British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Gateway to the Earth

Overview of field work and issues

(The geology of submarine landslide tsunami)

Dave Tappin

Tsunamigenic landslide model benchmarking and validation workshop
Galveston, Texas (USA), Jan. 9-11, 2017

Why am I here?

From Stephan (and Jim)

“More input from geologists about how we should be thinking about slides, structurally. It would be nice to have a presentation on that (different mechanisms, effect of rheology, triggering, etc...), and on characterizing events based on before and after surveys, etc. So, if you accept the invitation, we of course would not ask you to do any modelling, but we'd like you to make a presentation on your experience and interaction with modellers”.

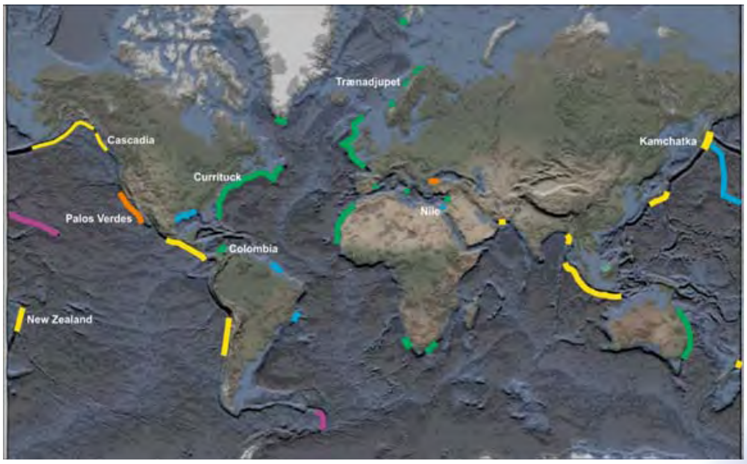
Fine with me – I was worried about producing a benchmark model!

Thoughts on SMF tsunamis

- Submarine landslide mechanisms from geology,
- Validation of numerical models from observations and sediments,
- How do theoretical models relate to ‘real life’ landslides,
- How to validate the theoretical models (computer time),
- In the context of mitigation how reliable are theoretical models - are they realistic and validated?
- Thus how reliable are the hazard (evacuation) maps produced from them?
- In the instance of the USA the only recorded historical tsunamis are in the northwest, yet a hazard to the USEC,
- How relevant are numerical simulations for the east coast?

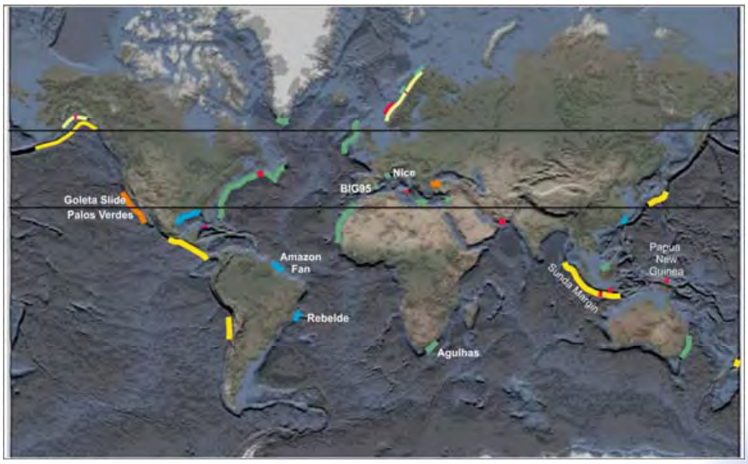
So I’ll try to address these issues from the geological perspective

Global submarine landslides



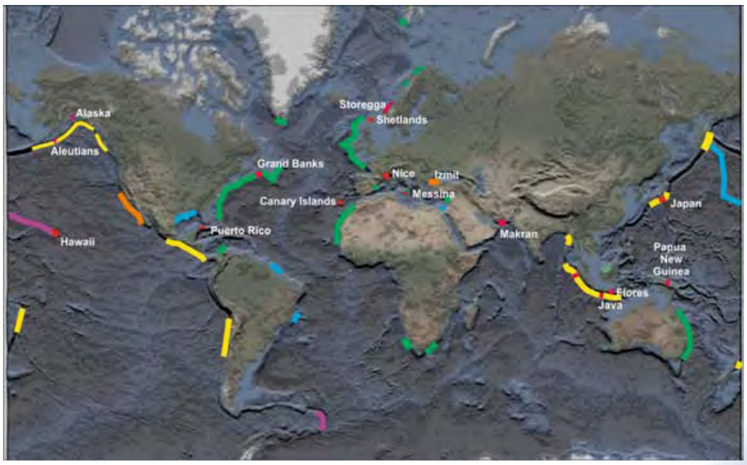
Mapped margins

Landslide Territories



Continental shelves
Convergent margins
River systems
Strike slip margins
Fjord margins
SMF tsunamis

Global submarine landslides



Although a number of events, only three or four well studied in the context of tsunamis

Well studied?

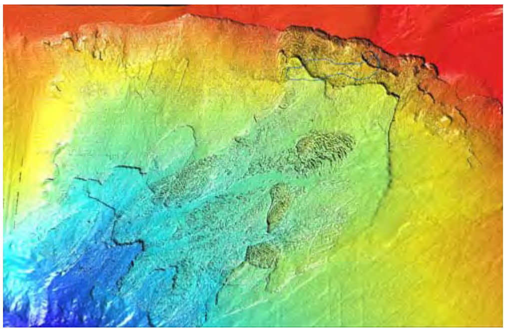
- Good geological landslide model based on hydroacoustics (multibeam, seismics etc), sampling (coring, seabed samples) and seabed imaging (still, video),
- Numerical simulations based on the geological model, and
- Validated by observations (historical events) and or sediments laid down as the tsunami floods the land.

- In my opinion there are still only a few well studied events (: Storegga, PNG, Alaska, maybe Japan (but probably not yet),
- These events (fortuitously?) cover both the main landslide environments – Passive and convergent margins,
- Volcanic collapse research is still uncertain – there are validated models for both Hawaii and Canary Islands, but not to the same standard as PNG and Storegga (in my view).

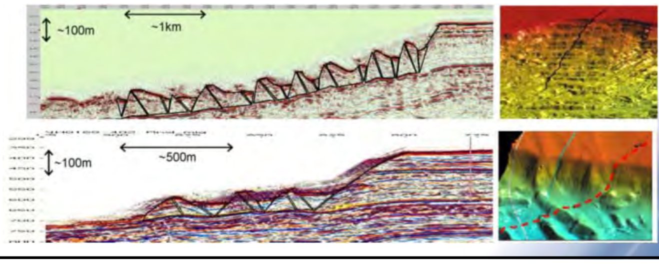
Storegga

- Still THE best studied submarine landslide tsunami,
- All sorts of the reasons – obviously Ormen Lange,
- But – when Carl Harbitz published his 1992 seminal paper this was but a dream (I think!),
- Motivation visionary;
  - Recently recognised sediments in Scotland,
  - The landslide (Bugge et al.),
  - But also the mechanism!
- Massive investigation – Ormen Lange – probably never to be repeated (but who knows what financial motives lie in wait?),
- Retrogressive (bottom up) landslide,

Storegga Hydroacoustics



Disaggregation during flow changes (weakens) slide properties – explains the turbidite and mud pond?



Storegga

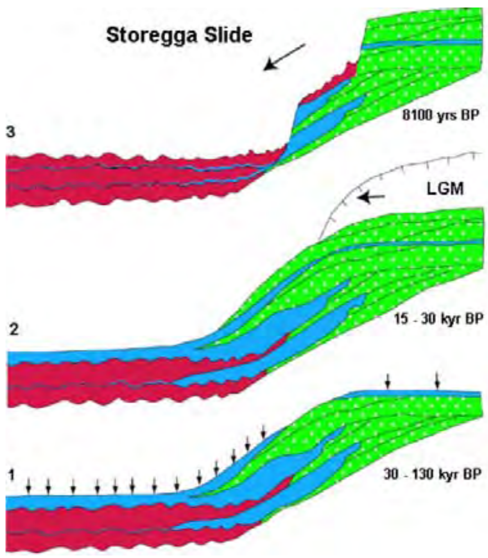


Illustration of the cyclic deposition and slide processes in the Ormen Lange area.

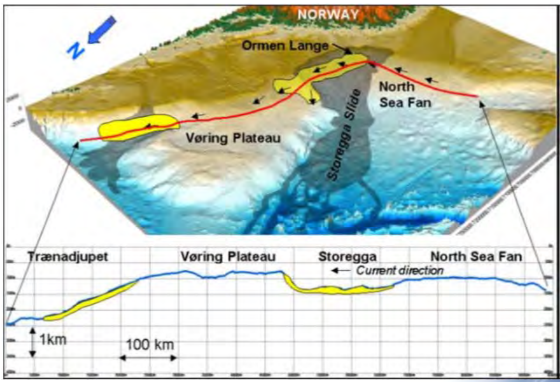
Green, glacial sediments; red, slide deposits; blue, marine sediments.

1. Last interglacial with deposition of soft marine clays.
2. Last glacial maximum (LGM) with the ice at the shelf edge and deposition of glacial sediments.
3. The Storegga Slide.

