Geomorphological and geotechnical Considerations towards tsunamigenic submarine slide risk assessment

by

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Abstract :

Over the last two decades submarine landslides have been more widely recognized as a significant source of tsunamis and therefore as a potential threat to offshore and coastal infrastructures such a nuclear power plants. What is the risk that a tsunamigenic slide causing significant damage to offshore structures either on the Pacific or on the Atlantic coast of the U.S.? After presenting some preliminary remarks related to the origin and types of submarine slide, the following presentation is mostly focus on the following elements: (1) morphology and strength, (2) mobility and strength and on (3) earthquakes and slides.

According to Nadim and Locat (2005), challenges for the geotechnical discipline includes: 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, and assessment of uncertainties in risk analysis.

Because of time limitation, the presentation will now mostly focus on how to reduce uncertainty on tsunami source landslides, i.e. a way of estimating their magnitude from morphological and mobility analyses. Because of the lack of good in situ measurements, most of the time we are limited to optimizing morphological and seismic profiles in order to reduce the uncertainty on the size of the slide, the triggering mechanism and their intensity, and the parameters governing their mobility and the initial acceleration in particular. Strength properties can also be derived from morphological analysis and by extrapolation from poor quality samples which has to make good use of general soil mechanics principles.

In many instances, one must consider very high pore pressure to exist at the time of failure and its source could be related to earthquake and the accompanying shaking. Many of the very large submarine landslides like the Storegga and the Grand Banks can be consider as spread failures and so far there are no tools existing to evaluate the risk of a spread failure for a given slope. On this aspect some general remarks include:

1. Presence of a weak layer (or weakable) ensuring a rapid propagation of the failure plane and the bulk mobilization of the sliding mass over on a remolded layer with a very low shearing resistance. Role of a film of water ?
2. Minimum acceleration must be reached before significant post-failure transformation takes place, e.g. desintegration, breakage into lumps, etc…
3. Actual signature of retrogressive failure are mostly concentrated near the final escarpment with little knowledge of the slide dynamics in the lower starting zone.
4. Any phase of a retrogressive failure can generate a tsunami, as long as a significant volume of the sliding mass gains enough acceleration (everything else being constant)

As triggers, it is interesting to see that in North America, one could analyze the remaining stresses in the earth crust in order to estimate the potential for large earthquakes. The actual seismic map is bias by historical data as seen by the Grand Banks earthquake of 1929 (M = 7.3) indicating that even now there could be some significant strain energy still stored in the crust supporting the need for further investigation aim at dating landslides and establishing the paleoseismicity of a region.

A final aspect discussed in the presentation is to consider the use of morphological data for mapping the slope in order to map existing landslide scars and therefore define the remaining areas still available for landslide.

Concluding remarks are as follows:

Critical geomechanical properties of tsunamigenic failures are:

1. Strength of material (drained or undrained): in situ measurements may be essential
2. Sensitivity of a weak layer;
3. Deformability and initial rate process (desintegration);
4. Structure (rocks)

Limits:

1. Development of spread failure criteria still ongoing (Ph. D. of A. Locat)
2. Acceleration still is difficult to predict correctly: Newer approaches using deformation models may help understand the transition between failure and post-failure;
3. Mapping areas prone to failure and potential triggers;
4. How about easy access to 3D seismic

Acknowledgements: U. ten Brink, J. Chaytor, H. Lee, F. Nadim, U.S. Nuclear Regulatory Commission, U.S. of Naval Research, National Science and Research Council of Canada, colleagues and graduate students.

Some of our recent contributions:

Lee, H.J., Locat, J., Desgagnés, P., Parson, J., McAdoo, B., Orange, D., Puig, P., Wong, F., Dartnell, P., and Boulanger, É., 2007. *Submarine Mass Movements. In: Continental-margin Sedimentation: Transport to Sequence,* Nittrouer et al. Éd., Special publication No. 37 of the International Association of Sedimentologists, pp.: 213-275.

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Locat, J., and Lee, J., 2005. Subaqueous Debris Flows. Chapter 9, *In: Debris-flows Hazards and Related Phenomena*, Mathias et Hungr, éd., Springer, pp. : 203-245.

