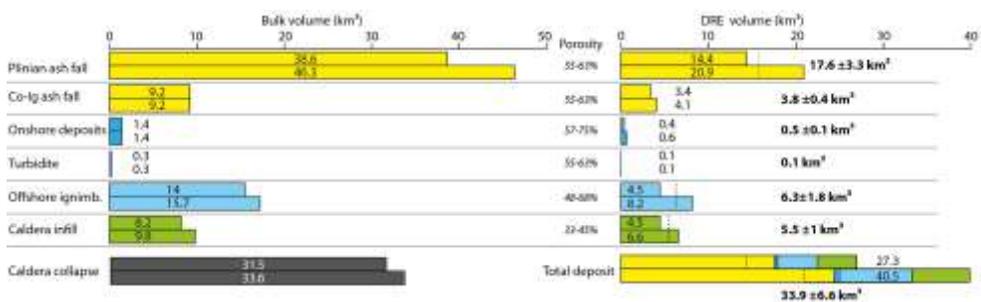
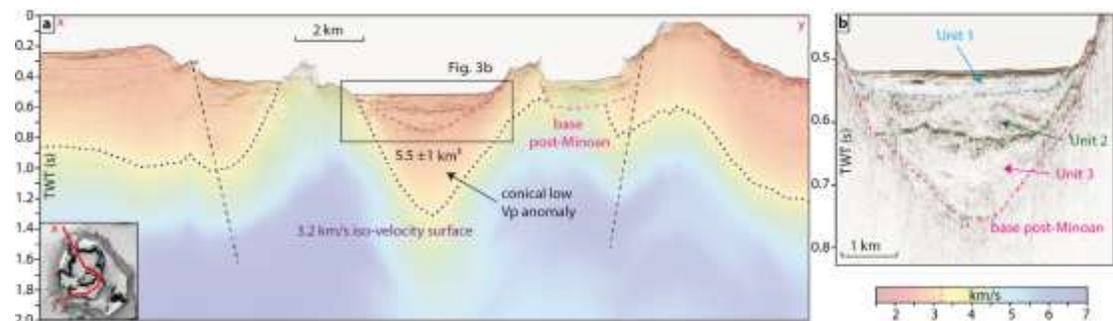
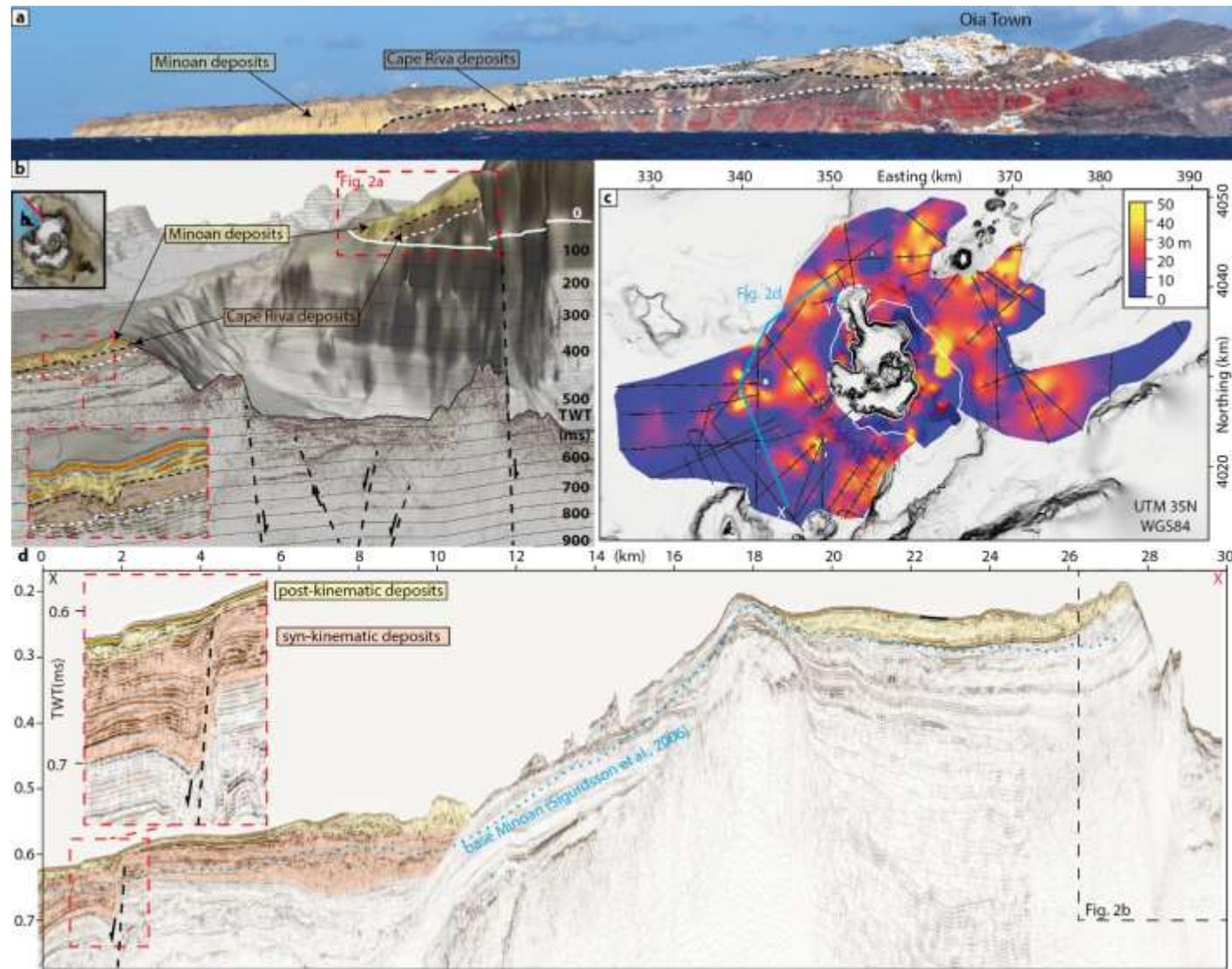
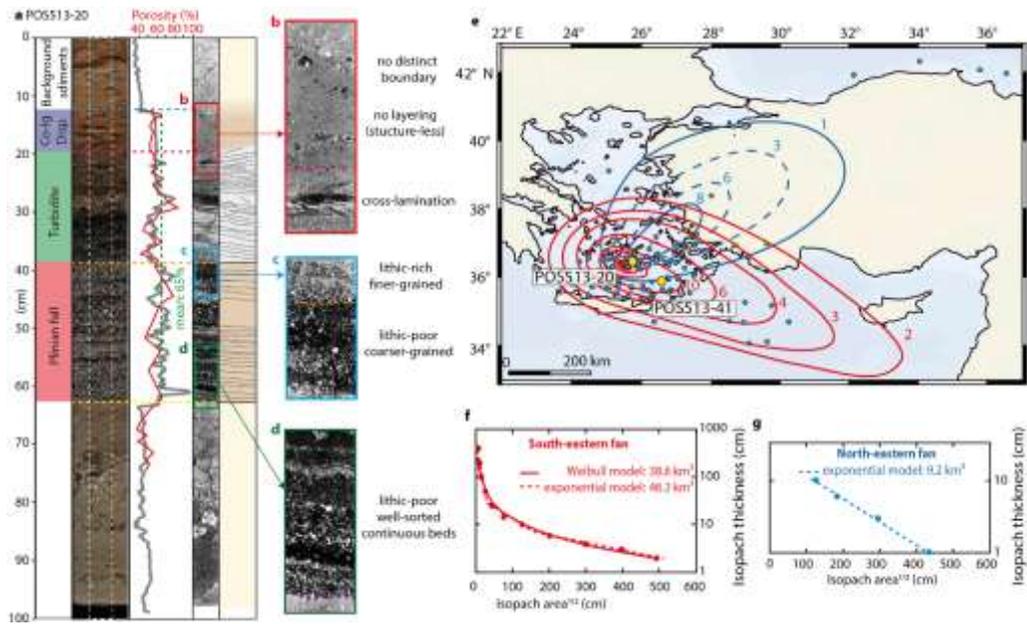
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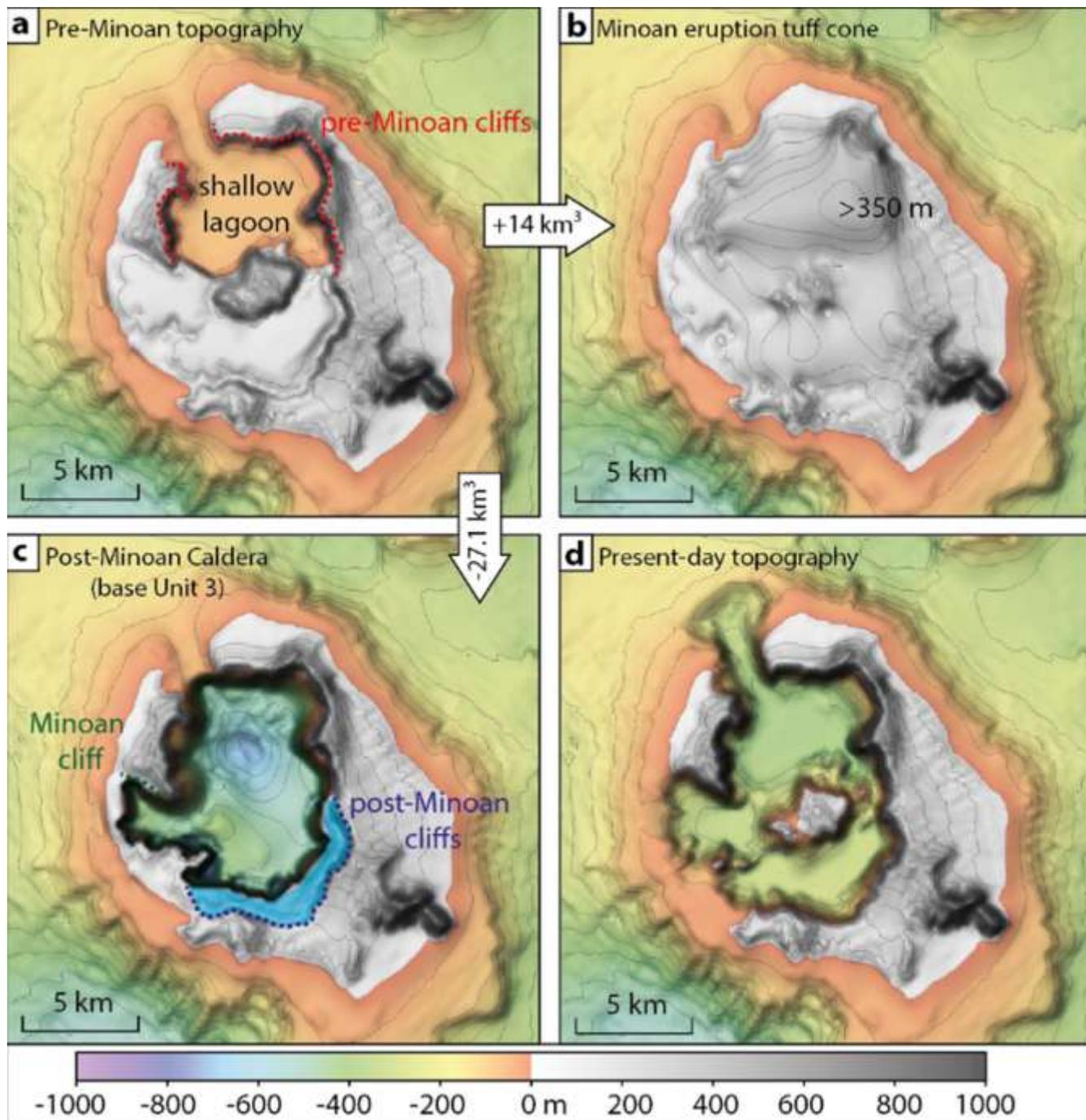


The highest waves in the Mediterranean sea for the past 2 centuries

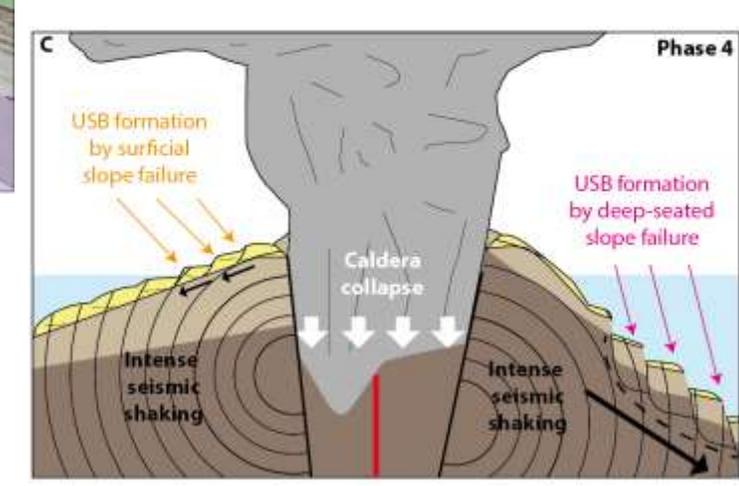
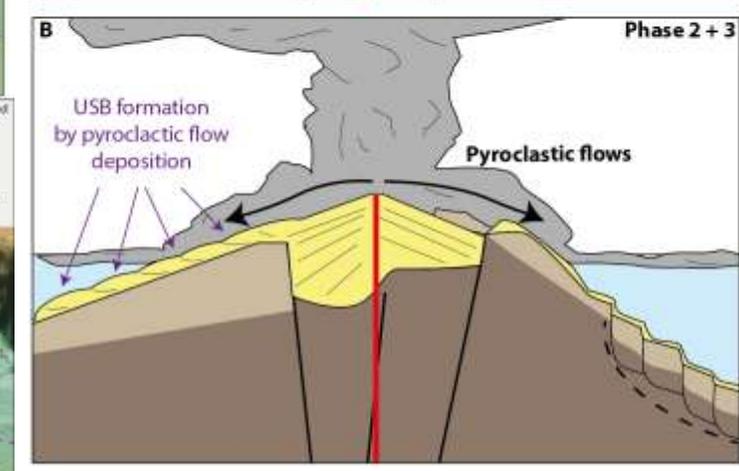
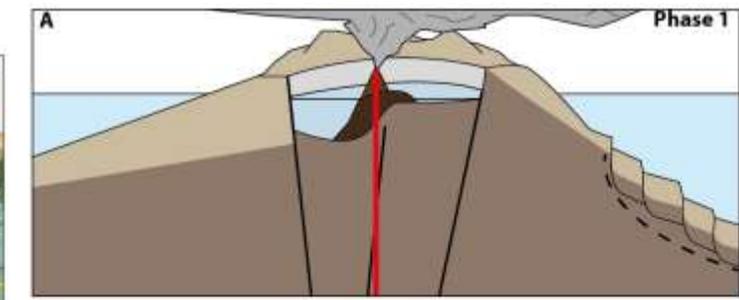
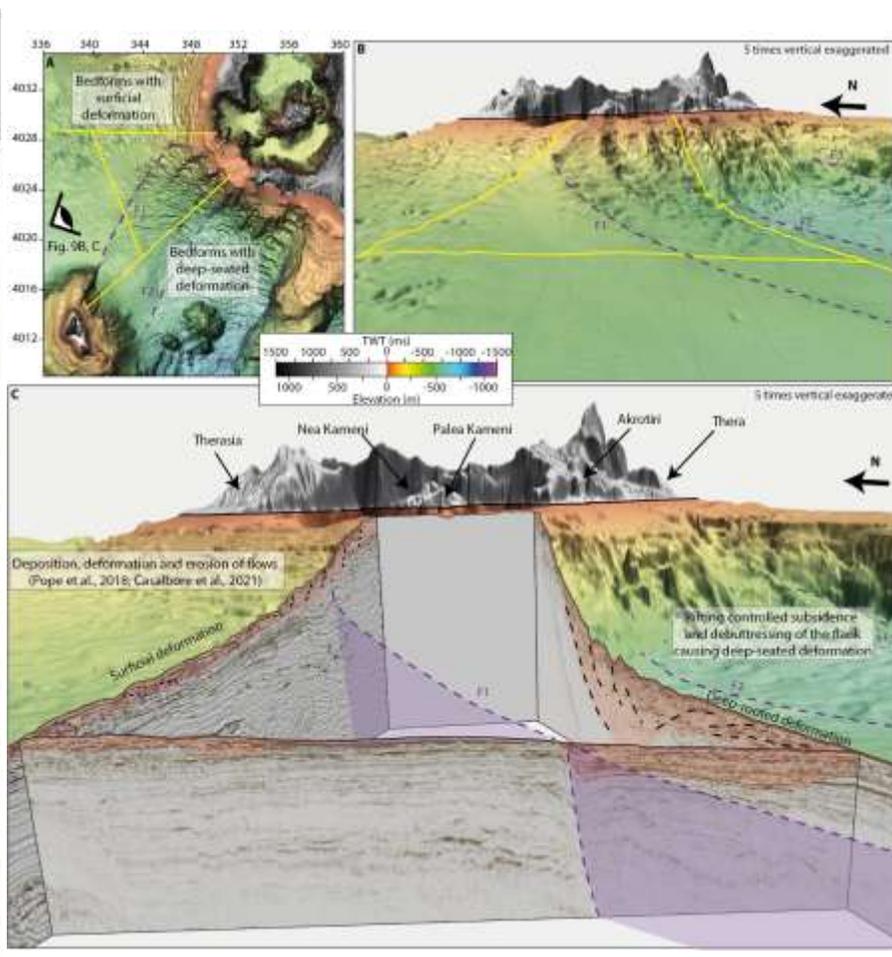
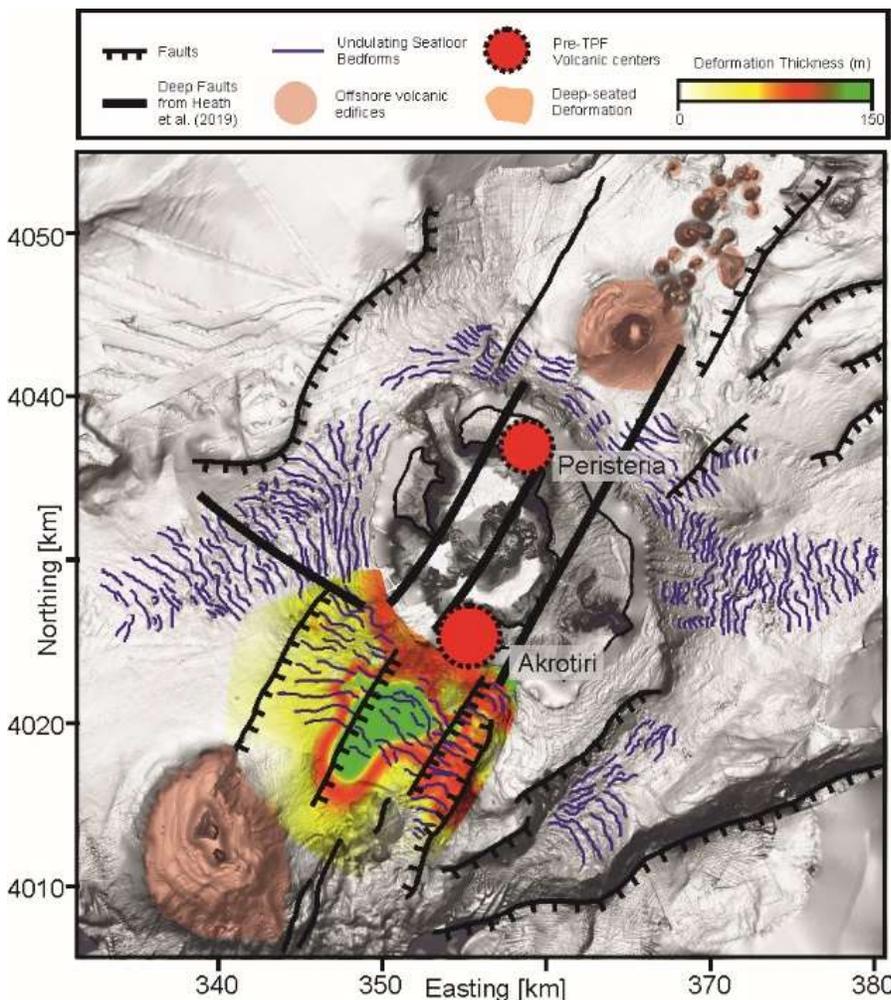




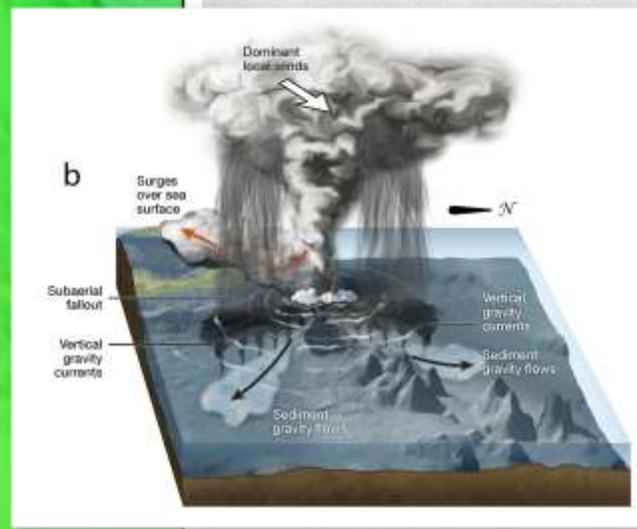
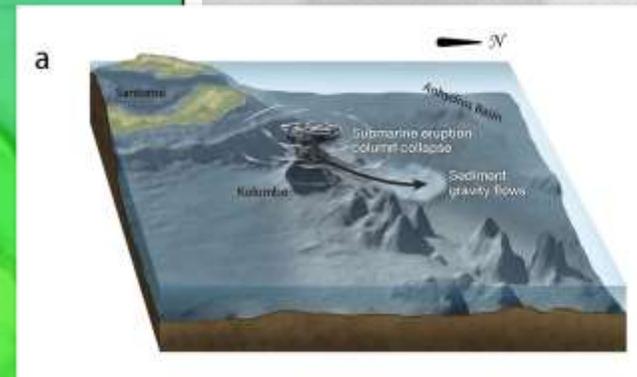
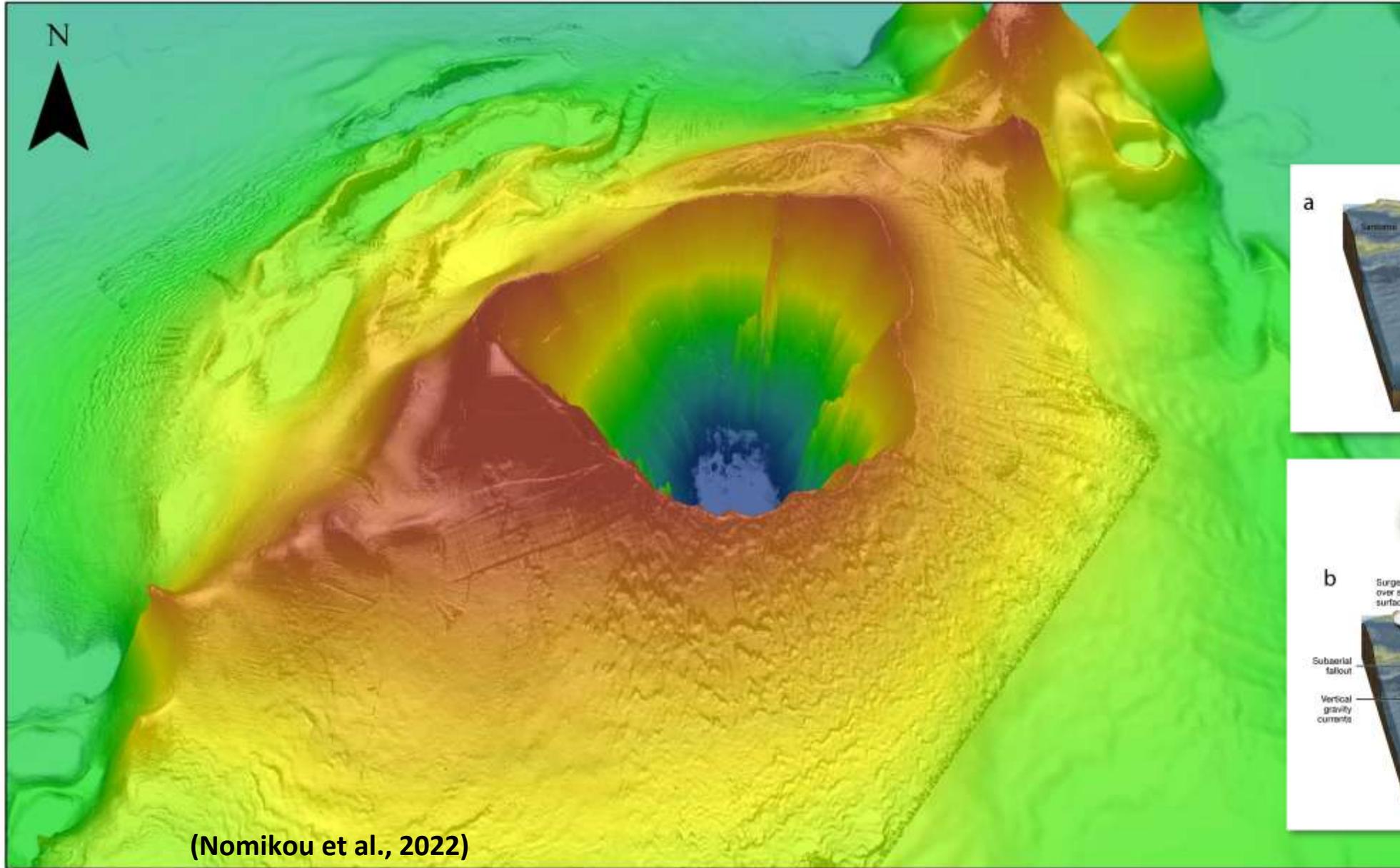




Despite their global societal importance, the volumes of large-scale volcanic eruptions remain poorly constrained. Here, for the first time, we integrate seismic reflection and P-wave tomography datasets with computed tomography-derived sedimentological analyses to estimate the volume of the iconic Minoan eruption. Our results reveal a total dense-rock equivalent eruption volume of $33.9 \pm 6.6 \text{ km}^3$, which encompasses $21.4 \pm 3.6 \text{ km}^3$ of tephra fall deposits, $6.9 \pm 2 \text{ km}^3$ of ignimbrites, and $5.5 \pm 1 \text{ km}^3$ of intra-caldera deposits. This is in agreement with an independent caldera collapse reconstruction ($\sim 32.5 \text{ km}^3$). Our analyses indicate that $\sim 2.7 \text{ km}^3$ of the material consists of lithics. **Our analyses show that the Plinian phase contributed most to the distal tephra fall, and that the pyroclastic flow volume is significantly smaller than previously assumed.** Our benchmark reconstruction demonstrates that complementary geophysical and sedimentological datasets are required for reliable eruption volume estimates, necessary for regional and global volcanic hazard assessments.



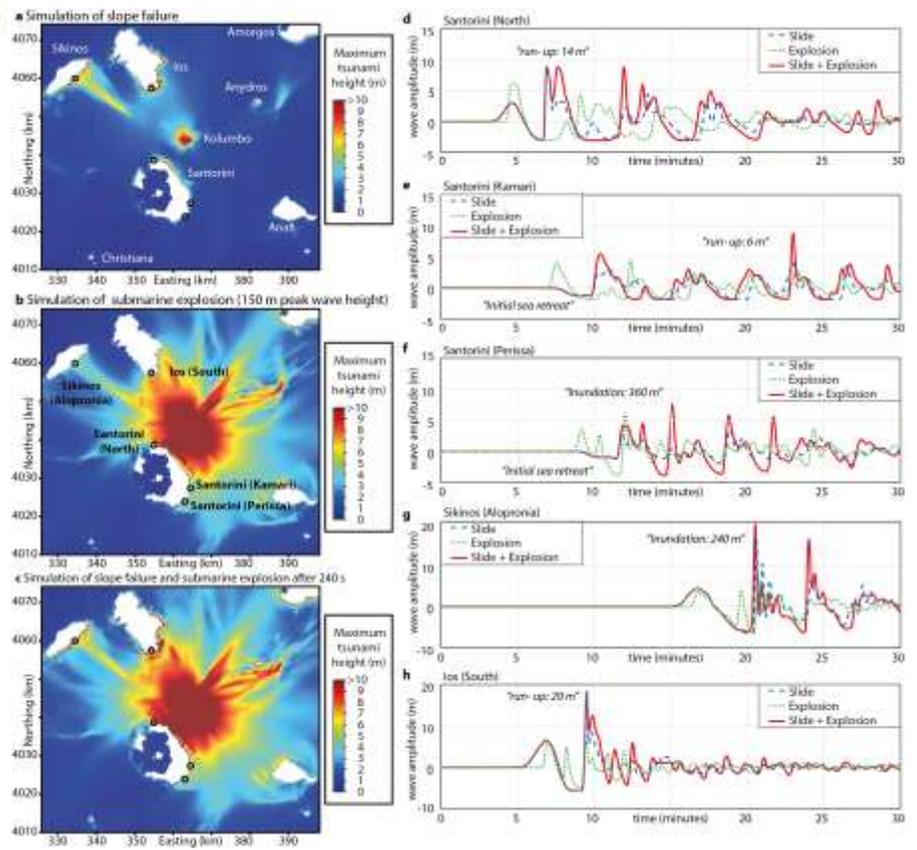
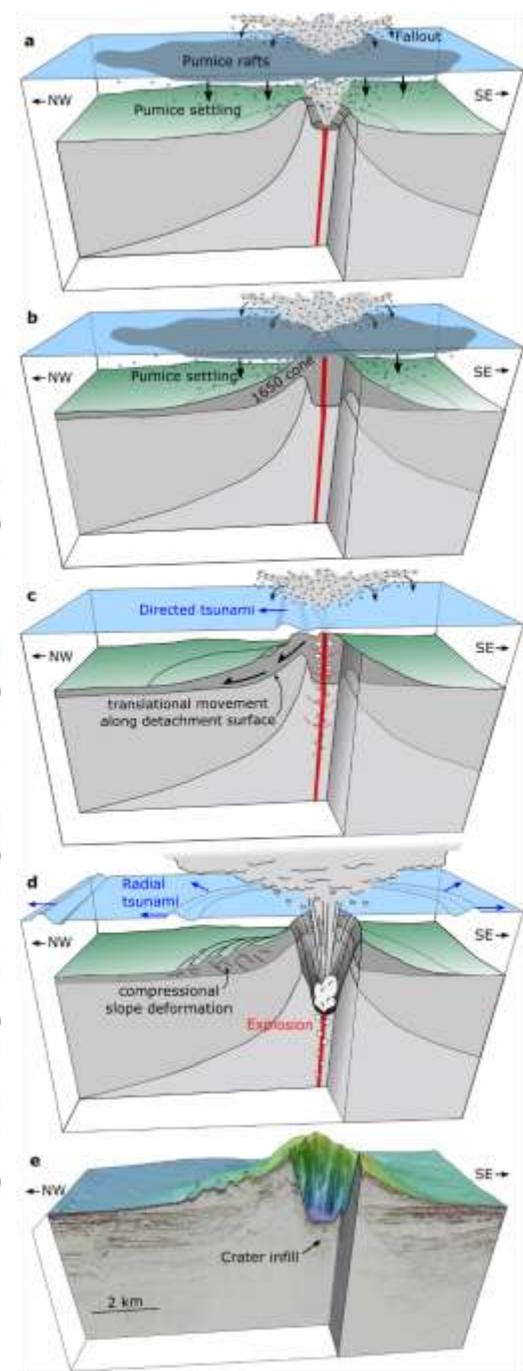
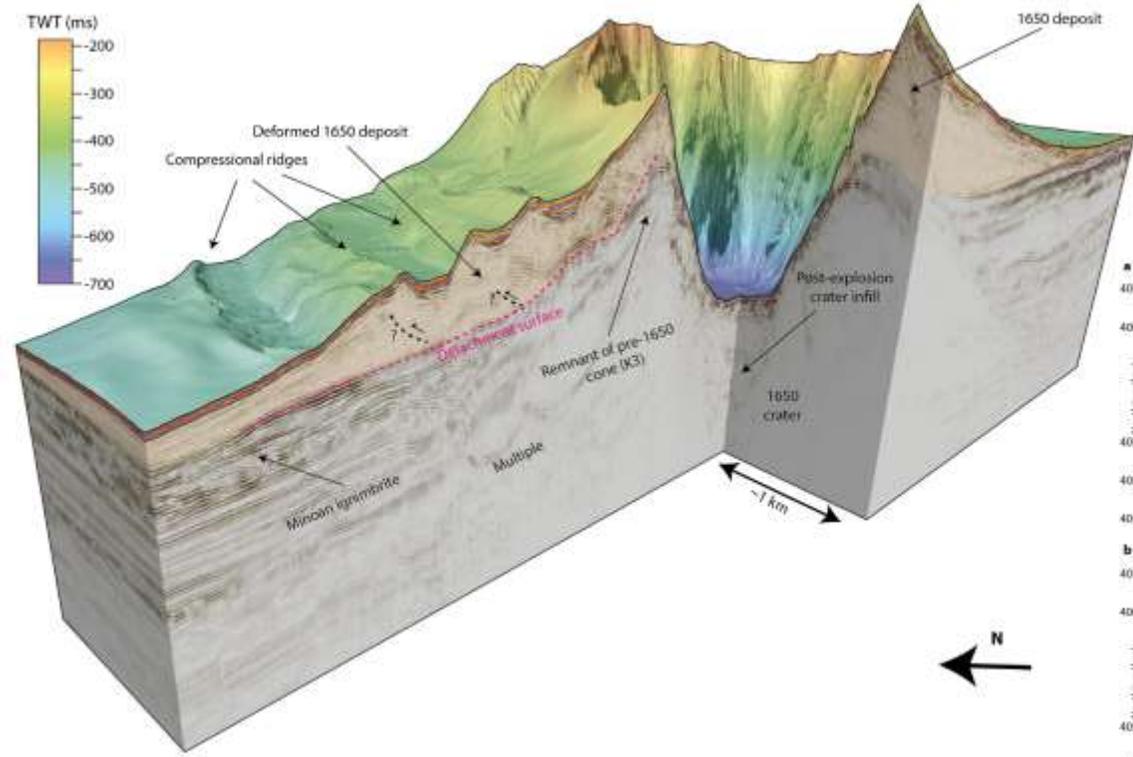
From a hazard perspective, **pyroclastic flow emplacement and slope failures are fundamental tsunami source mechanisms during volcanic eruptions.** It appears most plausible that both processes acted synchronously during the Minoan eruption, which most likely increased the magnitude of the resulting tsunami. This also highlights the potential of USBs as indicators of tsunamigenic processes during past eruptions.



