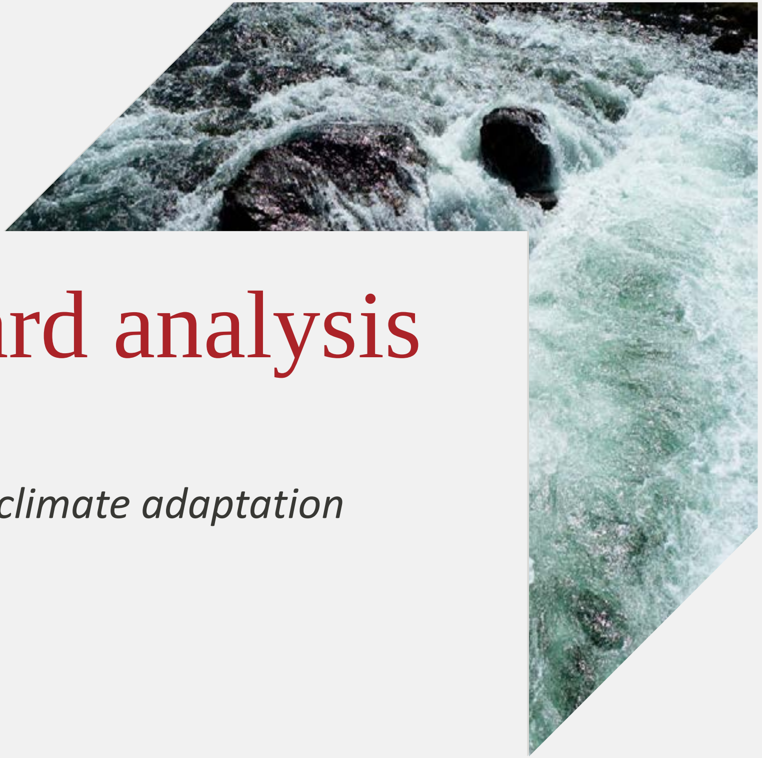


Landslide tsunami hazard analysis

Carl B. Harbitz, NGI

Head of Section Risk analysis, slope stability and climate adaptation

AGITHAR Kick-Off Conference

Malta, 7-9 October 2019

EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

Funded by the Horizon 2020 Framework Programme of the European Union

Contents

- Examples of landslide tsunamis
  - Why extreme?
- Landslide dynamics
- Landslide tsunami generation
- Landslide tsunami modelling
- Probabilistic landslide tsunami hazard analysis (LPTHA)

Submarine landslide tsunamis – key examples

Storegga 8150 BP

~3000 km^3,

>20 m run-up

Widespread effects

Grand Banks 1929

13 m run-up, 28 fatalities

Volume 150 km^3

Papua New Guinea 1998

15 m run-up, local tsunami,

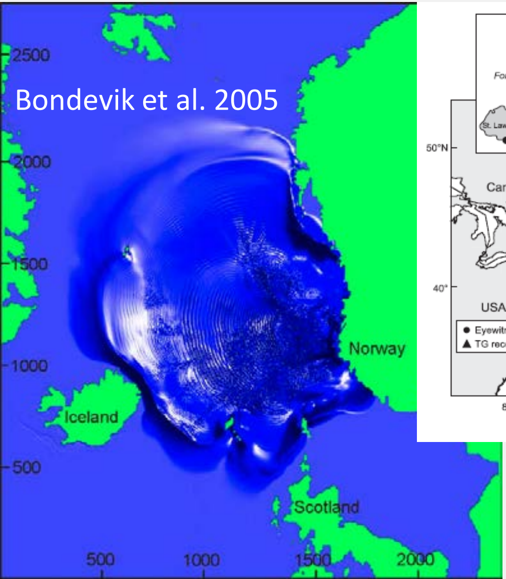
~2200 fatalities

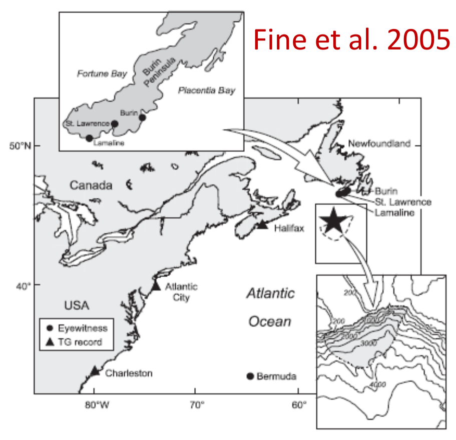
Volume 4 km^3

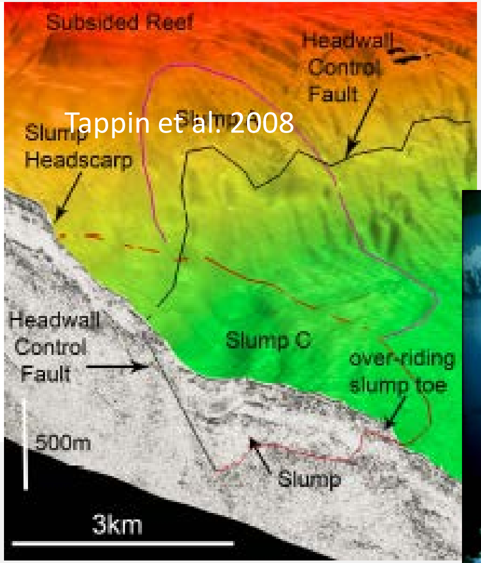
Alaska 1964

A series of secondary local submarine landslides caused tsunamis in Prince William Sound, responsible for ~90% of the 124 fatalities

Run-up up to 67 m







Subaerial landslide tsunamis – key examples

18th century Japan volcano flank collapses

Oshima-Oshima 1741

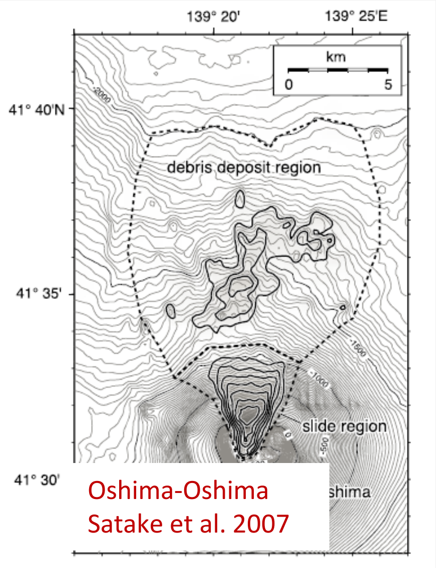
Volume 2.5 km^3

~2000 fatalities

Shimabara Bay 1792

Volume ~0.5 km^3

~4000 fatalities



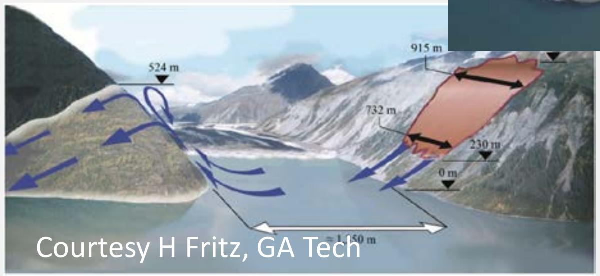
Oshima-Oshima
Satake et al. 2007

Western Norway: Loen 1905, 1936 and Tafjord 1934

174 Fatalities

Lituya Bay 1958

> 500 m run-up



Courtesy H Fritz, GA Tech

Recent events:

Stromboli, 2002

Aysen fjord, Chile, 2007

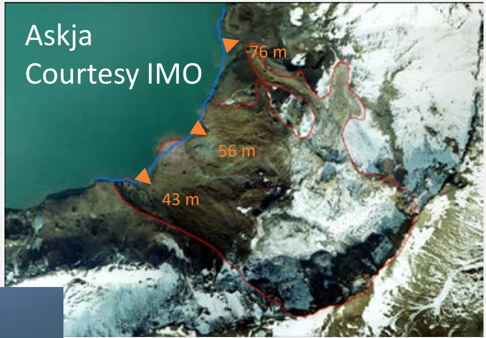
Chechalis Lake, Canada, 2007

Askja, Iceland, 2014

Taan fjord, Alaska, 2015

Yangtze River, 2015

Anak Krakatau, 2018



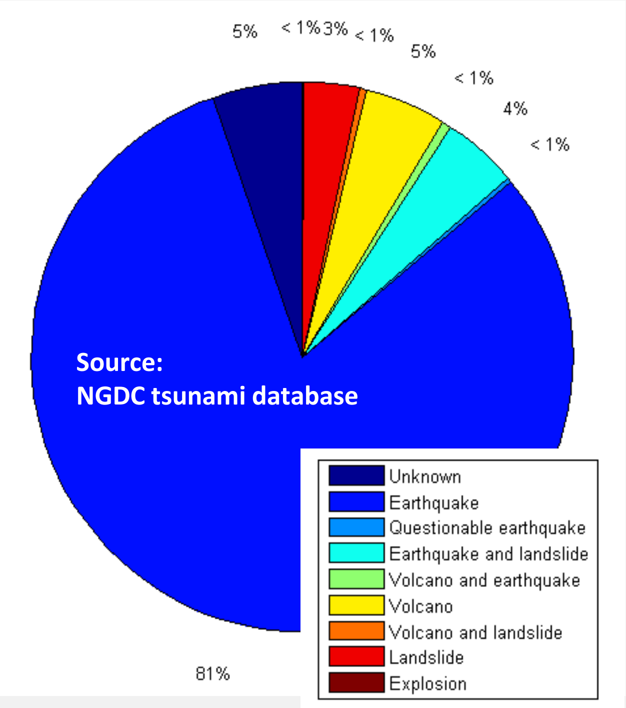
Askja
Courtesy IMO

Taan fjord
Courtesy C Larsen

Aysen fjord
Courtesy H Fritz, GA Tech

Landslide tsunamis make up a significant portion of the “global tsunami budget”

- May occur «anywhere» -
  not constrained to large tectonic structures
- Landslides and volcanoes comprise ~15% of the reported sources globally (earthquakes 80%)
- Likely cause for a majority of the “unknown” events
- Former events may have been underreported/ignored and the historical frequencies are likely too low
- Re-analyses of past events often introduce landslide tsunami sources, e.g.
  - 1856 Djijelli (Roger and Hebert, 2008)
  - 1945 Makran tsunami (Heidarzadeh and Satake, 2015)
  - 1908 Messina Strait (Favalli et al., 2009; Fu et al., 2017)
  - 2011 Tohoku (Tappin et al., 2014)



What makes submarine landslide tsunamis “extreme”?

- Submarine landslides may occur along “any” passive or active continental margin and at different water depths
- The landslide parameters governing the tsunami generation can all gain extreme values
  - Acceleration, maximum velocity, mass discharge, run-out distance
  - The high mobility of submarine landslides may be partly explained considering the large volumes involved and the landslide/water interaction, but
  - The hazard is not necessarily proportional to the volume
- ”Unpredictable” $\Rightarrow$ Unprepared $\Rightarrow$ Extreme consequences

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What makes submarine landslide tsunamis extreme?