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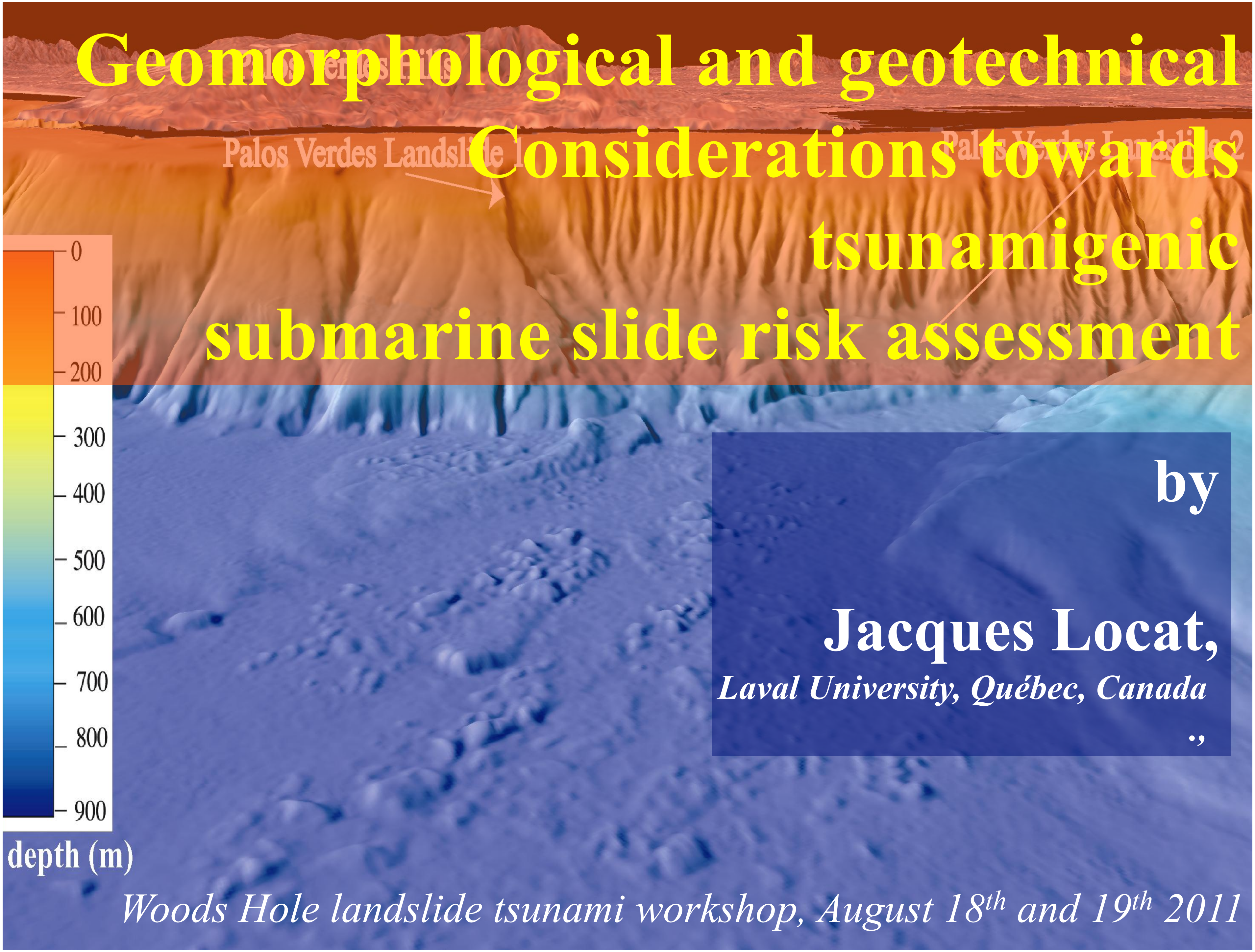
Locat, J., Lee. H.J., Locat, P., and Imran, J., 2004. Numerical analysis of the mobility of the Palos Verdes debris avalanche. *Marine Geology*, 203:269-280.

Locat, J., Lee, H., ten Brink, U., Twichell, D., Geist, E., and Sansoucy, M, 2009. Geomorphology, stability and mobility of the Currituck Slide. Marine Geology, 264: 28-40.

Nadim, F., and Locat, J., 2005. Risk assessment for submarine slides. *In: Landslide Risk Management*, Hungr, Fell, Couture, and Eberhardt, Ed., Balkema, pp.: 321-333.