(Fuller et al., 2018)

Kolumbo tsunami 1650 A.D.

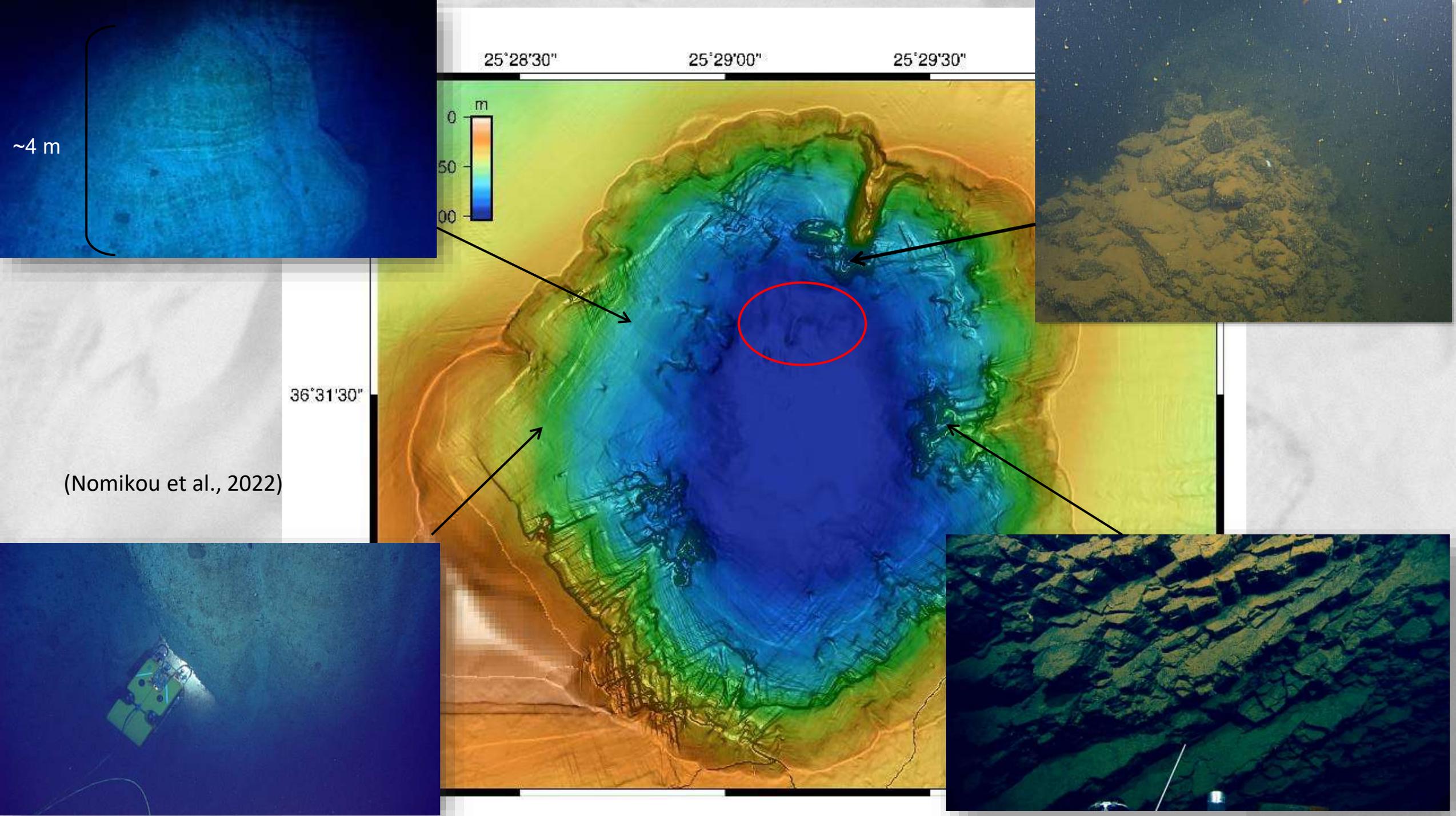
Numerical tsunami simulations indicate that only the combination of flank movement followed by an explosive eruption can explain historic eyewitness accounts.



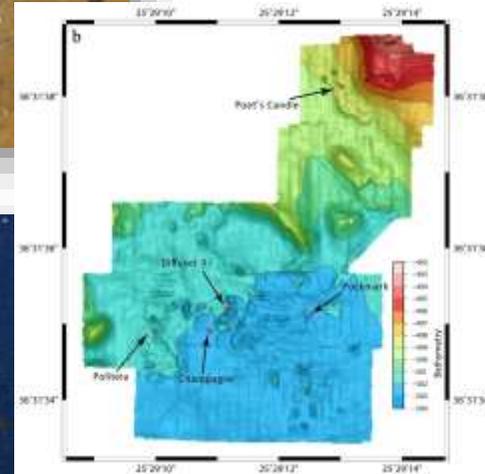
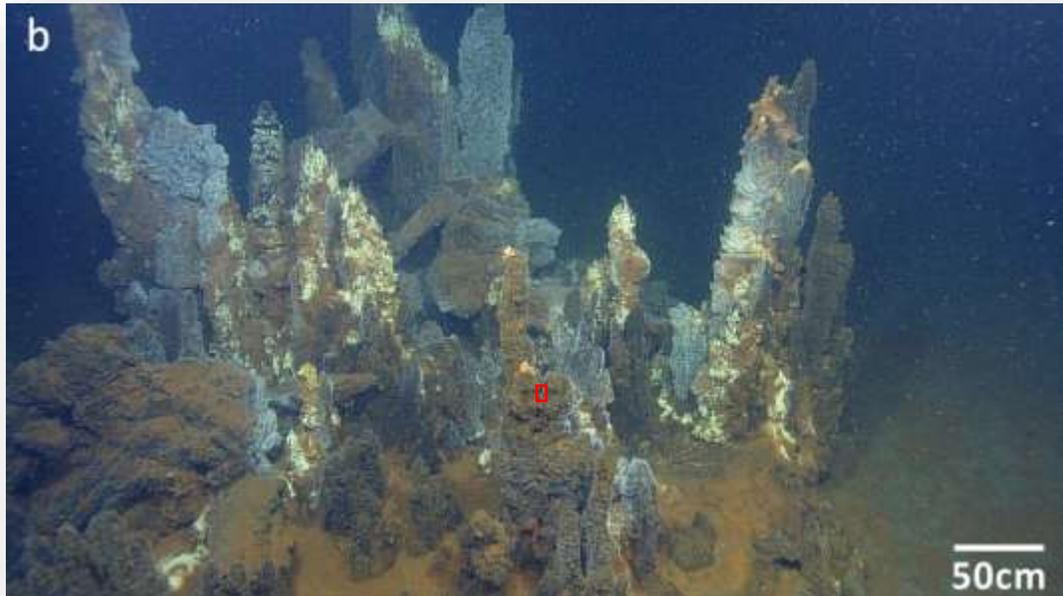
1.2 km³ of Kolumbo's northwestern flank moved 500 – 1000 m downslope along a basal detachment surface. This movement is consistent with depressurization of the magma feeding system, causing a catastrophic explosion.

(Karsten et al., 2023 Nat Comm)





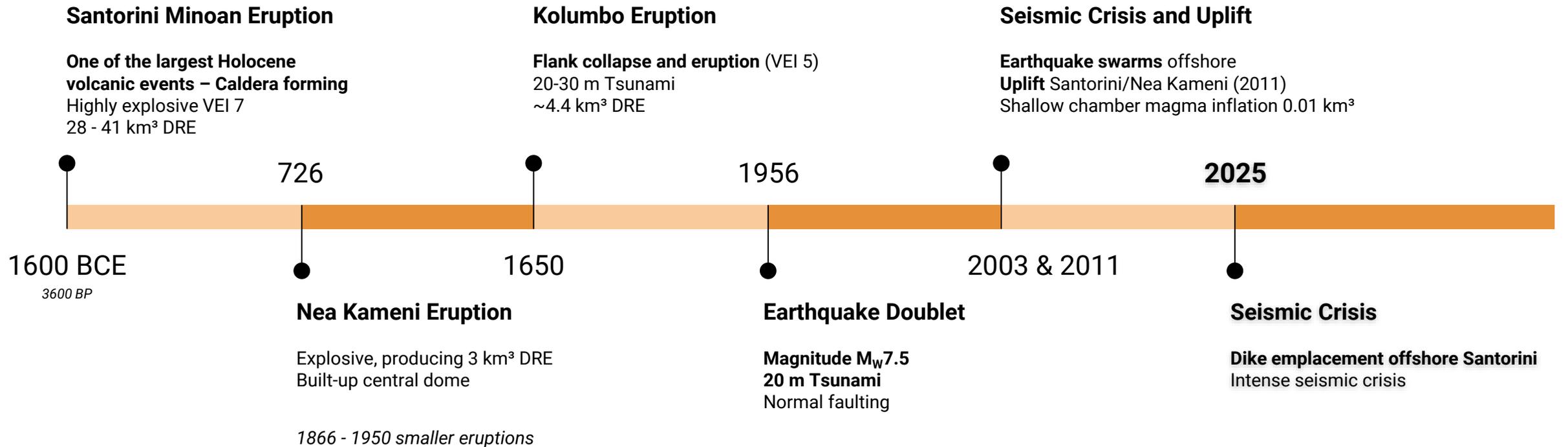
Hydrothermal vent field of Kolumbo



(Carey et al., 2013)

Volcanic-Tectonic History

Central Dome
Nea Kameni





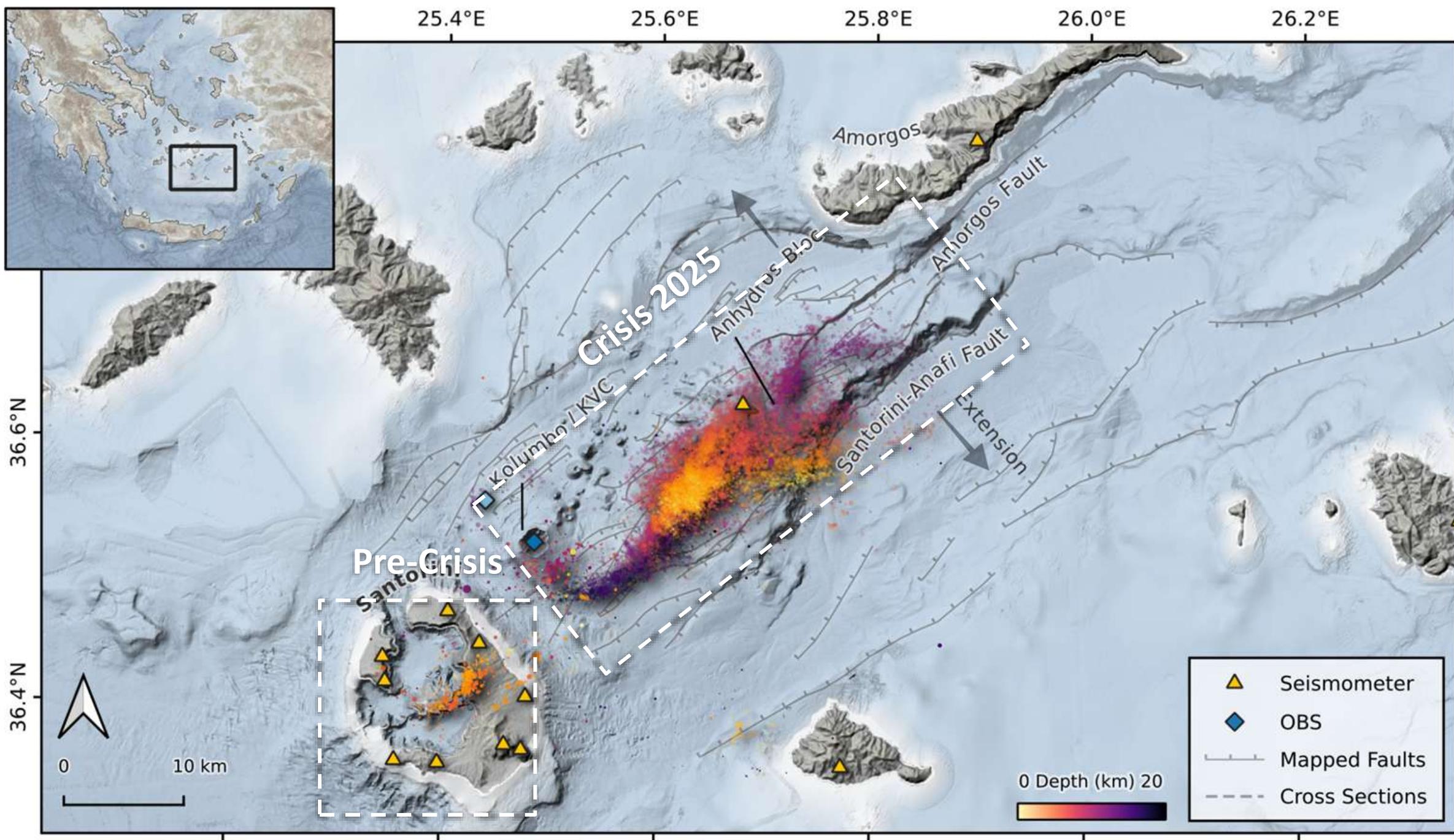
More than 3,000,000 visitors



State of emergency



Half of Santorini's residents left the island



Pre-Crisis Unrest

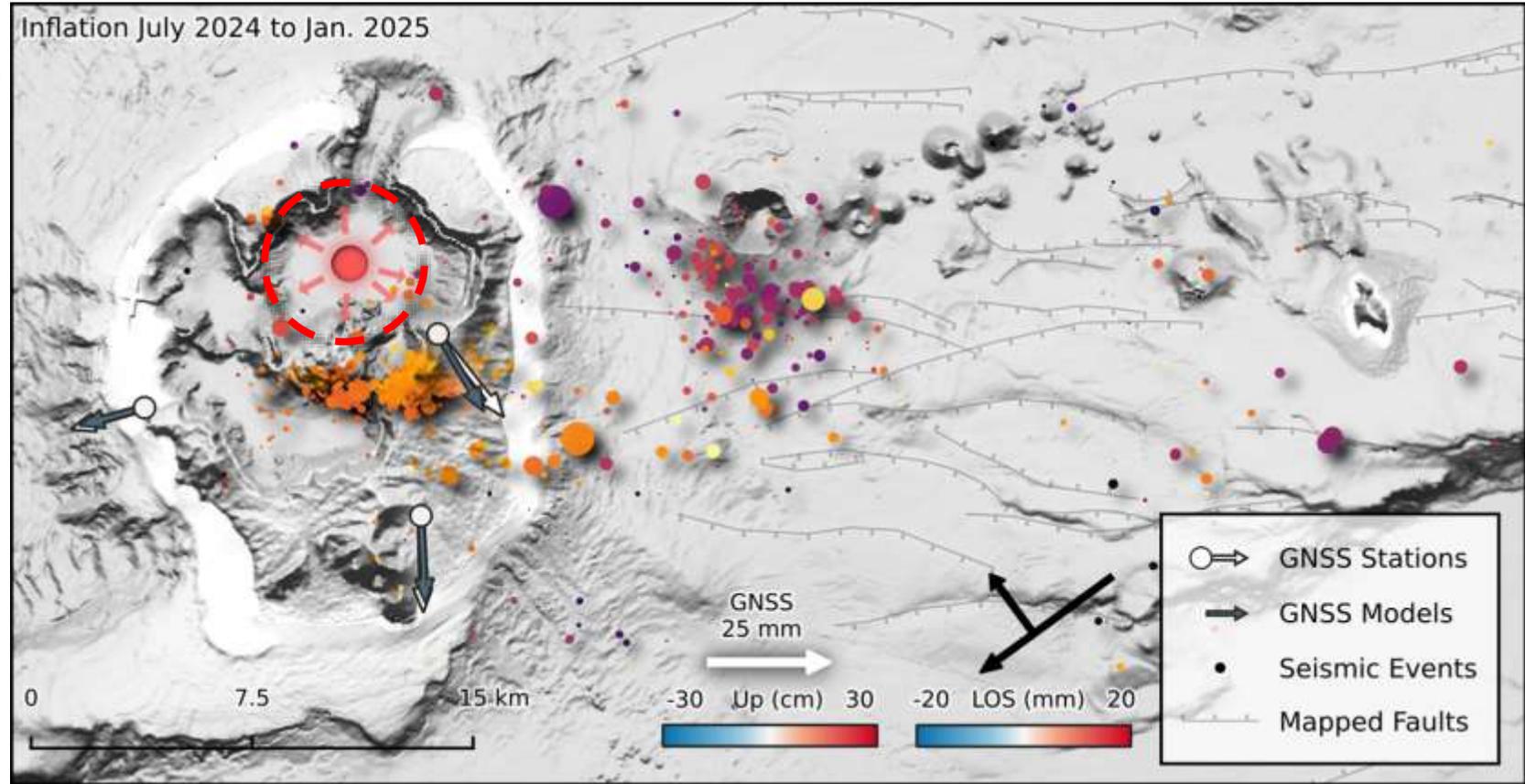
Mid 2024

Santorini Uplift

Shallow chamber

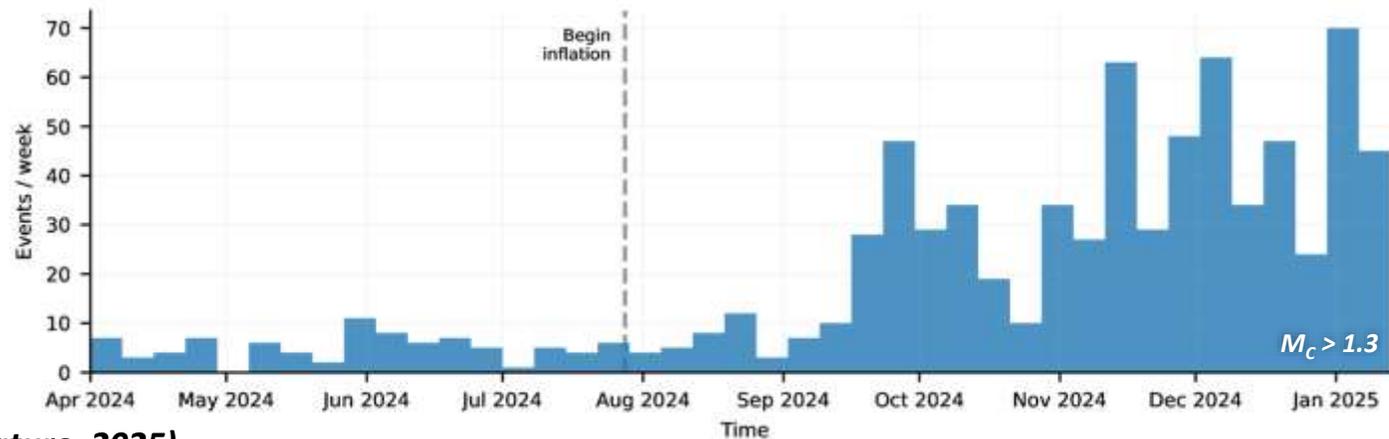
4 km depth

↗ 0.01 km³ inflation

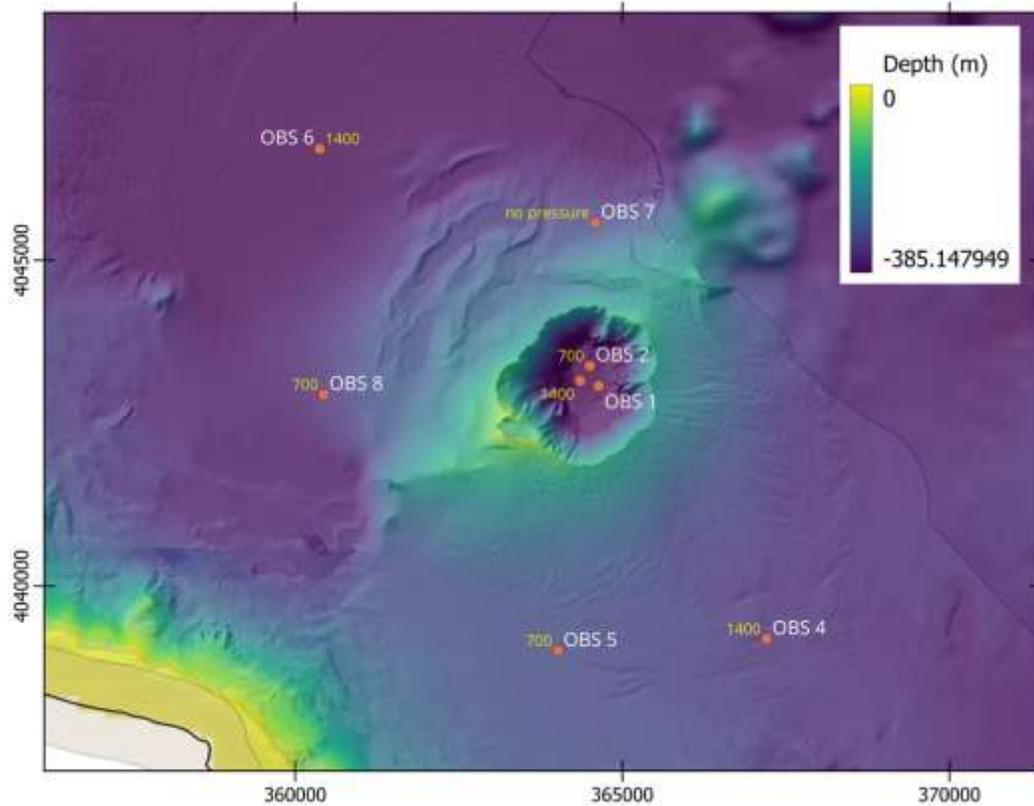


Elevated Seismicity

since September 2024



December 2024



- 1200 km of 2D seismic profiles
- 60 km² P-cable 3D seismic cube
- Several days of seafloor image and video footage
- Installation of 8 OBS with absolute pressure gauges

Qseek: High-Res Catalogs

Automatic machine-learning earthquake catalog

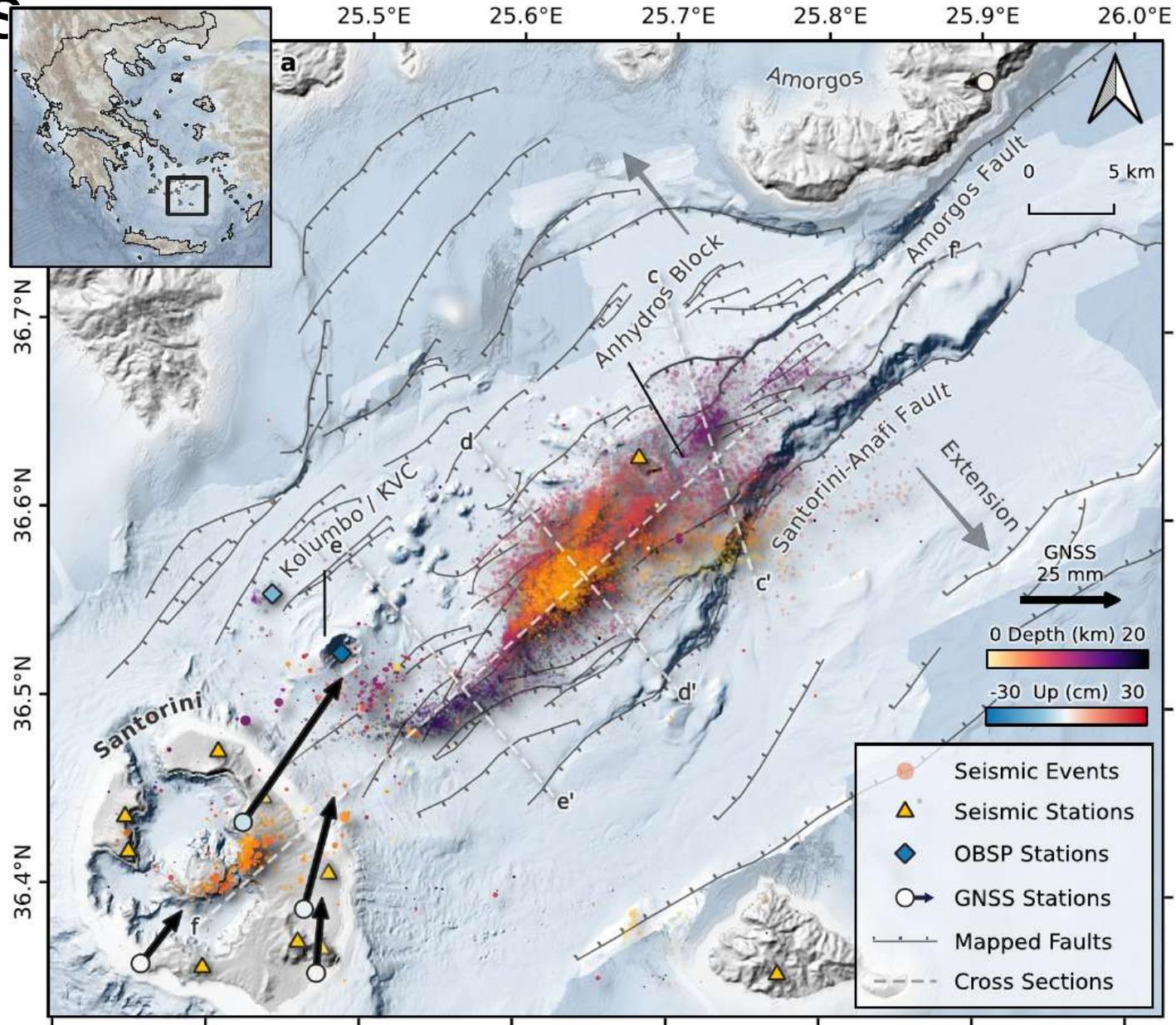
Data-driven stacking & migration

Tracking seismicity in real-time

Detection of **30k+** events within four weeks

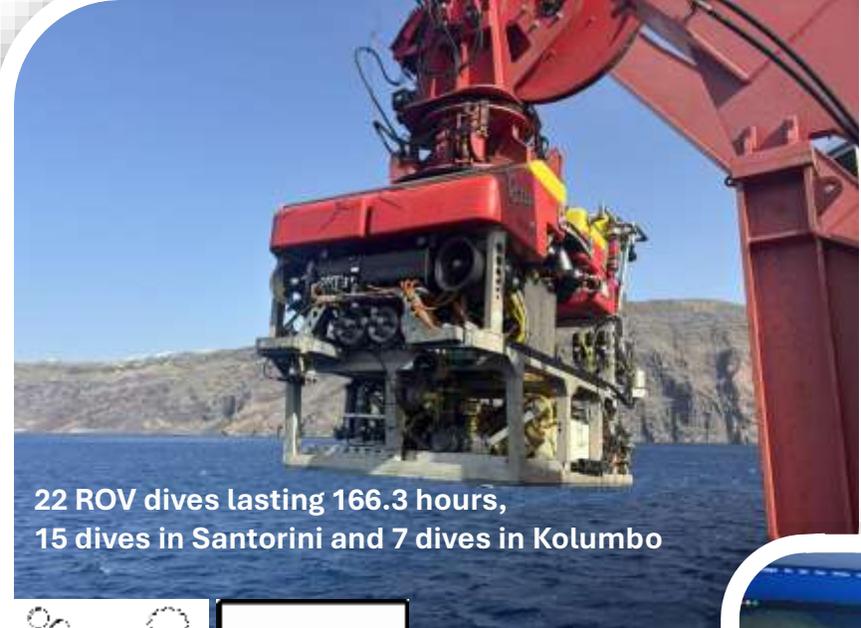
Intense swarm: 45 Events $M > 4.5$

The magnitude of completeness is M_w 1.3 on average. Black arrows show the horizontal displacement of the continuous GNSS stations on Santorini from 25 January to 25 February 2025.

