# Tsunamier
# Mekanismer og vitenskapelige utfordringer.

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# Outline



# List of Topics

# Definsjon av tsunami

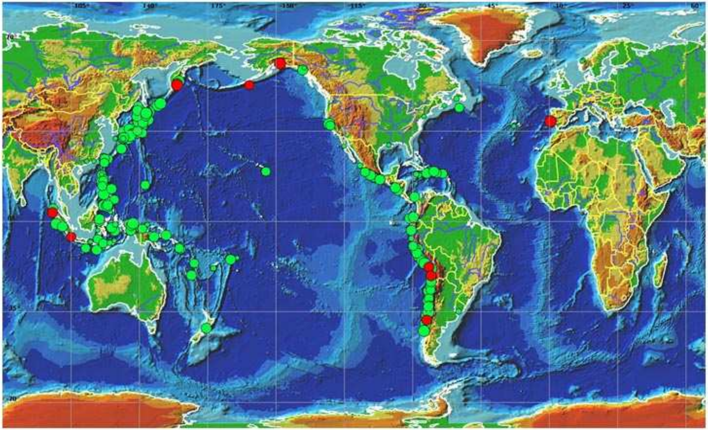
Ordet Tsunami er fra japansk: bølge havn

## Definisjon

Tyngdedrevet overflatebølge på havet, skapt av en brå geologisk hendelse

1. Jordskjelv
2. Skred. Undersjøiske eller ned i innsjøer/hav ("Mass gravity flows")
3. Vulkaner
4. Asteroider/kometer
5. Kjernefysiske eksplosjoner – jada, det er undersøkt det også

# Tsunami laboratory, Novosibirsk: Historiske tsunamier



Grønt 223 kjente tilfeller med dødsfall av totalt 2250

Rødt transoceaniske tsunamier

# Mer statistikk, Novosibirsk (**Hmax** = oppskylling)

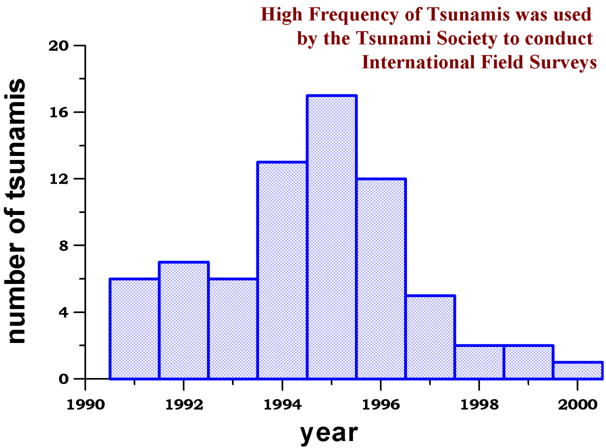
## Tsunami occurrence in XX century

| | World | Pacific |
|---|---|---|
| All tsunamis | 911 | 704 |
| (events per year) | 9.1 | 7.0 |
| Tsunamis with Hmax > 1 M | 252 | 213 |
| (events per year) | 2.5 | 2.1 |
| Tsunamis with Hmax > 5 M | 96 | 82 |
| (events per year) | 1.0 | 0.8 |

Tsunamis with heights more than 5 M at distance more than 5000 KM (so called trans-oceanic tsunamis) were observed only in 5 cases (all in the Pacific)

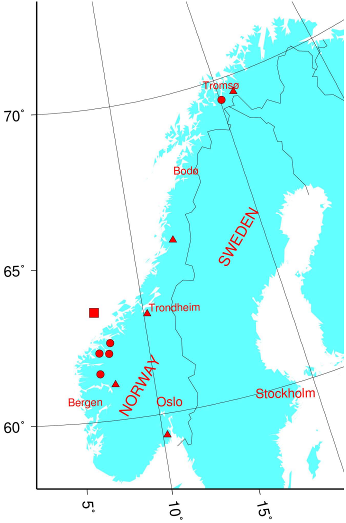
1946 Aleutians
1952 Kamchatka
1957 Aleutians
1960 Chile
1964 Alaska

# Økt tsunamiaktivitet på 90-tallet




Mange tsunamier 1990-2000 ⇒ stor forskningsaktivitet
Enkelte utropte det til "tsunamidekaden".

# Norske tsunamier




- ● Mer enn 10 døde
- ■ Storeggaskred (6.200 fKr.)
- ▲ Mindre hendelser (utvalg)

# Norsk tsunamiforskning

- UiO
  - Periodevis aktivitet 1980 →; forsøk, teori og modellering
  - 1992 →; økt aktivitet gjennom internasjonale og nasjonale prosjekter
- Beslektede tema: skred; Vedvarende stor aktivitet hos NGI, NGU, UiO etc.
- Rundt år 2000: Utbygging av Ormen lange
  - bred undersøkelse av Storeggaskred og tsunami
- 2002: ICG (International Centre for Geohazards)
  - Samarbeid NGI, UiO, NORSAR, NGU, NTNU
  - Tsunamier er ett av flere satsningsområder

# List of Topics

# Tsunamis

## Geological source
Earthquakes, slides, asteroids, volcanoes.
Models are challenging

## Tsunami propagation
Large propagation distances.
Dispersion often important.
Huge grids.

## Tsunami generation
Slide/wave dynamics is complex.
Earthquakes are simpler.

## Coastal impact
Difficult physics.
High resolution models.

# The Navier-Stokes (*NS*) equation

The primitive equations:

$$\frac{\mathrm{D}\vec{v}}{\mathrm{D}t} \equiv \frac{\partial \vec{v}}{\partial t} + \vec{v}\cdot\nabla\vec{v} = -\frac{1}{\rho}\nabla p + \mathcal{D} - g\vec{k}$$

$$\nabla\cdot\vec{v} = 0$$

where $\vec{v}$ = velocity, $\mathrm{D}/\mathrm{D}t$ = material derivative, $p$ = pressure and $\mathcal{D}$ is viscous/turbulent term. In words:

acceleration = - pressure gradient + friction + gravity

net outflux from any fluid volume = 0

Boundary conditions: impermeable, no-slip, free (surface), artificial

Key problems: turbulence model, free surface tracking, underresolved boundary layers, etc.

# Applicability of primitive models

- Robust free surface techniques (VOF, SPH)
- Industrial solvers (CFX, Fluent...)
- Analytic solutions are sparse, circumstantial and cumbersome
- Computations readily become very heavy ⇒ numerical solutions are under-resolved or unattainable ⇒ feasible only in local and idealized studies
- The burden of the computations often lead to wavering of the physics

Surprisingly (?) little insight in hydrodynamic wave theory yet stem from "full computational models".

**Simplified theories are crucial, but general models become increasingly important**

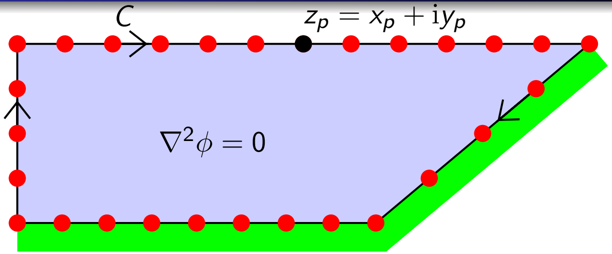
# Full potential theory

No viscosity, no rotation $\Rightarrow$ all velocity components can be derived from a scalar potential $\phi$ ($\nabla\phi \equiv \vec{v}$) that fulfills Laplace equation

$$\nabla^2\phi = 0$$

- Simpler than the Navier-Stokes system
- At a given time the velocity distribution in the fluid is given by one component at the boundary $\Rightarrow$ boundary integral equations
- Not incorporable: viscous effects, bottom and surface drag, turbulence, overturning waves, Corioli's force ...
- Water waves are often well described by potential theory

# Integral equation; example: Cauchy's formula




$$\alpha \mathrm{i} q(z_p) = \mathrm{PV} \oint_C \frac{q(z)}{z_p - z} dz$$

where $q = u - \mathrm{i}w$ ("complex velocity") or $q = \phi + \mathrm{i}\psi$ (complex potential), $\alpha =$ interior angle.

Interpolation between nodes, and one velocity comp. known $\Rightarrow$ implicit equation in boundary value only.