Geomorphological and geotechnical Considerations towards tsunamigenic submarine slide risk assessment



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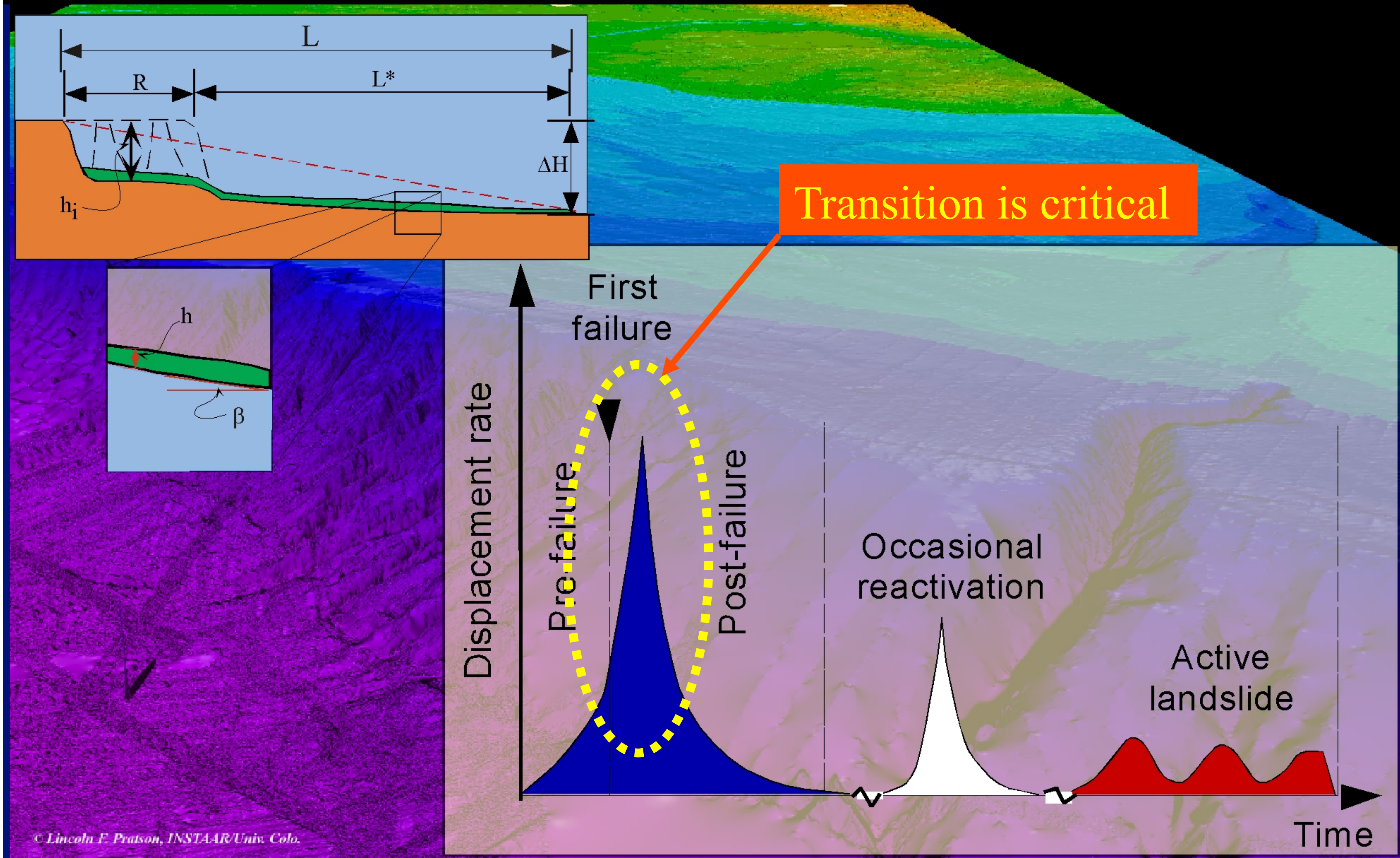
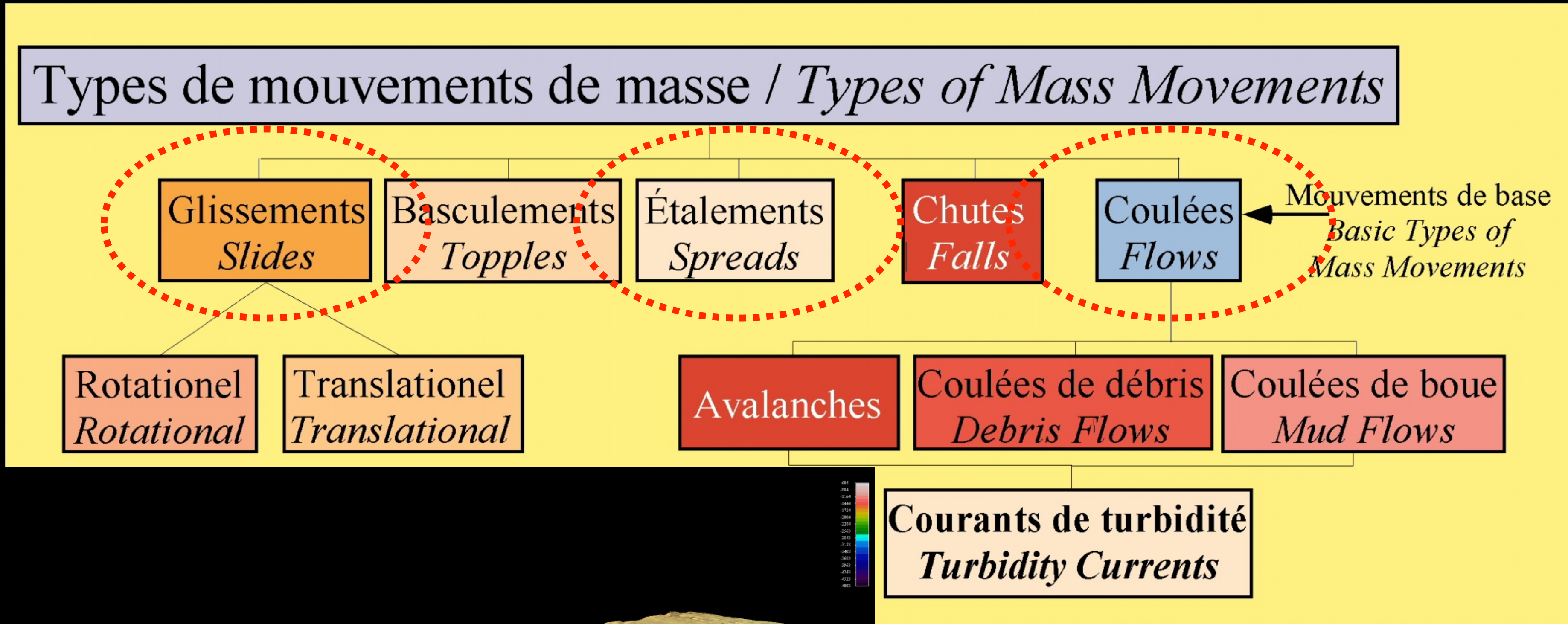
Woods Hole landslide tsunami workshop, August 18th and 19th 2011