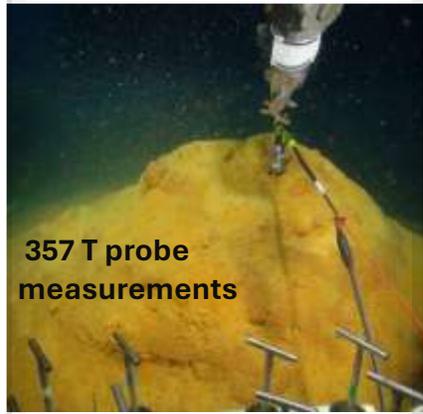


Isken M., Karstens J., Nomikou P. et al (Nature, 2025)





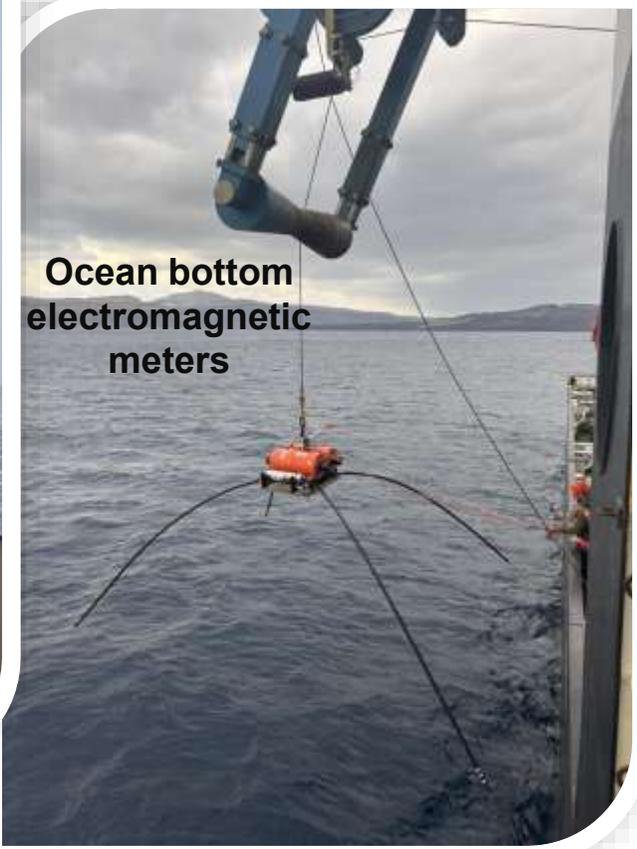
22 ROV dives lasting 166.3 hours,
15 dives in Santorini and 7 dives in Kolumbo



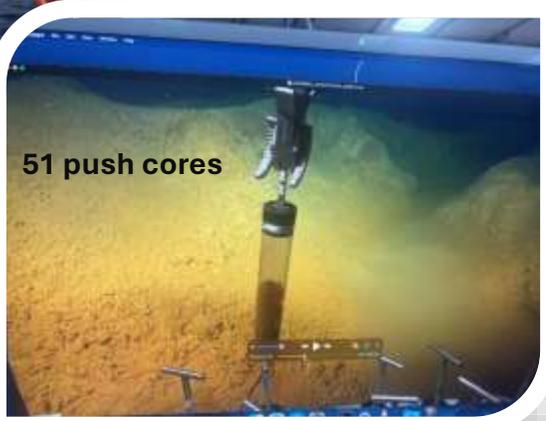
357 T probe
measurements



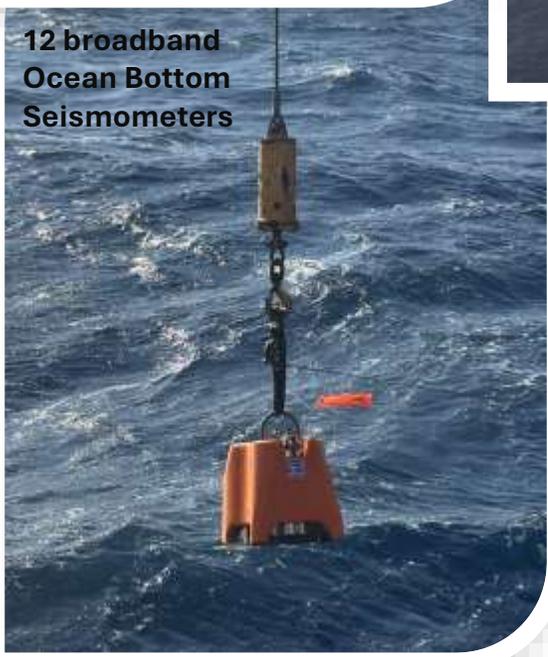
Gravity
cores



Ocean bottom
electromagnetic
meters



51 push cores



12 broadband
Ocean Bottom
Seismometers

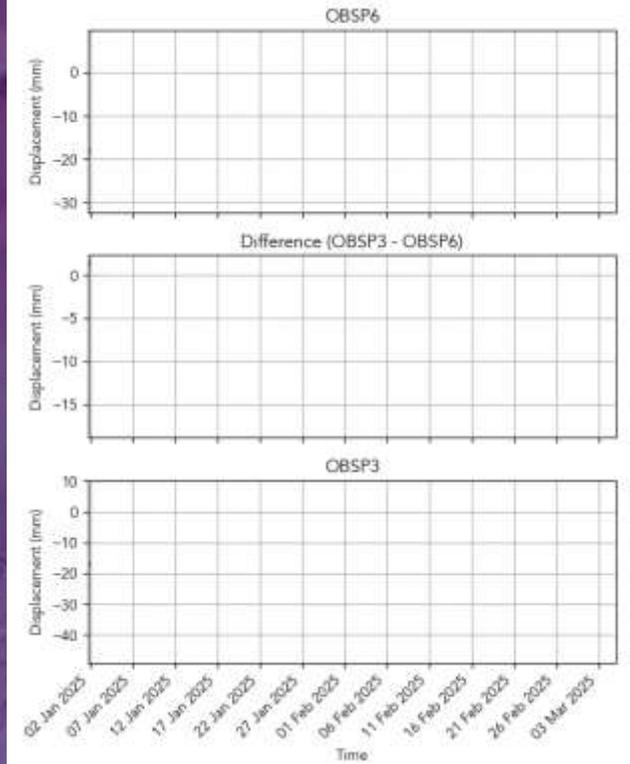
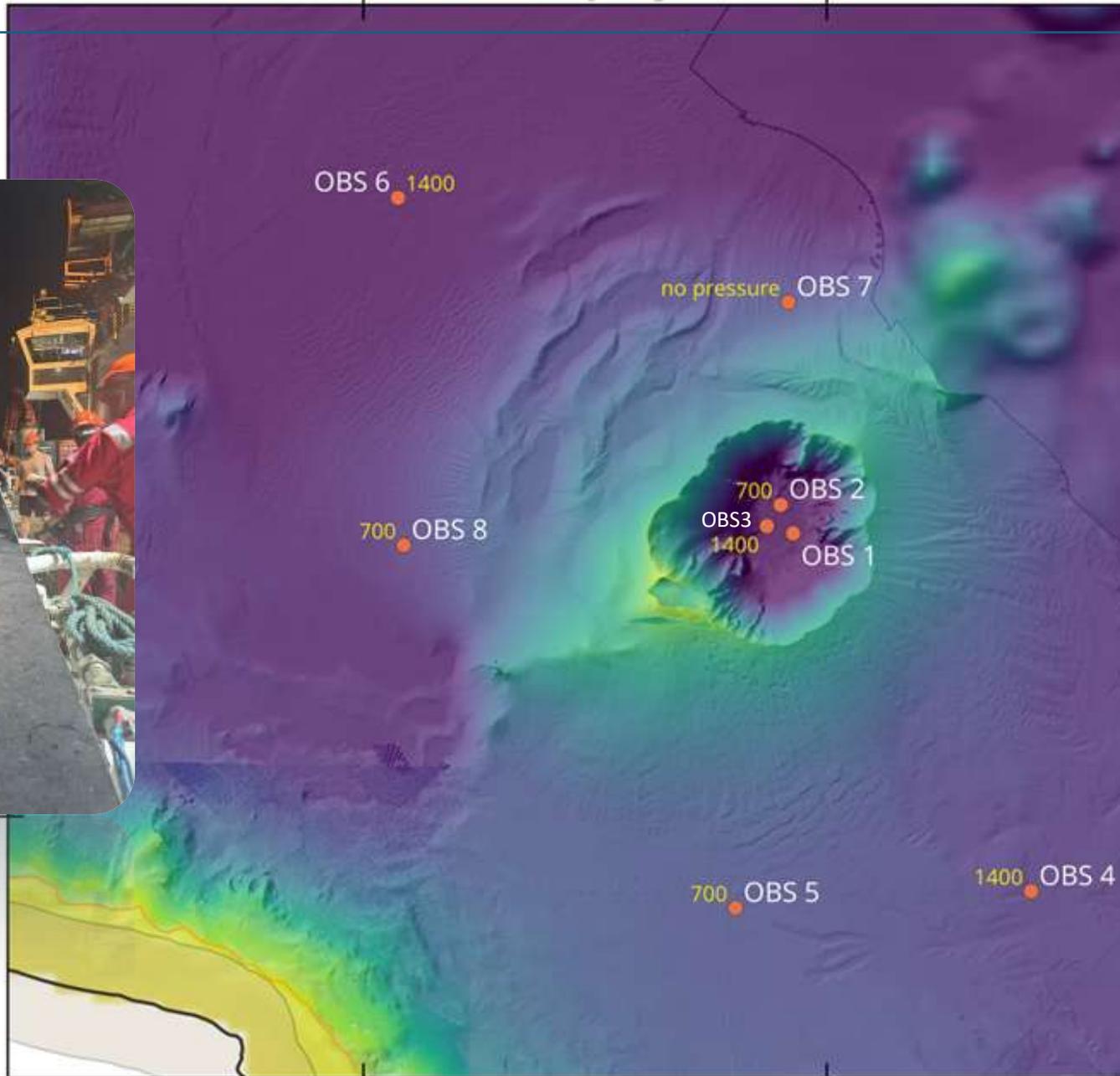
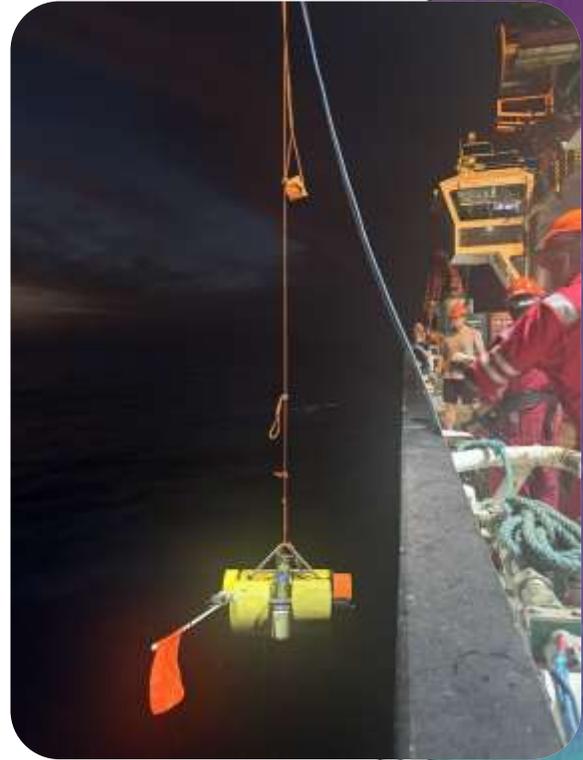


McIlane pumps measure
radium at vent fields



13 ocean
bottom nodes
OBX

R/V DISCOVERY



Pressure recordings converted to depth and processed time series: i) of OBSP3 recorded within the crater of Kolumbo showing a subsidence of ~32 cm and ii) of OBSP6 recorded on the northern flank of Kolumbo showing a subsidence of ~12 cm. Relative depth changes of ~19 cm between OBSP3 and OBSP6 (GEOMAR).

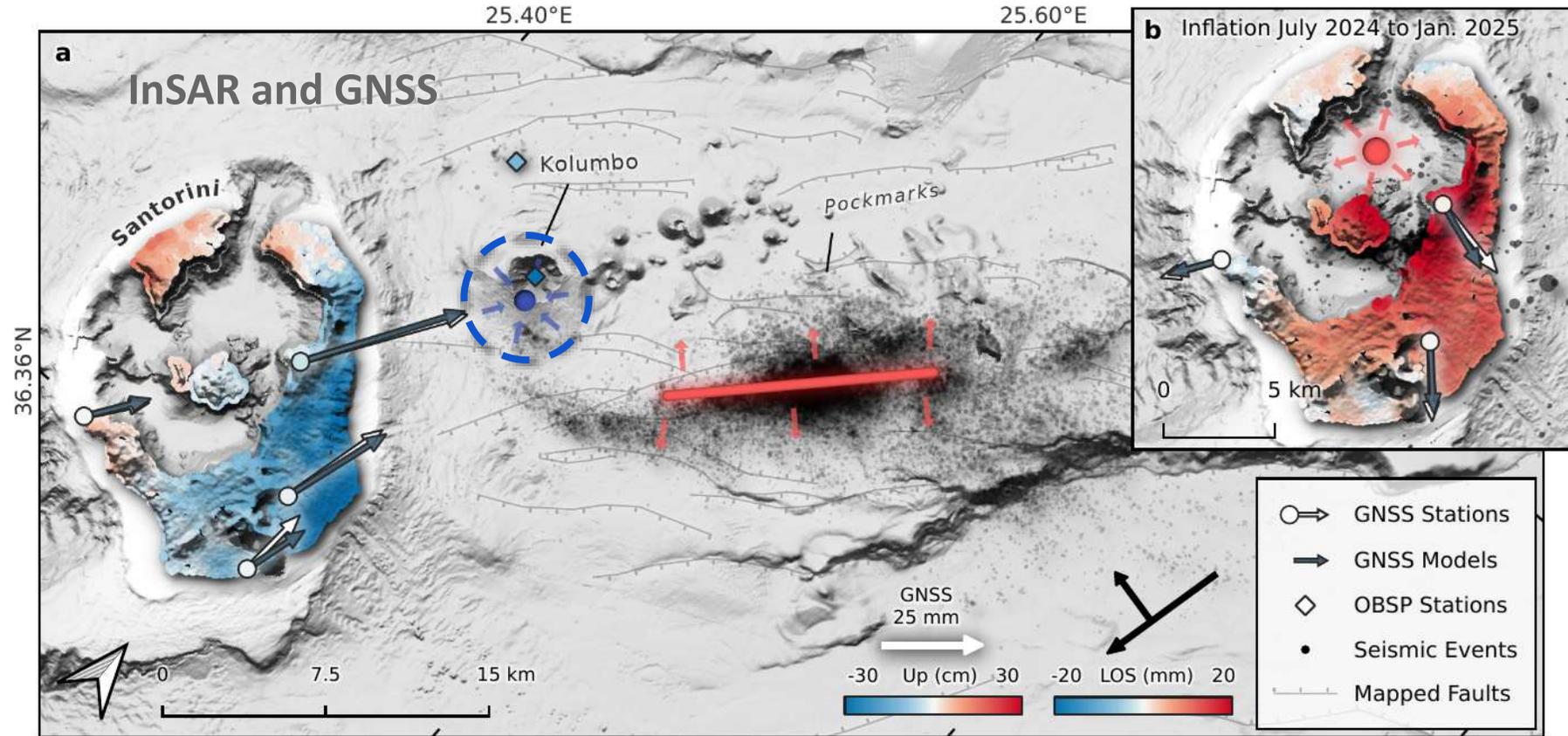
Geodetic Dike Model

Dike 13 km long
 Opening ~ 8 m
 Inflow ~ 0.31 km³

Deflating chamber
 8 km below Kolumbo
 Outflow ~ 0.12 km³

Temporal Inversion
 Max. 230 m³/s influx

Coincides with most
 intense seismicity



Pre-diking phase:

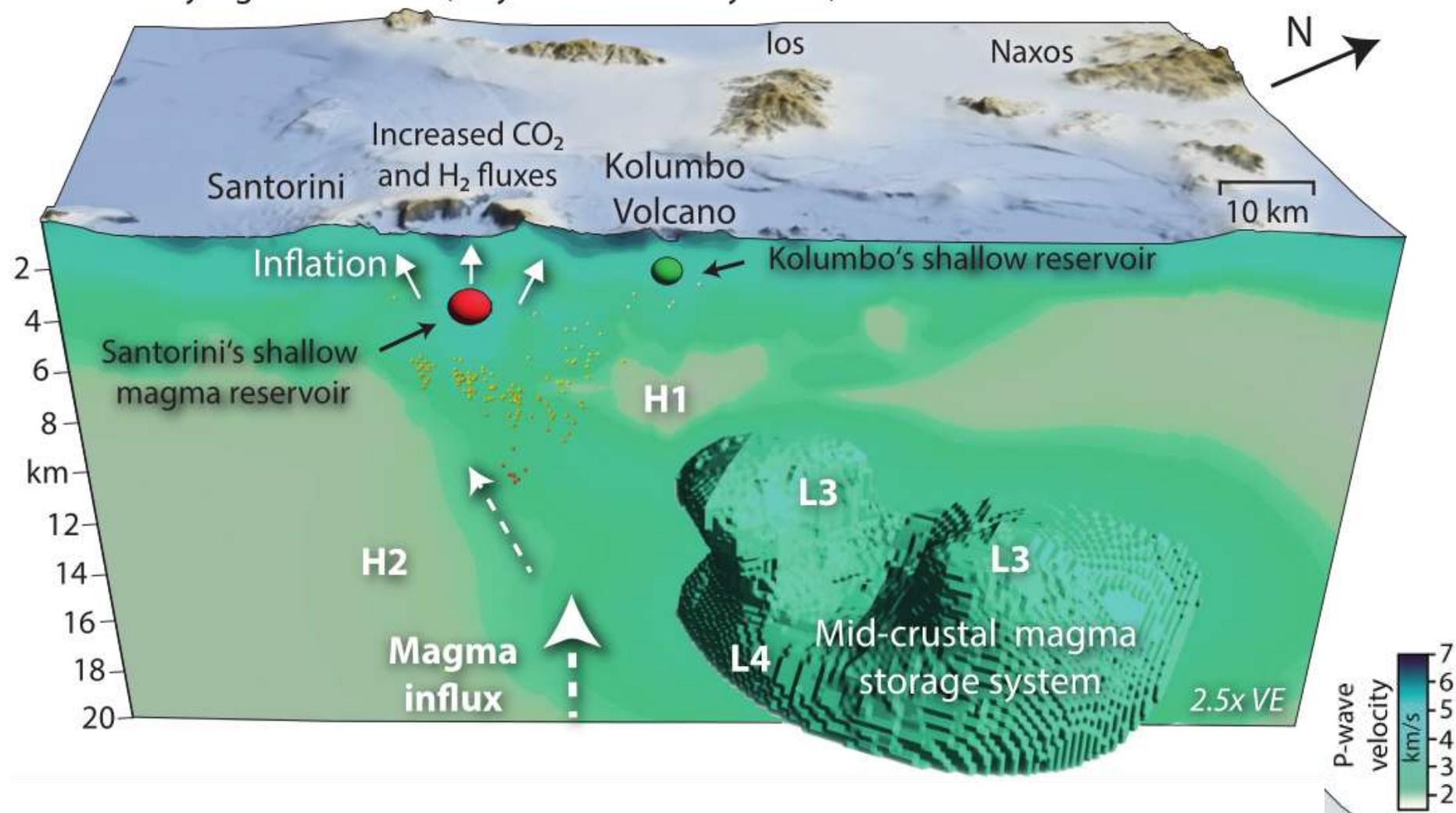
- Inflow of 4 Mm³ into Santorini's shallow magma reservoir at 3,8 Km depth
- Inflow rate 0.26 m³/s (2011/12: 0.49 m³/s)

Syn-diking phase:

- Dike (length of ~ 13 km and extends from 5 to 11.5 km in depth) intrusion with 313 Mm³ from mid-crustal reservoir at 7.6Km depth
 - Peak inflow rate 200 m³/s
 - Synchr. deflation by 76 Mm³
 - Diking vs. drainage ratio of 4:1
- ⇒ Indicative for rather primitive, mafic magma

2025 volcano-tectonic crisis

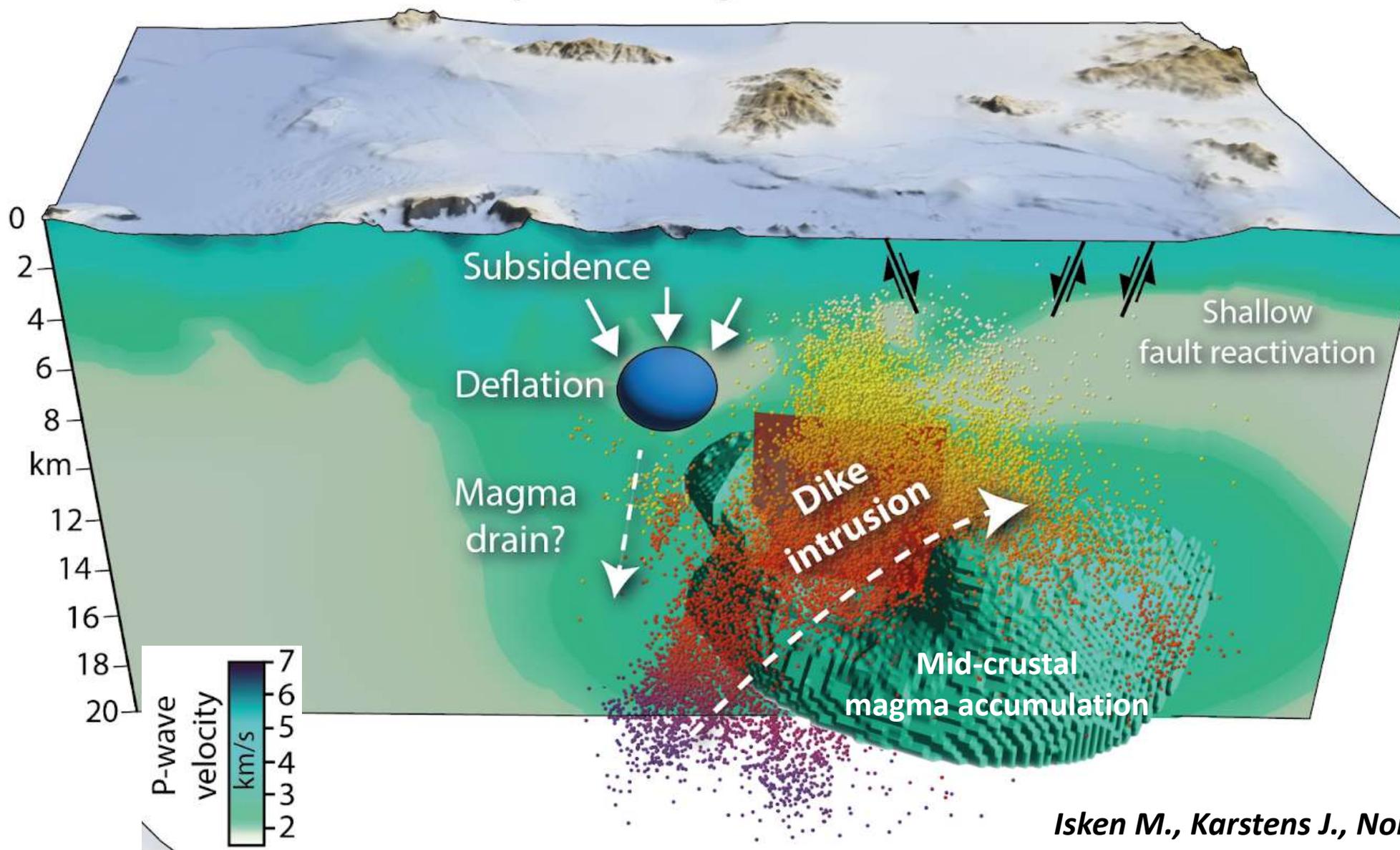
a Precursory signs of unrest (July 2024 - January 2025)



The preparatory phase from **June 2024 to January 2025**. The influx of magma from a mid-crustal magma reservoir into the shallow magma reservoir beneath Santorini resulted in **surface uplift** and increased seismicity at the caldera. The green 3D body shows the locations of a low P-wave velocity anomaly (21% lower V_p), indicating the presence of a mid-crustal magma domain.

2025 volcano-tectonic crisis

b Volcano-tectonic crisis: diking and faulting



Starting on **27 January 2025**, a dike intrusion was initiated from the mid-crustal magma reservoir and propagated laterally upwards into the Anhydros block. Seismicity occurred at the tip and boundaries of the dike rupture, and shallow crustal normal faults were activated by stress and fluid pressure changes. **The concurrent deflation of a shallower mid-crustal melt reservoir led to subsidence**, which was measured at Santorini and Kolumbo.

Isken M., Karstens J., Nomikou P. et al (2025)

Climate Change

New Technology, Innovation

Submarine Mineralogy

www.santory.gr

Blue Potential

SANTORY
SANTORini's seafloor volcanic observatory
NKUA, NTUA, HCMR, UNIWA,
INGV, ENS, GEOMAR

Blue Growth

Public awareness

Natural Hazards

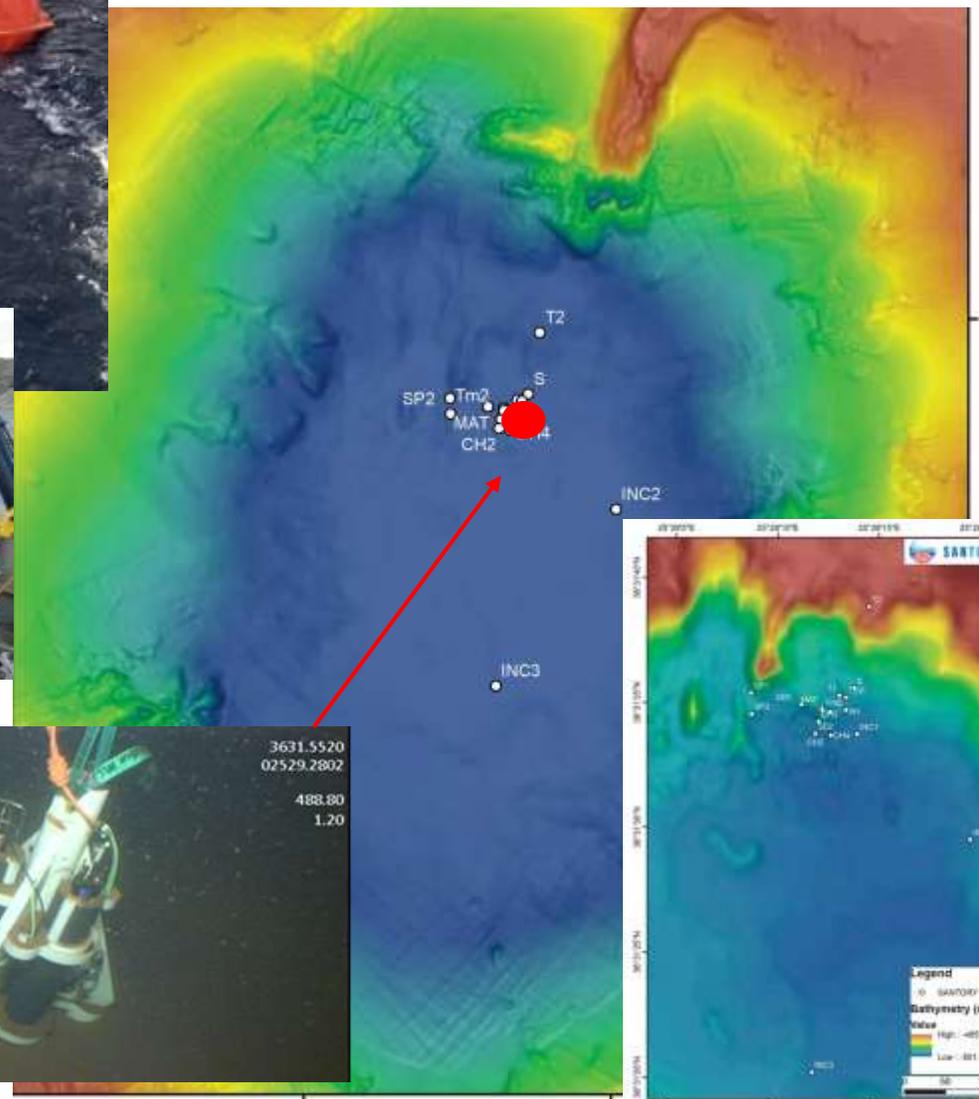
Biodiversity



Instruments-measurements

Deployment

- Seafloor observatory
 - 6 T-sensors
 - 3 Inclinometers
 - Water Sampling
 - Chimneys samples
- ROV 3D MODEL chimneys
- microbial mat samples



The oceanographic cruise was funded by Municipality of Thira

The **SANTORY volcanic observatory** consists of several sensors to measure physical and chemical parameters of seawater, influenced by the active hydrothermal field of Kolumbo, including acoustic data, CO₂, H₂S, O₂, T °C, pressure, EC, pH and turbidity.

07/12/22
Thyra 2022
Dive 5

0 15 30 45

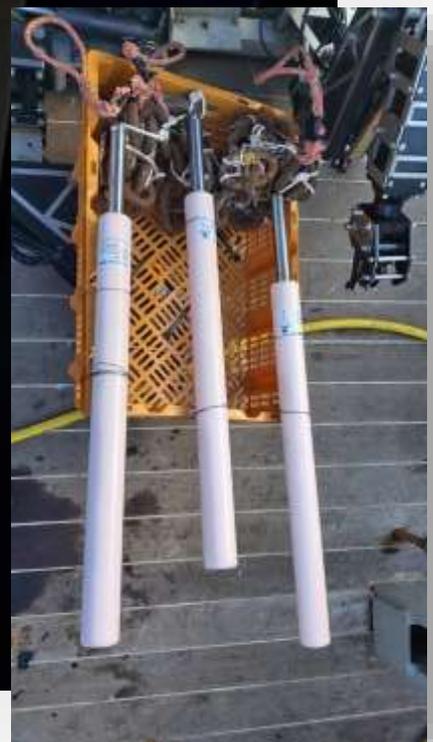
V-R201P-AFHD

3631.5628
00529.2002

22.15
487.80
1.60

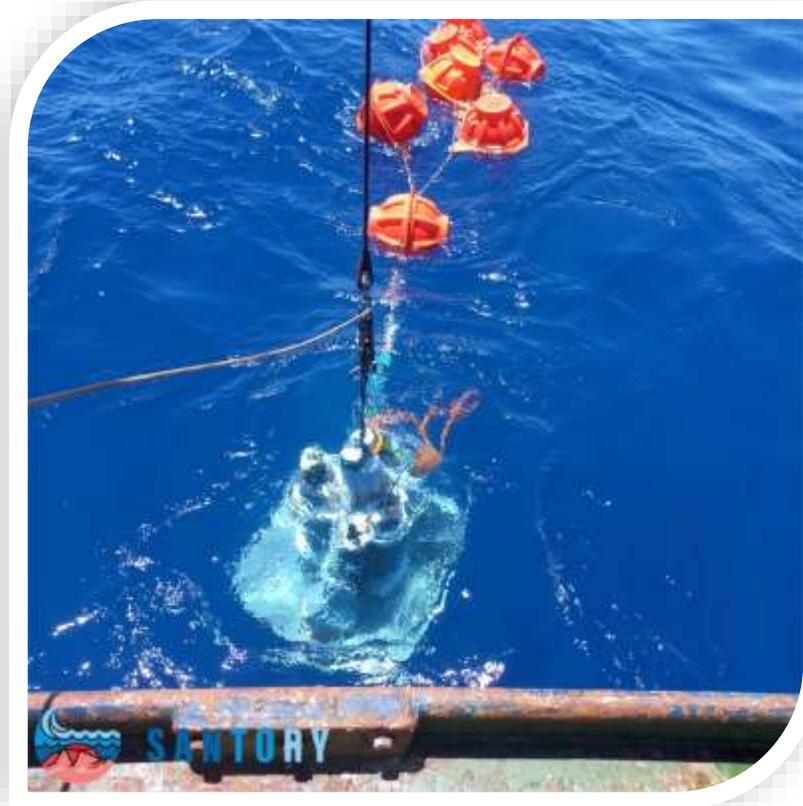
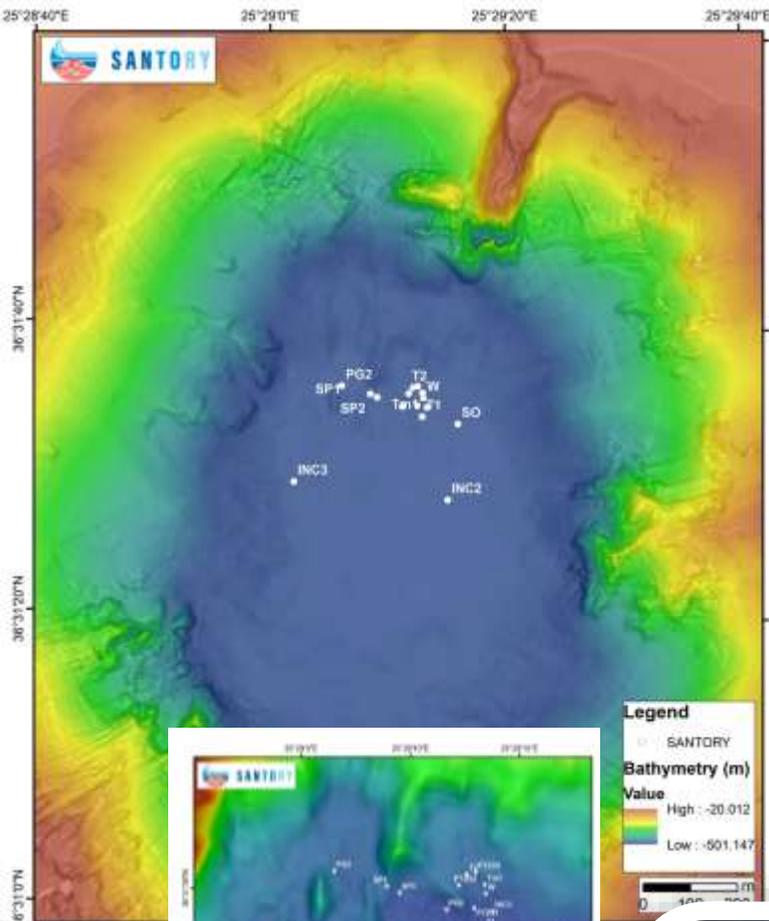


Temperature measurement inside an active chimney.
The maximum temperature recorded was 157 °C.