# Potential flow models

1. Integral equation discretized by panels. Boundary location updated in time as part of the method.
2. FFT techniques; approximations at free surface

Computation still heavy. Useful for local simulations and for assessing validity of simpler models. Cannot incorporate wave beaking and rotational effects. More efficient and robust models must be employed for large scale tsunami modeling

# Scales for surface gravity waves

**Acceleration scale**

$g$ acceleration of gravity

Remark: scale for particle acceleration in gravity waves is always the same, regardless of size of problem

**Length scales**

$\lambda$ wavelength $\quad$ $h$ depth $\quad$ $A$ amplitude (height)

$L_h$ depth variations $\quad$ $L_\lambda$ variation of $\lambda$

Often $L_h \sim L_\lambda$

**Velocity and time scales**

May be built from length and acceleration scales

# Approximations

- $\frac{A}{h}, \frac{A}{\lambda} \ll 1 \Rightarrow$ linear and weakly non-linear theories
- $\frac{\lambda}{h} \ll 1 \Rightarrow$ deep water
- $\frac{h}{\lambda} \ll 1 \Rightarrow$ **shallow water; long wave theory**
- $\frac{h}{L_h}, \frac{\lambda}{L_\lambda} \ll 1 \Rightarrow$ multiple scale methods: ray theory; narrow band (nearly uniform waves)

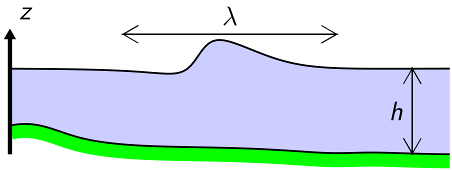
Different requirements may be combined; long wave theory is often combined with weak non-linearity.

Definition of characteristic scales may be vague or ambiguous

# Tsunami and ocean modeling

## Tools of the trade

- Depth integrated models for long waves
- Efficient and robust numerical techniques
- Ray tracing, wave kinematics




Long waves $\lambda/h \gg 1$

$U$, $W$ – characteristic horizontal and vertical velocities

$\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} = 0 \Rightarrow \frac{W}{h} \sim \frac{U}{\lambda} \Rightarrow \frac{W}{U} \sim \frac{h}{\lambda} \ll 1$

$\Rightarrow$ vertical motion is small

# Depth integrated theory; shallow water

Vertical acceleration neglected ⇒ hydrostatic pressure ⇒ no vertical variaton in horizontal velocity

Shallow water eq. $(\lambda/h > 20)$

$$\frac{\partial \overline{\mathbf{v}}_h}{\partial t} + \overline{\mathbf{v}}_h \cdot \nabla_h \overline{\mathbf{v}}_h = -g\nabla_h \eta$$

$$\frac{\partial \eta}{\partial t} = -\nabla_h \cdot ((h + \eta)\overline{\mathbf{v}}_h)$$

$\eta$: surface elevation, $\overline{\mathbf{v}}_h$: velocity (horizontal), $\nabla_h$: horizontal gradient operator

Efficient and simple numerical solution; hyperbolic equations

May include bores, Coriolis effects and bottom drag, *but wave dispersion is lost*.

Use: propagation of tsunamis, inundation. The dominant tsunami model (MOST at PTWS/NOAA, TUNAMI, COMCOT, CLAWPACK)

# Depth integrated theory; Boussinesq

Vertical acceleration small, but not neglected
$(\lambda/h > 2)$

$$\frac{\partial \bar{\mathbf{v}}_h}{\partial t} + \bar{\mathbf{v}}_h \cdot \nabla_h \bar{\mathbf{v}}_h = -g\nabla_h \eta + \frac{1}{2} h \nabla_h \nabla_h \cdot (h \frac{\partial \bar{\mathbf{v}}_h}{\partial t}) - \frac{1}{6} h^2 \nabla_h \nabla_h \cdot \frac{\partial \bar{\mathbf{v}}_h}{\partial t}$$
$$-\kappa h^2 (\nabla_h^3 \eta + \nabla_h \nabla_h \cdot \frac{\partial \bar{\mathbf{v}}_h}{\partial t})$$

$$\frac{\partial \eta}{\partial t} = -\nabla_h \cdot ((h + \eta)\bar{\mathbf{v}}_h)$$

Numerical solution much heavier than for shallow water eq. – implicit solution strategy needed. Still, much faster to solv than primitive equations. Wave dispersion included.

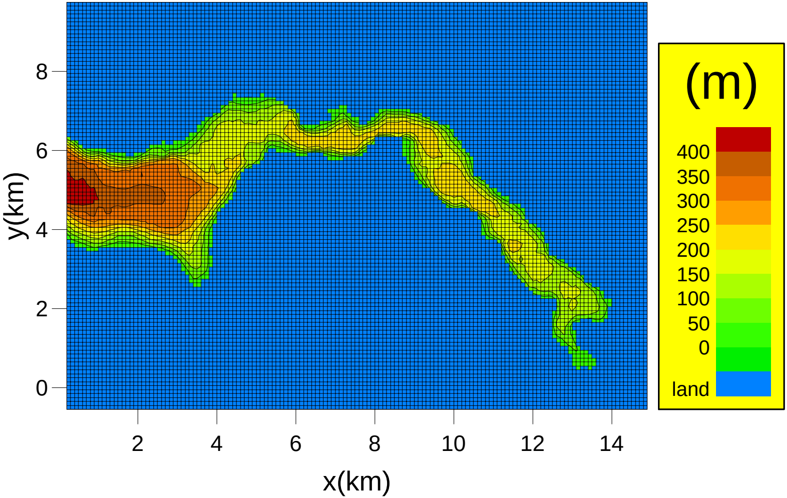
Use: propagation of moderately short tsunamis, particularly from non-earthquake sources. Boussinesq propgation models should always be considered for global propagation.

# What is gained by long wave theory

1. The number of dimensions reduced by 1 (depth integration)
2. Upper and lower bound of fluid replaced by coefficients PDEs in the horizontal coordinates
3. Shallow water equations are hyperbolic with characteristics and shocks $\Rightarrow$ simple models of wave breaking and surf may be included
4. Physical contents more transparent; analytic solutions

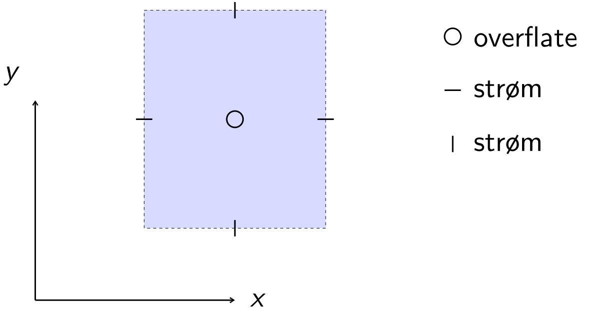
First two points important for numerics

# Finite Differences *FDM*




Finite size grid cells. Generally: staircase boundaries.

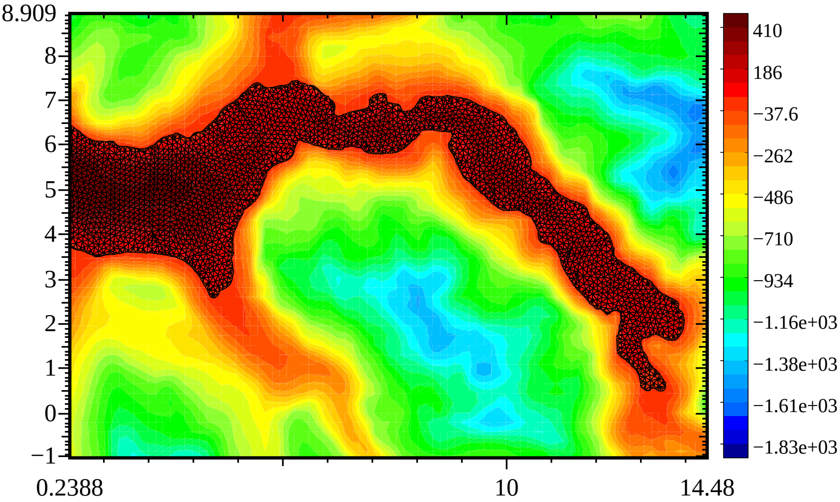
# Kontrollvolum i FDM




Skritt for skritt fram i tid:

1. Summerer strøm inn og ut ⇒ ny overflate
2. Forskjeller mellom overflater i nabobokser ⇒ trykkforskjeller ⇒ akselerasjoner ⇒ nye strømhastigheter
   Tillegg: adveksjon av bevegelsesmengde

# Finite Elements *FEM*




Simple representation of unknowns in each element, less common than FDM

# mathematical challenges

1. Large domains, costal resolution down to meters ⇒ millions and millions of grid points
   Parallel, local refinement, coupling of models
2. Many details (breaking, friction, interaction with structures) reuire full models – impossible
   Must be incorporated in approximate models
3. Inunduation on land ⇒ moving computational boundaries
4. Sources are difficult
5. High effiency desirable; Use in tsunami warning leaves only minutes for computation
6. Increased complexity, real applications ⇒ new problems concerning instability and performance arise

# List of Topics

# Tsunamien blant andre bølger

## Sammenlikning ($h$=havdyp, $T$=periode)

| type | hastighet | mekanisme |
|---|---|---|
| lys/radio... | 300000 km/s | elektromagnetisme |
| lyd(luft) | 340m/s=1200km/t | trykk/kompresjon |
| lyd(vann) | 1500m/s | trykk/kompresjon |
| seismiske | 2-7000m/s | Spenning/deform. |
| tsunami ($h = 5000\,\mathrm{m}$) | 220m/s=800 km/t | Fri overflate/tyngde |
| dønning ($T = 20\,\mathrm{s}$) | 31 m/s=110 km/t | Fri overflate/tyngde |

Media: tsunamier er ufattelig raske bølger
Bølger er raske, tyngdebølger, som tsunamier, er blant de treigere
$\Rightarrow$ viktig for varsling.

