Risk Assessment for Submarine Slides

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First Challenge: Terminology

- Probability
- Uncertainty
- **Threat (danger)**
- **Hazard**
- **Risk**
- Consequence
- Failure
- Vulnerability
- ……..

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Terminology: Danger (threat)

Danger (Threat): The natural phenomenon that could lead to damage, described in terms of its geometry, mechanical and other characteristics. The danger can be an existing one (such as a creeping slope) or a potential one (such as an earthquake). *The characterisation of a danger or threat does not include any forecasting.*

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Terminology: Hazard & Risk

Hazard: Probability that a particular danger (threat) occurs within a given period of time.

Risk: Measure of the probability and severity of an adverse effect to life, health, property, or the environment.

Risk and hazard

Hazard = Probability of occurrence of a dangerous event (/ Time unit)

(for example annual probability of slope failure)

Risk = Hazard x Potential worth of loss

(risk could be real or perceived)

Often we are not consistent, and mix up "risk" and "hazard"

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More general definition of "Risk"

Risk = f (hazard, elements at risk, vulnerability)

- ***Risk:*** Expected losses (i.e. the probability of specified negative consequence to life, well-being, property, economic activity and other specified values) due to a particular threat for a given area and reference period
- ***Elements at risk:*** All objects with a damage potential located within a given area
- ***Vulnerability:*** Degree of loss resulting from the occurrence of a specific type and magnitude of event

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Terminology: Vulnerability

- ***Vulnerability*** *relates to the consequences, or the results of an impact of a natural force, and not to the natural process or force itself.*

- ***Consequences*** *are generally measured in terms of damage and losses, either on a metric scale in terms of a given currency, or on a non-numerical scale based on social values or perceptions and evaluations.*

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Social sciences approach

- *Any natural hazard, natural risk, and consequently any form of "natural" disaster is caused by humans (Geipel 1992).*

- *If the person – or society – that is threatened or endangered can make decisions and react to potential process occurrence, the hazard becomes a risk. Consequently, if an individual or a society has no opportunity to make decisions, the natural event is "just" a hazard, not a risk (Pohl & Geipel 2002).*

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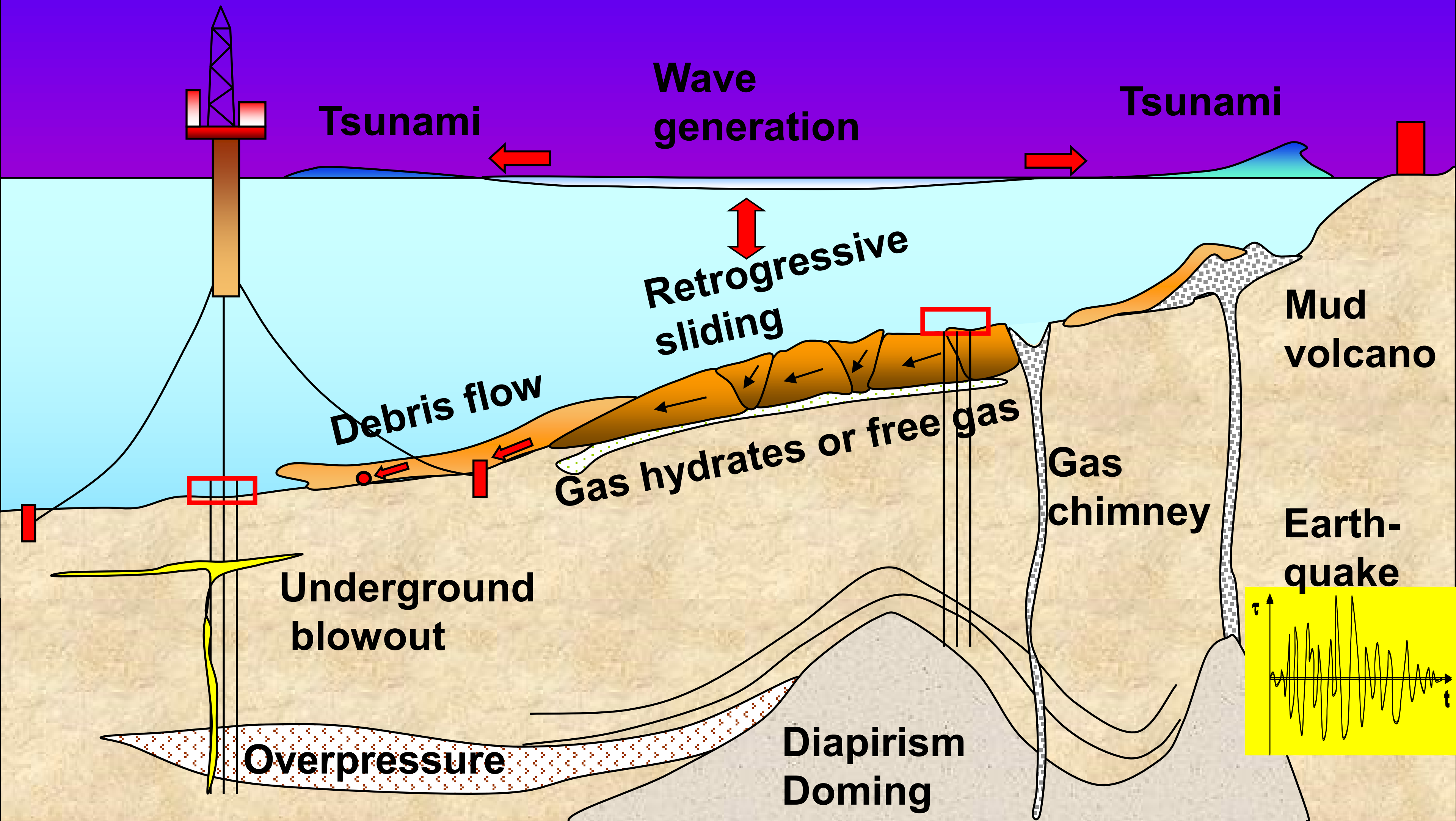
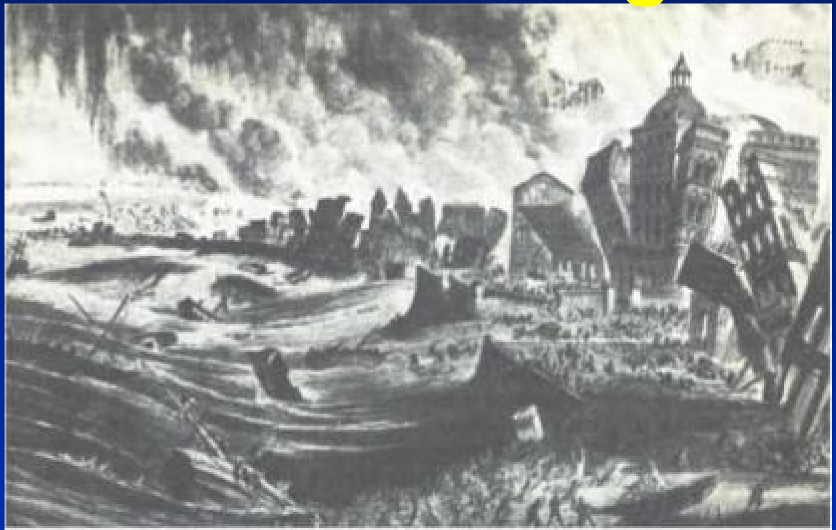
Offshore Geohazards

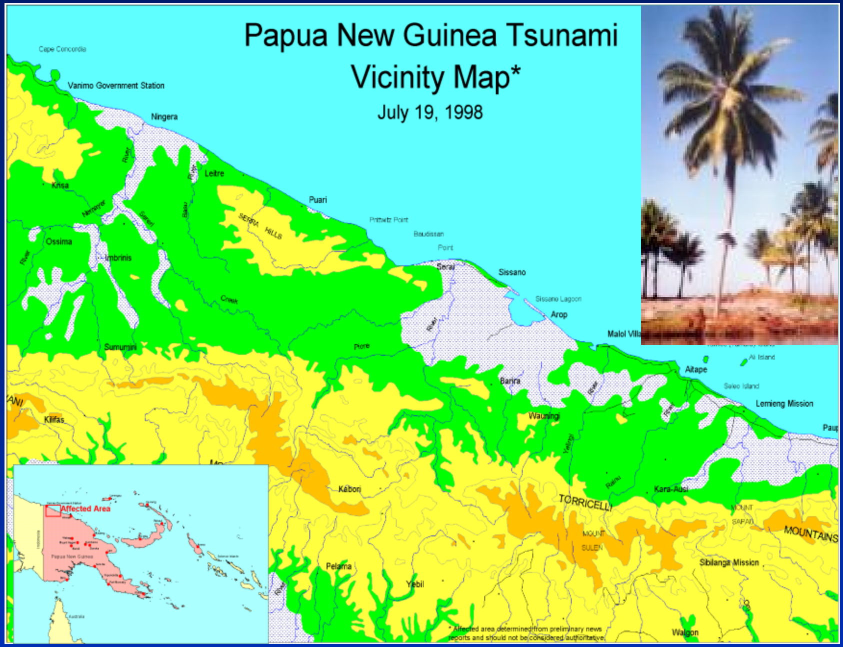


Tsunami damage



Lithography, Lisbon (Portugal), All Saint's Day 1755

1946 Hawaii tsunami caused by Aleutian eathquake
http://www.usc.edu/dept/tsunamis/alaska/



On 17th July 1998, at 08:49 (UTC), a magnitude 7.1 earthquake off the north coast of Papua New Guinea generated a locally very destructive tsunami. The tsunami damage was anomalously large for a quake of the magnitude:

- A fast-moving wall of sand-laden water left detritus in trees up to 17.5 metres above sea level,
- No structures were left standing along the 19 kilometres of coast fronting Sissano Lagoon,
- Concrete was stripped to the reinforcing,
- Some ripped-out trees were carried more than a kilometre,
- More than 2189 people died.

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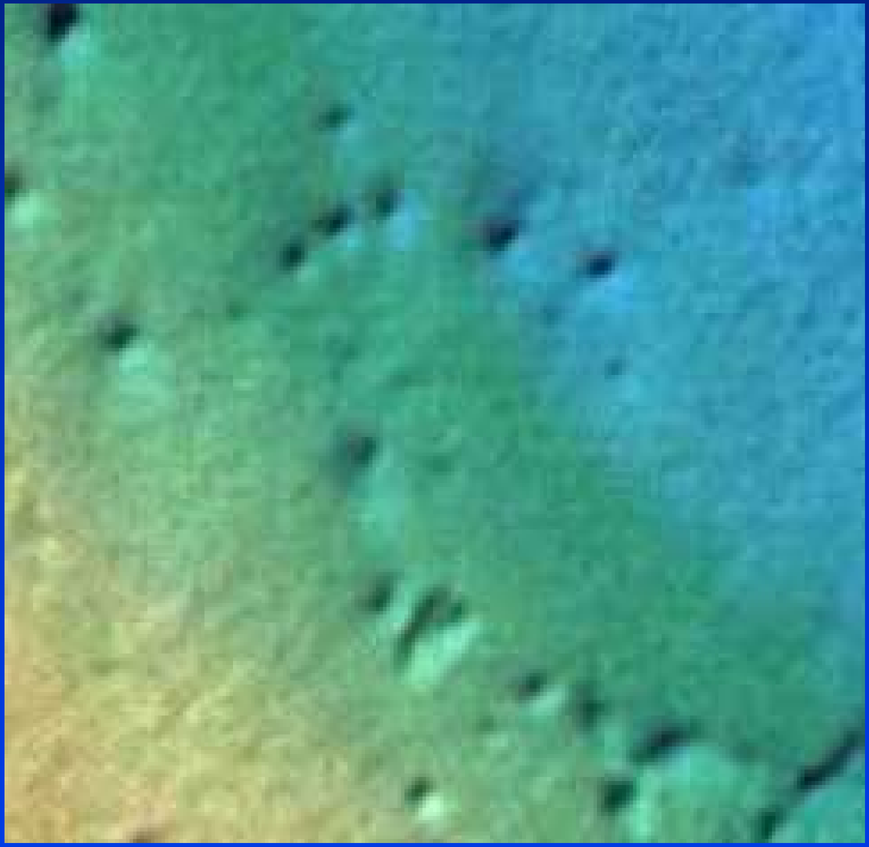
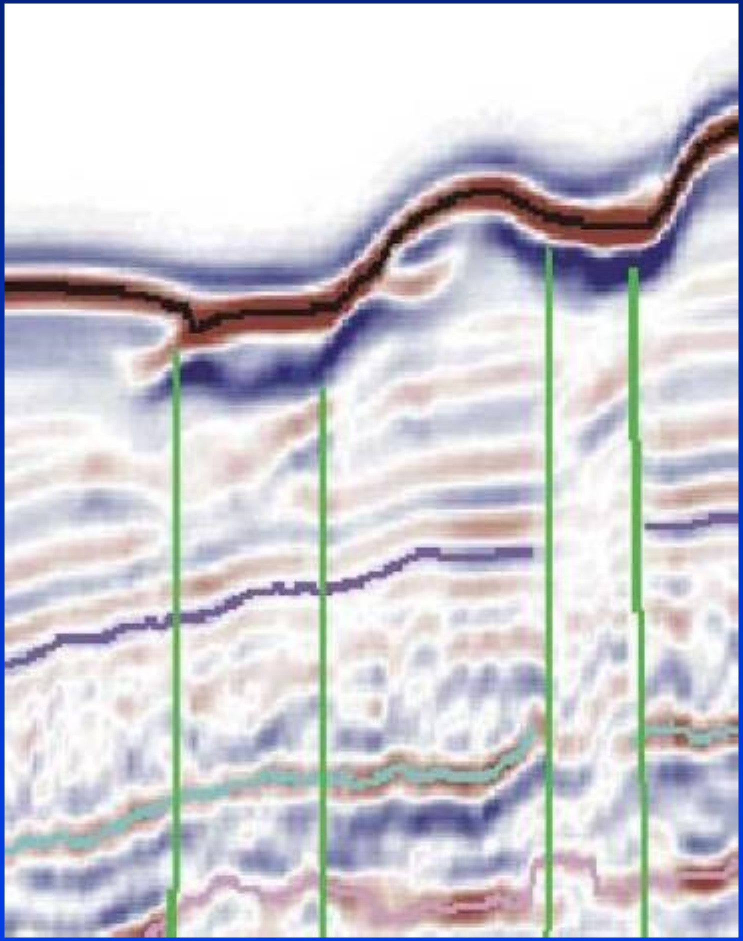
Gassy soils, pockmarks and fluid/gas escape structures