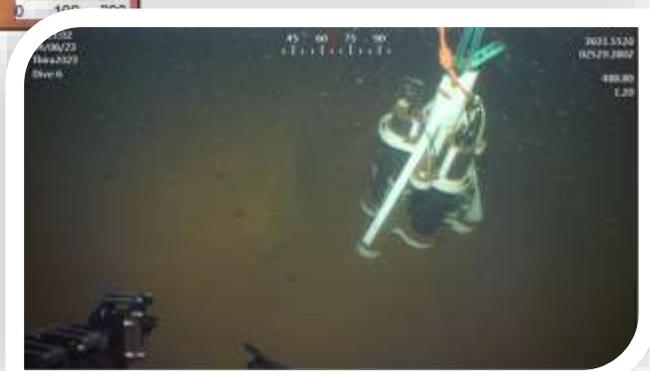
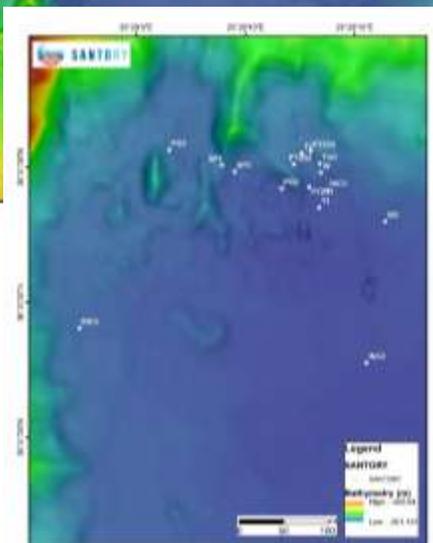
June 2023/2nd oceanographic cruise

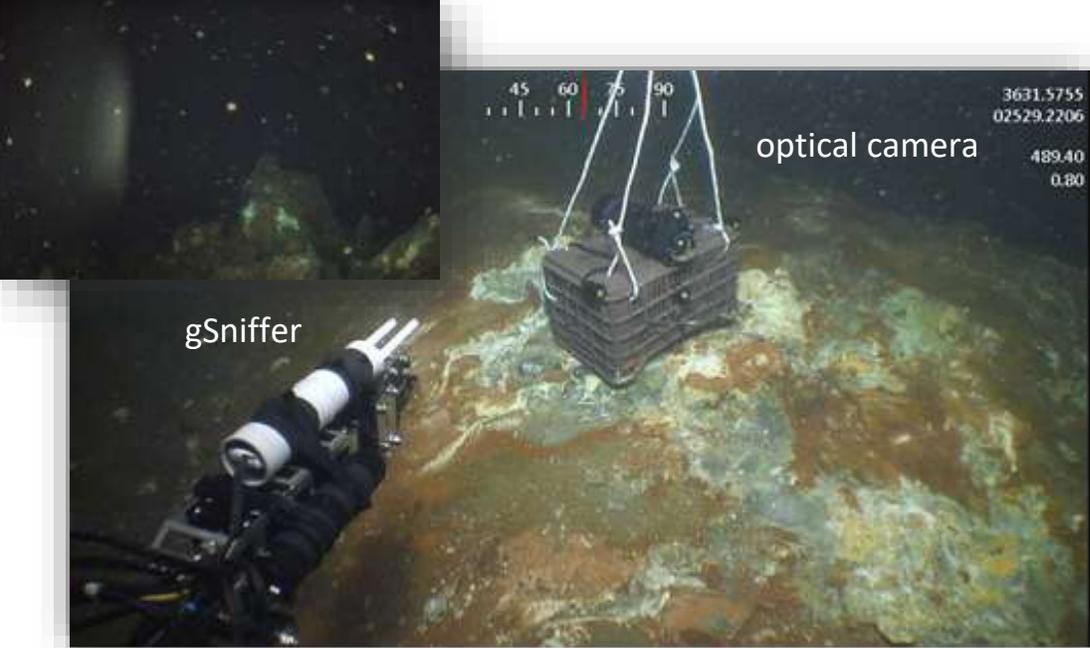
(funded by
Municipality of Thira)



Instruments-measurements-Deployment

- Seafloor observatory
 - 6 T-sensors
 - 3 Inclinometers
 - 2 Pressure gauges
- Stand-alone optical cameras x3
- Multispectra and stereo camera "THEIA"
 - gSniffer (real time measurements)
 - γ -radiation imager "SUGI" (real time measurements)
- UV-camera "CHERI" (UV sensitive camera for the search of Cherenkov radiation from hydrothermal vents)





Optical camera PTZ51 deployment and ethernet connection



Deployment of SANTORY thermometers T2



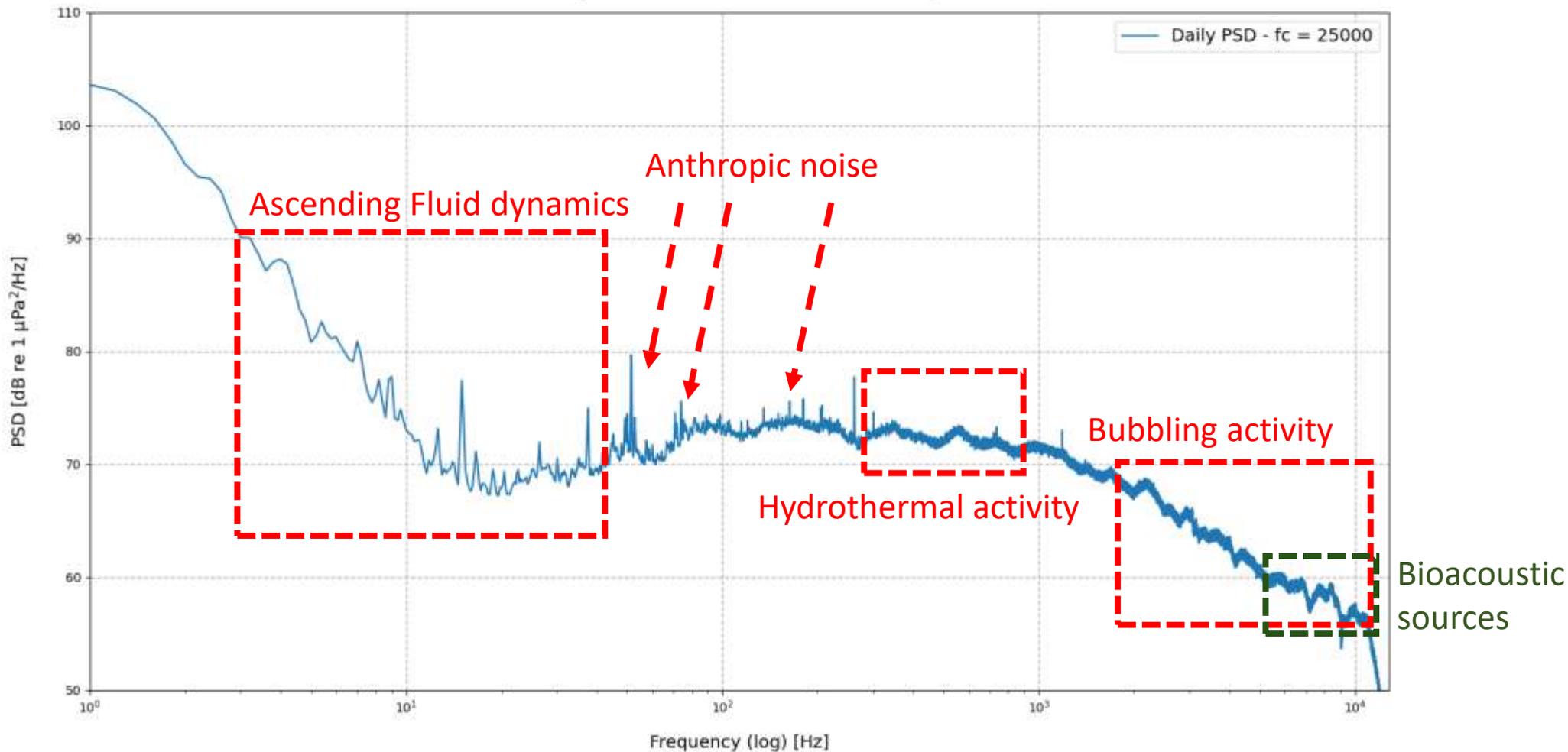
Deployment of 23a-PG2 SANTORY Pressure Gauge



Recovery of the THIRA22- INC3

Acoustic data

Daily PSD - 31/01/2023 - Santory



Basket 1 T6 temperatures

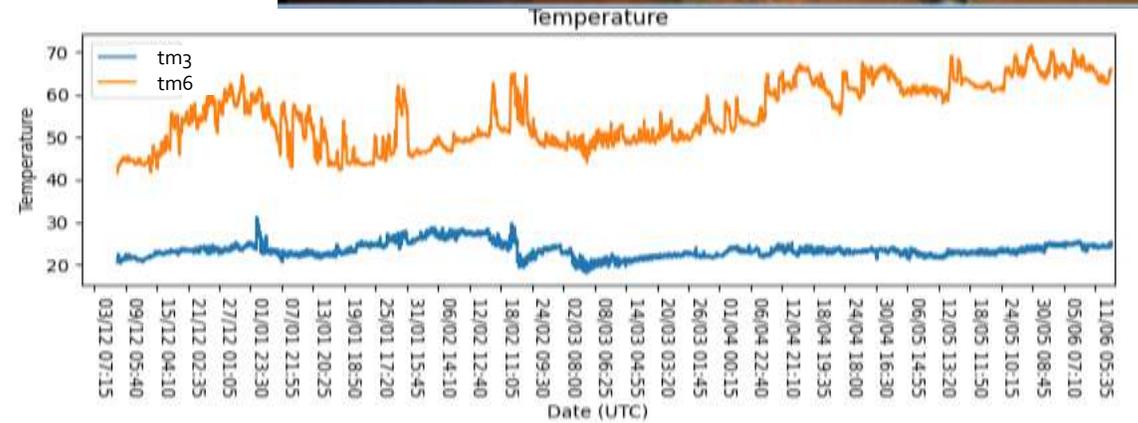
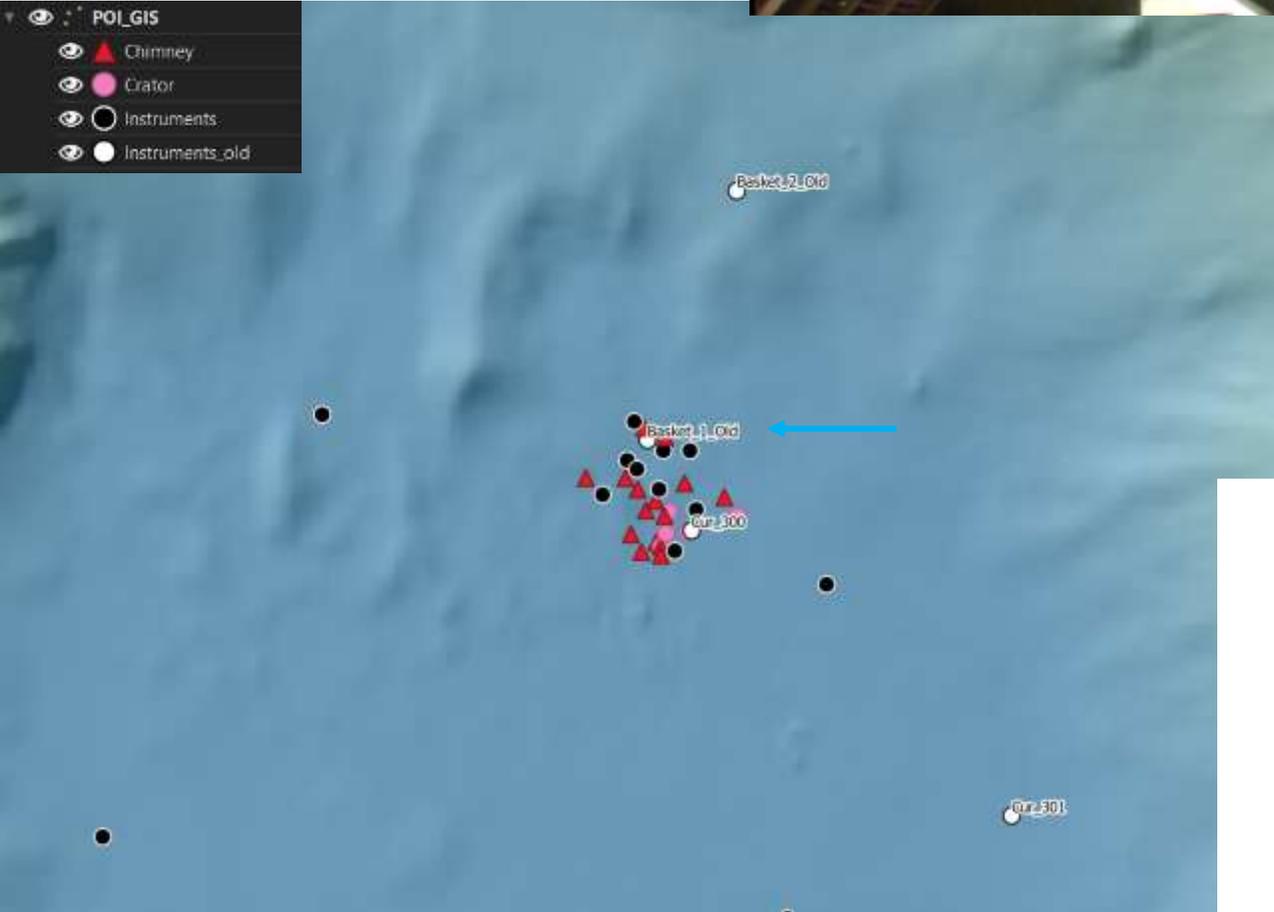
Deployment



Recovery



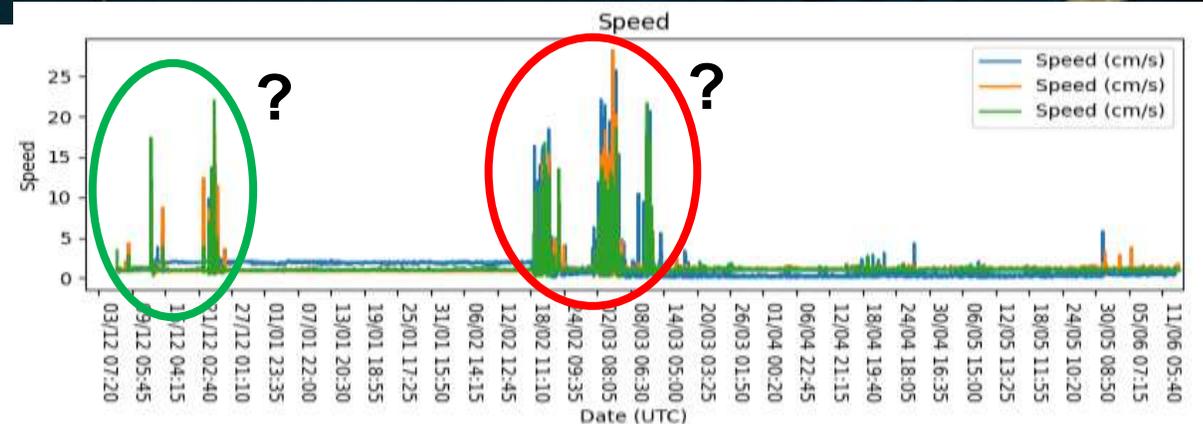
- POI_GIS
- Chimney
- Crater
- Instruments
- Instruments_old



Significant (>4) seismic events in the area Nov 22 - June 23

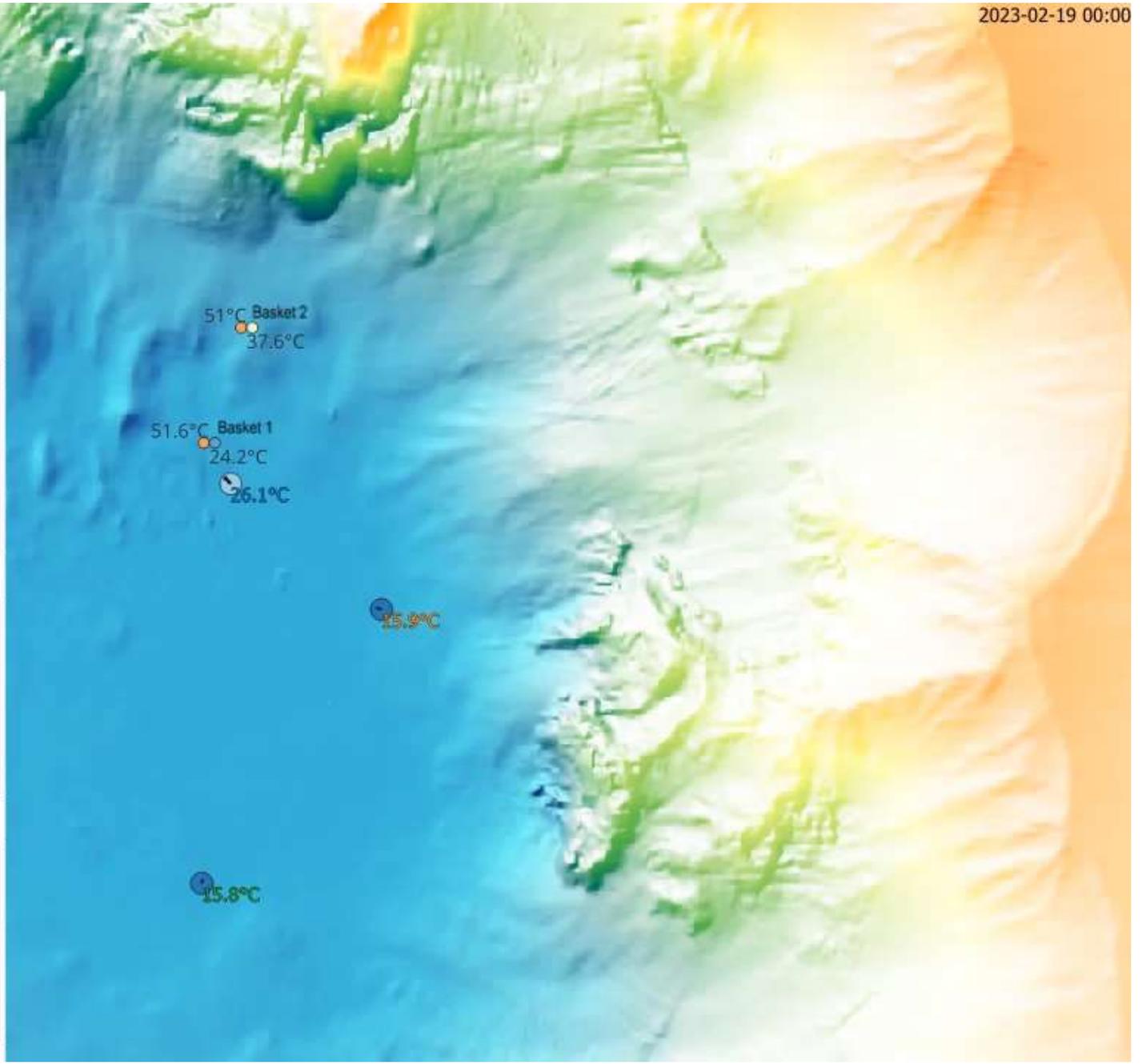
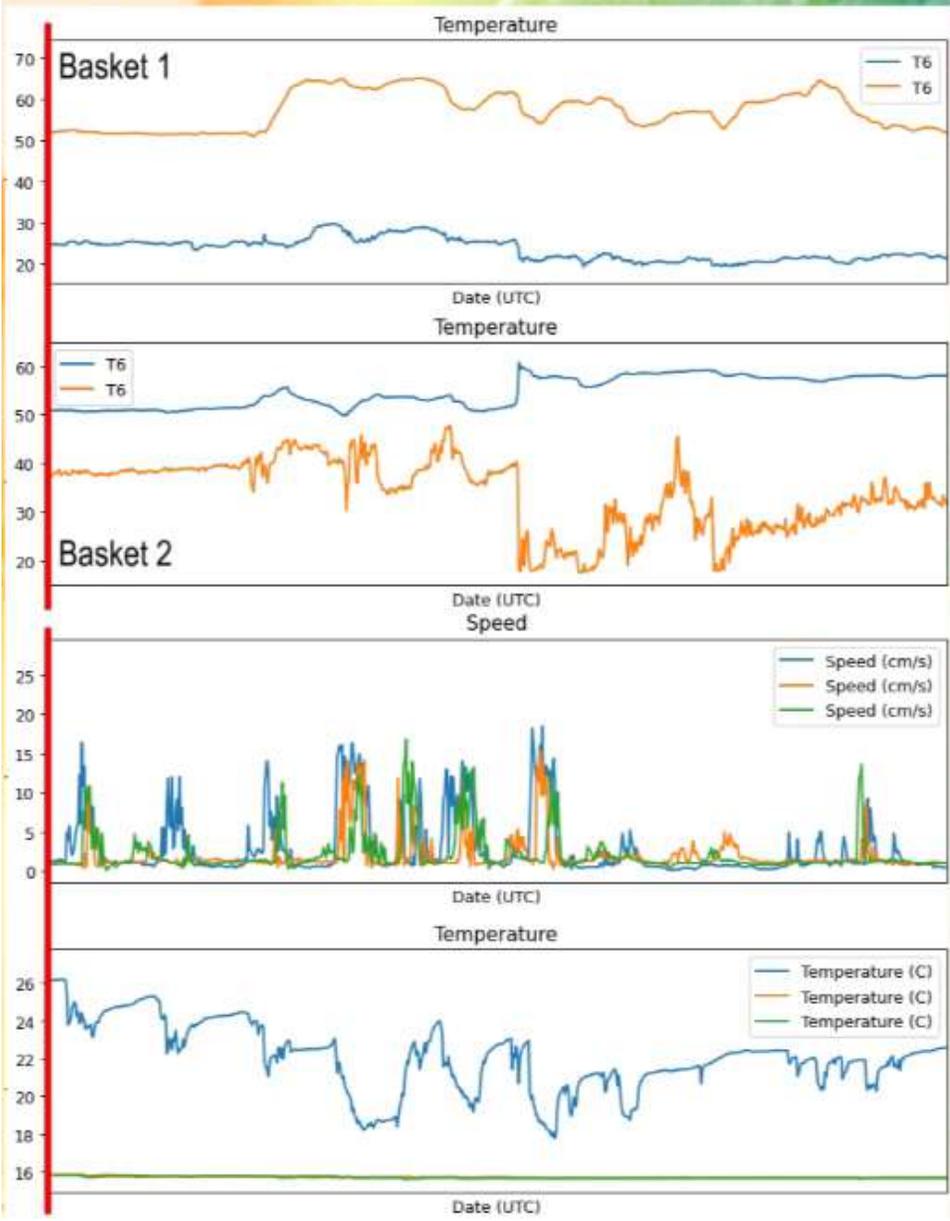


Possible link?



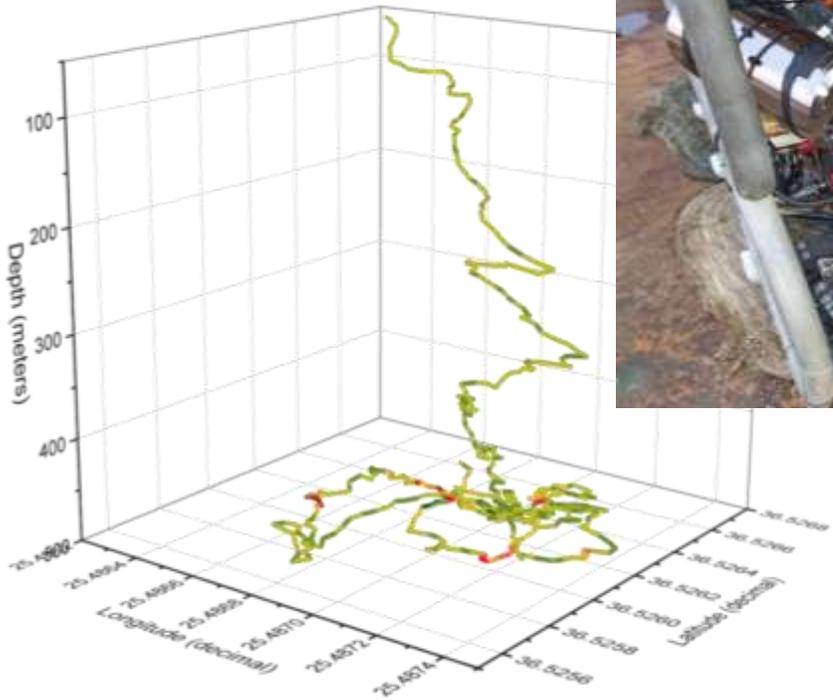
0 500 m

2023-02-19 00:00

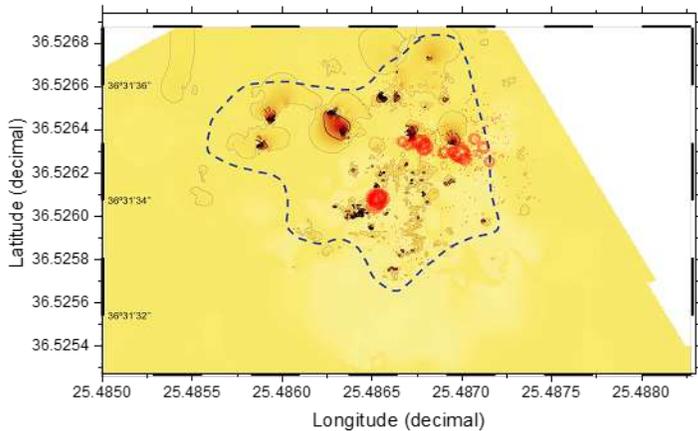
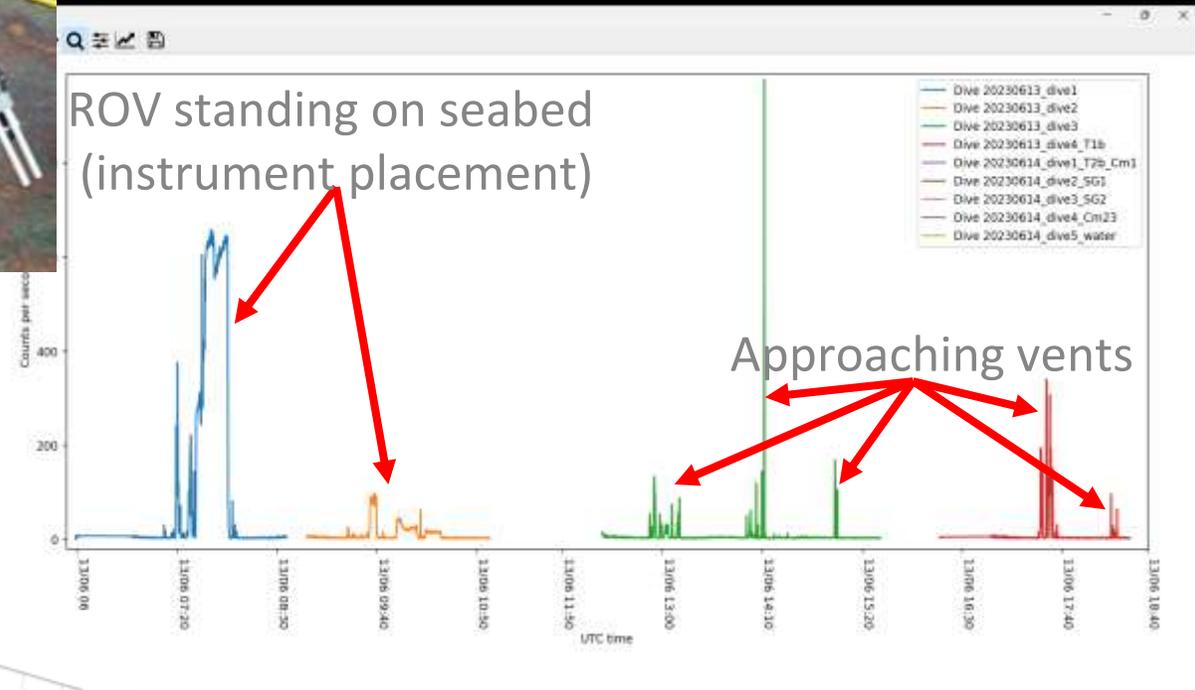




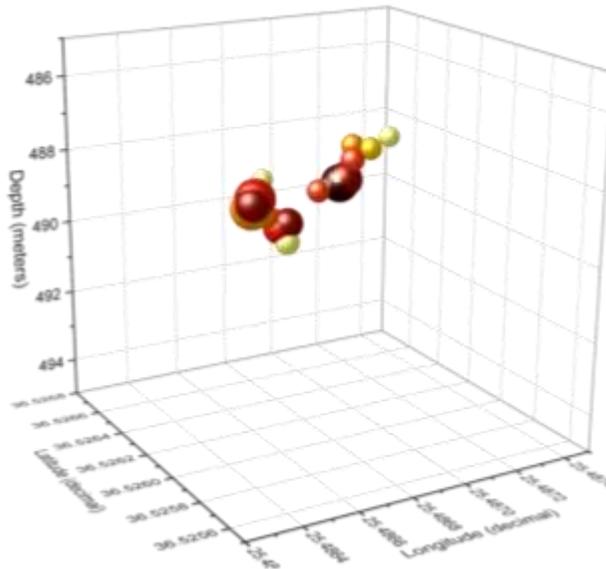
Gamma radiation recordings Day 1 (13/06/23)



ROV standing on seabed
(instrument placement)



(Correlation of measured hotspots with results from M. Christopoulou et al (2016))



Both the size and the color of the spheres depict the intensity of each measurement. All strong signals were obtained in depths ranging 485-495 m.

Counts per second vs time for the data collected of the first four dives



RAMONES



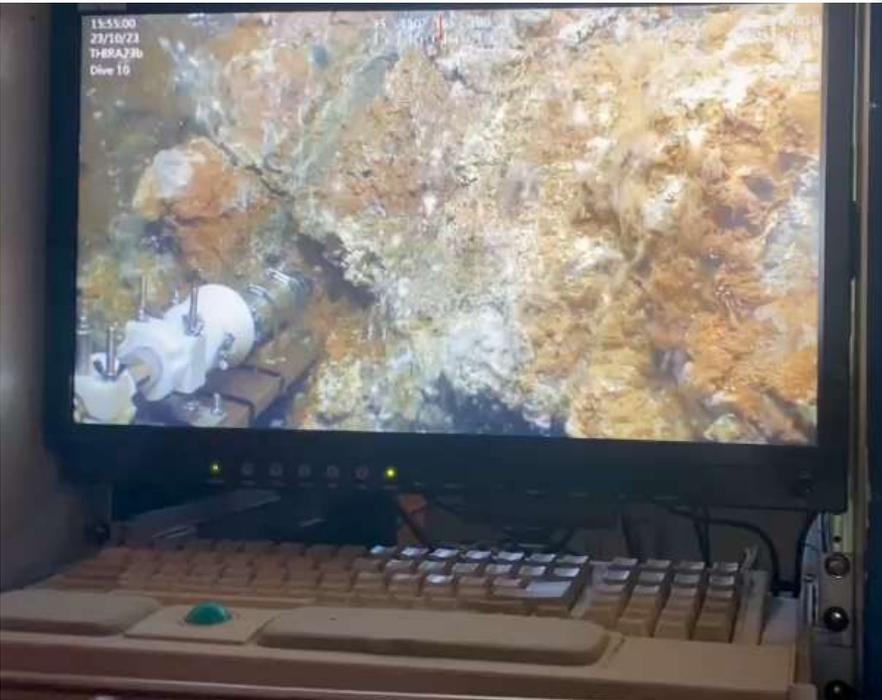
SANTORY

October 2023/3rd oceanographic cruise



Instruments-measurements-Recovery-Deployment

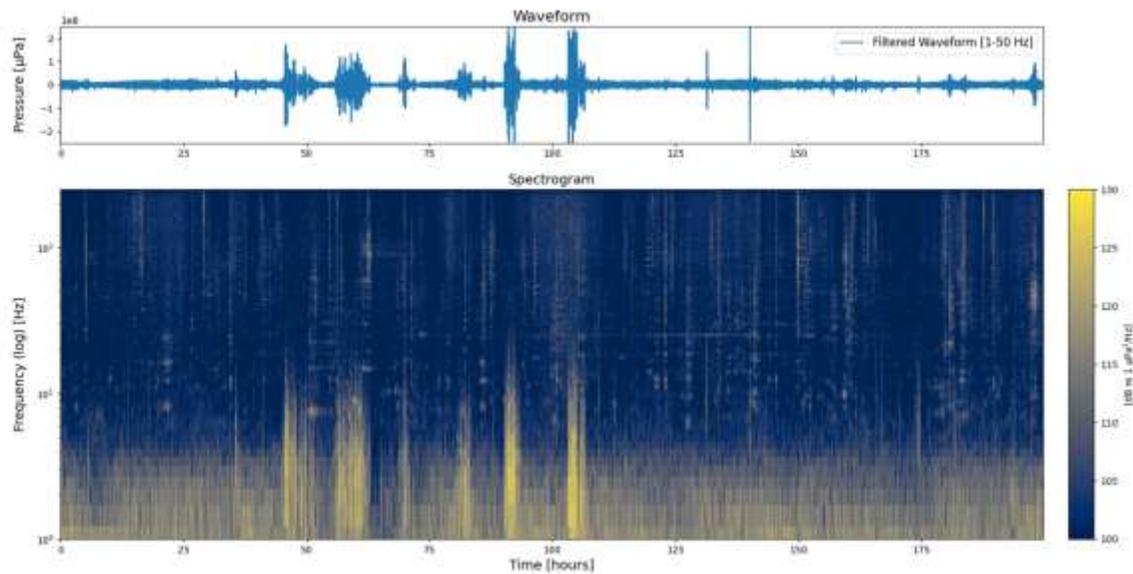
- Seafloor observatory (R)
 - 6 T-sensors (R)
 - 3 Inclinometers (1 R)
- 2 SeaGuard platforms monitoring (Oxygen, Pressure, Tide and wave, Conductivity, Temperature, Turbidity, Current)
 - 3 Stand-alone optical cameras ®
 - Multispectra and stereo camera “THEIA”
 - gSniffer (real time measurements)
 - γ -radiation imager “SUGI” (real time measurements)
 - UV-camera “CHERI”



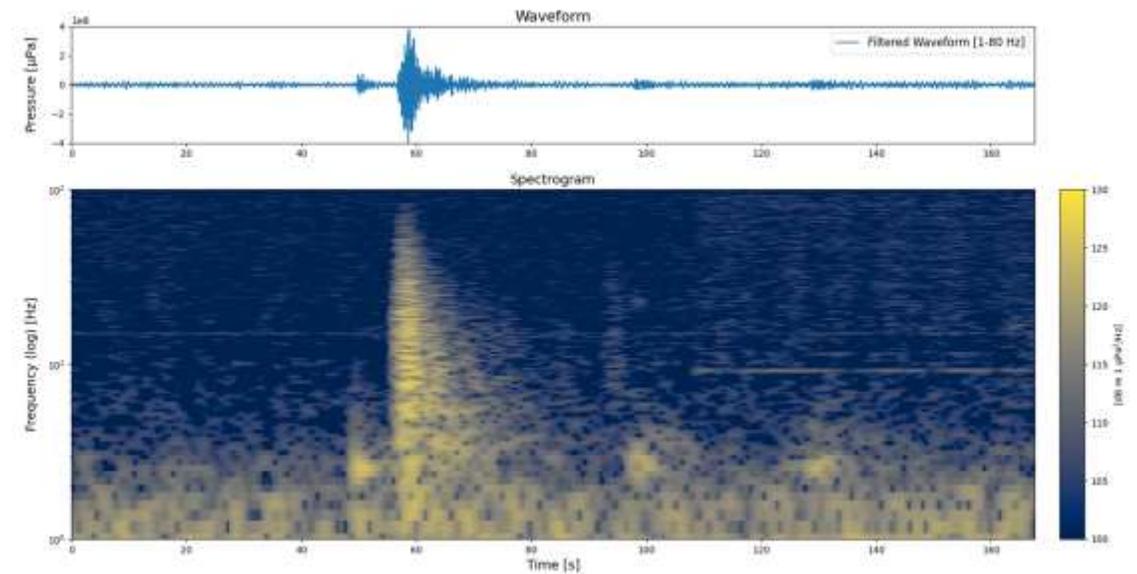


Several local fluid-filled cracks and VT events likely sourced in the deeper portion of the plumbing system together with other types associated to fluid-filled dynamics have been identified, testifying **how the hydrothermal reservoir is fed by the plumbing system.**