# Tsunami blant havbølger

| | Høyde maks. (m) | Bølge-lengde | Periode |
|---|---|---|---|
| Vindsjø | 25 | 0.1-500 m | 0.1-20 s |
| Dønning | 8 | 0.1- 1 km | 13-30 s |
| Flodbølger | 30/500[1] | 1-100 km | 1-30 min |
| Stormflo | 5 | 50-200 mil | 6-12 timer |
| Tidevann | 15 | 100-1000 mil | 12-24 timer |

Bølge lang i forhold til dyp: (nesten) uniform bevegelse til bunnen, fart avhenger av dyp

Bølge kort i forhold til dyp: mest bevegelse nær overflaten, fart avhenger av bølgelengde

[1]: maks oppskylling av jordskjelv/skred tsunami

# Tsunami i variabelt dyp

Enkle betraktninger av perioder og energi ⇒

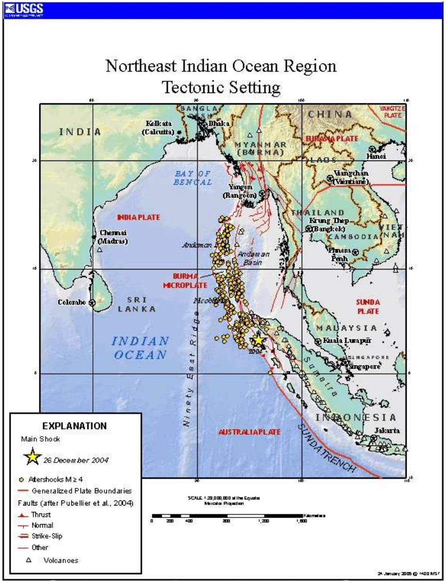
| dyp | høyde | lengde | bølgehast | strøm |
|---|---|---|---|---|
| 4000m | 1.0m | 100km | 713km/t | 0.18km/t |
| 1000m | 1.4m | 50km | 356km/t | 0.5km/t |
| 250m | 2.0m | 25km | 180km/t | 1.4km/t |
| 100m | 2.5m | 16km | 113km/t | 2.8km/t |
| 50m | 3.0m | 11km | 80km/t | 4.8km/t |
| 20m | 3.8m | 7km | 50km/t | 9.4km/t |
| 10m | 4.4m | 5km | 36km/t | 26.8km/t |

## Tsunami kontra dønning

Dersom lik amplitude i dyphav: samme energitetthet
Tsunami: større energitransport, starter vekst på dypere vann
Bryting ved strand: dønningen (kort) spises opp, tsunami (lang) er mindre påvirket
Tsunami skyller mye lengre inn

# List of Topics

# The 2004 earthquake (fra USGS)




Magnitude:
9.0-9.3

# Marine earthquakes

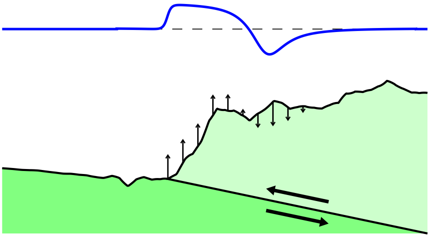
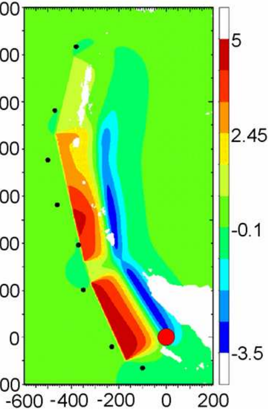


Illustration based on the Dec. 26'th 2004 event

- Seaquake: compression waves in water; do not penetrate shallow waters
- Lasting vertical uplift of sea bed ⇒ tsunamis
- Generally: Earthquake fast; gravity waves slow ⇒ tsunamis can be modelled from initial sea surface elevation at rest

# Computation of sea-bed uplift



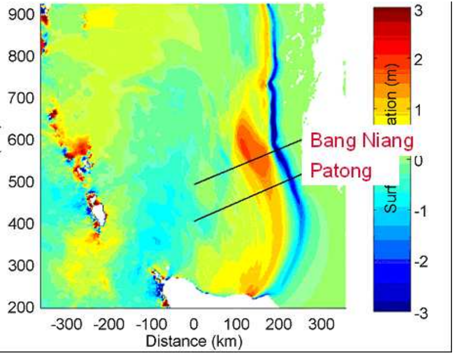

## Okadas formula

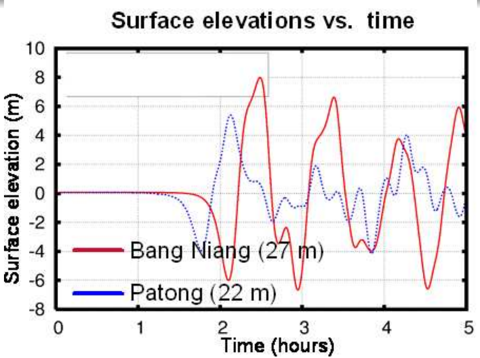
Uplift $\sim$ m, depth $\sim$ km $\Rightarrow$ tsunami generation is a linear process.

Okadas formula: Green function for crust surface deformation from straight fault between semi-infinite elastic plates.
Input: fault length, depth, slip, strike and dip components etc.

In true applications sub-faults may be combined. Example to the left: representation of the 26th December event (NORSAR/NGI/ICG)

# 2004 simulation




- Wide source $\Rightarrow$ shallow water theory
- Against Thailand: leading depression (other direction leading elevation)
- Source length $\gg$ source width $\Rightarrow$ strong directionality

# Animations

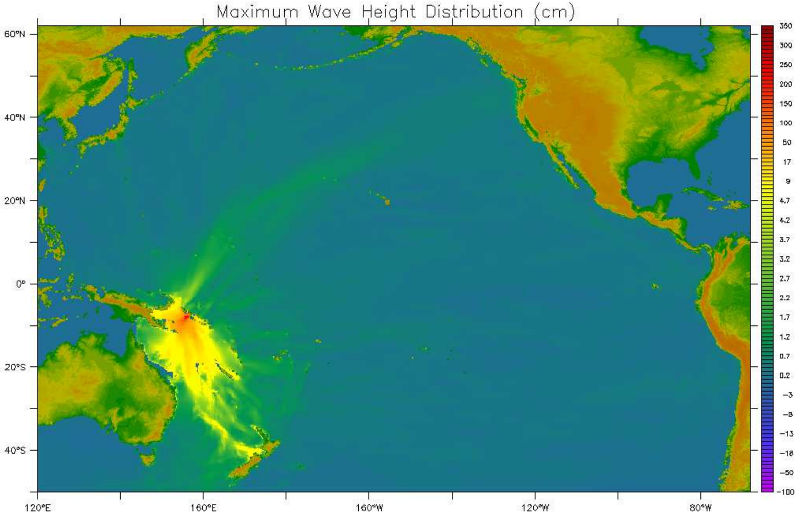
- 2D animation of tsunami from a an earthquake with large dip angle ( $50^\circ$ as compared to $12 - 14^\circ$ for the 2004 event)
- Japanese animation of simulation of the 1960 Chile tsunami Magnitude 9.5 makes this the strongest earthquake recorded

# Other examples

- 17th July, 1998, Papua New Guinea
  $M = 7.0$: weak earthquake, slide is to blame, 2.600 fatalities
- 27th March, 2005, Sumatra
  $M = 8.7$: strong!, local 4 m max. runup, no fatalities ?
- 17th July, 2006, South Java
  $M = 7.8$: slow earthquake, 20 m max. runup, 700 fatalities
- 13th Januray, 2007, Kuril Islands
  $M = 8.1$: Small waveheights
- 1th April, 2007, Solomon Islands
  $M = 8.1$: 52 fatalities

No strict relation magnitude $\Rightarrow$ tsunami
Warning cannot be based on seismic information alone.

