The Role of the Geotechnical Engineer in Supplying Future Energy Needs

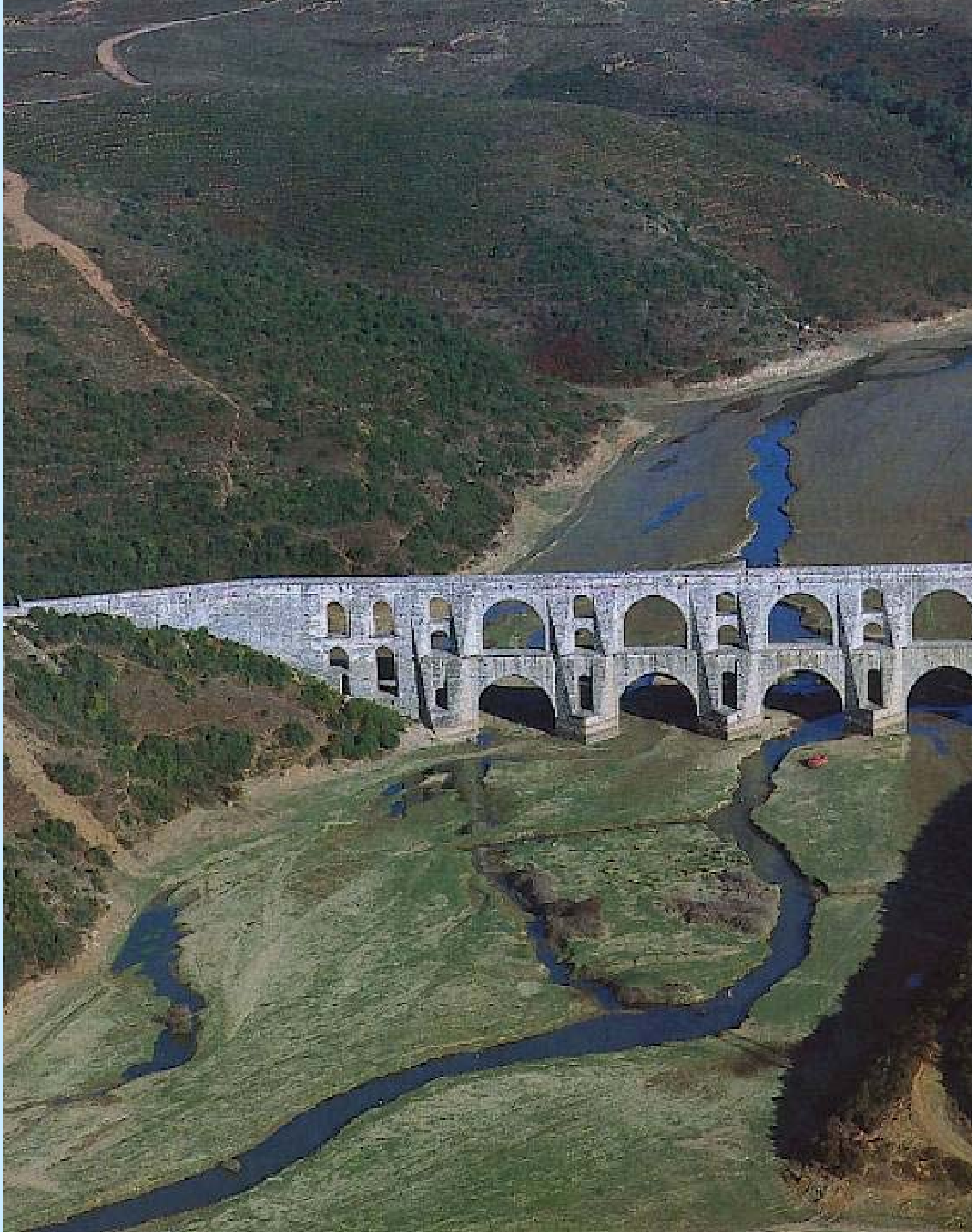
Fifth G.A. Leonards Lecture

Suzanne Lacasse, NGI

7 May 2007

A CHALLENGING ENVIRONMENT

with INCREASING ENERGY NEEDS



Basic needs of our society

- Roads, bridges, airport facilities, navigable waterways, water pipes/gas lines,
- Dams, energy facilities, harbour facilities
- Installations for drinking water, and disposal of wastewater, solid waste and hazardous waste.

Growing challenges

- The demand for energy increases.
- Yesterday's technologies for energy supply, water supply, housing, transportation, and land use are not sufficient for tomorrow's challenges.
- Waste keeps accumulating, we need solutions for radioactive waste.
- Because of land-use patterns, population growth and more extreme weather than before, more people and more property are at risk for natural disasters.

Role of geotechnical engineer

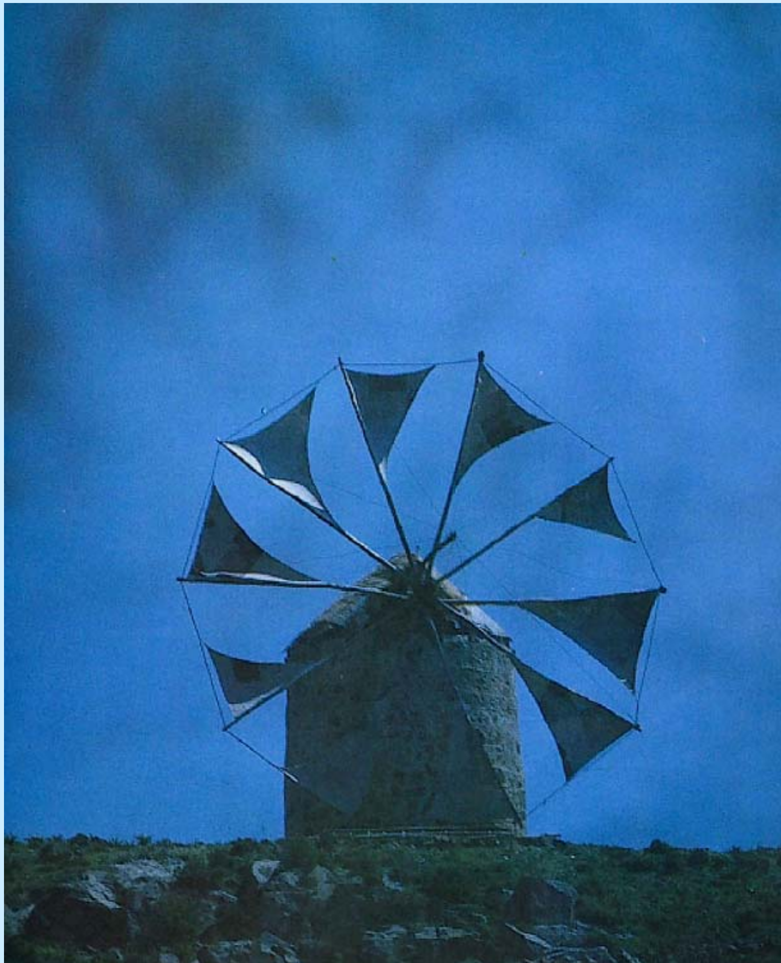
We need to put on our agenda increasing energy needs, effects of population growth, increasing needs for infrastructure, shrinking waste management options, environmental deterioration and threats from natural disasters.

More than before, our profession needs:

- **to highlight the value it adds to society**
- **to constantly reinvent itself by providing innovative solutions**

OUTLINE OF LECTURE

- **Exploitation of oil and gas resources**
- **Storage of radioactive waste**
- **Hydropower**
- **New challenges**

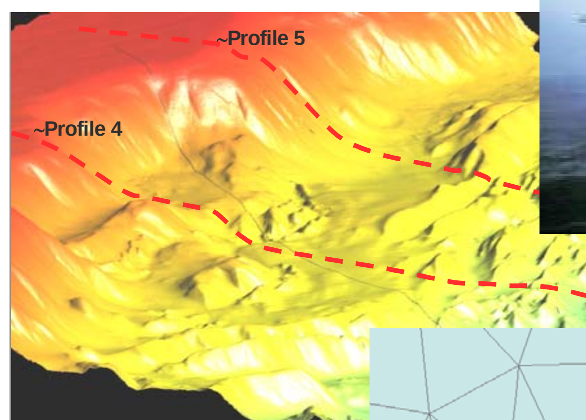


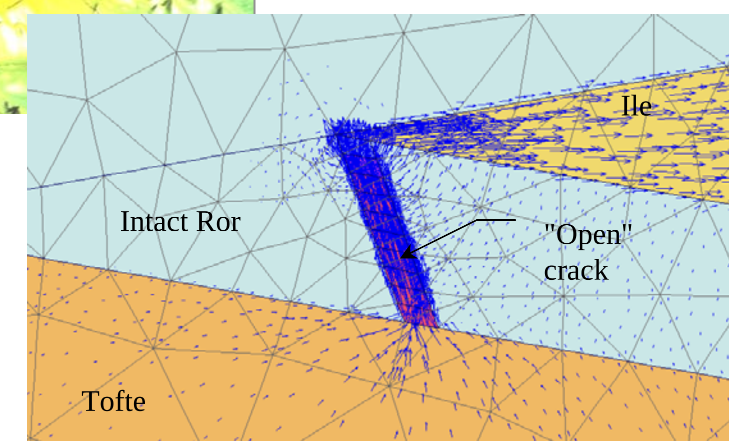
Focusing on

- **Cost-effective solutions**
- **Improved and safer solutions**
- **Innovative solutions**
- **Preserving the environment**

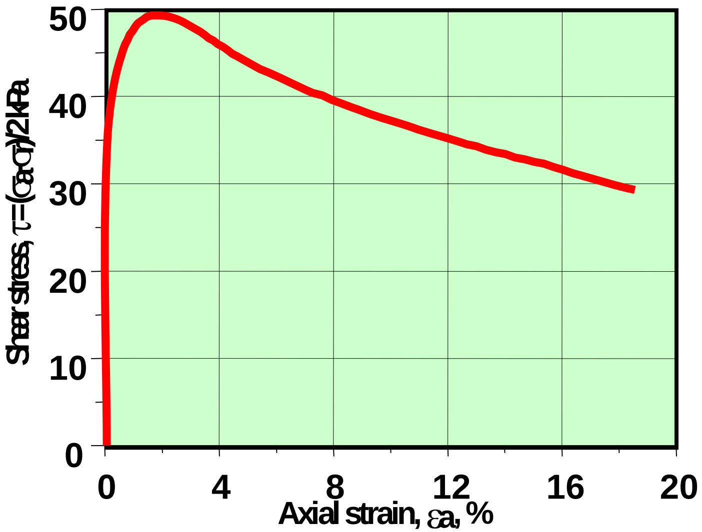
Geotechnical involvement in oil and gas exploitation

- Field investigations
- Geotechnical in situ and lab testing
- Model testing
- Foundation engineering
- Geohazards studies
- Instrumentation and monitoring
- Petroleum geomechanics
- Petroleum geophysics