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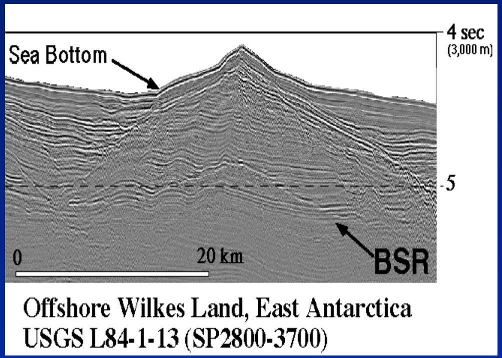
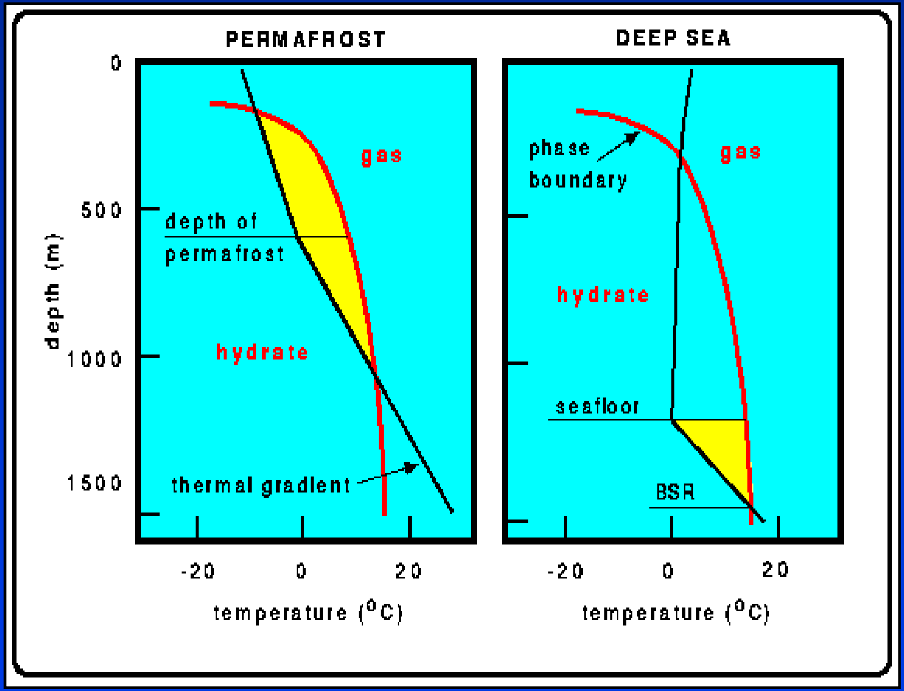
Gas hydrates





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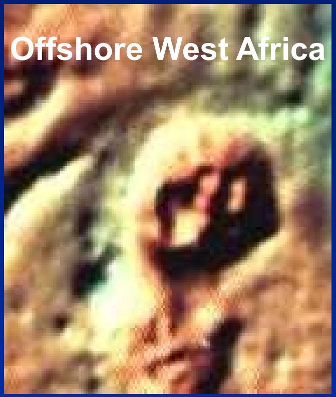
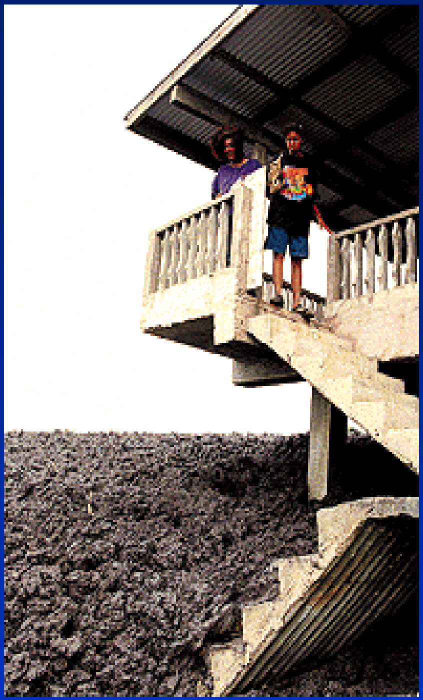
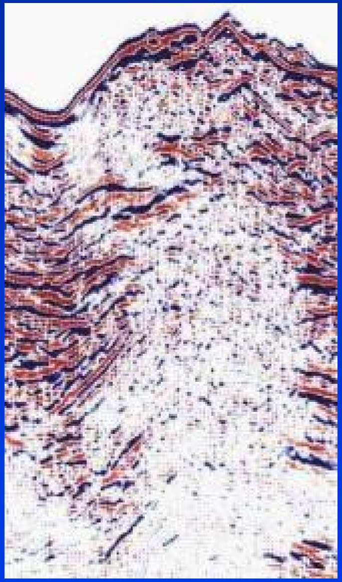
Mud volcanoes







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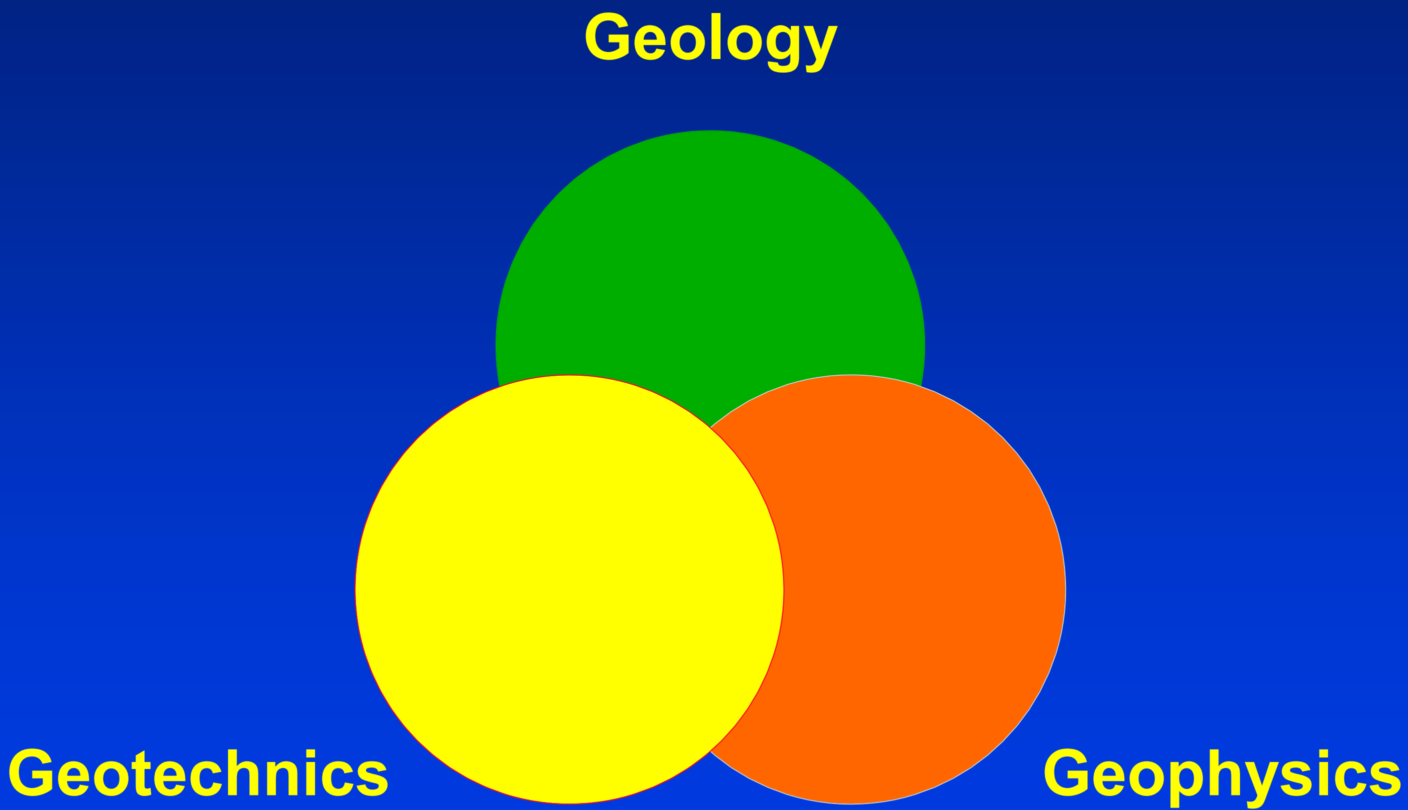
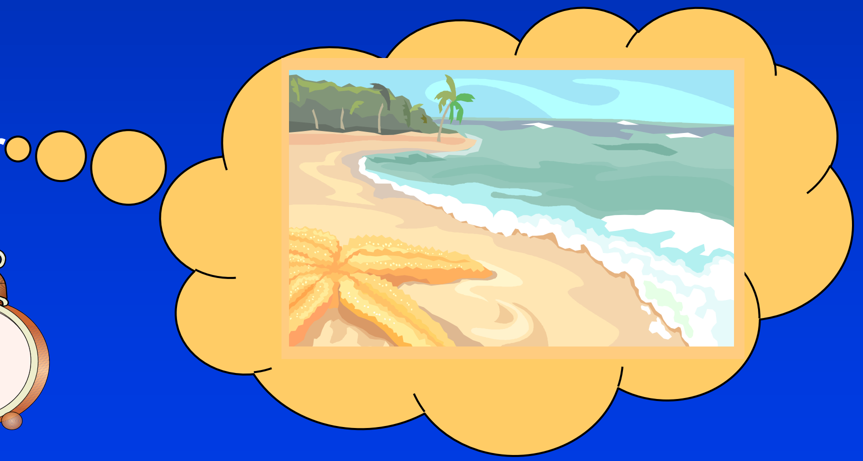
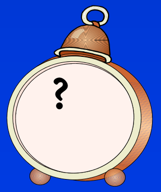
Disciplines supplement and complement each other



Geophysics

- Often available before offshore sampling
- Regional overview
  - *Stratigraphy*
  - *Structural patterns*
  - *Geohazards: shallow gas, hydrates, diapirs, old slides*
- No ground truth
  - *Geo-fantasies can occur*
  - *Ages often unknown without correlation*





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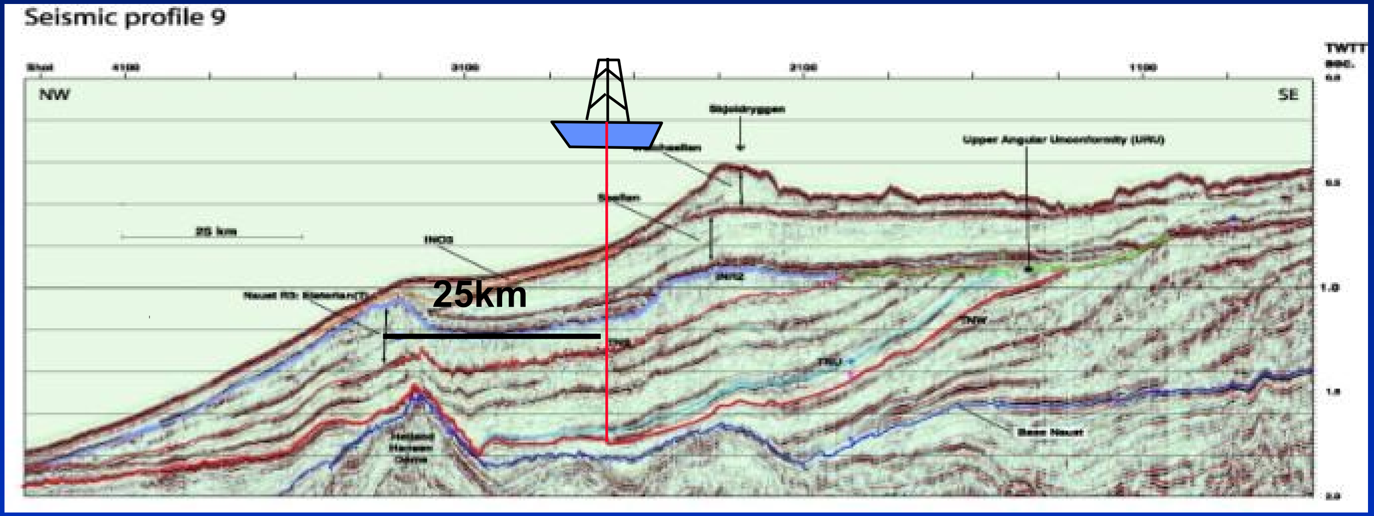
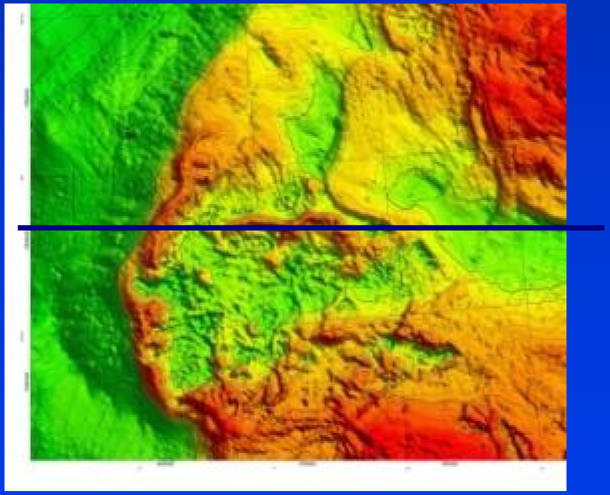
Seismic data and a few cores





The seismic profile is nearly 200km long.

The diameter of a core is 10cm!

It takes at least a geologist (and a fair amount of geo-fantacy) to interpret accurately

Geotechnical concerns

- **Ability to define relevant and critical failure modes**
- **Assessment of probability of occurence**
- **Calculate/predict consequences**
- **Uncertainties to addressed:**
  - *Limited site investigations and extrapolation over large areas and depths*
  - *Assessment of in situ effective stress and pore pressure conditions*
  - *Gas hydrates existence and quantification*
  - *Modelling of triggering mechanisms*

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Submarine slope stability on gentle slopes

- Field development on the continental slopes
- Enormous historic and paleo slides observed
- Gravity forces increasingly important even at very low slope angles of 0.5 to 3°
- Triggering mechanism not well understood
- Large runout distances, retrogressive sliding upslope/laterally and tsunami generation may threaten 3rd parties in large areas

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Submarine Slope Stability on Gentle Slopes (2)