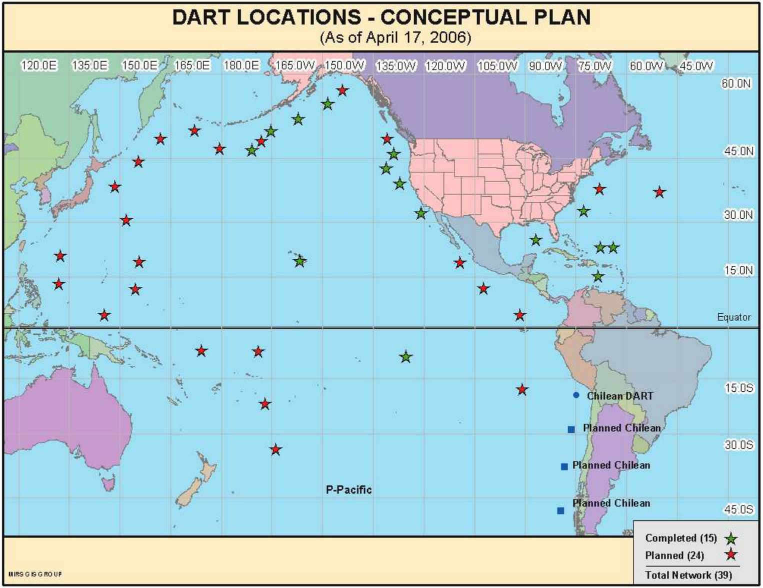
# Solomon Islands, Max. amplitude (NOAA)



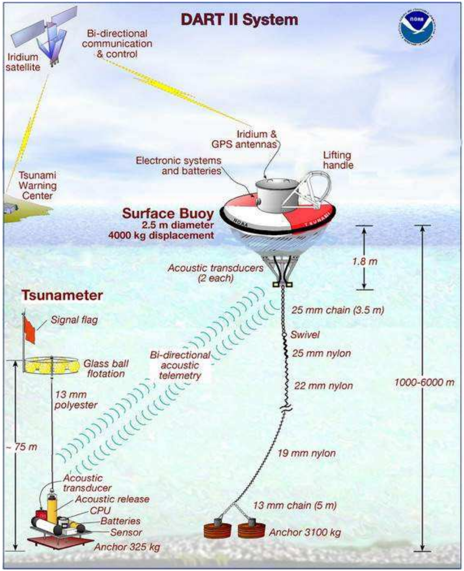
# Java 2006, photo: C. Harbitz ICG/NGI

# Java 2006 (C. Harbitz)

# Warning system, (source NOAA/PMEL)



# Dart buoys, (source NOAA/PMEL)

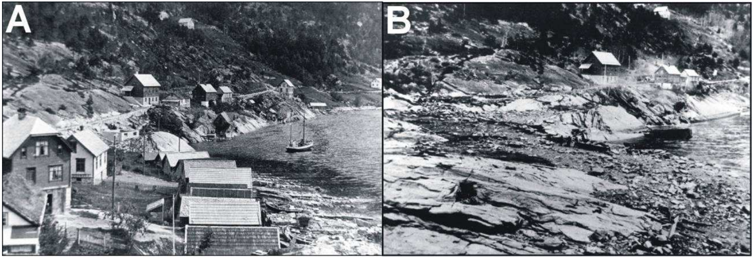



# List of Topics

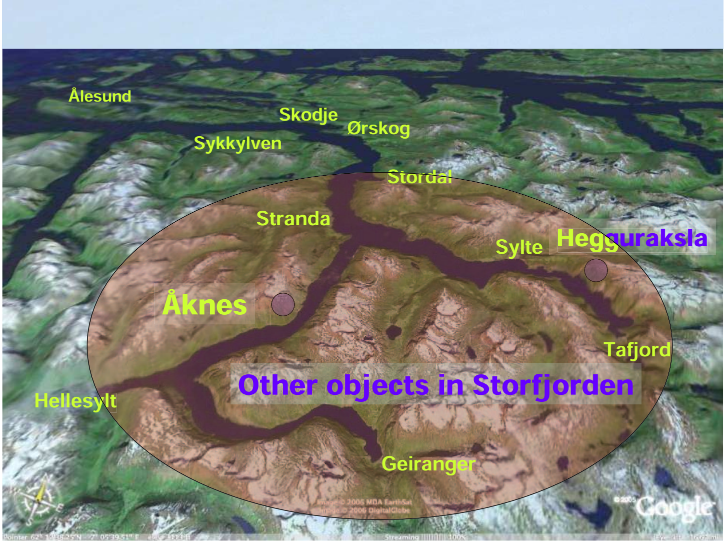
# Tsunamis from rock-slides

Local events, but with very high wave amplitudes.
Occur in mountain basins and fjords

Example: village damaged by event in 1934, Tafjord, Norway



# Monitored cite; Åkneset (L. Blikra)



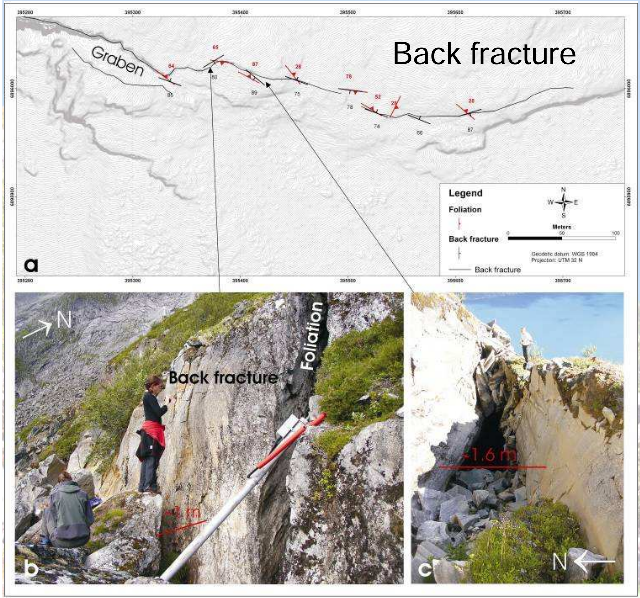
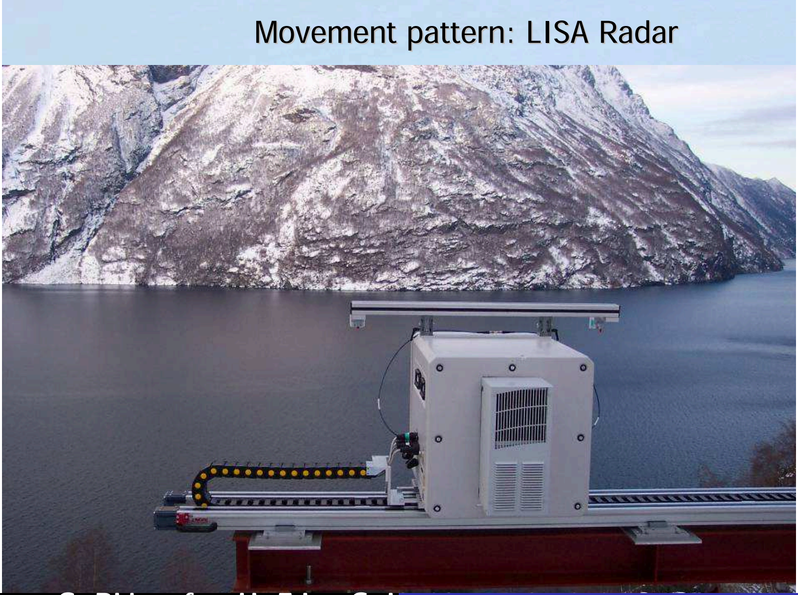
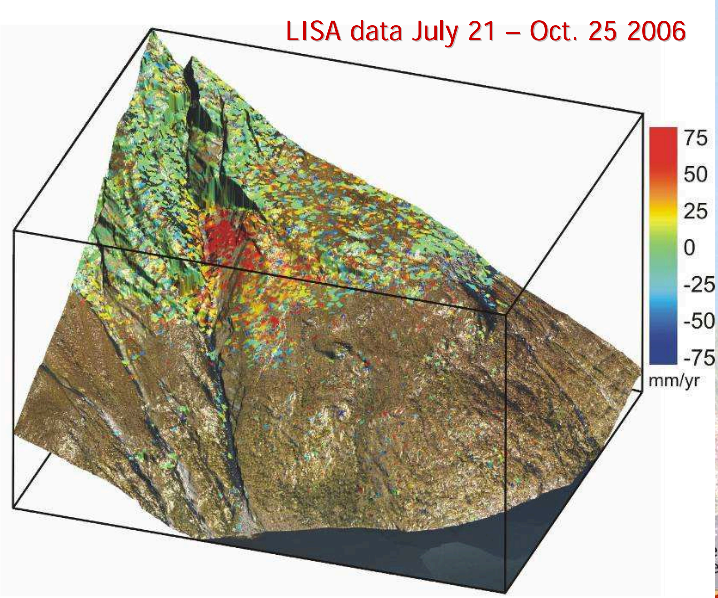