- Severe landslide tsunami impact is most often ”local”, but
- for the extreme landslide events the tsunami impact is regional
- Inundate otherwise sheltered areas (not like wind waves or swells)
- Shorter period than tidal waves or storm surges
  - → stronger currents and fluxes even for the same run-up height
- “Shorter landslide tsunamis” favour amplification
- Ignoring recurrence intervals, in most places the submarine landslide tsunami potential controls the local tsunami threat (not the earthquake tsunami potential)
- Important for design and location of critical infrastructure often based on return periods of thousands of years

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Post-failure dynamics

Submarine landslide transport mechanisms

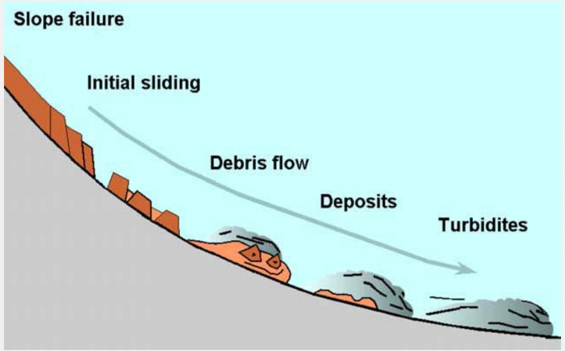
How do landslides move? Especially initially…

- We have never directly monitored a submarine landslide
- All we have are landslide deposits and turbidites
- In a few cases we have both landslide deposits and tsunami information
- Very few large landslides are precisely dated
- Multistage landslides

Storegga landslide tsunami deposits.
Bondevik et al. 2005

Landslide dynamics

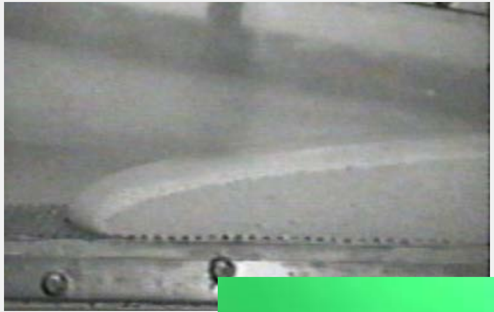
- The high mobility of submarine landslides may be partly explained considering the large volumes involved and the landslide/water interaction
- The quantification of the landslide parameters is complicated by the transformation of the landslide from a huge slab to smaller blocks, then to a highly viscous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



From Bryn et al. 2005

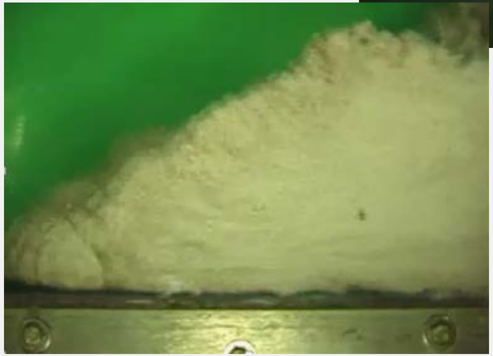
Landslide material influences landslide typology

- High clay content (subaerial)

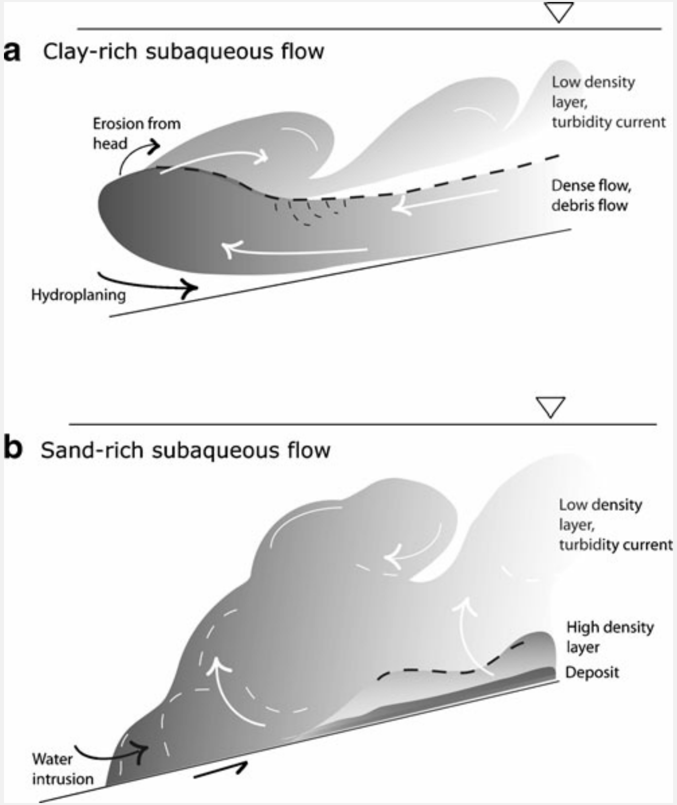


- High clay content (submarine)

- Low clay content (submarine)



From Elverhøi et al. (2010) Ocean Dynamics



From Elverhøi et al. (2010) Ocean Dynamics

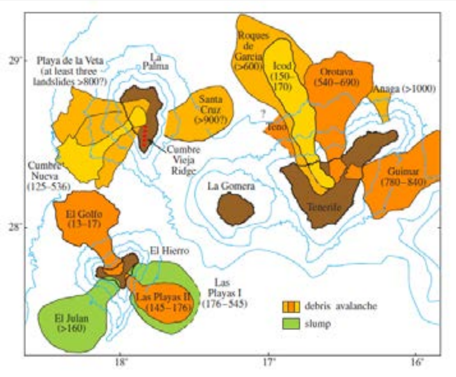
«Sticky» masses allow for hydroplaning, high velcities, stretching and long run-out

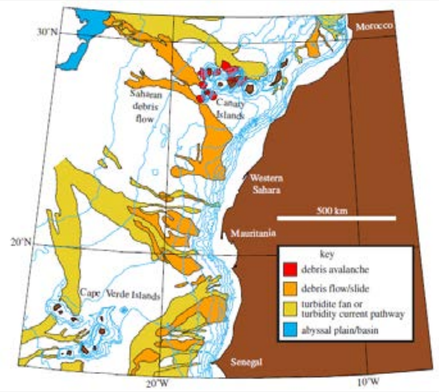
The primary source of sediments plays an important role for the mobility and dynamics of submarine landslides

Landslide tsunami generation

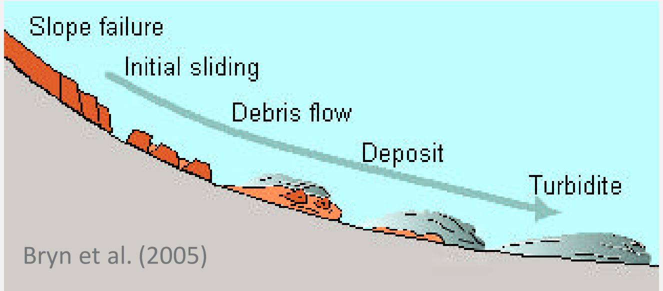
Processes that determine the tsunamigenic potential of submarine landslides

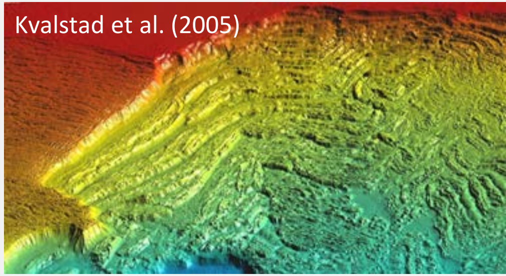
Masson et al. (2006)

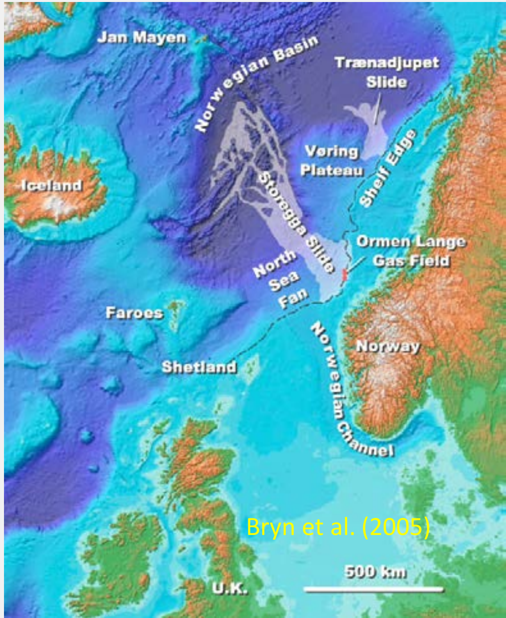




- Initial failure process and retrogression
- Transition of blocky debris during initiation, from solid to fluid
- Time-dependent material properties
- Key: the contribution from different flow phases on tsunami generation

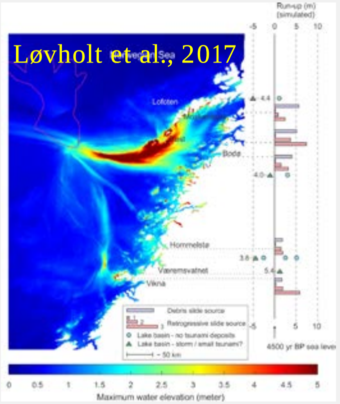


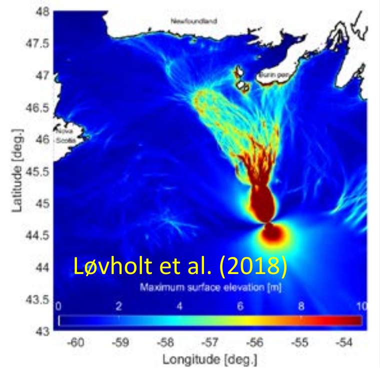


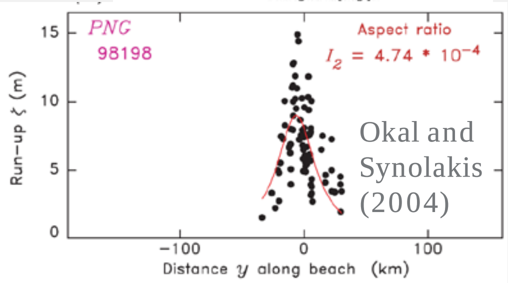


Slide volume not the only decisive factor

- ~4000 BP Trænadjupet ~500 km³ – retrogressive slide source
  - Coastal source proximity ~200 km
  - Run-up not known, mean value less than 2-3m over coastal stretch of ~500 m, modelled local maximum up to ~5 m
- 1929 Grand Banks ~100 km³ – debris flow cause? or larger slump?
  - Coastal source proximity ~200 km
  - Local run-up 5-13 m (Newfoundland), far field run-up ~0.5 m (New Jersey)
  - Flow velocities up to ~30 m/s revealed from cable breaks
  - Mechanism not fully known - models deviate from field evidence
- 1998 PNG ~4 km³ – slump source
  - Coastal source proximity ~10 km
  - Maximum run-up exceeding 10-15m, far field height ~0.1 m (Japan)
  - Slump source and close proximity to the coast rendered PNG very destructive

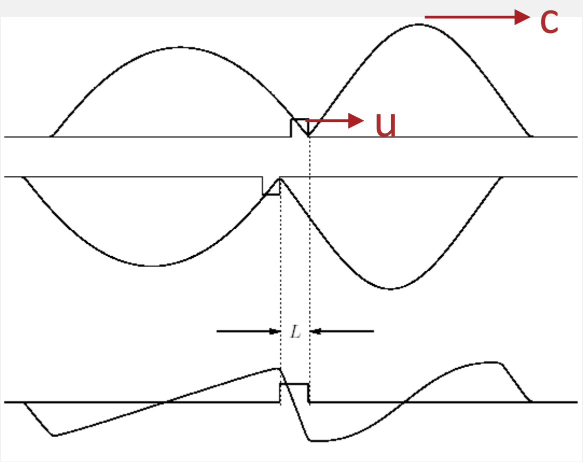






Importance of landslide parameters

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



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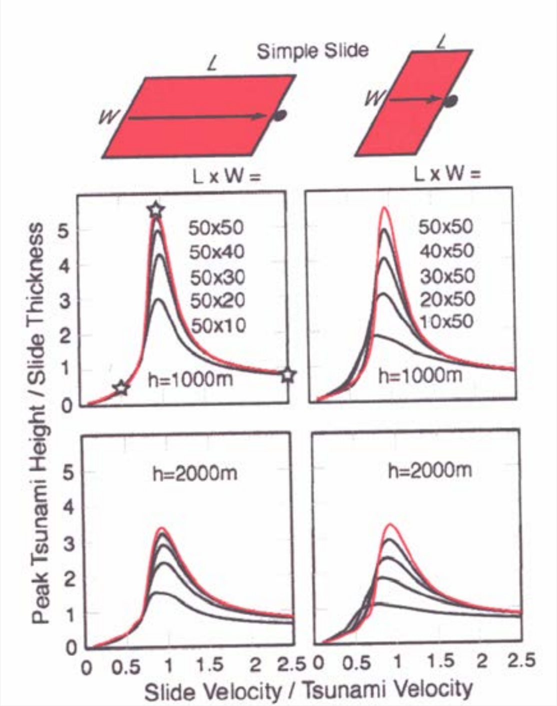
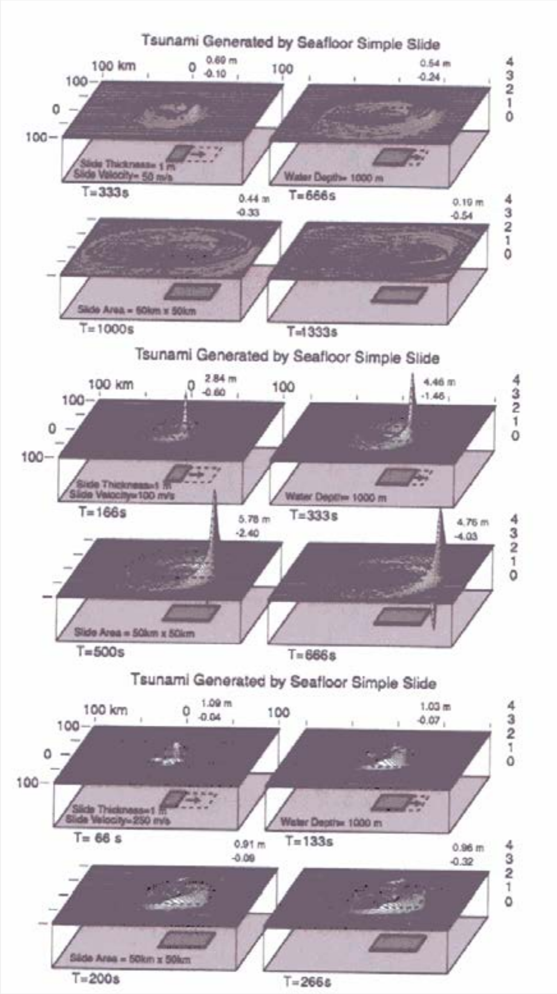
Sub- and supercritical slide motion – Ward (2001)