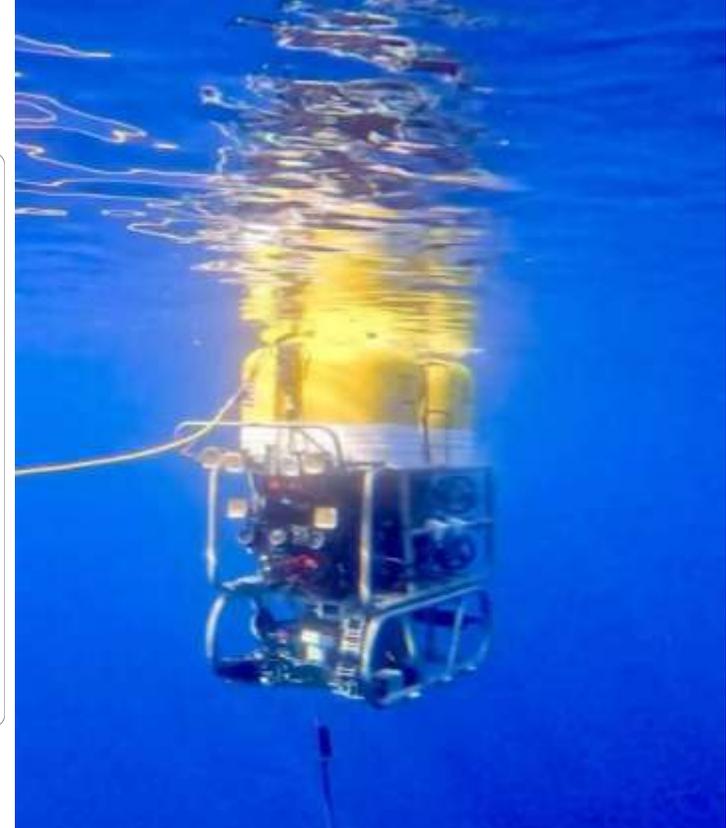
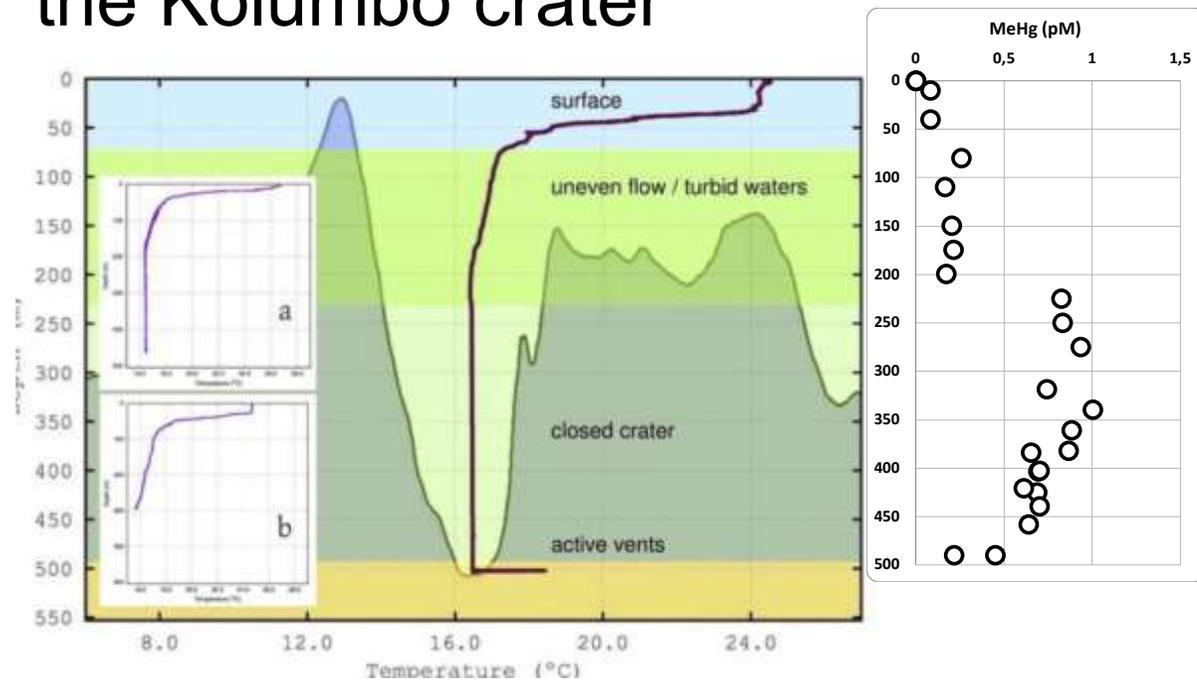
Spectrogram vs Waveform - 01-09/03/2023



Spectrogram vs Waveform - 26/01/2023 [13:18 - 14:23 UTC]



1st mercury (Hg) measurements in the Kolumbo crater

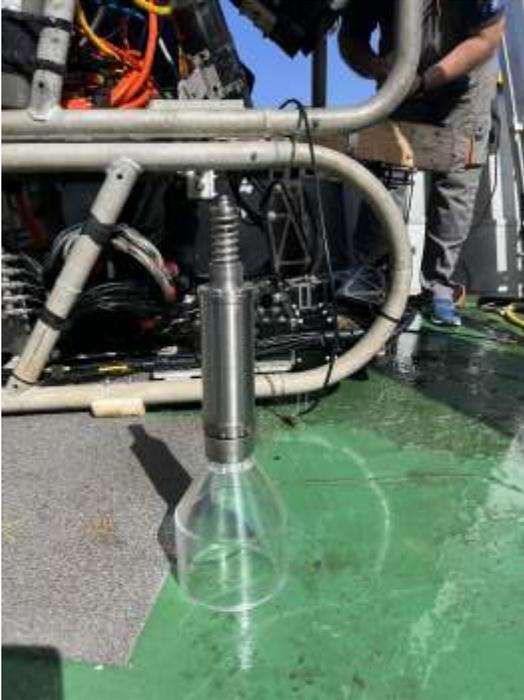


- Vent fluids highly enriched in Hg
- high Hg inputs (up to 500 kg/y)
- Highest methylmercury (MeHg) in the Mediterranean
- MeHg is a bioaccumulative neurotoxin
- Potential "natural" contamination of the marine resources



Gas Sampling technique and analytical results

Andrea L. Rizzo



Gas-tight sampler for submarine fluids sampling



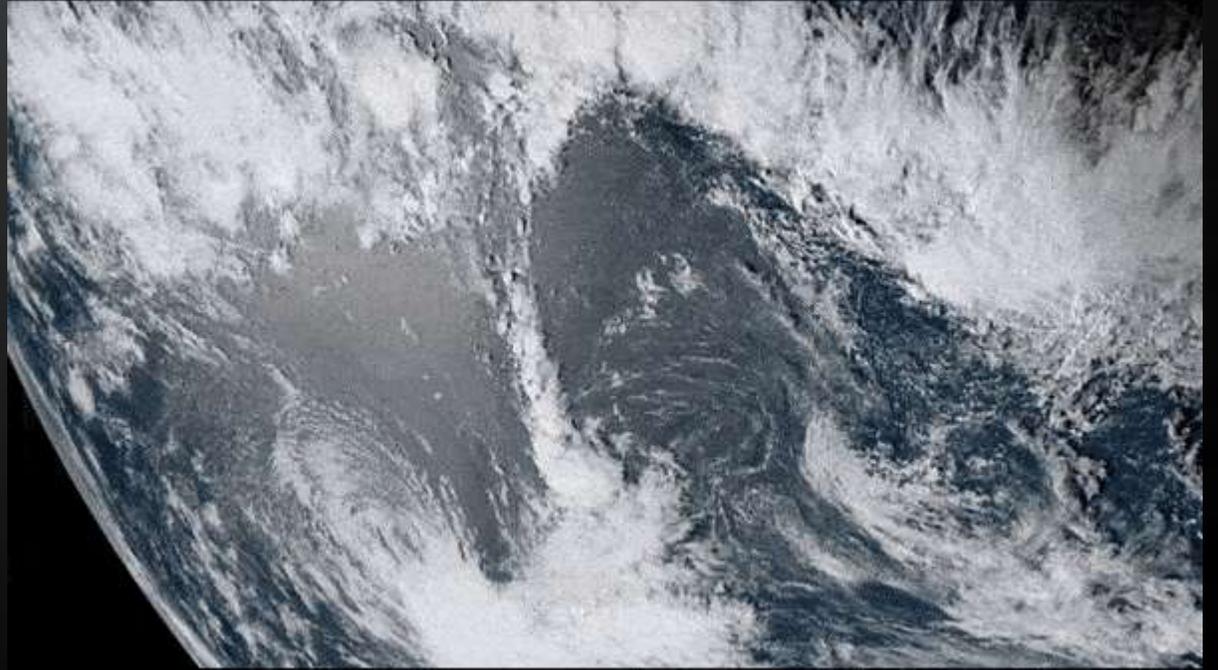
Gas-tight sampler connected to the ROV



Gas extraction system from the Gas-tight sampler

Authors	R/Ra	He/Ne	CO ₂ (%)	δ ¹³ C-CO ₂
Carey et al., 2013	6.84	990	99.4	not measured
Rizzo et al., 2016, 2019	from 6.84 to 7.05	from 9 to 270	from 88.3 to 98.4	from -0.04 to 1.15
October 2023	6.84	622	96	-0.3

Volcanic Risk Management

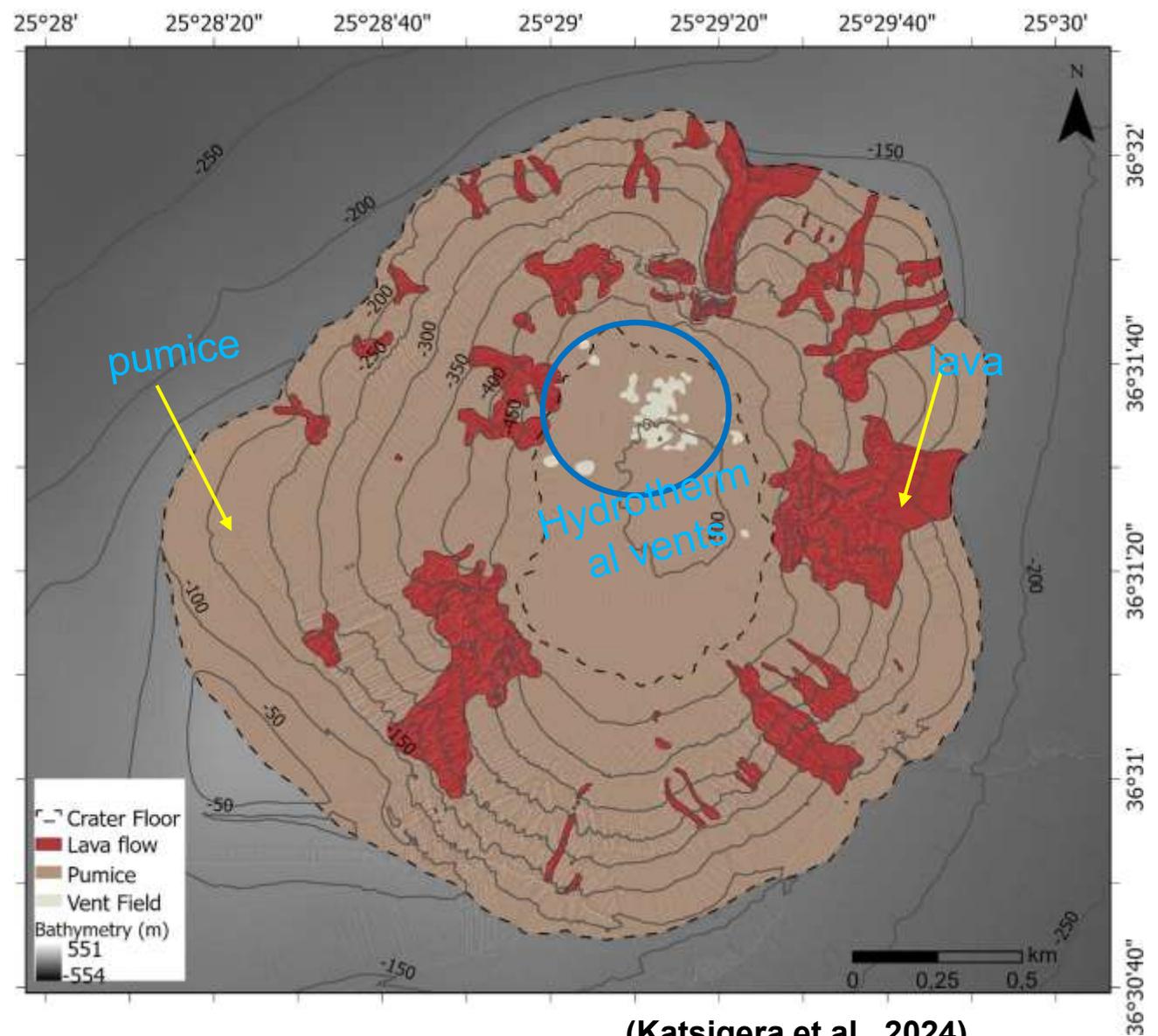
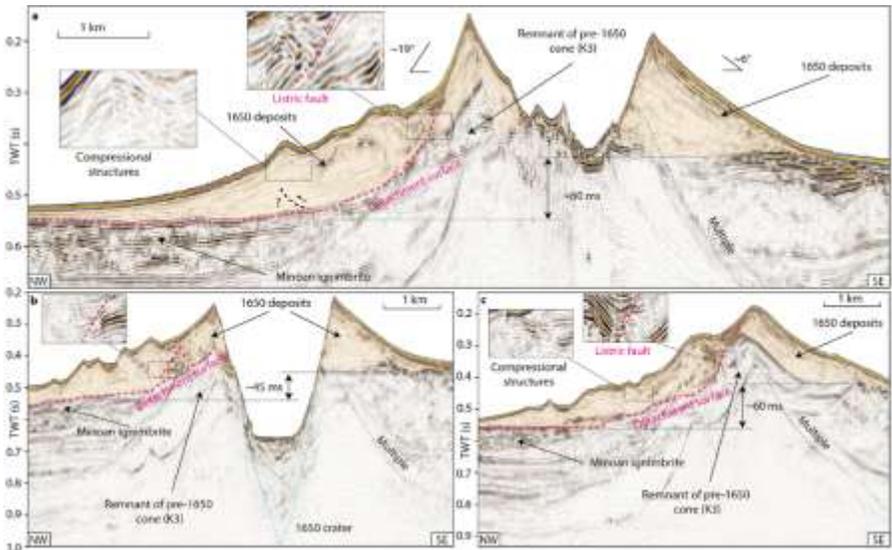
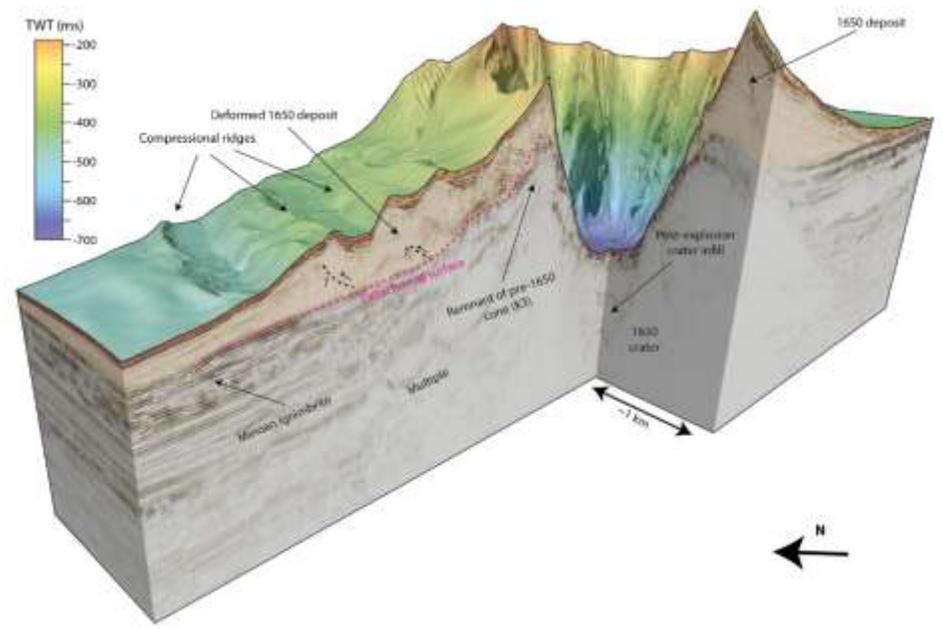


Hunga Tonga–Hunga Ha'apai eruption 2022



Anak Krakatau collapse 2018

Kolumbo underwater geological map

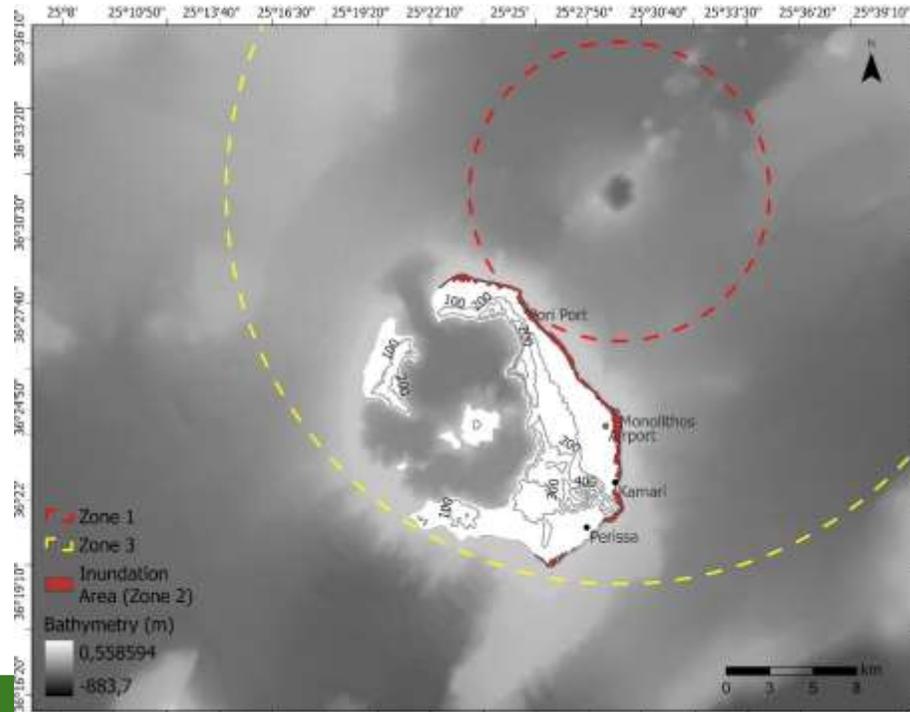


(Karstens et al., 2023)

(Katsigera et al., 2024)

Hazard zonation

The 1650 eruption and subsequent tsunami had detrimental consequences for the east coast of Santorini. Historical accounts mention flooding of up to 2km² of land.



Zone 1 exclusion zone	Zone 2 inundation area high-	Zone 3 moderate- risk zone
<ul style="list-style-type: none"> • 7 km <Kolumbo • access must be strictly prohibited due to the 	<ul style="list-style-type: none"> • The coast of Santorini • The area should be evacuated to prevent 	<ul style="list-style-type: none"> • 22 km off Kolumbo • Less likely to be affected by a tsunami,

Pre-eruptive Phase

- Scientists aid the government agency and help with early assessments of hazards and action plans

Eruptive Phase

access to the offshore area should be prohibited and the gauges should be implemented to monitor the area for a possible tsunami generation

partial or complete evacuation of the eastern coastal area of Santorini and its ports on the east coast

Consider effects on transport, communications, health and environment

by toxic gas emission, and the

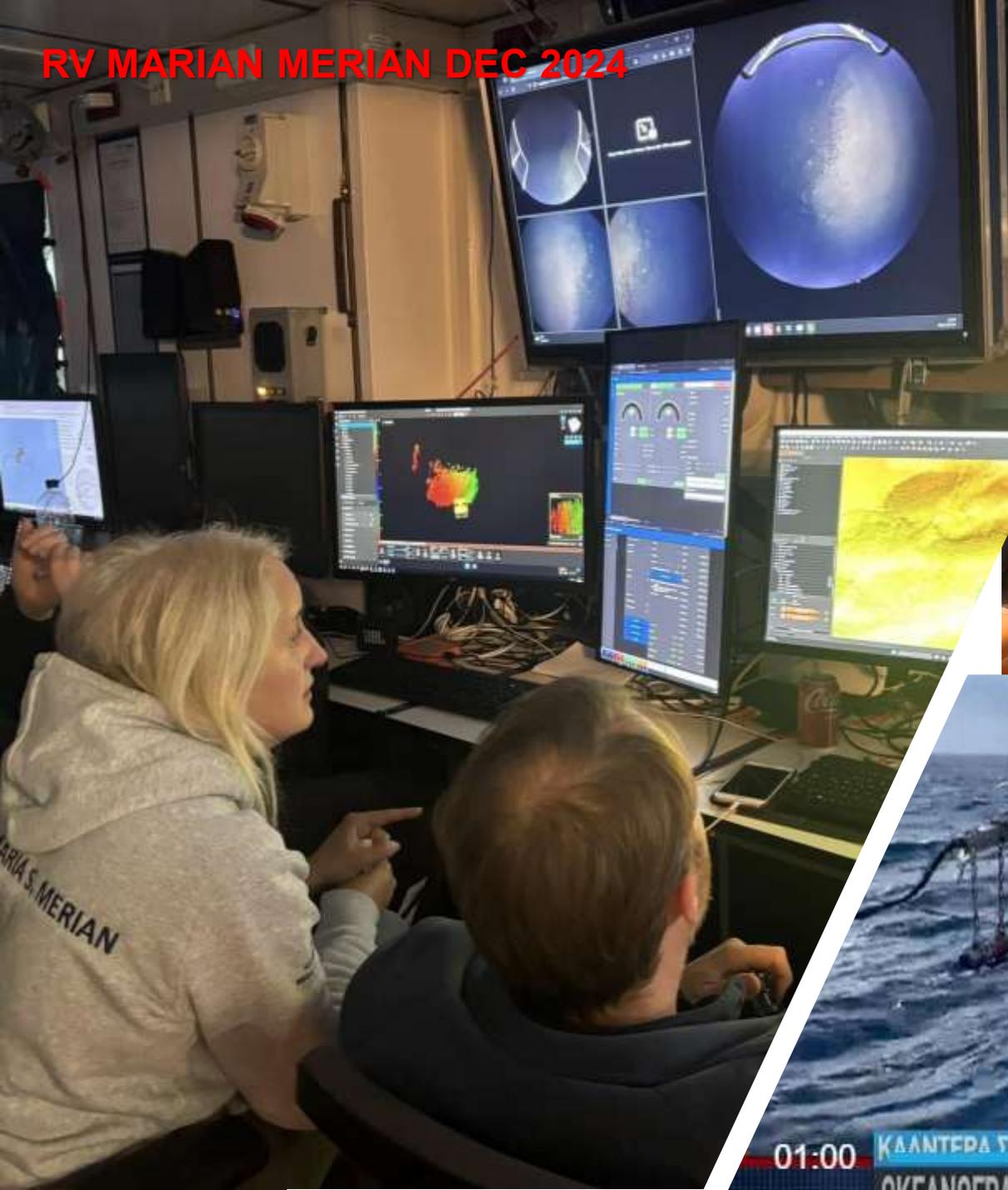
of the 1650 casualties both inland and

emissions and ashfall still pose a hazard.

(Katsigera et al., 2024)



RV MARIAN MERIAN DEC 2024



01:00

ΚΑΛΑΝΤΕΡΑ ΣΑΝΤΟΣΙΝΗ | Εύα Νομικού, Καθηγήτρια Τμήματος Γεωλογίας Πανεπιστημίου Αθηνών

ΟΚΕΑΝΟΓΡΑΦΙΚΗ ΑΡΧΟΤΟΜΗ ΕΡΕΥΝΑ ΤΑ ΥΠΕΡΑΛΛΑΞΙΑ ΜΦΑΙΣΤΕΙΑΚΑ ΚΕΝΤΡΑ ΣΤΟ ΑΙΓΑΙΟ

05:42

ΠΕΡΙ

The **geohazards of Santorini-Kolumbo field**, one of Europe's most volcanically hazardous region—ranging from **explosive eruptions** and **caldera collapses** to **flank failures**, **tsunamis**, and **hydrothermal explosions**—are intimately linked to the interplay between tectonic deformation and magma migration. The recurrent volcanic unrest in the region, together with evidence of sector collapses and persistent venting, highlights the potential for **cascading hazards**.

Recent studies show that a future explosive event of Kolumbo poses a **significant hazard** to the northern and east coasts of Santorini, however there is no relevant management protocol in place. Therefore, it is proposed that a combination of scientific research (active monitoring, hazard maps), community engagement, preparedness planning with government agencies (Civil Protection), and timely response strategies is crucial to minimize the **hazard risks** and avoid casualties and the detrimental consequences to the area's economy and infrastructure.



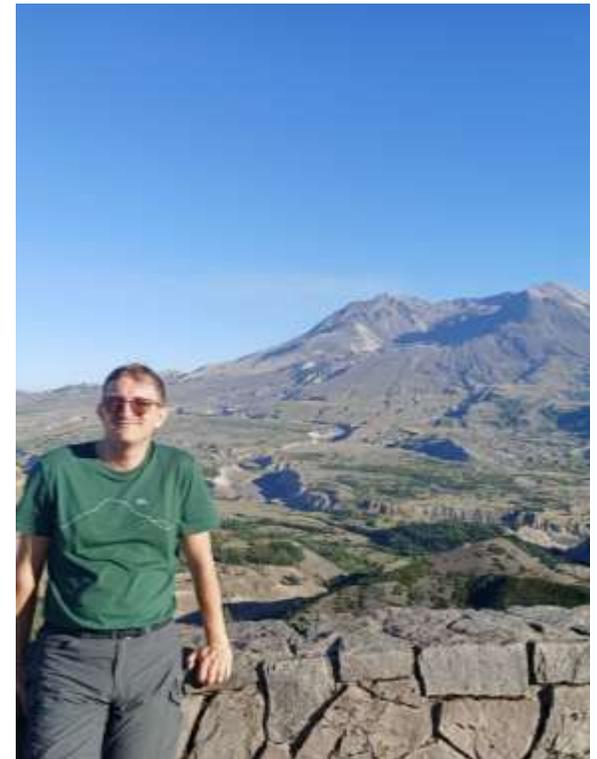
Ευχαριστώ πολύ!

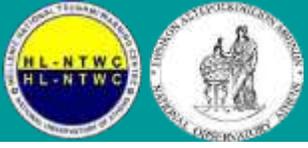


Burning Question(s)

Panelist

- **Dr Marinos Charalampakis**, NOA, Greece & **Alessandro Tadini**, INGV, Italy.
- **Dr Alessandro Tadini** is a researcher at INGV Pisa since 2022.





The NEAM-COMMITMENT project

NEAM-COMMITMENT
NEAM Collaboration for Improved
tsunami risk mitigation and management

✓ **Aim:** Improve tsunami preparedness in the NEAM region, at different scales, for effective risk, evacuation and emergency management.

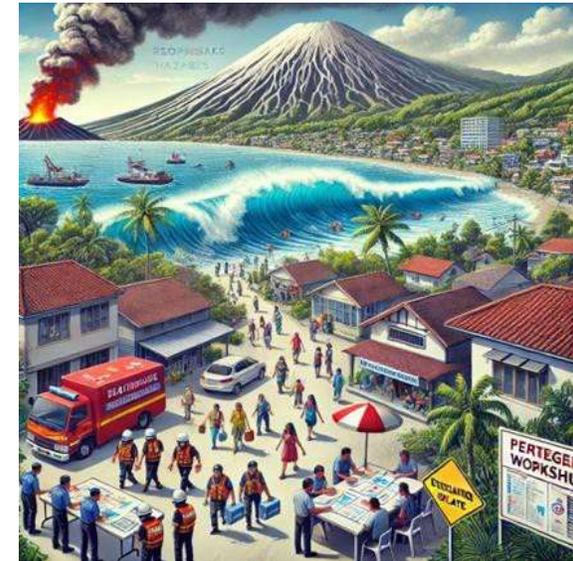
✓ **Objectives** are spanning from the national to local levels, addressing needs for national tsunami risk planning and for enhancing multi-hazard preparedness in coastal communities at risk.

- **National level:**

- National-level tsunami inundation maps are crucial for coastal planning and risk management.
- Support local tsunami hazard assessment and evacuation planning.
- Contribute to important global tsunami initiatives like IOC-UNESCO's Tsunami Ready Recognition Programme (TRRP) and Ocean Decade Tsunami Programme (ODTP) by scaling hazard assessment nationally.

- **Local level:**

- Tsunamis from earthquakes and volcanic activity pose significant risks for coastal communities in the NEAM region.
- A multi-hazard approach considering cascading effects is needed for effective tsunami evacuation and emergency management.
- Emphasis on science-informed participatory and decision-making workshops to improve local planning and implementation effectiveness.