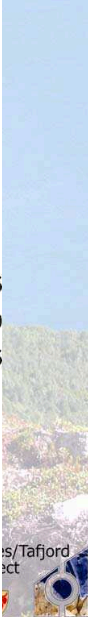

Figure:
Guri Venvik
Ganerød, NGU

Åknes/Tafjord
project

# Radar across the fjord (Blikra)

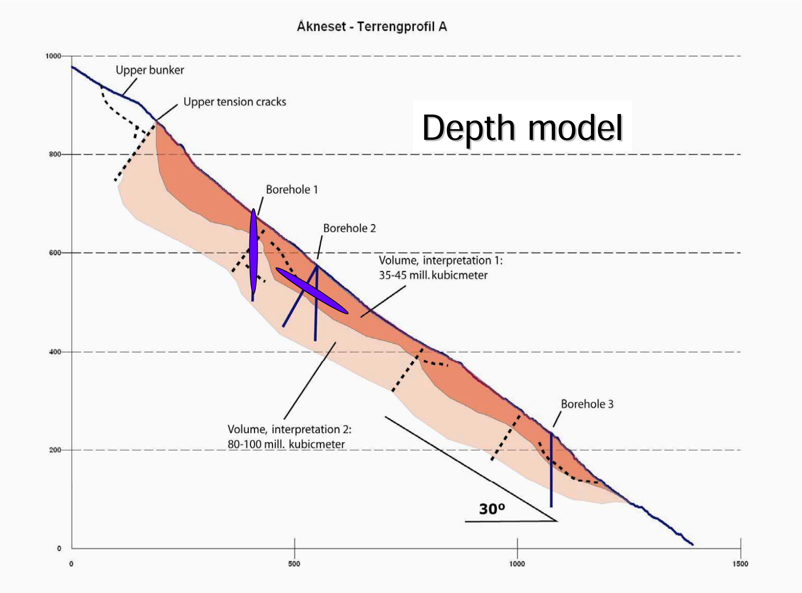



LISA data July 21 – Oct. 25 2006
75
50
25
0
-25
-50
-75
mm/yr


s/Tafjord
ct

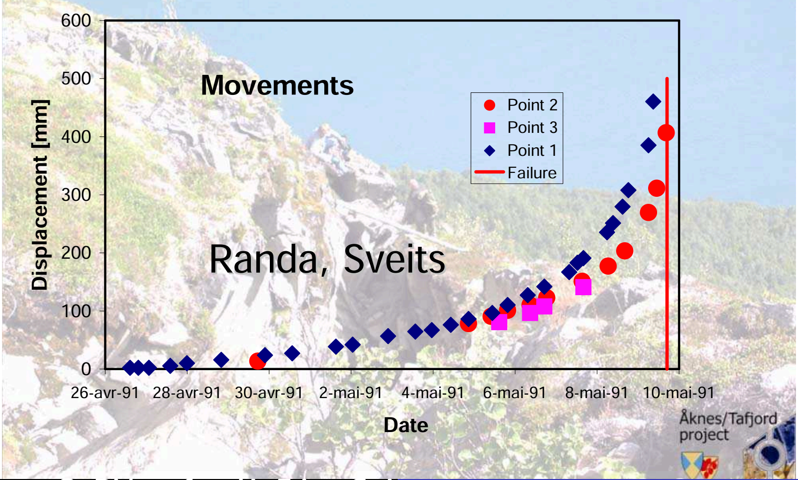
# Core samples with breccia (Blikra)

# (Blikra)

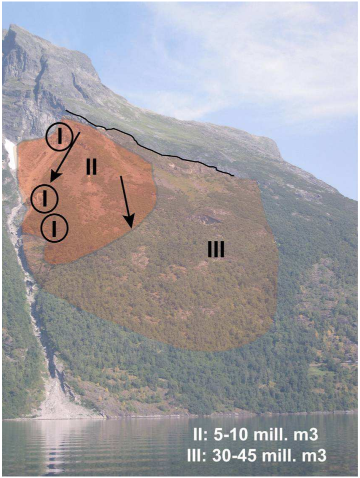

Åkneset - Terrengprofil A
Depth model
Upper bunker
Upper tension cracks
Borehole 1
Borehole 2
Borehole 3
Volume, interpretation 1:
35-45 mill. kubicmeter
Volume, interpretation 2:
80-100 mill. kubicmeter
30°
1000
800
600
400
200
0
0
500
1000
1500

# Release of slide in Randa (Jogerud/Blikra)

The early-warning is based on the fact that large rockslides gives many pre-failure signals



# Scenarios

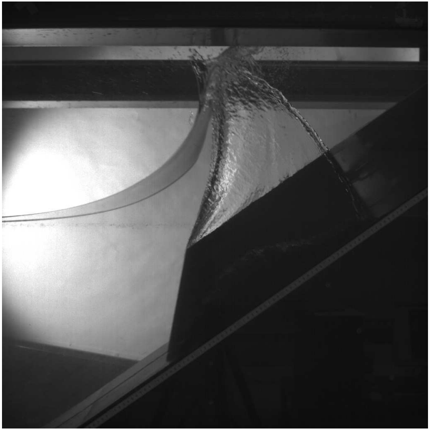



- I: Small failures at margin
- II: 5-25 $Mm^3$
- III: 30-80 $Mm^3$

II and III $\Rightarrow$ disaster

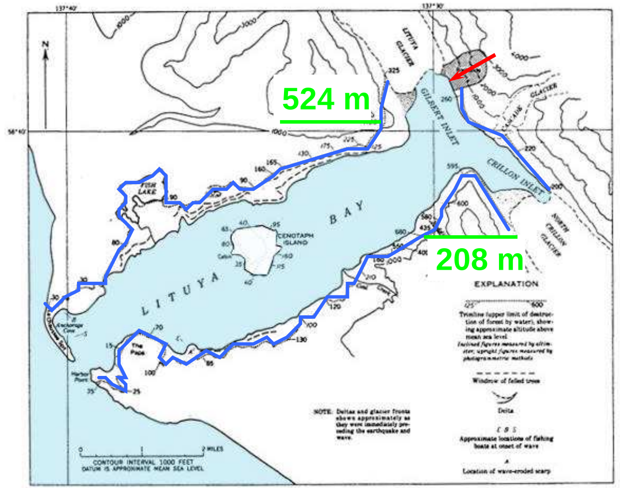
Tafjord 1934: 1.5–3 $Mm^3$, 41 perished

# The Åkersneset project



-Ongoing
-Geological surveillance
-2D exp. Dep. Math. UiO
-3D exp. at SINTEF
-Modeling, analysis

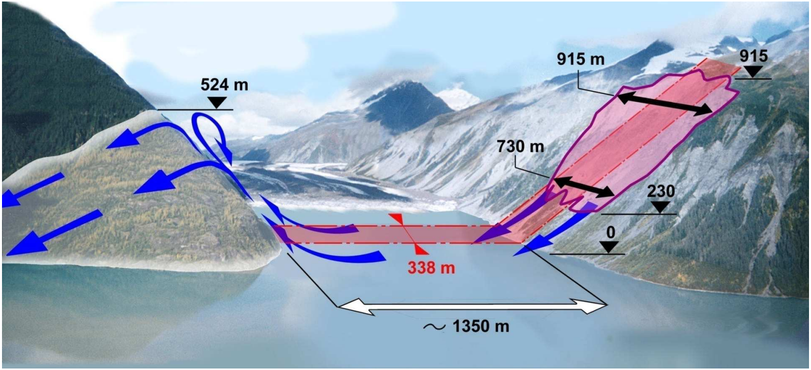
# Lituya Bay, Alaska 1958; From H. Fritz




Georgia Tech Savannah Campus

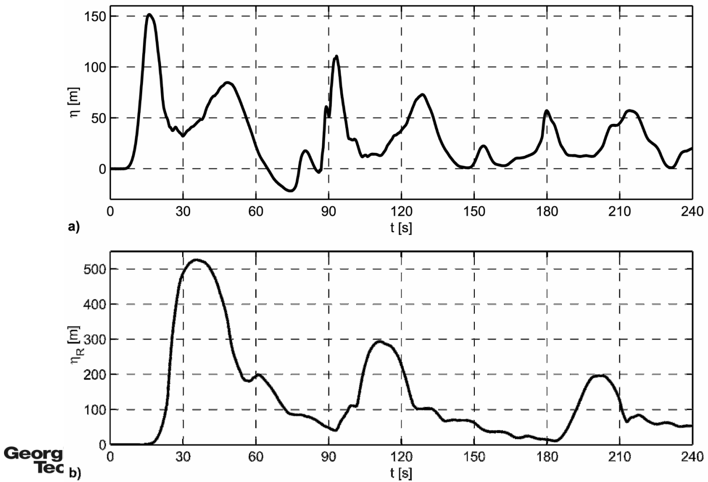
# From H. Fritz

## Lituya Bay
## impact and run-up site



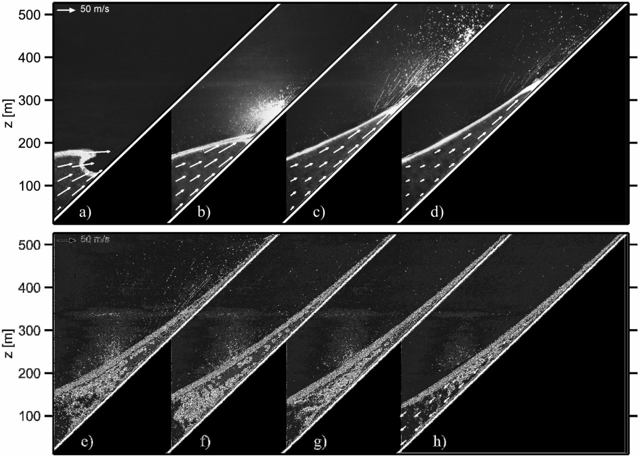
# Omregnet til fullskala (H. Fritz)