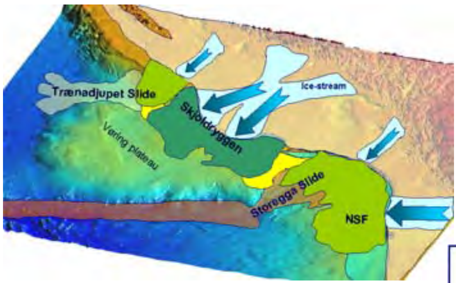
The figure shows two older slide scars that are filled with marine clays.

Storegga controls

- Glacial/interglacial sedimentation,
- Coarse polymict sediments during glacial periods,
- Deposition of soft marine clays (yellow) during interglacials which form weak layers,
- During deglaciation earthquakes triger failures

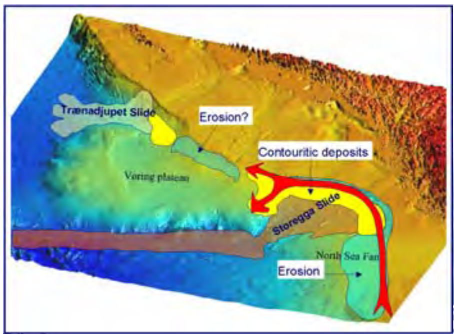


Storegga - sedimentation

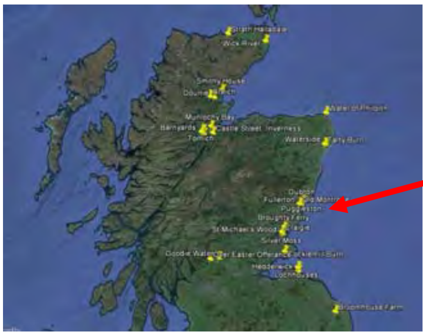


1. The main depocenters of glacial clays (green) seen in relation to past ice stream locations. Yellow fields mark contouritic drift (2.) deposits overlain by the glacial fan deposits. (NSF=North Sea Fan).

2. Location of the main contouritic drifts (yellow), controlled by the seabed topography, current direction and the position of the thermocline. Sediment supply to the Storegga area is from erosion of the North Sea Fan and areas further south.

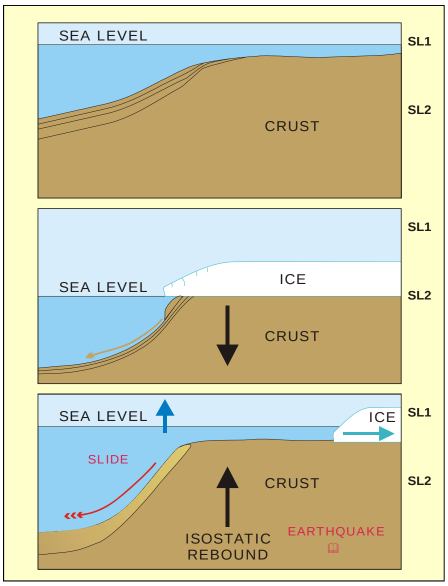


Validation – tsunami sands



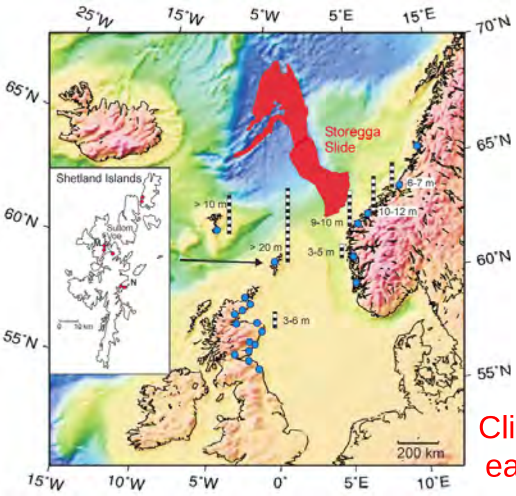
Maryton Scotland

Dawson et al., 1988



Geological Model of glacial isostacy and the causes of slides

Storegga Slide tsunami – 8,200BP

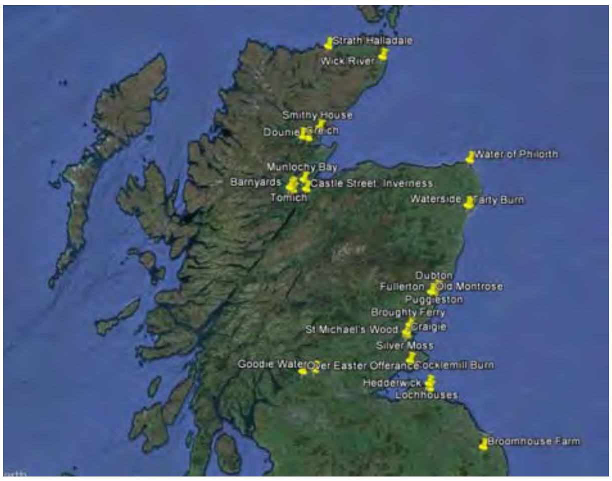


Tsunami heights of +20 metres on Scottish coast

Climate control, sedimentation, earthquake triggering and sea level change

(*Bondevik et al, 2004*)

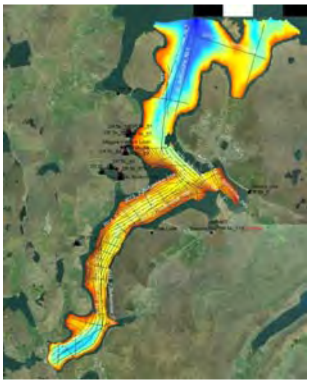
Tsunami sediments - Scotland



Most are 8,200 years old from Storegga, but on Shetland some are much younger at 5,000 and 1,200 years

Yell - Storegga 8,200BP

Shetlands



Sullom Voe mapped

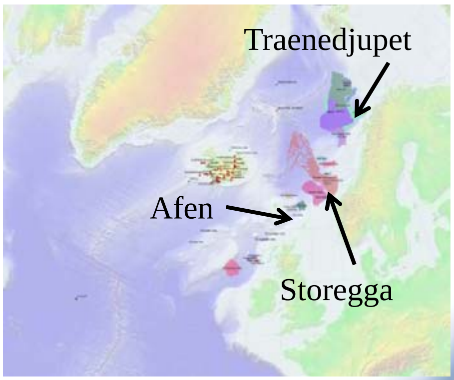
Need more bathymetry to find Landslides

Evidence of Storegga but tsunami sands at 5,000 (Garth Loch) and 1,500 BP (Basta Voe), with no obvious origin

10-15m above sea level

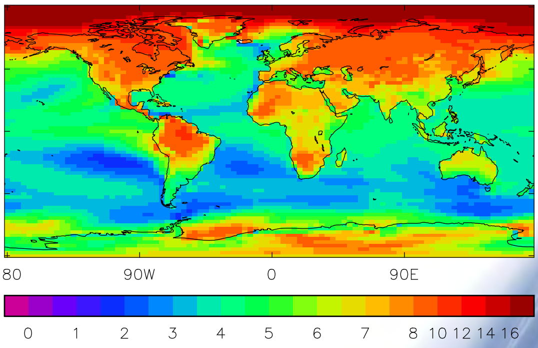
Younger tsunami sands - origin?

- Numerous submarine landslides off of Norway and northwest Britain,
- Storegga - 8,200 BP,
- Traenedjupet, 2,500 and 16,000BP,
- No evidence in Norway for a tsunami
- Young landslides found in Sullom Voe, Eriboll and west coast – local hazard?
- Also Afen – 2,880BP



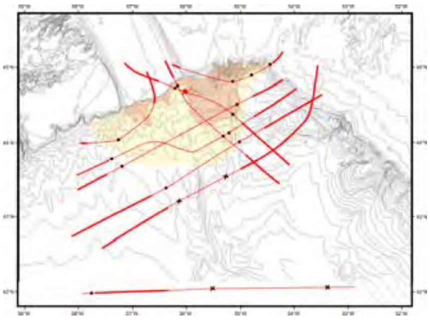
An emerging picture of young offshore landslides – tsunamigenic? The 100,000 year Storegga model challenged

The future? Global warming impact on seabed slope stability in high latitudes

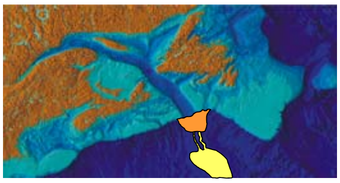


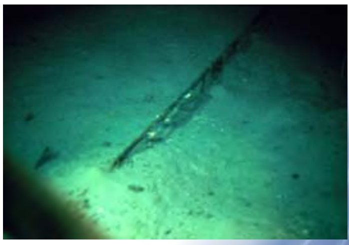
Temperature change (°C) by 2090s compared to 1990s:

Other relevant passive margin landslide tsunamis



- Grand Banks – 1929,
- Again seminal, submarine cable breaks,
- Tsunami sediments,
- But the tsunami is not well studied,
- Most research on the landslide (Piper, Mosher et al.),
- Only one (2D) numerical model,