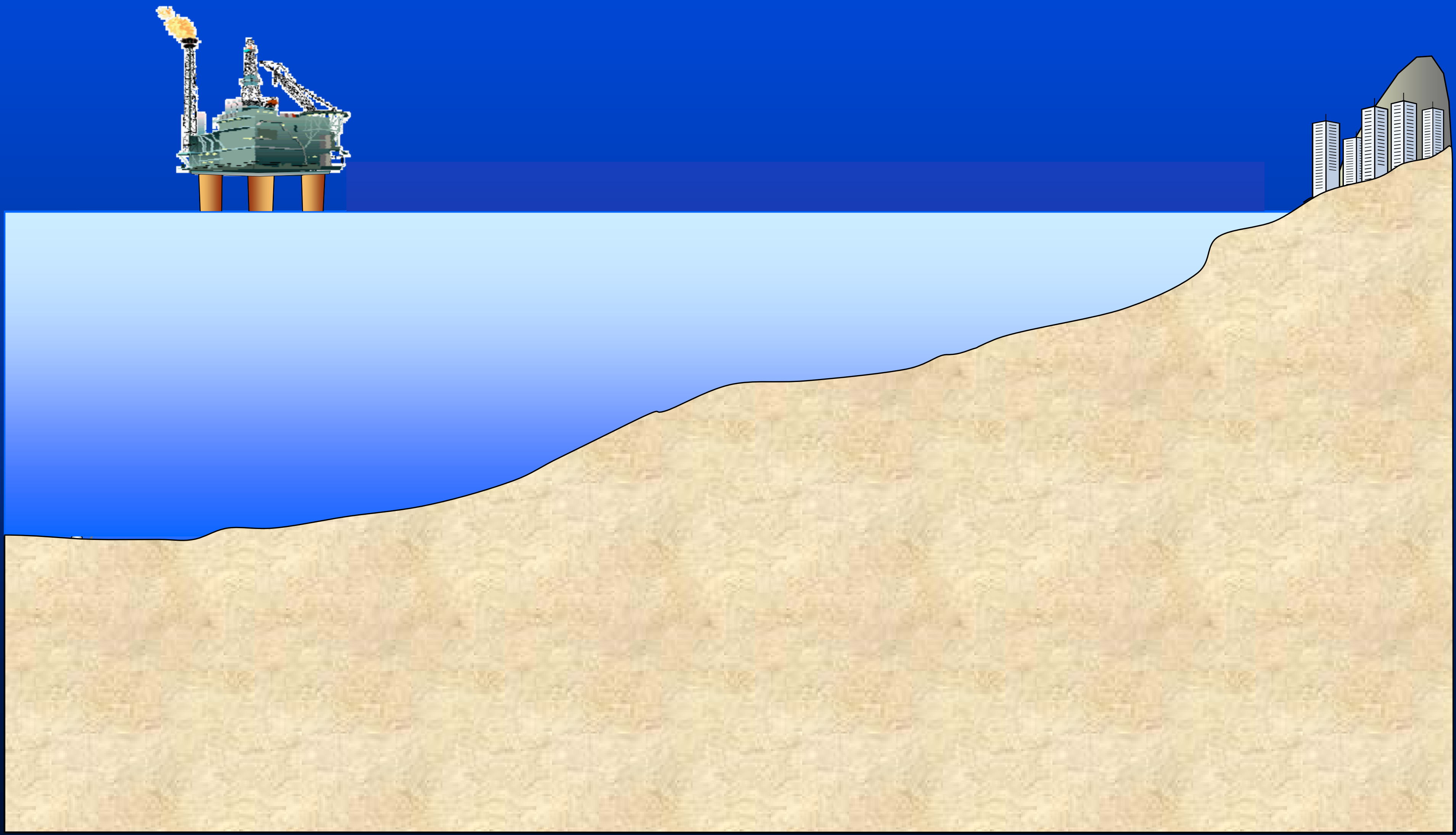
Geotechnical Laboratory



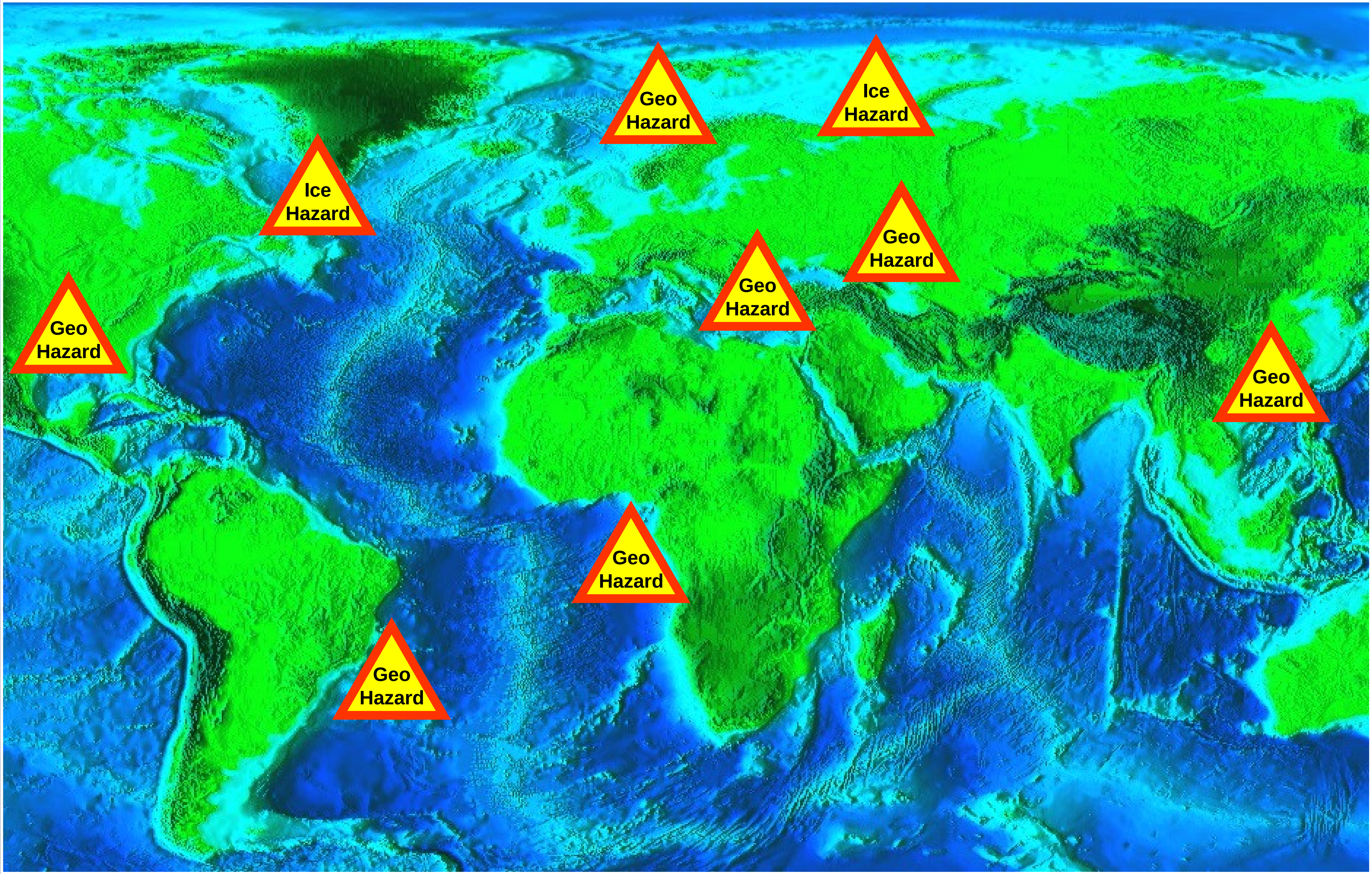
High quality

Skilled personnel

Geohazards – challenges for the oil and gas industry



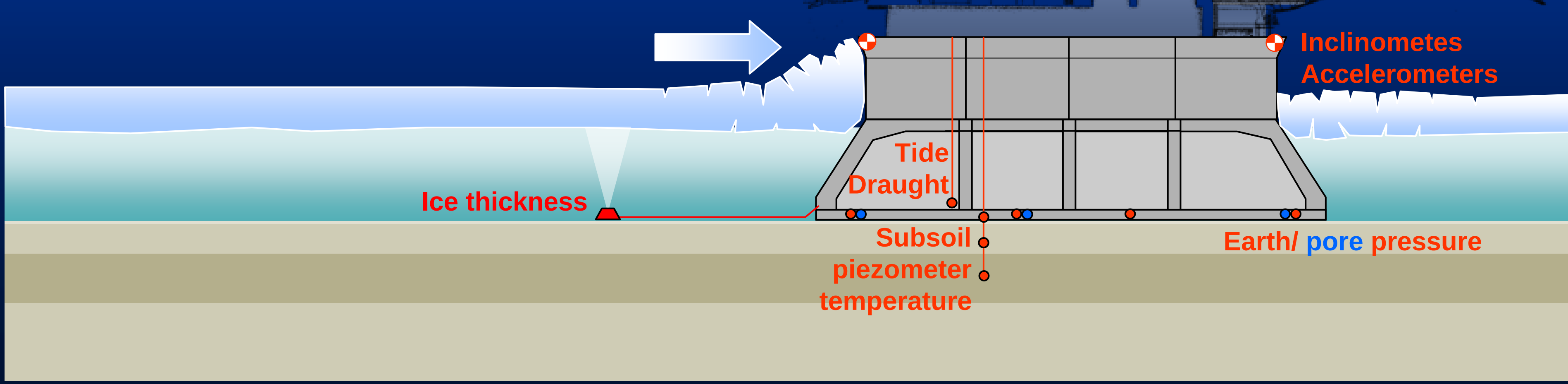
Geohazards around the world



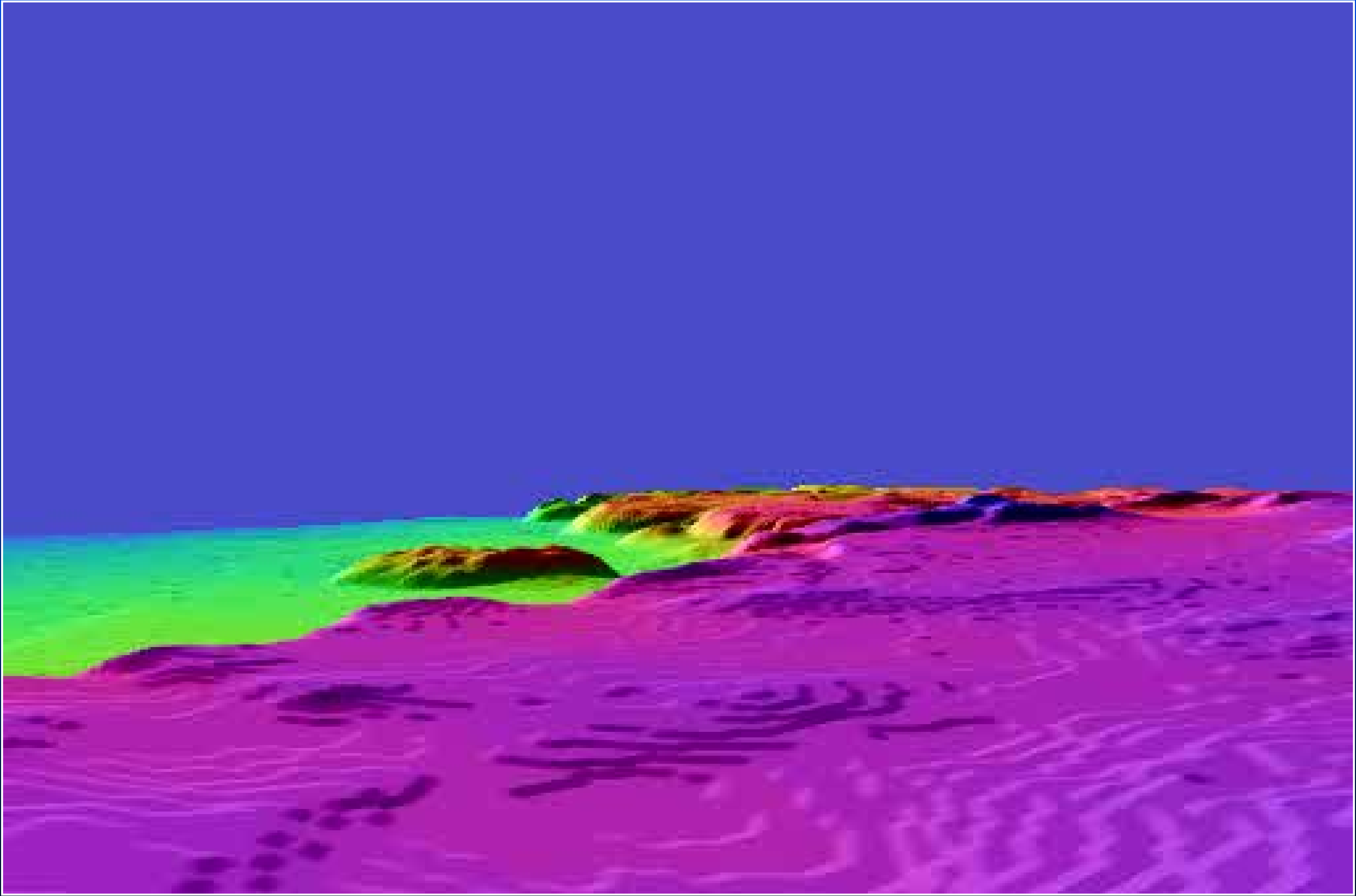
Prirazlomnoye platform

Ice loading – Lateral failure

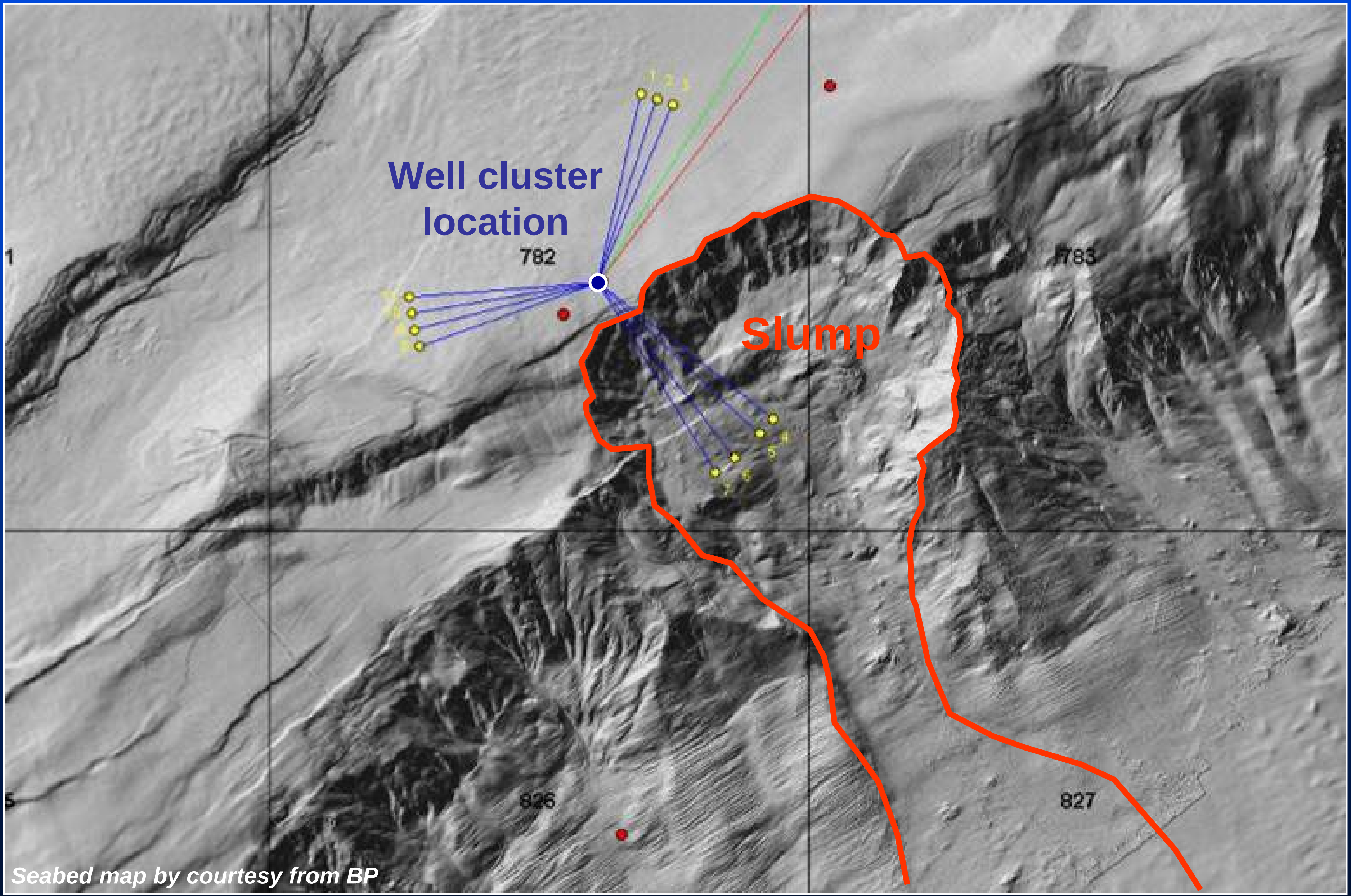
Structural and Environmental monitoring



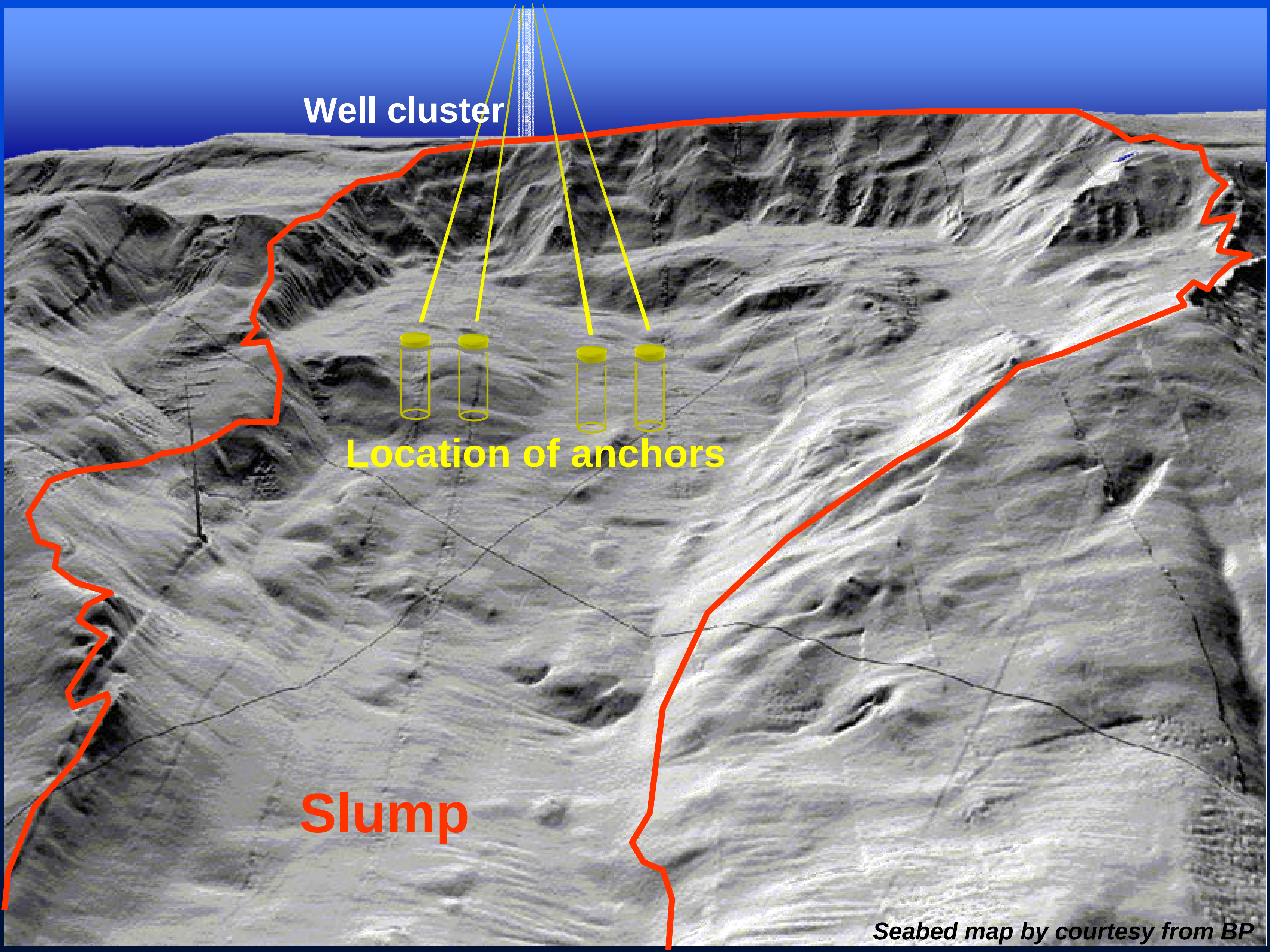
GoM - Slopes, slumps and canyons…



Risk assessment

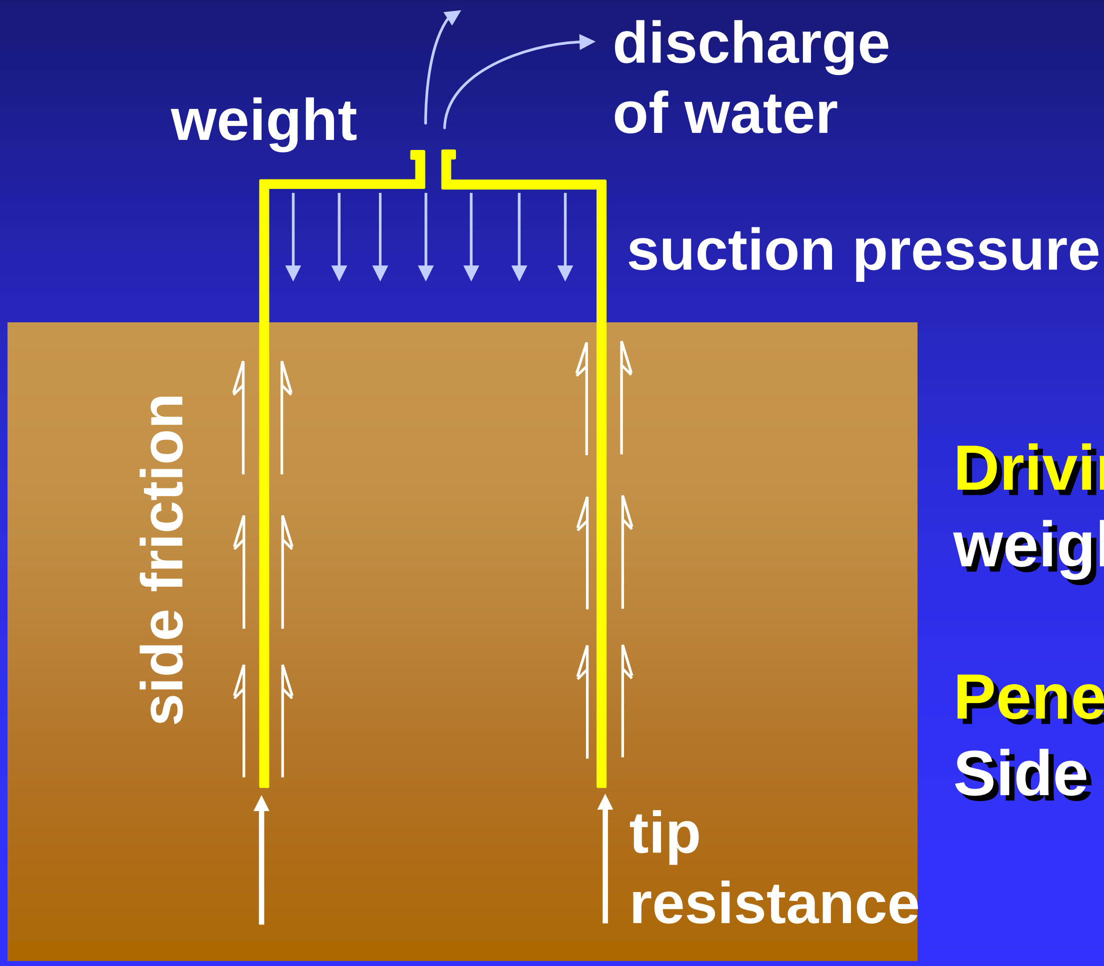


Risk assessment



Penetration of skirted foundation

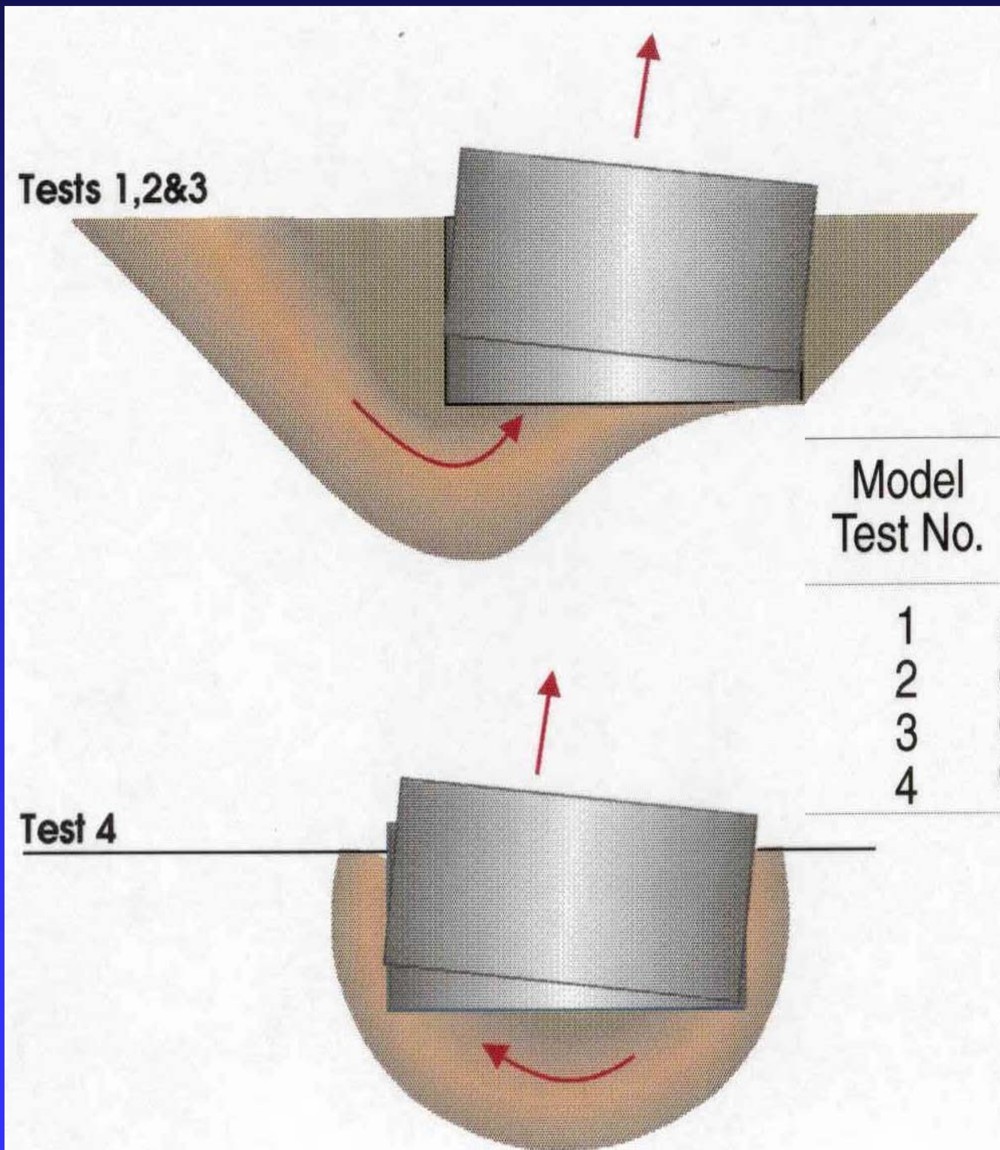
Penetration Resistance = Driving Force



Driving Force =
weight + suction force

Penetration Resistance =
Side friction + tip resistance

Predicted and measured failure loads

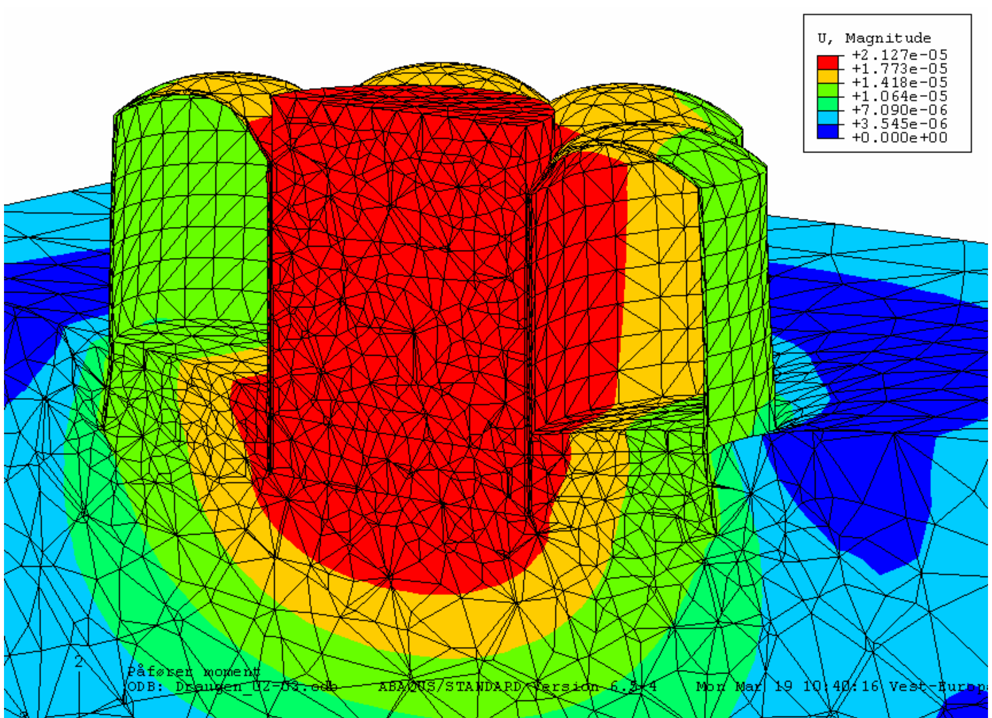


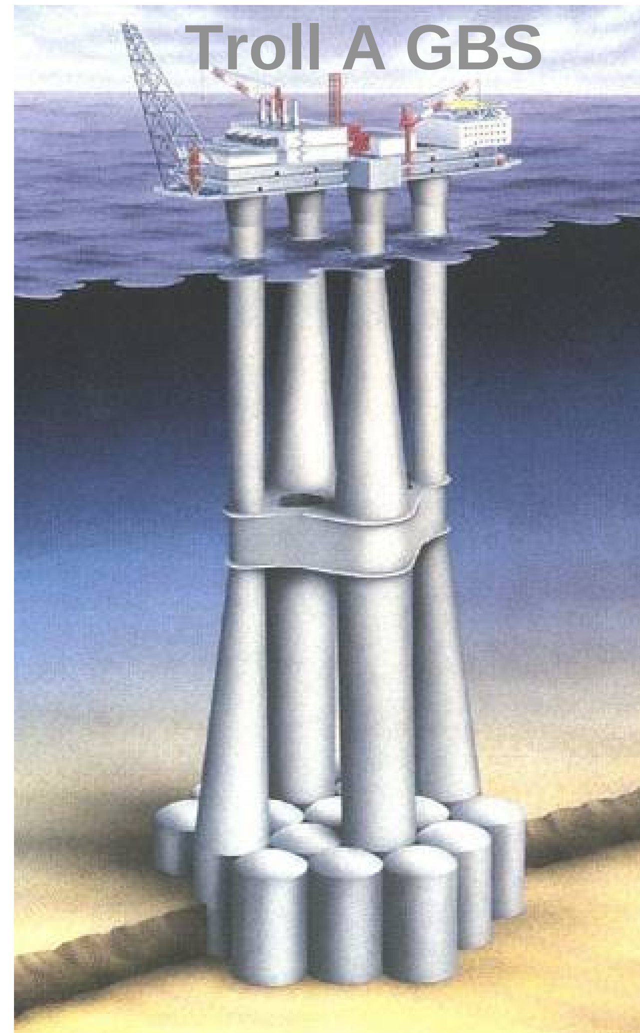
Model Test No.	Test Type	Failure Load (kN) Predicted	Measured	Pred./Meas.
1	Static	138	137.7	1.0
2	Cyclic	118	112.9	1.05
3	Cyclic	105	99.5	1.06
4	Cyclic	92	90.5	1.01

Offshore foundation design by FEA

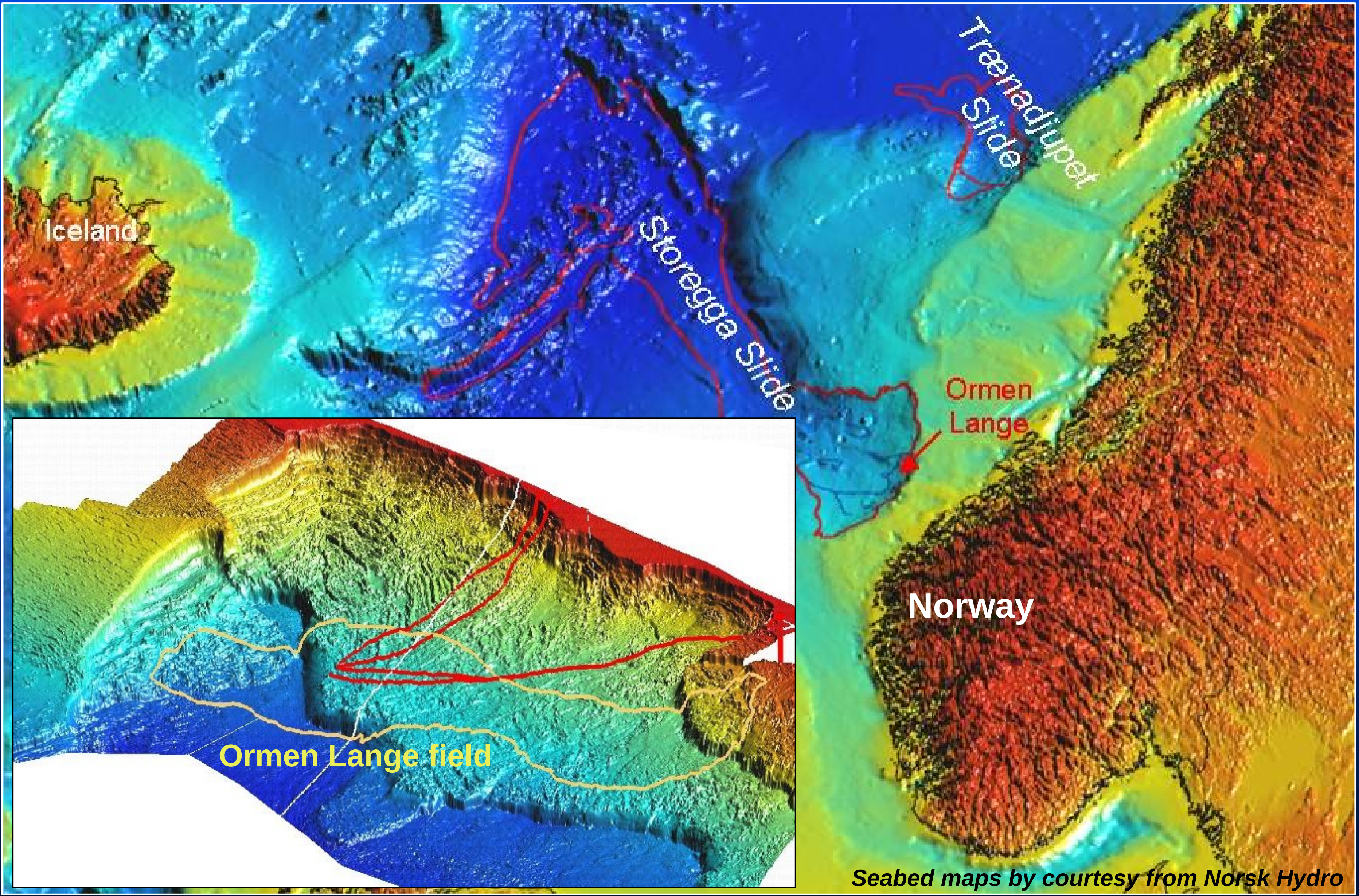
Cyclic loading due to waves:

- Dynamic stiffness
- Bearing capacity
- Settlements
- Soil-Structure-Interaction



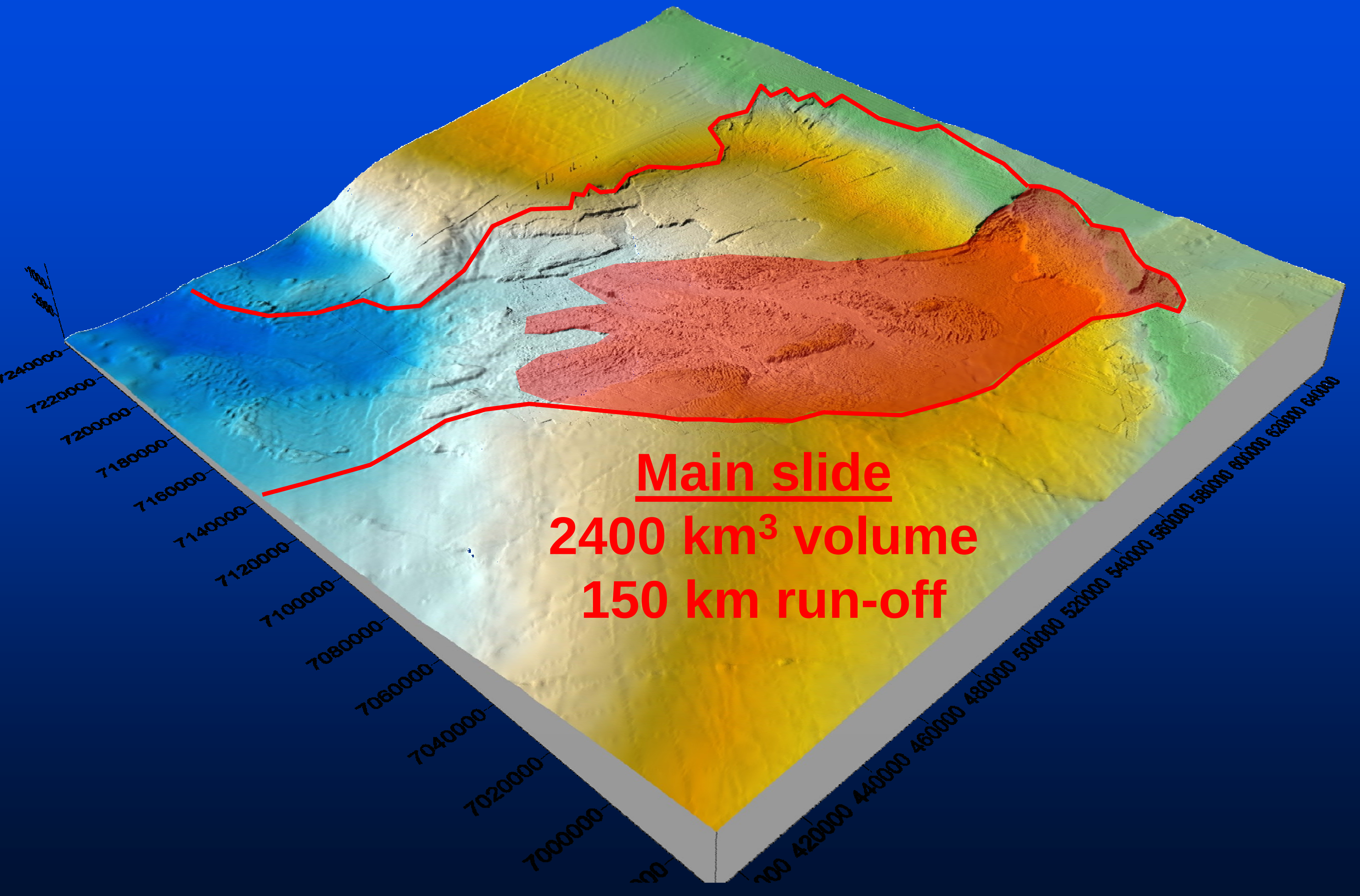


Slope stability – Ormen Lange field



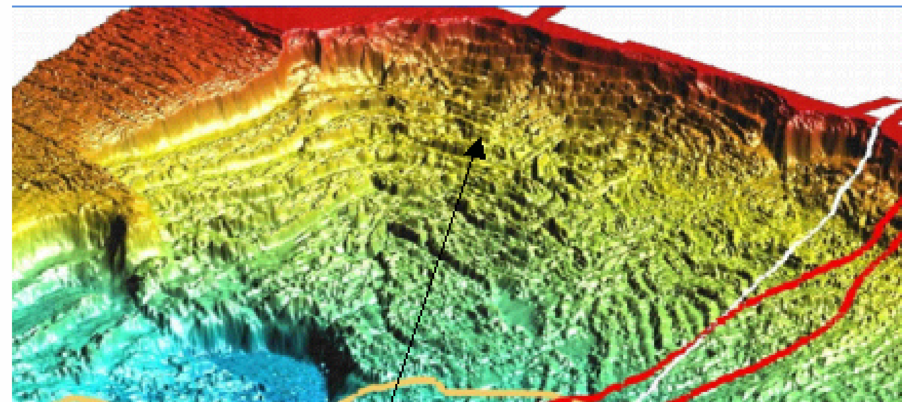
Seabed maps by courtesy from Norsk Hydro