Duration: 24 months, started on 01 February 2025

Call: European Union Civil Protection Mechanism-2024-Knowledge for Action in Prevention & Preparedness

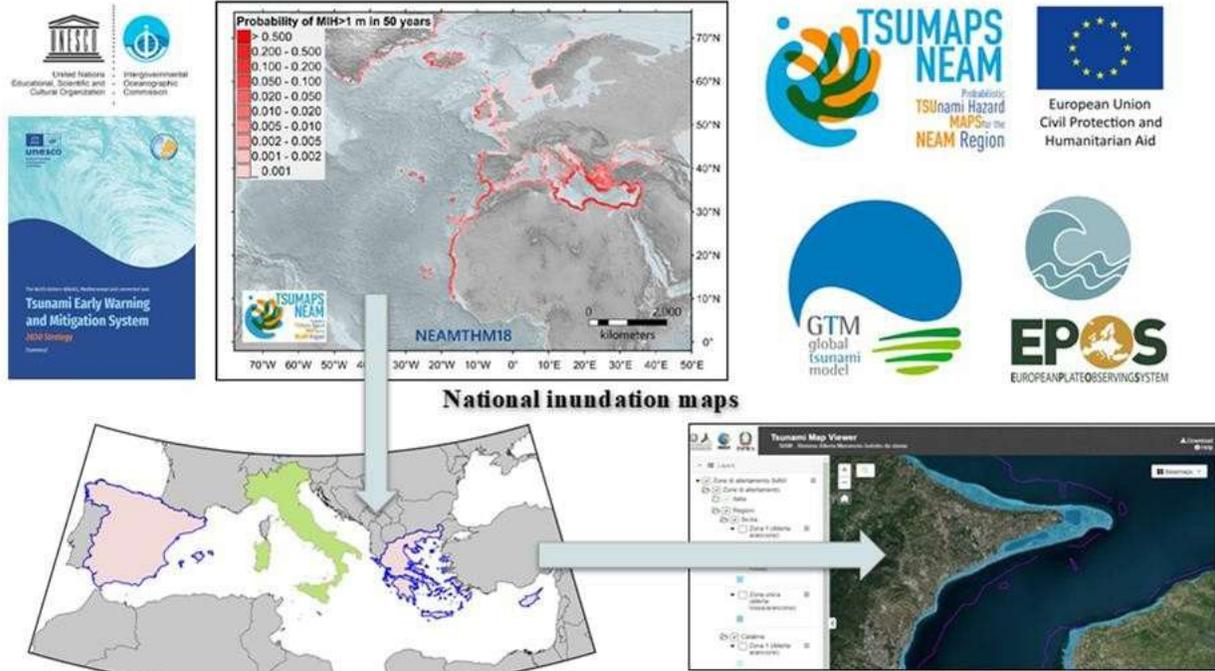
Title: NEAM Collaboration for Improved tsunami risk mitigation and management

Estimated Project Cost: €985 629.70



Co-funded by
the European Union

Objective 1 – common national maps across NEAM countries



→ National level

- Development of national tsunami Inundation maps (CY, GR, ES)
- Development of guidelines and tools for implementation in other countries/regions
- Dissemination of results across relevant national stakeholders
- Dissemination of methodological approach at the international level

Objective 2 – location-specific multi-hazard risk management

Earthquake + tsunami

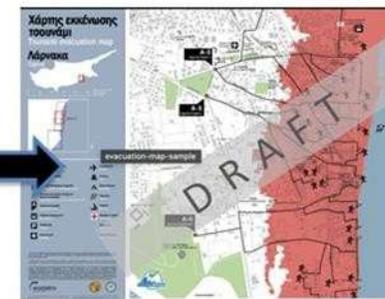
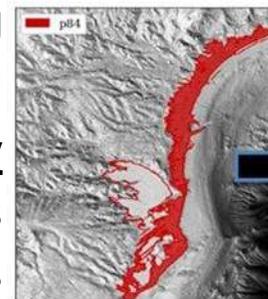


Volcanic activity + tsunami



→ Local level

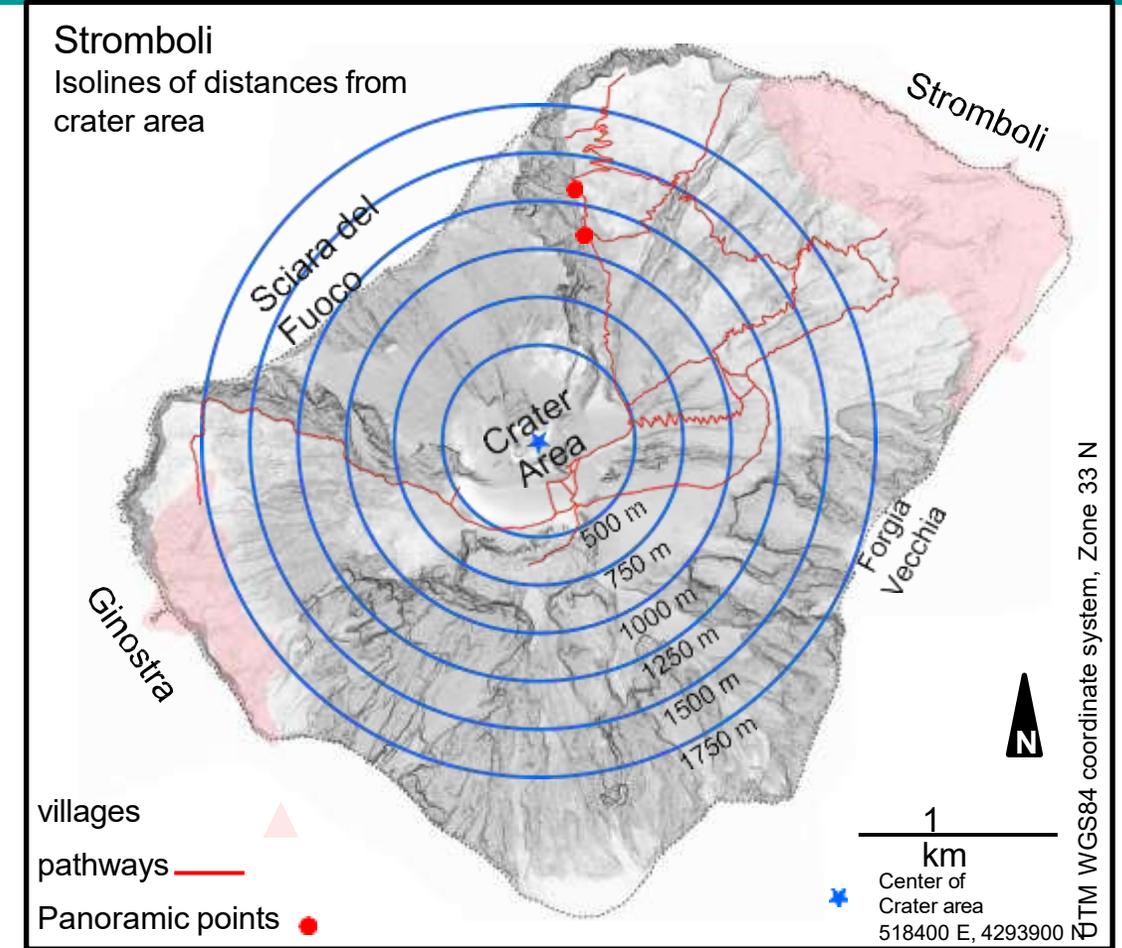
- Application @ two pilot sites in **Greece** and **Italy**
- Local evacuation mapping through science-informed and participatory decision-making, considering multi-hazard cascading effects, i.e. earthquakes and **volcanic activity**



- Development of guidelines
- Awareness raising activities



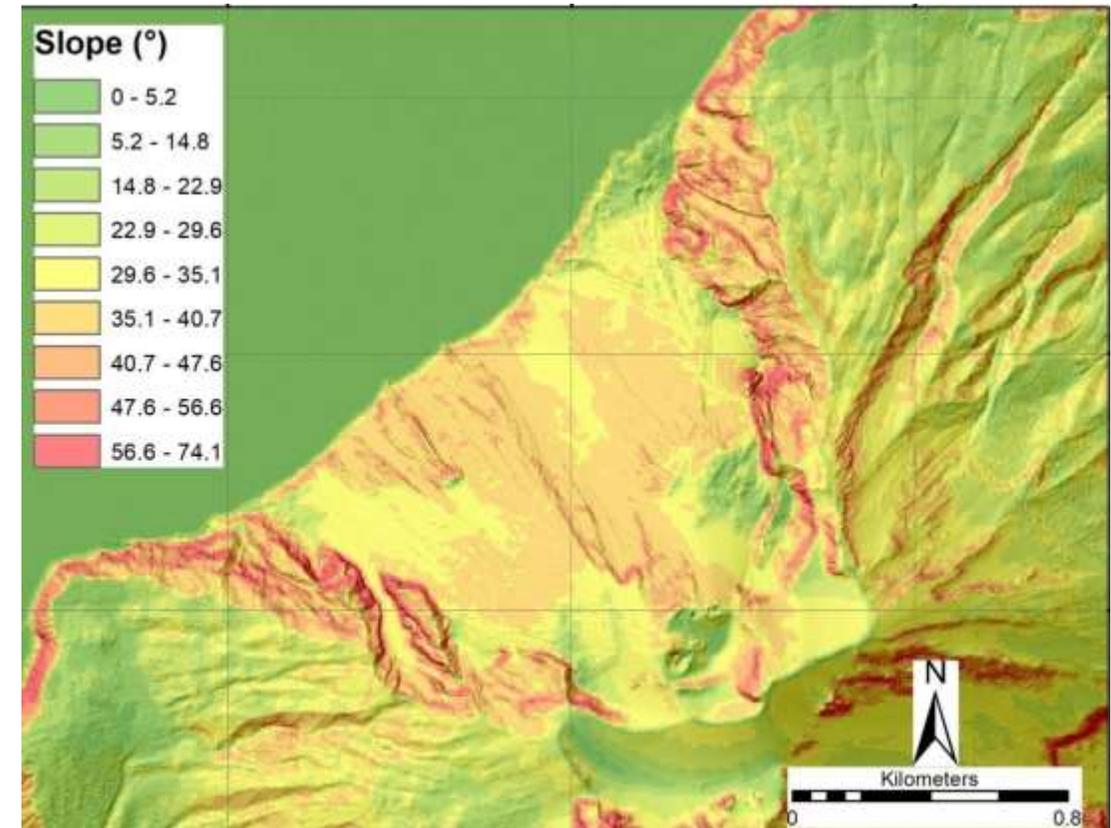
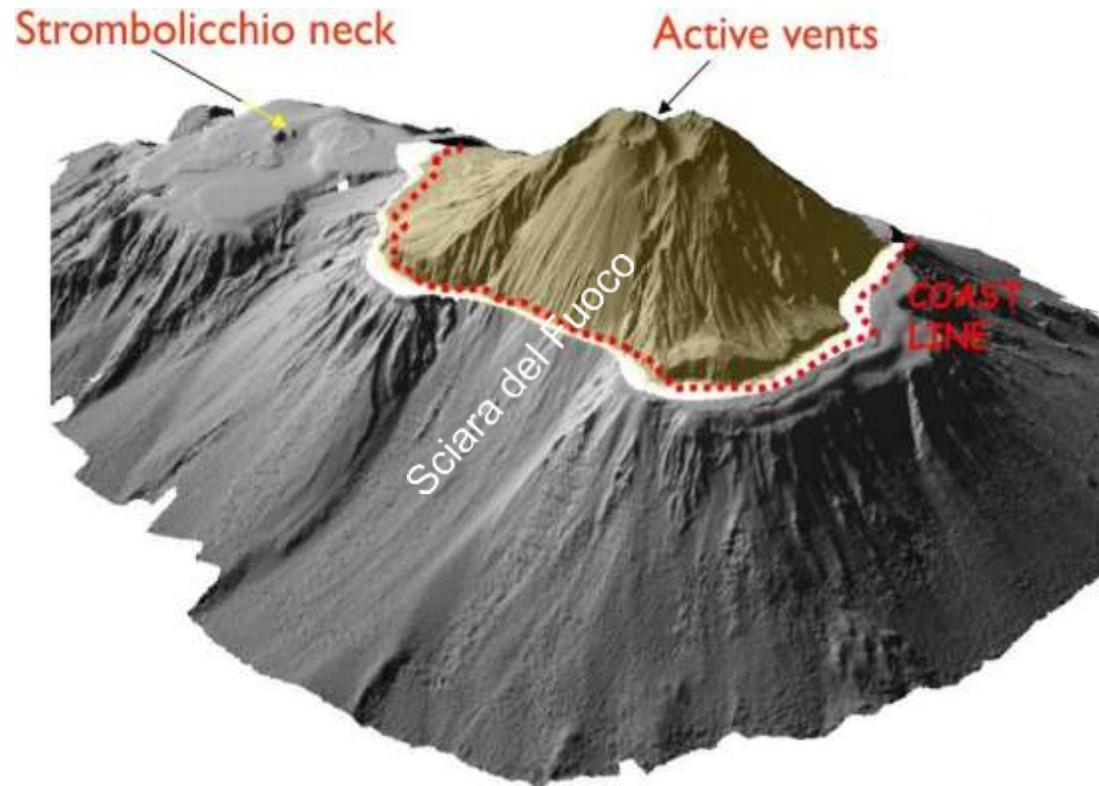
Stromboli volcano



- Stromboli is the Northernmost Aeolian island – its activity is an expression of **arc volcanism**;
- Its total surface is 12.6 km² with two villages (Stromboli and Ginostra) with < 500 permanent inhabitants.
- Important touristic center, with daily arrival of > 2,000 tourists during summer season



Stromboli volcano



- Stromboli is characterized by **frequent explosive and effusive activity**;
- Current type of activity has not changed significantly starting since **VIII century CE** (Bertagnini et al. 2008; Rosi et al. 2013).
- Large structure to the NW of the volcano («Sciara del Fuoco») with subaerial and submarine part, characterized by steep slopes made of both unconsolidated material and lava flows. Volcanic products from Stromboli activity tend to concentrate here.



Overview of explosive activity



Normal activity



Major explosions



Paroxysms

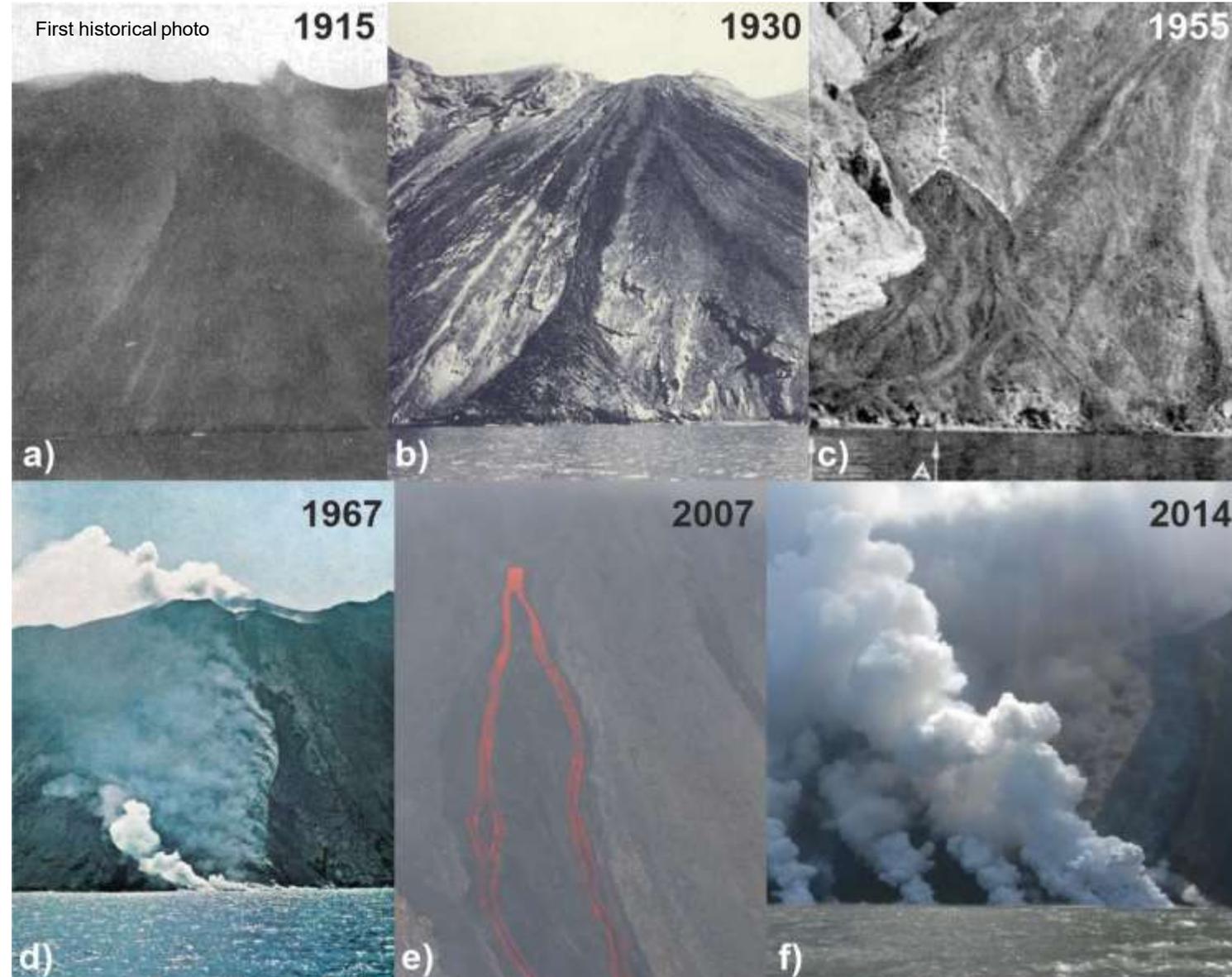
<i>Total duration</i>	4-30 s	< 2 min	5-10 min
<i>Fallout volume</i>	1-10 m ³	10 ² -10 ³ m ³	10 ⁴ -10 ⁵ m ³
<i>Ballistic range/size</i>	200-250 m / centimetric	1000 m / decimetric	Entire island / metric
<i>Column height</i>	50-400 m	1000 m	3000-4000 m
<i>Involved vents</i>	1	Multiple	All

Increasing magnitude/explosive

Source: Rosi et al. 2006; 2013

Overview of effusive activity

- Effusive activity could span from small, short-lived overflows that are confined to the crater area up to large lava emission that could interests the whole SdF with durations > 1 month;
- In between these two end-members, there is a continuous range of effusive phenomena with variable durations. There is a correlation with explosive activity but there are also isolated effusive phenomena;
- Effusive products of the current activity are almost entirely located within the crater area and the SdF. Lava effusion (both from crater overflows or from new vents/fissures at lower elevation) along the SdF can affect its stability.



Historical photographs of some of the most significant lava flows in the last century. For more details see Marsella et al. (2011).



Tsunami hazard from tsunamigenic landslides/1

With the term “**tsunamigenic landslide**” (TL) we refer to any tsunamigenic sub-aerial or submarine mass flow, including pyroclastic avalanches and primary PDCs.

At Stromboli TL with associated tsunamis caused on Stromboli:

- | | | |
|--|--------|--|
| • Extremely large inundation (at least three times in medieval times); | —————> | ~180x10 ⁶ m ³ (cumulative) |
| • Medium to large inundation (1916, 1919, 1930, 1944 and 2002); | —————> | ~1-30x10 ⁶ m ³ |
| • Little or no inundation (1921, 1959, 2019, 2021, 2022 and 2024). | —————> | ≤ 10 ⁶ m ³ |

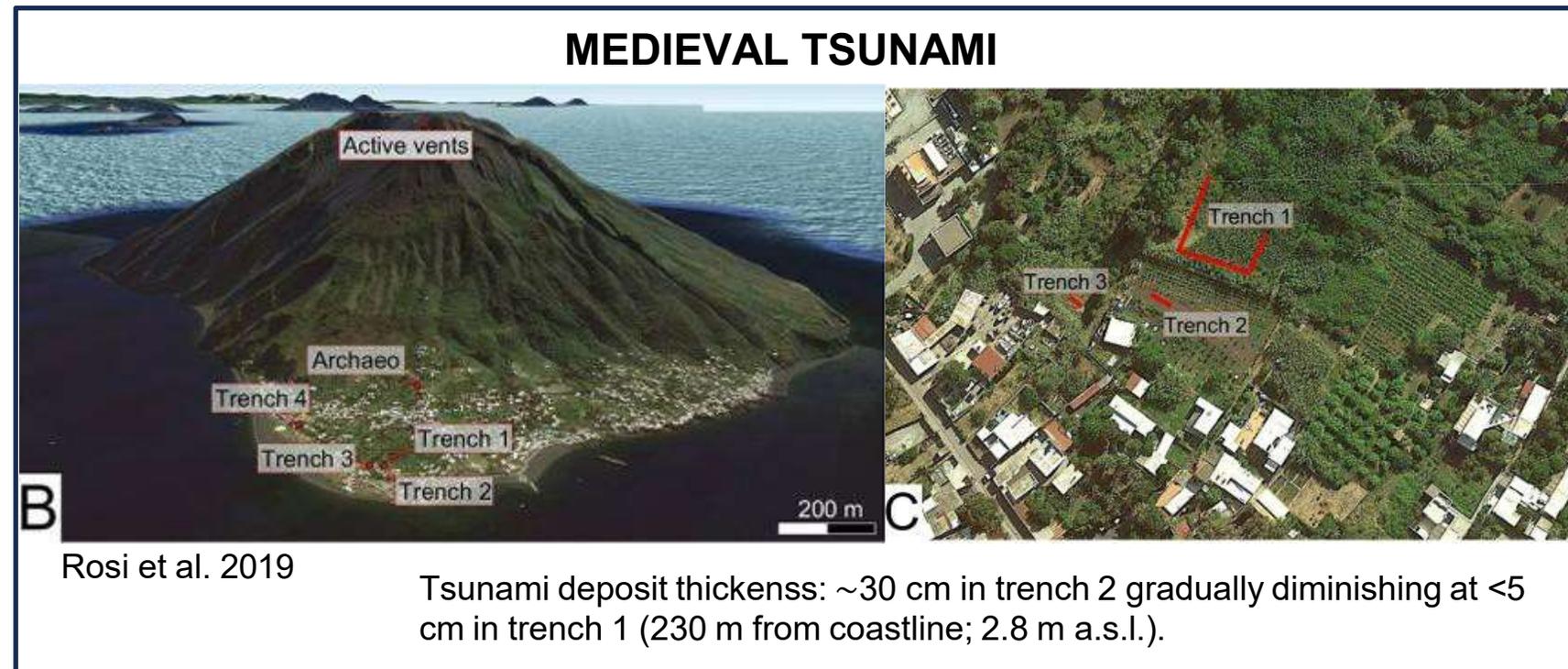
TL estimated volumes

~180x10⁶ m³ (cumulative)

~1-30x10⁶ m³

≤ 10⁶ m³

30/12/2002 tsunami wave in front of Stromboli village



Tsunami hazard from tsunamigenic landslides/2

In the last ca. 150 years, there were 41 Strombolian paroxysms and **5 major tsunamis**, i.e. characterized by tens to hundreds of meters water ingress in the inhabited areas. In total, **80% of the major tsunamis**, all except 2002, were associated to paroxysms, whereas only **10% of the historical paroxysms** were associated to a major tsunami.

4 additional paroxysms before 1960 are reported to be associated to great waves, agitated seawater and limited inundations, possibly indicating smaller tsunamis, similar to those occurred in 2019-2024. Such minor phenomena are likely to be historically **under recorded**, particularly when they were not associated to a paroxysm.

SEA INGRESSION CHRONICLES – tsunamis reported at about the same time of the main explosions

1916 - tsunami wave of **ca. 20 m ingress** on the North shore (Spiaggia Lunga?), while at Scari only agitated sea.

1919 - water **retreats of 200 m and then inundates 300 m** (Pta. Lena?).

1930 - water **retreats of 100 m and then inundates 200 m** (Pta. Lena).

1944 - water **inundates 200-300 m** (Pta. Lena).

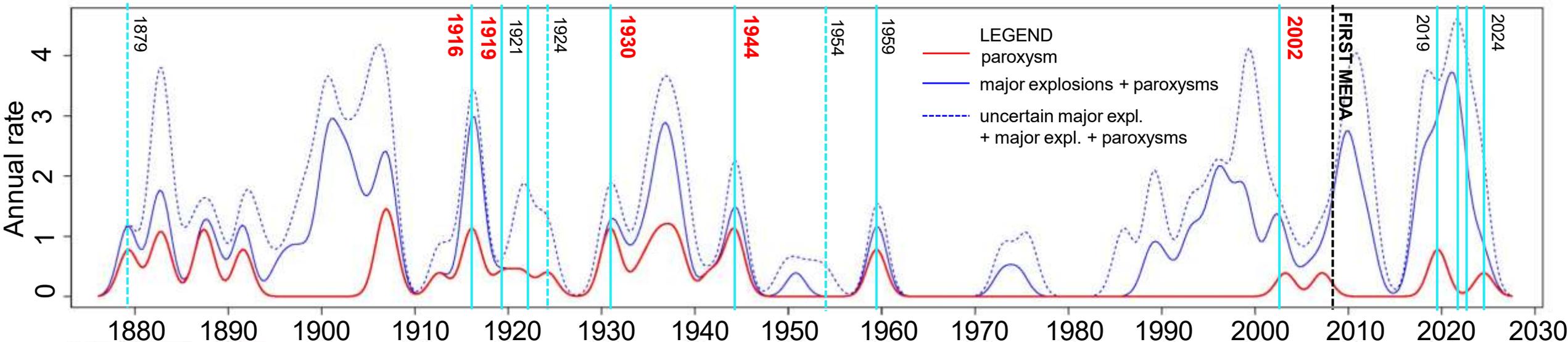
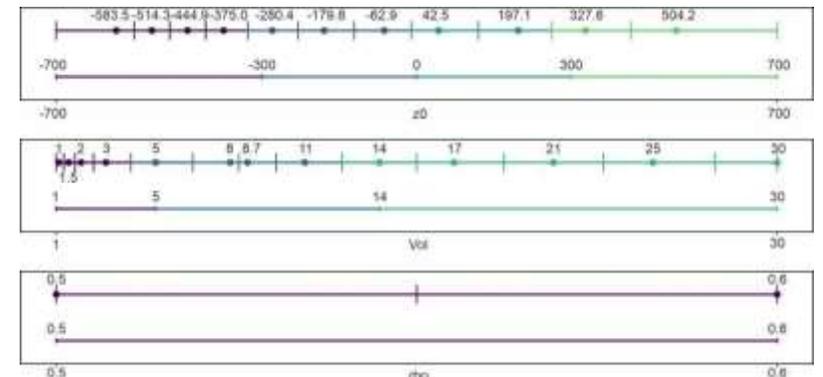
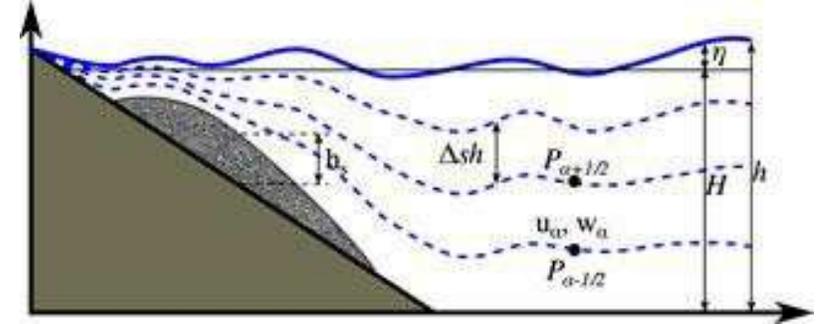


Figure. Kernel density estimation of the **annual rate of paroxysms**, major explosions, and uncertain major explosions. **Historical tsunamis** are marked by cyan vertical lines; those not characterized by significant water ingress in the village are marked by dashed lines.

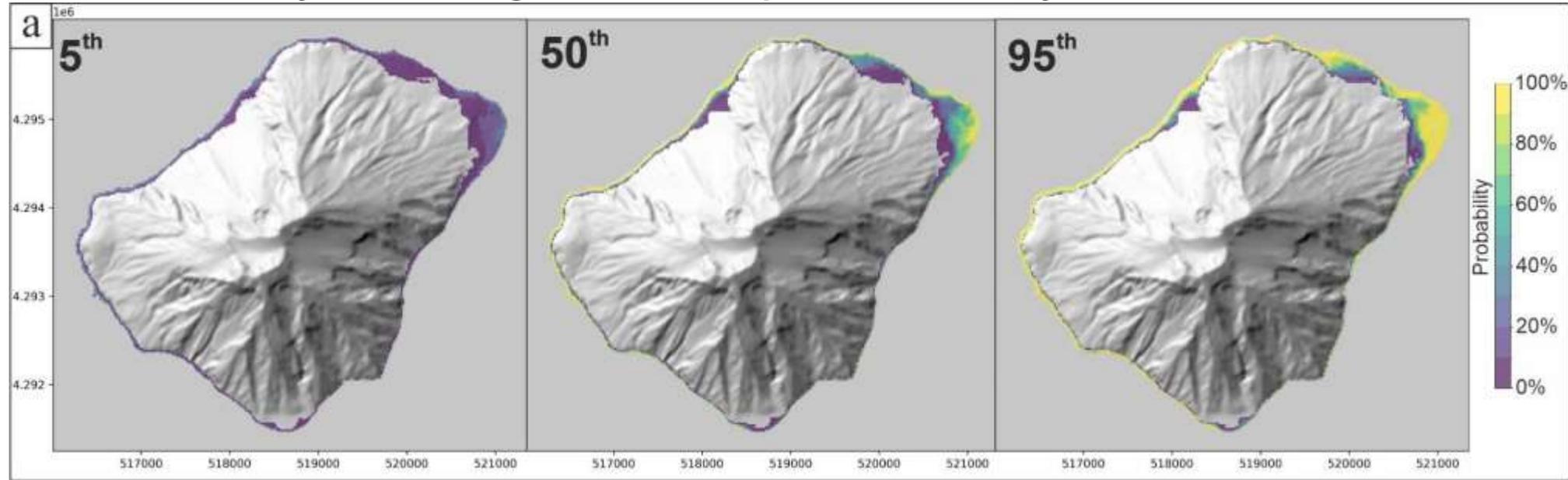
Approach to develop preliminary probabilistic tsunami hazard maps

1. Numerical simulations with the Multilayer-HYSea model (Macías et al. 2020) to get inundation maps
2. Expert elicitation to assign probabilities at different scenarios and to create a temporal model
3. Procedure to combine inundation maps with probabilities from elicitation

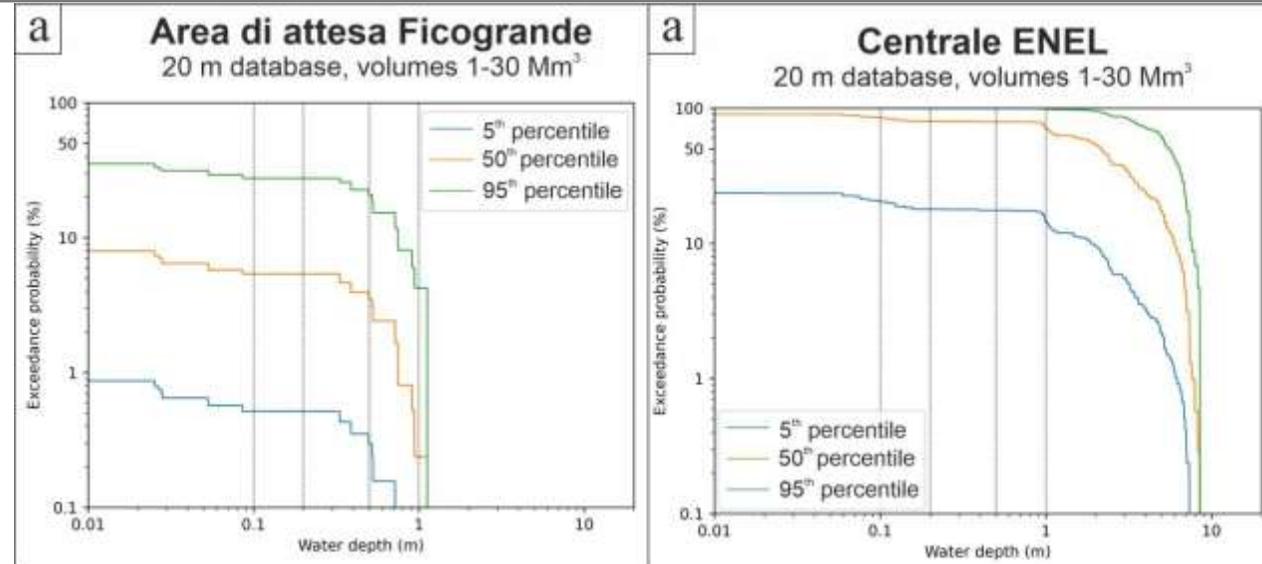


Results

Probability of exceeding 0.5 m water depth in the next 50 years



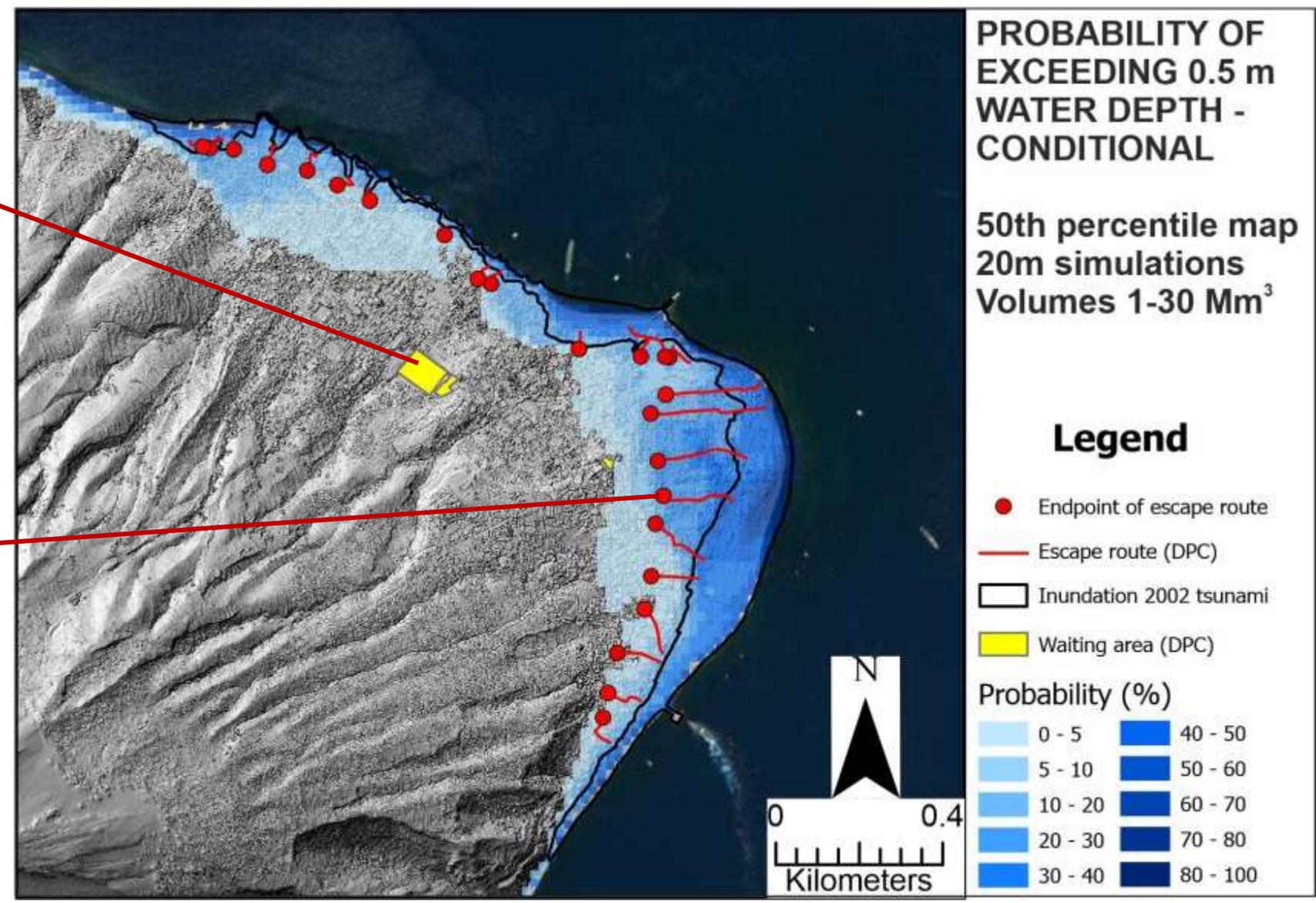
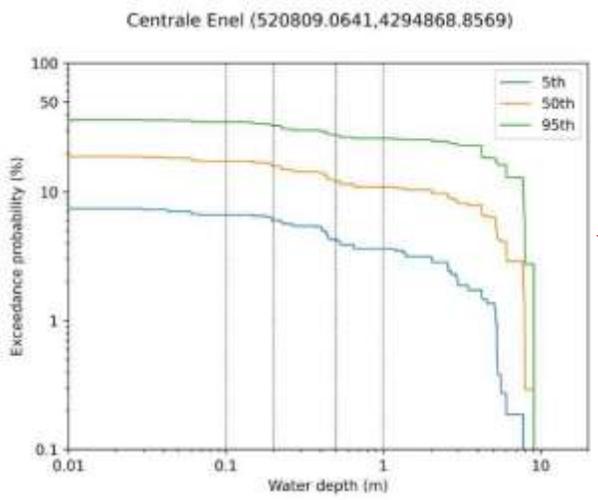
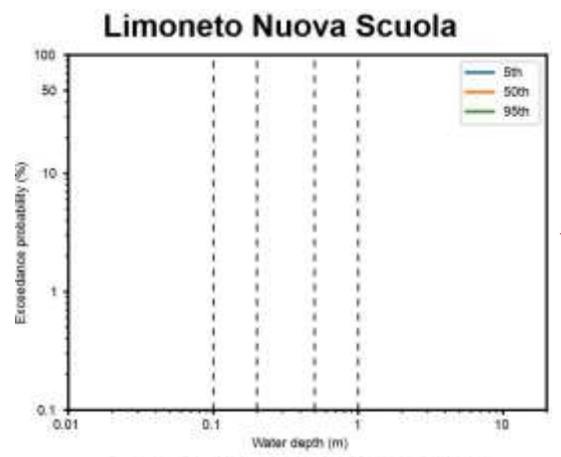
Hazard maps