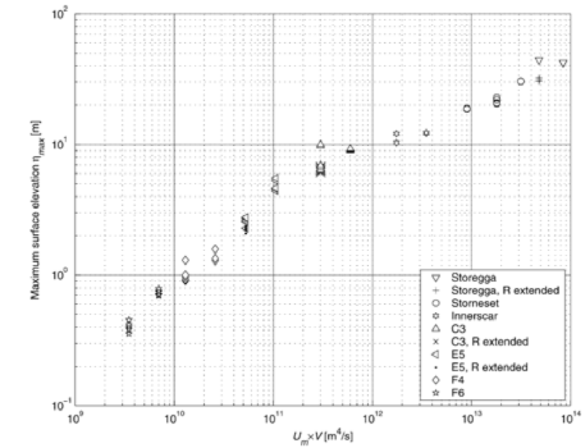
- In practice:
  - Submarine landslides are subcritical (Fr < 1)
  - Rockslides are supercritical (Fr > 1)

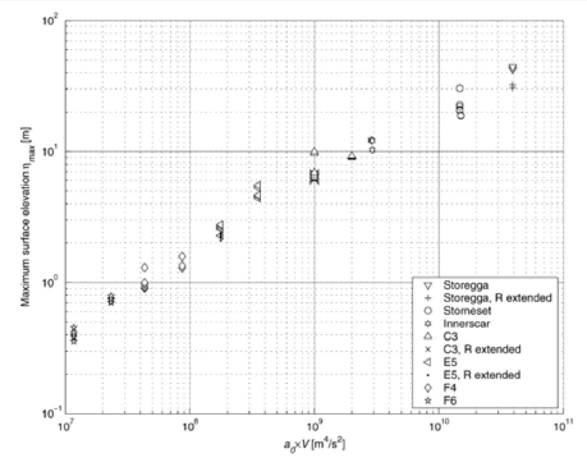




Correlating translational landslide parameters and tsunami metrics – basis for LPTHA

- Relation between the metric describing the tsunami threat and geo-parameter values that can be related to probability for quantification of tsunami hazard and risk
- Maximum surface elevation close to the shoreline correlates well with momentum u·V *and even better with momentum rate a_0·V*
- *Parametric relations depend on the nature of the source and on bathymetric effects*
- *Relations should be applied for specific purposes only; not general*





Løvholt et al. 2005

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Landslide material control on tsunami genesis – Kim et al. 2019

- Simulating the Storegga Slide and tsunami using the depth-averaged landslide model BingClaw
  - visco-plastic rheology and remolding
  - coupled to a standard tsunami propagation model
- A broad sensitivity study varying the landslide material strength parameters in BingClaw
  → the initial soil yield strength and remolding rate are most important for the tsunami genesis
  → the residual strength determined the final runout distance
- First attempt to quantify more systematically how landslide material parameters are constrained by landslide and tsunami observations
  → can help in the selection of plausible parameter ranges for hazard assessments

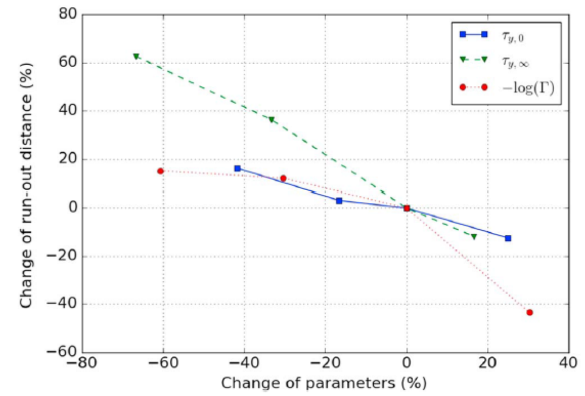

Figure 13. Parameter sensitivity tests for runout distance. Change of runout distance is shown with respect to the change of parameters. Parameter changes are relative to $\tau_{y,0} = 12$ kPa, $\tau_{y,\infty} = 3$ kPa, and $\Gamma = 5 \times 10^{-4}$. The runout distance is most sensitive to changes in $\tau_{y,\infty}$.

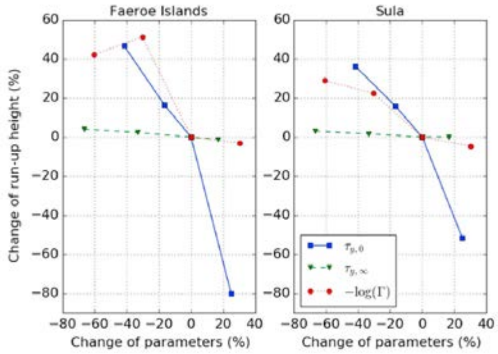

Figure 14. Parameter sensitivity tests for the maximum tsunami heights at two locations. The changes of the maximum tsunami height at the Faroe Islands and Sula are shown with respect to the change of parameters. The maximum tsunami heights in both locations are rather sensitive to the choice of $\tau_{y,0}$ and Γ.

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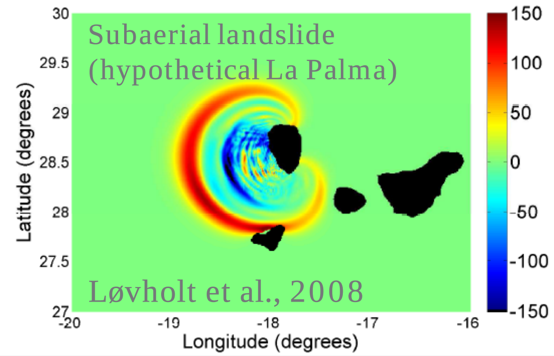
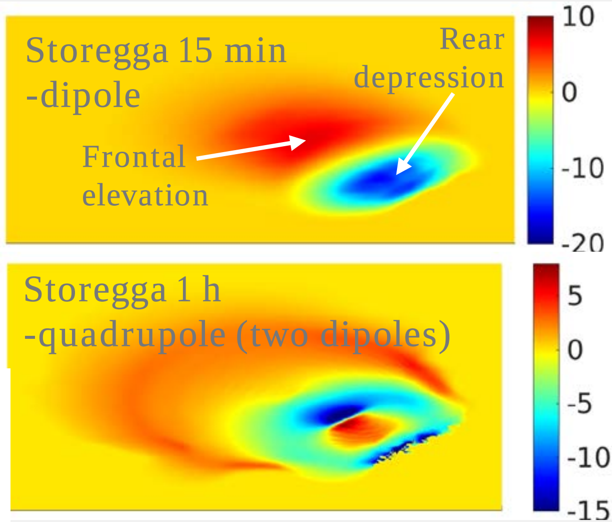
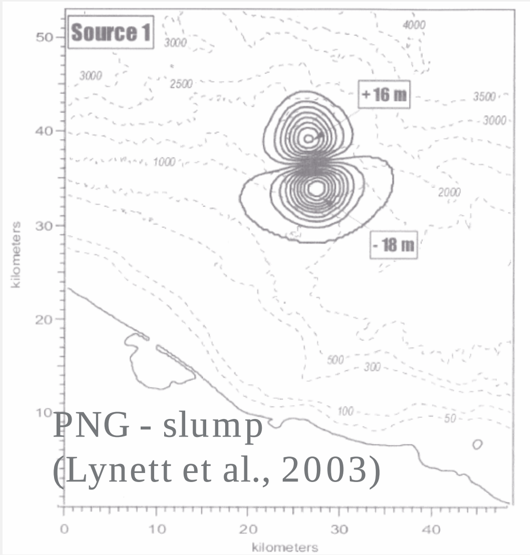
Landslide tsunami shape





- Frontal wave induced by volume displacement at slide front
- Rear wave drawdown
- Slide acceleration and deceleration yields complex **quadrupole** (two interacting dipoles)
- For rapid slide motion like **slumps** – rear and front wave do not have time to interact – **dipole**
- Asymptotic far-field behavior as a function of distance depends on net added volume
  - $\eta \sim r^{-5/6}$ (subaerial landslide - net added volume)
  - $\eta \sim r^{-7/6}$ (fully subaqueous landslide – zero net volume)



1929 Grand Banks slump and tsunami – Zengaffinen et al., work in progress

- Larger slump volume than previously anticipated (Schulten et al 2019)
- Deformable slump
- BingClaw Hershel-Bulkley viscoplastic rheology

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Correlating slump parameters and tsunami metrics – basis for LPTHA

- Maximum landward surface elevation vs. maximum bed-parallel and vertical slump velocity (left) or acceleration (right)
- Different colors indicate different initial slump surface slope angles
- H = 2000m is typical water depth and d = 250m typical slide thickness
- Bad correlation for bed-parallel acceleration

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NGI SLATE

Submarine Landslides and their impact on European continental margins

Correlating slump parameters and tsunami metrics – basis for LPTHA

- Maximum landward surface elevation vs. maximum bed-parallel and vertical slump momentum (left) and momentum rate (right)
- Different colors indicate different slump volumes per unit width
- H = 2000m is typical water depth and d = 250m typical slide thickness
- Bad correlation for bed-parallel momentum rate

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Submarine Landslides and their impact on European continental margins

Correlating slump parameters and tsunami metrics – basis for LPTHA

- Maximum landward surface elevation vs. Froude number based on maximum horizontal centre-of-mass velocity
- Different colors indicate different initial slump surface slope angles
- H = 2000m is typical water depth
- Sub-critical conditions
- Good correlation with Fr based on CoM velocities

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NGI SLATE
Submarine Landslides and their impact on European continental margins

Correlating slump parameters and tsunami metrics – basis for LPTHA

- Maximum landward surface elevation vs. maximum angular momentum rate
- Different colors indicate different initial slump surface slope angles (upper) or slump volumes per unit width (lower)
- The scale H = 2000m is the typical water depth and d = 250m the typical slide thickness
- For a slump, angular momentum rate gives good correlation
  - more important than bed-parallel acceleration

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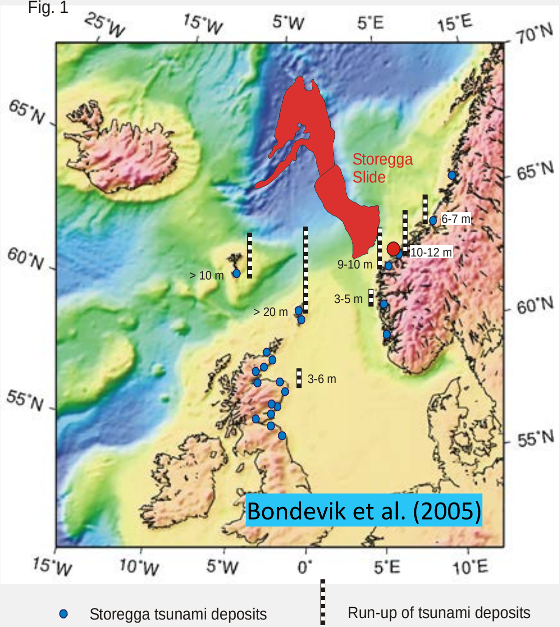
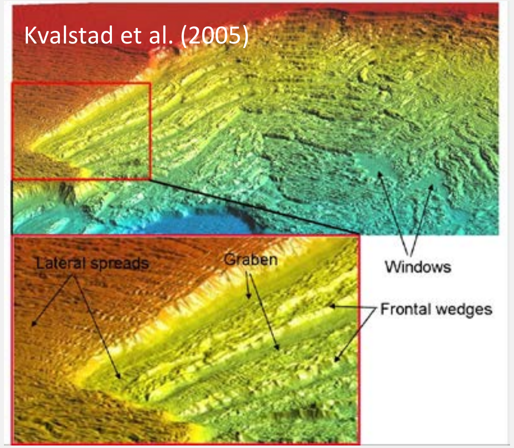
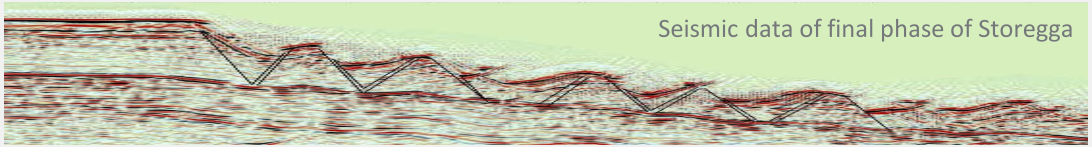
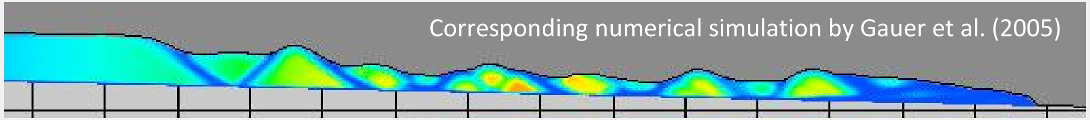
Retrogressive landslide development