Slope stability – Storegga slide

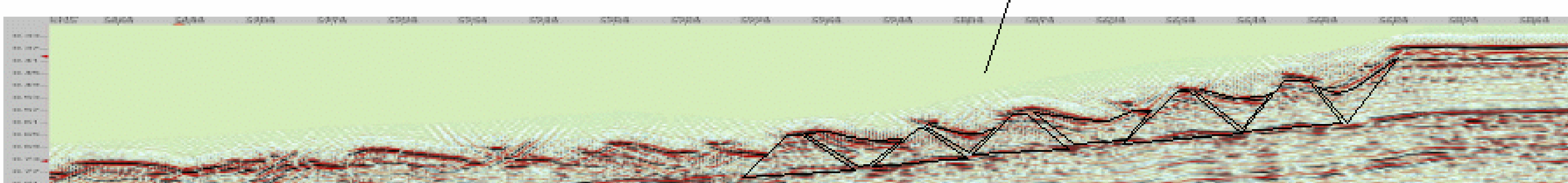


Analogy to quick clay slides

Norwegian quick-clay slide

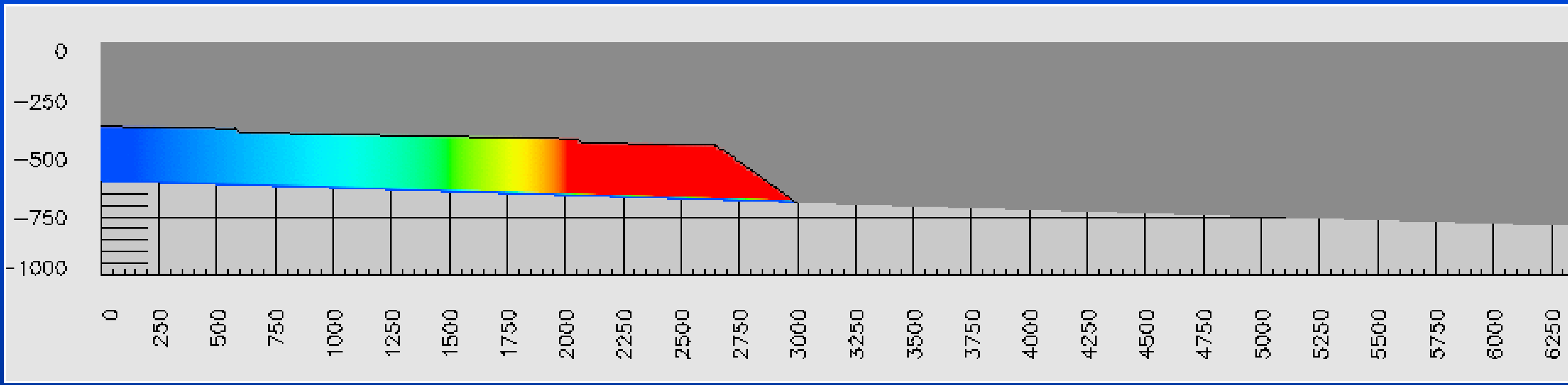


Storegga slide



Slope stability – Ormen Lange field

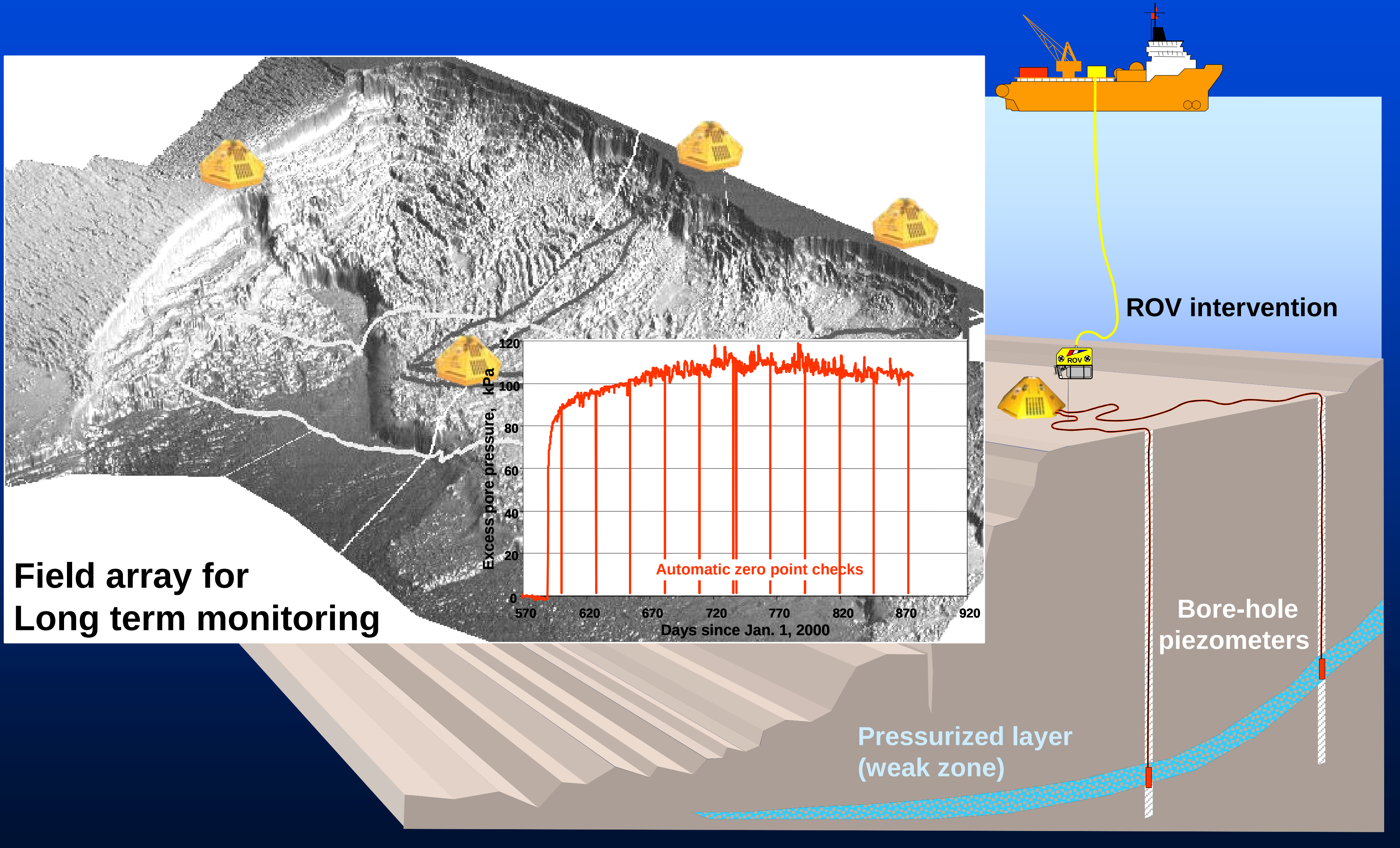
Storegga slide model



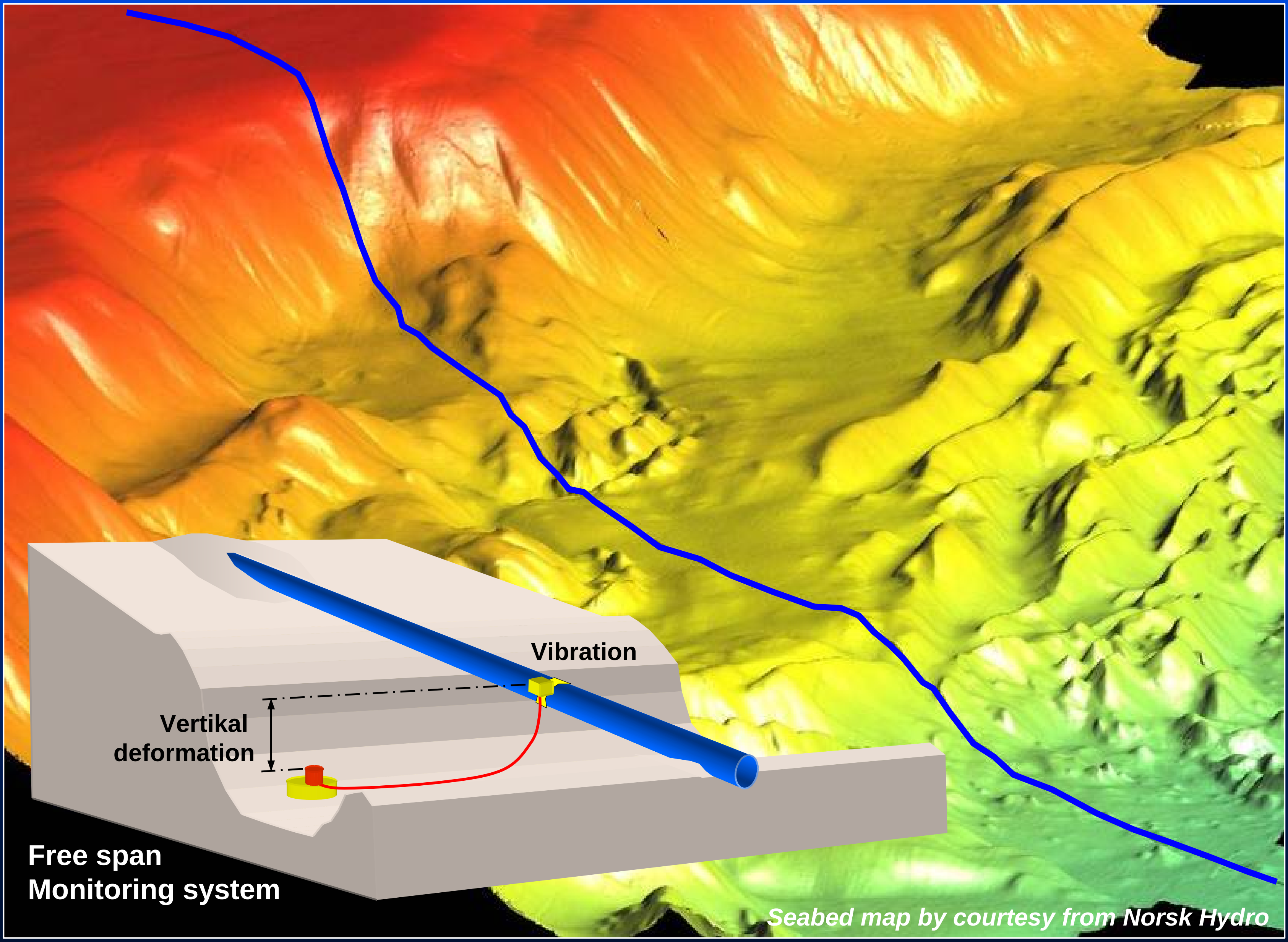
Tidal wave

Duration 2.5 hrs

Slope stability – Ormen Lange field
Permanent pore pressure monitoring



Ormen Lange pipeline routing



Deepwater Riser touchdown

Soil resistance

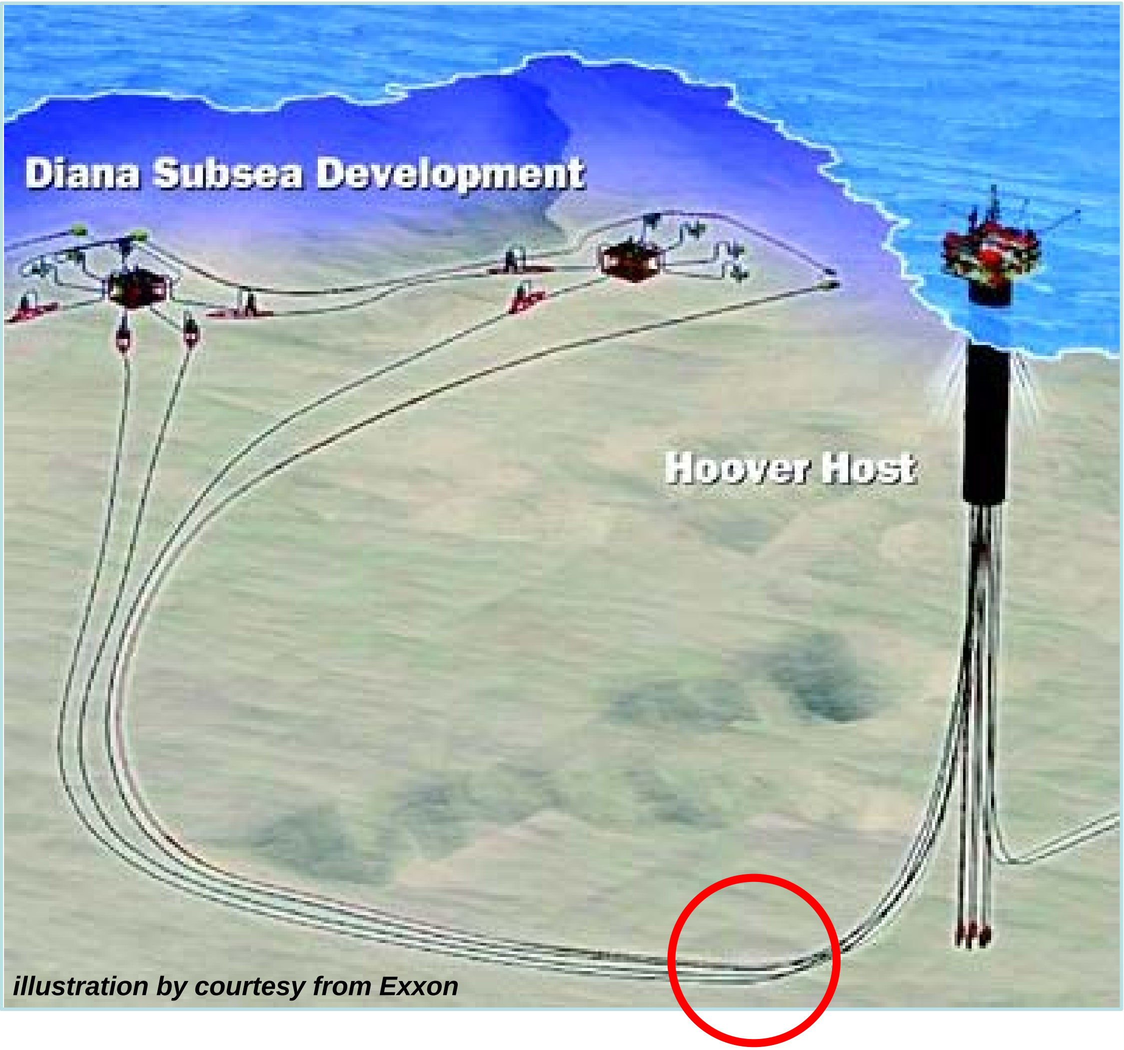
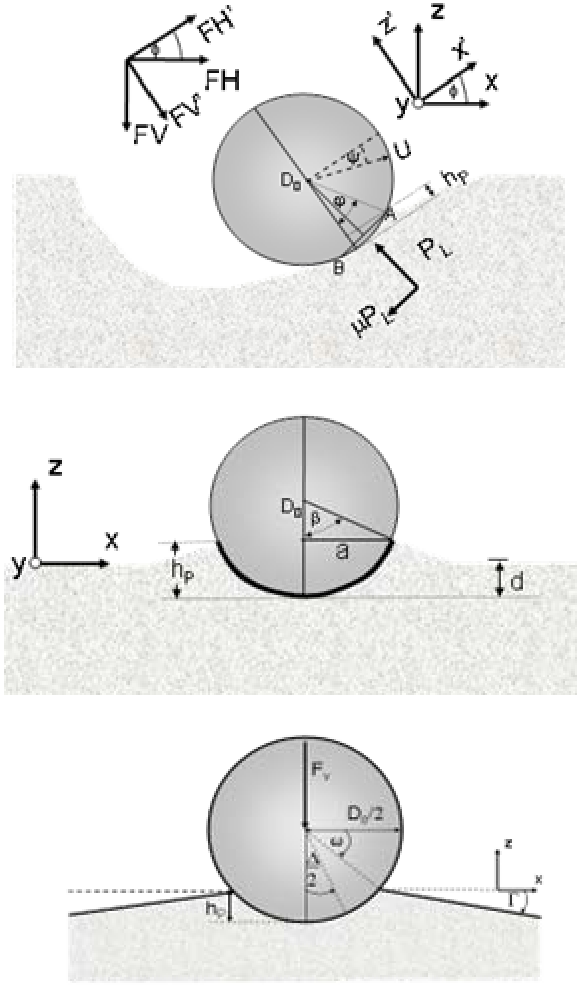
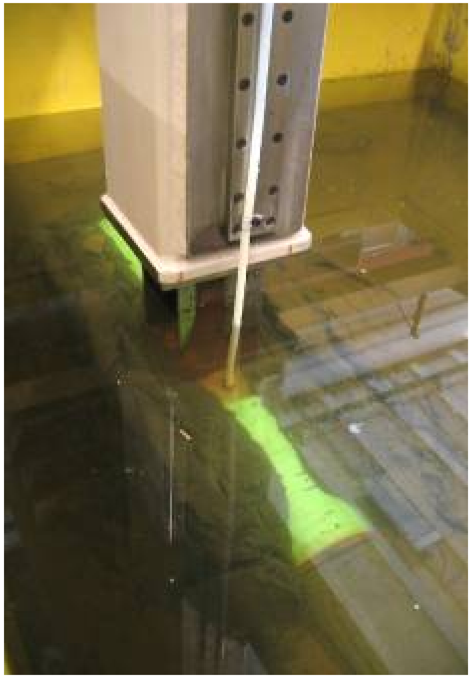


illustration by courtesy from Exxon



Deepwater Riser touchdown

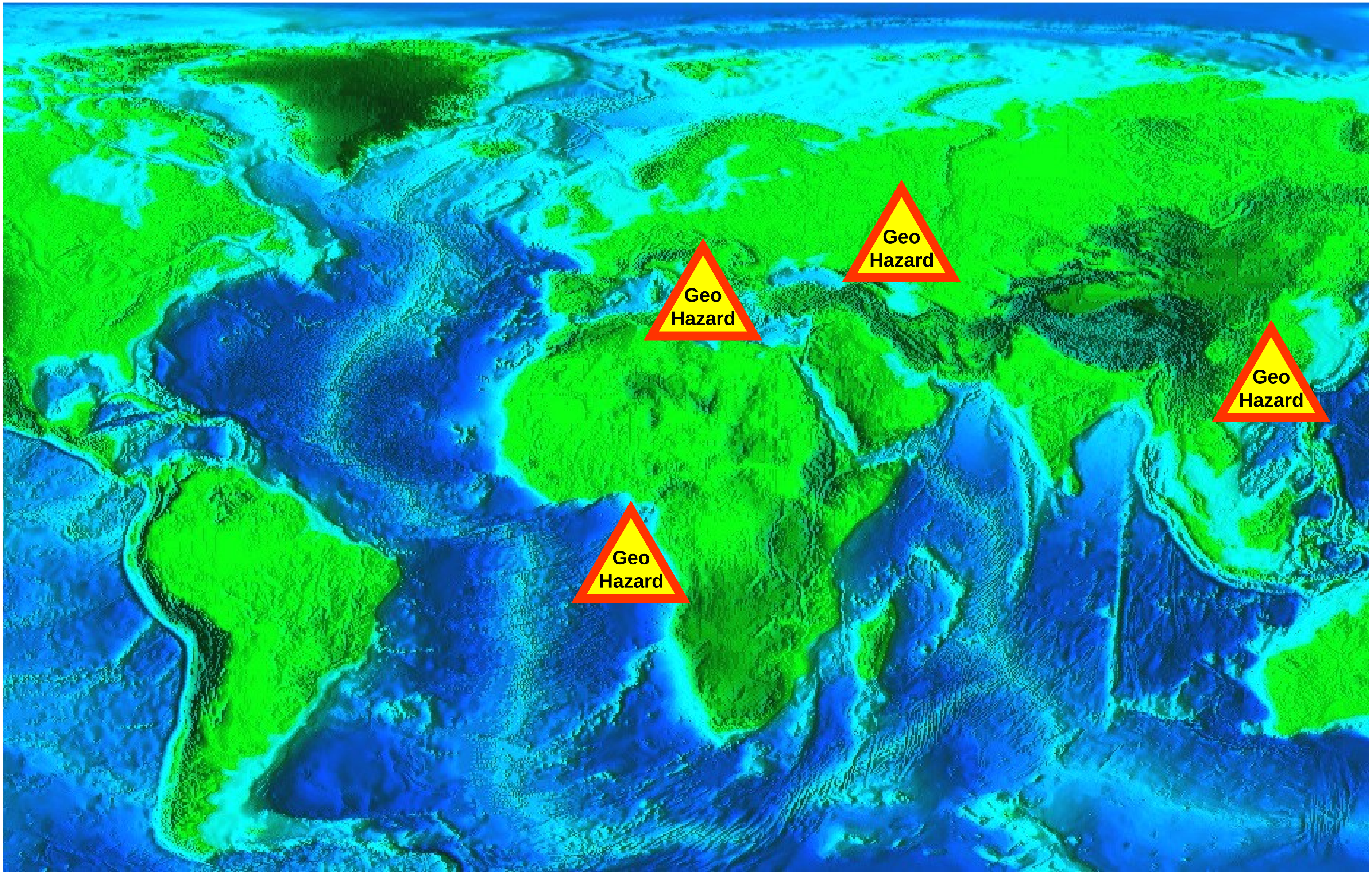
Soil resistance - Model testing and analysis



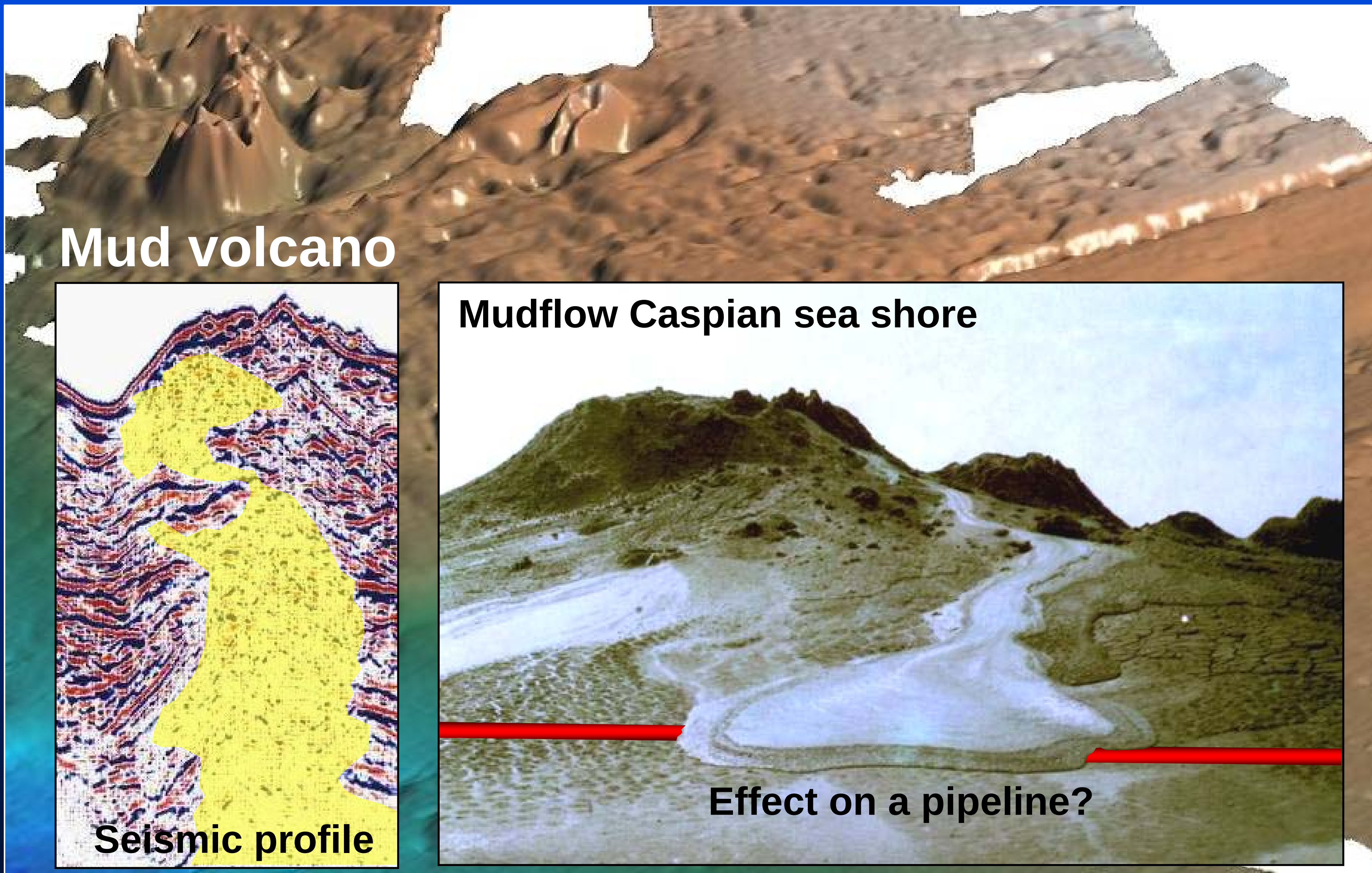
Model tests
Pipe-seabed interaction

3-D non-linear soil springs for riser fatigue design

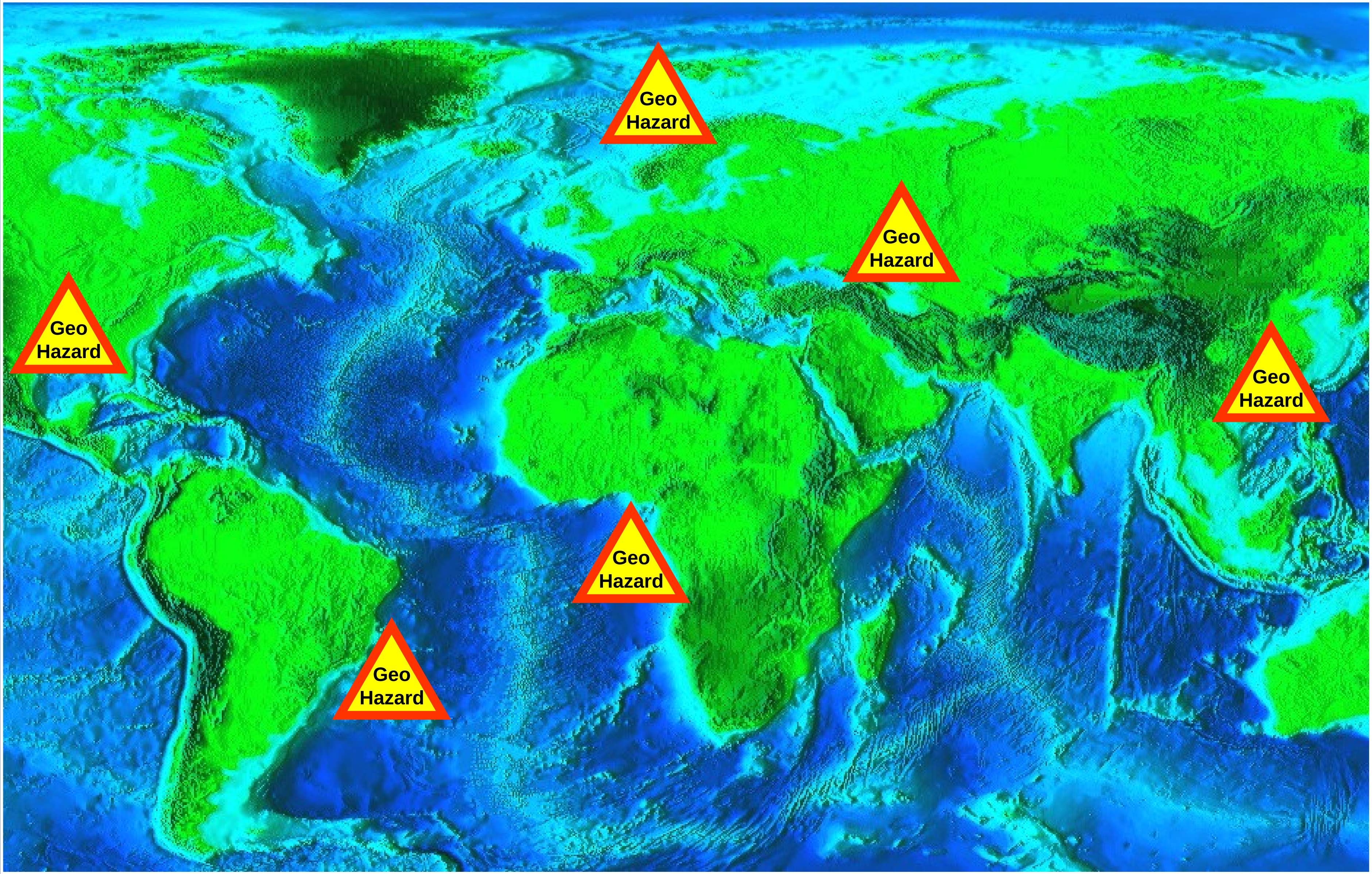
Mud volcanoes and flow



Mud volcanoes and flow – Bonga field



Gas Leakage and Pressurised layers



Gas leakage

Causes

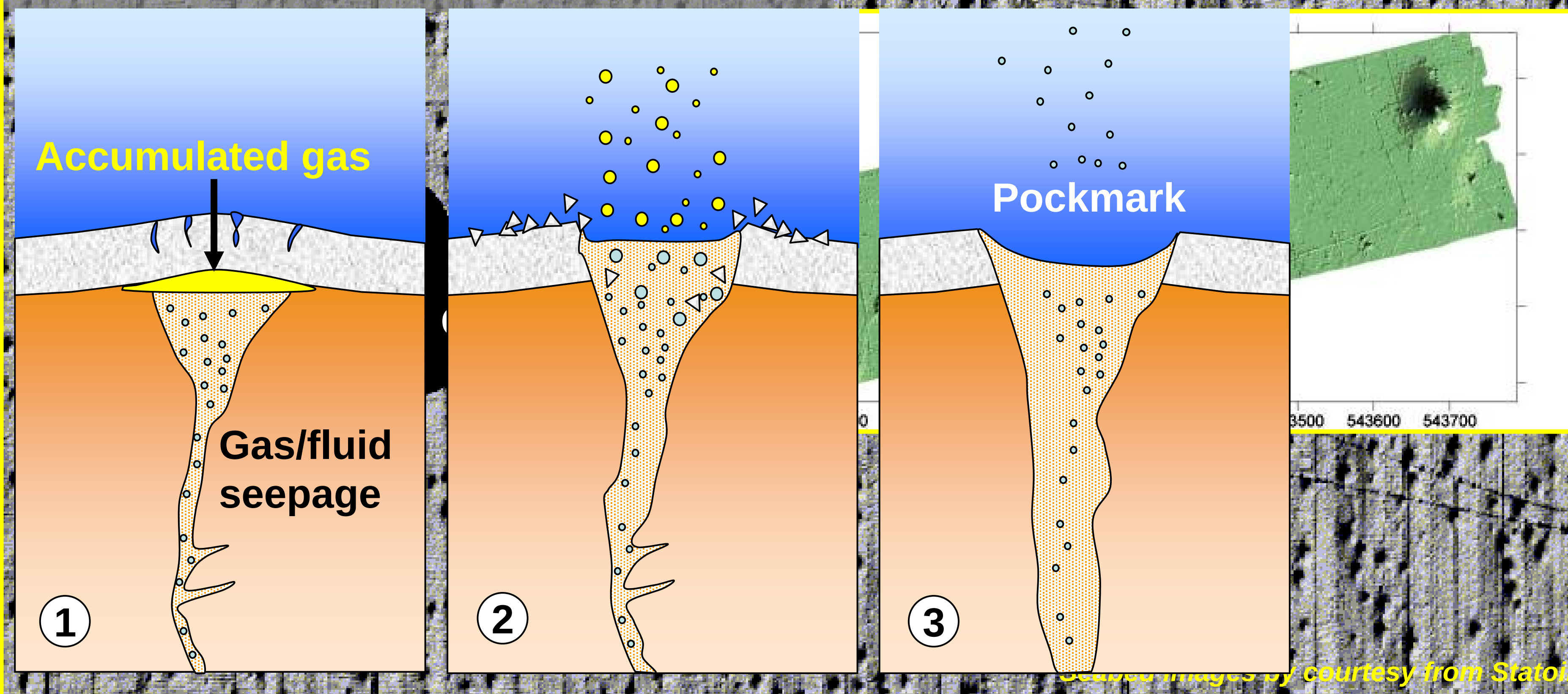
- Natural seepage (migration and diffusion)
- Shallow pressurized (gas) layers
- Increased reservoir pressure (injection, fractured cap)
- Well completion (seal integrity, poor cementing)
- Drilling and well operations (hydr. Fracture)

Why concern (use monitoring, where possible)

- Early warning (safety and environment)
- Influence on seabed infrastructure (stability)
- Effect of production (injection and subsidence)
- Understanding leakage mechanism and time scale
- Control remedial actions (bleeding, relief wells…)

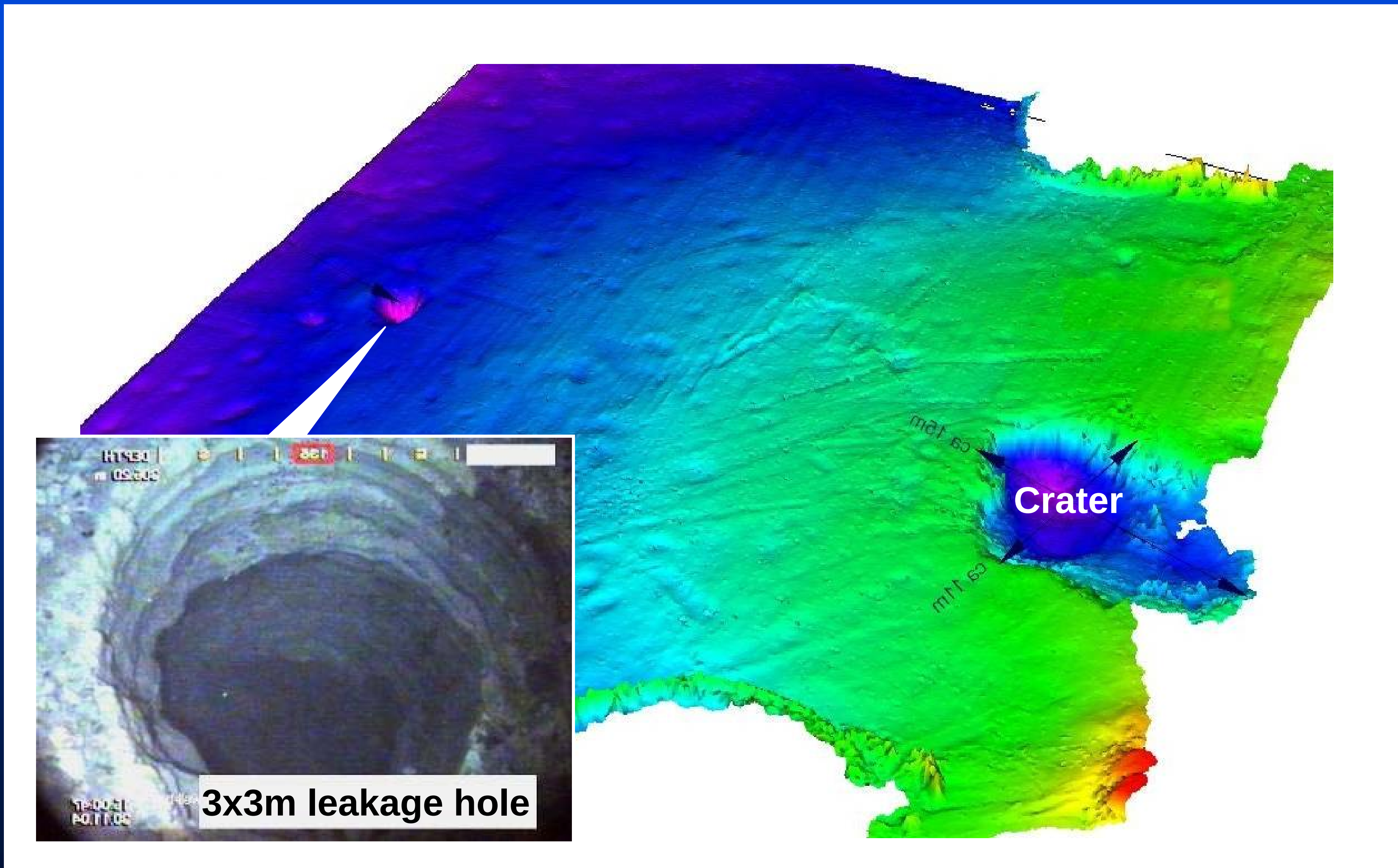
Pockmarks...what are they?

- Fluid escape ?
- Gas seepage ?
- Reservoir chimneys ?
- Still active ?