Infinite slope analysis

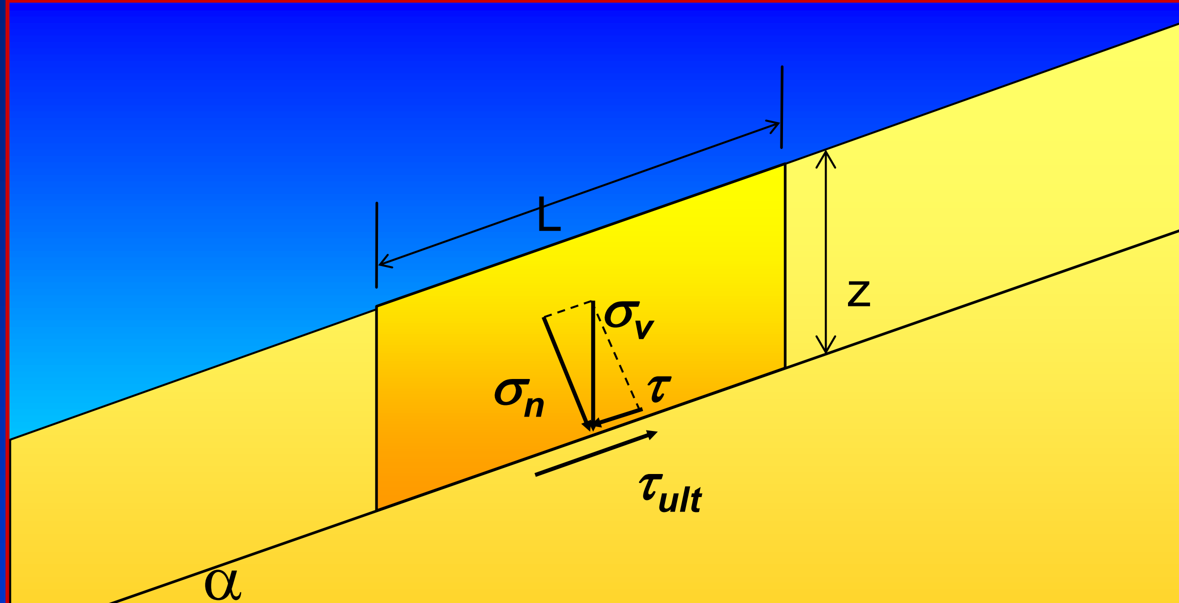
Strength:

$$\tau_{ult,d} = (\sigma_n - \Delta u) \cdot \tan\varphi'$$

$$\tau_{ult,u} = s_u = k(\sigma_n - \Delta u)$$

Pore pressure ratio:

$$r = \frac{\Delta u}{\gamma' \cdot z}$$



$$\tau = \gamma' \cdot z \cdot \sin\alpha \cdot \cos\alpha$$

$$\sigma_n = \gamma' \cdot z \cdot \cos^2\alpha$$

Drained factor of safety:

$$FS_d = \frac{(\cos^2\alpha - r)\tan\varphi'}{\sin\alpha \cdot \cos\alpha}$$

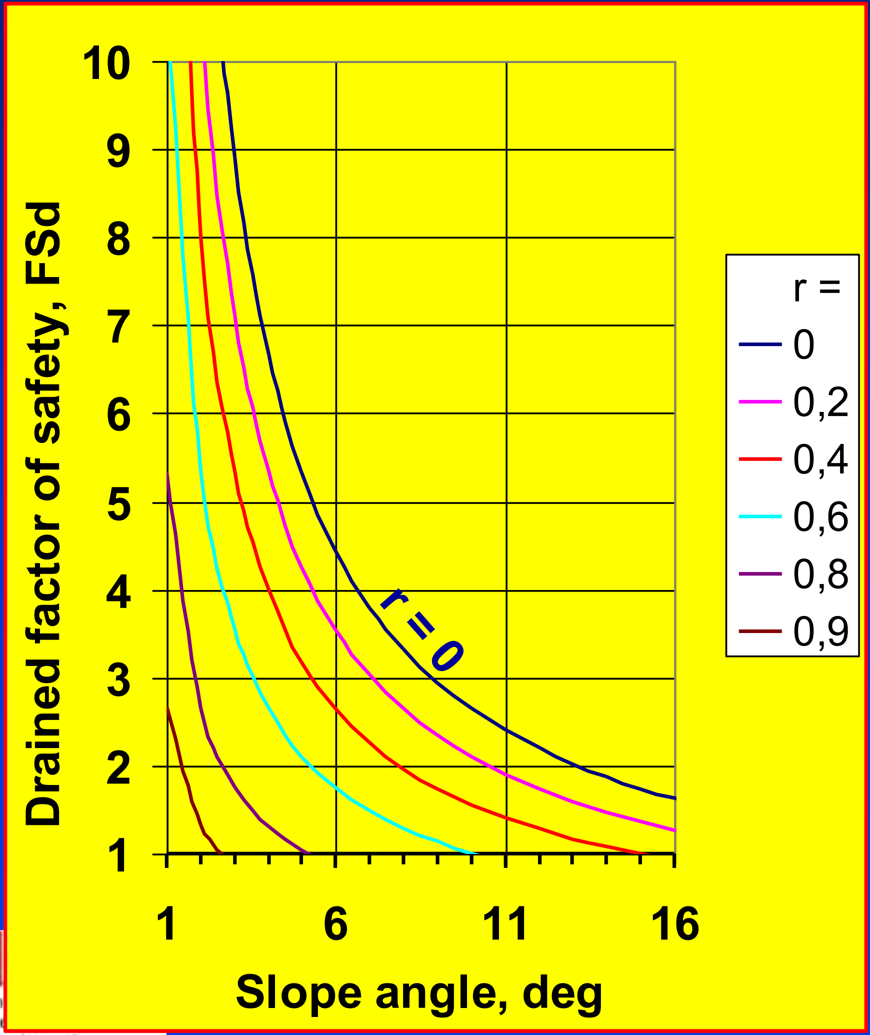
Undrained factor of safety:

$$FS_u = \frac{k \cdot (\cos^2\alpha - r)}{\sin\alpha \cdot \cos\alpha}$$

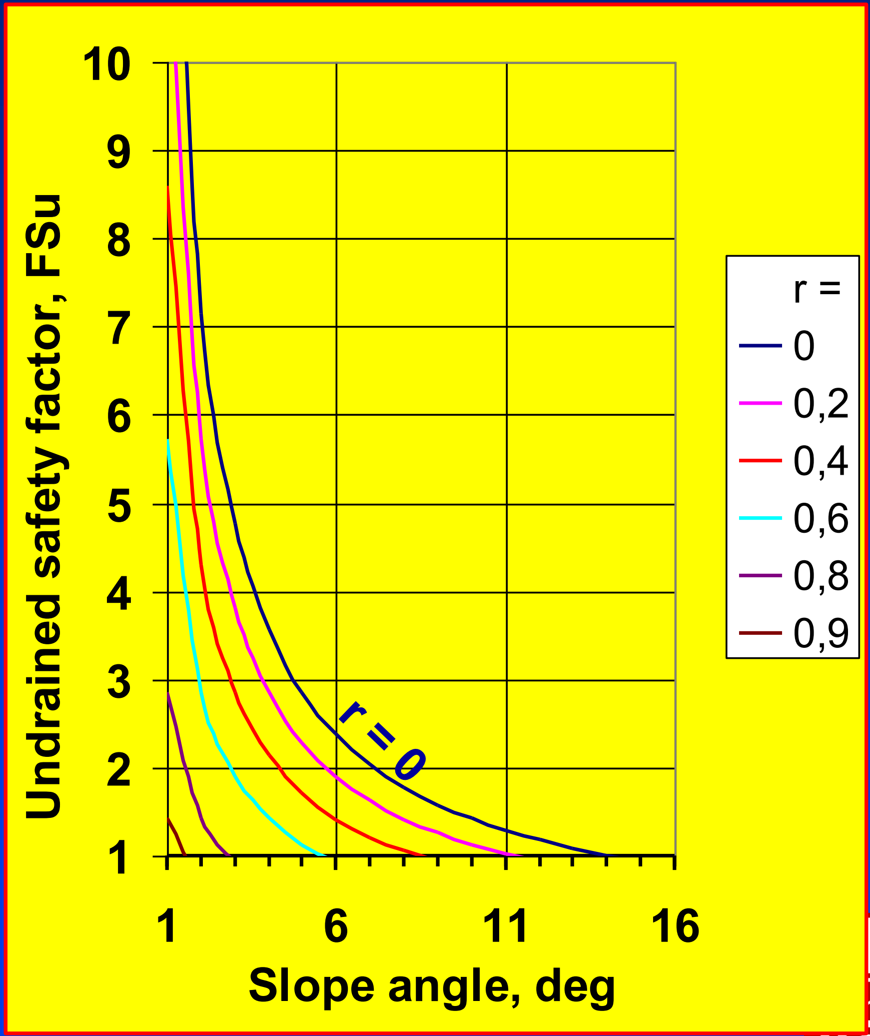
Submarine Slope Stability on Gentle Slopes (3)

Safety factors vs. α and $r=\Delta u/\gamma' z$

Drained; $c'=0$ $\varphi'=25°$



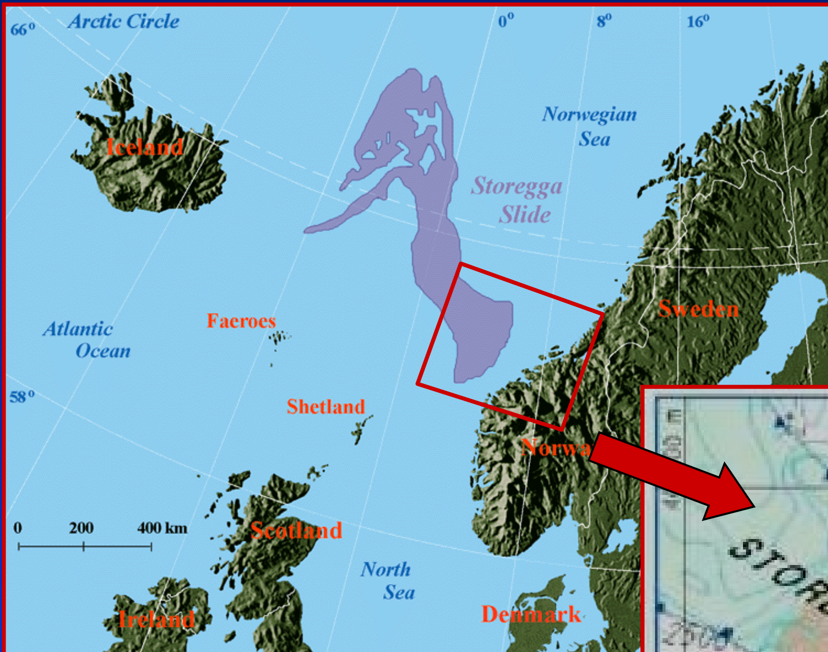
Undrained NC; $s_u = 0.25\,\gamma' z$



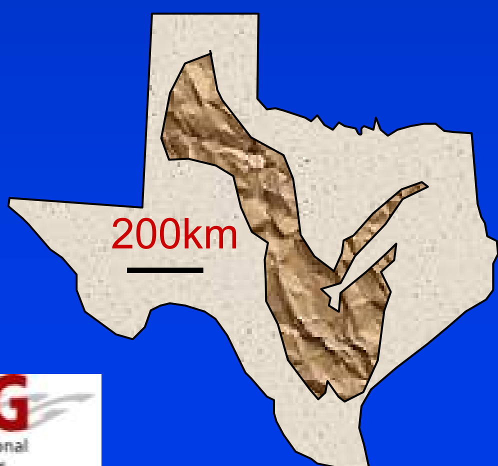
Pore pressure generating mechanisms

- Rapid sedimentation → Underconsolidation
- Earthquake and shear strain induced pore pressure generation in collapsible and sensitive soils
- Pressure decrease and temperature increase in gassy soils (Climate and human induced)
  - → *Gas exsolution and free gas expansion*
  - → *Melting of gas hydrates and gas expansion*
- Underground blow-outs → pressurizing shallow layers
- Smectite -Illite conversion → Water release T>60°C

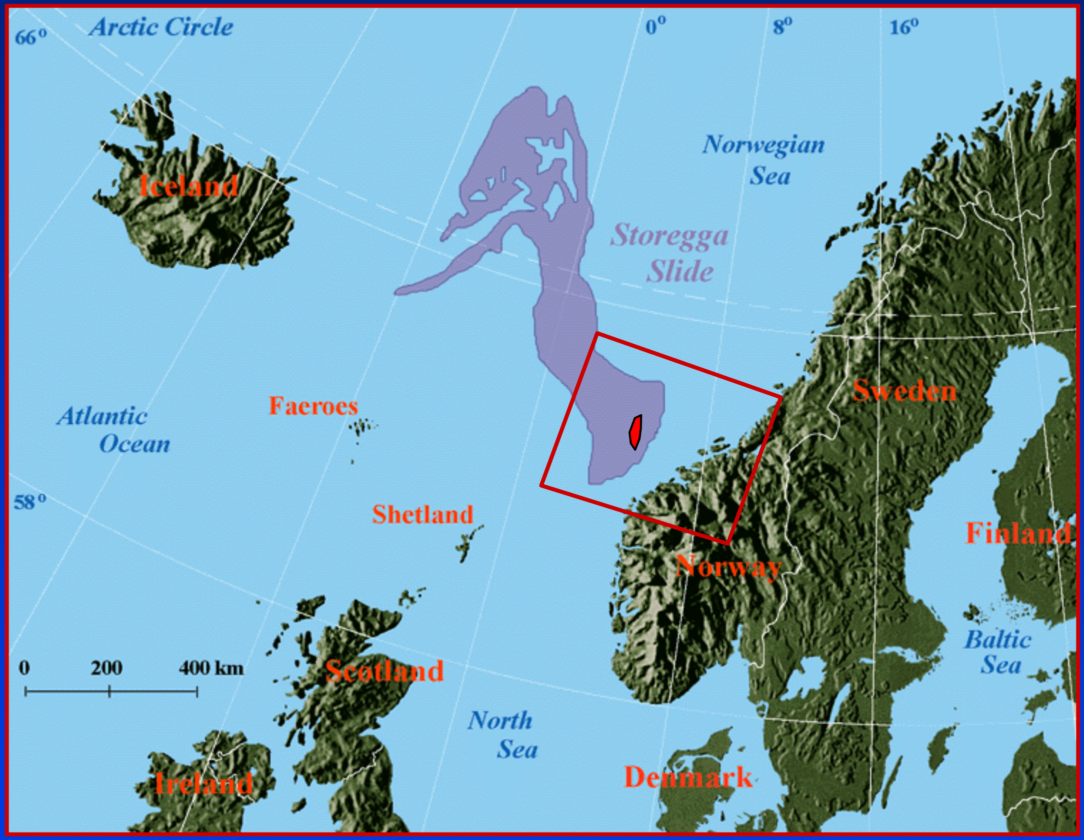
The Storegga Slide (8000 yrsBP)



Headwall 300 km
Run-out ~ 800 km
Volume ~ 5.600 km^3
Area ~ 34.000 km^2



Anwer: The Storegga Slide (~8200 yr. BP)

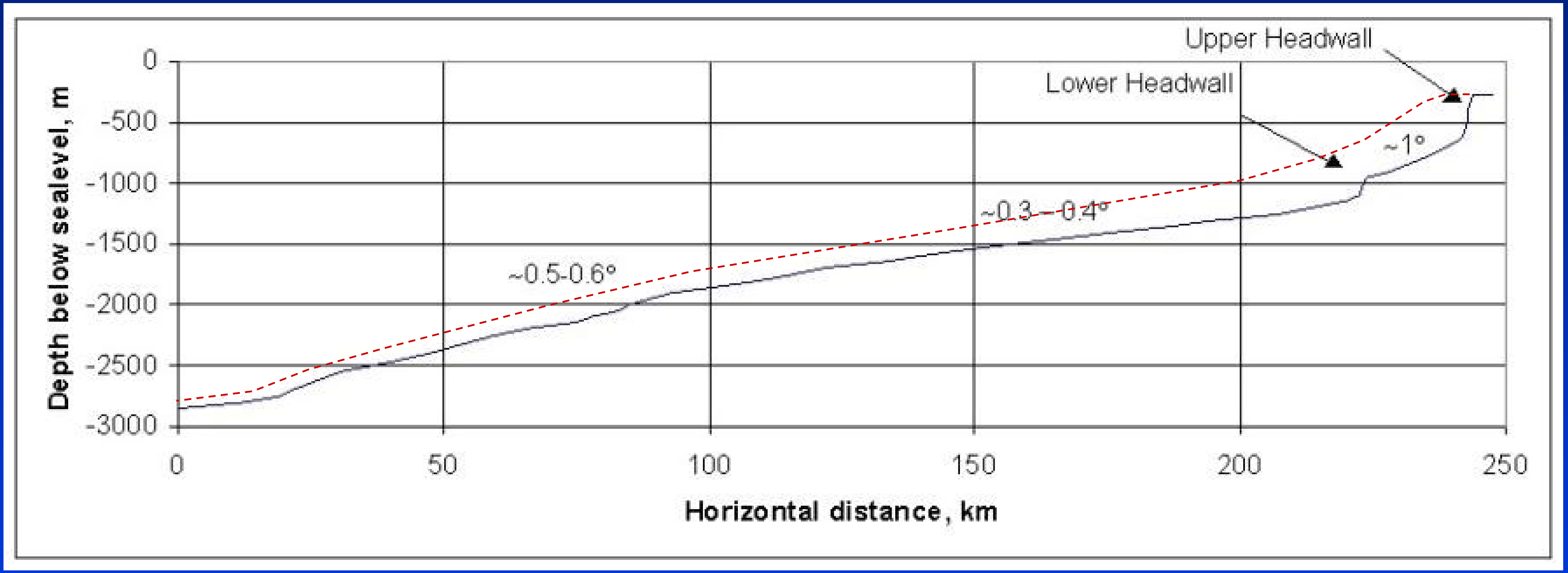


Headwall ~ 300 km
Run-out ~ 800 km
Volume ~ 3.000 km^3

Tsunami:
The slide generated a tsunami that hit the coastlines of Norway, Scotland, Shetland and the Faeroes