Hazard curves



Comparison hazard maps/existing escape routes



Preliminary assessments of areas affected by ballistic projectile fallout from paroxysms at the endpoints of tsunami escape routes

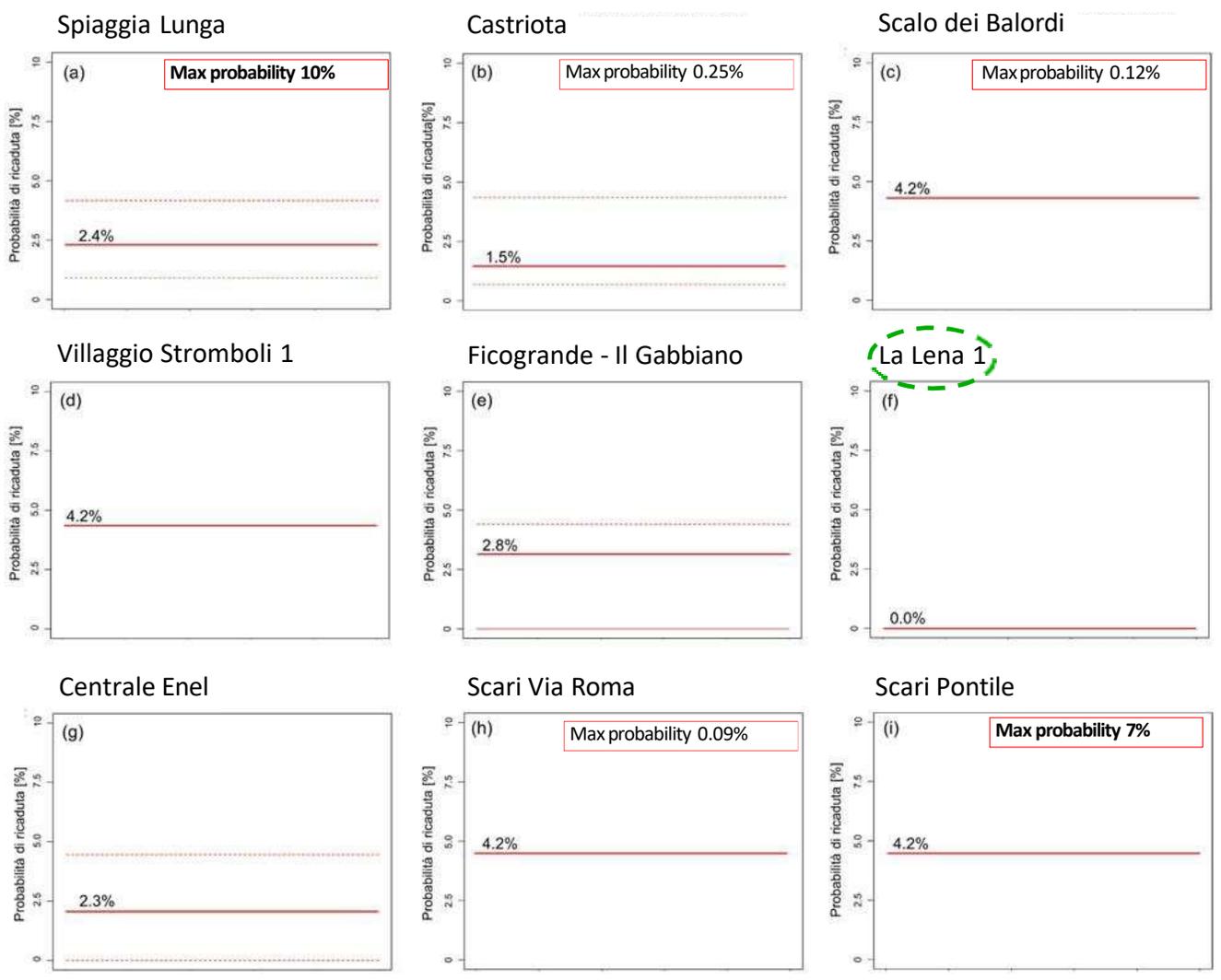
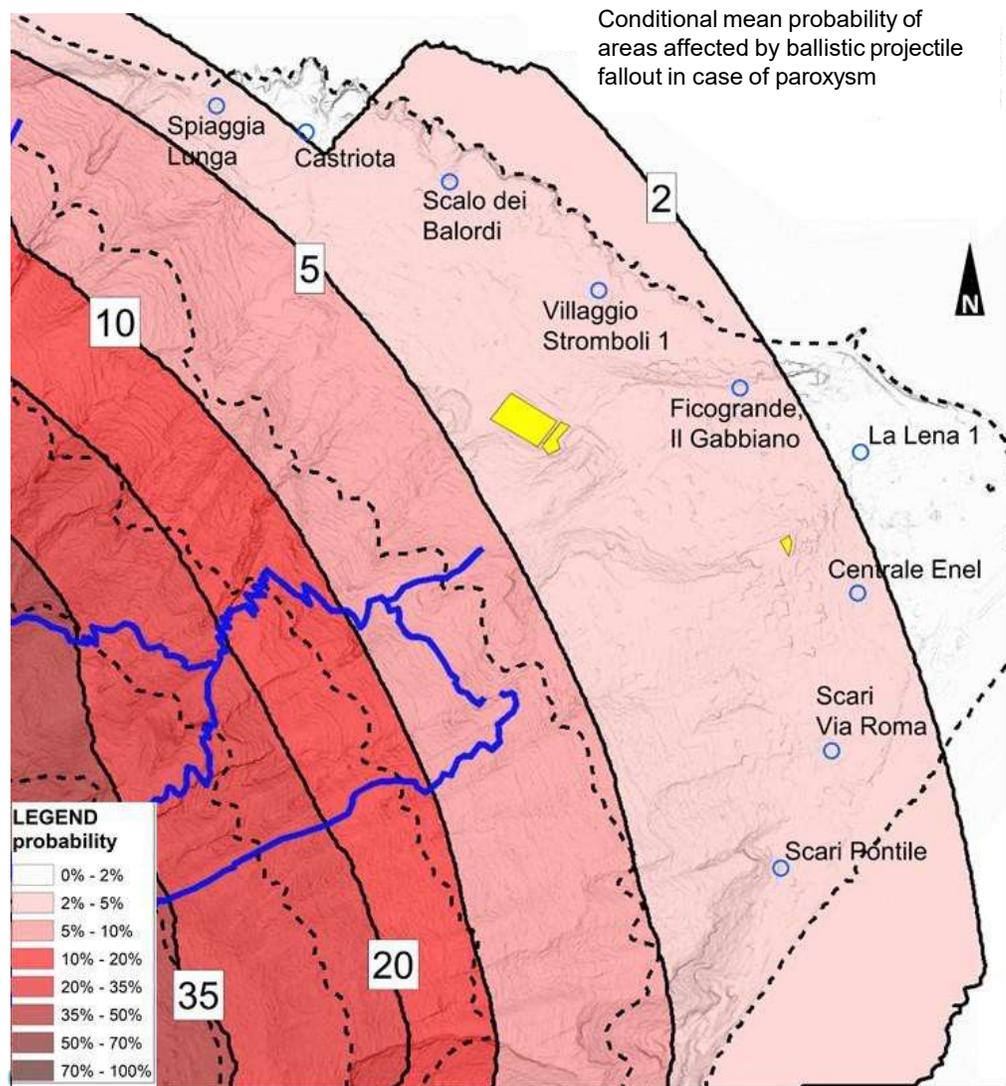


Figure. Probability of ballistic projectile fallout conditional on the occurrence of a paroxysm, and examples of probability estimates at the endpoints of tsunami escape routes. The red lines are the mean value; the pink lines refer to any uncertainty in the estimate.



Preliminary assessments of the hazard from deposit-derived PDCs at the endpoints of tsunami escape routes

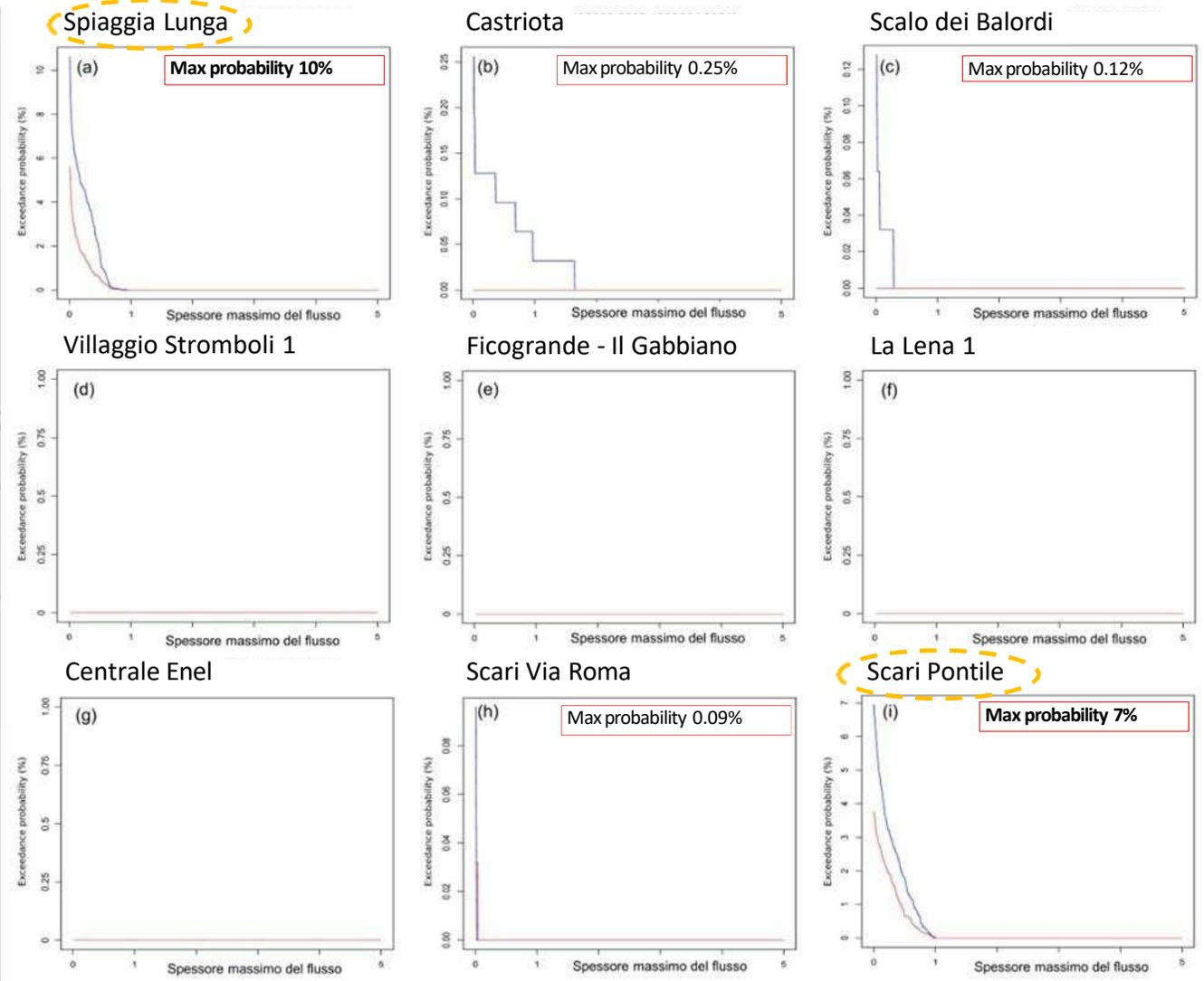
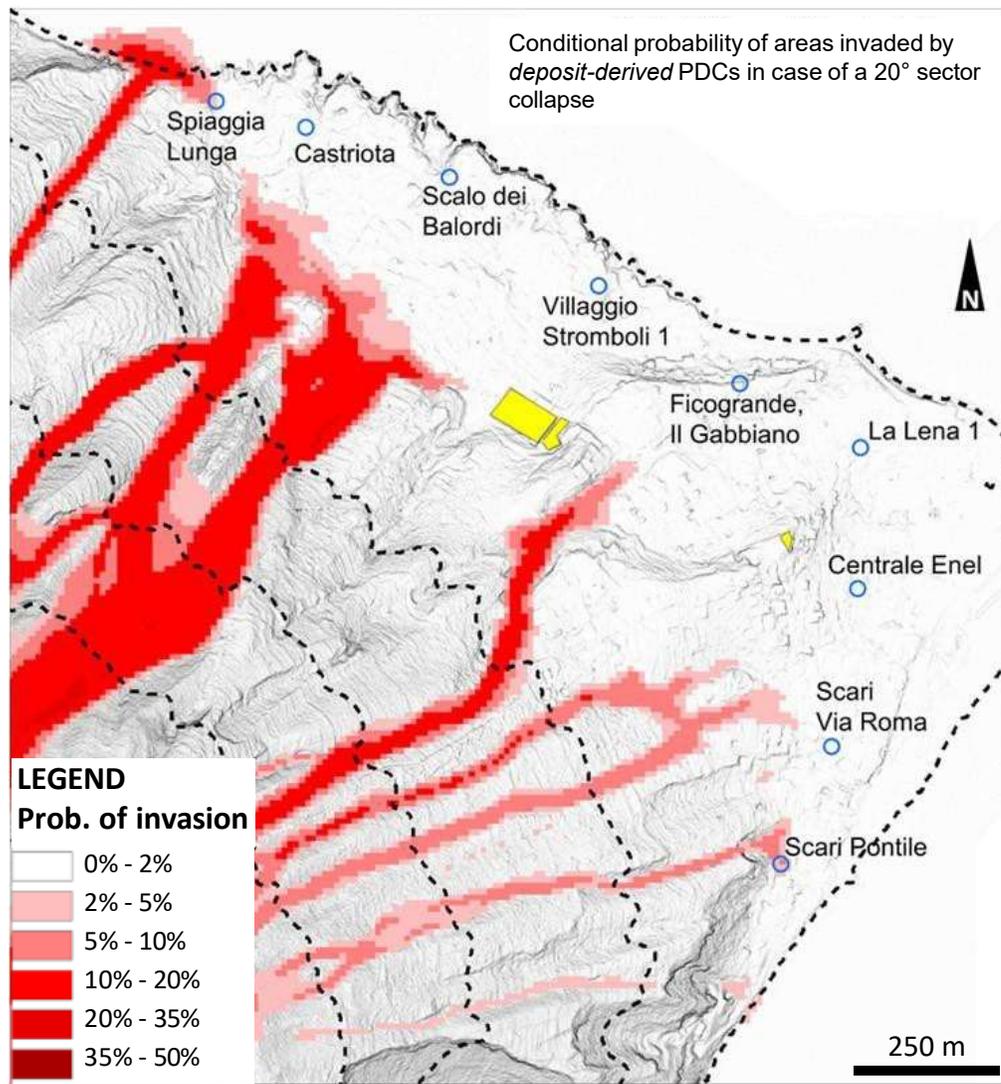


Figure. (left) Probability of invasion by remobilization pyroclastic flows conditional on the collapse of a **random 20° circular sector**, with respect to a maximum flow thickness threshold of 0.1 m. (right) Hazard curves at the endpoints of tsunami escape routes with respect to variable thickness thresholds and circular sectors of 20° (red) and 45° (blue).



Conclusions

- The NEAM-COMMITMENT project, among its tasks, include the update of tsunami escape routes at Stromboli volcano through science-informed and participatory decision-making
- At Stromboli, inhabited areas have been affected (and could be affected in the future) by volcanic-induced tsunamis.
- In addition, ballistics, deposit-derived pyroclastic density currents and wildfires could be source of hazard interfering with tsunami escape routes.
- Within the framework of the DPC-INGV agreement, various research groups of INGV are finalizing preliminary probabilistic hazard maps of the above-mentioned hazards.
- Regarding the tsunami hazard at Stromboli, as part of the DPC-INGV agreement, preliminary probabilistic tsunami inundation maps and hazard curves for selected sites of interest are being finalized and delivered.
- These maps and curves were produced using an innovative process that combines numerical modeling, expert elicitation, and statistical approaches. The products include explicit uncertainty quantification, are available for various databases, and have a 50-year validity period.
- As part of the NEAM-COMMITMENT project, we proposed several comparisons:
 - Between selected maps and current escape routes and waiting areas
 - Between different hazard curves developed for the end points of escape routes and waiting areas (this latter done for tsunami, ballistic and PDC hazard)

Significant work still needs to be done by INGV with respect to:

- Study the occurrence probabilities of the various phenomena
- Start developing multi-hazard evaluations (e.g., tsunami + other hazards)
- Harmonize (where possible) the format with the PTHA of NEAM-COMM.





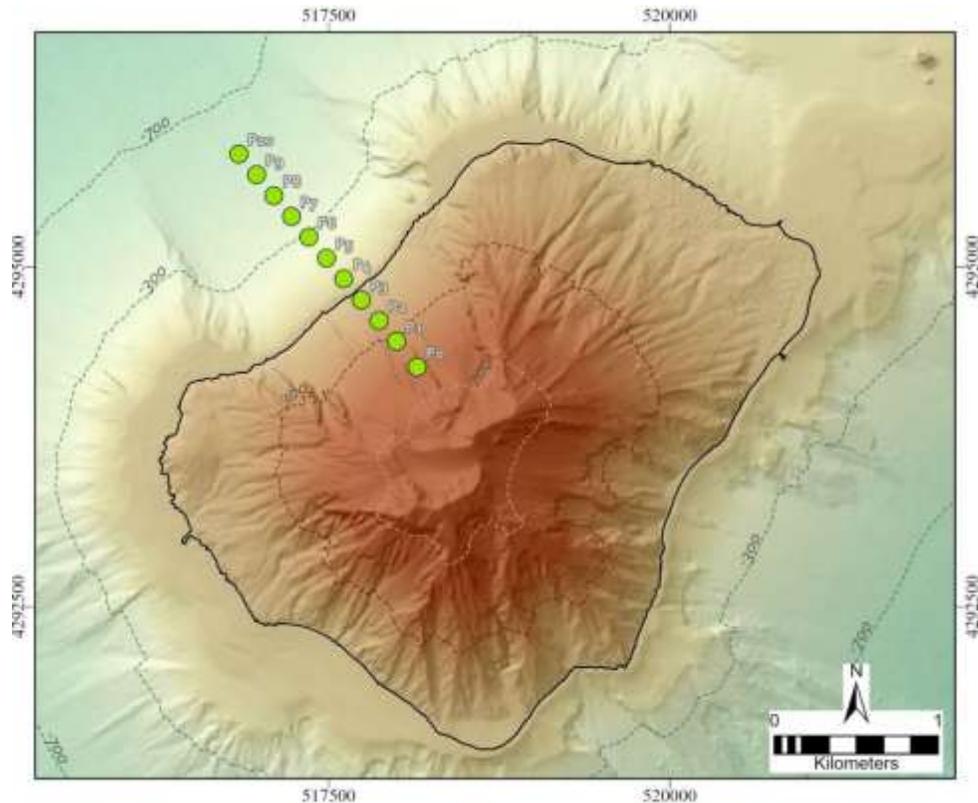
Burning Question(s)

ADDITIONAL SLIDES



Approach to develop tsunami probabilistic invasion maps

1. Numerical simulations (Multilayer-HySEA) along the SdF, varying initial positions, volume and landslide density



11 positions (P0-P10) along the Sciara del Fuoco centerline

48 at elevations +300/+700 (P00,P01)

48 at elevations 0/+300 (P02, P03)

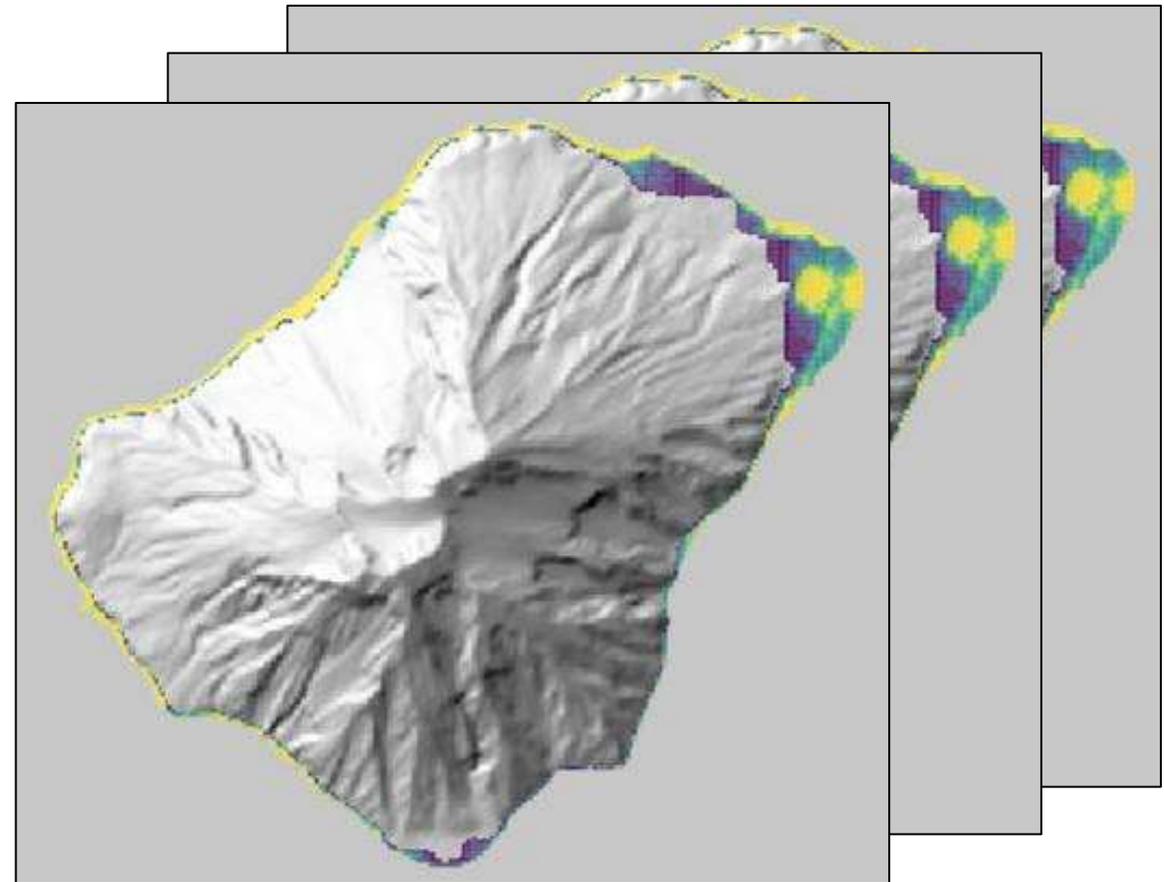
72 at depths 0/-300 (P04, P05, P06)

96 at depths -300/-700 (P07, P08, P09, P10)

12 volumes (1, 2, 3, 5, 8, 8.7, 11, 14, 17, 21, 25, 30 Mm³)

2 landslide densities (2000, 1670 kg/m³)

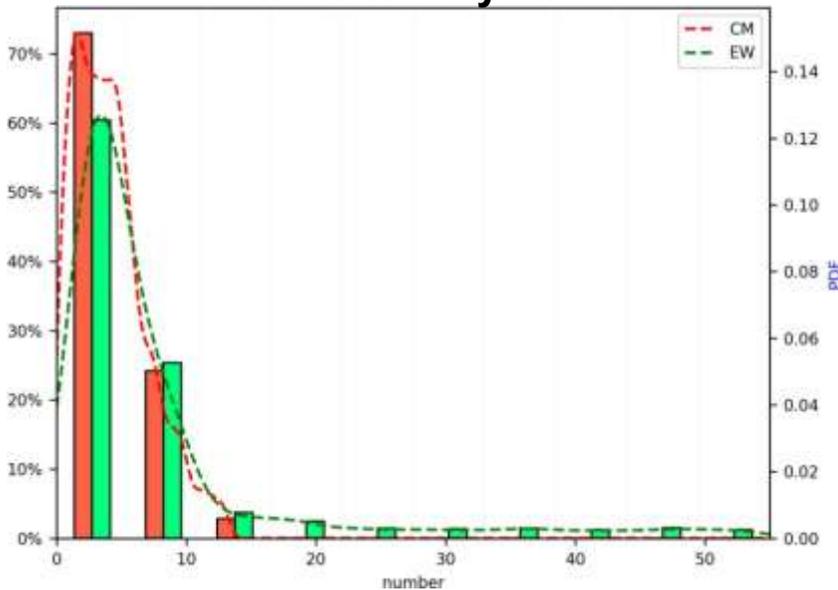
286 simulations
286 inundation maps (water depth)



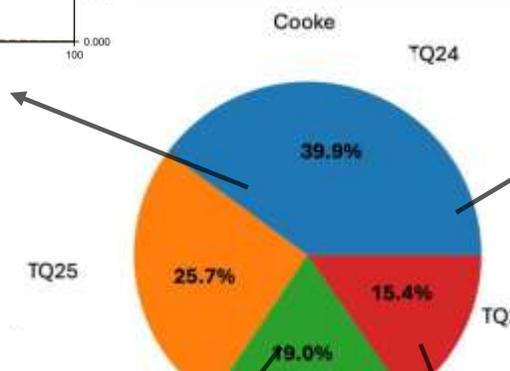
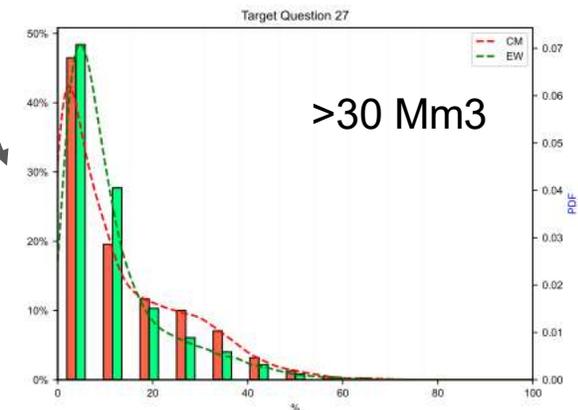
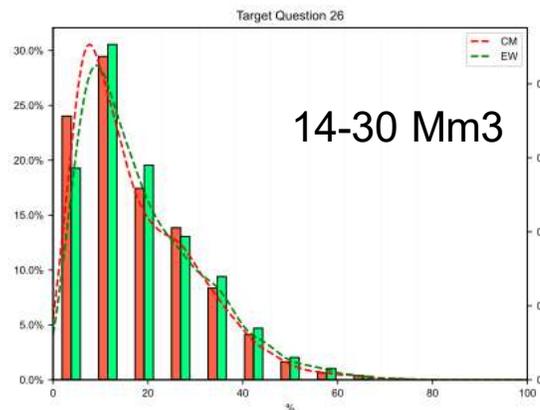
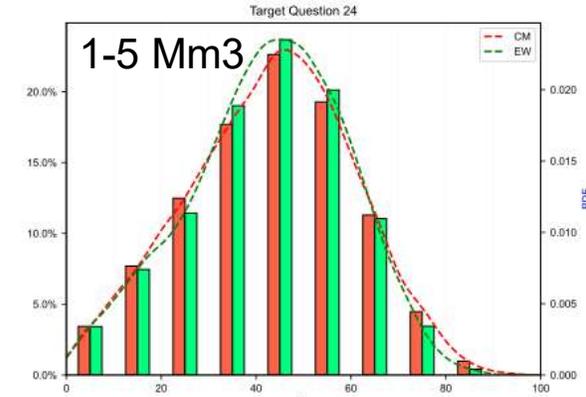
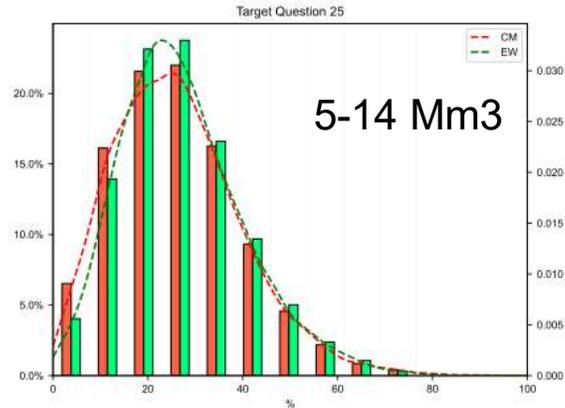
Approach to develop tsunami probabilistic invasion maps

2. Expert elicitation to assign weights to different simulations and to develop a temporal model for the next 50 years (with uncertainty quantification)

TQ3: n° of Tsunamigenic Landslides in the next 50 years

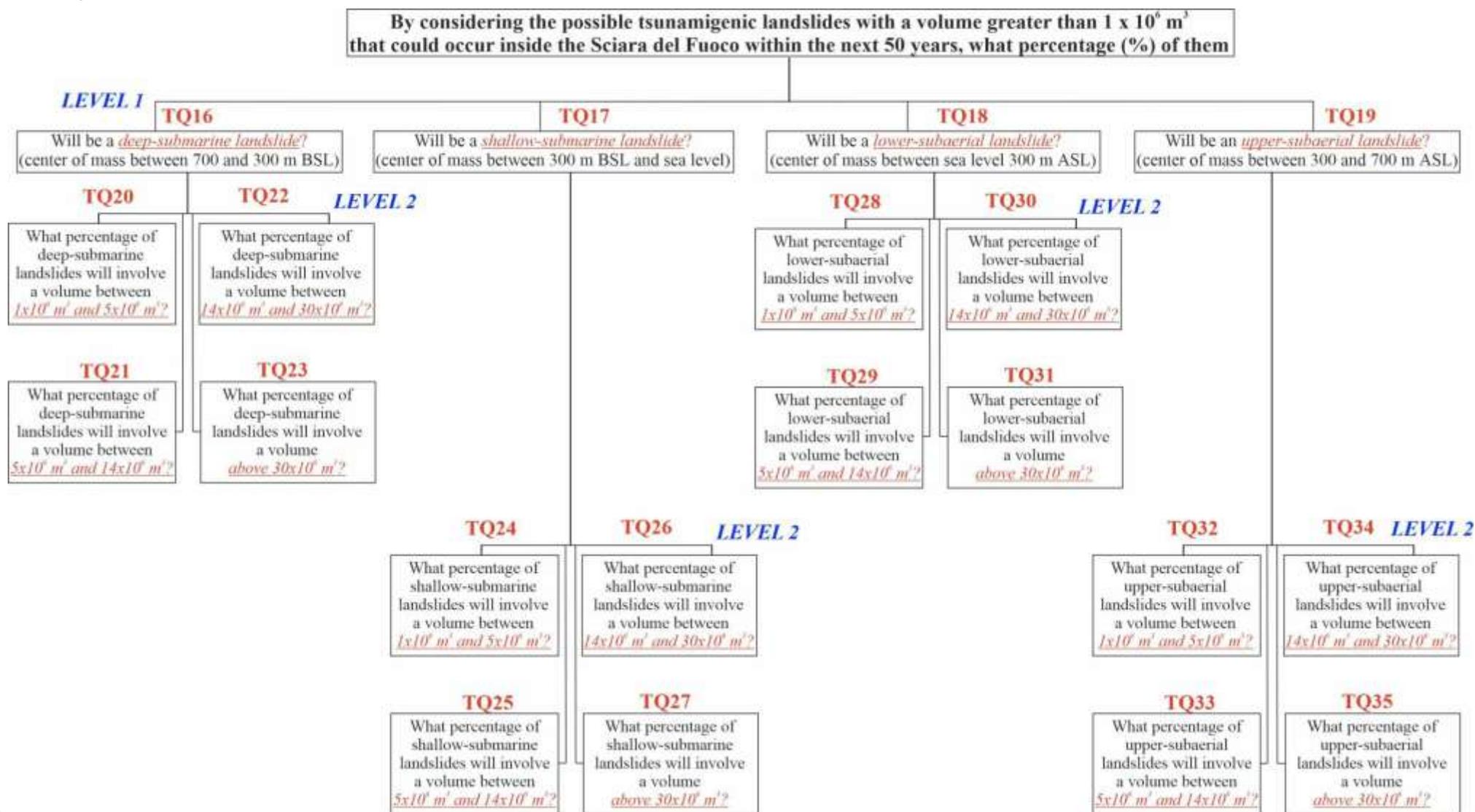


TQ24: Shallow Submarine position, 1-5 Mm3
TQ25: Shallow Submarine position, 5-14 Mm3
TQ26: Shallow Submarine position, 14-30 Mm3
TQ27: Shallow Submarine position, >30 Mm3



Approach to develop tsunami probabilistic invasion maps

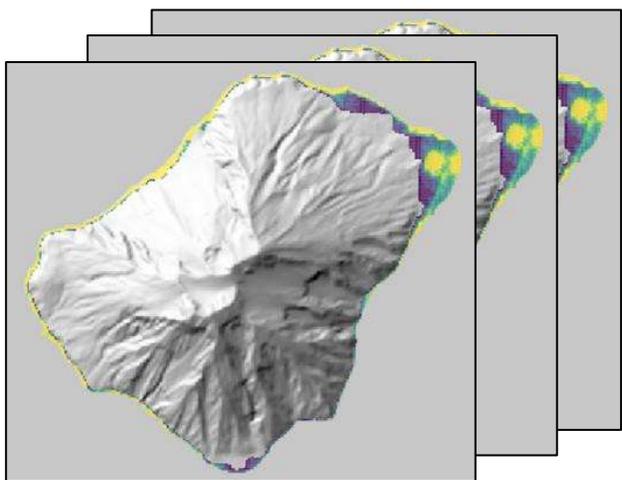
2. Expert elicitation to assign weights to different simulations and to develop a temporal model for the next 50 years (with uncertainty quantification)



Approach to develop tsunami probabilistic invasion maps

3. Combination of inundation maps with weights from elicitation, in order to produce probabilistic maps for fixed water depth thresholds, maps for fixed probability and hazard curves for specific sites of interest

For each chosen inundation threshold (e.g. 0.5 m) and for volumes between 1 and 30 Mm³



286 binary maps

1 if < thresh.
2 if >= thresh.