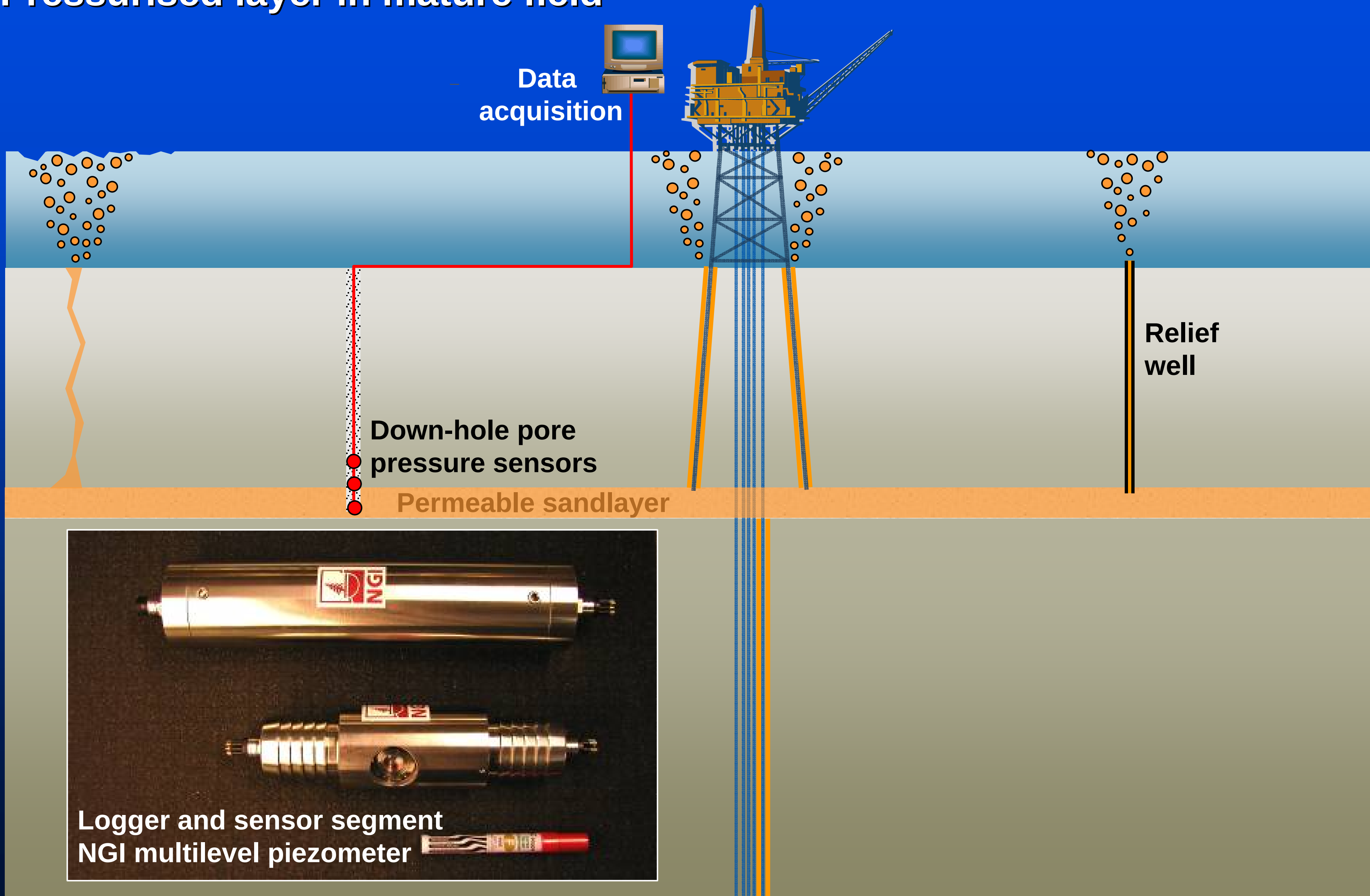
Seabed images by courtesy from Statoil

Effects of rapid gas leakage



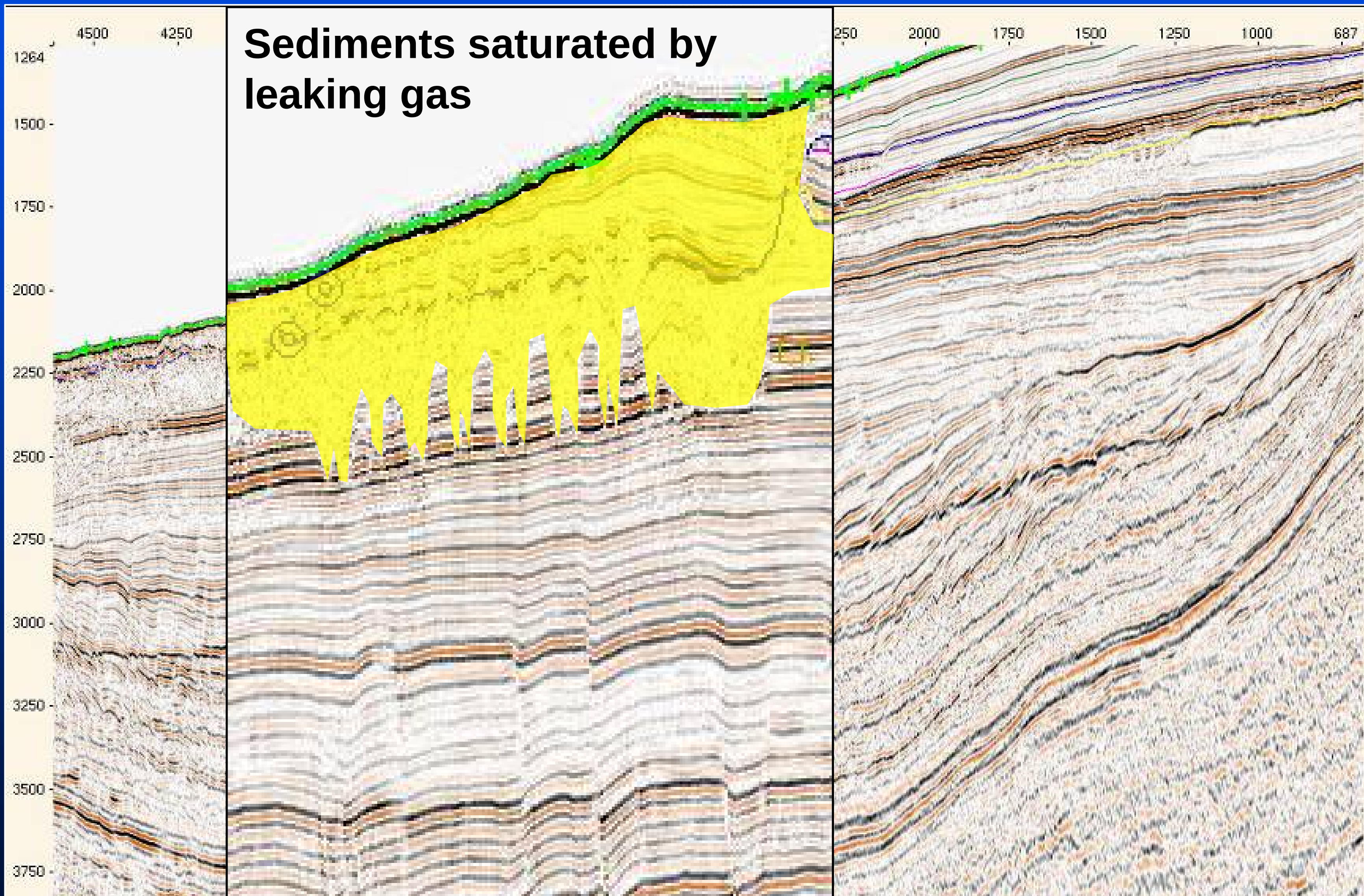
Gas leakage

Pressurised layer in mature field

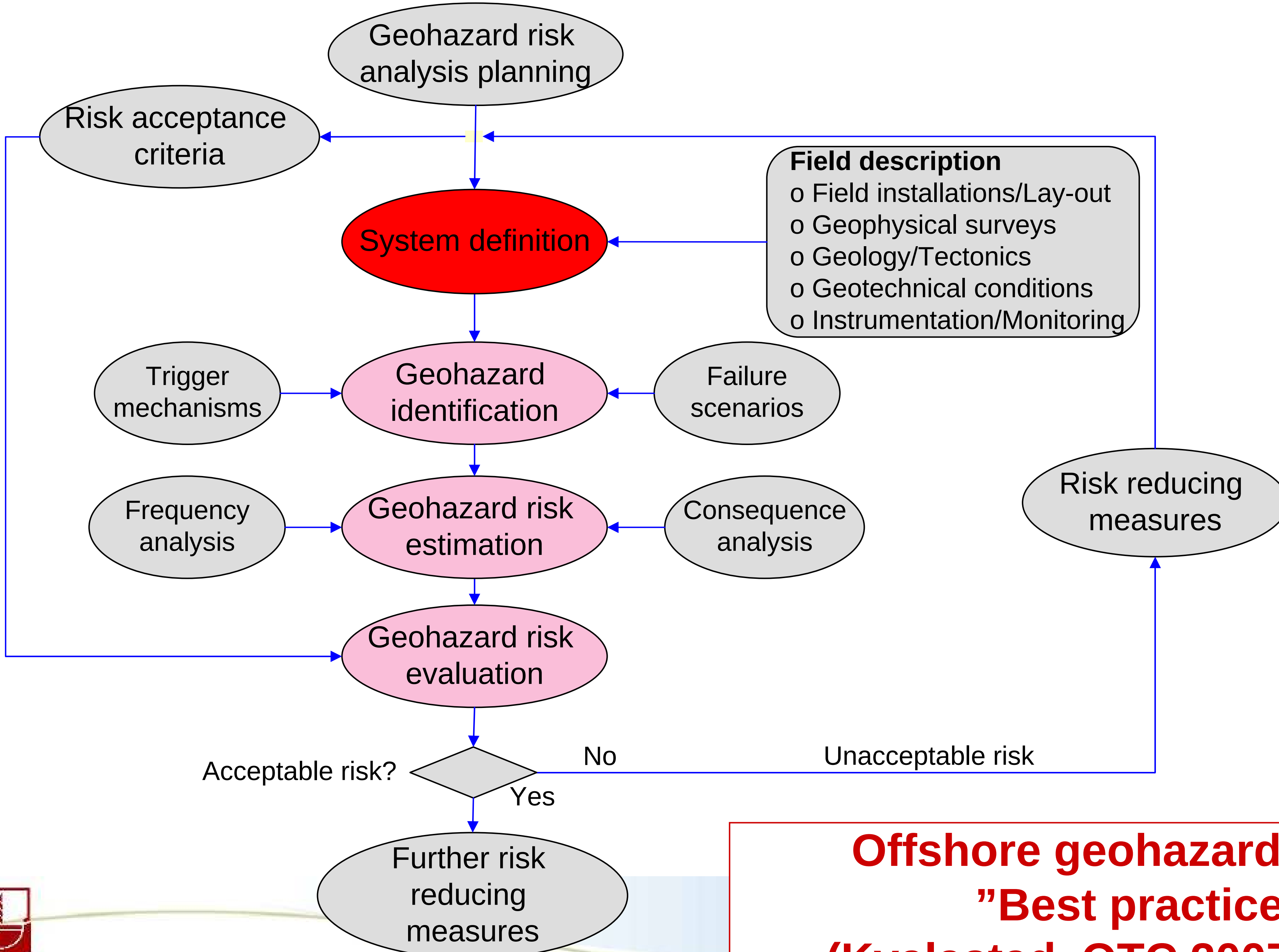


Gas leakage

Seabed Gas leakage
Seismic methods



Offshore geohazards ”Best practice” (Kvalastad, OTC 2007)



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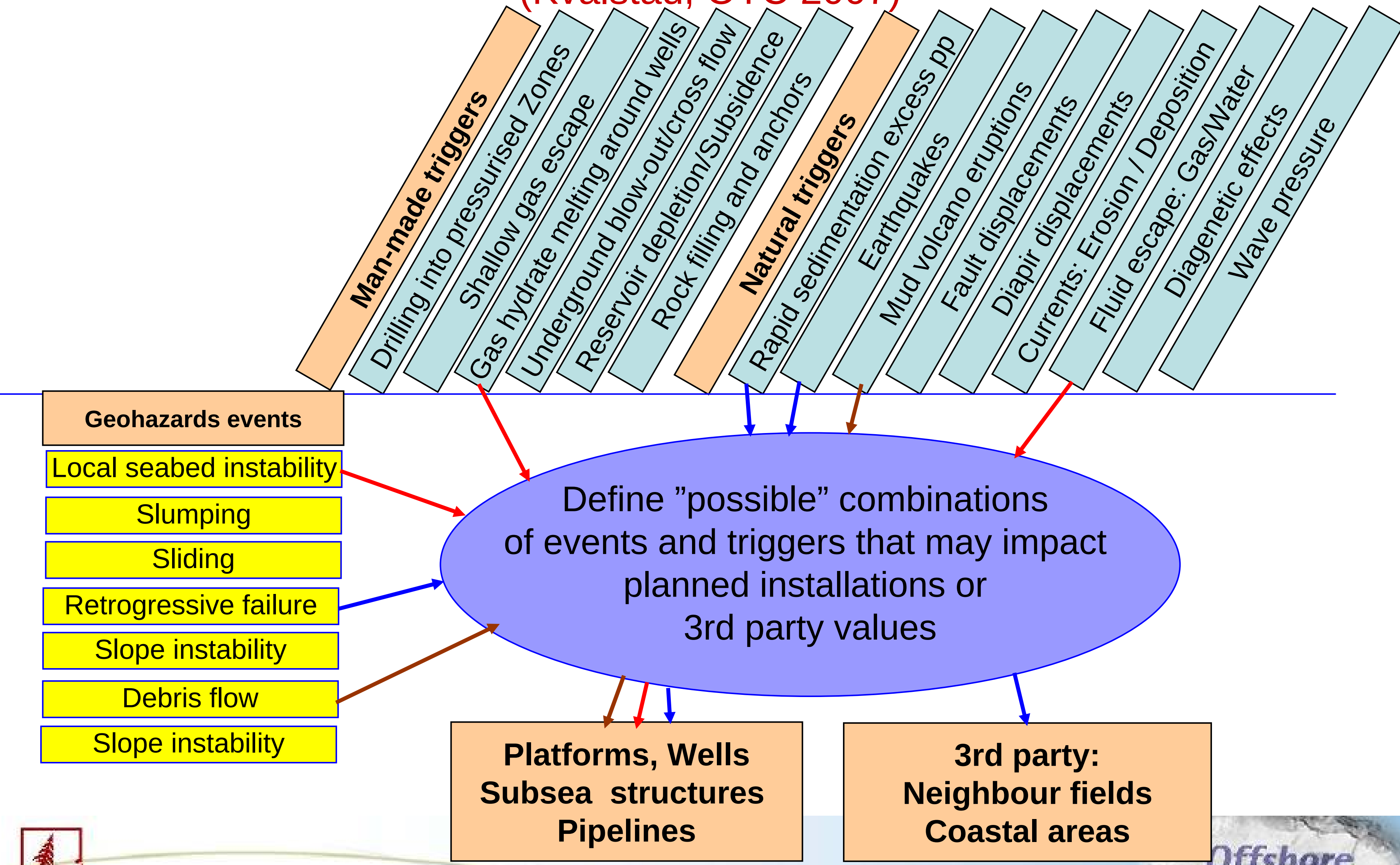
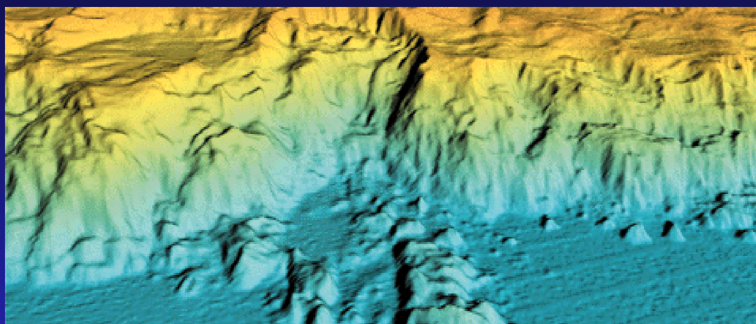
Define failure scenarios (GeoHAZ-ID)

(Kvalstad, OTC 2007)



Integrated geosciences

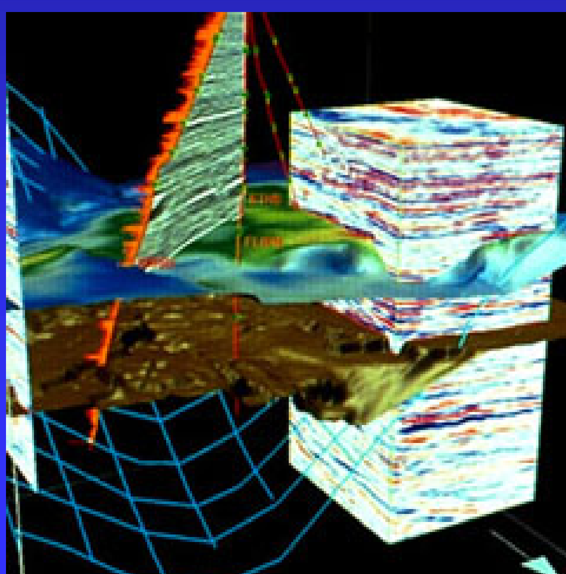
Multibeam SWATH Bathymetry

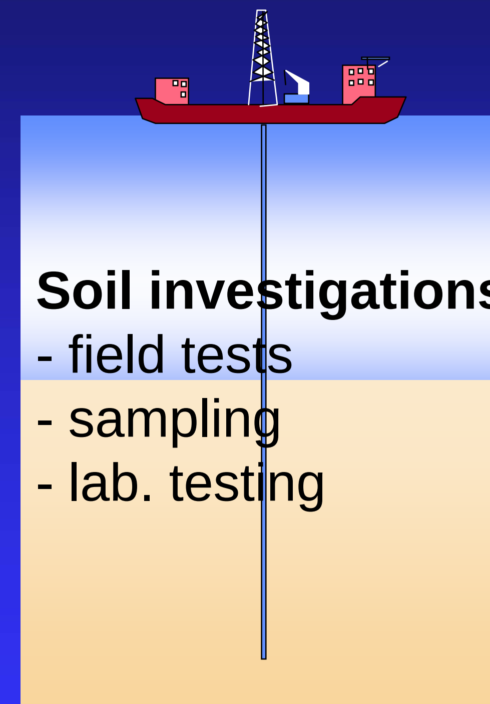


Geological model
- depositional climate
- age
- historic slide activity

Physical model for geohazard assessment

3D Seismics + HR 2D





Soil investigations
- field tests
- sampling
- lab. testing

Soil properties (K, G, e, v_p, v_s, s_u, etc.)
- effect of pore water pressure
- effect of gas and gas hydrates
- effect of temperature/pressure changes

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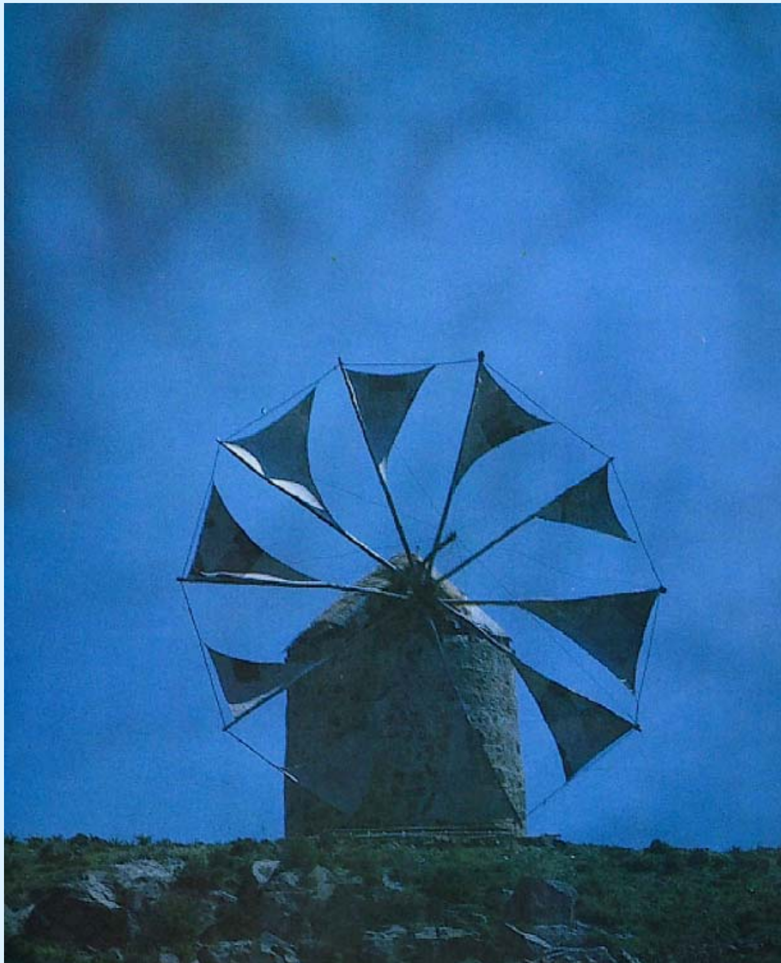
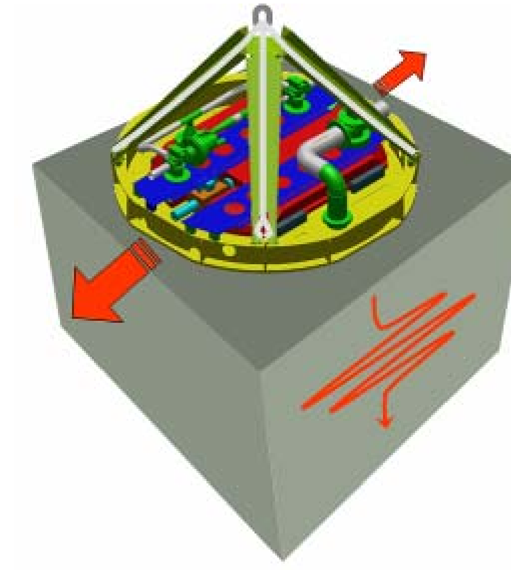
OUTLINE OF LECTURE

- **Exploitation of oil and gas resources**
  - **Petroleum geophysics**
  - **Risk associated with tsunami**
  - **Storage of CO_2**
- **Storage of radioactive waste**
- **Hydropower**
- **New challenges**



Development and testing of a seabed coupled shear wave vibrator



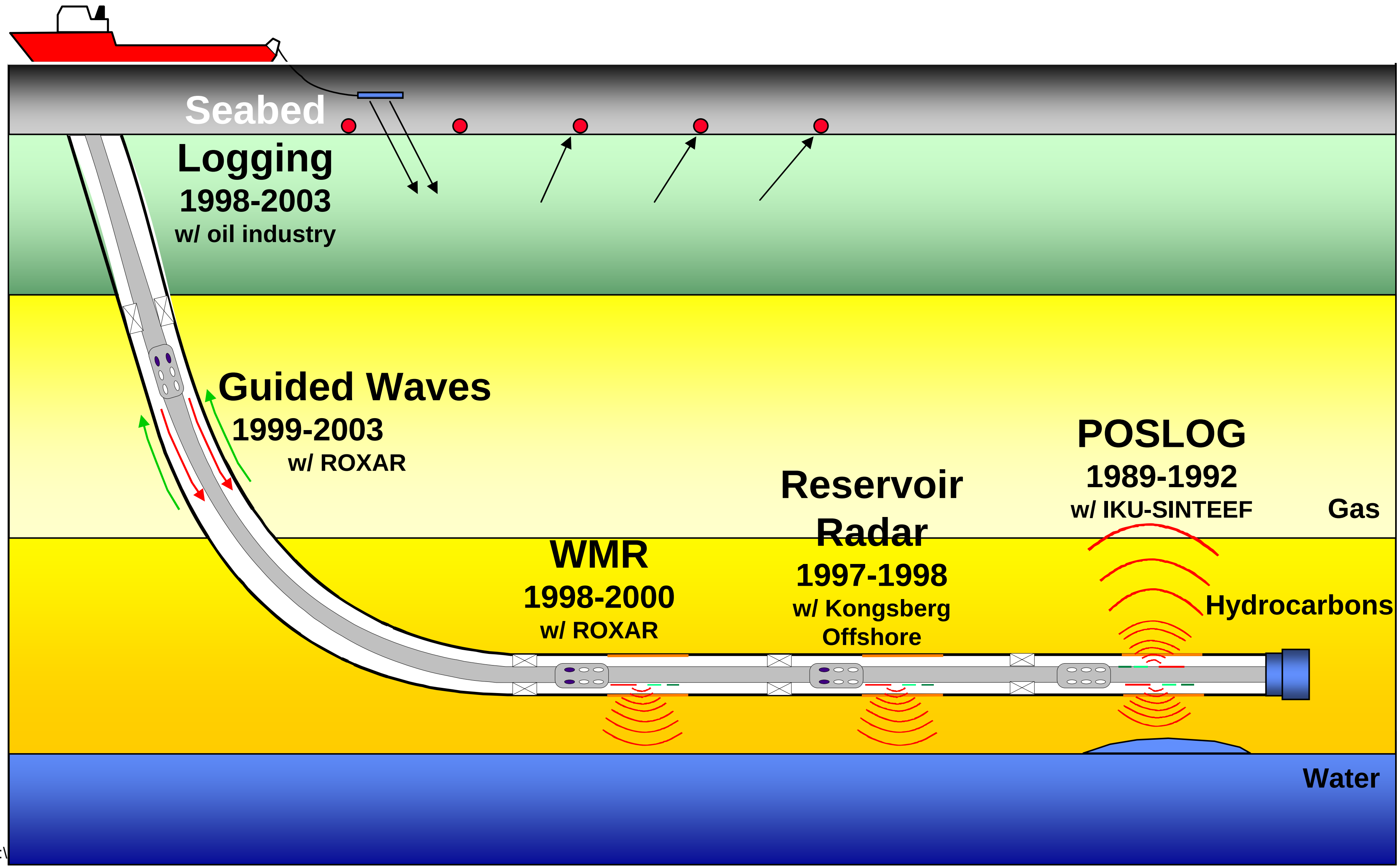
- As a calibration tool
- For imaging in "problem areas"
- Improved mapping of reservoir

STATOIL

HYDRO

Petroleum geophysics R&D 1989-2003

Norwegian Geotechnical Institute
On safe ground
NGI



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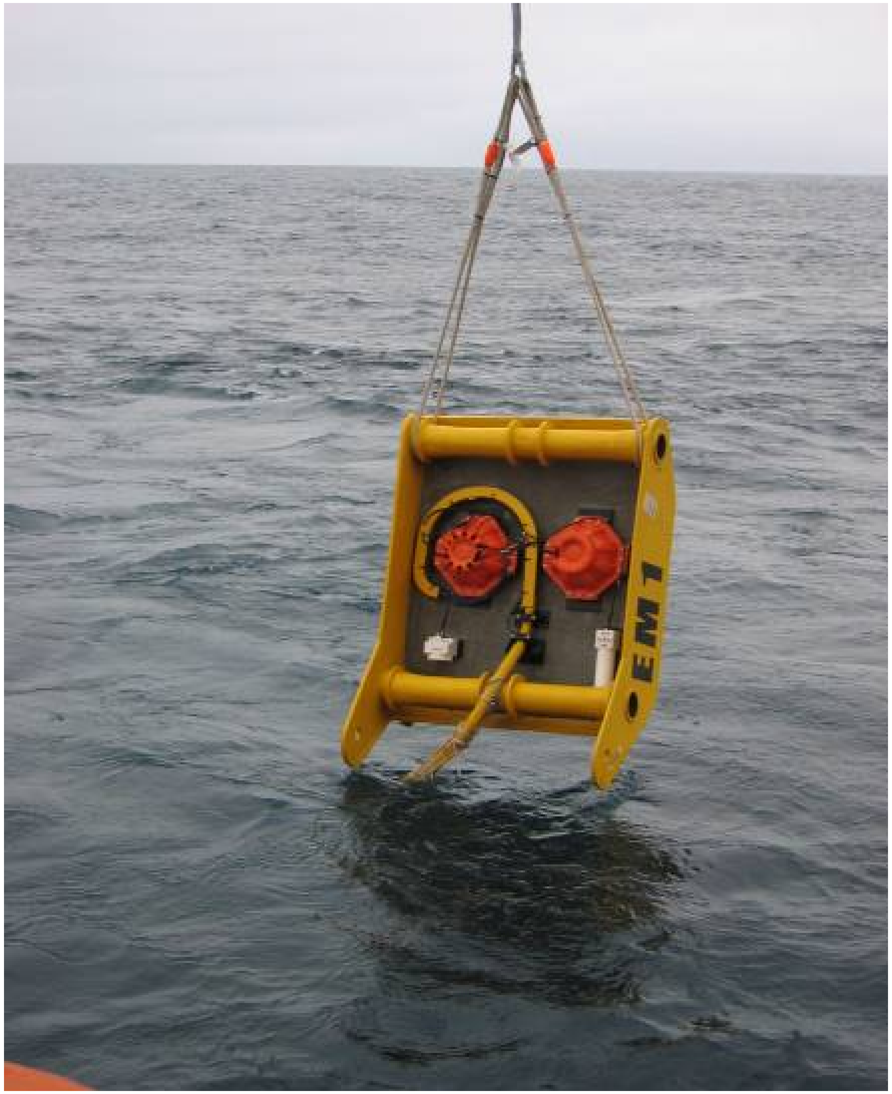
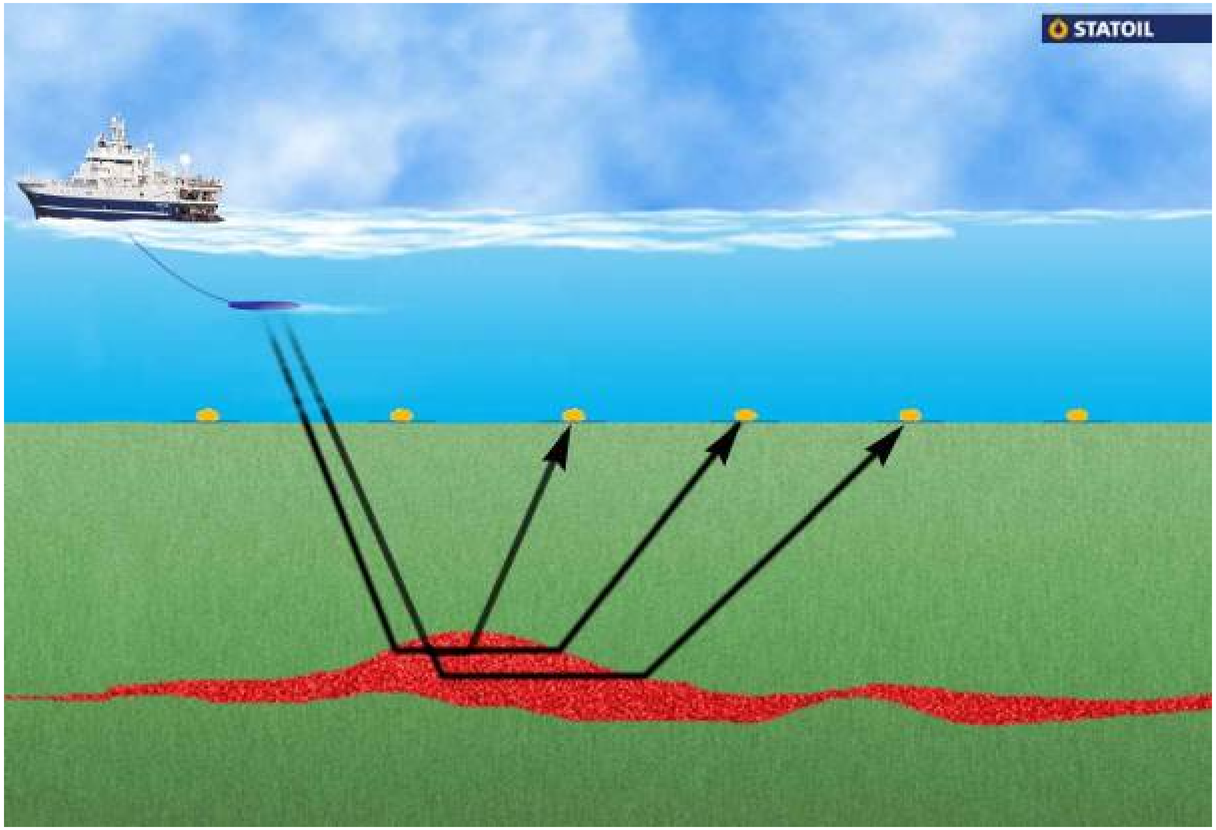
EM Receiver station