- Retrogression
  - Retreating slide release starting from slide toe
  - Time-variable landslide mass and momentum
- Storegga
  - 8150 BP, ~3000 km^3
  - Paleotsunami data widely available
  - Good understanding of the main landslide development



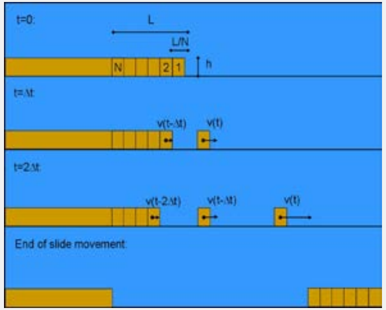


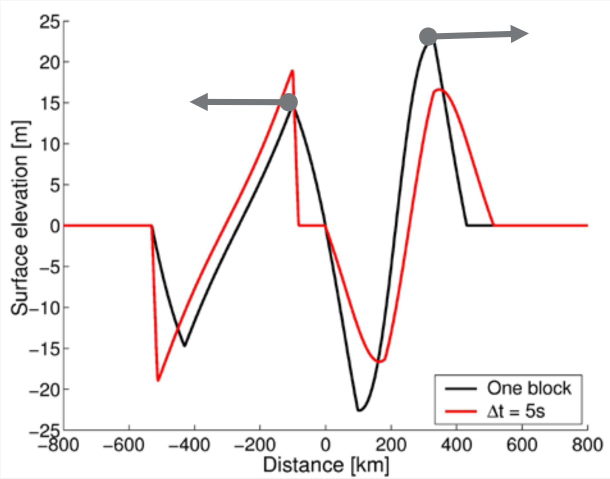


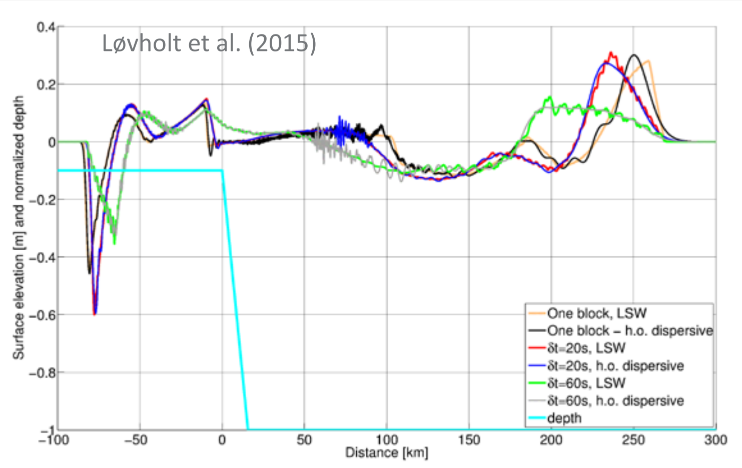


Retrogressive landslide as a series of blocks

- Wave height normally reduced by increased time lag
- Positive interference may enhance shoreward wave
- Moderately large time lags stretches the waves
- Effects most pronounced for large landslides (many blocks)







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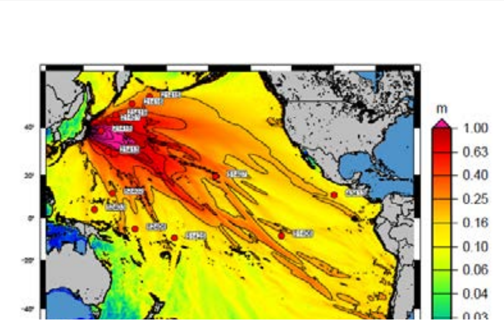
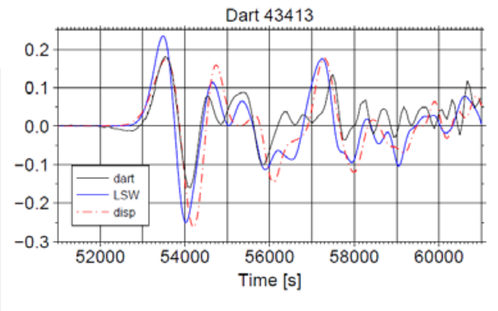
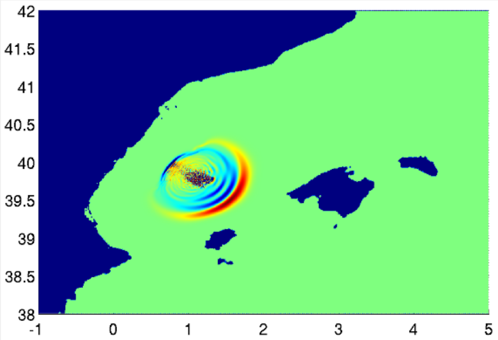
Wave frequency dispersion

- Wave propagation speed dependent on wave length
  - Longer waves travel faster than shorter ones
  - The longest wave in front of the wave train
- May be important for long distances
  - Even for large earthquakes
  - Shorter propagation of smaller earthquakes
- The effect is more pronounced for landslide tsunamis
- Dispersion is sensitive to the source
  - → More sensitive to wavelength than to propagation distance and time
- Generally, the leading-order wave is reduced due to dispersion
- The limited wavelengths of landslide tsunamis favour amplification due to shoaling

Glimsdal et al. (2013)

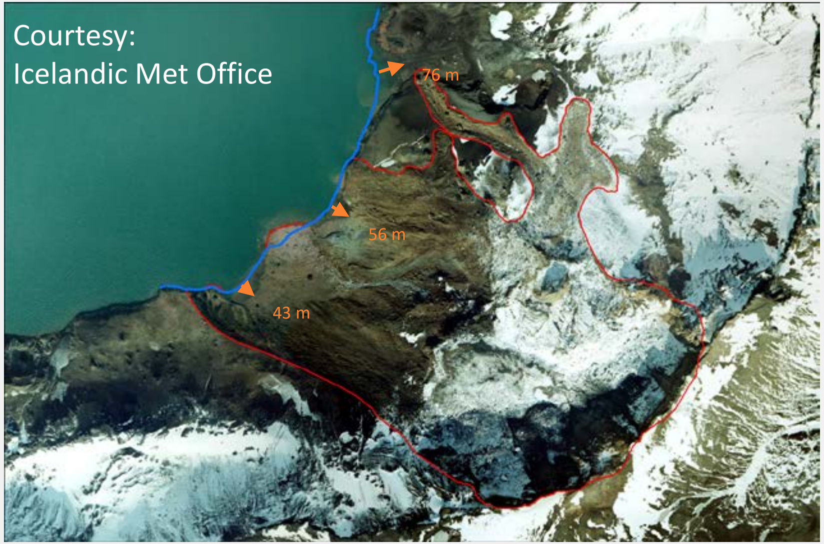


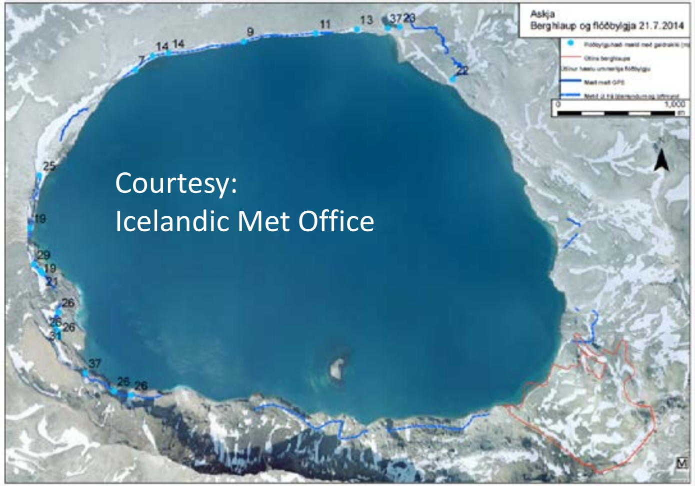


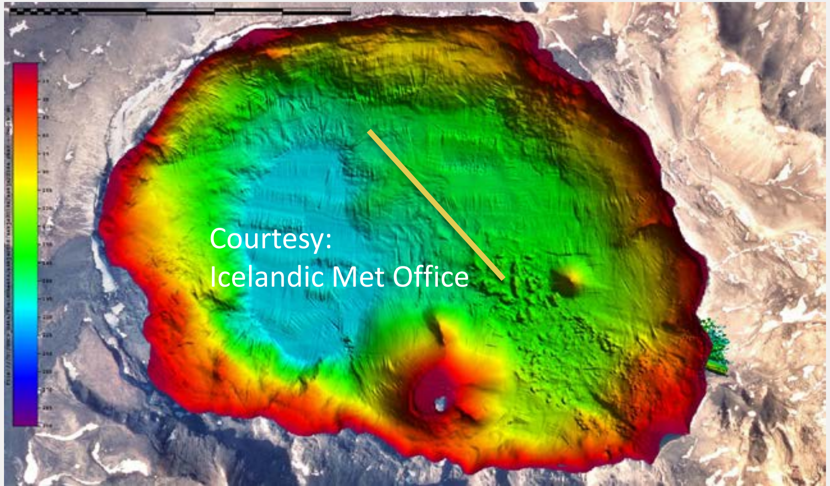


The 2014 Lake Askja event

- Volume ~20 Mm^3- 10 m^3 deposited in lake (from increased elevation)
- Run-up measurements densely sampled along the lake
- Well suited "lab" for model testing

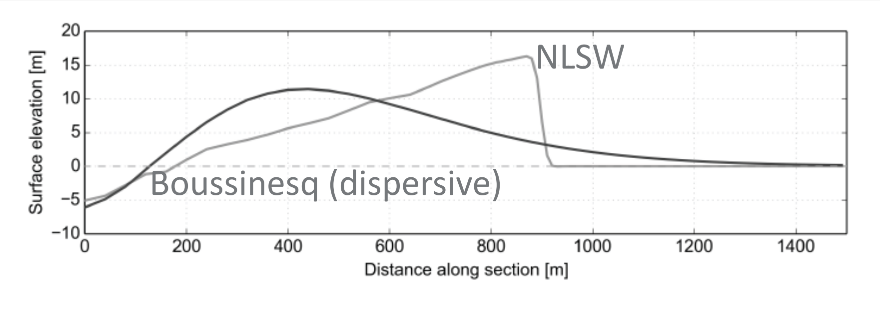


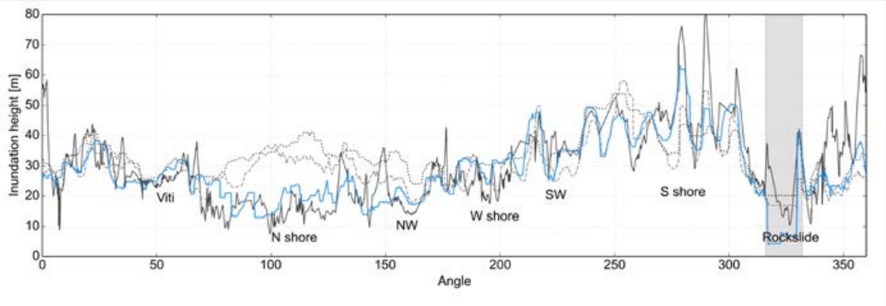




Lake Askja simulations using BoussClaw – Gylfadottir et al. (2017)

- Block model for the landslide
- Optimization procedure for obtaining best fit landslide kinematics from Monte Carlo runs
- Systematic misfit using NLSW model
- Mean trend captured using Boussinesq model





Measurement
BoussClaw (dispersive)
GeoClaw (NLSW)