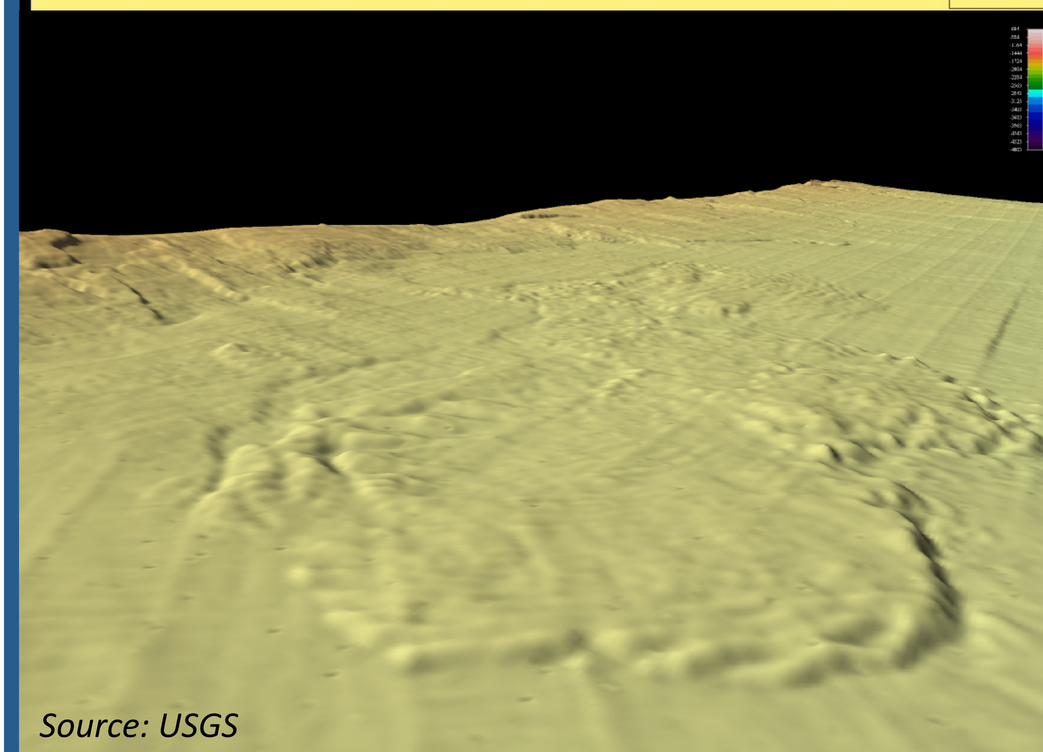
Content:

Preliminary remarks
Morphology and strength
Mobility and strength
Earthquakes and slides
Concluding remarks

Different Stages of Submarine Mass Movements



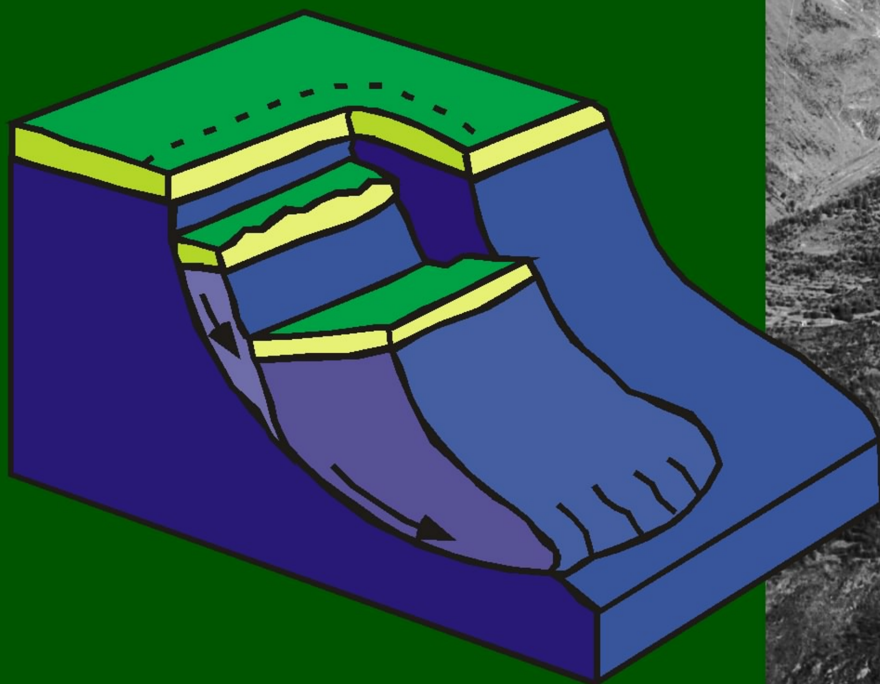




Source: USGS

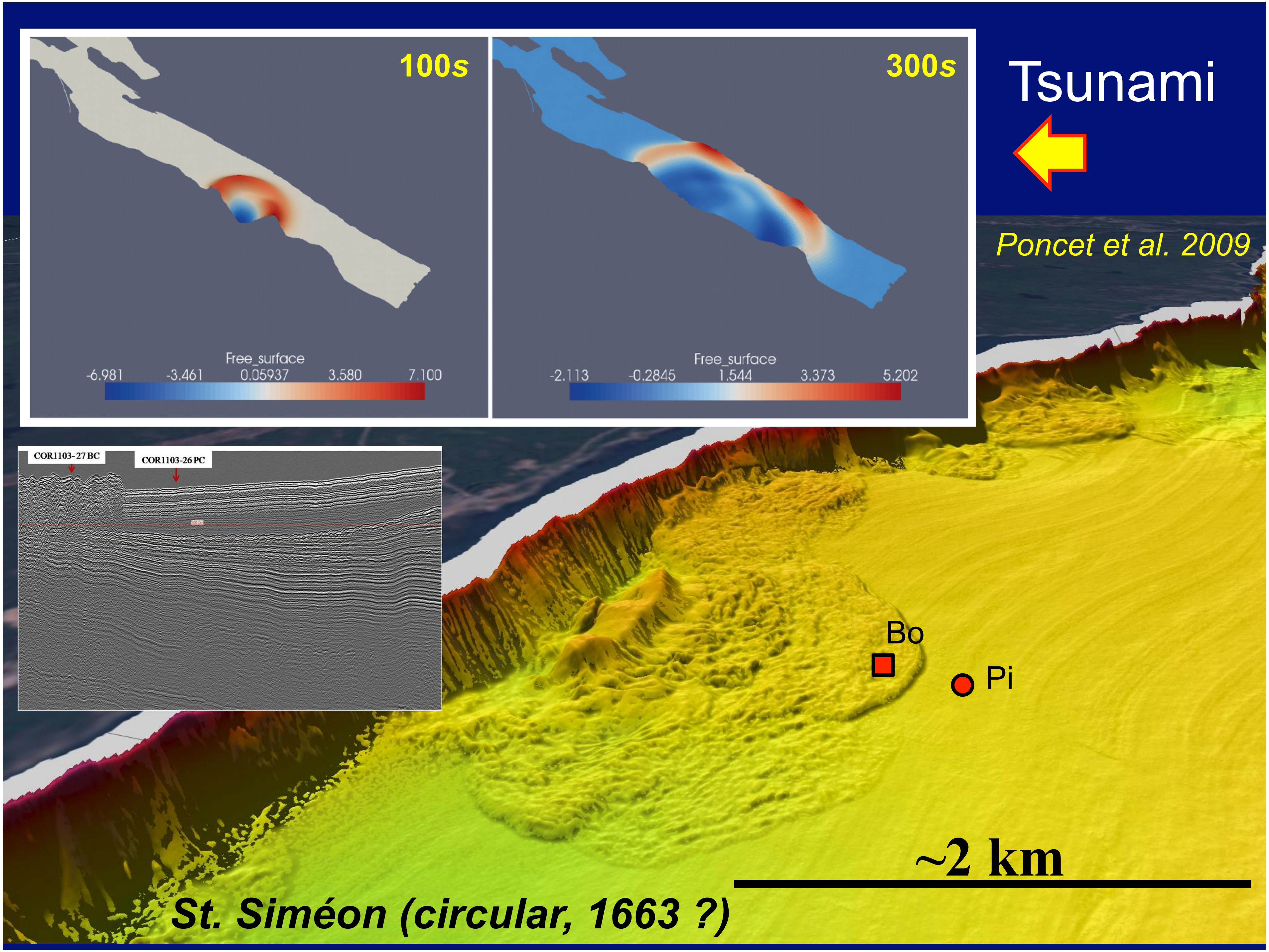
In some cases, one event will take place via many of the physical types: e.g. a slide can generate retrogression if the failed material can move away and this can result in a flow slide in the downstream part.