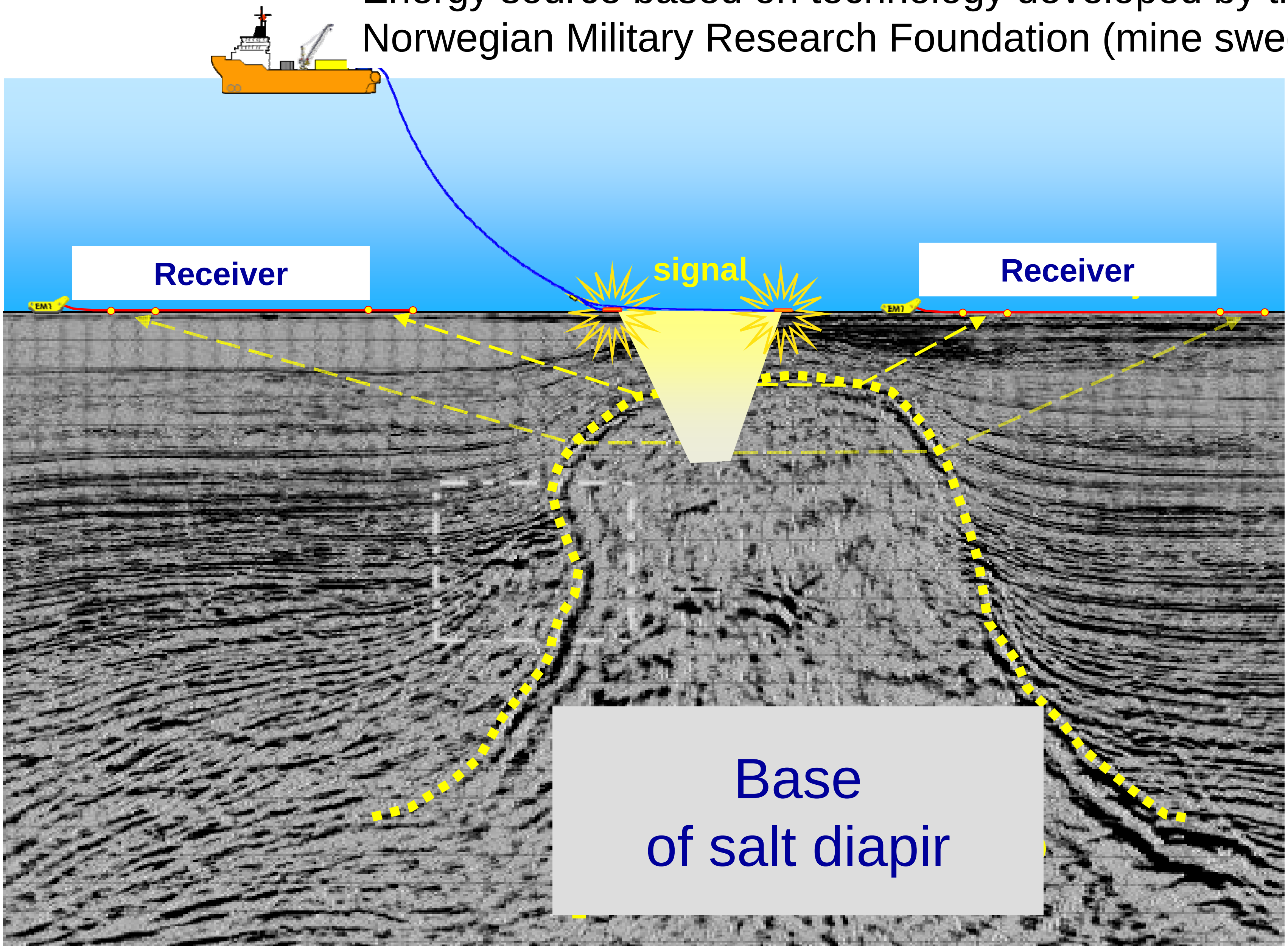


Electro-Magnetic (EM) Geophysics Seabed Logging

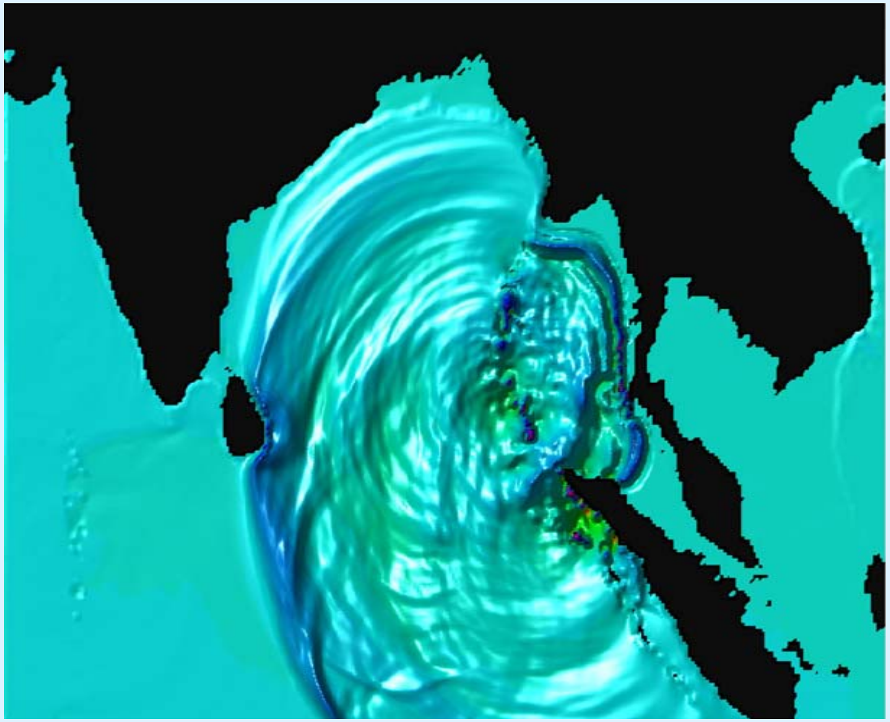
A vessel pulls a deep towed powerful EM-source and a number of receivers detect multi-offset



Energy source based on technology developed by the Norwegian Military Research Foundation (mine sweeping)

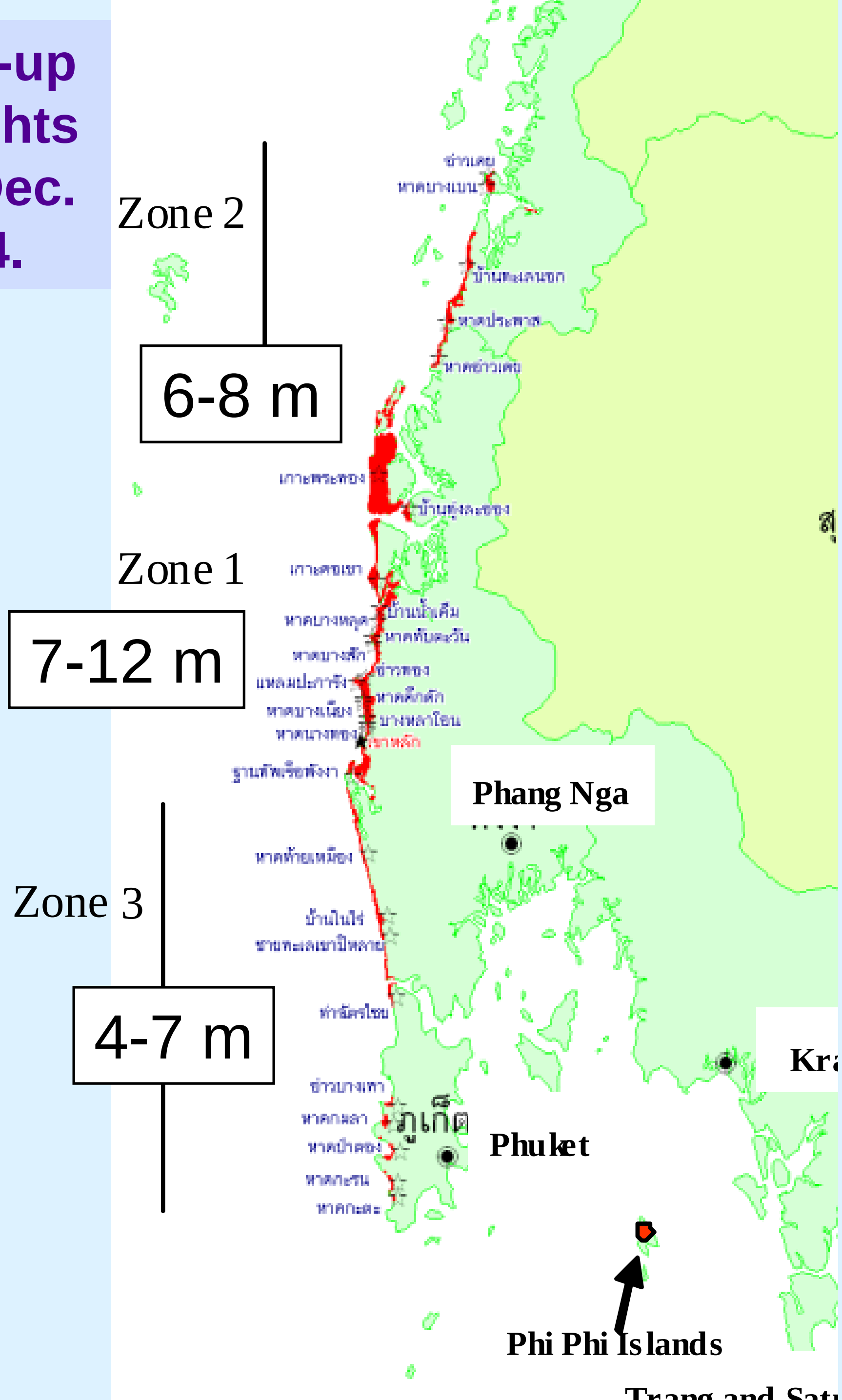


Tsunami in Indian Ocean, 26 December 2004



Threat:
Generated by M = 9.3 earthquake

Run-up heights 24 Dec. 2004.

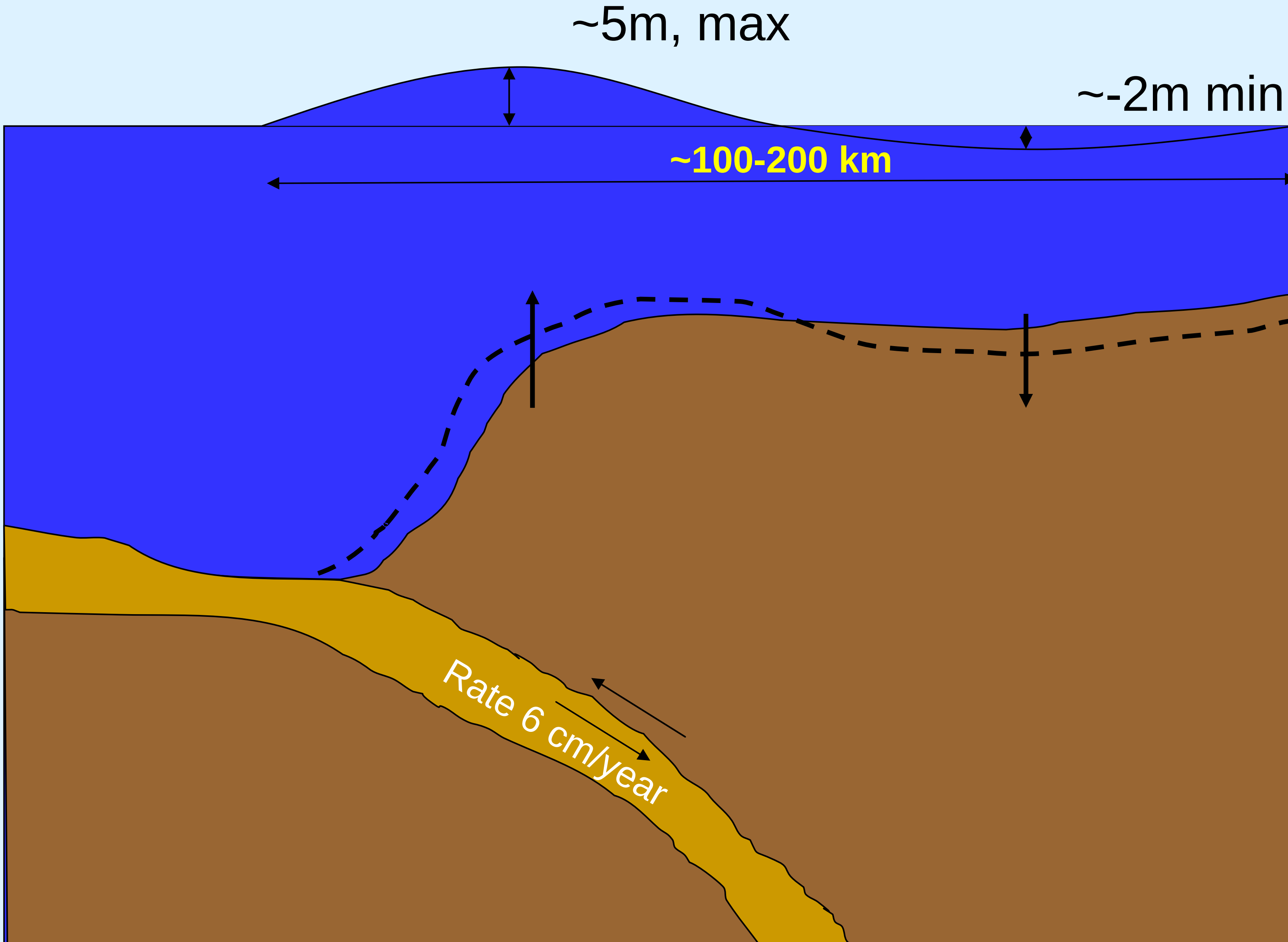


Tsunamis in Indian Ocean (USGS and others)

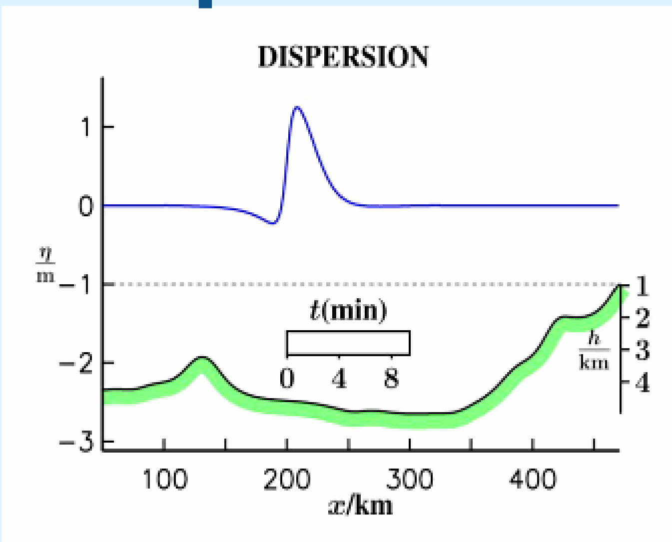
Norwegian Geotechnical Institute
On safe ground
NGI

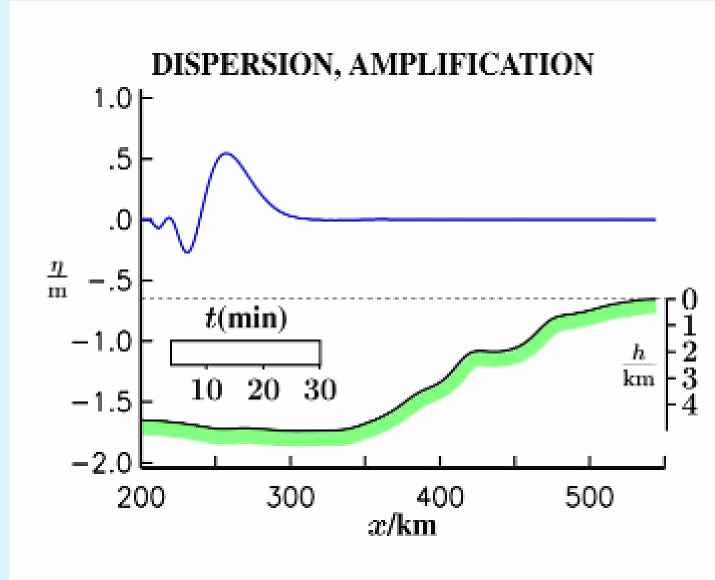
1797	M 8.4, central Sumatra. Tsunami flooded Padang, >300 fatalities
1833	M 8.7, south coast of Sumatra. Huge tsunami flooded Sumatra. Numerous victims
1843	A tsunami from the southeast flooded the Nias Island. Many fatalities
1861	M 8.5, western Sumatra. Several thousand fatalities
1881	M 7.9, Andaman Island region generated a 1 m high tsunami on India's coast
1883	Krakatau explosion. 36,000 fatalities, primarily on the islands of Java and Sumatra
1941	M ~7.7, Andaman Islands. Anecdotal accounts exist of a tsunami, no official record

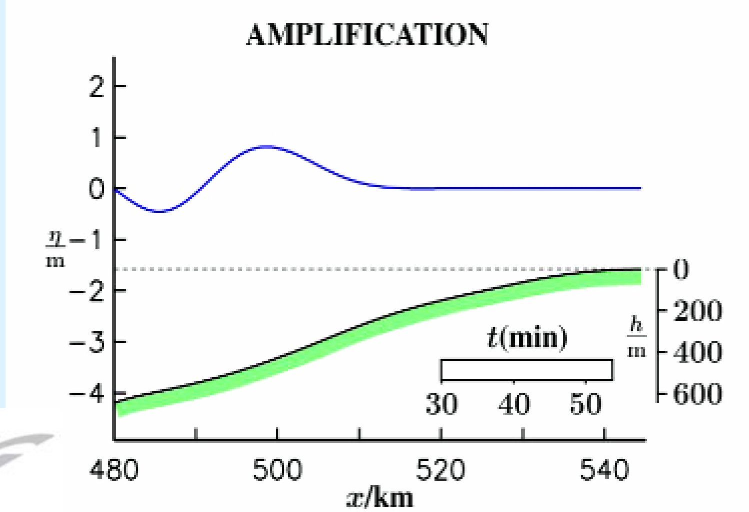
Tectonic movement

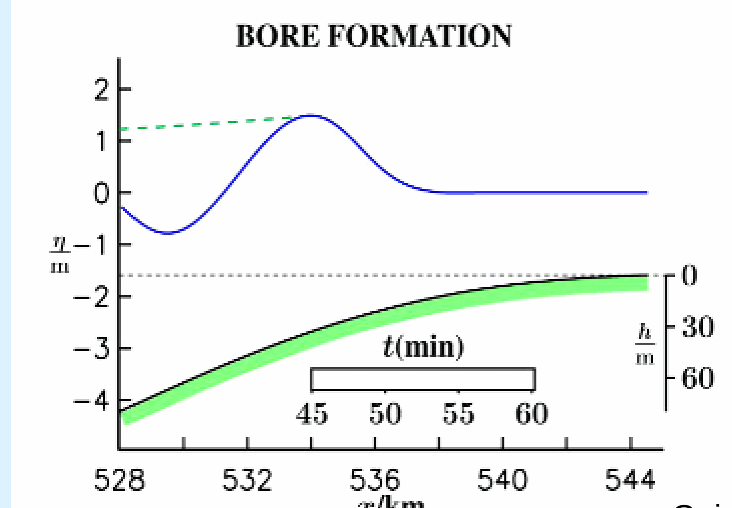


Propagation, dispersion, amplification and bore formation





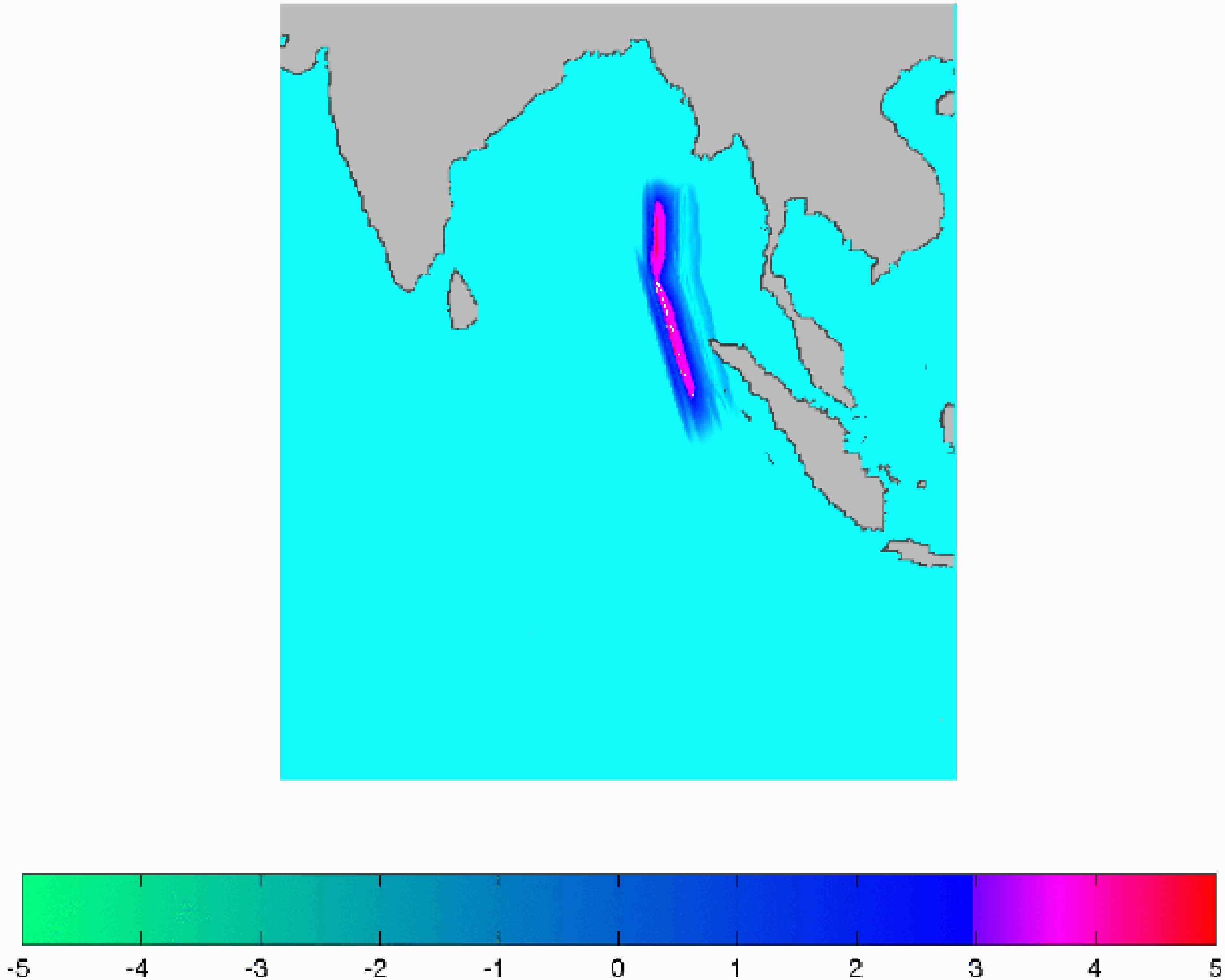




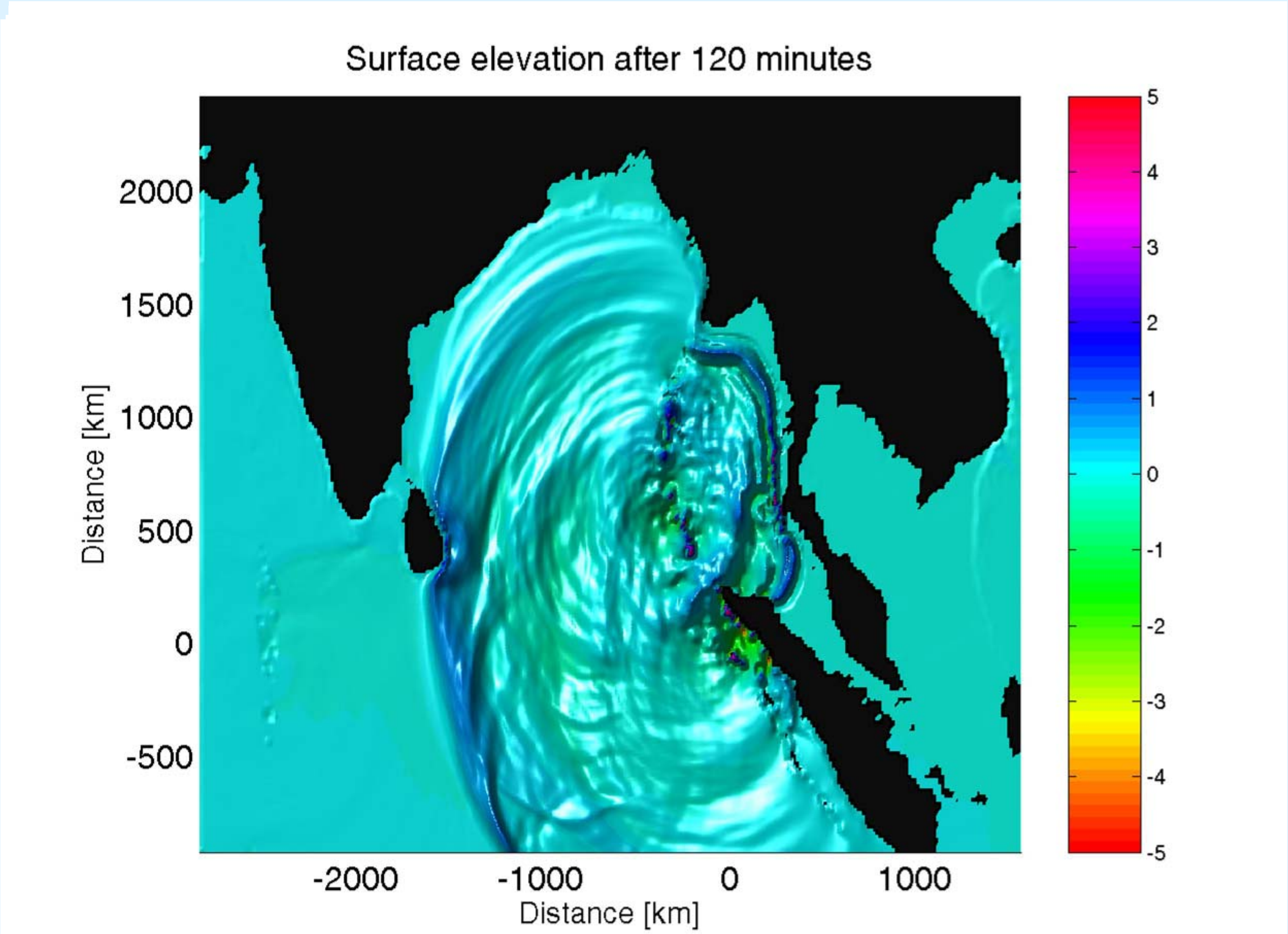
Courtesy:
Geir Pedersen, UiO

First simulation:

Norwegian Geotechnical Institute
On safe ground



Wave pattern



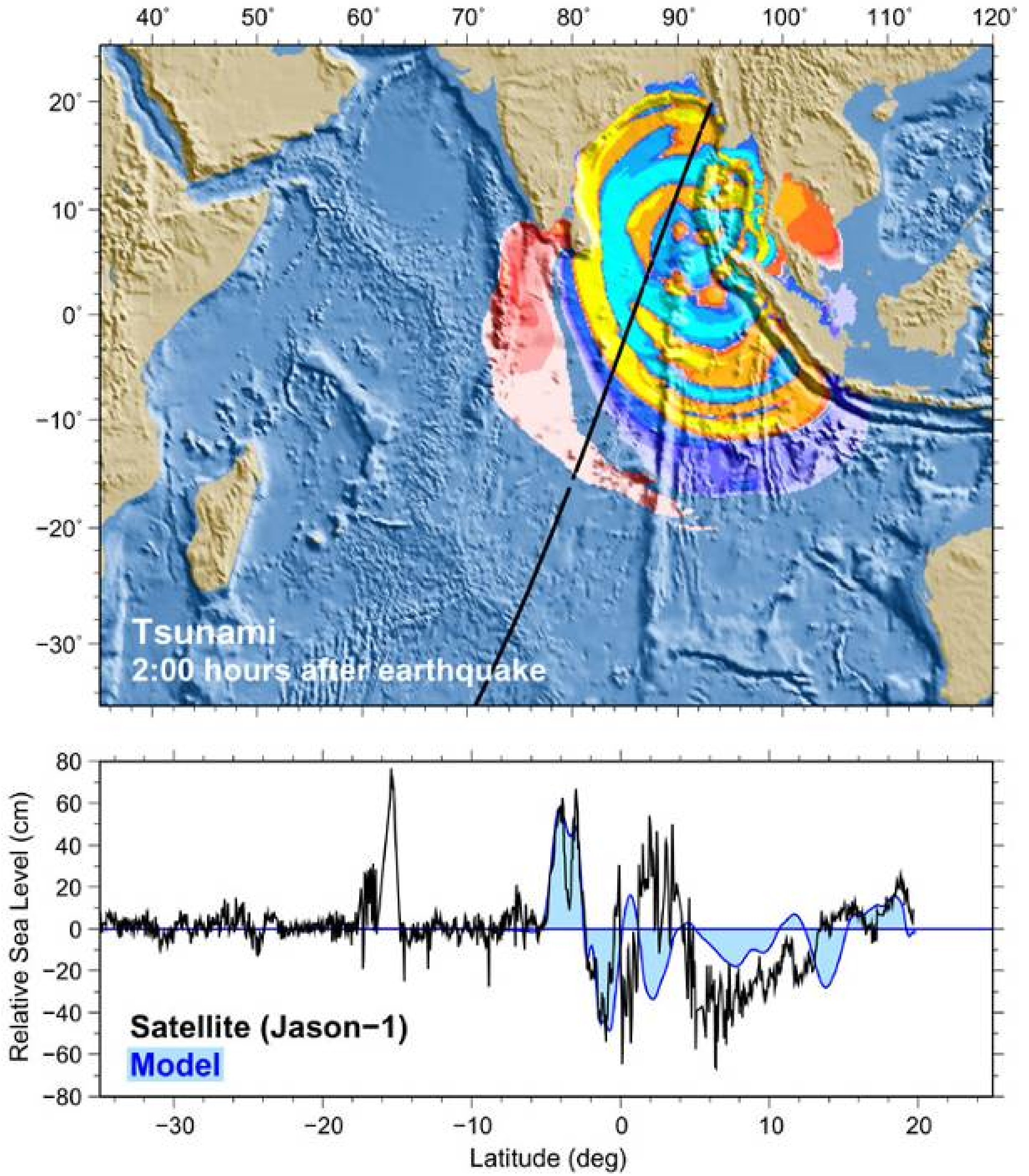
Verification of predicted wave heights

By chance, the Jason-1 satellite (Smith *et al.* 2005) recorded the tsunami as it passed over the Indian Ocean. The recording started approximately 1h 55m after the tsunami was generated, and used about eight minutes to traverse the path from south to north.