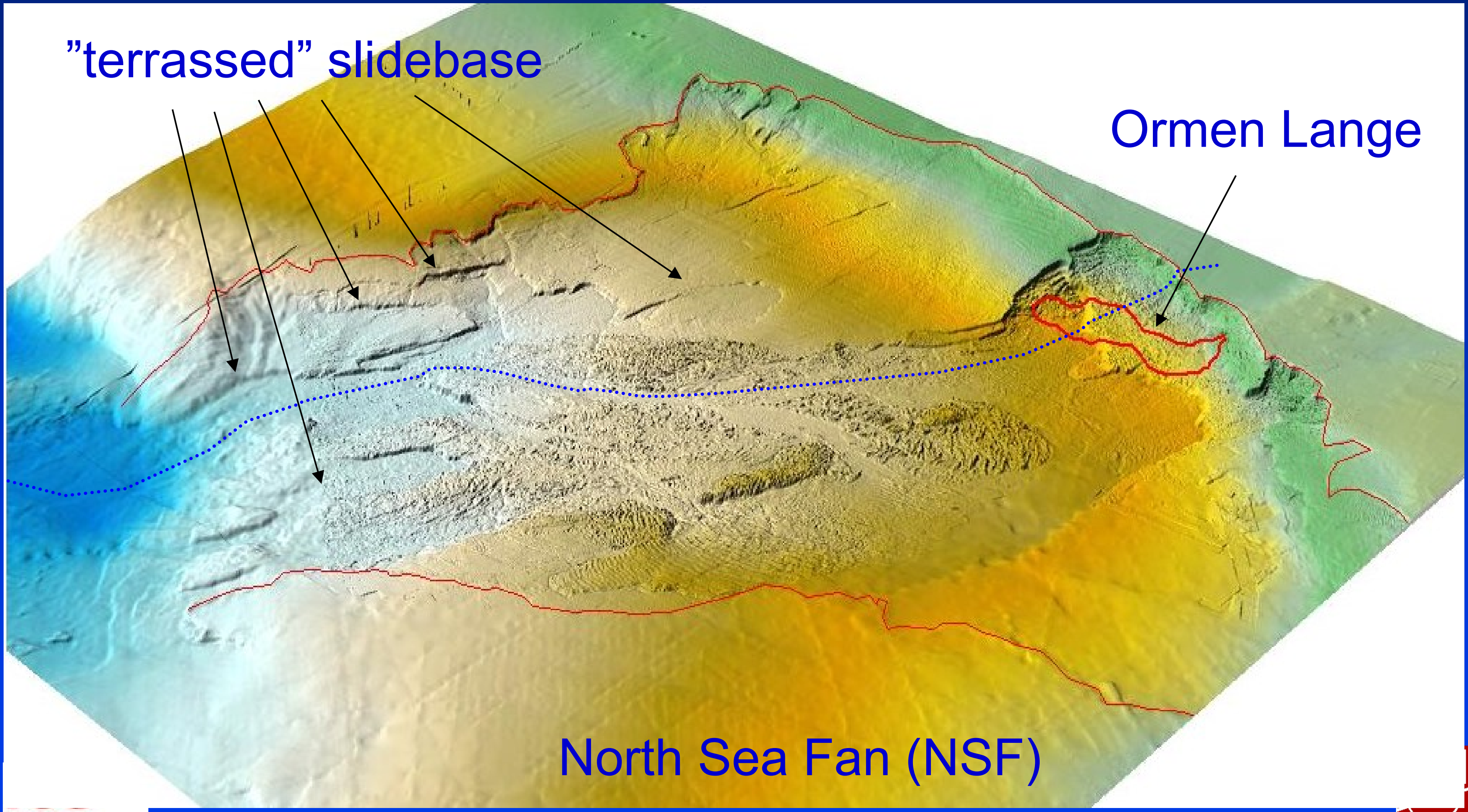
In situ conditions:

Profile from shelf edge to deep basin



How could the Storegga slide develop?

Answer:
Located in the Storegga slide area



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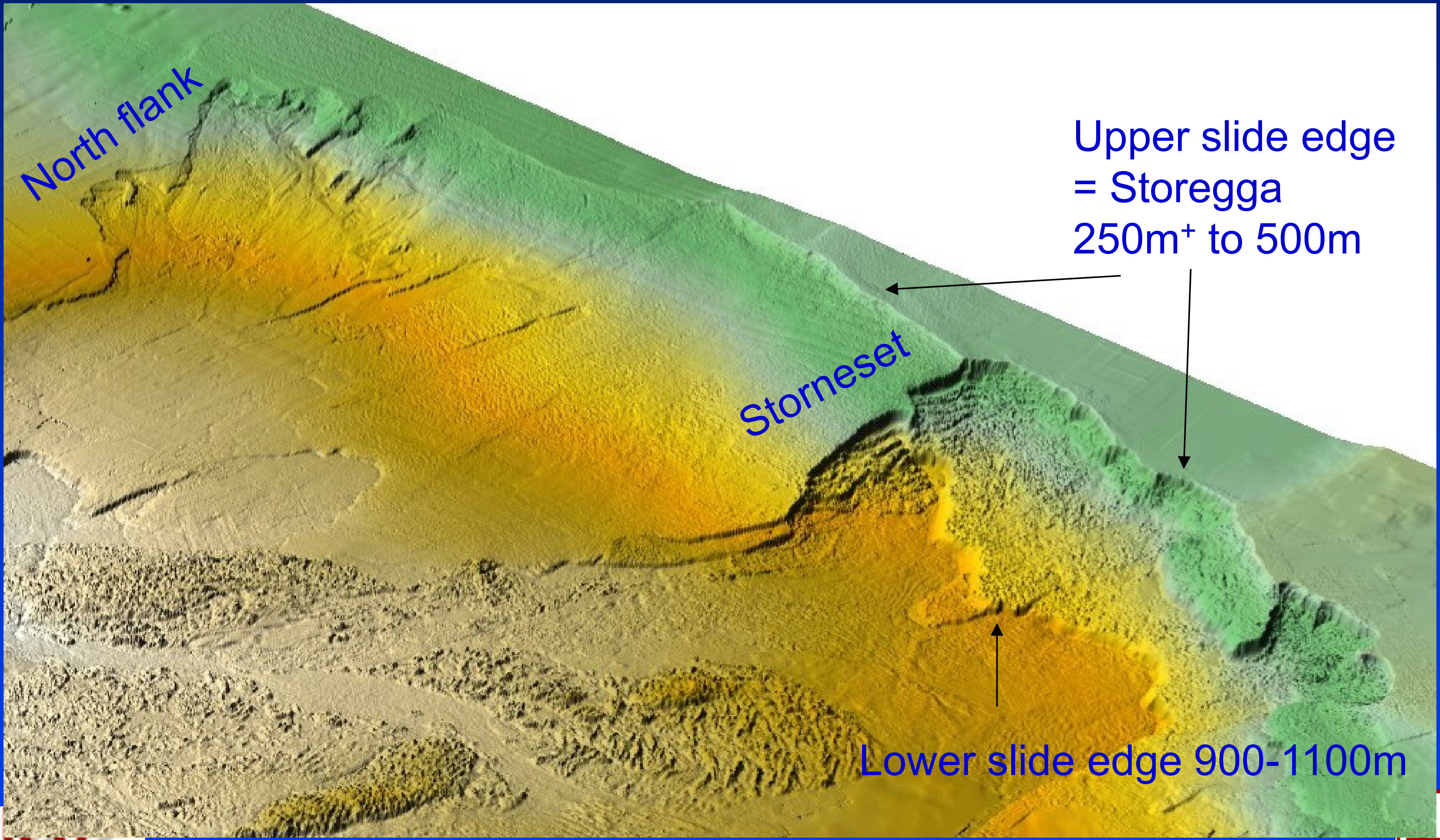
The shelf edge and the central part



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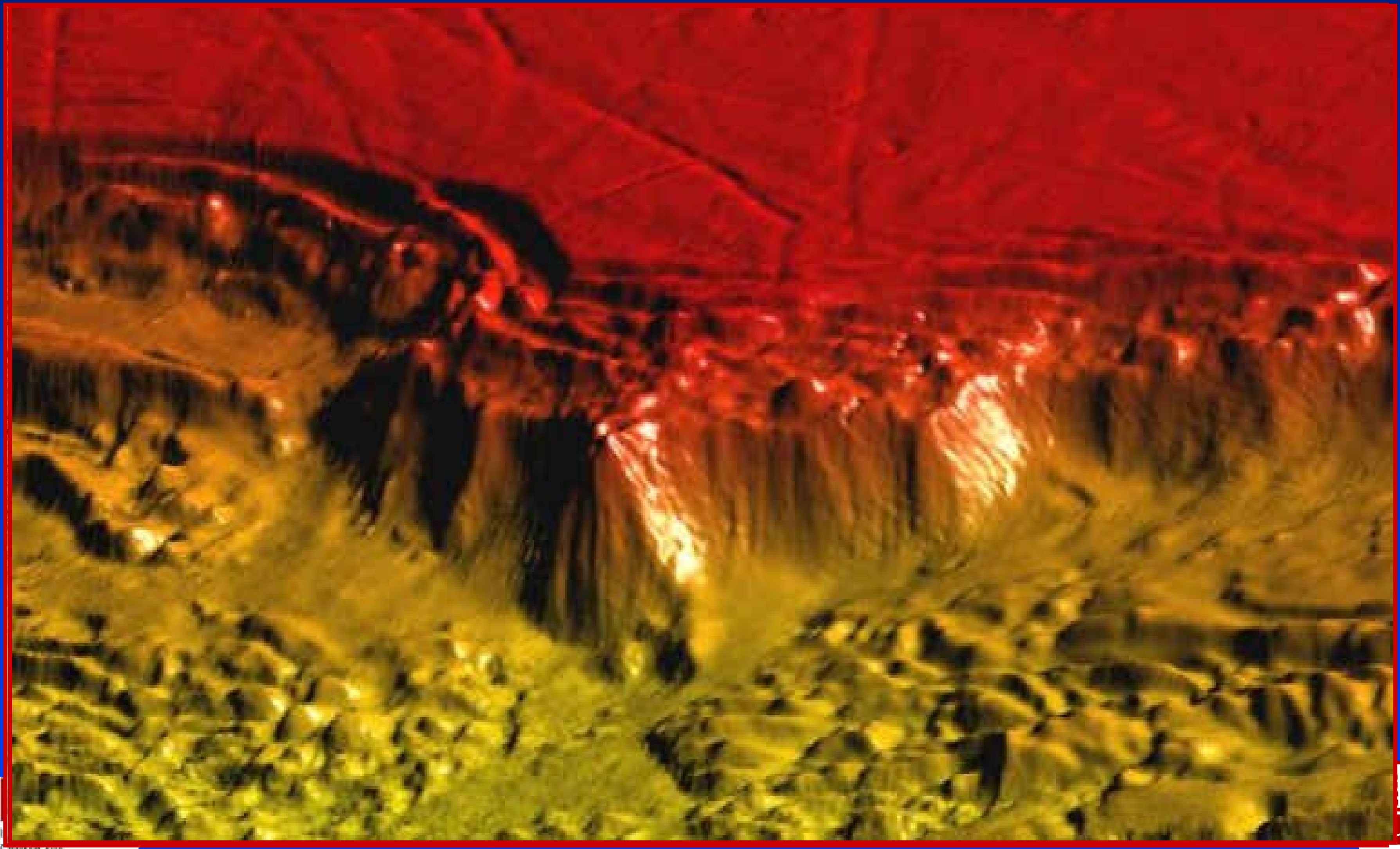
Technical challenge:

Bathymetry in the Ormen Lange area



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Simulation of the Storegga slide tsunami

The main questions for the oil and gas industry were:

- Do we have access to this area?
- Is the natural risk related to new slides too high ?
- Can field development influence slope stability? New Storegga slide? New tsunami?
- Is it safe to develop the Ormen Lange gas field close to the steep headwalls (30 - 40 deg.) of the Storegga Slide?
- How can we explain the Storegga slope failure when the slope angle was close to 1 ° prior to the sliding?