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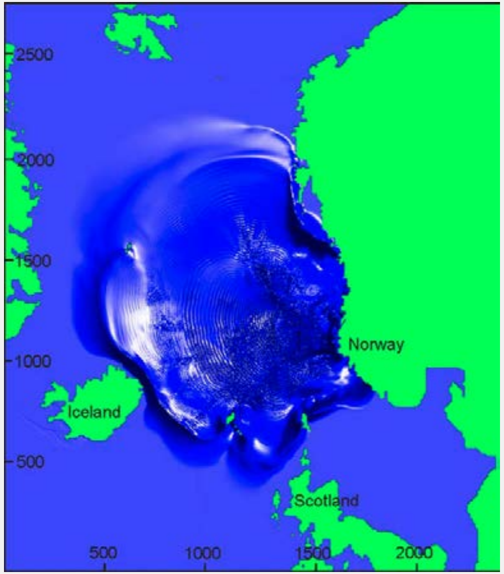
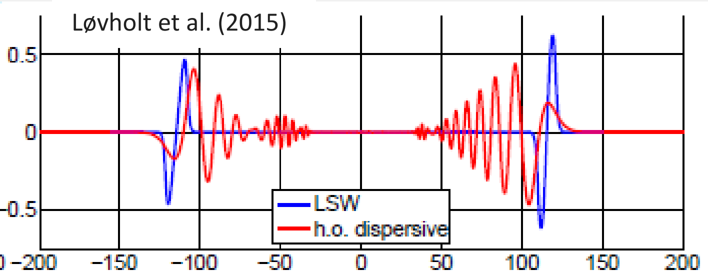
Landslide tsunami modelling

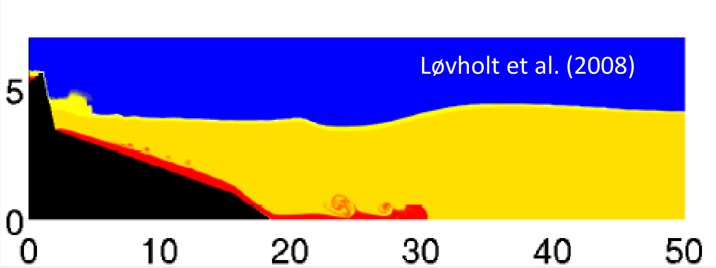
Various types of landslides represent different modelling challenges

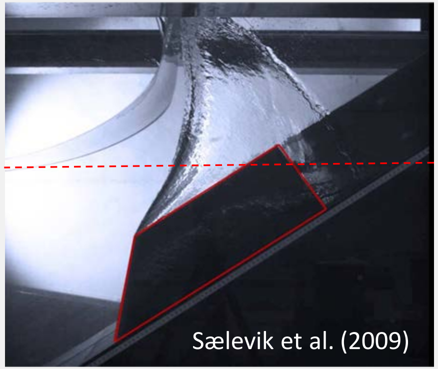
- Large submarine landslides with long run-out (e.g. Storegga, Trænadjupet, BIG'95, Currituck landslide)
  - Retrogression, landslide rheology, material transition
  - Long waves
- Slumps, short duration and run-out (e.g. PNG 1998)
  - Impulsive (high acceleration), efficient tsunamigenesis, short high-frequency waves
- Volcanic flank collapses and rock slides
  - Violent impact, demanding hydrodynamics, strong non-linearity
- **Need for different models and model coupling**

Bondevik et al. (2005)



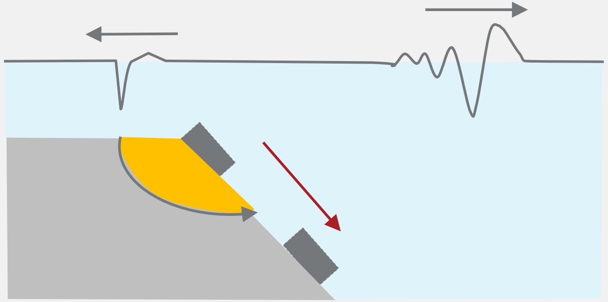


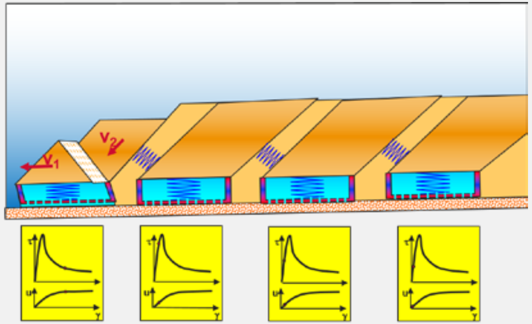


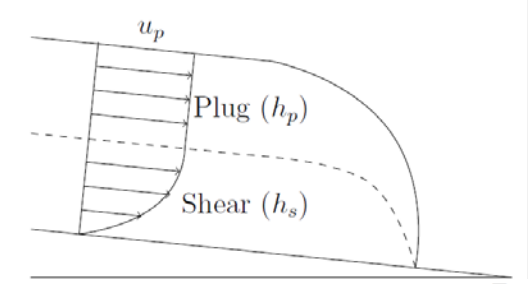


Landslide tsunami source models

- Block models
  - Simple sliding block
  - Rotational slumps
  - Retrogressive blocks
- Depth-averaged debris flow models
  - Viscous
  - Frictional collisional (e.g. Coulomb type)
  - Viscoplastic (e.g. Hershel-Bulkley)
  - Unified (e.g. Jop-Pouliquen et.al. rheology)
- Multiphase CFD models – coupled to the ambient fluid and wave generation
  - Can include any of the above rheologies







$$\tau_y(\gamma) = \tau_{y,\infty} + (\tau_{y,0} - \tau_{y,\infty})\, e^{-\Gamma\gamma}$$

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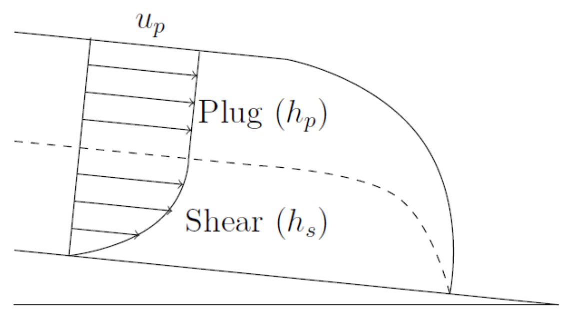
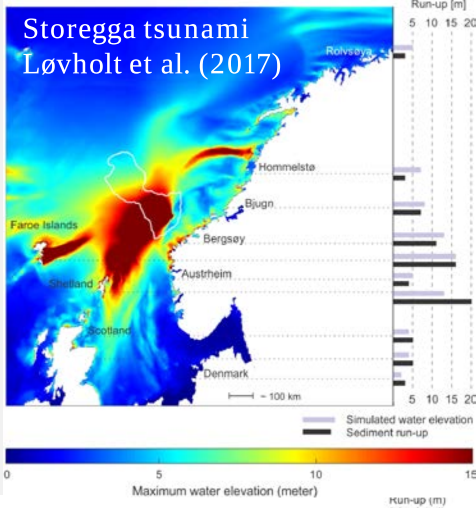
New landslide model BingClaw – Løvholt et al. 2017

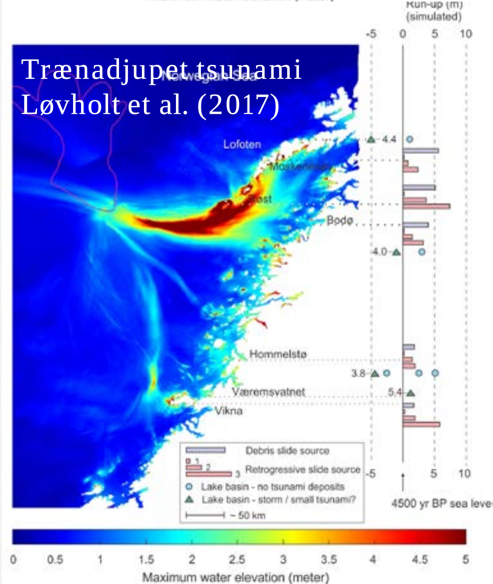
- Viscoplastic Hershel-Bulkley rheology
  - Depth-averaged
  - Two Layers:
    - Plug component (h_p)
    - Shear component (h_s)
  - Yield strength remolding due to strain softening
  - Viscous drag and added mass
- Necessary to explain dynamics and tsunami generation due to complex submarine landslides
- Allows top-down or bottom-up failure
- Slide model coupled to tsunami model GloBouss
- Two horizontal dimensions with terrain deflection



Comparing tsunami generation from the Storegga and Trænadjupet by different landslide source models

- Two of the largest submarine landslides in the world
- Evidence of retrogressive slide development
- 8150 BP Storegga Slide ~3000 km^3
  - Viscoplastic Hershel-Bulkley model
  - Includes retrogressive mechanisms – but more rapid failure development and transition into a debris flow
  - Improved agreement with paleo-tsunami data compared to previous analysis
  - Complies with remoulded material on the abyssal plain
- ~3000-5000 BP Trænadjupet ~500 km^3
  - Retrogressive block model
    - Viscoplastic model too tsunamigenic
  - Complies with blocky slide material on abyssal plain





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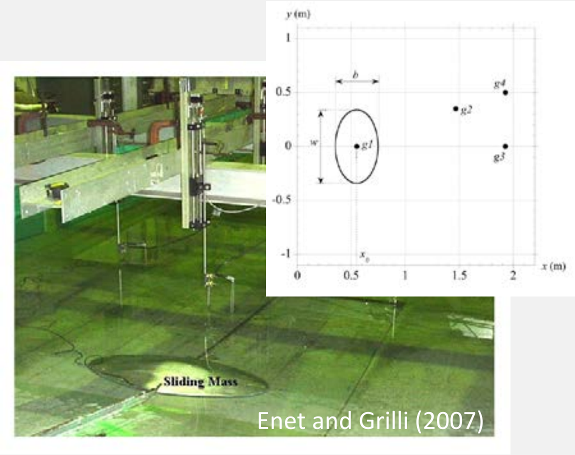
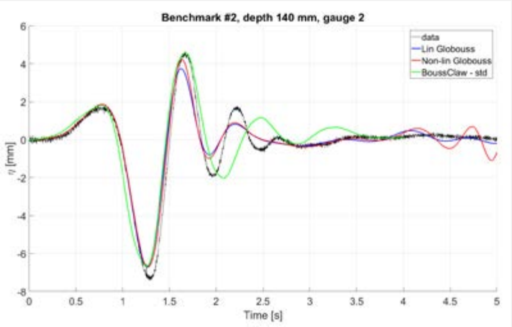
NTHMP benchmark tests for landslide tsunami models

http://www1.udel.edu/kirby/landslide/problems.html

- Seven benchmark cases
- Predominantly designed to match laboratory experiments – one field case
- Submerged and subaerial slides
- Blocks and deformable slides
- Frequency dispersion important for all cases
- Details in slide models less critical
- Workshop in Jan 2017 Galveston Texas






Non-seismic
tsunami
hazard

Non-seismic sources – submarine and subaerial landslides: Volcano flank collapses

- Tsunamigenic potentials have been disputed
  - retrogressive multistage release mechanism
- No examples of volcano collapse of lava domes, flank failures, pyroclastic flows, lahars, or debris flows that have caused severe tsunamis of regional impact in historical times
  - eruptive volcano tsunamis excluded here
- Due to their potential catastrophic impact, these types of massive events have received considerable attention, albeit being rare
- Several local volcano flank collapse tsunami events with reported run-up heights up to 15 m are observed (some with significant loss of lives), in the Caribbean, 2002 Stromboli Island, 1640 Komaga-Take, 1741 Oshima-Oshima, and 1792 Shimabara Bay (Mount Unzen, Japan), 1871 Ruang and 1979 Iliwerung (Indonesia), 1888 Ritter Island (Papua New Guinea), and 2018 Anak Krakatau

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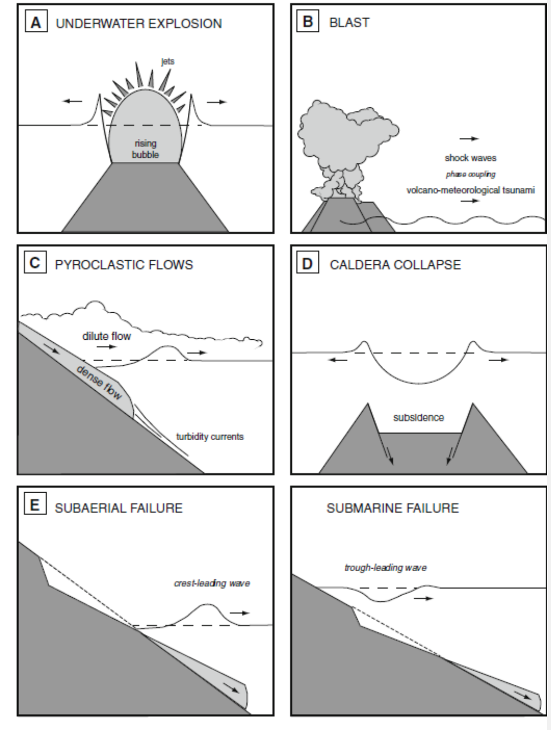
Non-seismic sources – Volcano tsunamis