A comparison of the wave heights predicted a with the recordings from the Jason-1 satellite was done.

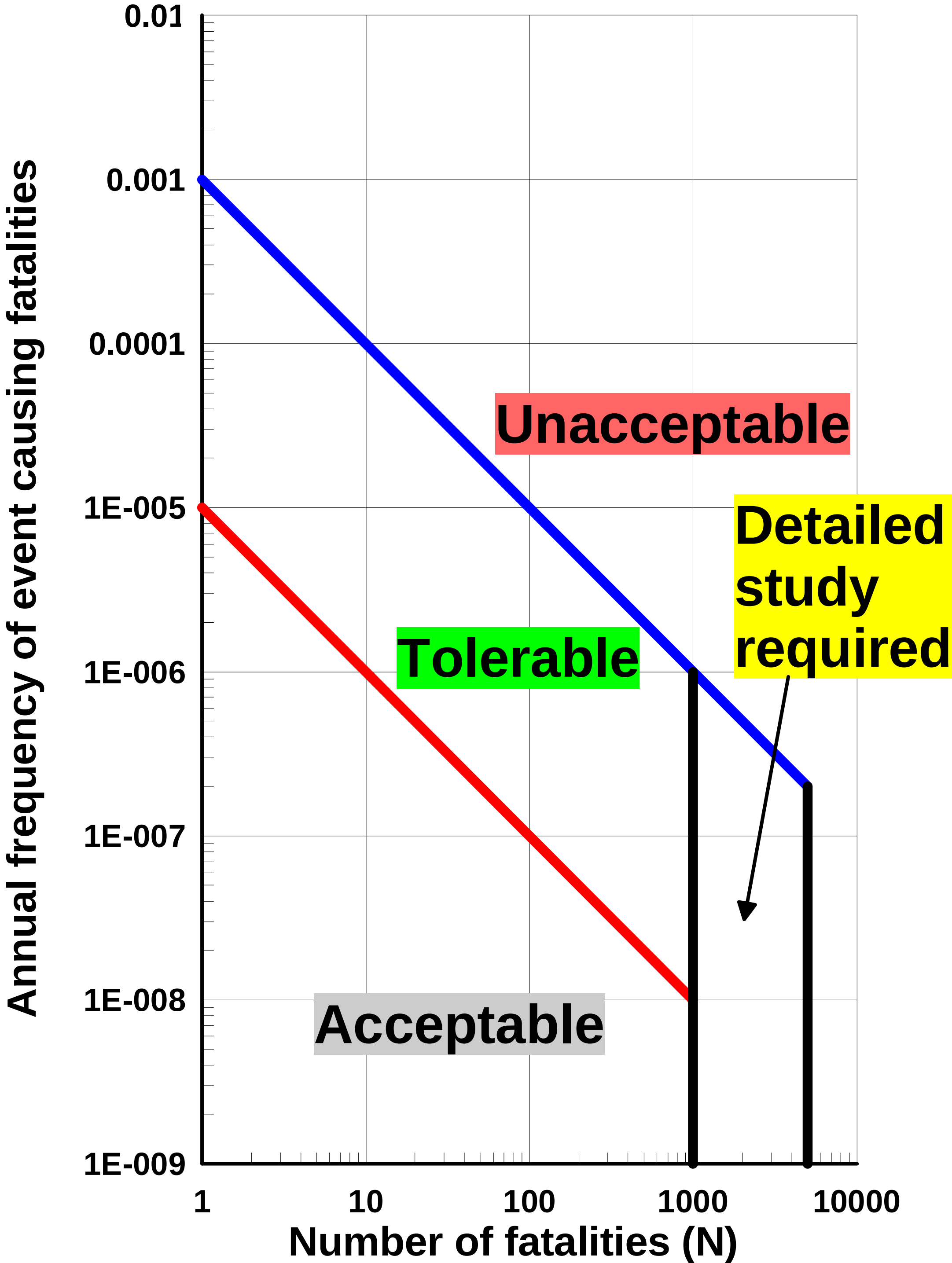
Satellite observations NOAA

- Typical surface elevation ~50cm
- Main characteristics reproduced in simulation



Maximum
run-up height predicted

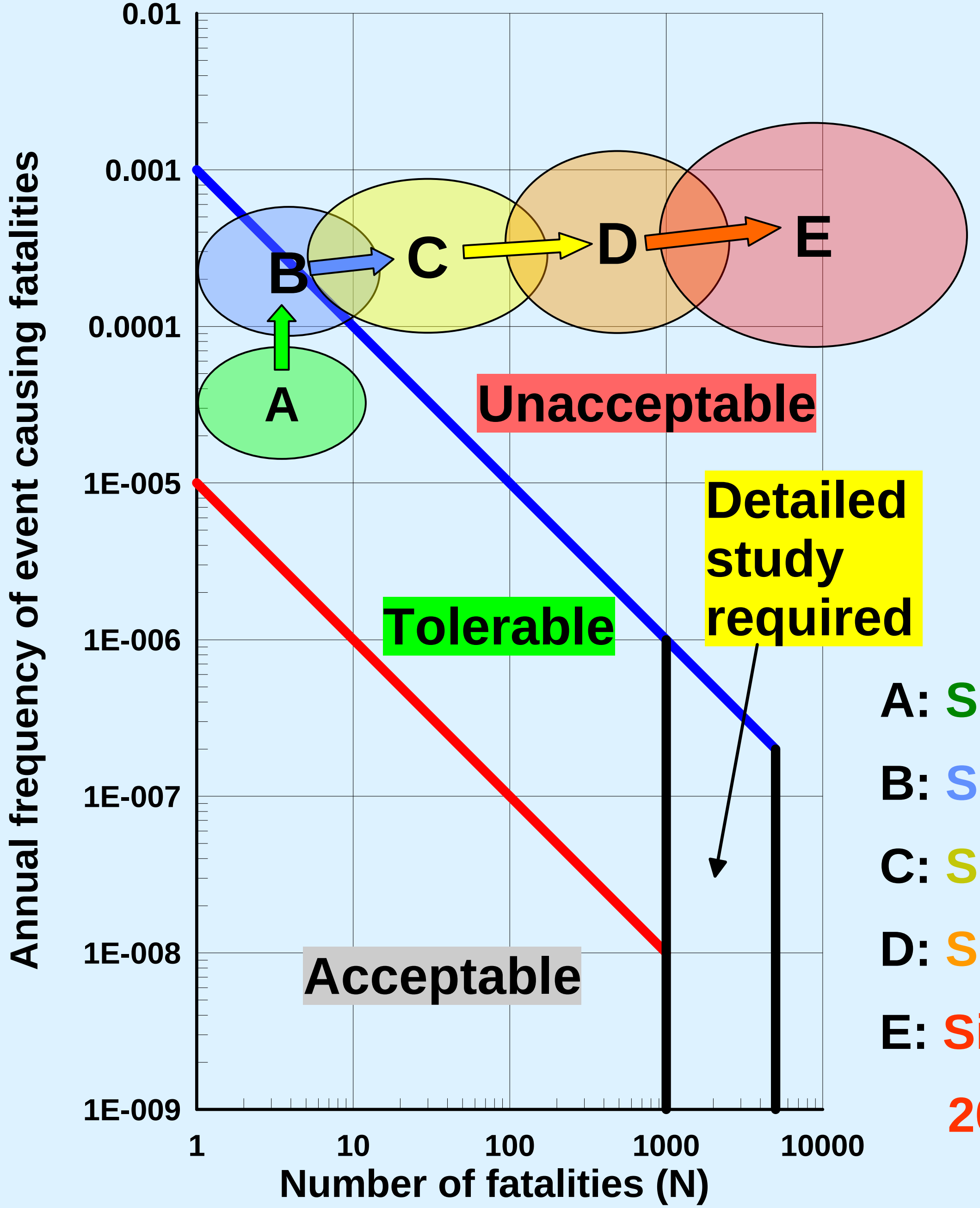
- The best estimate of the maximum tsunami surface elevation under M 8,5 earthquake, was found to be 1.5–2 m above mean sea level. If one accounts for variations in the tides (+0.8 m to +1.5 m), the maximum water levels was 2.5-3 m at high tide.
- On the longer term (> 50-100 yrs), the potential for earthquakes of magnitude and consequences as those of December 2004 will increase.
- Conclusions apply to west coast of Thailand only.



Hong Kong criteria (GEO, 1998)

Acceptable, tolerable, and unacceptable societal risk from geohazards

Evolution of tsunami risk with time (Nadim et al, 2006)



A: Situation today

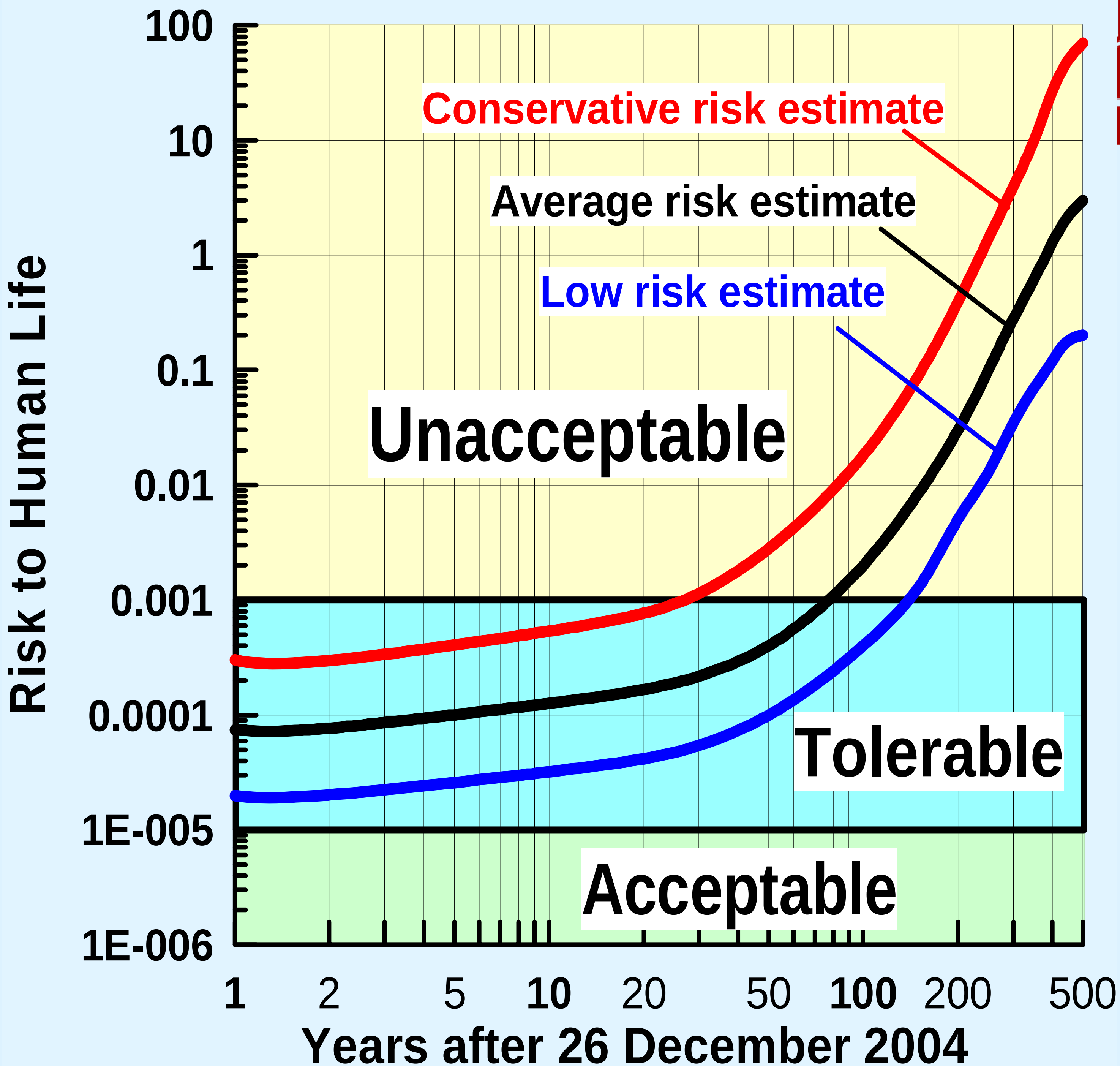
B: Situation in 50-100 years

C: Situation in 100-200 years

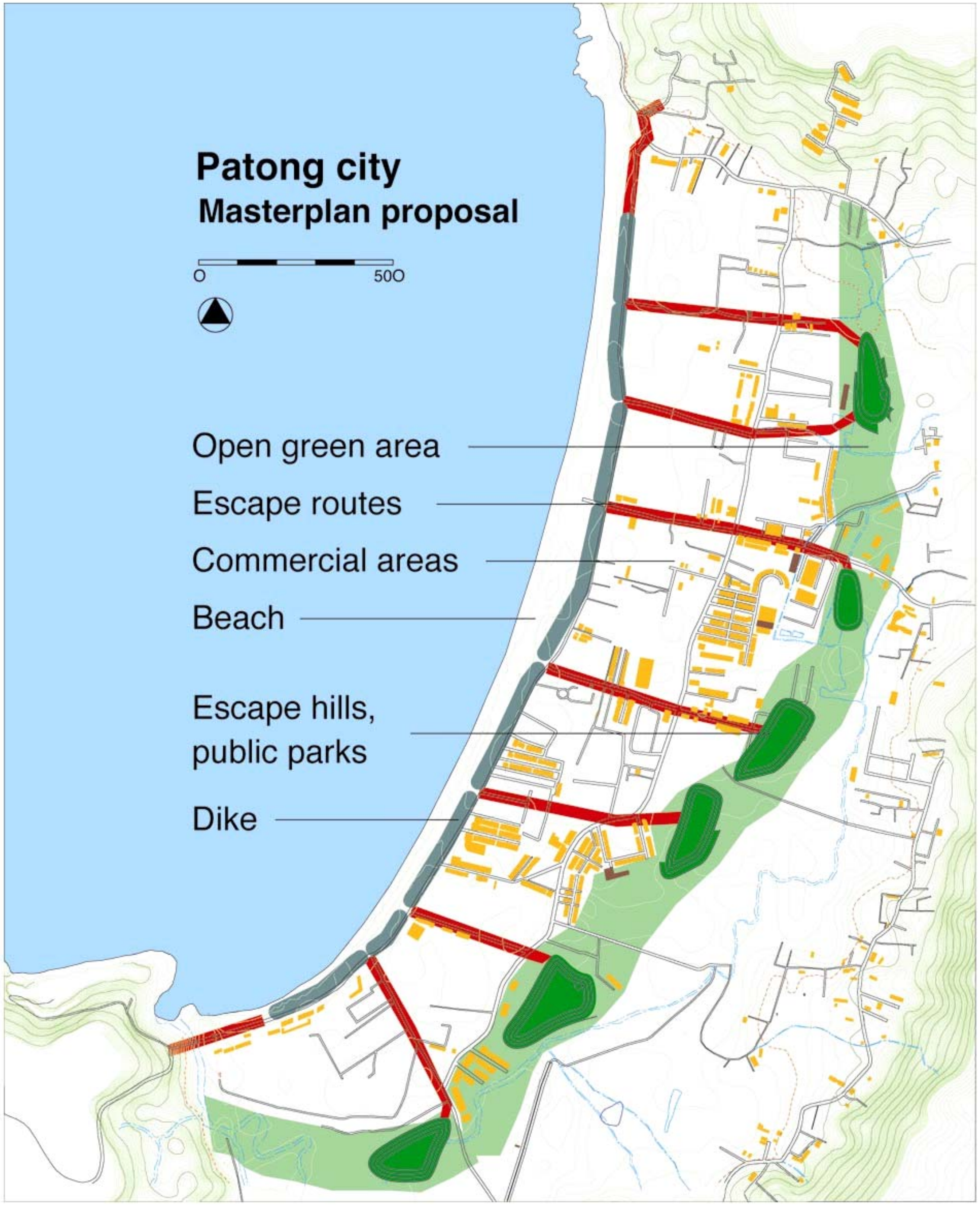
D: Situation in 200-300 years

E: Situation before 26 Dec. 2004 and after ~300 years

Estimated future tsunami risk to human life in Thailand (Nadim et al, 2006)

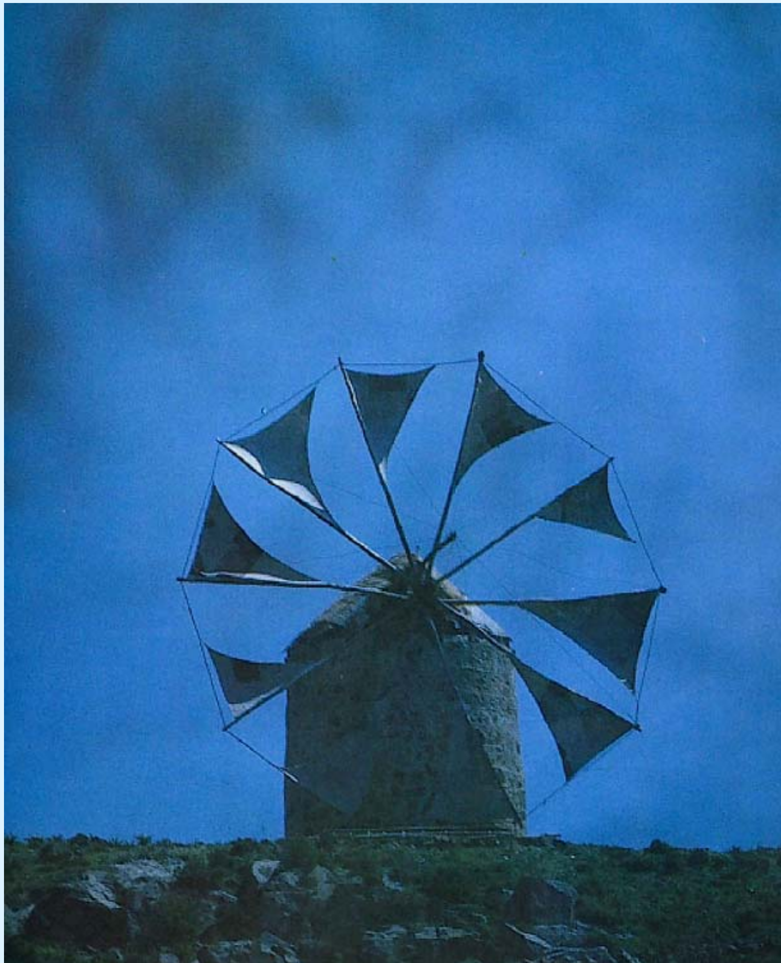


Remedial measures (risk mitigation) (Karslrud et al, 2006)



OUTLINE OF LECTURE

- **Exploitation of oil and gas resources**
  - Petroleum geophysics
  - Risk associated with tsunami
  - **Storage of CO_2**
- **Storage of radioactive waste**
- **Hydropower**
- **New challenges**



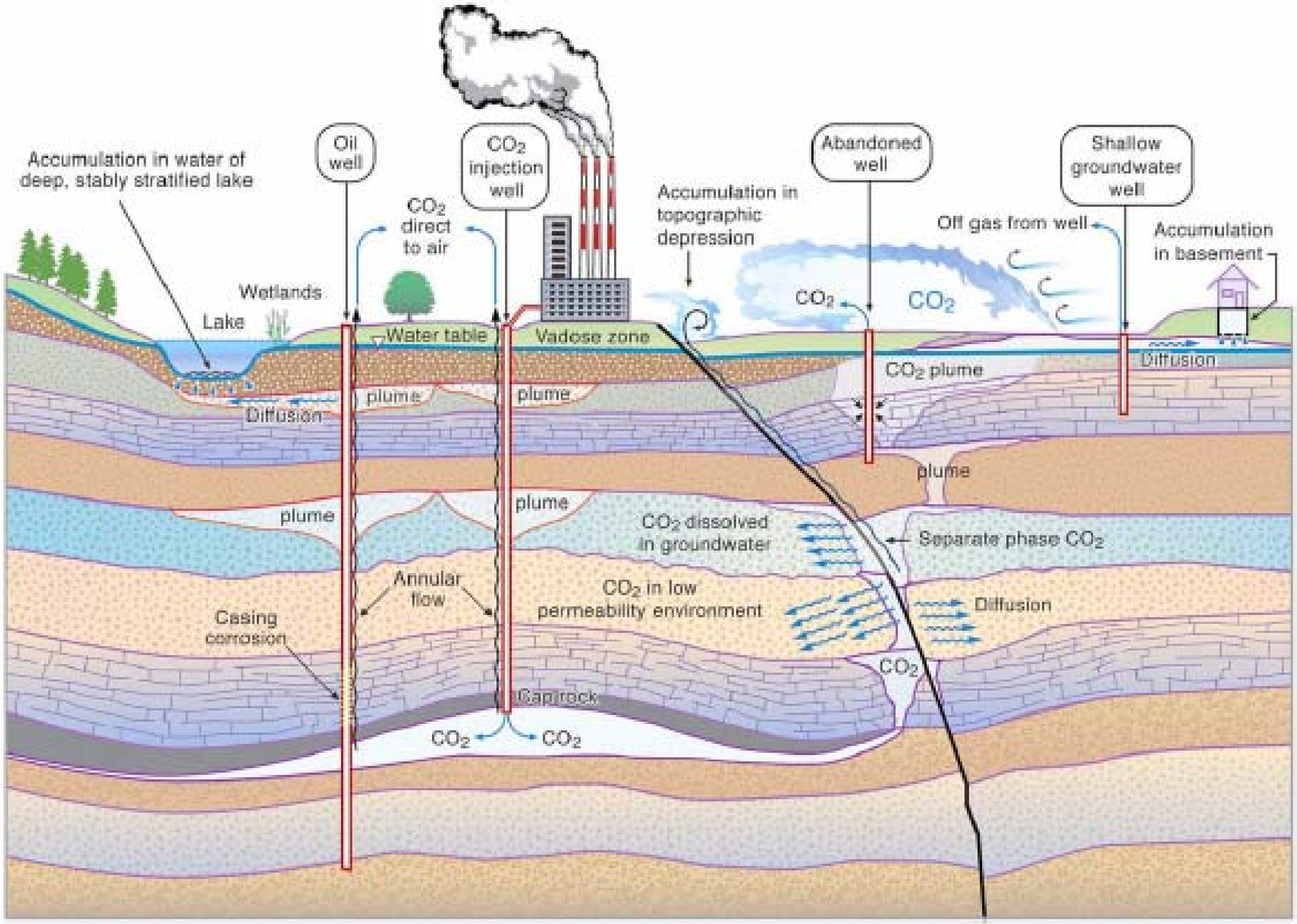
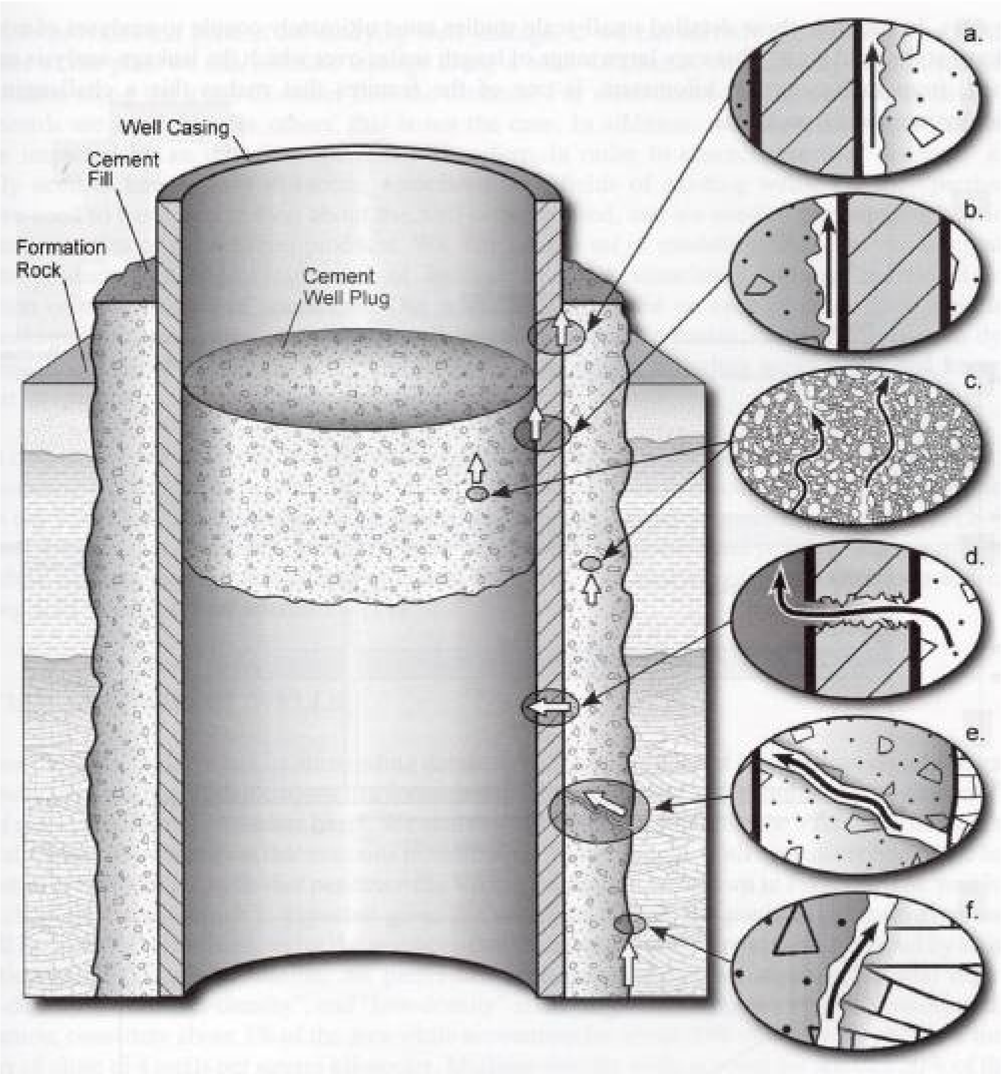


Figure 5.19 Schematic showing scenarios for leakage from a storage project.

IPCC-spec.report CCS, 2005

Well integrity – leakage mechanisms



Scherer et al., 2005

Most urgent gaps in knowledge for subsurface geologic storage:

- Full scale demonstration plants to quantify storage czpacity in sedimentary basins
- Risks of leakage from abandoned wells and methods of leakage need to be determined
- Improve fracture detection and characterization of leakage potential
- Leakage rate data from actual sites
- Develop reliable coupled hydrogeological – geochemical – geomechanical simulation models to use as prediction tools

Challenges:

- Risk analysis - Monitoring - Remediation
- Long-term validation requires state of the art evaluation tools based on experiments and fundamental theoretical work
- How is CO_2 storage different from oil, gas and water, and different from radioactive waste storage?

Challenges:

- Experimental procedures/standards for combined testing of geochemical and geomechanical properties
- Limited or missing lab data and *in situ* data
- Input parameters for geomechanical models
- Software development

Experimental test program

Geomechanics….

…and geochemistry

Experimental test program - fluid transport

Geochemical monitoring....

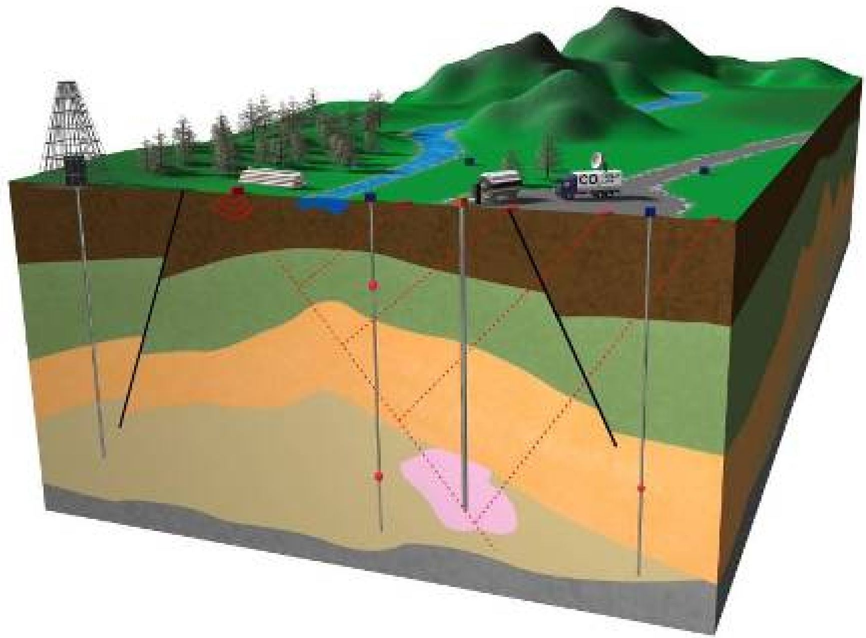
Geophysical monitoring....