Glissement / *Slide*



La Clapière, CETE Méditerrannée, 1990

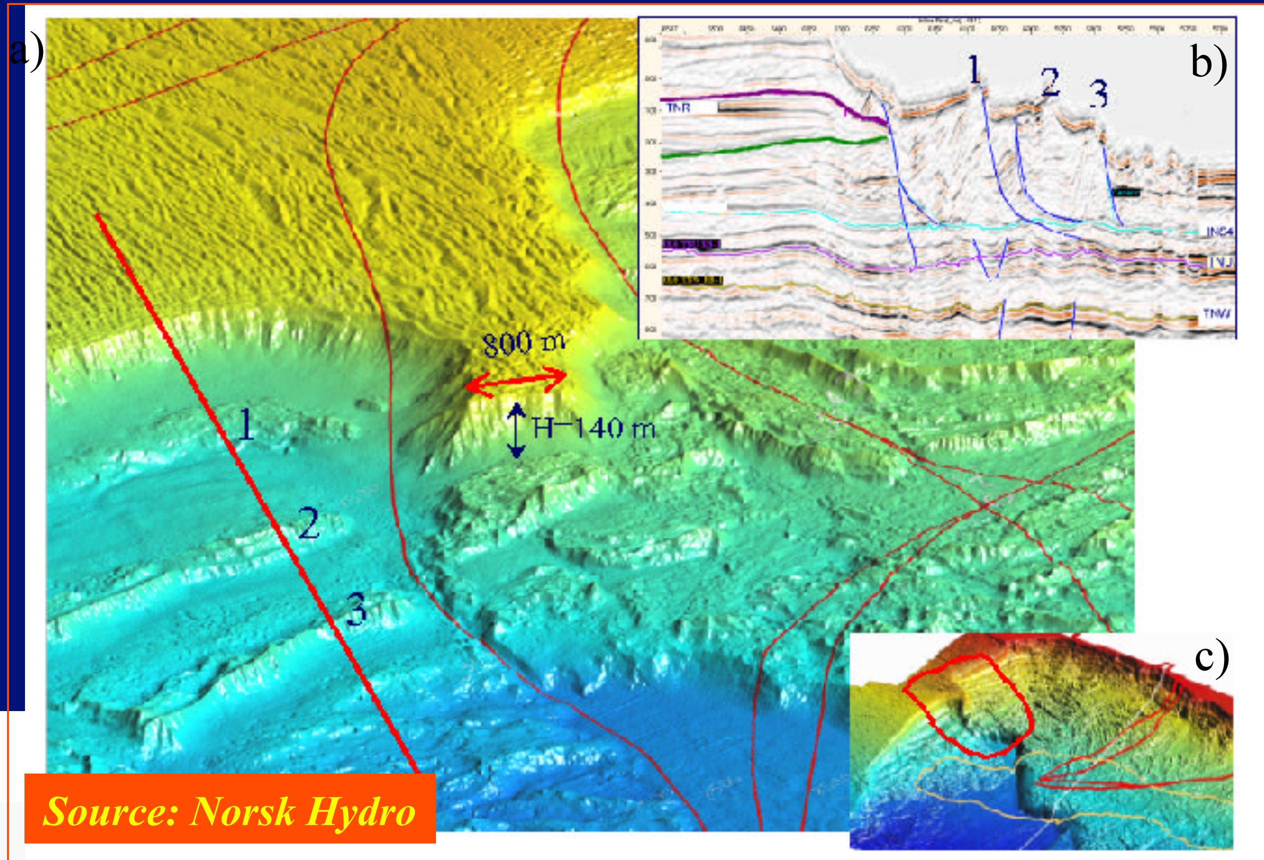
UNIVERSITÉ LAVAL


Tsunami
Poncet et al. 2009
100s
300s
Free_surface
-6.981 -3.461 0.05937 3.580 7.100
Free_surface
-2.113 -0.2845 1.544 3.373 5.202
COR1103-27 BC
COR1103-26 PC
Bo
Pi
~2 km
St. Siméon (circular, 1663 ?)