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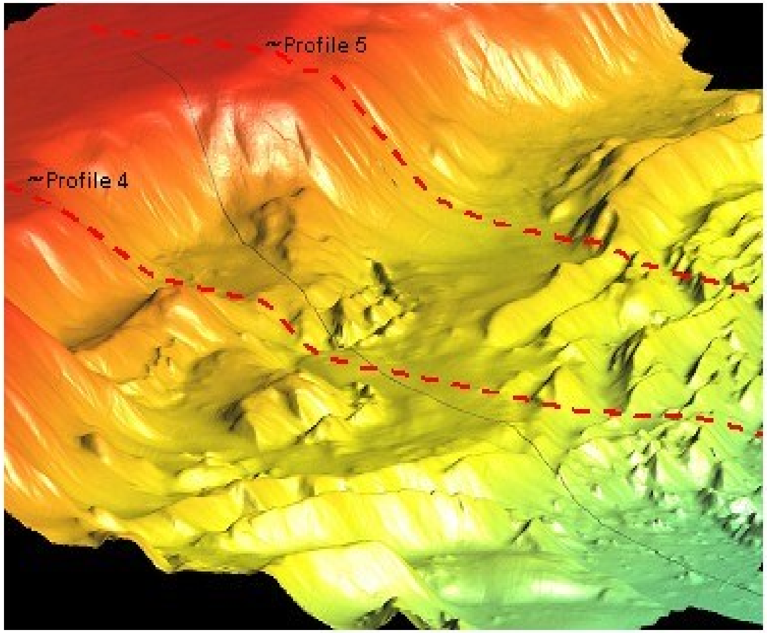
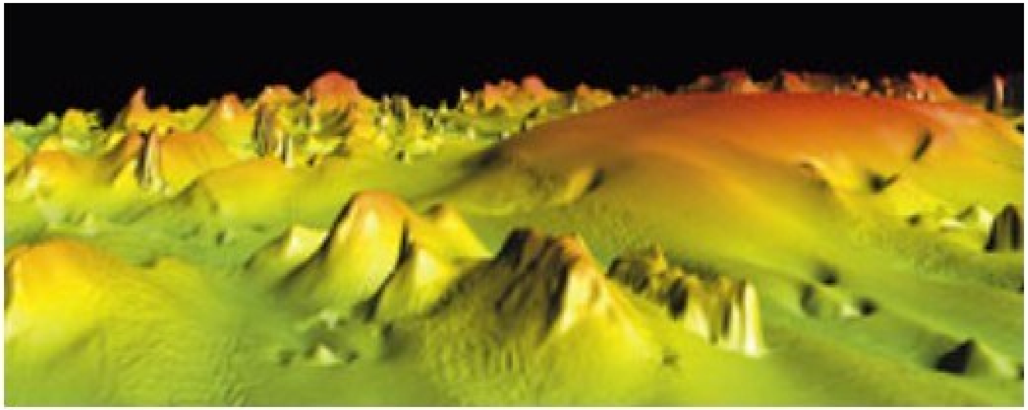
Technical challenge:

Local bathymetry - routing



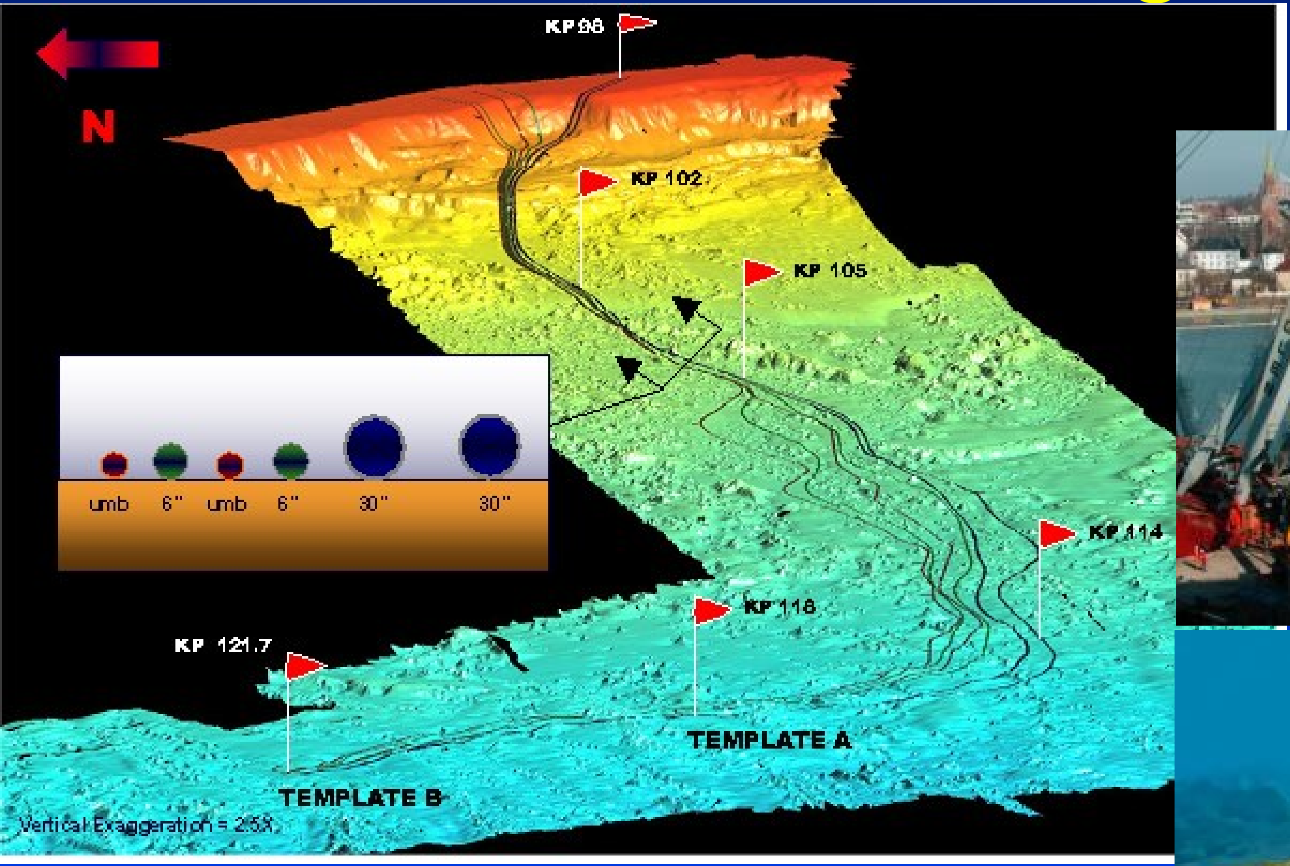
Upper headwall pipeline crossing area

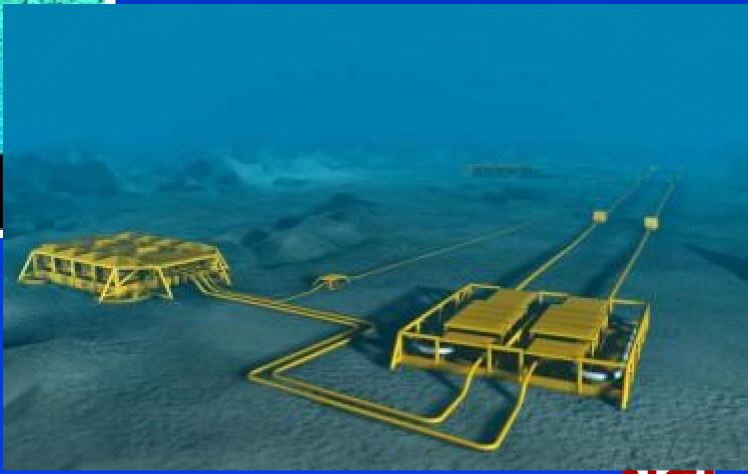


Field development area

Investments in deepwater field development area:

Wells, subsea equipment, pipelines, MEG and umbilicals, trenching, rockfill





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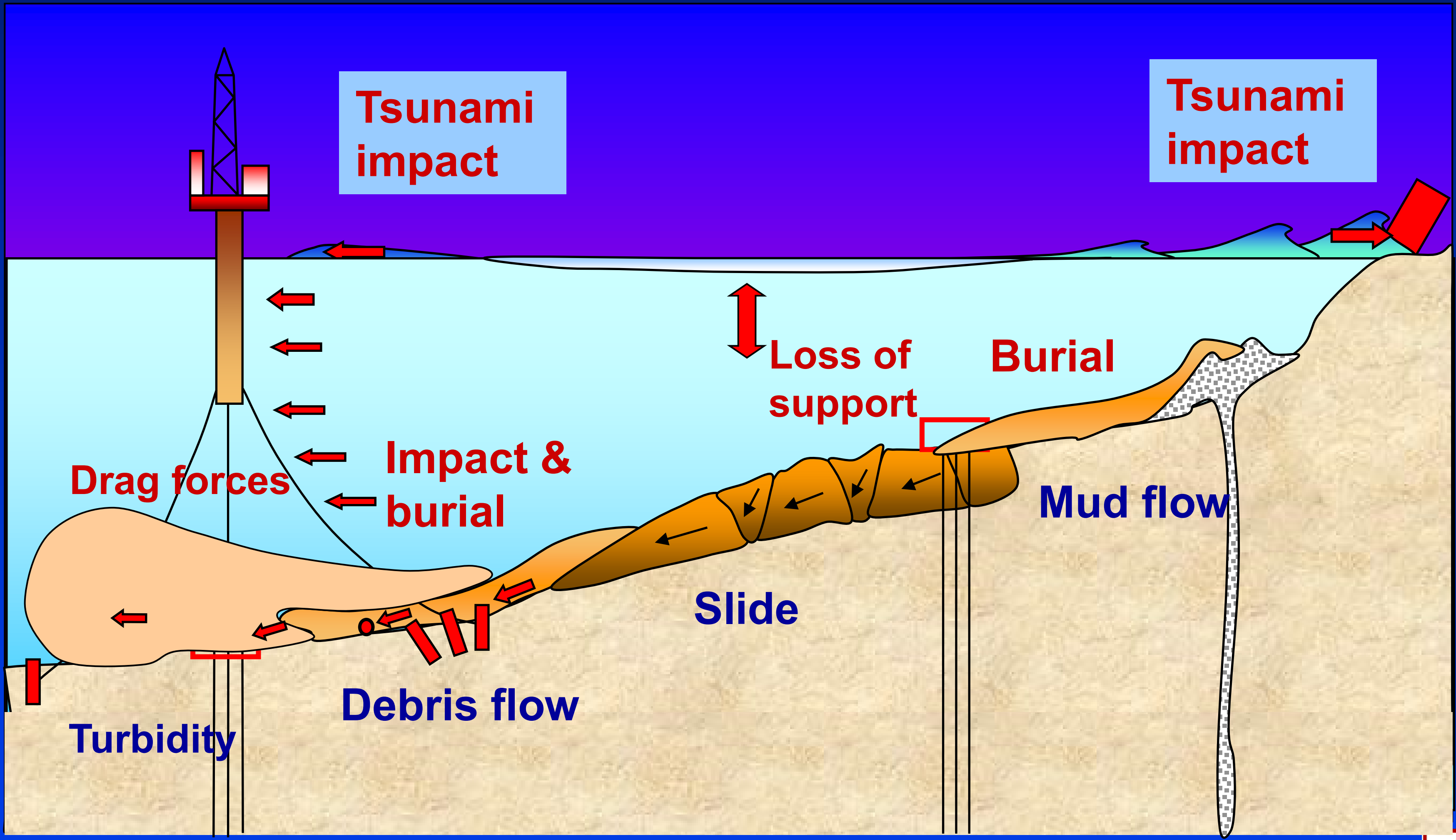
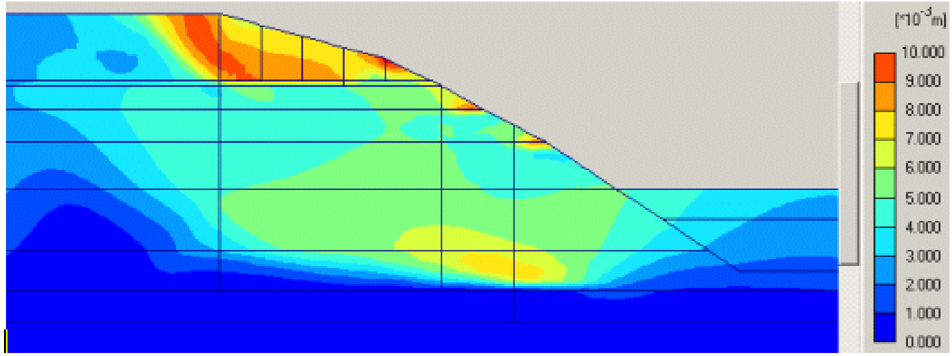
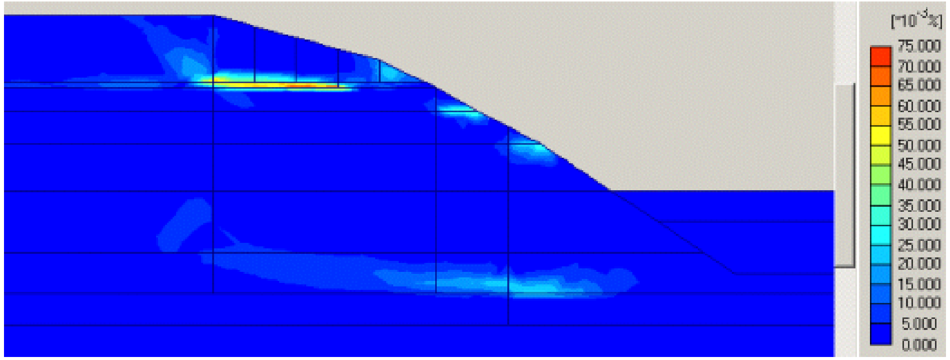
Slide consequences



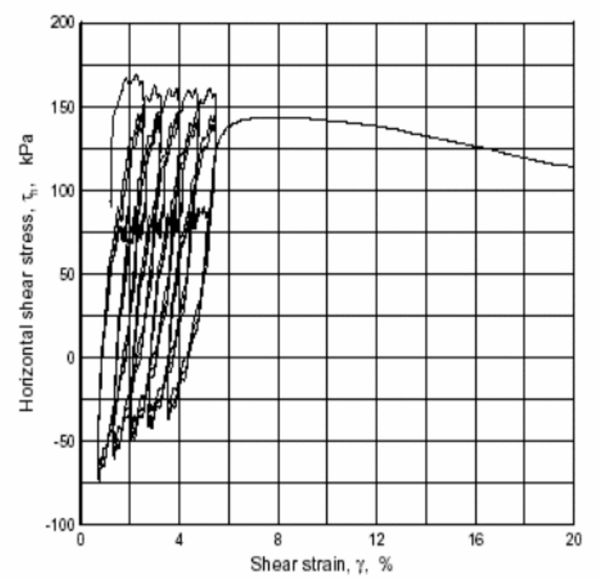
2-D Earthquake analyses:
Post earthquake accumulated displacements and strains

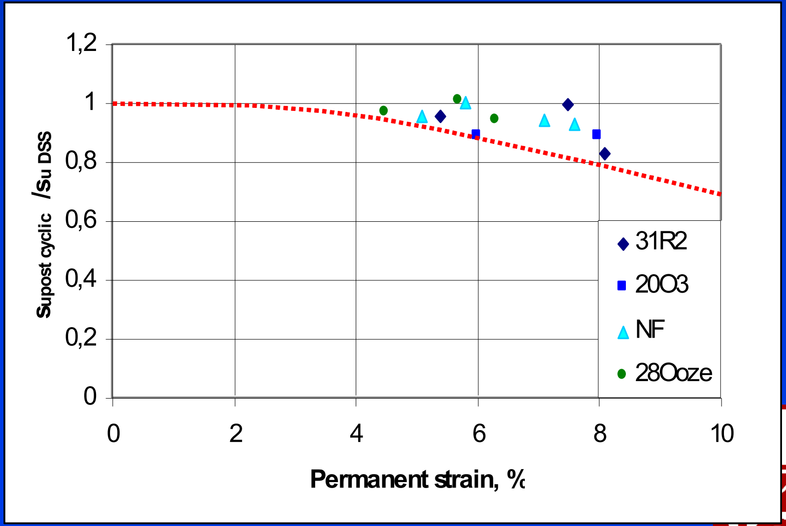


Permanent displacements at end of earthquake shaking: Base Case with Δu=10%, PGA = 0.3 g.



Permanent shear strains at end of earthquake shaking: Base Case with Δu=10%, PGA = 0.3 g.