International collaborations

BRGM = Centre scientifique et technique, France
GEO = Geoteknisk Institut, Danmark
G2R = UMR CNRS 7566 G2R et CREGU,
IFP = Institut français du pétrole, France
LMTG/CNRS Université Paul Sabatier Toulouse
University of Liège, Belgium
Kyoto University, Yamaguchi University

Colorado School of Mines
Louisiana State University
Stanford University
Los Alamos National Laboratory
Lawrence Berkeley National Laboratory
University of Hawaii

CO_2 Field Laboratory



Objectives

Determine requirements for monitoring systems applied in future industrial CO_2 storage projects

Monitor and quantify unforeseen migration out of the storage containment and leakage into the atmosphere or ocean

cmr NGU Norges geologiske undersøkelse IFE IRIS International Research Institute of Stavanger UNIFOB UNIVERSITETSFORSKNING BERGEN NIVA UNIVERSITY OF OSLO NGI

OUTLINE OF LECTURE

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  - Petroleum geophysics
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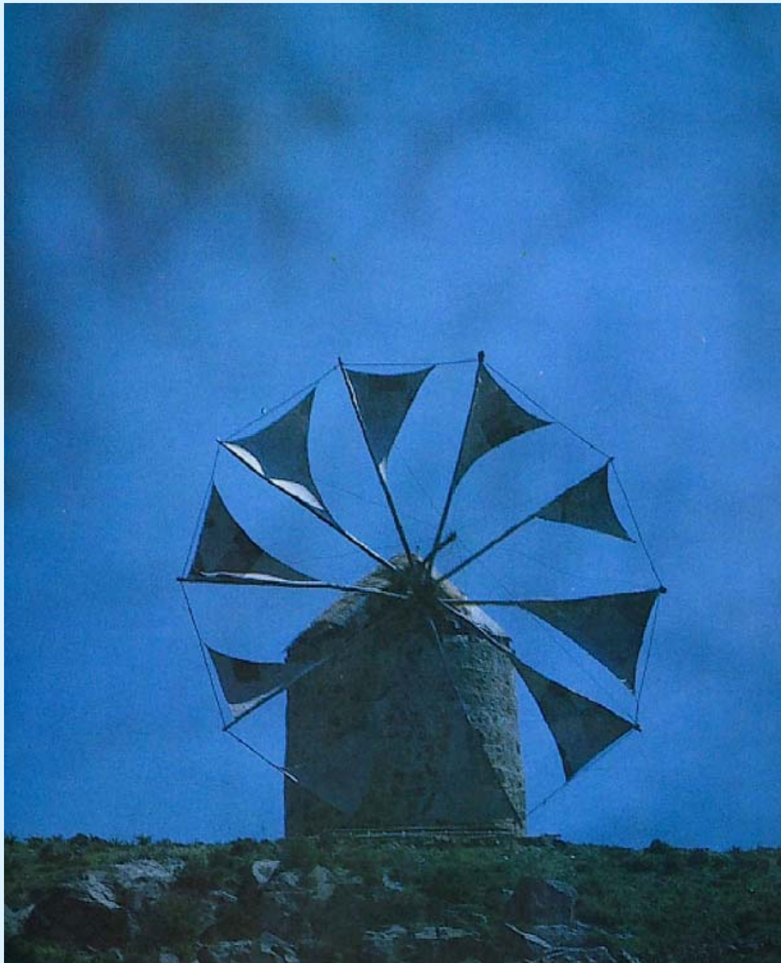
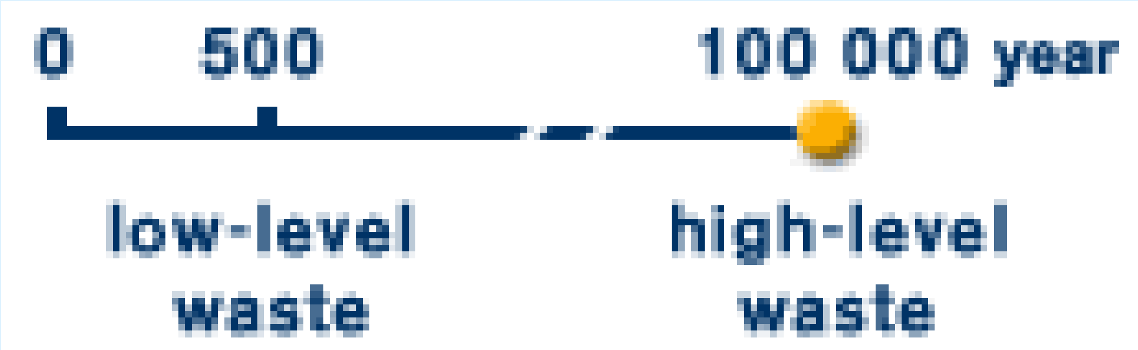
  - Storage of CO_2
- **Storage of radioactive waste**
- Hydropower
- New challenges



Nuclear Waste Containment

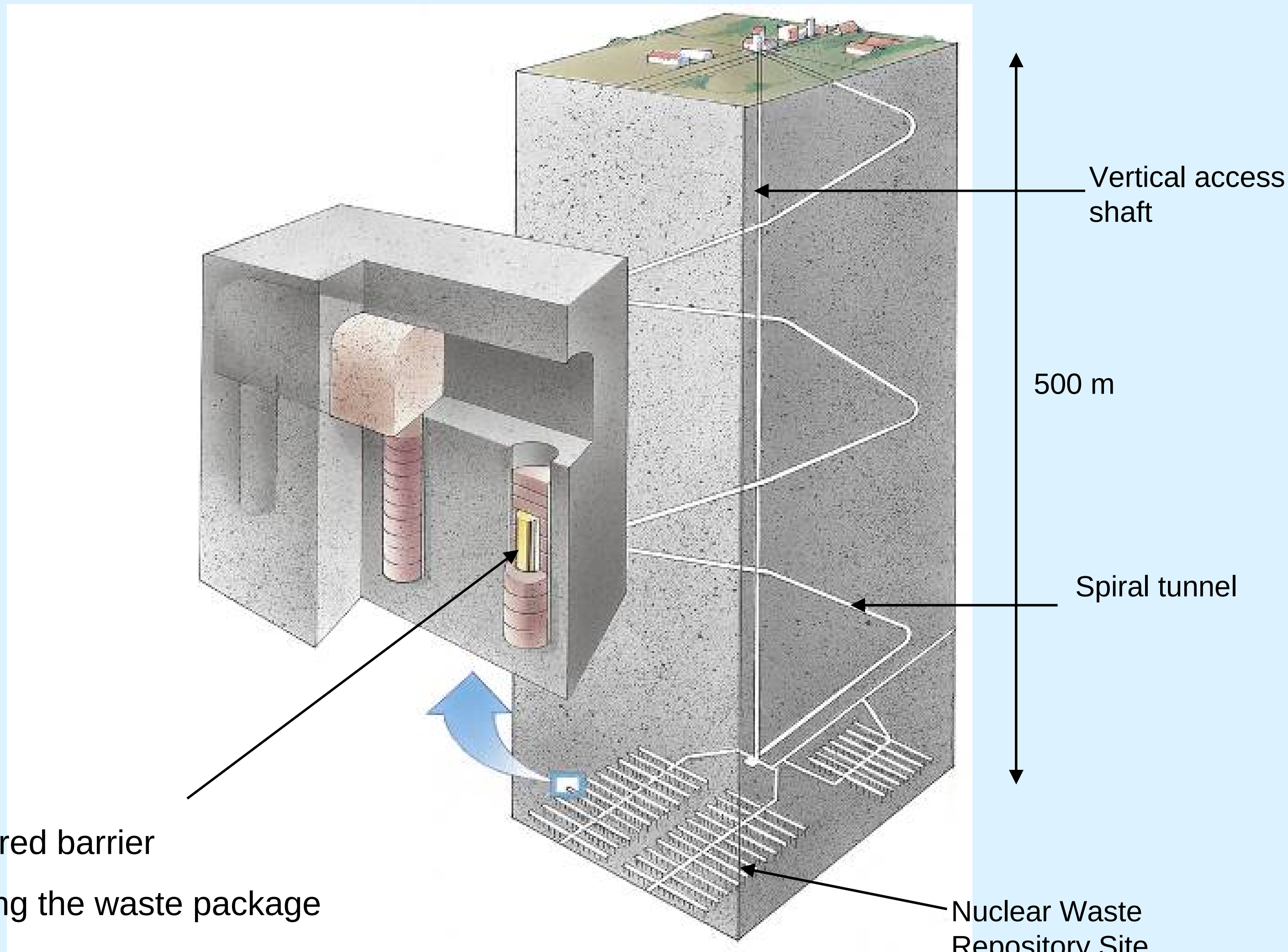
Usually based on a multi-barrier approach

- Engineered barriers, contains waste package itself within a container
- Geological barriers, for stable natural rock formation for isolation of high level waste



SKB Pilot Nuclear Waste Repository, South-East Sweden (Äspö)

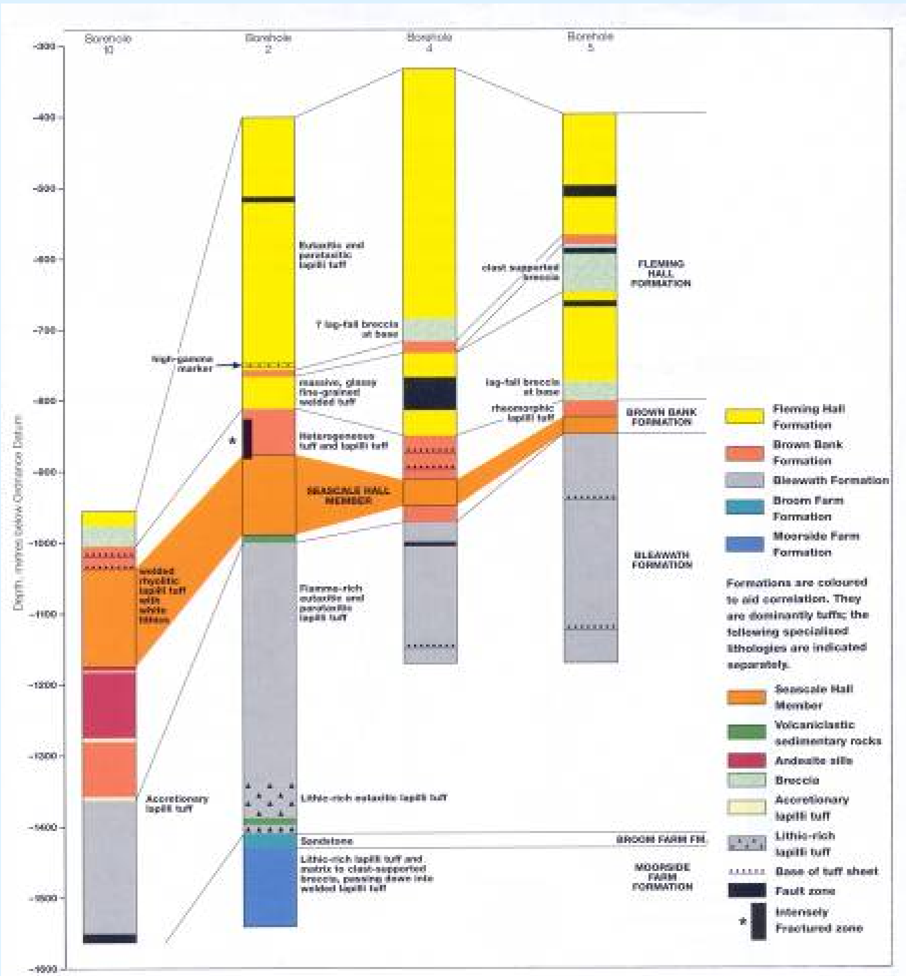
Norwegian Geotechnical Institute
On safe ground
NGI

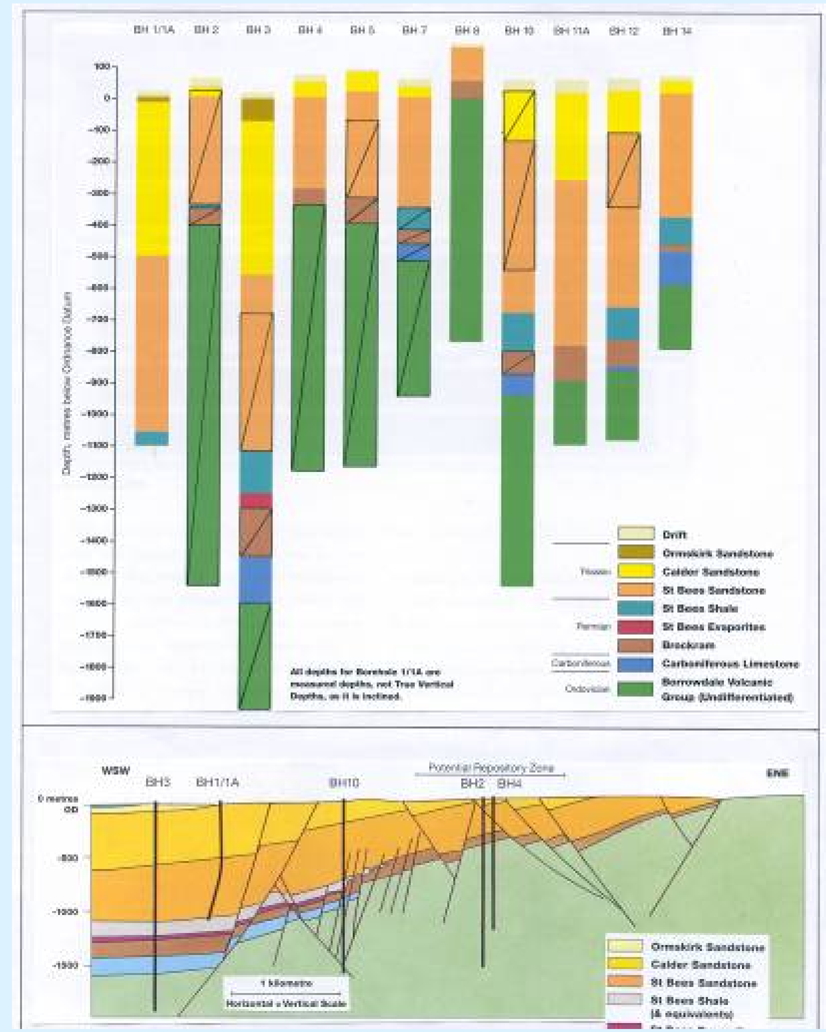


Nuclear waste disposal geo-work

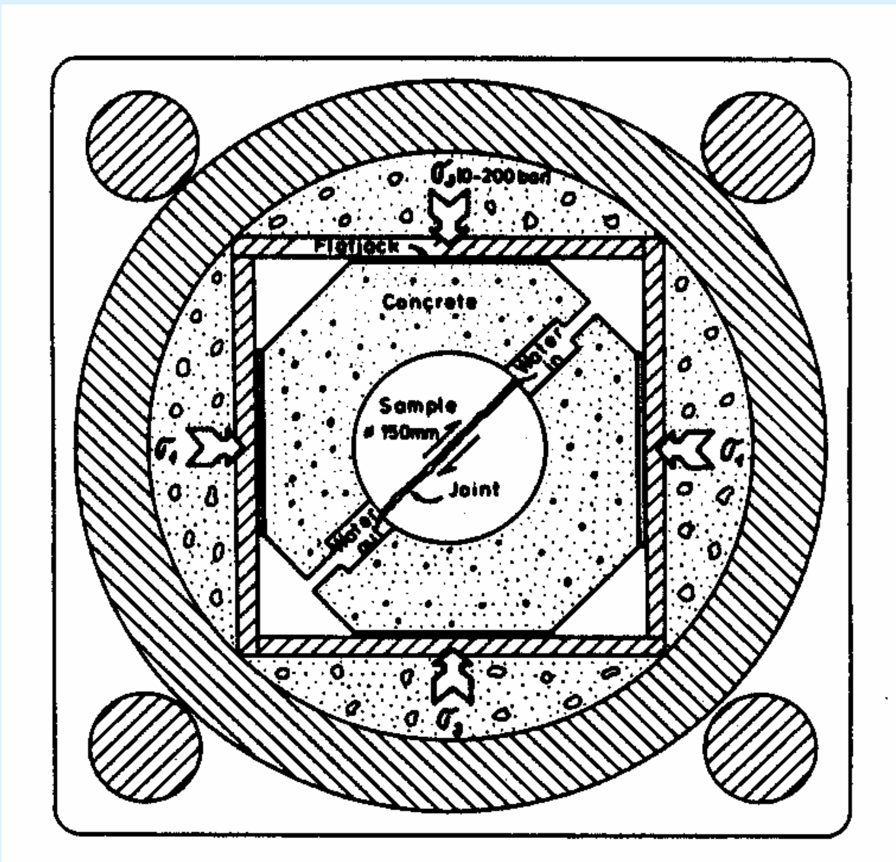
- Geotechnical Rock Mass Characterisation
- Geotechnical core logging
- Advanced in-situ and laboratory testing for assessment of ground conditions and assess potential for effective waste containment
- Numerical modelling
- System for all recorded geo-data

Site characterisation

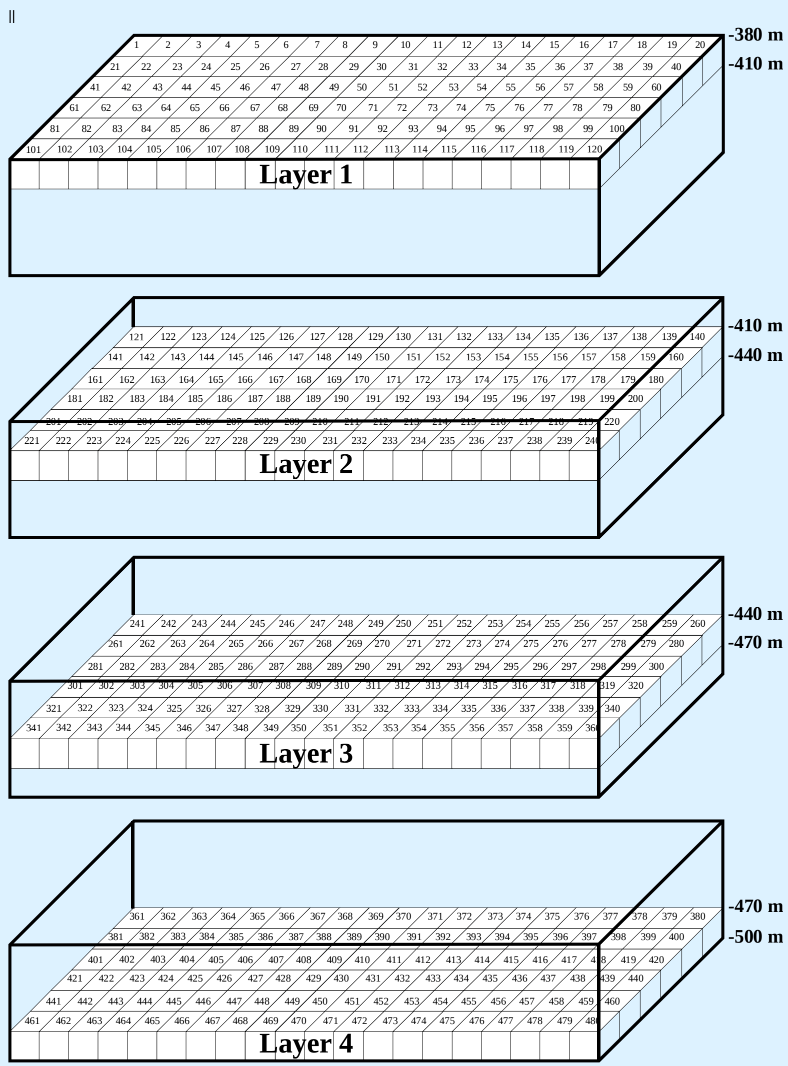




Advanced Laboratory testing for sealing of rock joints with microcement (CSFT apparatus)



Rock Mechanical Model



Rock Mechanical Model

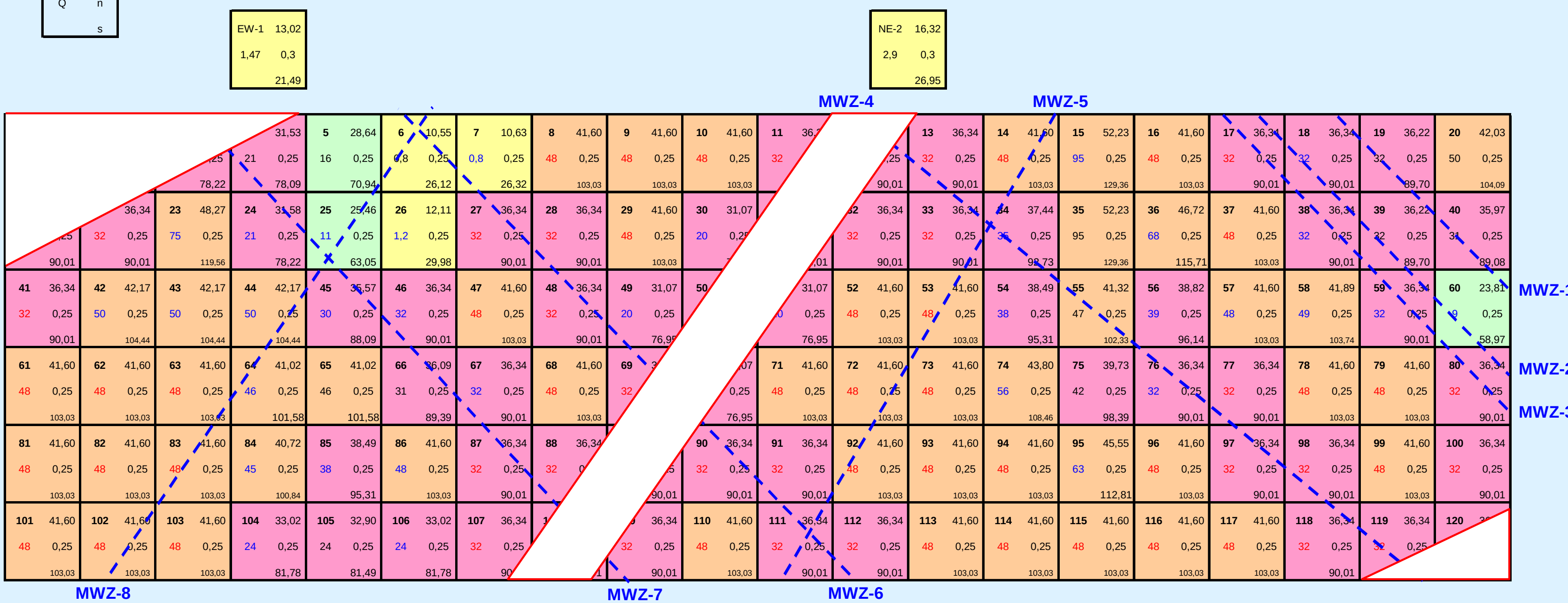
Model B

$E_{m\ (cha)}$

Grid Block Number: 1-120

Depth: -380 to -410 m

Bl.no.	E
Q	n
	s



$E_{m(cha)}$

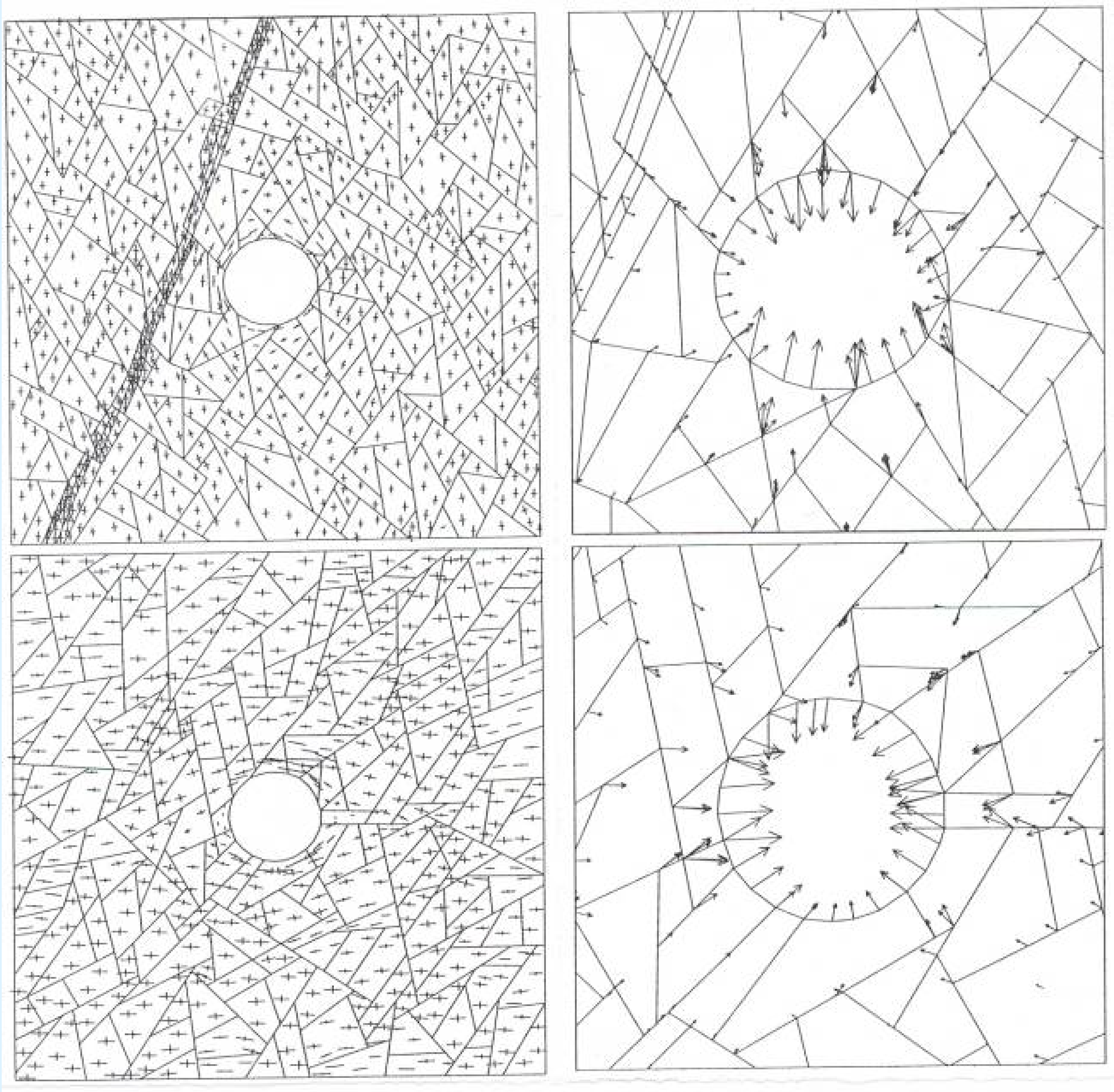
NE-1	15,74
2,6	0,3
	25,99

- < 10
- 10-20
- 20-30

Central zone:

NE-1	2,55
0,011	0,4
	4,20

Numerical modelling



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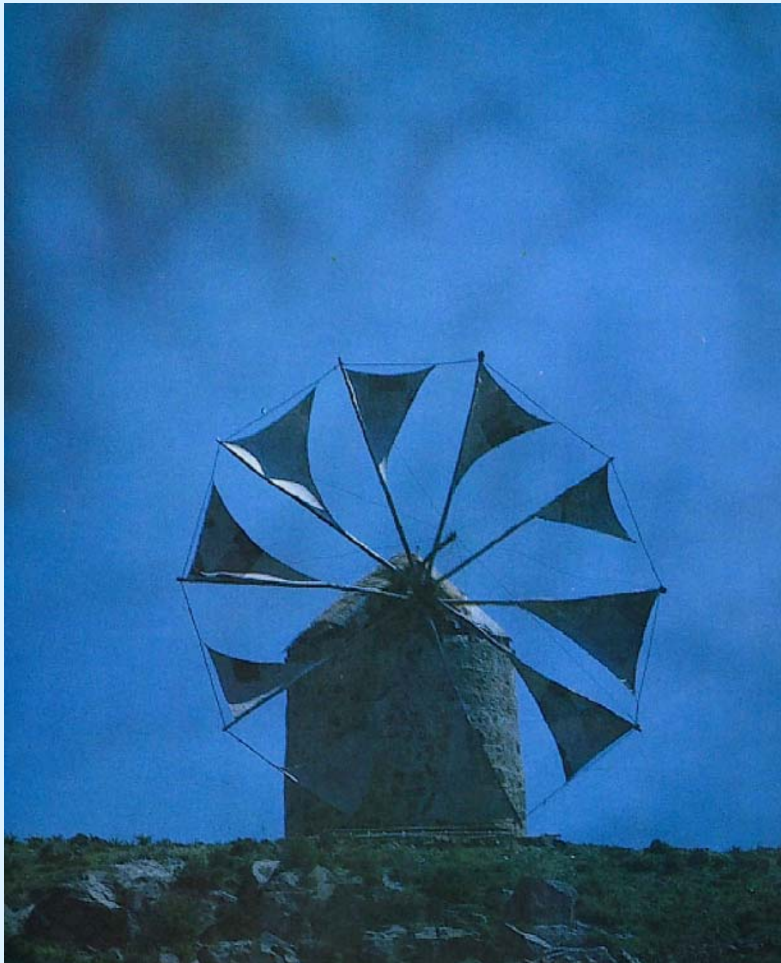


Hydropower Embankment Dams Safety Evaluation, Risk Analysis and Upgrading

Worldwide there are approx. 30 000 dams higher than 15 m. More than half of these are built since 1950. However, many are > 100 years old.