- *From Paris 2015:*
- Volcano tsunamis are less frequent than seismic tsunamis
- Short to moderate wavelengths
- Far-field impact often limited
  - however, the local impact is potentially disastrous
- Diversity of waves poses difficulties for integration and harmonization of sources into numerical models and PTHA



From Paris et al. (2014)

Non-seismic sources – Meteo tsunamis

- *From Pattiaratchi and Wijeratne (2015):*
- Meteotsunamis are generated by meteorological events
  - Moving pressure disturbances due to thunderstorms, frontal passages, etc.
- Temporal and spatial occurrence is higher than for seismic tsunamis
- High-energy events occur only for very specific combinations of resonant effects
  - destructive meteotsunamis are exceptional compared to seismic tsunamis

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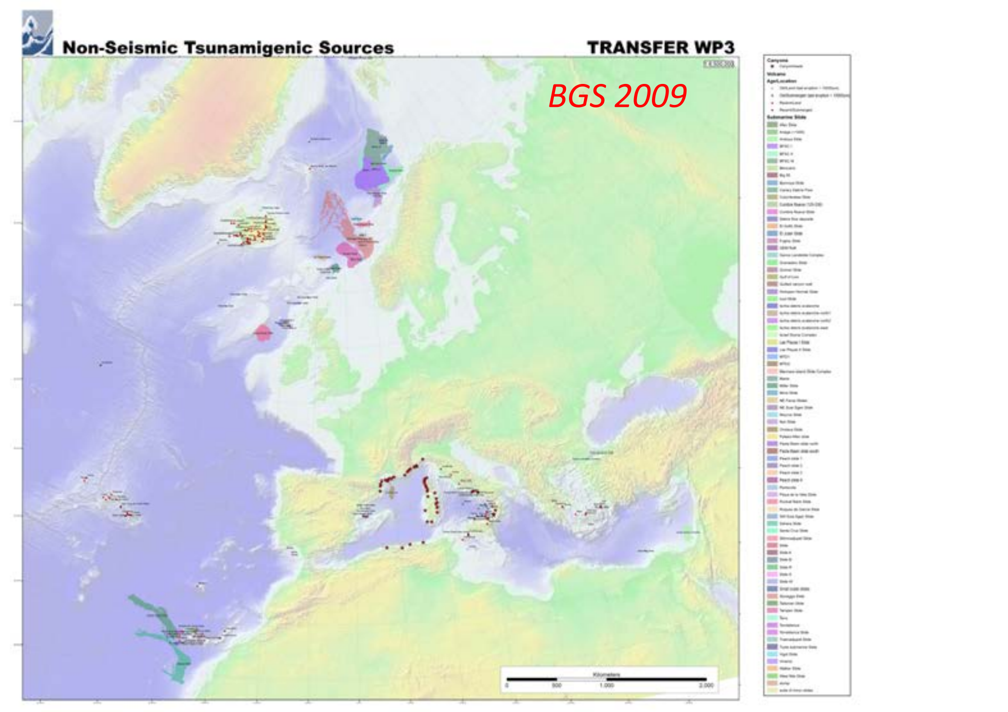
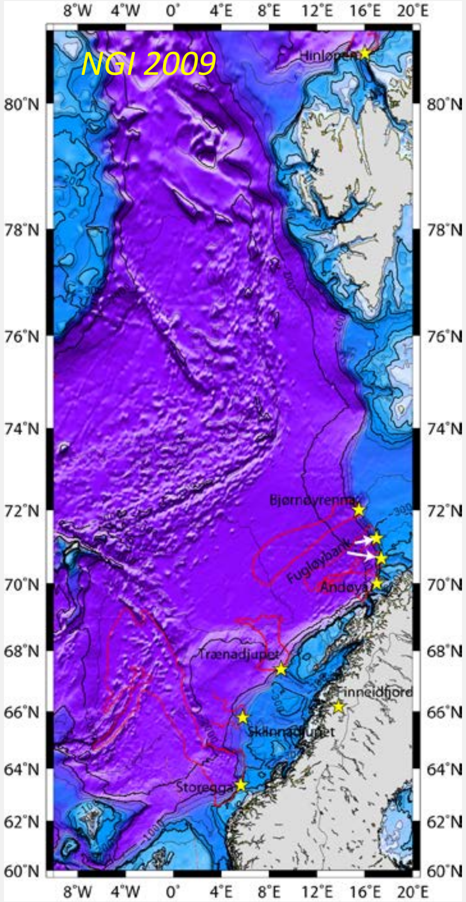
Non-seismic tsunami sources along the European coastlines: NEA





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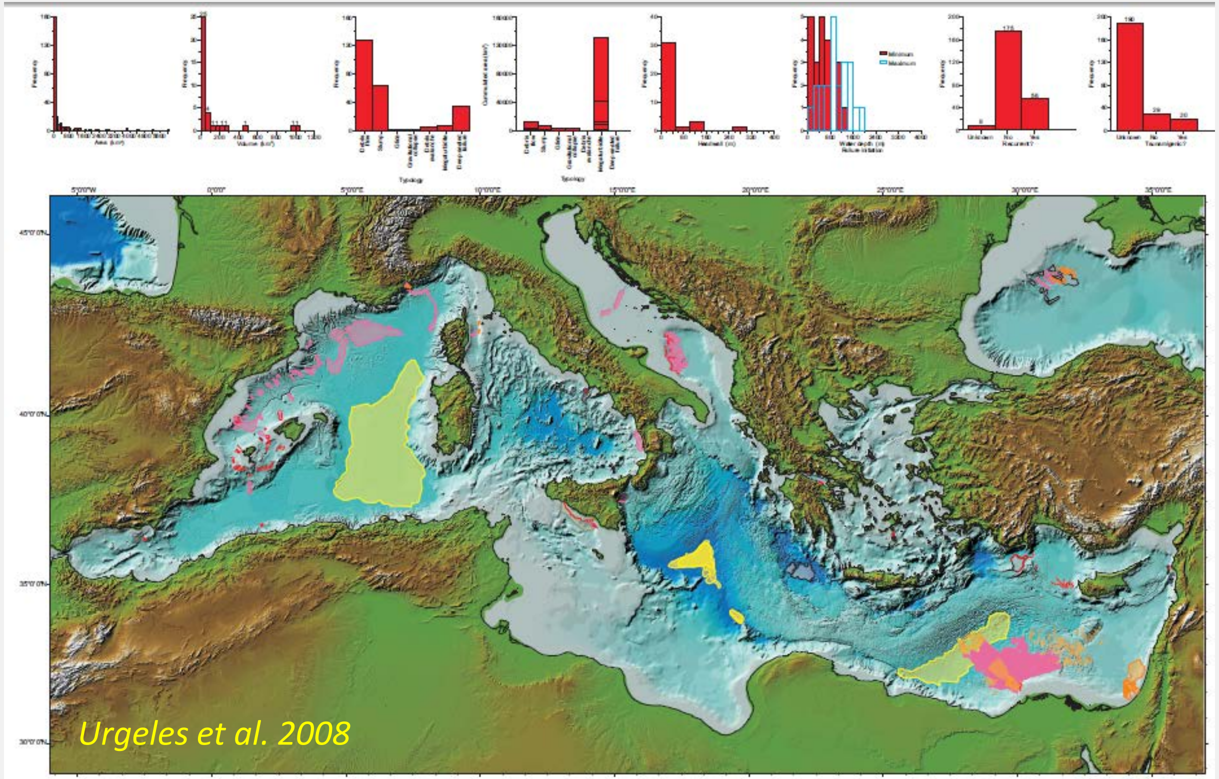
The Mediterranean Sea



GIS analayses provide statistics on main landslide parameters

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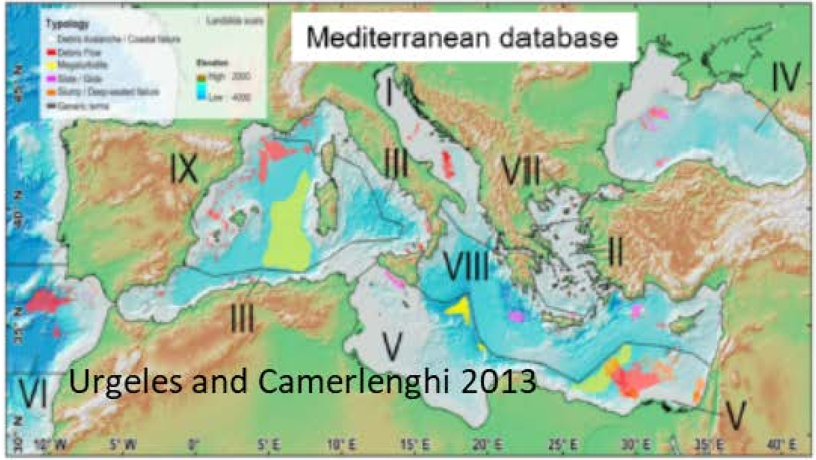
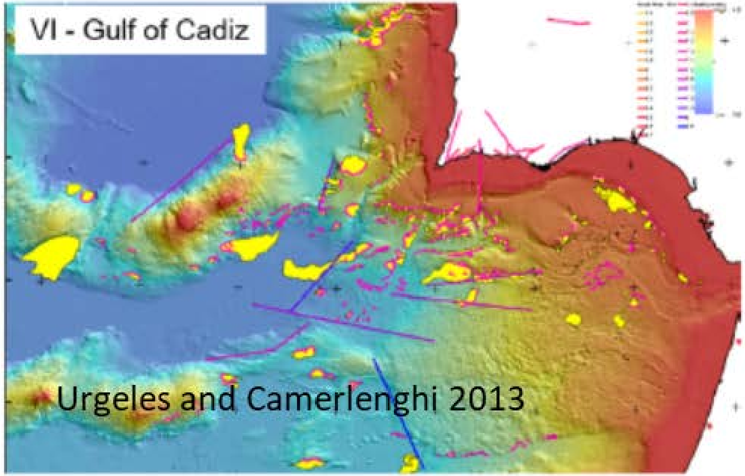
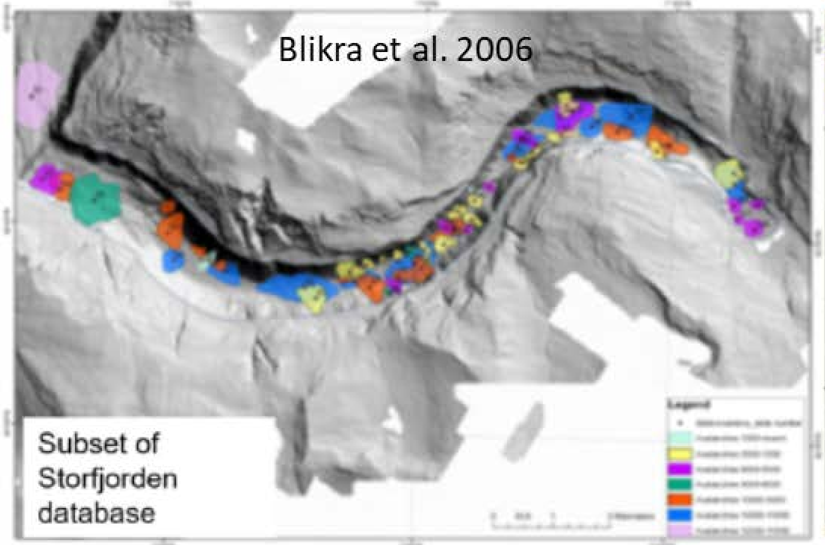
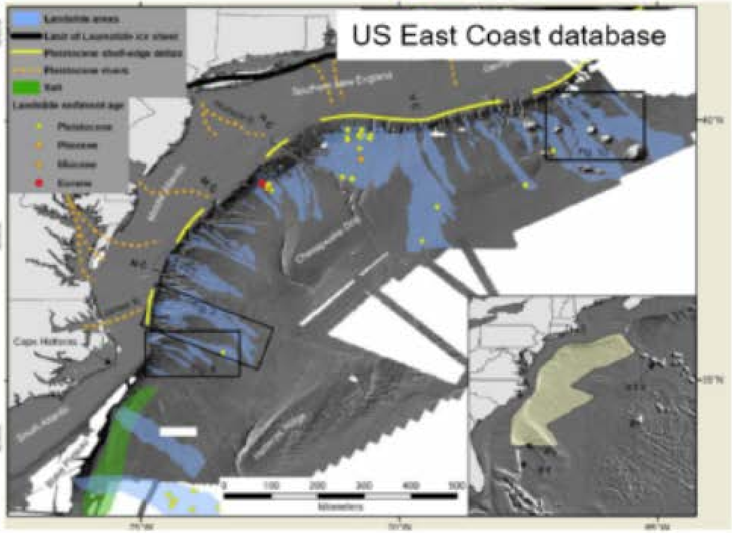