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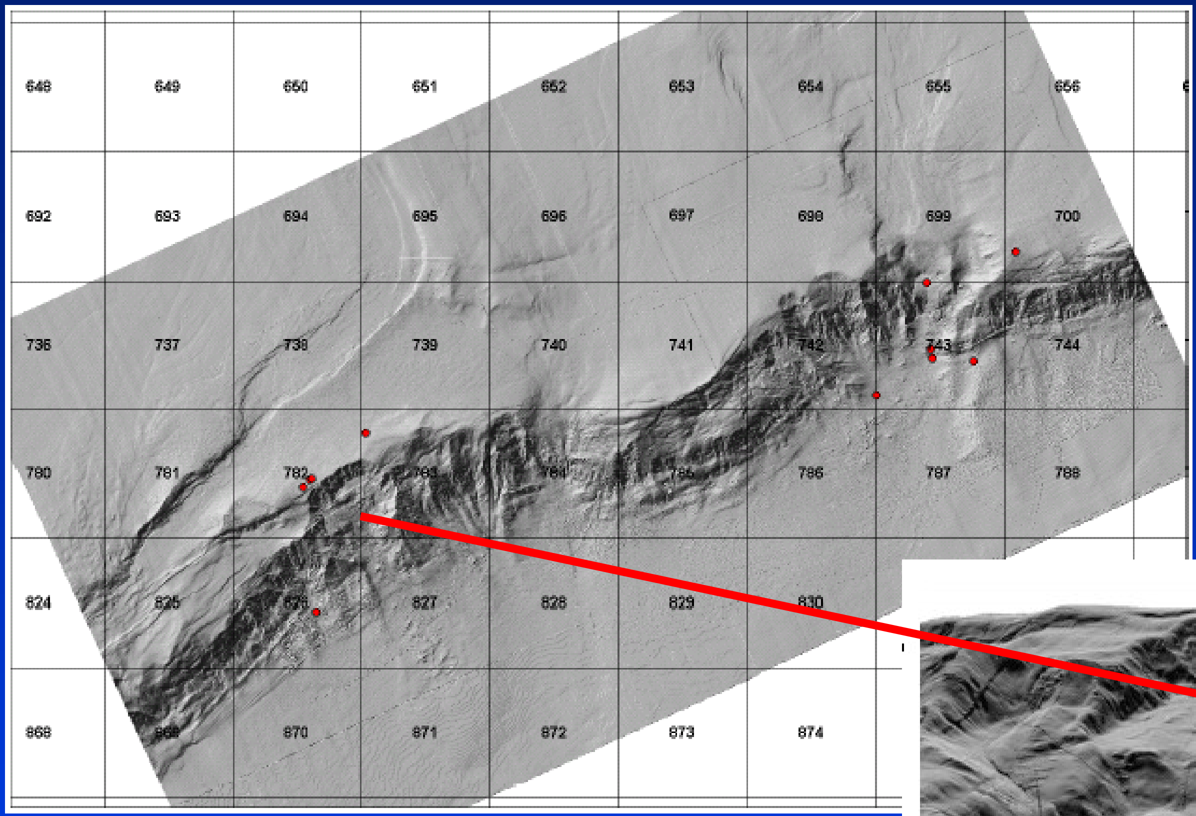
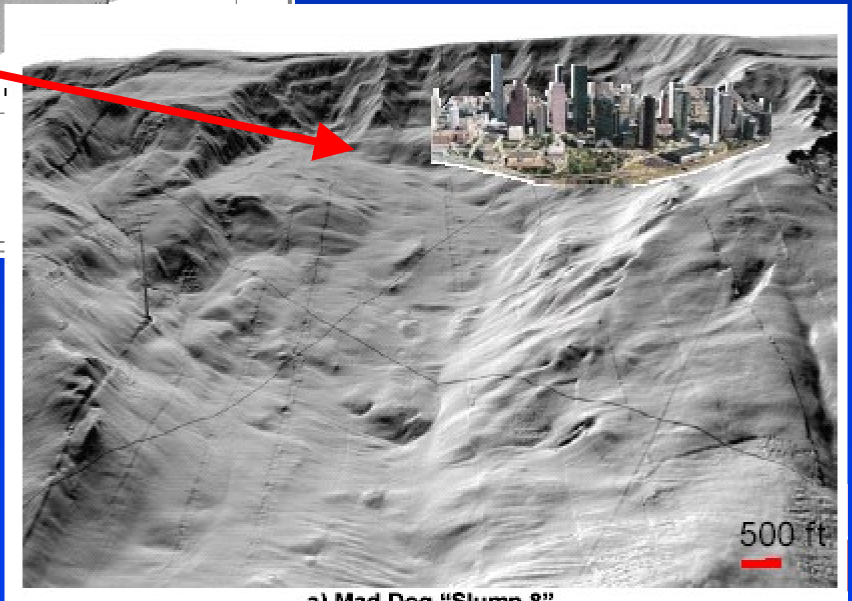
Not only in high latitudes!



The Sigsbee Escarpment in GoM is formed by salt tectonics, which is still ongoing. Several slides occur along the escarpment, which is an area of petroleum exploration.



a) Mad Dog "Slump 8"

Slump 8 of the Mad Dog field is not of Storegga size, but still…..

Jeanjean et al., 2003

Uncertainty in soil shear strength

- The uncertainty in the undrained soil shear strength is derived from the probabilistic description of the parameters entering the SHANSEP equation in each layer:

$$\alpha, \ \gamma', \ m, \ h, \ \Delta\sigma, \kappa$$

NOTE:

Strength Anisotropy: $s_{u,\ at\ inclination\ \theta} = s_u\,(1 + (\kappa - 1)\sin 2\theta)$

κ = shear strength anisotropy factor (1.0 - 1.5)

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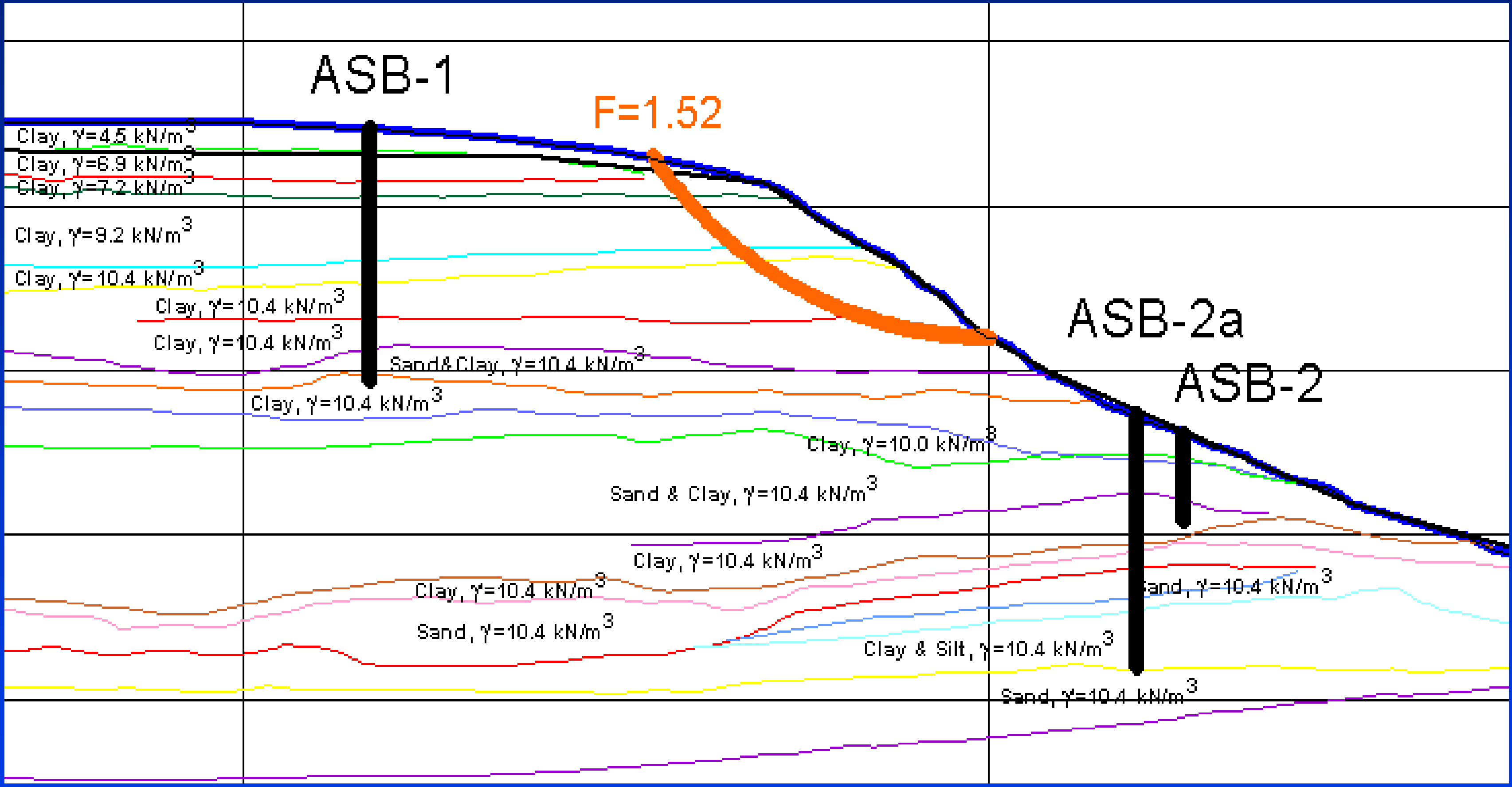
Atlantis Field, Slump E – Undrained stability



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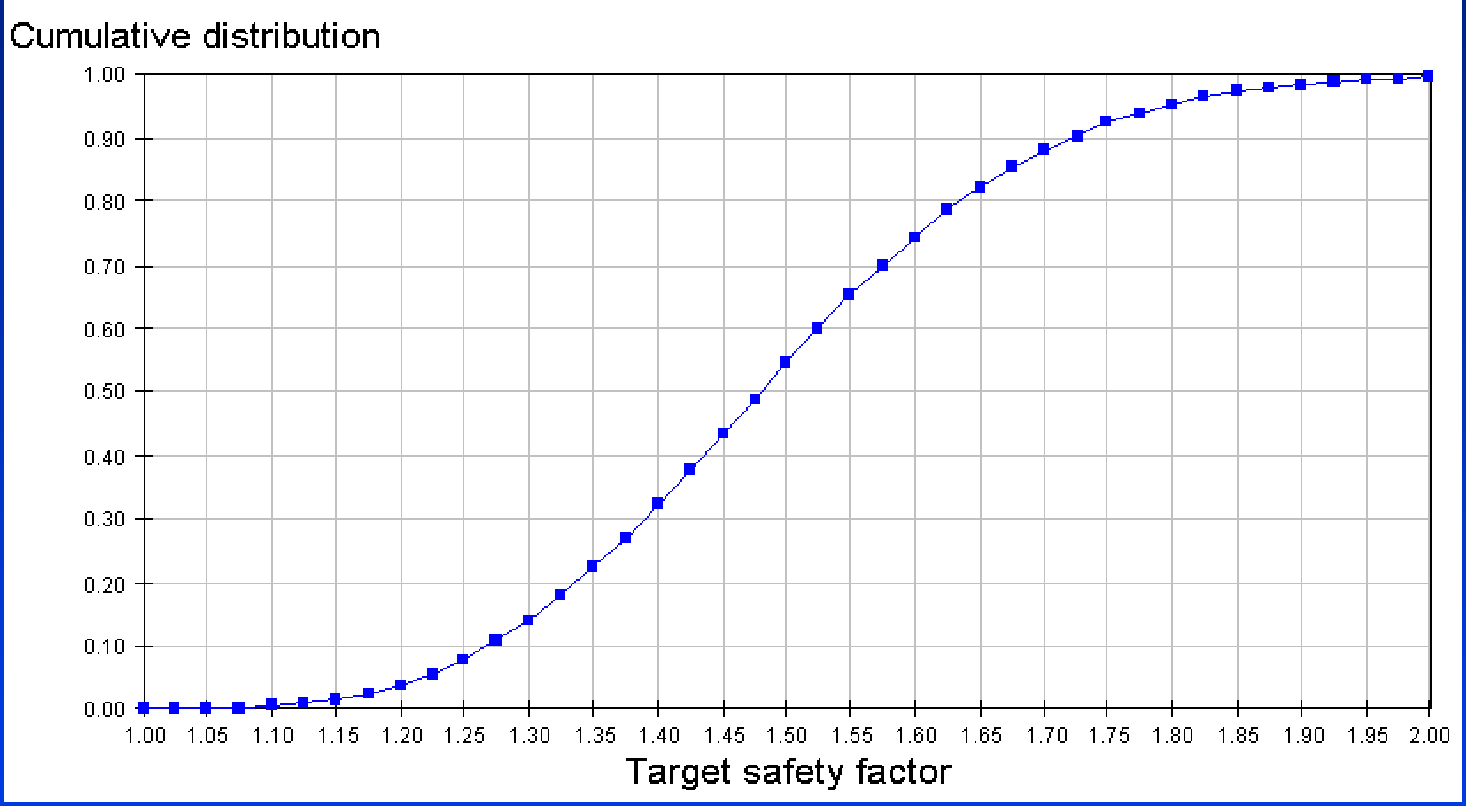
Distribution of safety factor - Slump E