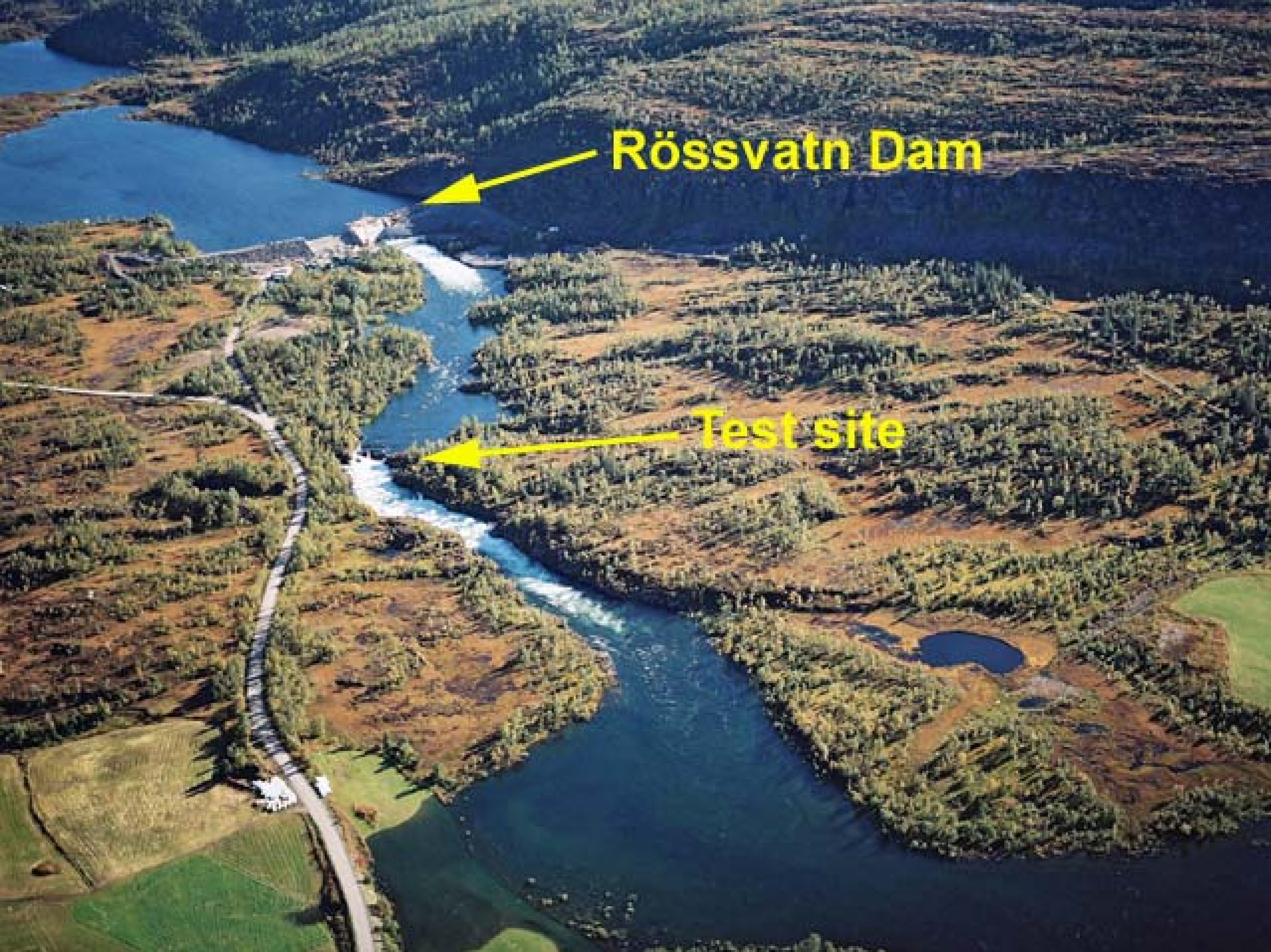
The safety evaluation and upgrading of existing dams to satisfy present criteria is a challenge no less demanding than the original design and construction.

Statistics on Dam Incidents and Failures

Causes of incident or failure	% of 240 dams
• External erosion (overtopping/wave action)	29
• Internal erosion (in dam body/foundation)	38
• Foundation instability	14
• Excessive dam deformation	13
• Deterioration (chemical/physical)	2
• Malfunction of gate	2
• Earthquake effects	1
• Construction errors	1

Recent Research Program in Norway

A research program to study dam drainage capacity, instability and the breaching process was recently completed. It included numerical modelling, small scale laboratory tests and the testing of 6 m high field “model” embankments brought to failure (Höeg et al., 2004).


Rössvatn Dam
Test site


NCC

Gravel embankment without core

① Gravel 0 – 60 med mer, vibratory compaction, 0.5 m layer thickness

② Rock from tunnel spoil 0-500mm, removed before breach test

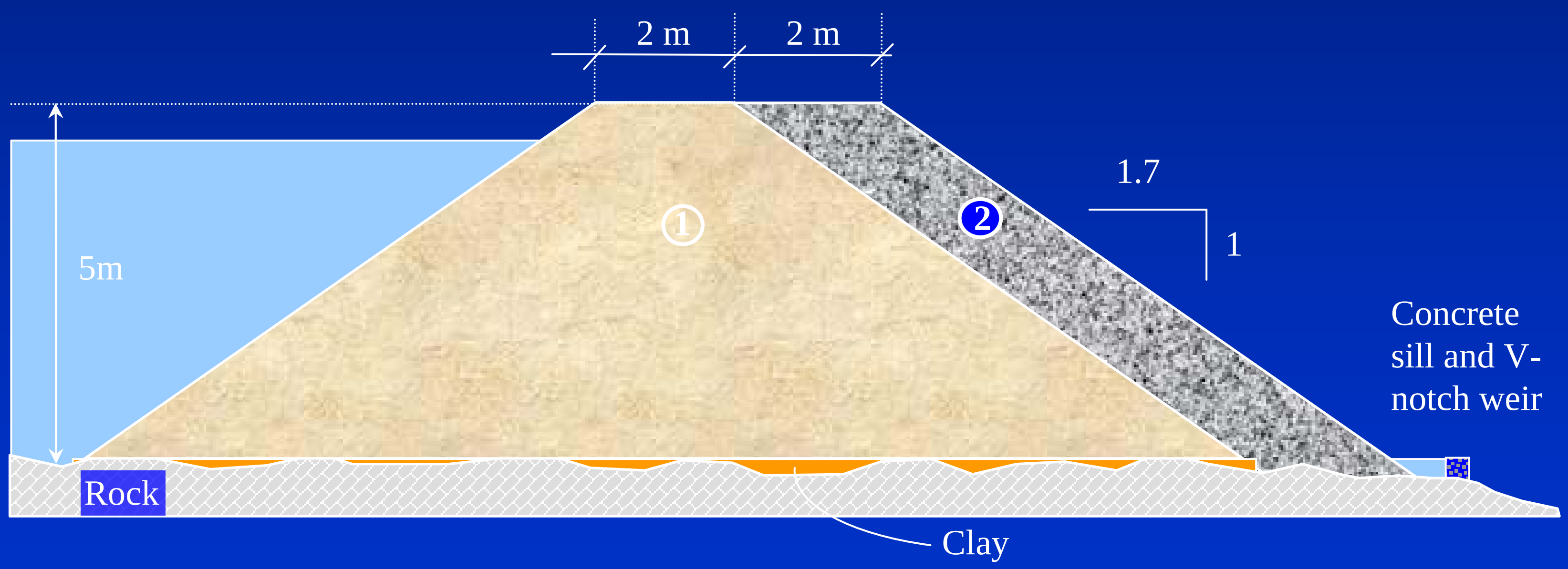


Fig. 3 Test No. 3 - Homogeneous gravel dam

Rockfill dam with moraine core with defects

1. Moraine, vibratory compaction, 0.5 m layer thickness
2. Rock from tunnel spoil 0-500mm, vibratory compaction, 1 m layer thickness
3. Rockfill 300-400mm, vibratory compaction, 1 m layer thickness

Defects built into dam for initiation of piping, uniform sand

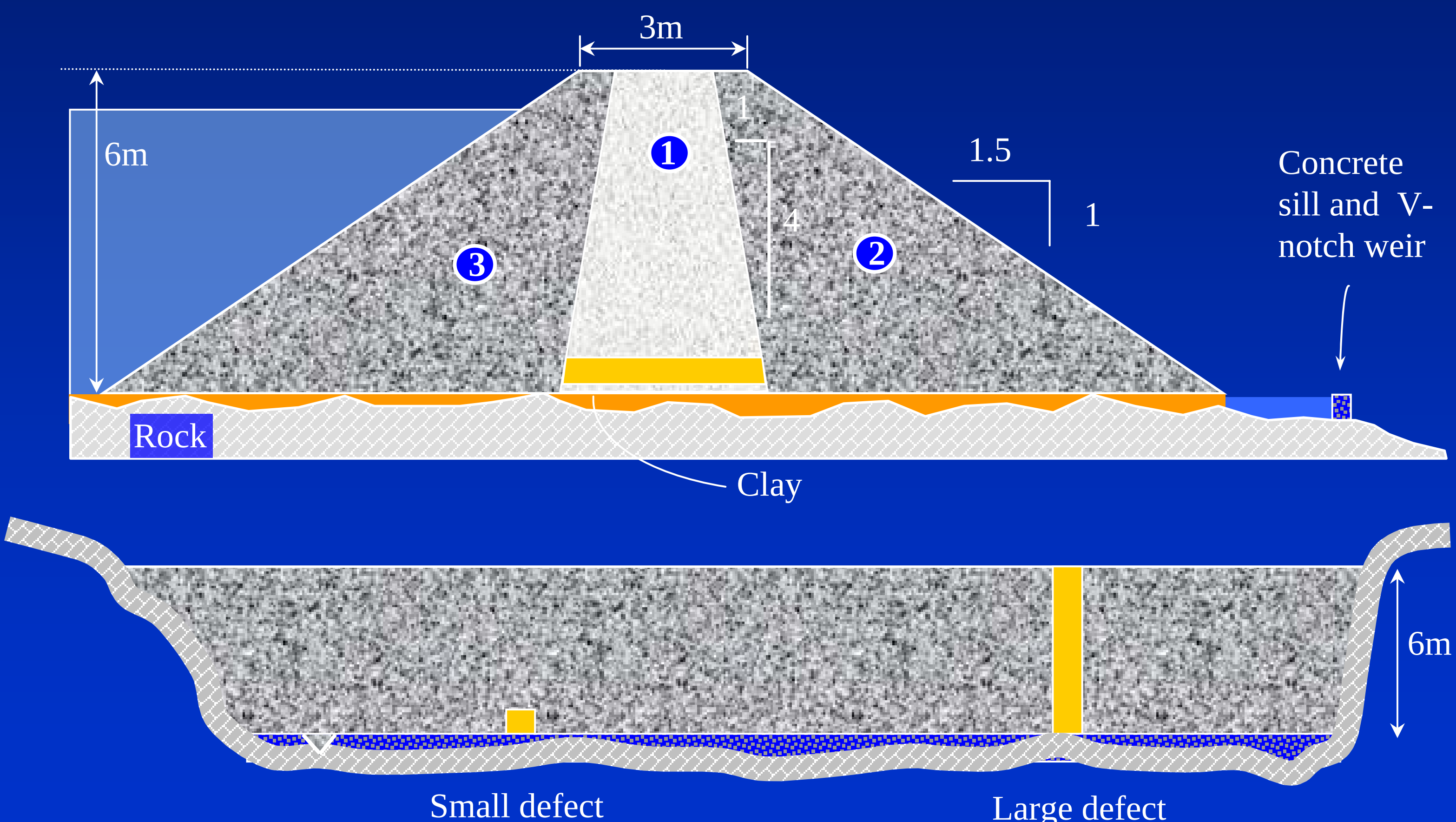


Fig. 4 Test No. 6 – Rockfill dam with central moraine core


NCC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Some results from research program:

- Drainage capacity (safety against ravelling of downstream slope and toe during accidental through-flow and overtopping);
- Shearing resistance of rockfill and gravel materials;
- Data on breach initiation and progression, and flood wave characteristics.

New Dams – Optimum Designs

Which embankment type is best suited for the local conditions, considering:

- economy (construction and operation)
- safety/reliability
- environmental effects


Kárahnjúkar Dam
September 15th 2005


Kárahnjúkar Dam, Iceland
February 11th 2006

Storglomvatn Dam near completion

Compaction of asphalt concrete core and transition zones

Looking ahead – dams for hydropower

- There is urgent need for safety evaluation and upgrading of existing dams. In many countries this has been overlooked for too long. China recently embarked upon such a program (Xi'an Conference, 2005).
- There is need for more active dam safety regulation and legislation. The World Bank recently issued proposed a "Regulatory Framework for Dam Safety" (a comparative study among 22 countries).
- There is need for dam engineering education and training programs. In most industrialized countries there are few new dams being built, and the new generation of engineers, responsible for the safety of existing dams, receives little hands-on experience with design and construction.

Looking ahead (cont'd)

The world continues to build dams and dikes for many purposes, especially in the developing countries, to satisfy critical human and societal needs.

A more systematic procedure of option assessment, using risk analysis concepts, should be developed and practiced, to facilitate a "fair" decision making. The option assessment must also include the "do-nothing option".

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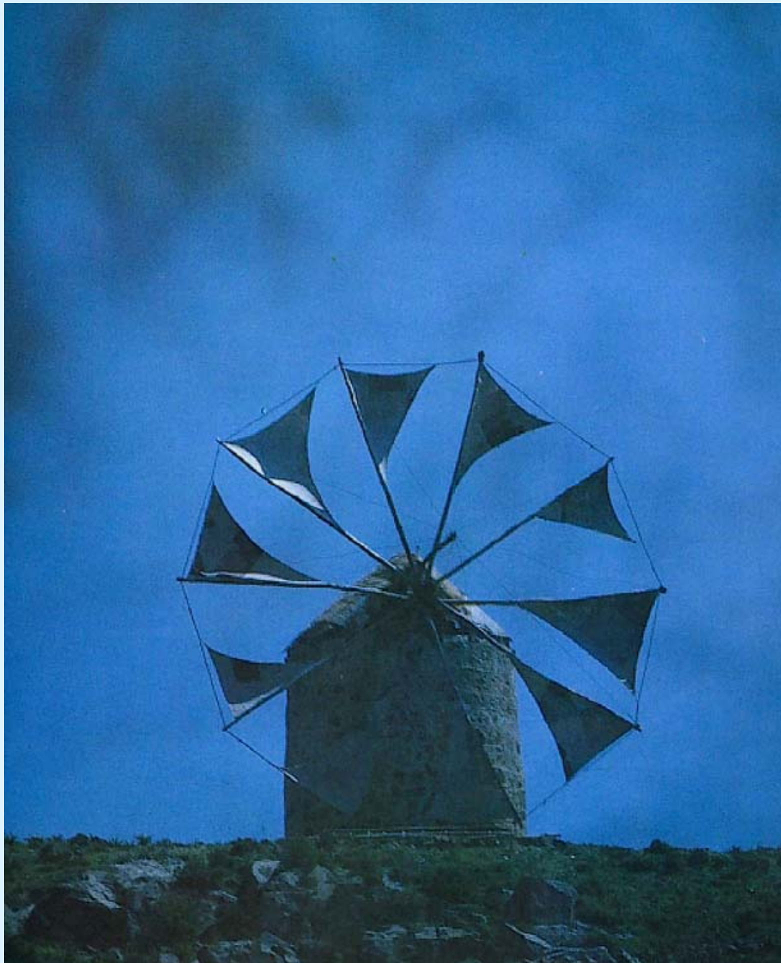
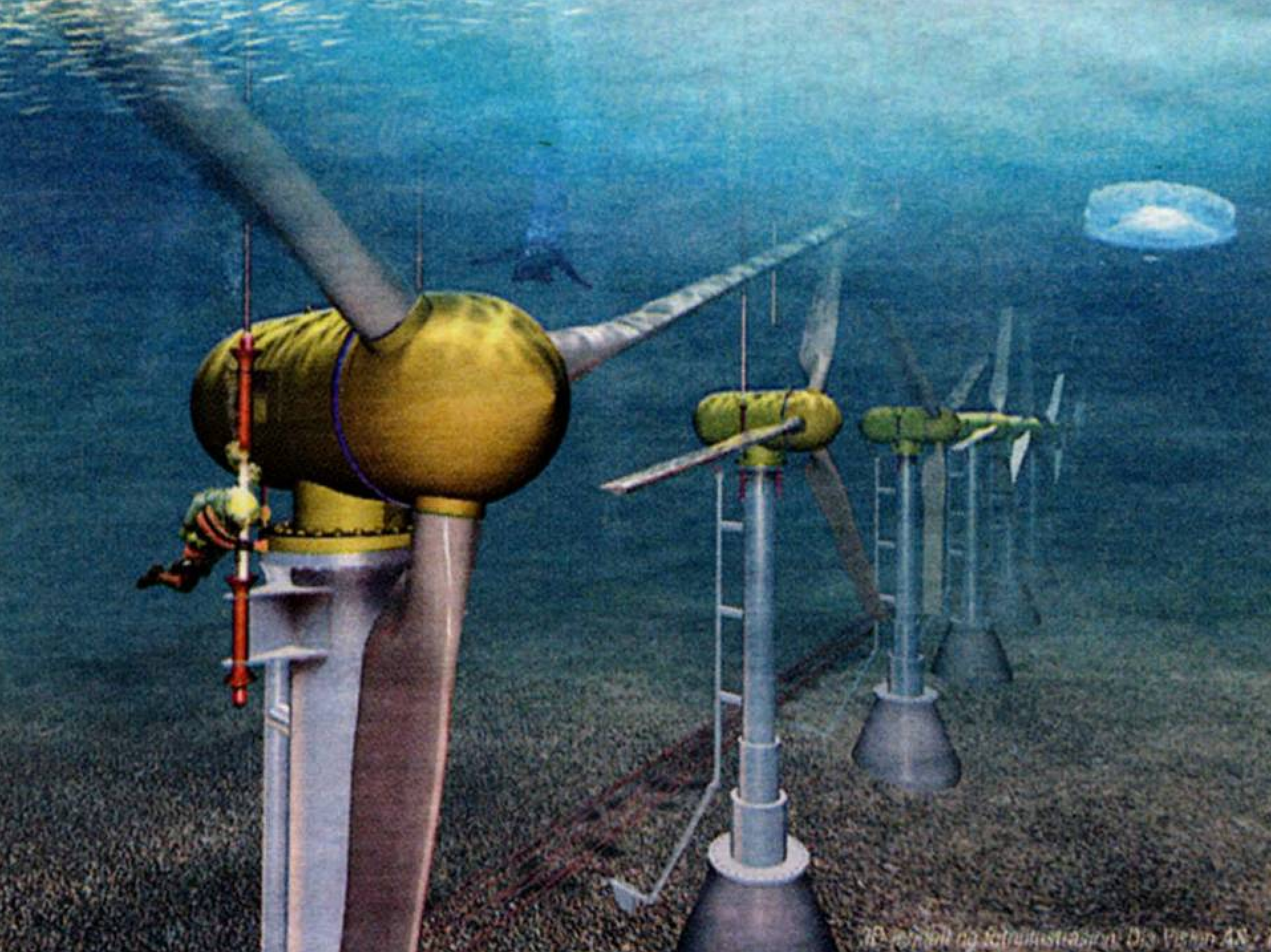


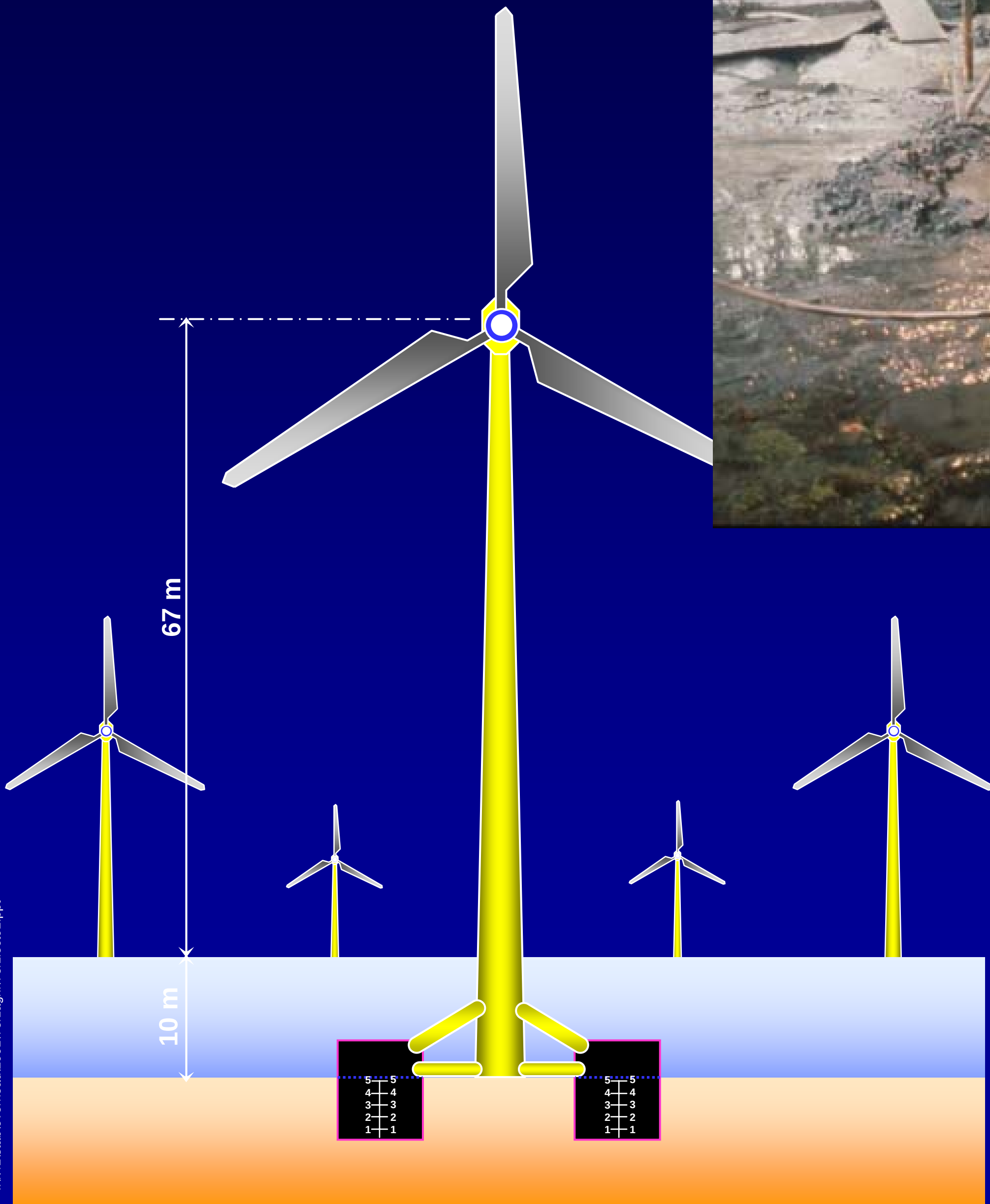
New energy sources

Oilsands (tar sands)

Unconventional gas

- Natural gas from coal (90% methane)
- Tight gas sands and carbonates (trapped in low k formations)
- Shale gas (natural gas in organic-rich, fine-grained rocks)
- Gas hydrates (methane molecules are trapped in formation, natural gas frozen into ice and sediment)

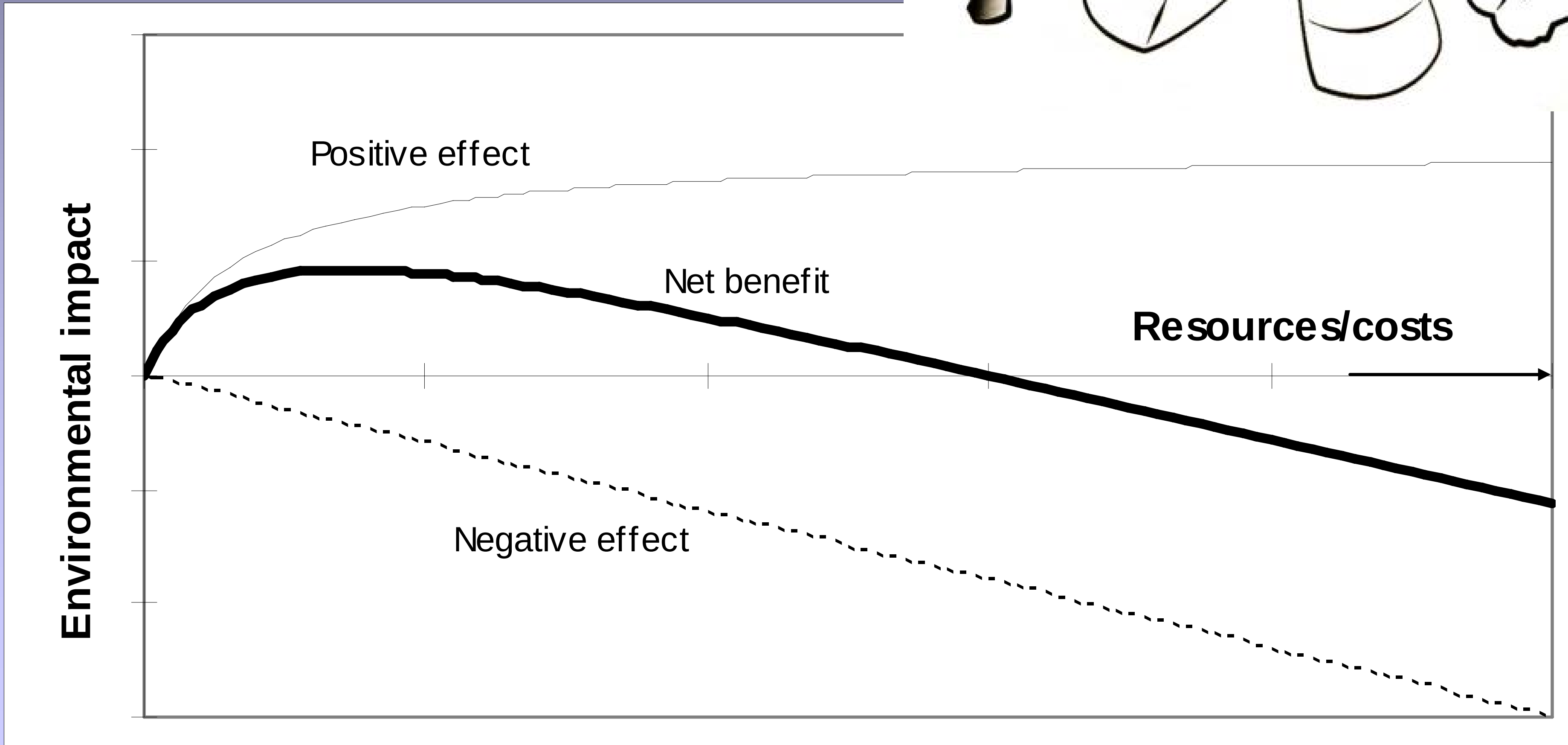




Tripod for nearshore windmills

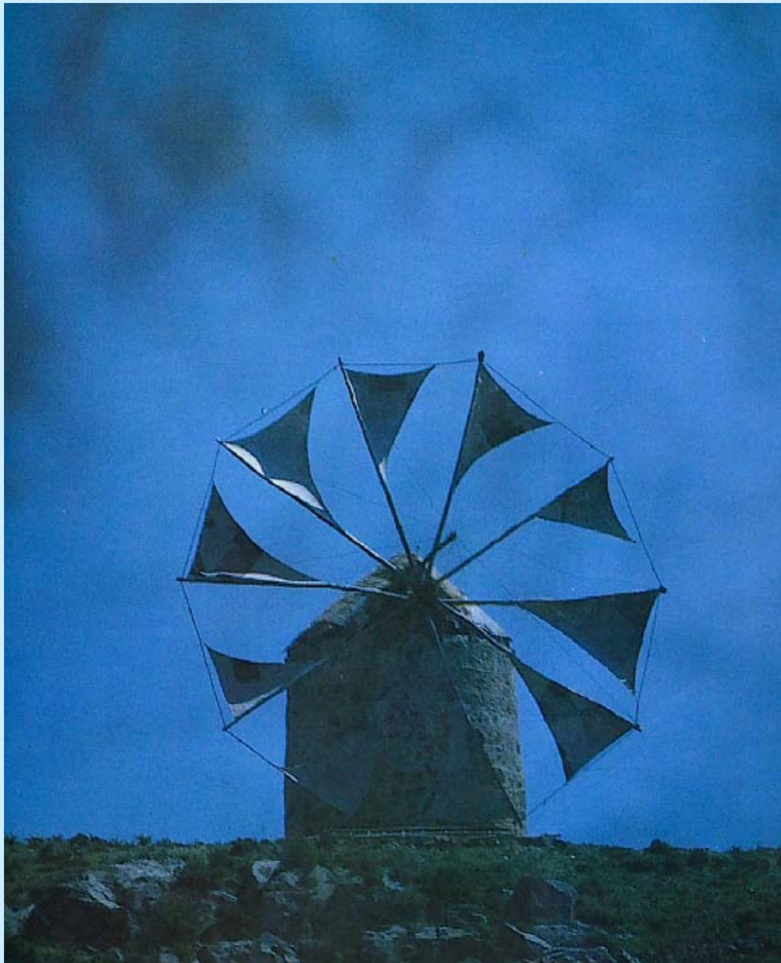
Environmentally responsible strategy

Finding an optimum solution



Geotechnical engineer's role future energy needs

- **Exploitation of oil and gas resources**
- **Storage of radioactive waste**
- **Hydropower**
- **New challenges**



Focusing on
- **Cost-effective solutions**
- **Improved and safer solutions**
- **Innovative solutions**
- **Preserving the environment**

Technical challenges

- Revitalise the use of in situ measurements and performance monitoring, and the careful interpretations of the observations
- Increase our efforts to evaluate the risk of natural hazards, develop improved methods for the analysis of slopes and develop mitigating measures

Technical challenges

- Achieve a more effective dialogue and cooperation among the geosciences. Geotechnical engineers should be more aware of the omnipresent influence of geology.
- Do consequence analysis of alternatives and gradually move towards a quantification of the risks involved.
- Include automatically the environmental component to our solutions.

Conclusions

Our profession needs to offer safe and reliable solutions that serve society. We need to recognise our social responsibility.

There is a unique role for geo-engineers and geo-scientists to play in the development of society, not as technologists alone, but as well-rounded professionals working in a well-defined environment.

The geo-profession adds value by saving lives, preserving the environment, improving performance, reducing risk and costs and exploiting natural resources in a responsible manner.

Acknowledgement

My colleagues at NGI

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Eyvik Aker

James M. Strout

Harald Westerdal

Thank you for inviting me to deliver the Leonards Lecture!

Thank you for your attention!