Papua New Guinea Tsunami – 1998

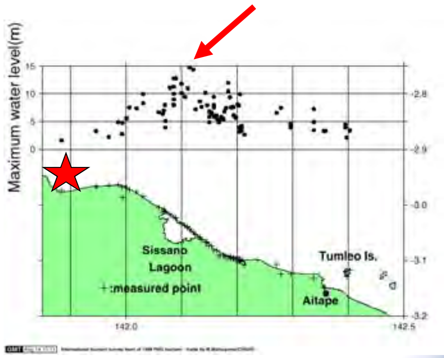
Tsunami wave 15m high

2,200 died

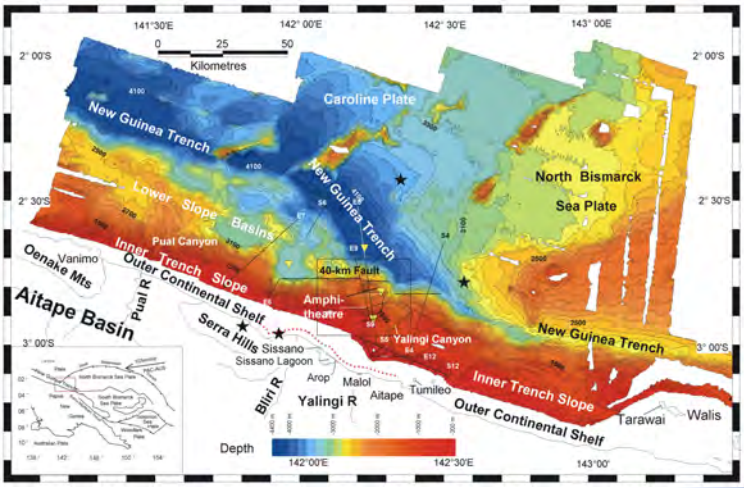
Recognition that seabed slumping was very dangerous

Several observations indicated an unusual tsunami source:

- An earthquake of magnitude 7.1 could not generate a 10 - 15 metre tsunami – especially a shallow dipping thrust mechanism
- The peaked run up was not characteristic of an earthquake source
- The EQ epicentre was west of the peaked runup
- The 20 minute delay between the EQ and the tsunami

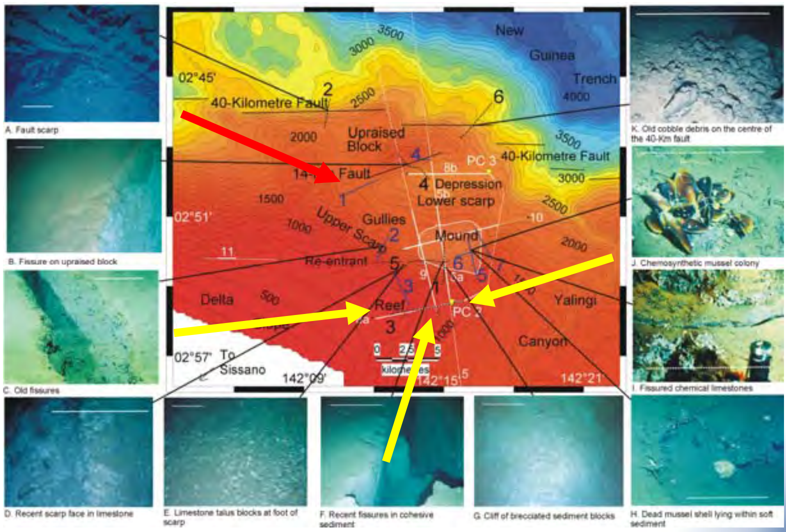


Multibeam Bathymetry –offshore PNG



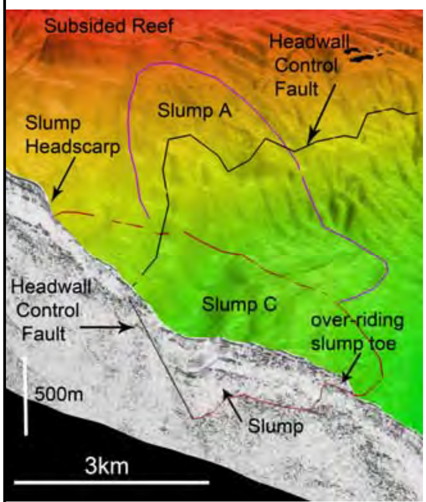
19,000 square kms were mapped – in 14 days 2-D

Seabed Observations - ROV and Manned Submersible

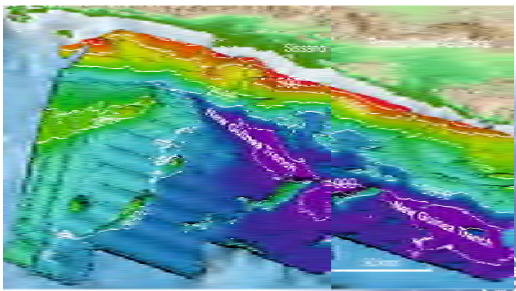


Shows mound area to be seabed slump tsunami source

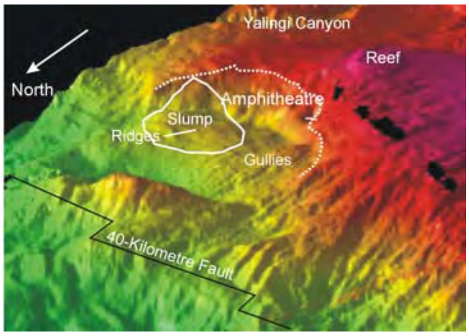
Papua New Guinea imaging

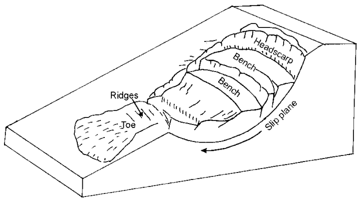


2D to 3D and model built from seismic data



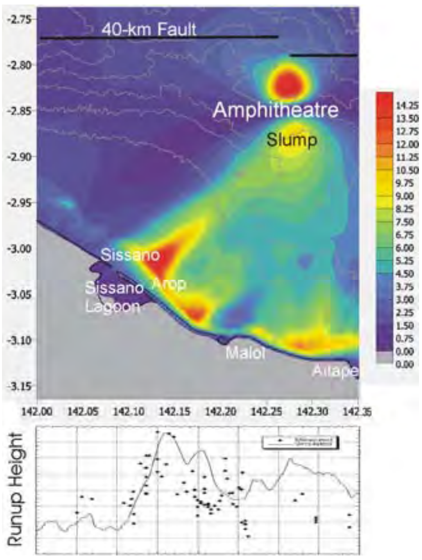
Offshore Papua New Guinea 3-D Image - amphitheatre





Classic rotational failure

Sediment piston core of cohesive sediments



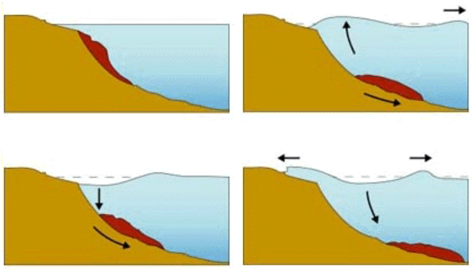
Most likely source mechanism - simulation based on 6km² slump

Sediment failure in the upper headwall (Headscarp)

Focused runup due to effects of nearshore bathymetry

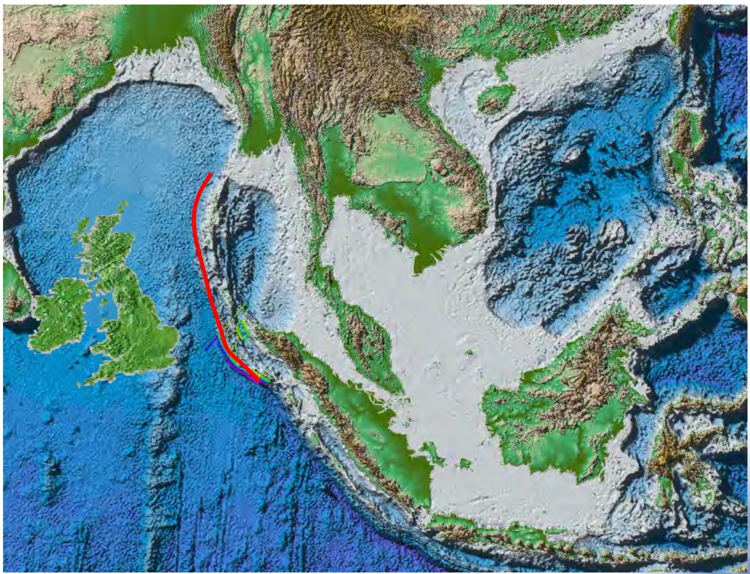
PNG a seminal event

- First time a historical seabed failure was proved to have created a devastating tsunami,
- First time a focussed marine survey had taken place to investigate,
- First time use of new mapping technology – MBES,
- First time tsunami modelled using the mapping results,
- First time the new maths was used to model,
- Very controversial (despite the Harbitz paper of 1992!



Seabed slumping causes tsunamis – but we sort of knew that didn't we?

Indian Ocean 2004



Massive surprise!