## Wave and Run-up Gauge Records



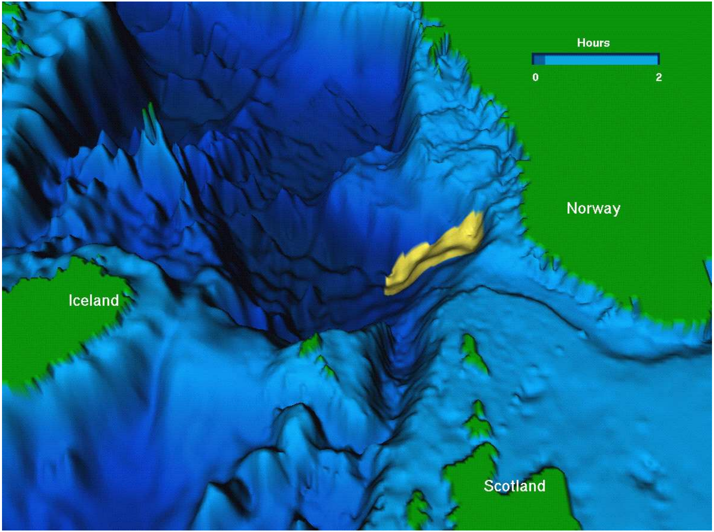
# From H. Fritz

## 530m Tsunami Wave Run-up

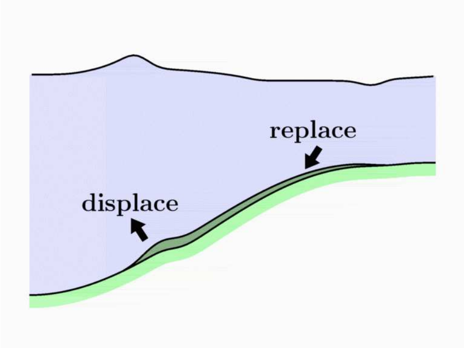



Georgia Tech Savannah Campus

# The Storegga slide



# Tsunamis from slide at continental margin



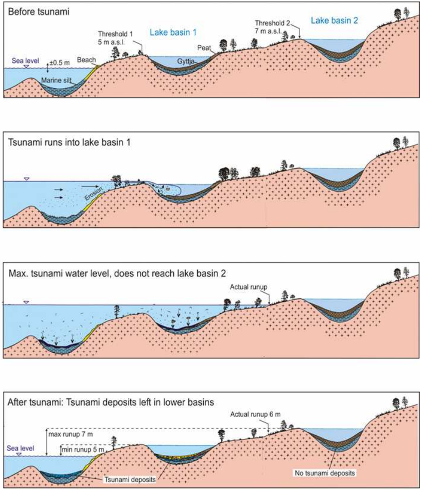

**Simplest case: dense, progressive slide**

Source at front sink in the rear of the slide body
Leading drawdown at adjacent coast
Important: Froude number = (speed of slide)/(local wave speed)

# Storegga tsunami

Numerical simulation. LSW
Volume$=2 \cdot 10^{12}\,\mathrm{m}^3$

# Geological evidence of tsunami



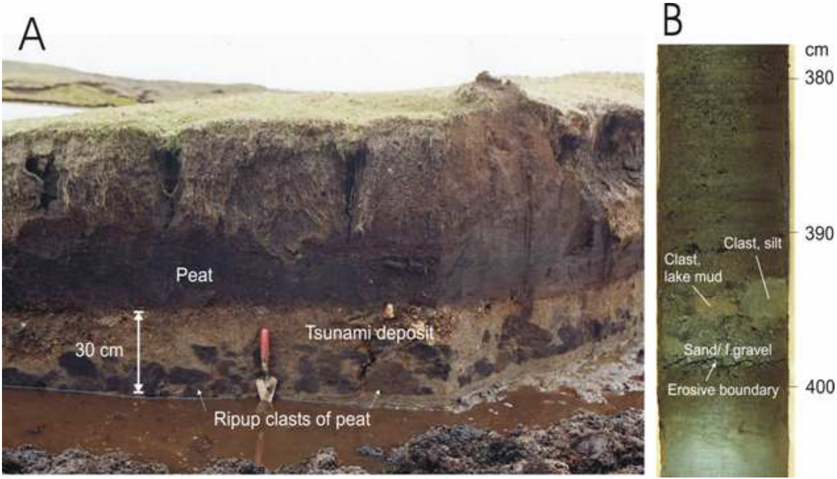

Land uplift ⇒ ponds detached from fjords

Tsunami intrusion easily detected in sweet-water sediments

Altitude of basins with tsunami traces ⇒ run-up height

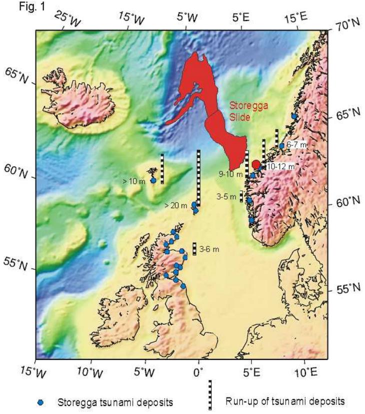
From S. Bondevik

# Tsunami deposits



# LSW model versus core samples.

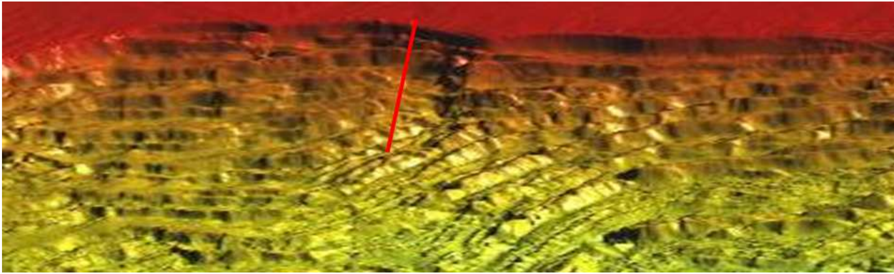
Fig. 1




| cite | obs. | mod. |
|---|---|---|
| Gurskøy | 9–13 | 17 |
| Ålesund | 10–12 | 13.5 |
| Bjugn | 6–8 | 7 |
| Scotland | 3–6 | 4 |

Bondevik et al. (2004)

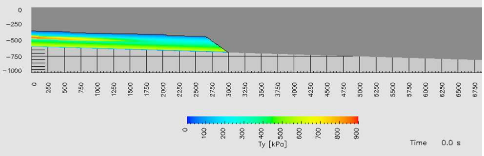
# The real Storegga slide

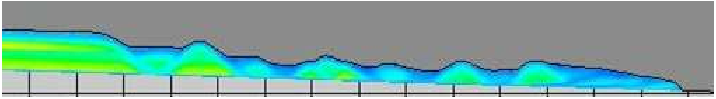


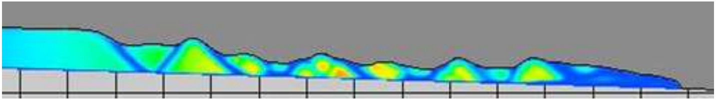
Model by Gauer et al.

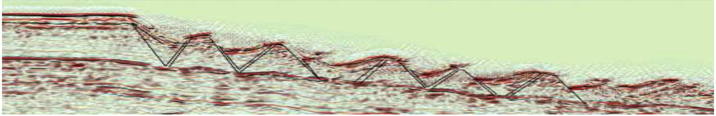
- Two phase model; water and slide body
- Rheology in slide: Bingham fluid with a history dependent yield strength
- Slide released due to initial supercritical stress. Real slide probably destabilized by earthquake

# Retrogressive slide

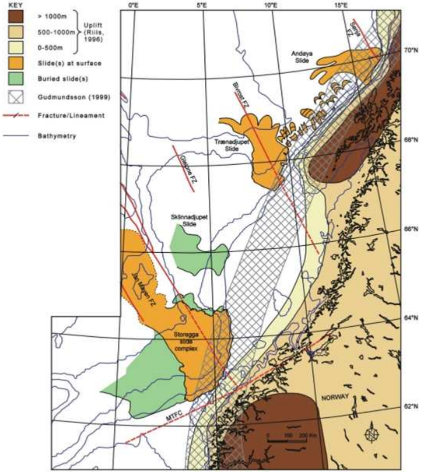






# Identified slides




Orange: surface slides

Green : buried slides (earlier glaciations)

Griding: high crustal stress due to land lift

Potential slides: North Sea Fan

(After Bugge)