10000 arrays of 286 weights

Normalization and distribution

10000 hazard curves

For each point of interest

10000 maps

Maps/curvs representing the 5°, 50° and 95° percentiles (for visualization purposes only)

N.B.: these maps/curves describe the elicited uncertainty

12 sampling of weights (3 V and 4 P intervals)

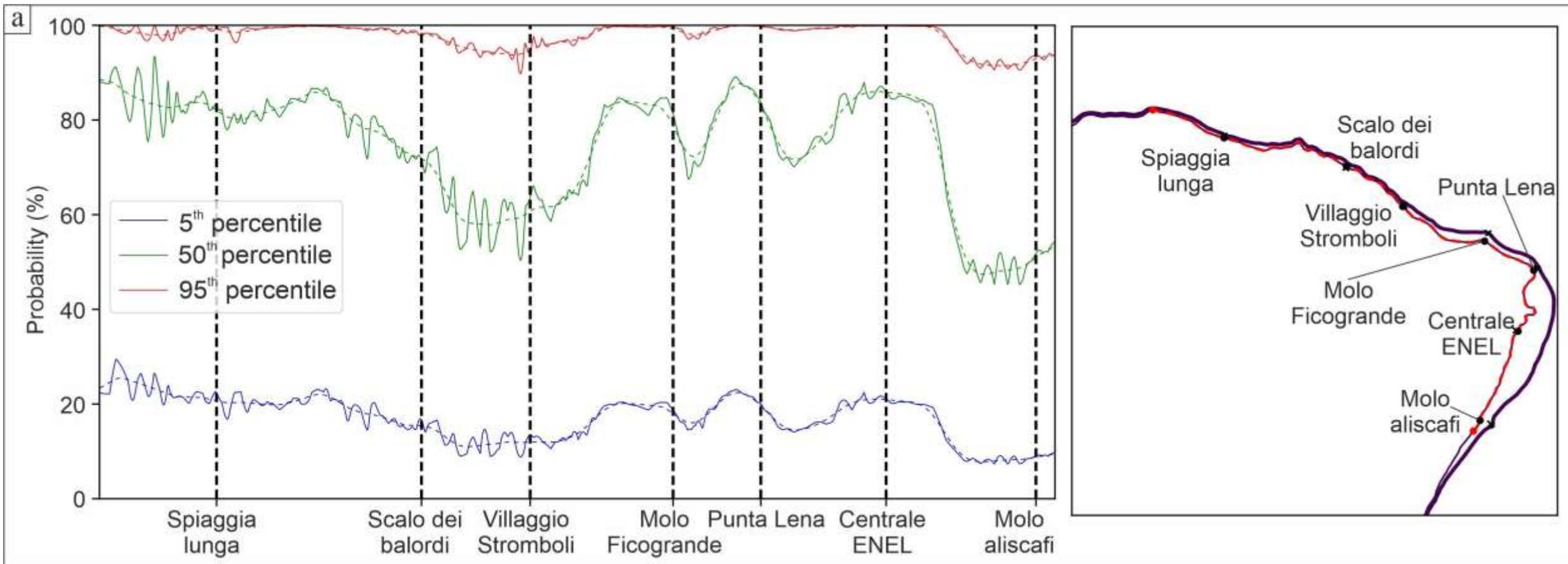
target_20	target_21	target_22	target_23	target_24	target_25	target_26	target_27	target_28	target_29	target_30	target_31
2.71E+01	4.15E+01	5.98E+00	2.50E+01	3.31E+01	4.78E+01	1.83E+01	1.52E+01	4.06E+01	2.65E+01	1.40E+01	1.10E+01
4.56E+01	1.37E+01	1.18E+01	3.22E+01	9.66E+01	3.82E+01	3.14E+01	3.40E+01	4.61E+01	2.09E+01	6.99E+00	2.74E+01
9.47E+01	1.71E+01	4.17E-01	6.87E+01	4.71E+01	1.94E+01	3.26E-01	6.73E+01	2.97E+01	8.76E-01	1.63E-02	6.56E+01
2.93E+01	4.47E+00	1.86E+00	5.76E+01	6.49E+00	1.51E+01	5.58E+01	6.60E+01	1.73E+01	3.00E+00	2.88E-02	6.41E+01
1.12E+01	3.67E+01	6.68E+00	5.16E+01	1.11E+01	3.12E+01	6.77E+00	5.70E+01	2.36E+01	1.04E+01	6.18E+00	4.93E+01
1.70E+01	2.22E+01	3.69E+01	1.05E+01	4.88E+01	2.74E+01	1.10E+01	7.03E+00	5.12E+01	3.94E+01	3.01E+01	3.63E+01
1.75E+01	5.68E+00	1.29E-01	7.43E+01	1.15E+01	1.06E+01	4.32E+01	7.57E+01	6.62E+00	1.38E+00	2.06E+00	9.24E+01
1.13E+01	1.02E+01	2.53E+01	3.53E+01	1.25E+01	7.49E+01	1.70E+01	3.07E+01	5.53E+01	3.13E+01	3.38E+01	1.72E+01
6.10E+01	6.61E+00	4.42E-01	8.79E+01	3.34E+01	9.56E+00	4.17E+00	6.92E+01	1.93E+01	2.35E+00	4.96E-02	9.18E+01
5.50E+00	4.21E+01	3.84E+01	4.01E+01	2.72E+01	2.86E+01	4.79E+01	2.18E+01	9.45E+00	8.81E+00	2.93E+01	6.58E+01

10000 samples for each question



Probability variation along isoline

Probability of exceeding 0.5 m water depth within the next 50 years along the 5 m a.s.l. isoline

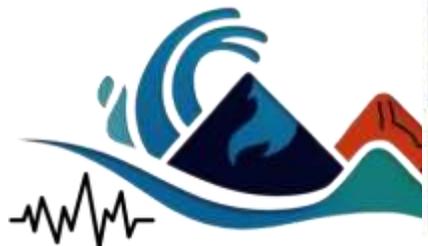


Preliminary study on escape routes in case of tsunami at Stromboli

Within the DPC-INGV agreement, it has been produced a **first evaluation on escape routes and evacuation times at Stromboli**, and the material has been published in two papers on NHESS and Annals of Geophysics (Bonilauri et al., 2024a,b).

Figure.
Example of
escape routes
and evacuation
times within
Ficogrande
beach,
Stromboli.

Modified from
Bonilauri et al.,
2024.

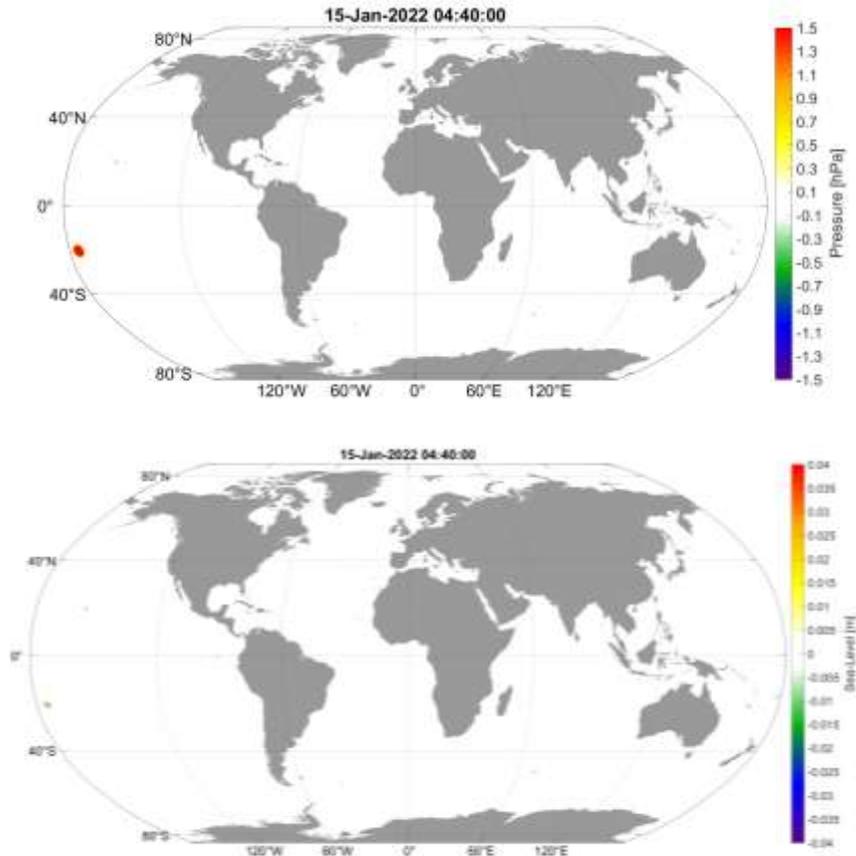


Panelist

- **Dr Cléa Denamiel,**
Rudjer Bošković Institute,
Croatia.



Hunga Tonga–Hunga Ha’apai (HTHH)



Unveiling Global Meteo-tsunami Hazards from Volcanic Explosions: A Probabilistic Approach

Cléa Denamiel, Tomaso Esposti Ongaro, Xun Huan

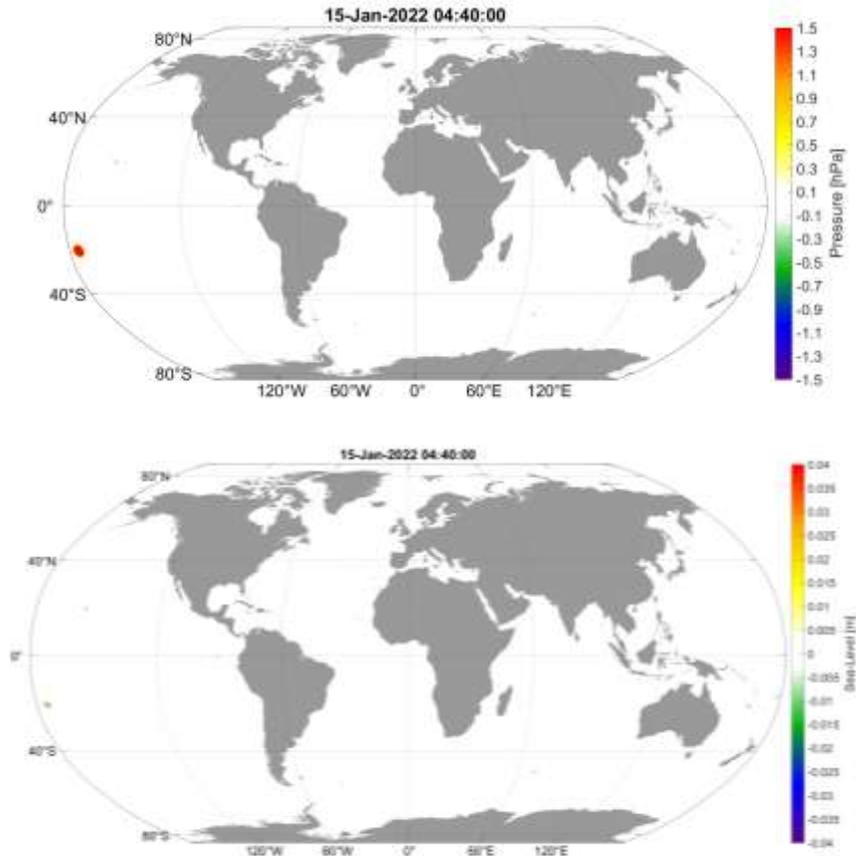
cdenami@irb.hr



Ruđer Bošković Institute
Division for Marine and
Environmental Research



Hunga Tonga–Hunga Ha’apai (HTHH)



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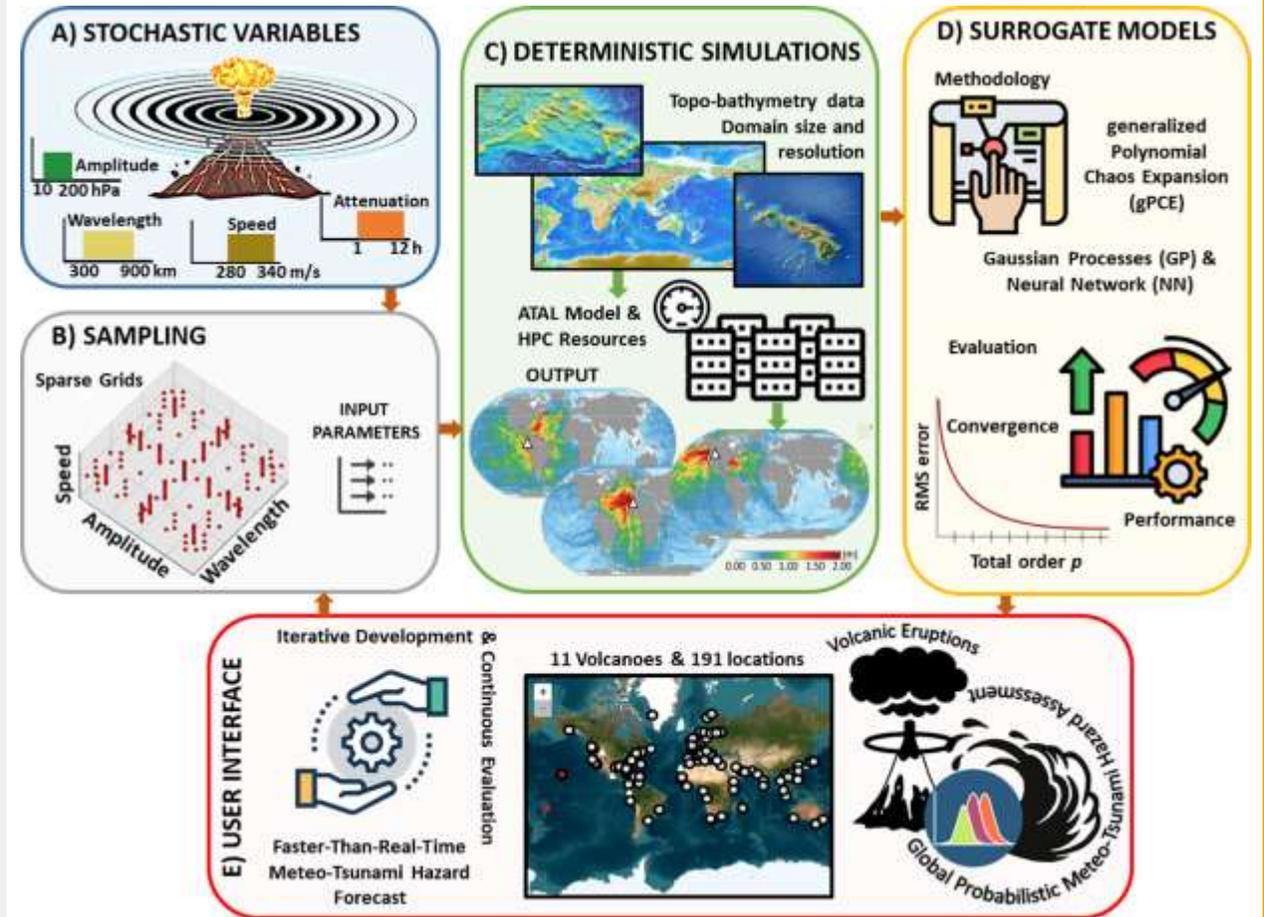


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Environmental Research



PTHA Framework

- **11 volcano locations:** Askja, Campi Flegrei/ Vesuvius, Cotopaxi, Cumbre Vieja, HTHH, Katla, Pinatubo, Popocatepetl, Saint Helen, Sakurajima, Yellowstone
- **4 stochastic variables:** (1) Amplitude P_0 linked to Ejecta volume V , (2) speed c , (3) wavelength λ , and (4) attenuation in time τ of the pressure wave
- **PTHA for 105 Cities + 86 IOC tide gauge's locations:** enable hazard measure calculations, directly useful to the decision-making under an emergency



Mathematical Framework

- **Synthetic pressure:** as simple as possible
- **Prior distributions: uniform** as not much information available
- **Generalized Polynomial Chaos Expansion (PCE):** complex mathematical method that “interpolates” the results obtained with wisely chosen synthetic simulations
- **Simulations:** $641 \times 11 = 4,487$ in total
- **Output:** maximum elevation, maximum speed and time of arrival

Direct modeling of the coupled explosion–atmosphere–ocean process is computationally expensive and not yet state-of-the-art as the physical mechanisms remain only partially constrained. Idealized traveling pressure pulses, parameterized by four stochastic variables depending on a set of elementary events (ω):

$$P(x, y, t, \omega) = \begin{cases} P_0(\omega) e^{-\frac{t}{\tau(\omega)}} \cos\left(\frac{2\pi}{\lambda(\omega)}(r - c(\omega)t) + \pi\right) & \text{if } 0 \leq (r - c(\omega)t) + \frac{\lambda(\omega)}{2} \leq \lambda(\omega) \\ P(x, y, t, \omega) = 0 & \text{otherwise} \end{cases}$$

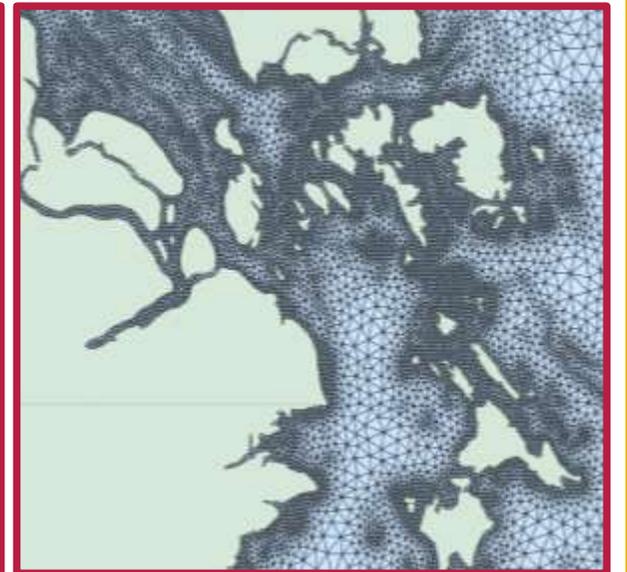
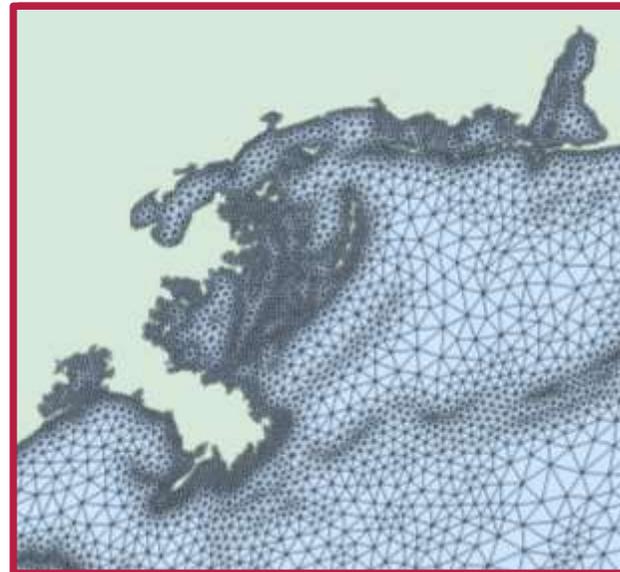
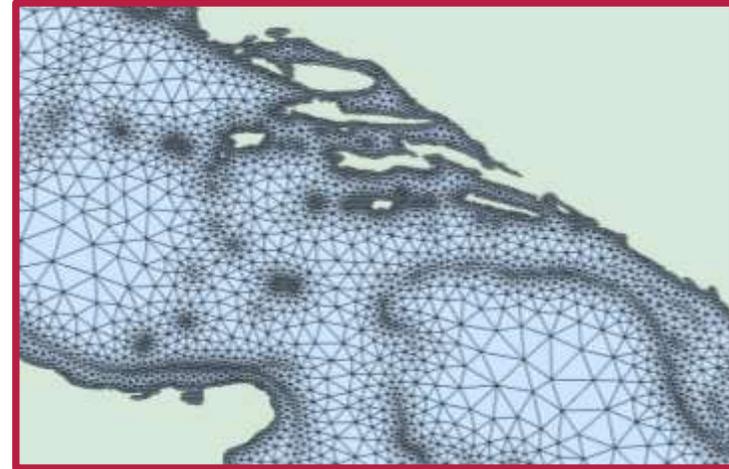
	VEI 5	VEI 6	VEI 7	VEI 8
$P_0(\omega) \boxtimes U([10, 200])$ hPa				
$\lambda(\omega) \boxtimes U([300, 900])$ km				
$c(\omega) \boxtimes U([280, 340])$ m/s				
$\tau(\omega) \boxtimes U([1, 12])$ hour				
Ej. Vol. (km ³)	5-10	10-100	100-1,000	1,000-10,000
Amp. (hPa)	10-20	20-45	45-95	95-200

The generalized Polynomial Chaos Expansion (gPCE) framework combined with the Pseudo-Spectral Approximation (PSA; Gerstner and Griebel, 1998; Constantine et al., 2012):

$$\begin{cases} \xi_p(P_0, c, \lambda, \tau) = \sum_{\max(0, p-3) \leq |\alpha| \leq p} (-1)^{p-|\alpha|} \binom{3}{p-|\alpha|} \sum_{\beta} C_{|\alpha|, \beta} Le_{\beta}(P_0, c, \lambda, \tau) \\ C_{|\alpha|, \beta} = \frac{Q_{\alpha}^{(1,4)}(\xi Le_{\beta})}{\|Le_{\beta}\|^2}, \quad Q_{\alpha}^{(1,4)}(\xi Le_{\beta}) = \sum_{\alpha} w_{\alpha}^{(1,4)} \xi(s_{\alpha}^{(1,4)}) Le_{\beta}(s_{\alpha}^{(1,4)}) \end{cases}$$

Modelling Framework

- **ATAL Model: Global unstructured mesh** used with the **ADCIRC model**
- **No inundation** - 1 km resolution maximum along the coast
- **Synthetic Pressure: coded** within ADCIRC model
- **Deterministic simulations: 2-3 hours** of computation on **400 CPUs** for each simulation on **ECMWF HPC**
- **PCE surrogates:** allow to explore the distributions in **real-time** and with **more samples**



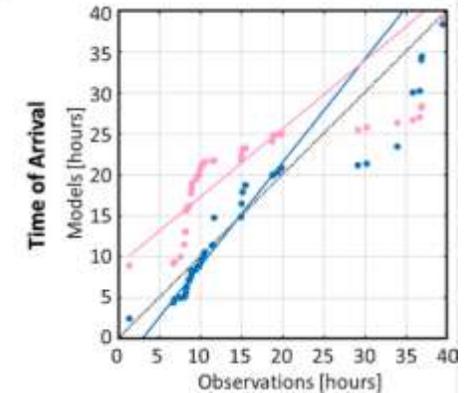
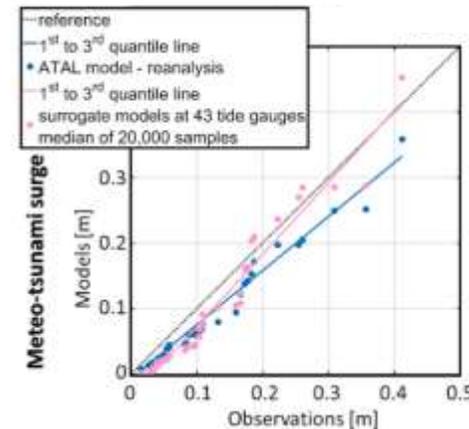
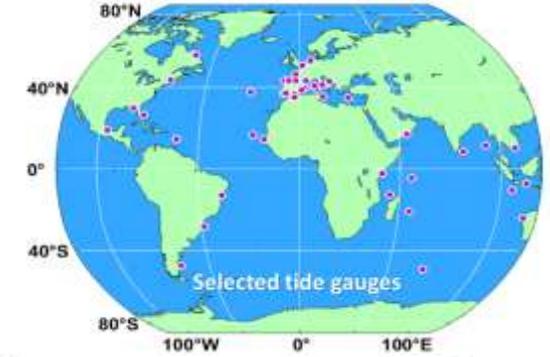
Skill/Evaluation of the Surrogate Models

- **Convergence:** for the 105+86 chosen cities + tide gauges (error should converge towards 0) \Rightarrow $p = 5$ converge
- **Accuracy:** compare surrogate results at $p = 5$ with the 256 x 11 independent simulations to reach $p = 6$
- **HTHH 2022 event:** surrogates located at and compared to the 43 tide gauge locations used to evaluate the ATAL model (reanalysis simulation)

Hunga Tonga – Hunga Ha’apai

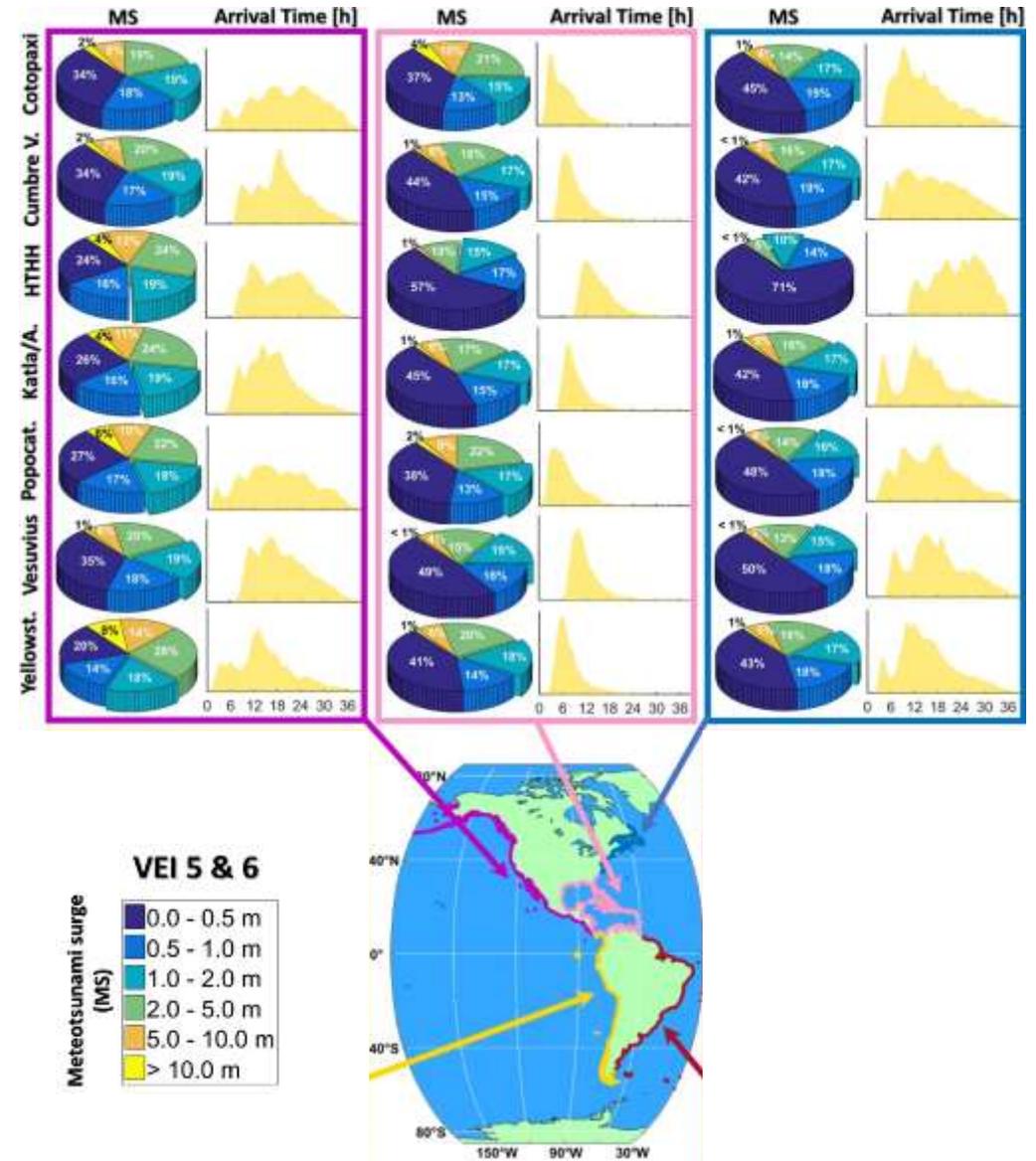


$$\begin{cases} P_A(\omega) \boxtimes U([16,18]) \text{ hPa} \\ \lambda(\omega) \boxtimes U([550,650]) \text{ km} \\ c(\omega) \boxtimes U([310,320]) \text{ m/s} \\ \tau(\omega) \boxtimes U([4,5]) \text{ hours} \end{cases}$$



Meteotsunami Hazard Distributions

- Acoustic meteotsunamis **stronger close to the source** but **certain coastlines are more sensitive** to this hazard (e.g., **western coast of the U.S.A.**)
- Explanation: **partial Proudman resonance** above the deepest areas of the Pacific Ocean and amplification linked to **reflection**

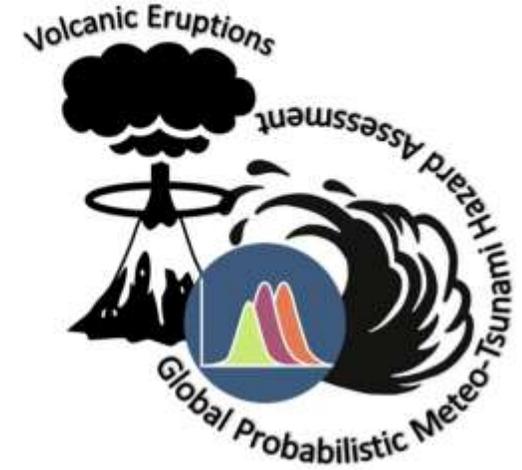


Volcano-Meteo-Tsurrogate Model v1.0



CLEAR

Volcano:



“Live” Demonstration

Perspective

- **Source:** need to cover (1) all explosive volcanoes with potential to reach VEI 5 and more & (2) asteroid impacts
- **Inundation:** need to translate the coastal hazards into actionable inundation data
- **Nearfield:** need to properly characterize the transfer of energy from the volcanic explosion (or asteroid impact) to the atmospheric disturbance
- **Farfield:** need to use atmospheric model forced by real temperature (including climate change) and need to couple with tsunamis (when explosions occur at Sea)



**“MORE MUST BE DONE TO FORECAST AND TRY TO
MANAGE GLOBALLY DISRUPTIVE VOLCANIC ERUPTIONS.
THE RISKS ARE GREATER THAN PEOPLE THINK.”**

Michael Cassidy & Lara Mani - Nature 608, 469-471 (2022)

THANKS !





Final Questions



2021 United Nations Decade
2030 of Ocean Science
for Sustainable Development

UNESCO Intergovernmental Oceanographic Commission (UNESCO-IOC)

NEAM Regional Online Webinars on Tsunamis Generated by Non-Seismic Sources

27 November 2025

CLOSING