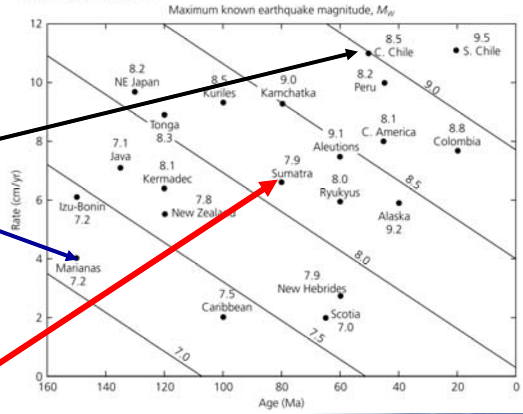
LARGEST SUBDUCTION ZONE EARTHQUAKES WHERE YOUNG LITHOSPHERE SUBDUCTS RAPIDLY

Efforts to interpret seismic slip fraction in terms of physical processes of subduction have not yet been successful. Although the term "seismic coupling" implies a relation between the seismic slip fraction with properties such as the mechanical coupling between the subducting and overriding lithospheres, this has been hard to establish

Idea originally posed in terms of two end members: coupled Chilean-type zones with large earthquakes and uncoupled Mariana-style zones with largely aseismic subduction.

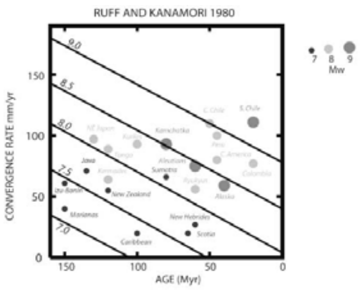
Largest subduction zone earthquakes appear to occur where young lithosphere subducts rapidly, where we might expect minimum "slab pull" effects and strongest coupling

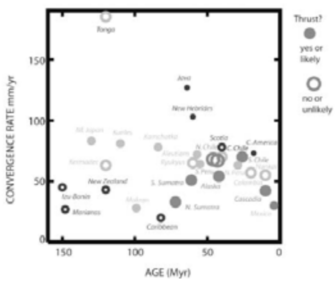
Figure 5.4-30: Peak subduction zone magnitude as a function of plate age and subduction rate.



Sumatra 2004

Ruff & Kanamori, 1980



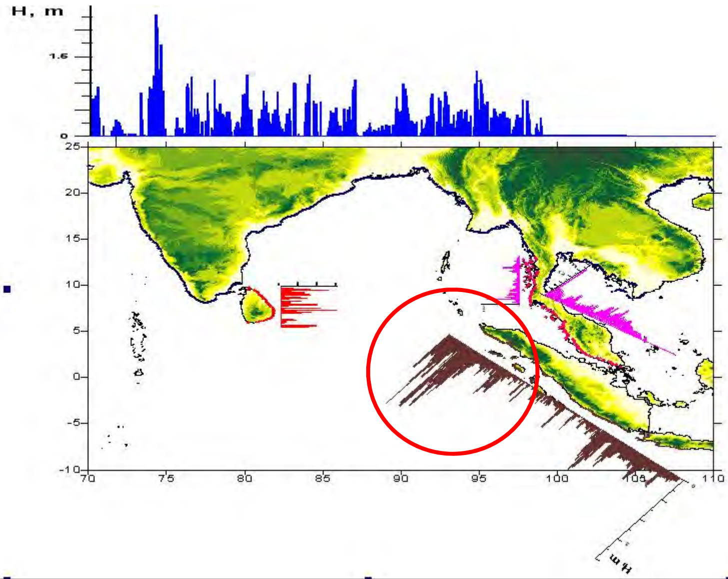


Revised analysis of Great EQ locations

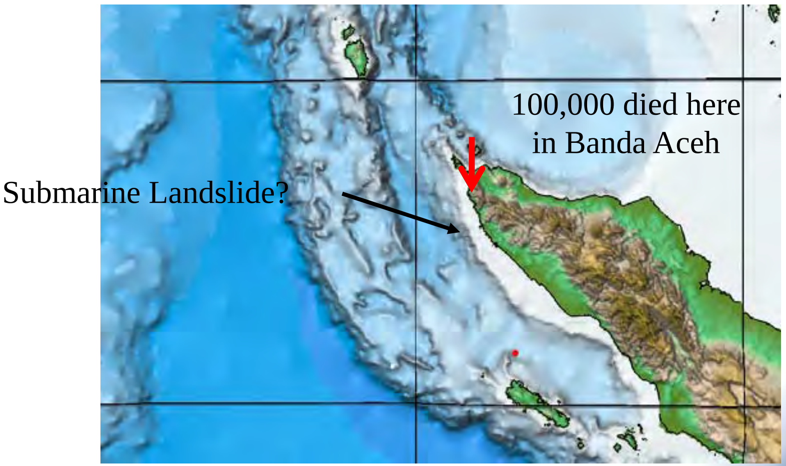
- No clear effect of age,
- New plate tectonic models,
- Revision of EQ mechanisms – some are not thrusts, but normal faults,
- Uncertainty of older events,
- What is 'seismic coupling',
- Effect of sediment thickness,
- But – seismic record too short,
- Each new Indian Ocean event will make us wiser!

(Stein and Okal, 2007)

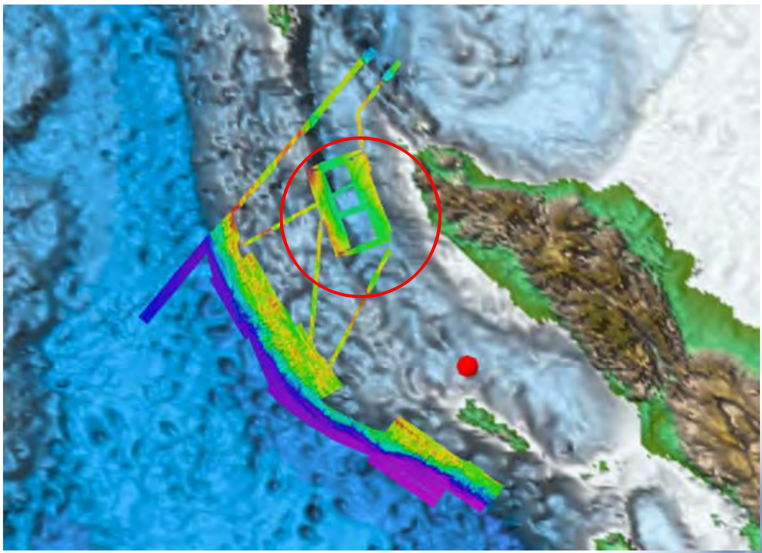
Major aspect – North Sumatra run up



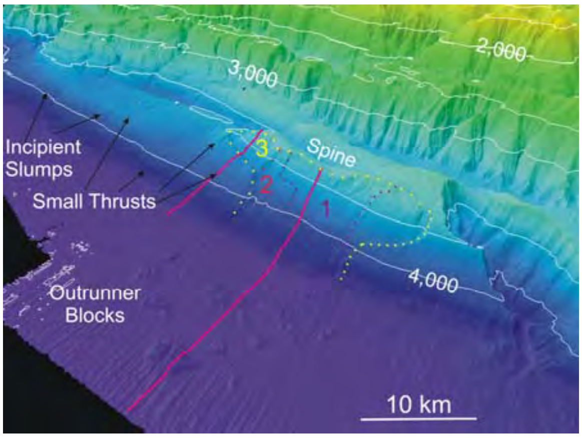
Pre-2004 bathymetric data indicated a major slump offshore Sumatra that could have generated a local tsunami



Multibeam (and seismic) data



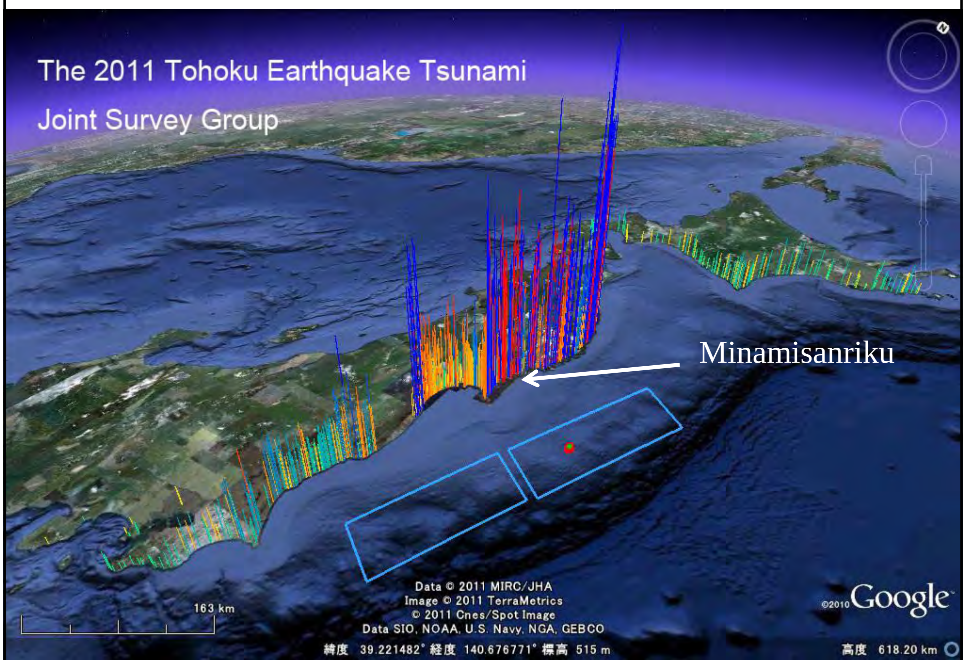
Even at 5000m only small failures



The Indian Ocean tsunami was earthquake-generated

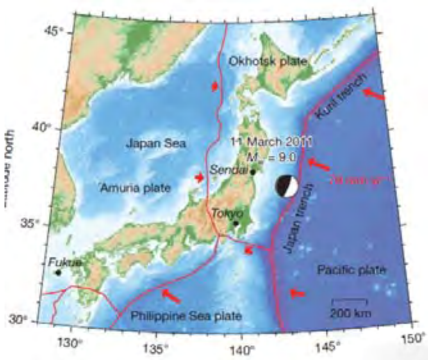
Japan - Tohoku 2011

- 15,870 dead
- 2,814 missing – almost certainly dead,
- 300,000 homeless
- Total material cost of ~$120-235 billion
- 23,600 hectares of farmland, mostly rice paddies, damaged,
- 26,000 fishing boats rendered unusable,
- Clean up – $12 billion