# The LaPalma case

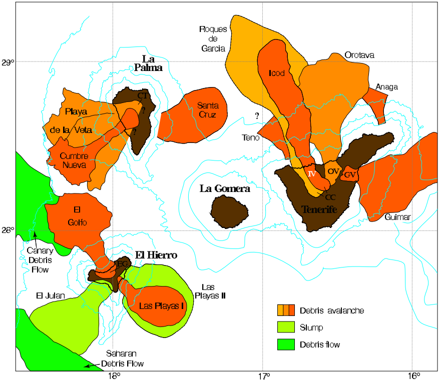
## Potential mega-tsunami

- Large public interest and mass media attention
- Low probability event, but with potentially large consequences

## La Cumbra Vieja volcano, La Palma island

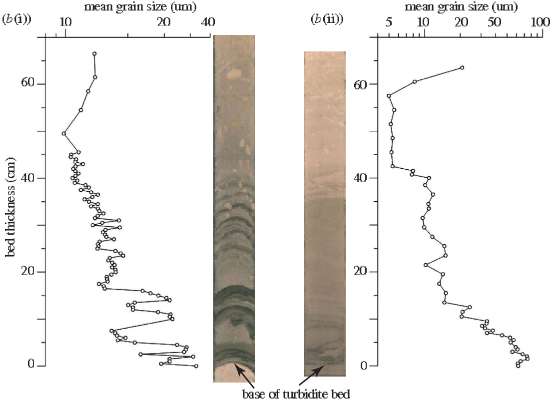
- Alarming investigation by Ward and Day (2001)
  - Surface elevations up to 30 $\mathrm{m}$ along the coast of America
  - Geological basis questioned by others (Wynn and Masson, 2003; Masson et al., 2006)
- Other authors report order of magnitude smaller waves (Mader, 2001; Gisler et al., 2006)

# Canary Island landslides (from Masson et al. 2006)




- Many landslides, occurrence cycle ∼ 100 000 years
- Geological evidence of multistage development

# Core sediment samples (from Masson et al. 2006)

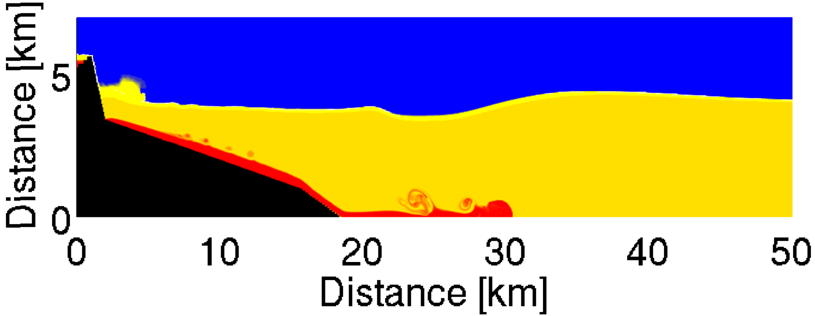



- Canaries (left), and Saharan landslides (right)
- Stack sequence of fining-upwards beds at the Canary Islands
- Debris avalanches, multi-stage development over hours or days

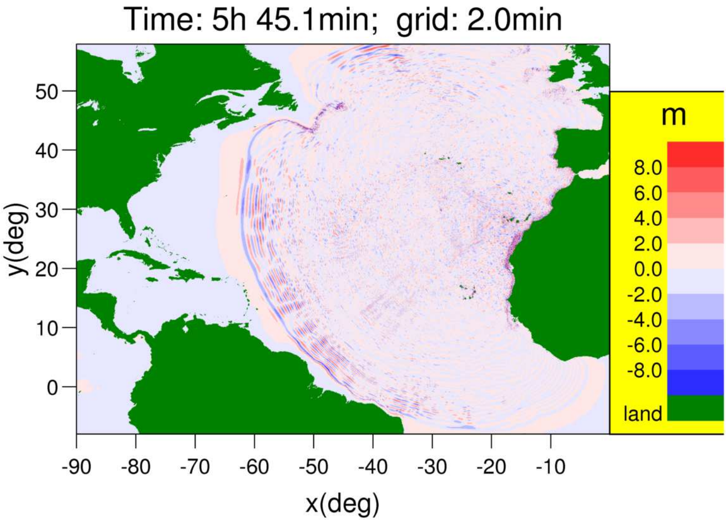
# Wave generation

## SAGE multi-material simulation

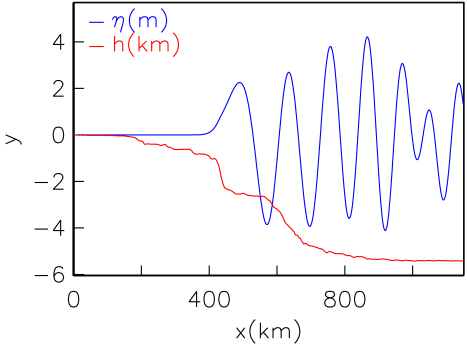
- Slide volume of 375 $\mathrm{km}^3$, modified from Ward and Day (2001)
- $u_{max,slide} \approx 150\,\mathrm{m/s}$, almost critical slide motion
- Debris flow combined with turbidity currents



# Atlantic propagation



# Example; E-W transect at 32° N (Georgia/South Carolina)




## Series of incident waves

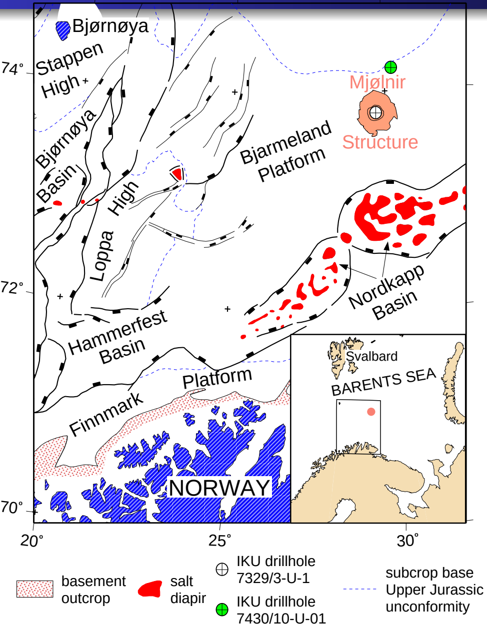
- Heights of several meters outside continental shelf
- Leading crest not largest (typical feature in present case)
- Typical lengths $\sim 100\,\mathrm{km}$ and more
- **Reminiscent of waves from series of strong earthquakes**

# List of Topics

# Marine impacts

- 170 known impact craters, 34 are marine
- Most recent: 1 km impactor, Bellinghausen Sea (off southern Chile), 5000 m depth,1.8 mill. yeras ago
  Chemical and ejecta evident, but no crater. Simulations points to local amplitudes up to 1 km (Shuvalov; Gisler et al.)
- Most famous: The Chicxulub impact (Yacatan), 65 mill. yeas ago.
  Marks the K/T boundary and held responsible for mass extinction of species
- Studied at UiO/SIMULA/ICG: the Mjølnir impact

# Jurassic tsunami

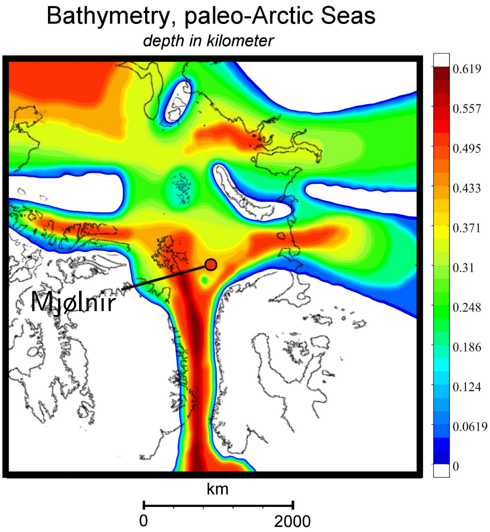



## LOCATION

The Mjølnir structure was first detected in seismic survey. (Gudlaugsson 1993)

Age: 142 million years. (Dated by fossils in sediment layers)

# Paleo Barents Sea (142Myears ago)




Reconstructed bathymetry

Gentle gradients.

Depths $h < 600\,\mathrm{m}$.

Desirable resolution:

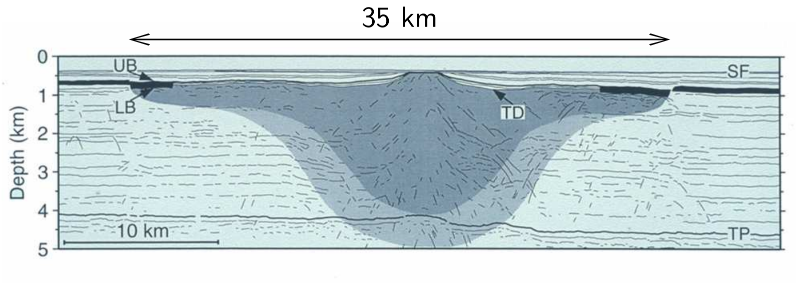
$\Delta x \sim 200\,\mathrm{m}$,

Domain size:

$2000 \times 2000\,\mathrm{km}^2$

$\Rightarrow$ 100 Mpoints.