Mediterranean database
Typology
Elevation
I
IV
IX
III
VII
II
VIII
III
V
VI
V
Urgeles and Camerlenghi 2013
10° W
5° W
0°
5° E
10° E
15° E
20° E
25° E
30° E
35° E
40° E


VI - Gulf of Cadiz
Urgeles and Camerlenghi 2013


Blikra et al. 2006
Legend
Subset of
Storfjorden
database


US East Coast database
0
100
200
300
400
500
kilometers

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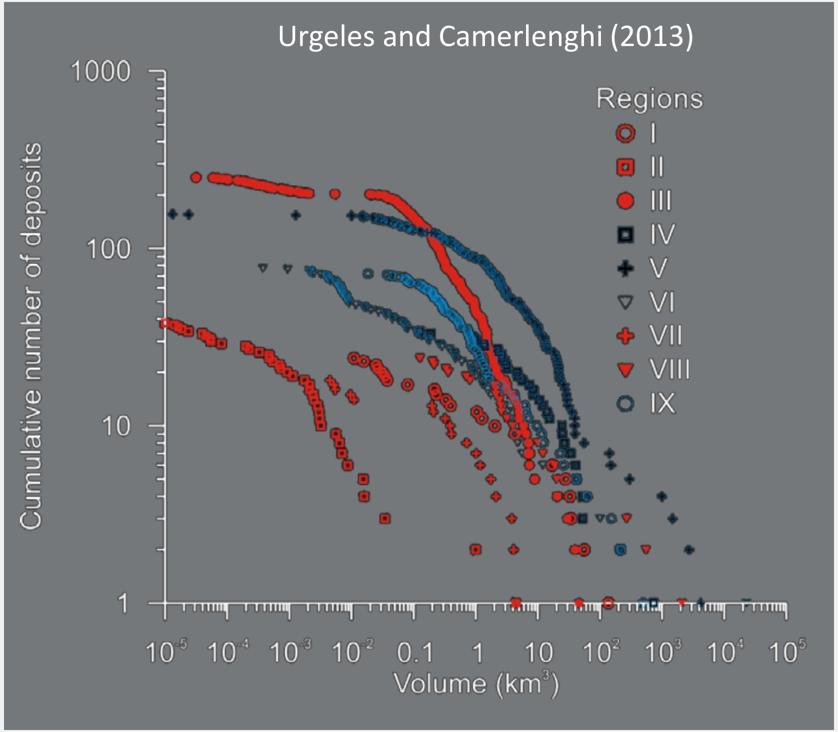
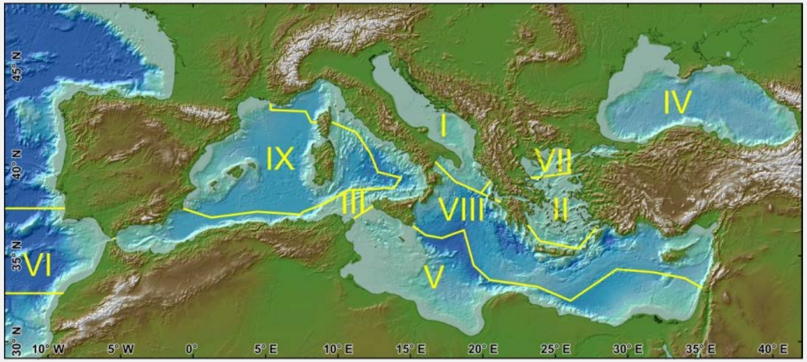
The hazard: Active vs passive margins





- Active margins more frequent
- Passive margins reveal larger maximum volumes

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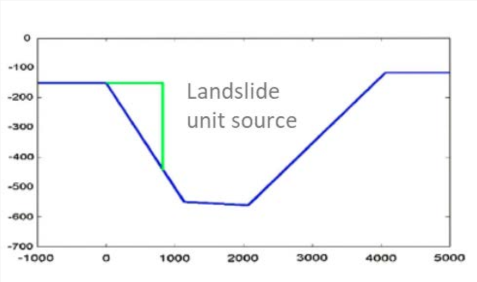
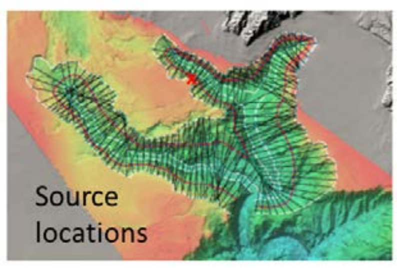
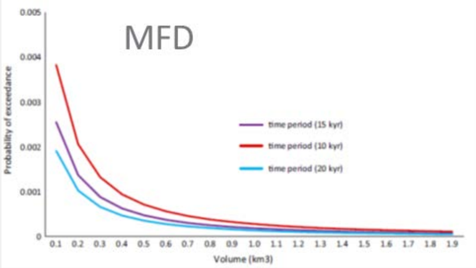
Probabilistic
landslide tsunami
hazard analysis

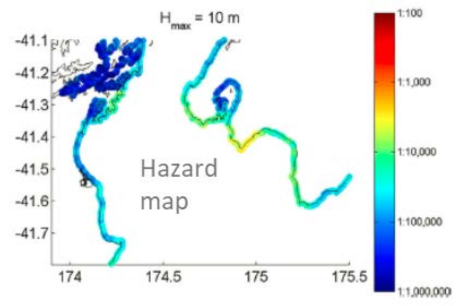
Probabilistic landslide tsunami hazard analysis

- More premature than for earthquake sources
- Larger uncertainties
  - Event recurrence
  - Effect of local setting
  - Magnitude (volume)
  - Dynamics
- Example by Lane et al. (2016)
  - Cook Strait Canyon, NZ
  - Simplified landslide dynamics
  - Relatively controlled geological setting
  - Volume MFD available









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Challenges related to recurrence

- We have a problem with sample size
- We are working with observations quite unevenly spaced in time
- Giant submarine landslides are rare and probably related to climate changes or glacial cycles
  - The events in the database belong to different distributions?
  - Extreme-value statistics is also likely to fail since the extreme values are also poorly sampled

- It will be difficult, due to insufficient sampling, to establish a reliable distribution for the available submarine landslide observations

- Revert to a more simple and data-driven approach where we extract information from observations without the benefit from the underlying statistical distributions?

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Submarine landslide susceptibility mapping based on simplified slope stability analysis – Collico et al. (work in progress)

SLATE
Submarine Landslides and their impact on European continental margins

- Morphological and geotechnical parameters as well as expected PGA are modeled through a spatially correlated random field approach
- Uncertainties in soil properties and slope stability are reduced
  - Bayesian approach for geotechnical data variability
- ➔Objective: Probabilistic regional hazard map based on 1D infinite-slope stability model

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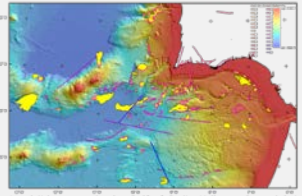
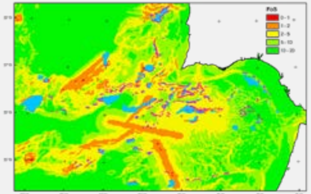
MFD based approach when a sufficient amount of data covering a wide range of volumes is available – Løvholt & Urgeles (2017; in progress)

Proposed method: Create a set of random slide sources based on the source statistics combining volumes, slopes, structural, seismic, and other sources of information:

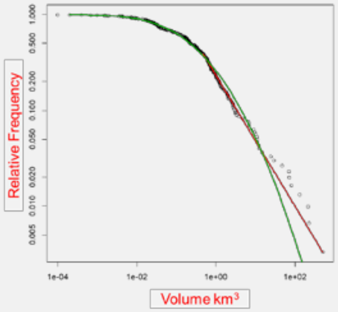
- Use landslide magnitude-frequency probability distribution to create unit sources for given parameter combinations
  - large sources to be treated separately
- Use deterministic slope stability vs. actual observations to evaluate spatial probability of occurrence
- Based on source statistics, conduct Monte Carlo sampling of sources
  - MFD curves used to quantify probabilities
- Treat epistemic uncertainty by sampling tsunami simulations over different (unknown) landslide strength parameters
- Different sources will be simulated, the offshore tsunami metric tabulated and the integrated impact at the coastline (hazard) determined



Landslide events in the Gulf of Cadiz. Yellow colour, debris lobes. Red curves, slide headwalls. Faults (SHARE database) are color coded according to potential max. magnitude.



Deterministic Factor of Safety map for the Gulf of Cadiz and landslides (blue). Seismic shaking along faults has a clear impact on slope stability.



Magnitude frequency distribution for landslide volumes in the Gulf of Cadiz. Power-law (red) and lognormal (green) probability distributions are shown.

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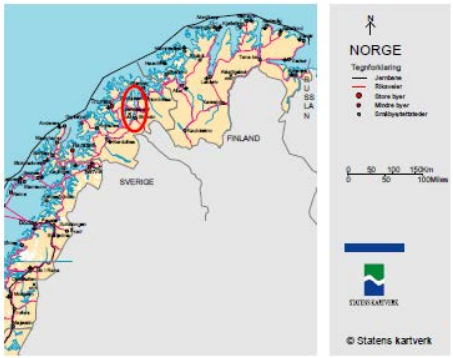
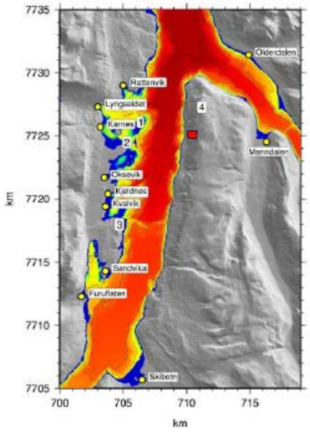
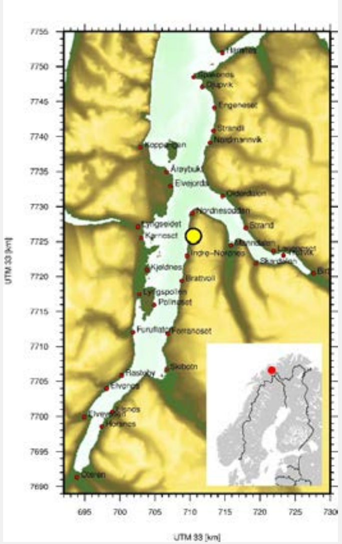
Probabilistic tsunami hazard analysis for Lyngen, Northern Norway

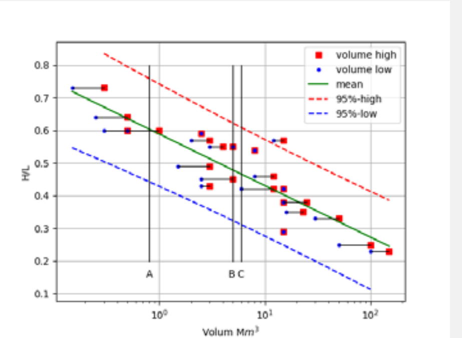


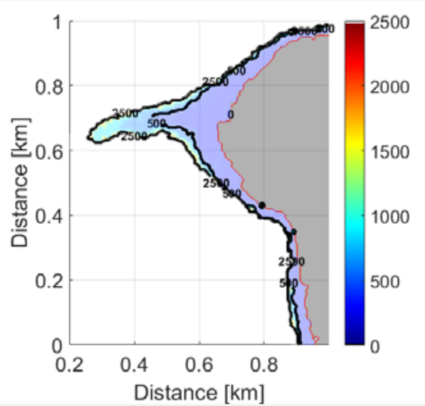


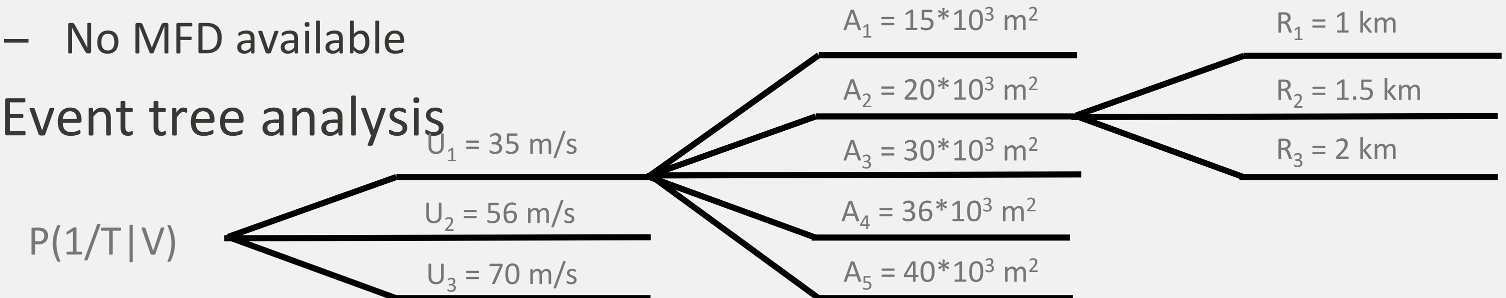
LPTHA at NGI – ongoing work

- Lyngen, northern Norway
  - Four unstable rock slopes
- Epistemic uncertainty
  - Speed
  - Frontal area
  - Run-out
- Return period range imposed
  - Scarce previous landslide data
  - No MFD available
- Event tree analysis