Japan tsunami - 2011

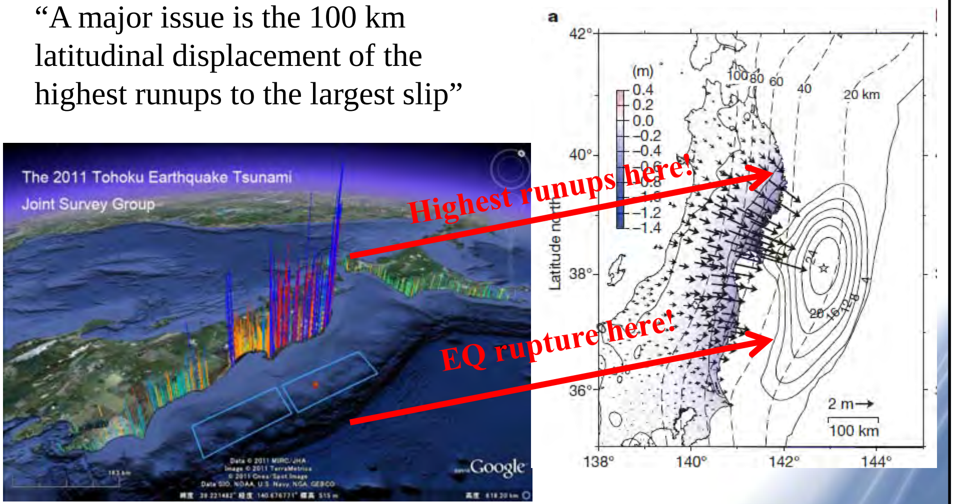
- Probably the most comprehensively geophysically recorded EQ and tsunami,
- Global and local seismic networks,
- Geodetic networks across Japan,
- Onshore tide gauges,
- Nearshore GPS pressure gauges,
- DART buoys,
- Onshore runup and inundation measurements,



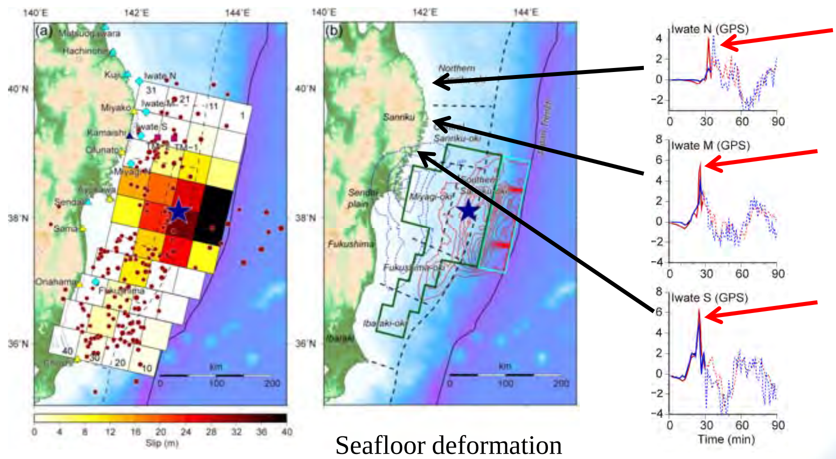
But some aspects of the tsunami do not tie in to the M9.1 earthquake

Japan tsunami runups

"A major issue is the 100 km latitudinal displacement of the highest runups to the largest slip"



Tsunami waveform inversion



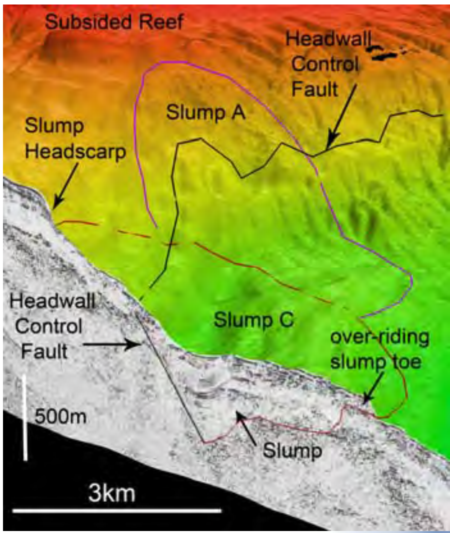
Slip distributions estimated by tsunami waveform inversion. (*Fuji et al., 2011*)

Seafloor deformation computed from the estimated slip distribution(red uplift, blue subsidence.

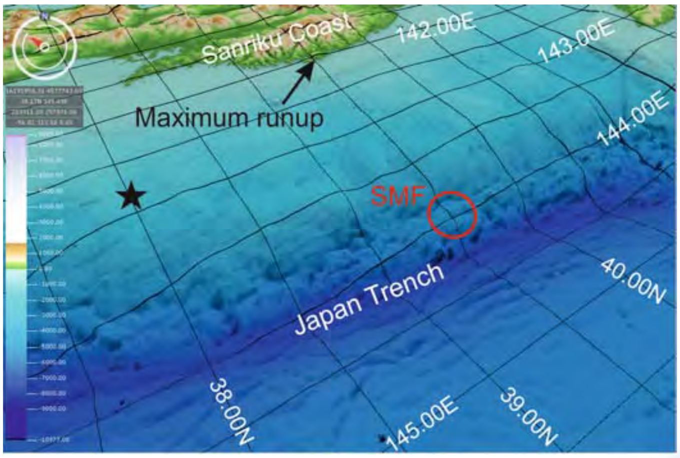
But wave inversion does not explain the high runups in the north.

Papua New Guinea

Did a submarine landslide contribute to the Tohoku tsunami?

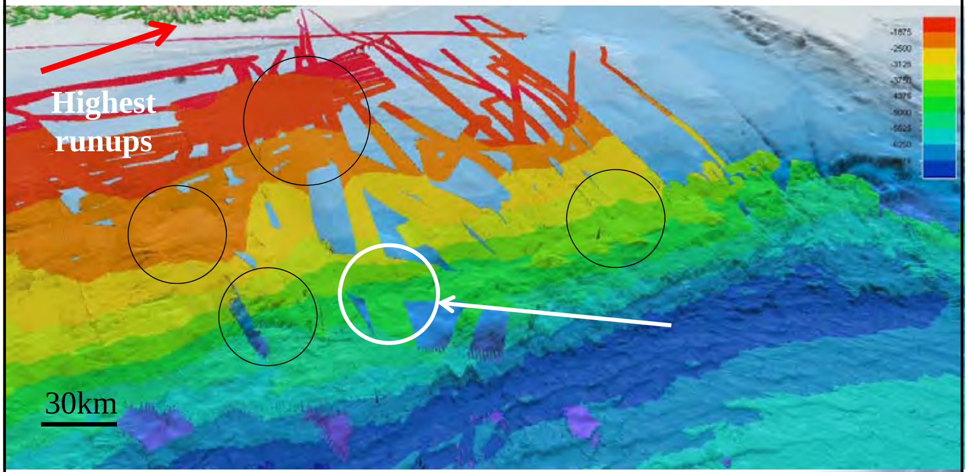


Submarine landslide source?



Is a SMF present where the ray tracing suggests?

Overview northern Honshu



One of the few regions where there is before and after bathymetry and seismic - pre-2011 bathymetry shows numerous SMFs (Courtesy of JAMSTEC and IFREMER)

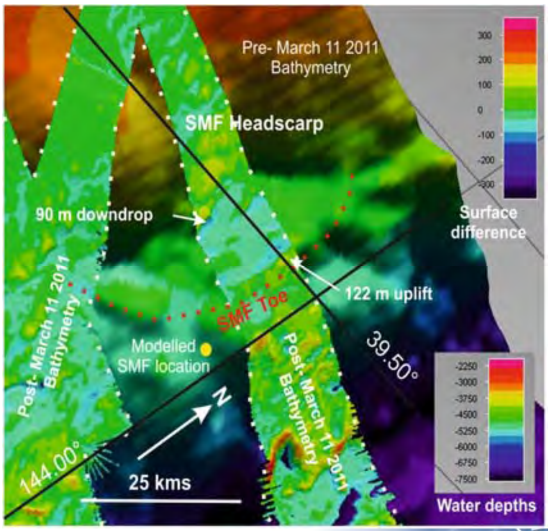
Bathymetry of seafloor failures

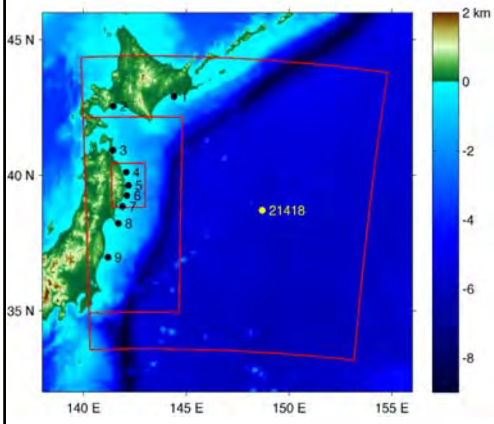
Direct observations of SMF ?