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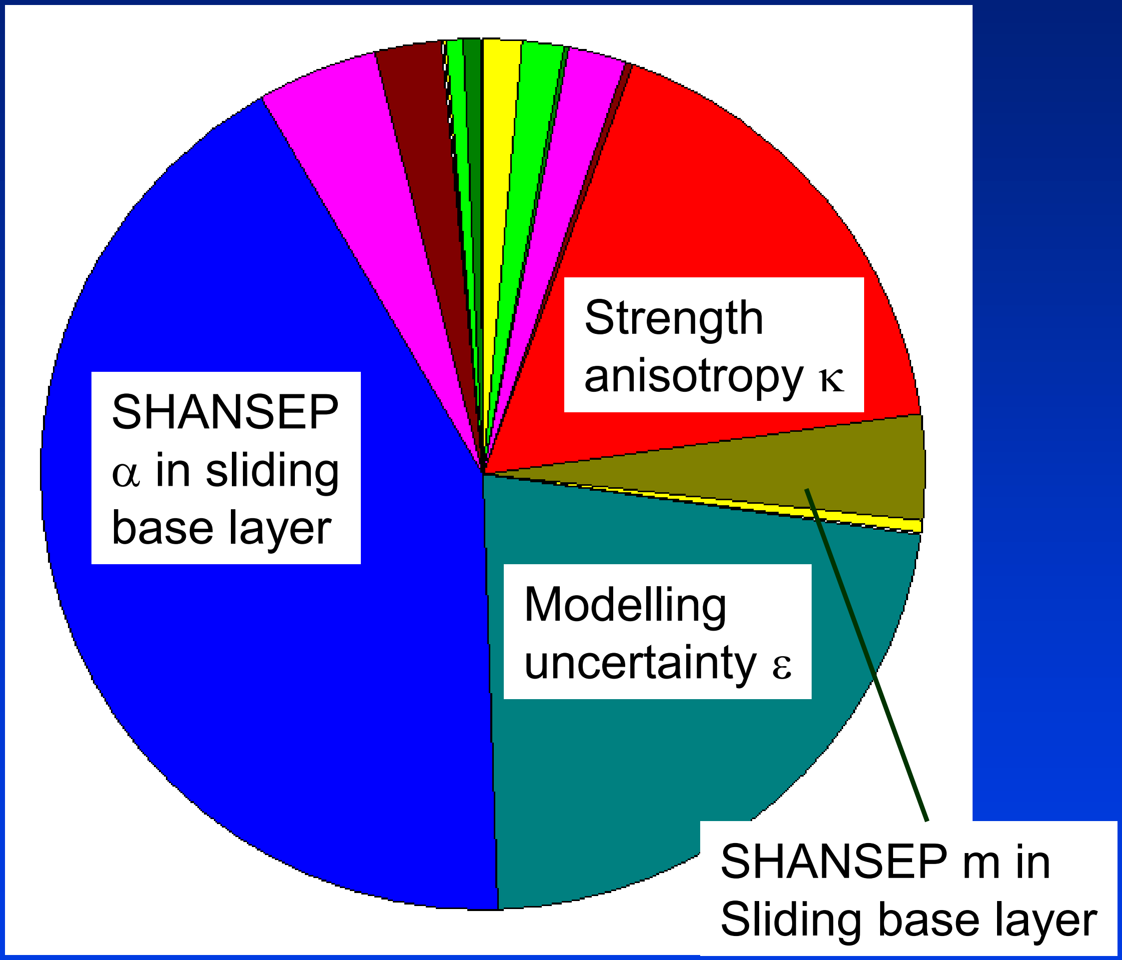
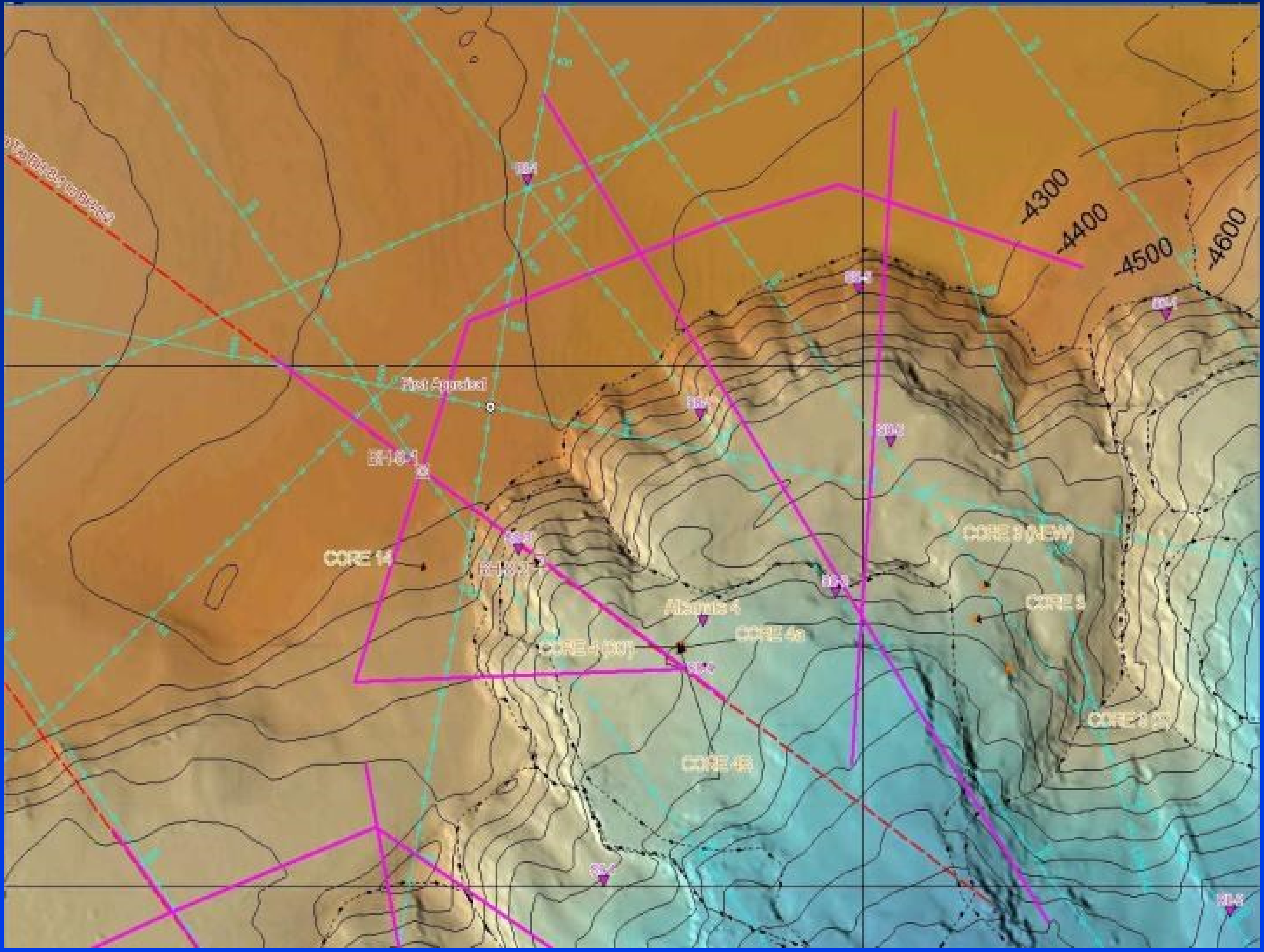
Sensitivity factors for random variables - Slump E

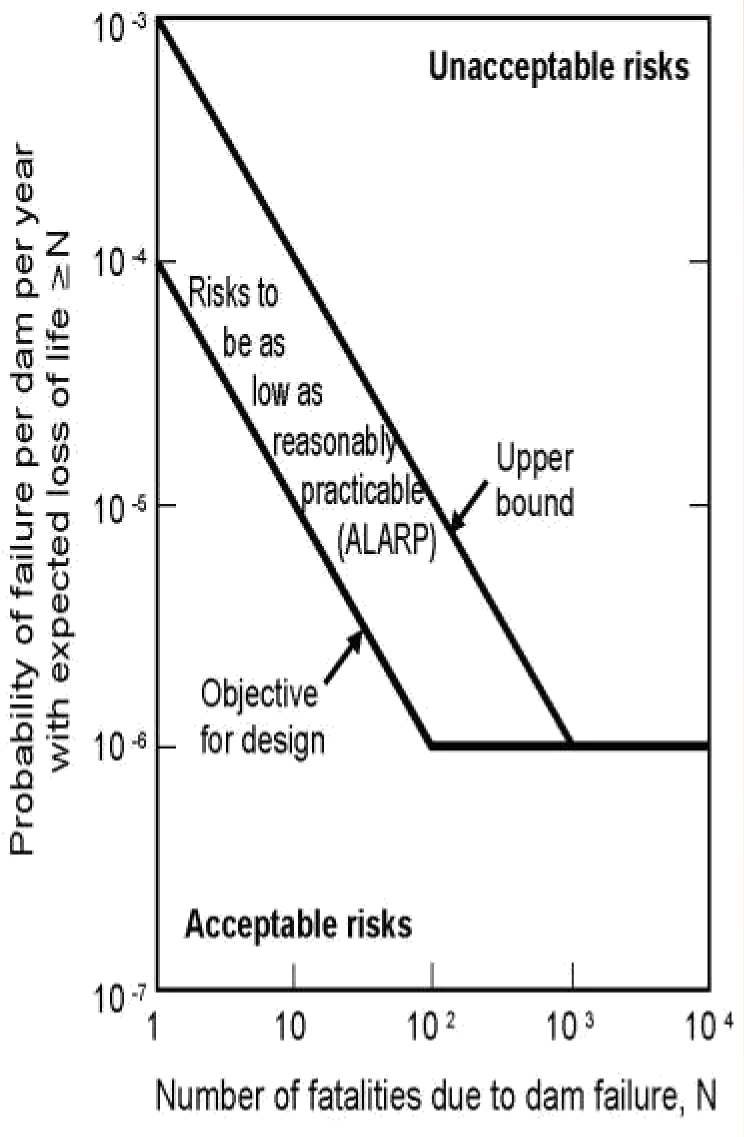


Parameters contributing most to total uncertainty:

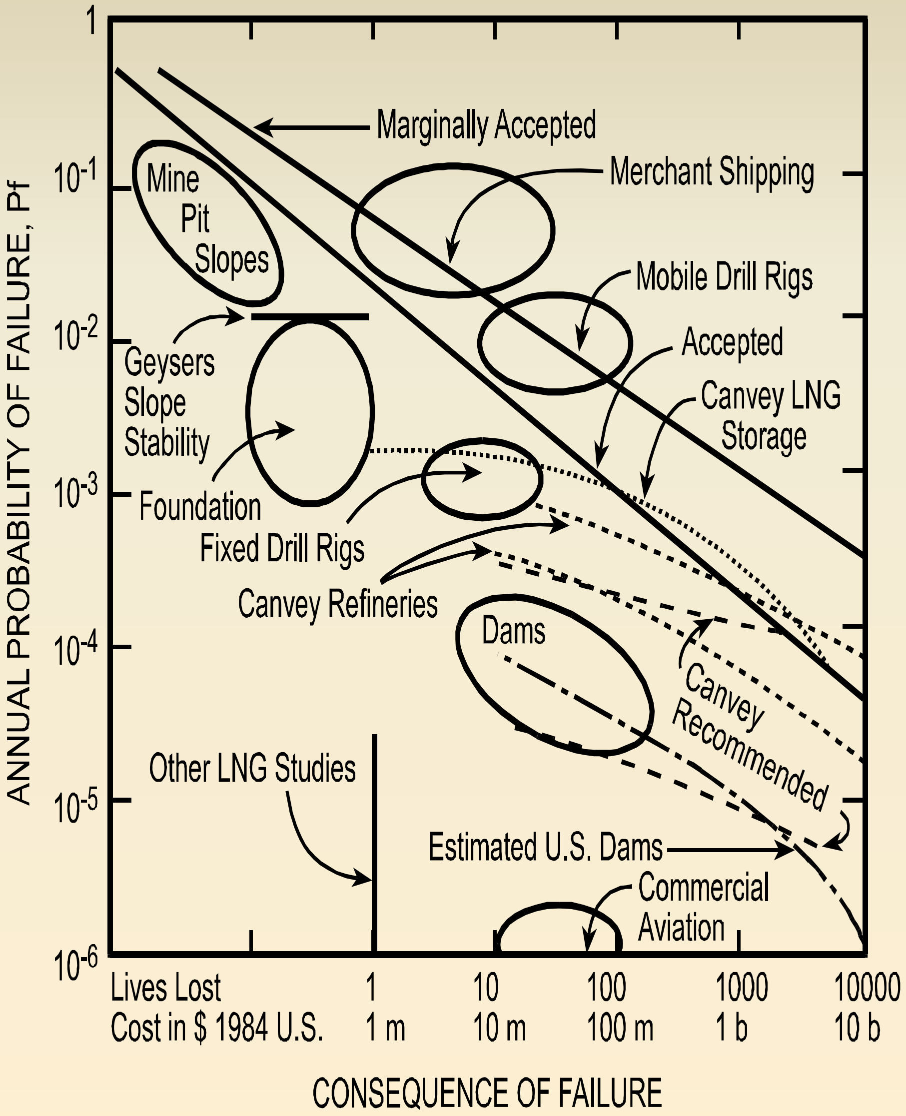
1. Soil shear strength parameters α and m (increasing importance with depth)
2. Modelling uncertainty
3. Anisotropy parameter
4. Elevation of seabed prior to previous slide
5. Maximum past pressure in deep layers

Mad Dog Prospect
Slumps 8_1, 8_2, 8_3 and 8_4





Unacceptable risks
Risks to be as low as reasonably practicable (ALARP)
Upper bound
Objective for design
Acceptable risks
Probability of failure per dam per year with expected loss of life ≥N
Number of fatalities due to dam failure, N
10 -3
10 -4
10 -5
10 -6
10 -7
1
10
10 2
10 3
10 4



ANNUAL PROBABILITY OF FAILURE, Pf
1
10-1
10-2
10-3
10-4
10-5
10-6
Marginally Accepted
Merchant Shipping
Mine Pit Slopes
Mobile Drill Rigs
Accepted
Canvey LNG Storage
Geysers Slope Stability
Foundation
Fixed Drill Rigs
Canvey Refineries
Dams
Canvey Recommended
Other LNG Studies
Estimated U.S. Dams
Commercial Aviation
Lives Lost 1 10 100 1000 10000
Cost in $ 1984 U.S. 1 m 10 m 100 m 1 b 10 b
CONSEQUENCE OF FAILURE

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Figure 2 Qualitative risk prioritisation matrix

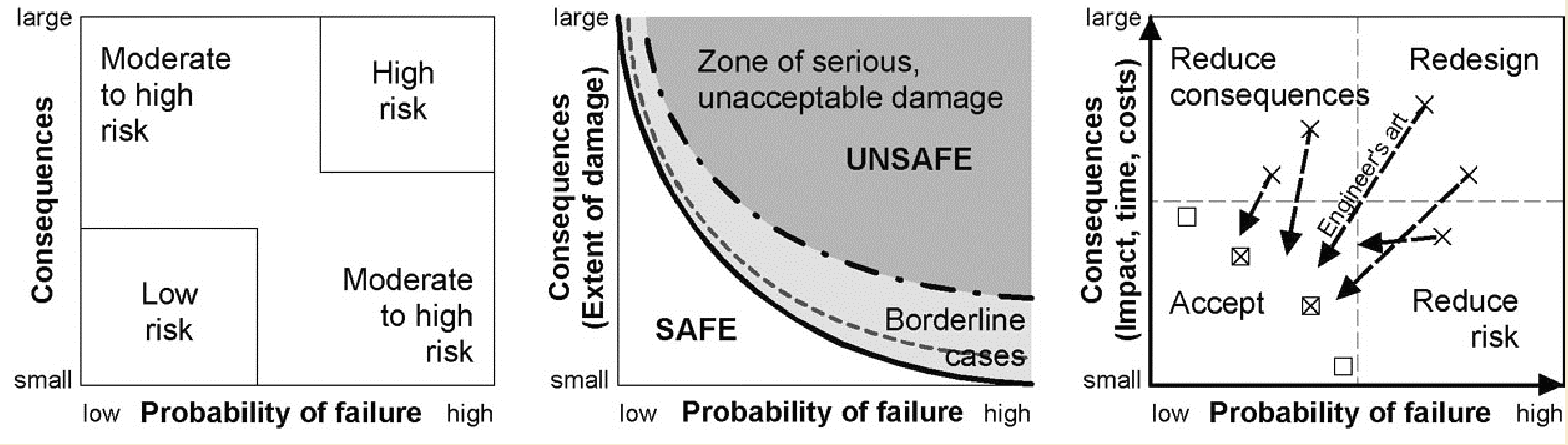

Figure 3 Typical components of a geohazard study and multi-disciplinarity interaction