# The Mjølnir structure




Interpretations:

Thin lines: constant seismic velocity.

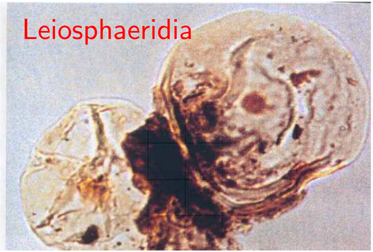
Shades: re-configured by impact.

Assumed characteristics:

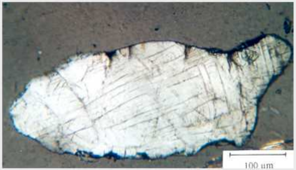
Water depth: 400 m (time of impact).

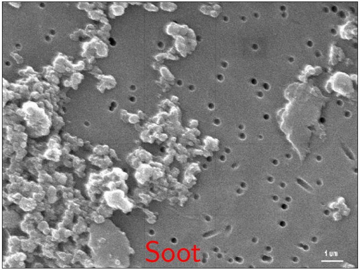
Diameter of asteroid: 1.6 km.

# Core samples




Shocked quartz



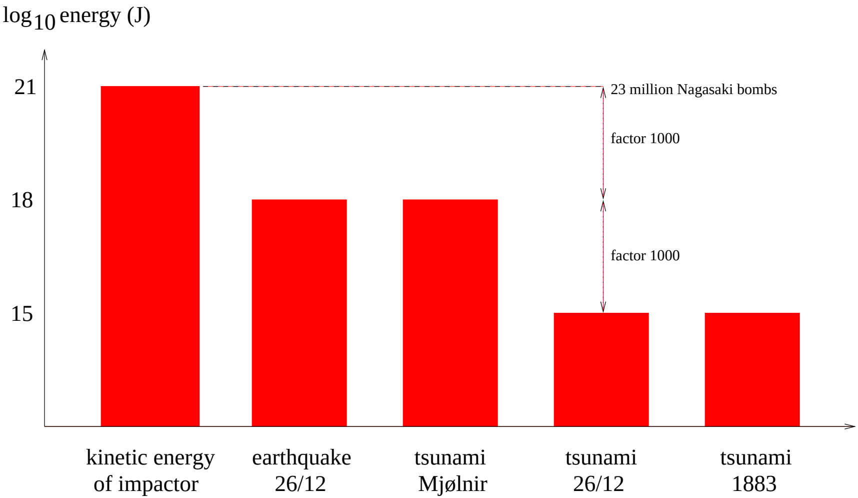

Also found

Breccia.

Iridium anomaly.

Enrichment in sulphides and Ni, V, Cr above iridium layer.

# Energy in impact



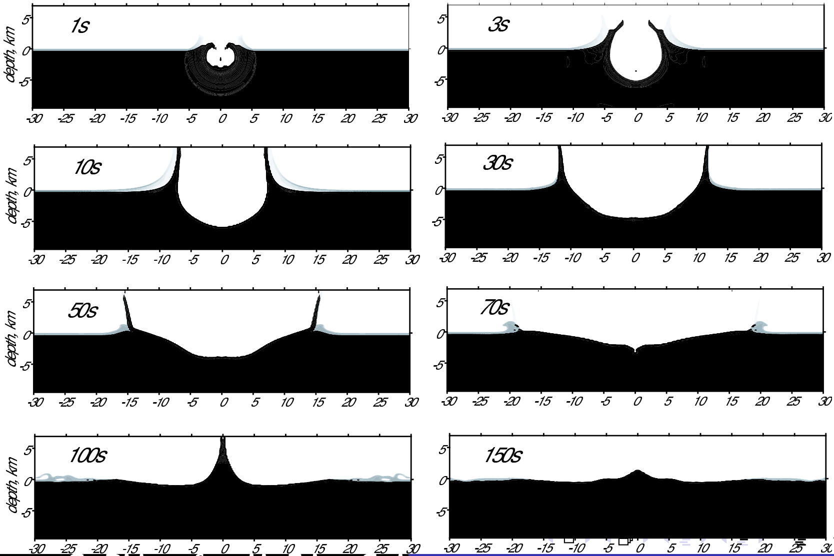

## Asteroid

Radius: 800m, density: 3kg/ℓ, speed: 25km/s

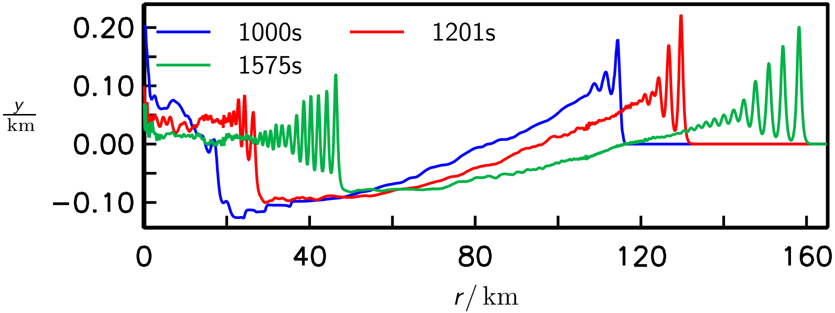
# Models

- Impact: Multi-material code
  - Crust with Bingham model
  - Ocean, atmosphere and ejecta included
  - Run in 3D version for initial stages of impact
  - With radial symmetry: longer time, larger horizontal extent; still very coarse grids
- Tsunami propagation
  - Nonlinear dispersive long wave equations (Boussinesq)
  - Full potential theory
  - Ray theory for solitary waves

# Impact simulation



# Boussinesq solution ($t > 1000\,\mathrm{s}$)




- Two undular bores (front wave and resurge), fission into solitary waves
- Amplitude growth followed by decrease (radial spread).
- Second bore close to breaking.
- Wave heights $\sim$ 200 m, fluid velocities $\sim$ 100 km/h
- Full potential models indicate 10% errors in Boussinesq solutions.

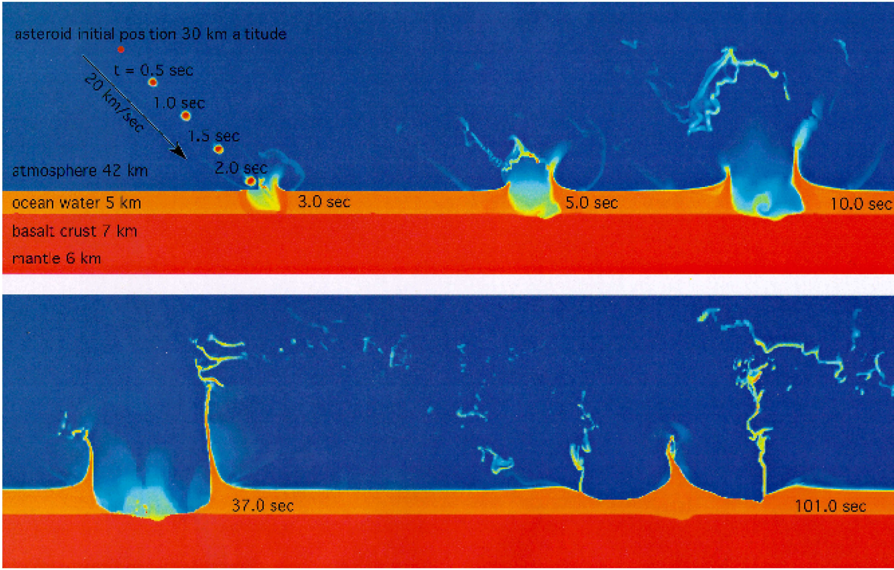
# Environmental consequences

Regional consequences of distrubution of vapor and dust in the atmosphere.

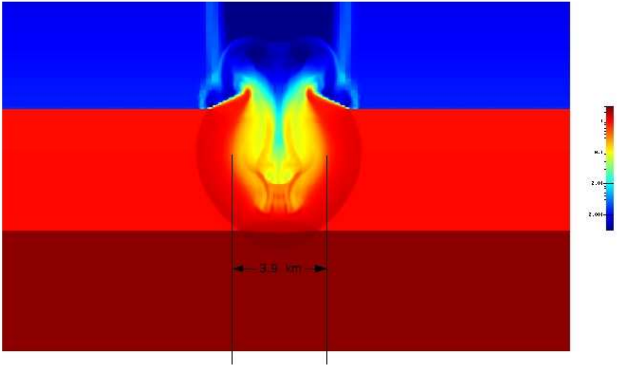
Run-up is not analyzed – must have been monstrous.

The tsunami caused series of current pulses; 30–70 km/h.
Sea floor was a thick succession of unconsolidated, organic rich clays.
Release of nutrients and toxins ⇒ changes in marine environment (bloom of Leiosphaeridia).

# An oblique deep water impact



# Normal impact, dunite (1 km, 20 km/s), at 0.57 s, in depth 5km




Asteroid has been completely decelerated and destroyed.
Density less than 1.0 is water vapor
The vaporization is due to shock wave and subsequent rarefaction