Difference [multibeam echosounder swath data, acquired during the R/V YOKOSUKA cruise YK11-E06] shows SMF/slump with average -100, +100 m displacement

(Data JODC, JAMSTEC)

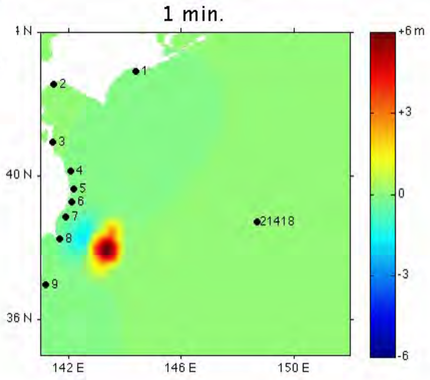
Pre and post tsunami bathymetry





=> NHWAVE (300 s) & FUNWAVE Simulation of FEM co-seismic source + SMF (best location)

High frequency wave train from the SMF



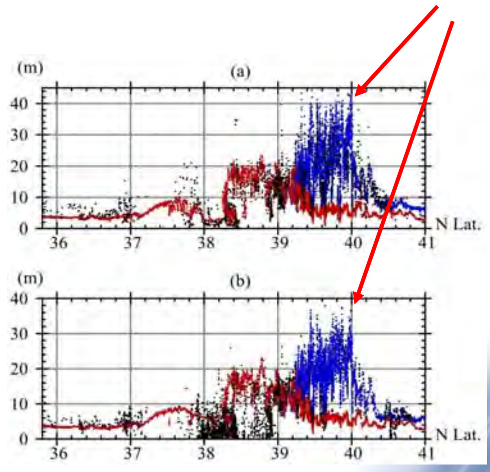
Nested Grids

Near field: 50m, 250m, 1000m; and Ocean (2') tsunami grids

Tohoku Tsunami source – EQ and SMF combined

- Tsunami simulations from a solely earthquake source cannot explain the 40 m runups in northern Honshu, the Sanriku coast,
- Explained by focussing along the ria coast – NO!
- An additional (SMF) source is required

SMF source



Context - Japan 2011

- 2011 – Tohoku
- 1933 – Edo
- 1896 – Great Meiji
- 1611 - ????
- 869 Jogan – probably similar to 2011
- 150AD – BC50 ?
- 50AD – BC140
- 670-910BC

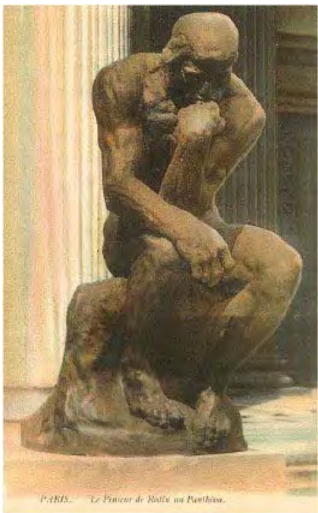
Although the validation was from tide gauges and GPS buoys,
There was evidence of large-scale older (historical) events from tsunami sediments on the east coast of Honshu

Explanations for underestimating the Japan 2011 earthquake

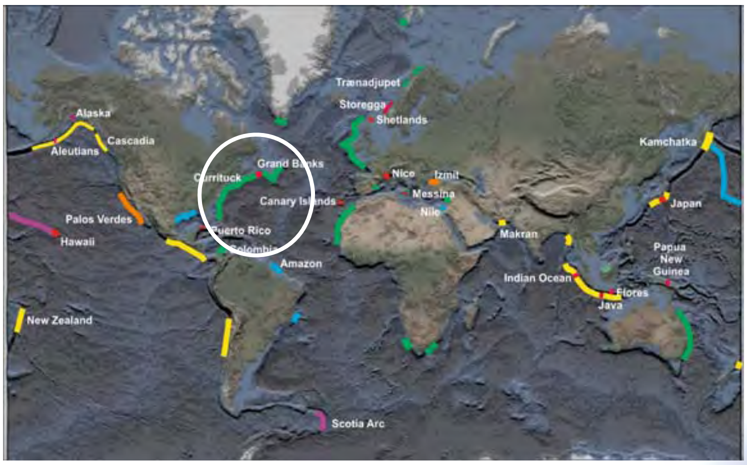
- Analysis of EQ events only from Japan,
- Based on short timescales – up to 400 years BP,
- 80–90% probability that the area would have a large earthquake of magnitude 7.7–8.2 within 30 years,
- But not a magnitude-9 earthquake affecting a 400–500 kilometre coastline.
- Focus on areas to the south of inundated area,
- Reliance on estimates of aseismic versus seismic slip deficits or seismic coupling,
- Empirical - geological evidence on tsunami frequency not fully considered.

Geological context – a few points

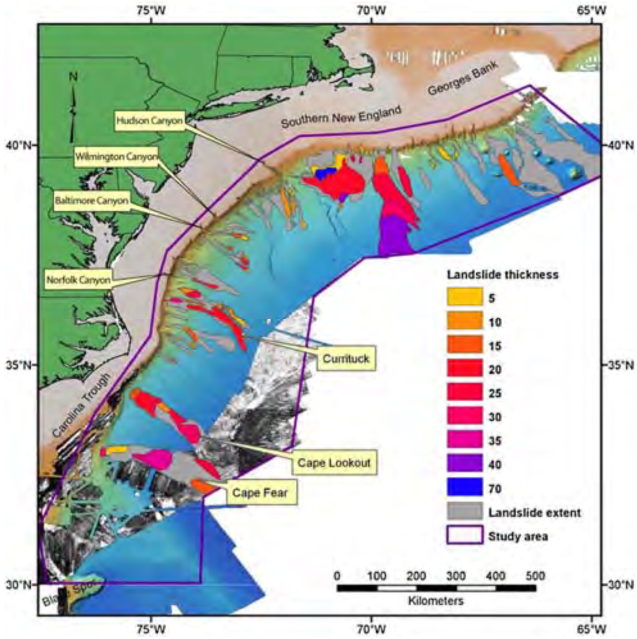
- Technologies available to map the seabed (hydroacoustics, sampling),
- Easy to produce digital 3D models,
- Straightforward (but complex?) to use the geology as a basis for the models,
- Need to validate models (observation or sediments),
- How do these seminal events relate to the USA,
- Particularly their source mechanisms.



Global submarine landslide tsunamis



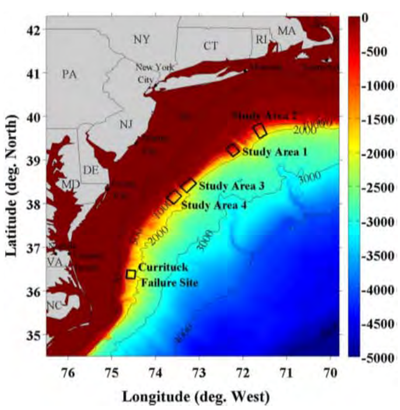
What about the USA? Passive margins.



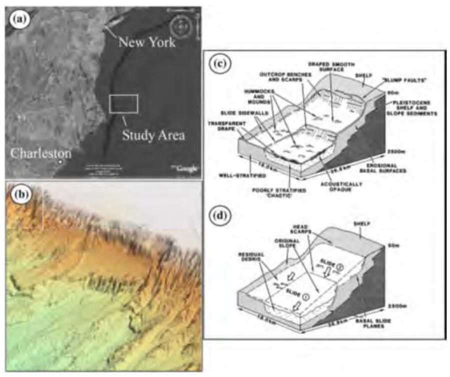
US eastern passive margin

Submarine landslides confined to the shelf break as most formed during lowered glacial sea levels but age dating poor

Currituck modelled

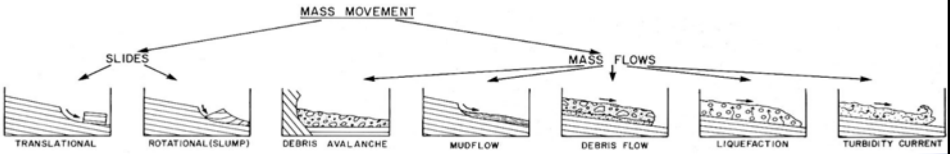


(Grilli et al., 2015, Geist et al., 2009)



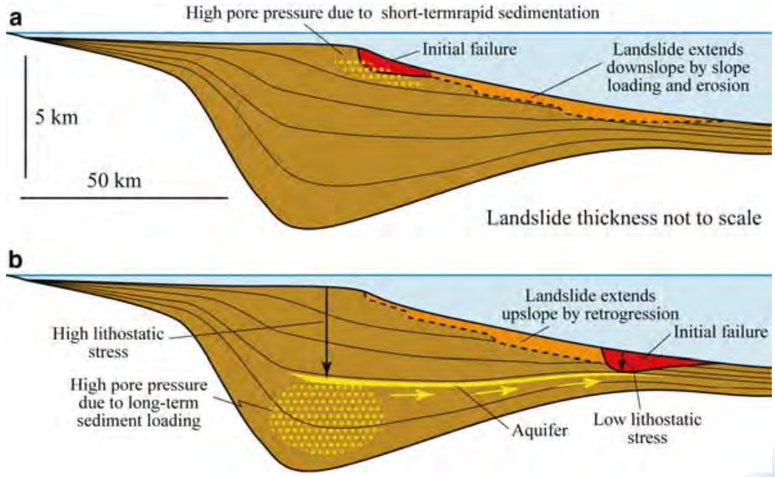
- Currituck well mapped with multibeam and seismic,
- Shows a translational failure mechanism,
- Simulated as a rigid slump,
- Tsunami generated,
- But not validated (no sediments).