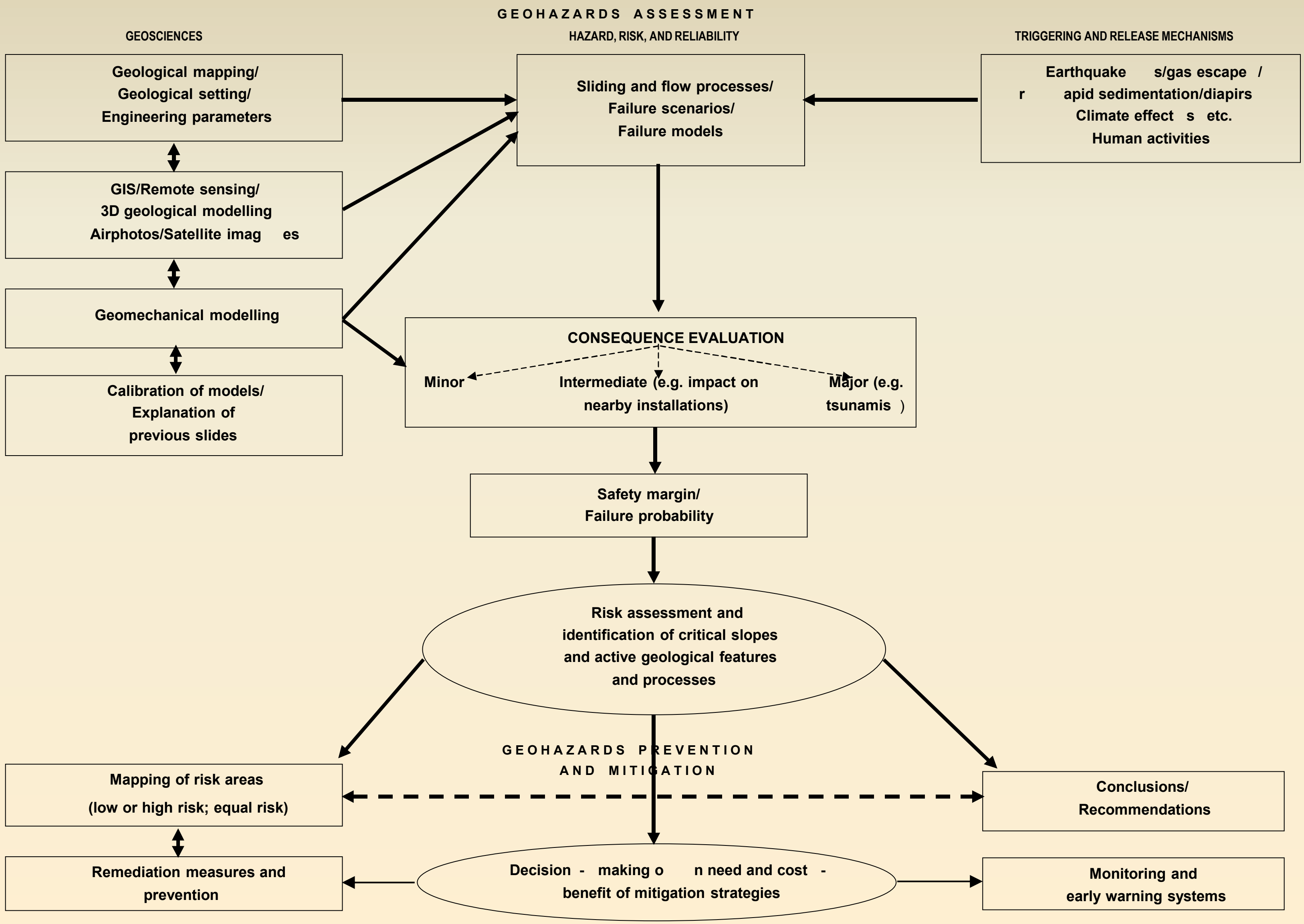

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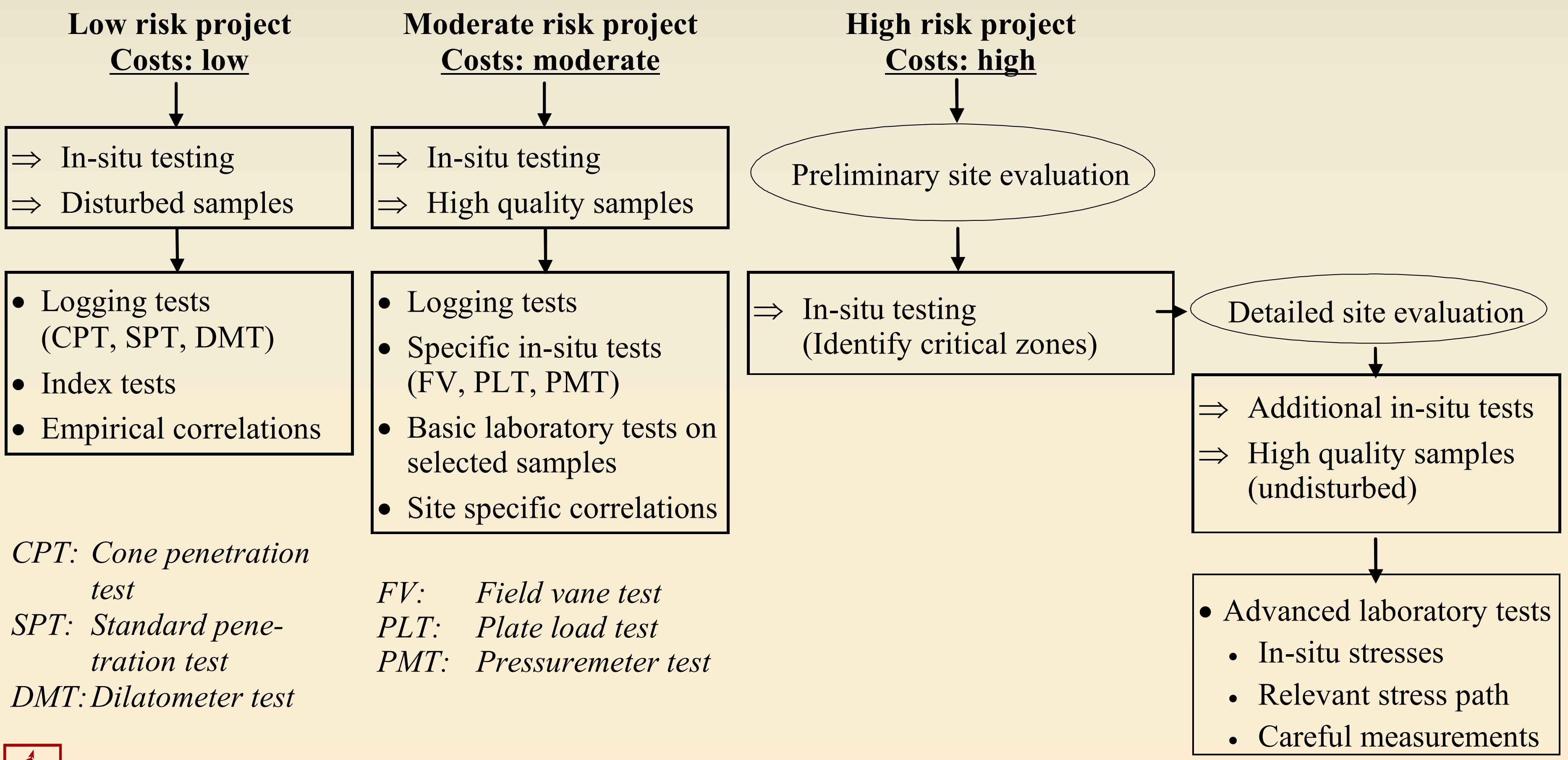
Figure 4 Risk-based soil investigations



CPT: Cone penetration test
SPT: Standard penetration test
DMT: Dilatometer test

FV: Field vane test
PLT: Plate load test
PMT: Pressuremeter test

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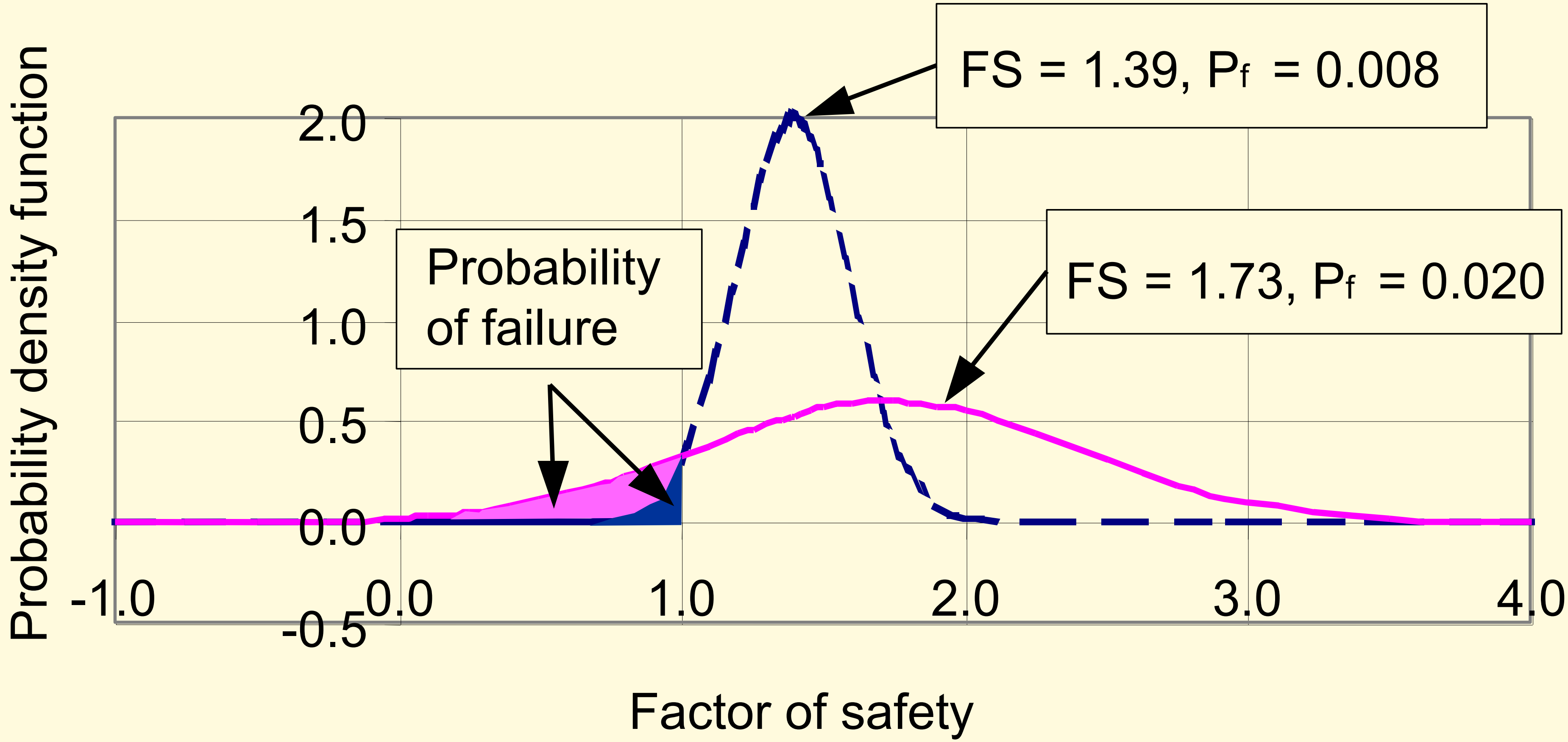
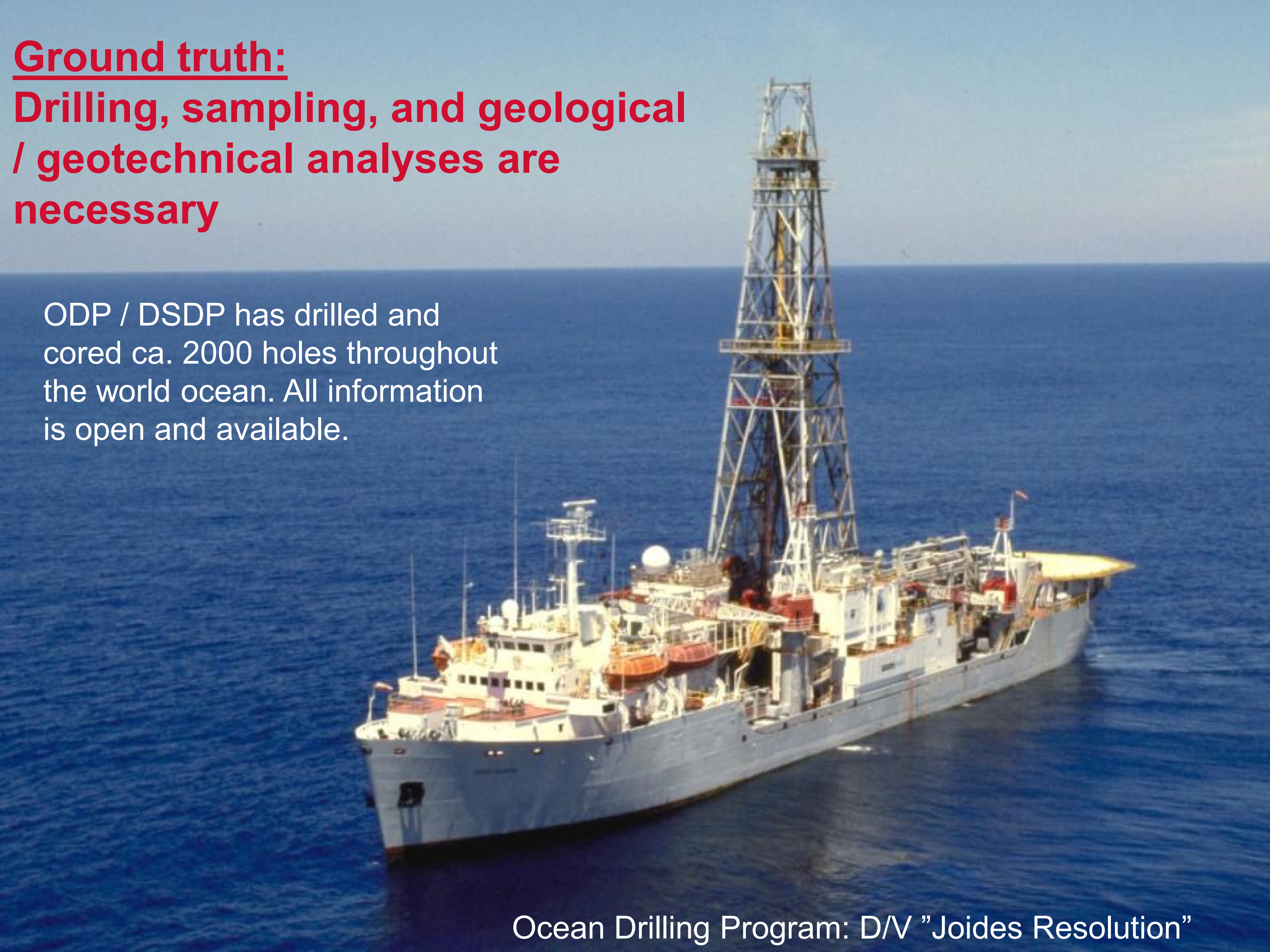
Figure 5 Safety factor and probability of failure for most heavily loaded pile



<u>Ground truth:</u>
Drilling, sampling, and geological / geotechnical analyses are necessary

ODP / DSDP has drilled and cored ca. 2000 holes throughout the world ocean. All information is open and available.



Ocean Drilling Program: D/V ”Joides Resolution”

Conclusions

- Geohazard assessment require multi-discipline geoscience cooperation and understanding
- Thorough understanding of natural and human induced effects in order to identify the relevant failure scenarios for field development
- Areal extent and volumes of potential slides on continental slopes can be very large:
  - *Project risk (total damage, local damage - repair)*
  - *3rd party risk*

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Conclusions

Challenges for the geotechnical discipline:

- In situ conditions; pore pressure, gas hydrates
- Gassy soils and gas hydrate material models
- Brittle/sensitive soils; sampling disturbance, testing
- Analysis methods for retrogressive sliding that explain observed megaslides and slide initiation processes
- Slide dynamics and consequence assessment; run-out, impact, tsunami
- Assessment of uncertainties in risk analysis

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