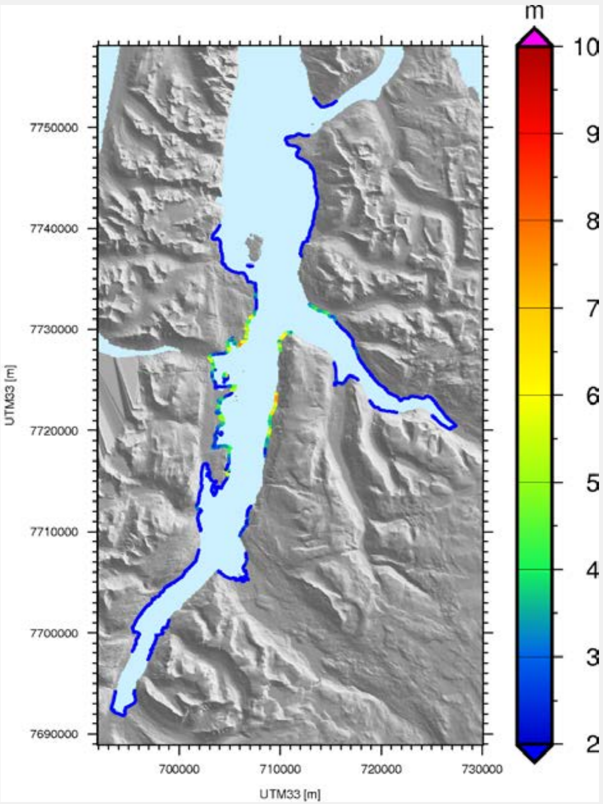




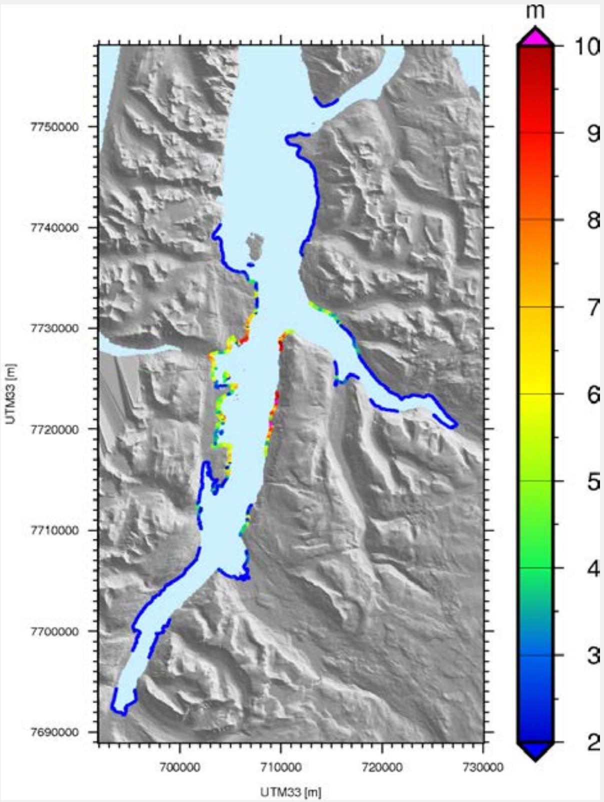


Regional tsunami hazard maps –
Maximum runup combining 600 rock slide scenarios

Annual probability >=1/1000



>=1/5000



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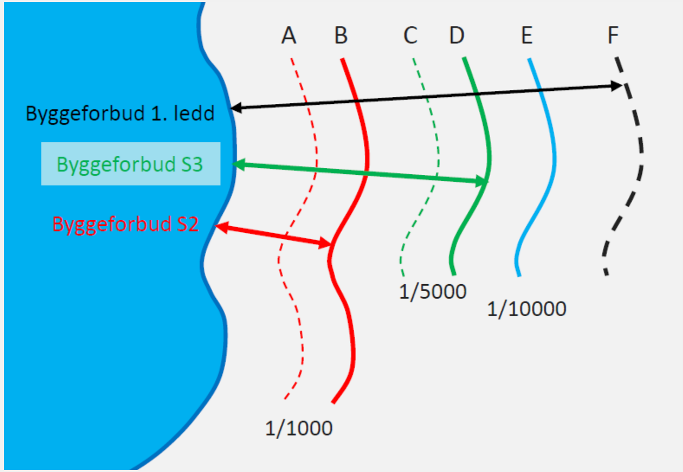
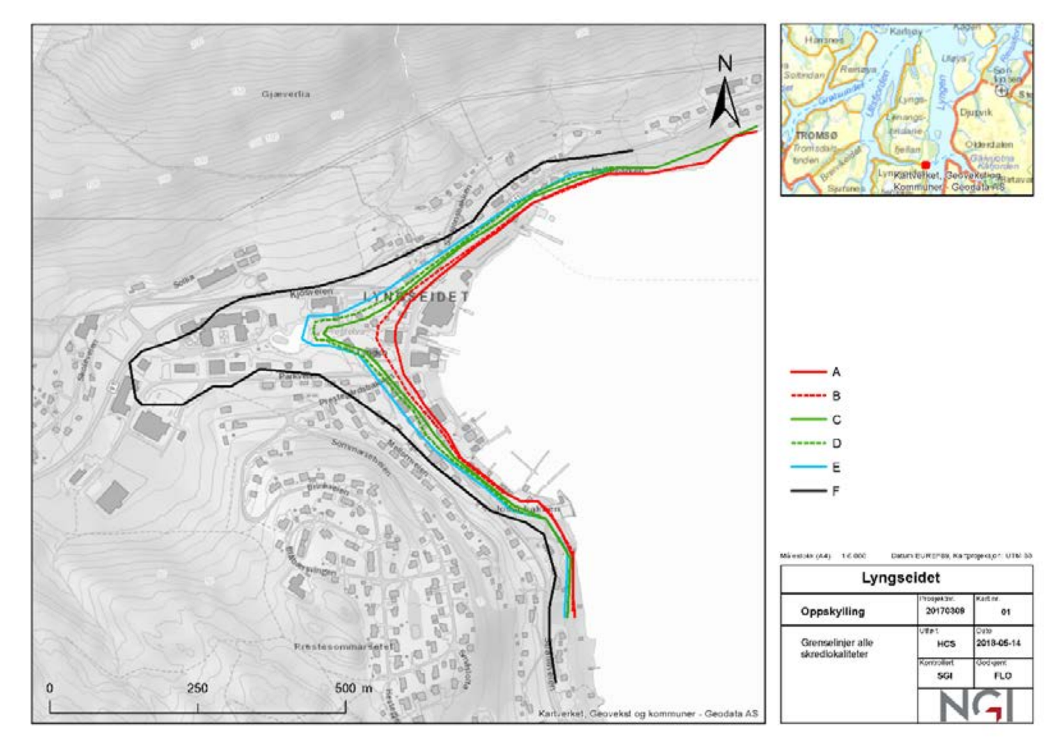
31 exceedance probability inundation maps adapted to safety classes in the Norwegian PBA – example hazard lines for Lyngseidet (all 600 rock slide scenarios)



Grenser for faresoner flodbølger:
A: Grense stort skadepotensiale, sannsynlighet > 1/1000 pr. år
B: Oppskyllingsgrense, sannsynlighet > 1/1000 pr. år
C: Grense stort skadepotensiale, sannsynlighet > 1/5000 pr. år
D: Oppskyllingsgrense, sannsynlighet > 1/5000 pr. år
Andre grenser:
E: Grense for sannsynlighet 1/10000 (til hjelp for planlegging av evakuering)
F: Maksimal oppskylling (til hjelp for planlegging av evakuering og 1. ledd)



EU FP7 ASTARTE Deliverable D3.12

astarte
ASSESSMENTS, STRATEGY AND RISK REDUCTION FOR TSUNAMIS IN EUROPE

- *Risk driving tsunami sources (in NEAM) – parameters, sensitivity, and uncertainties*
- Earthquake, landslide, volcano source mechanisms
  - Landslide kinematics (translational vs. slump motion)
  - Retrogression
- Source compilations
- Rough descriptions of likelihood and uncertainty of source parameters
- Sensitivity of tsunamis to source modelling
  - impact of source aleatory (e.g. slip distribution during an earthquake) and epistemic uncertainty (e.g. landslide rheology) on tsunami applications
- Complexity (accuracy of results) vs. feasibility

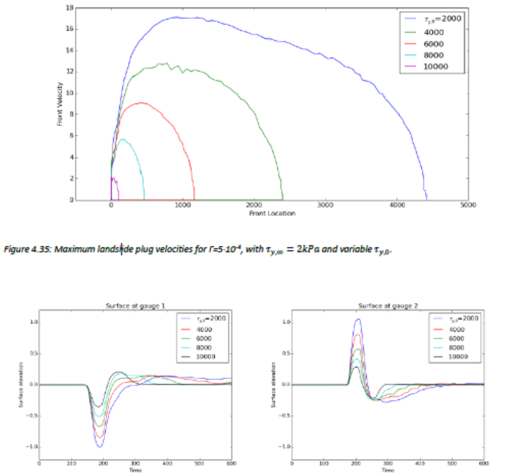


Figure 4.35: Maximum landslide plug velocities for $\Gamma=5\cdot10^{-4}$, with $\tau_{y,\infty}=2kPa$ and variable $\tau_{y,0}$.

Figure 4.36: Time series of the induced tsunamis due to a Bingham fluid with different initial yield strengths $\tau_{y,0}$. Gauge 1 and 2 are located at $x=-5000$ (behind the landslide) and $x=15000$ (in front of the landslide), respectively.

Example: Sensitivity of maximum landslide velocity and corresponding tsunami heights to varying initial yield stregth

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Proposed next steps for LPTHA

- Direct relationships between landslide parameters and submarine landslide dynamics probability
- Uncertainties in these relationships to be quantified by matching large sets of landslide run-out field data with numerical models using machine learning techniques
- Coupling the landslide models with tsunami simulations to understand how tsunami characteristics can be traced back to landslide material properties and landslide dynamics
- Use unique data in different geological settings to determine landslide occurrence probability
- ➔ *A multi-disciplinary methodology with emphasis on uncertainty quantification, enabling us to dissect how different physics, landslides, and models influence and determine the hazard*

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Concluding remarks

- Transferring probabilistic methods to landslide tsunami hazard assessment is challenging as recurrence rates and likelihood as well as the tsunamigenic seabed deformation are much more *uncertain* owing to limited observations, dating, and statistics, as well as to changing conditions for landslide release
- It is expected that the landslide tsunami risk is dominated by large return periods, generally carrying the largest uncertainties
- The probability of a tsunami exceeding a certain value is often dominated by one (risk-driving) event. But, the most important risk-driving events are also generally not known
- PTHA would provide a probabilistic representation of the hazard with large epistemic (knowledge based) uncertainties related to location, release mechanisms, evolution, and return periods of the scenarios, and with much higher computational resources
- The aleatory (random) uncertainties will tend to be underestimated?
- ➔ Either underestimated PTHA results due to unrealistic assessment of uncertainties, or
- ➔ very high hazard levels driven essentially by large uncertainties
- Insufficient sampling is a major obstacle for a landslide tsunami PTHA

Concluding remarks – future needs

- In most continental margins, a more complete mapping of landslide sources would certainly improve assessment of landslide tsunamigenic potential
- For the past events, mechanical analyses of the release, disintegration, and flow mechanisms will help in understanding landslide dynamics
- Laboratory-scale experiments and the pertinent discussions on how they relate to corresponding natural phenomena are particularly important for submarine landslides that are difficult to observe at full scale
- Better dating would improve assessment of recurrence and relation to climatic or glacial cycles
- For potential sources, more sophisticated investigations are needed with respect to potential trigger mechanisms, slope stability, source locations, and source parameters with corresponding recurrence rates
- Probability distributions, heterogeneities, randomness, and uncertainties should preferably be constrained by analysis of field data and used as input to both numerical tsunami propagation models and probabilistic hazard and risk assessment
- For risk assessment and quantification of uncertainties, probabilistic methods that properly take into account the physics of the complex landslide evolution and tsunami generation process are desirable
- Quantification of both distributions (mean values as a minimum) and uncertainties of source parameters constitutes a fundamental basis for a possible PTHA approach
- Source parameterization has to be made in a way still enabling sensitivity analysis (feasibility!)

#onsafeground