Classification (Varnes, 1958) for subaerial landslides



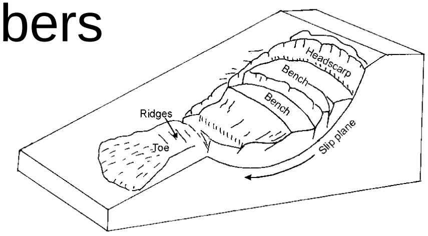
Numerous attempts to classify marine landslides on the basis of subaerial examples

Translational landslides



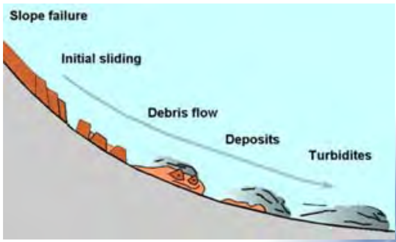
End member' initiation mechanisms for giant landslides **(a)** Landslide initiated on the upper slope due to rapid sedimentation. (**b) Landslide initiated on the** lower slope due to lateral advection of high pore pressure from thicker sediment accumulation beneath the upper slope. In both (**a) and (b), development of the landslide beyond the initial failure** is controlled by weak layers within the parallel bedded slope sediment sequence (Masson et al., 2009)

Landslide mechanisms – end members



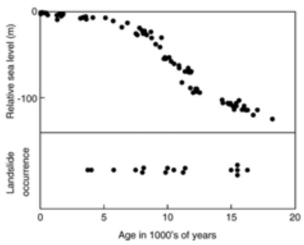
Rotational landslide

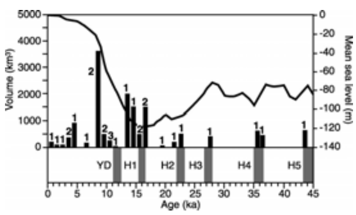
- Although end members, differences in between,
- Top down (Currituck) and bottom up (Storegga)

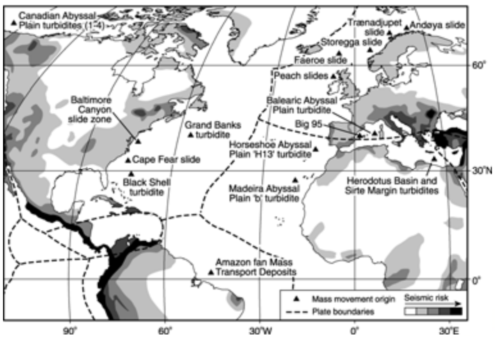


Translational

Landslide triggering?



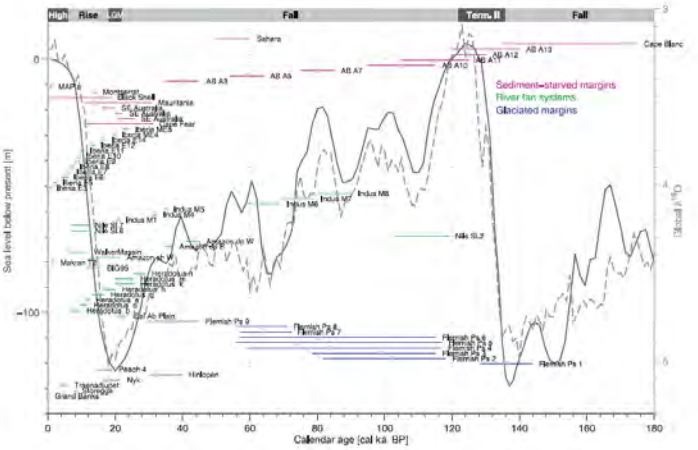




Maslin, M., Owen, M., Day, S. & Long, D. 2004

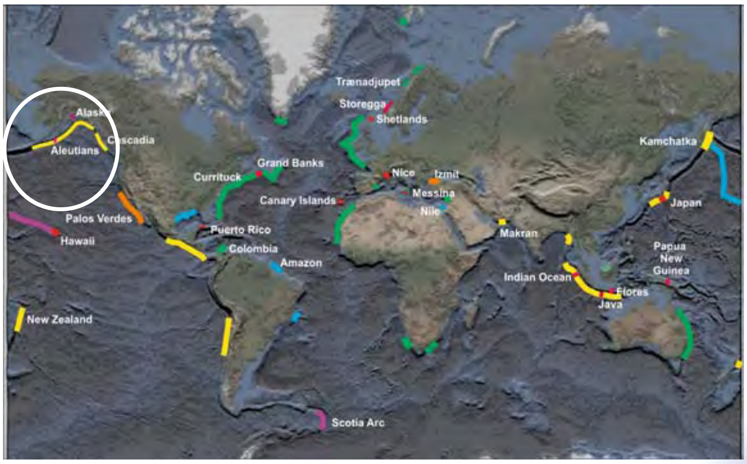
- Correlation with climate change,
- Earthquakes?
- Glacial/interglacial cycles?

SL ages versus Global sea level



No correlation – Poission distribution (*Urlaub et al., 2013*)

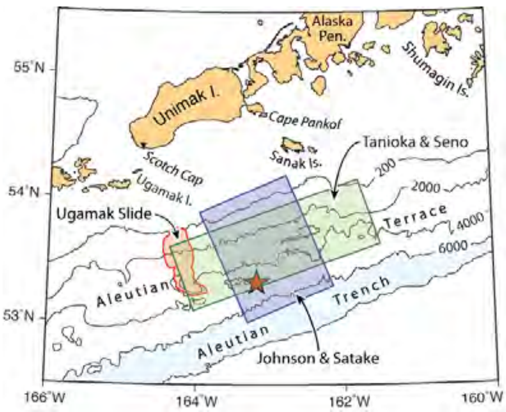
Global submarine landslide tsunamis



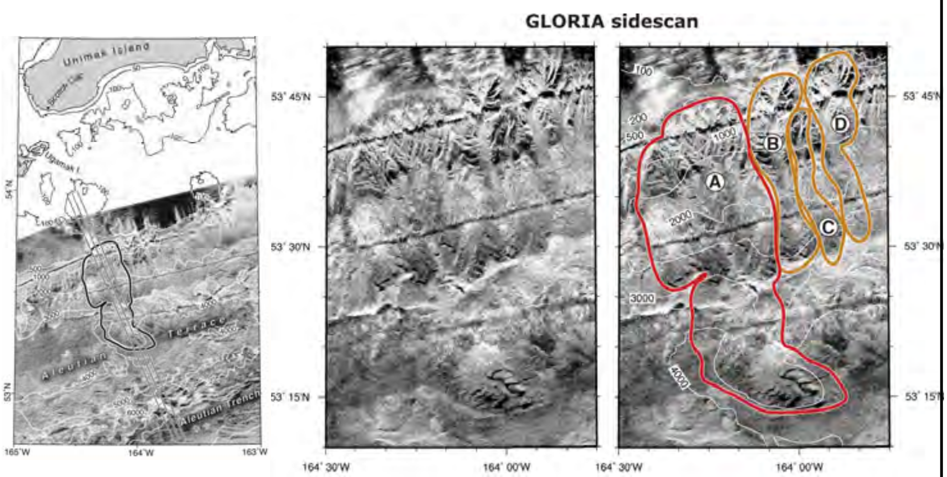
What about the USA? Convergent margins

1946 Aleutian earthquake

- Moment is poorly established (little broadband),
- Source duration was exceptionally long and the rupture area small, 1. 80 km long and 100 km wide or
  2. 180 km long and 115 km wide,
- Using an earthquake source 160 km long (T&S) reproduced the tide record at Honolulu but with a 26 m slip sediment uplift at the forearc,
- Hard to explain the tsunami,
- So Fryer et al (2001) suggested a submarine slide

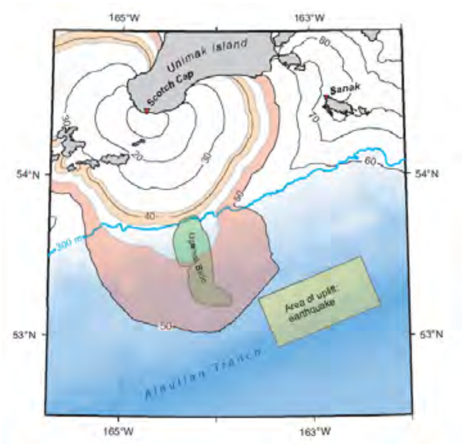


1946 Aleutian tsunami – submarine landslide?

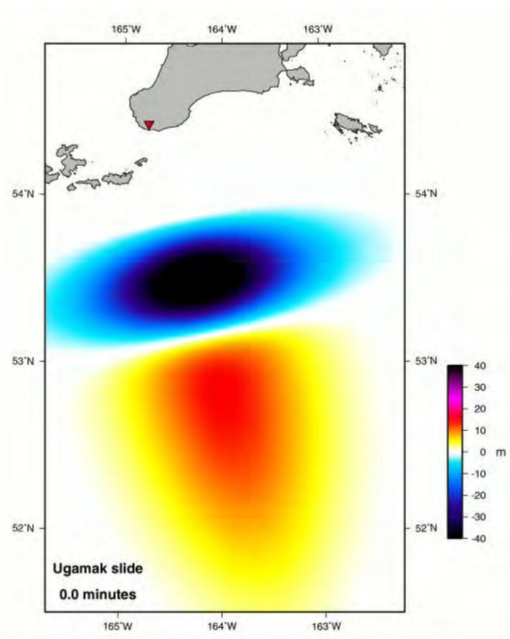


Fryer, et al.,2004

1946 Aleutian tsunami – slide source



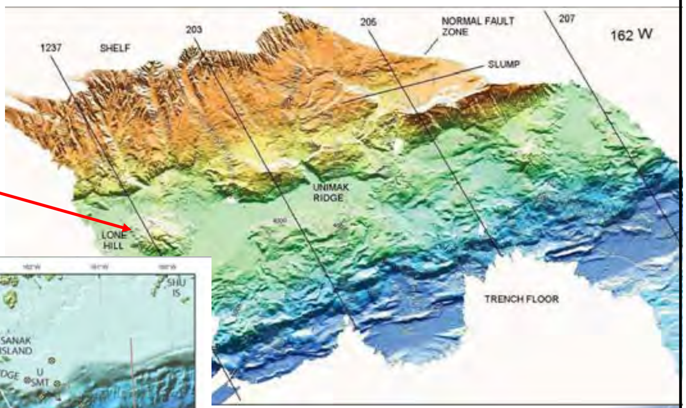
- The slow rupture, the tsunami directivity, the rapid variation in near-source wave heights, the period of the waves, and the strong T-phase generation, together suggest an earthquake-triggered landslide rather than a purely tectonic source.
- A landslide with a volume of 200-300 km^3 would produce a tsunami matching the observations while still satisfying the seismic data.

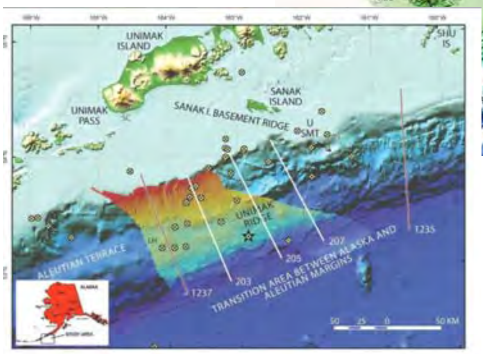


1946 Aleutian tsunami – slide model

1946 Aleutian tsunami - 2005

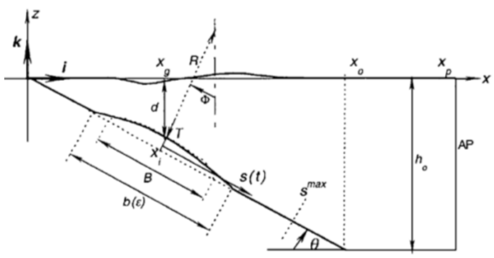
- New mapping in 2004 found a landslide

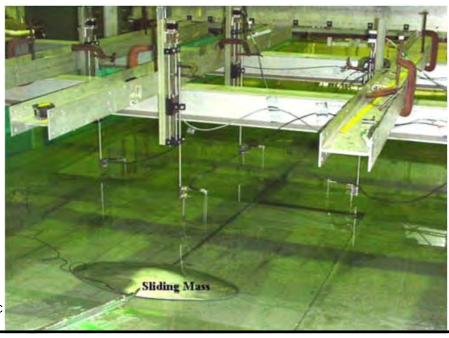




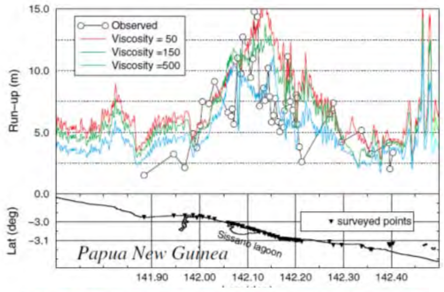
- Is this the landslide mechanism?
- Requires modelling

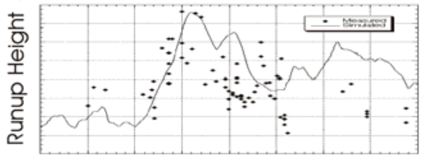
Idealised models

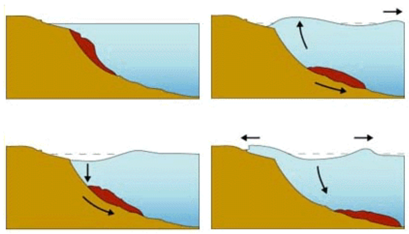




The importance of the right mechanism?



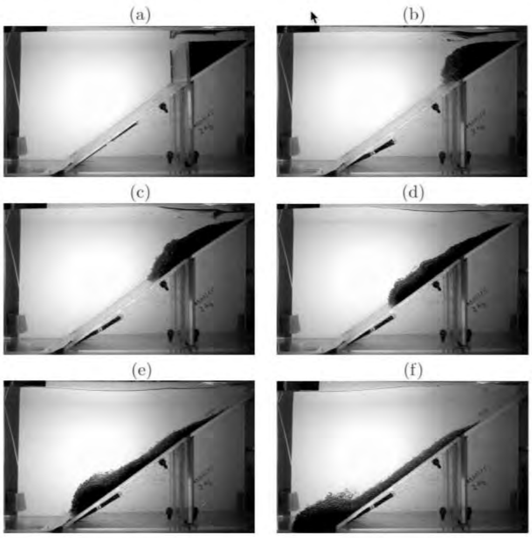




Viscous flow (Heinrich et al., 2001)

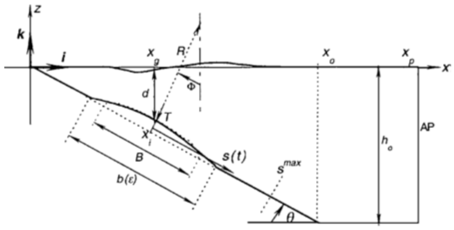
Rotational slump (Tappin et al., 1999, 2001, 2008)

Idealised models

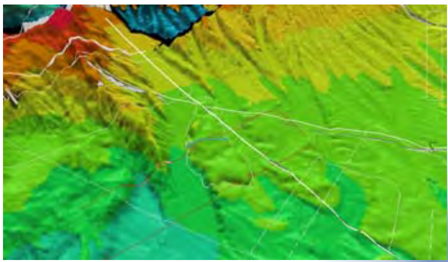


Does the specific failure mechanism matter?

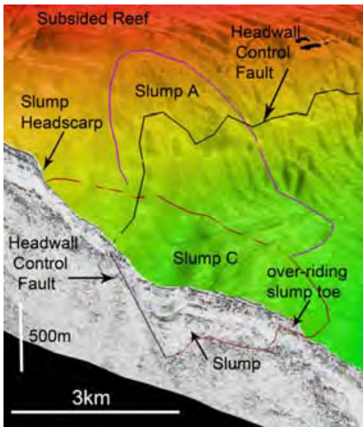
Types of failure and models



Messina, 1946?

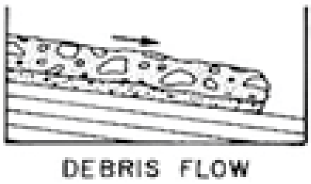


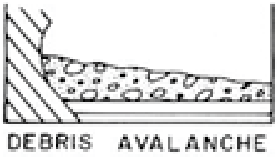
Types of failure and models

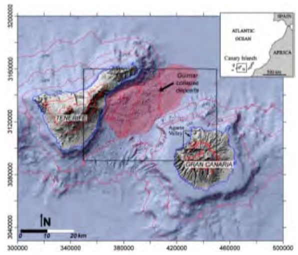


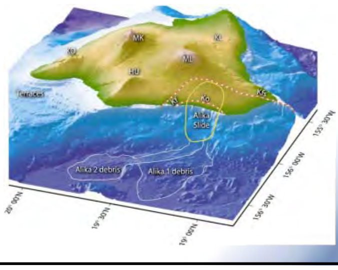
PNG, Japan

Types of failure and models



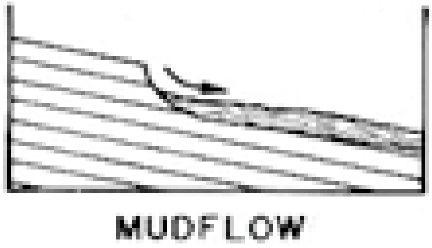






Hawaiian and Canary
Island volcanoes

Types of failure and models



??????

Summing up

- Submarine landslides complex
- Different and varied mechanisms,
- Still few modelled realistically for tsunamis,
- Models that we have span the spectrum from passive to convergent margins,
- Realistic models require good a foundation mechanism
- Validation too,
- Lot of models but still mainly sliding blocks,
- More complex mechanisms are dual EQ and SMF,
- Benchmarks are necessary, but what validates the benchmarks?
- Hopefully during the workshop we can discuss further