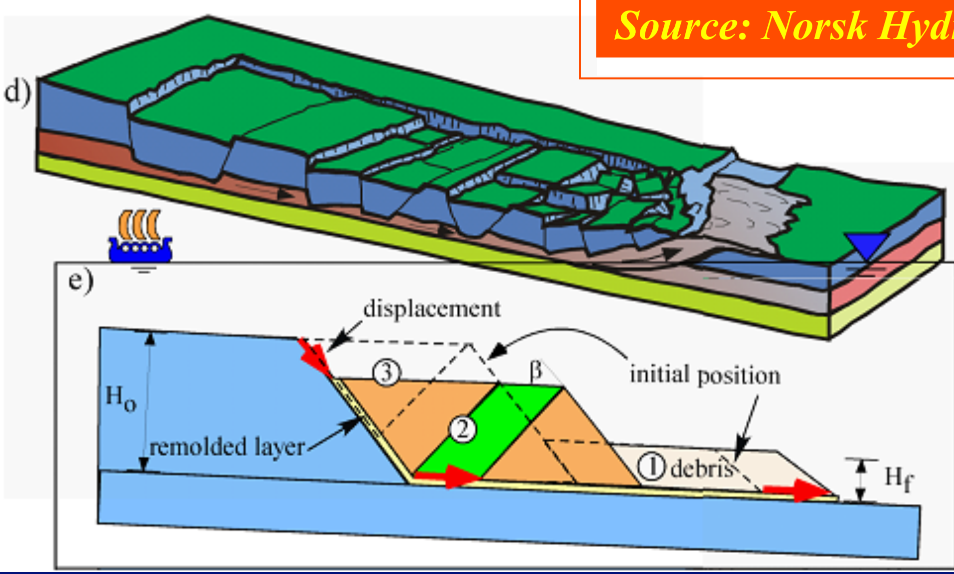
Spread failure

Details of the Storegga slide showing the spreading failure

Role of sensitivity on weak layer development

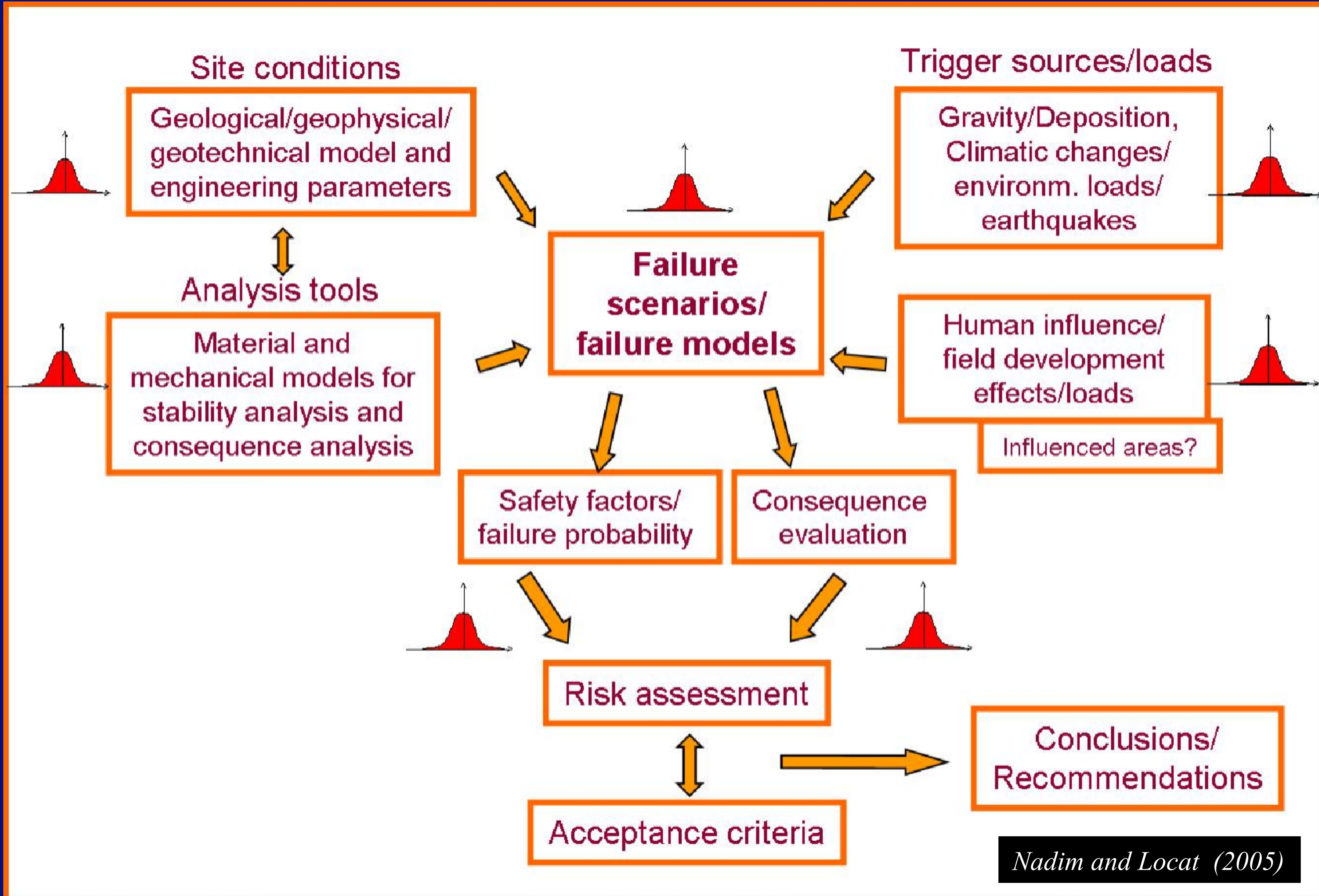


Source: Norsk Hydro




(1996 St. Boniface slide, R. Couture)

General Framework for Risk Assesment



The magnitude of a tsunami triggered by a submarine or a coastal mass movement may be function of:

Tsunami initiation	Geomechanics	Phase
Volume	Size, Shape, Material Morphology, Structure	Pre-failure
Mass balance Mass acceleration	Material properties, type of movement, triggering	Failure
Water depth Underwater bathymetry	Flow properties	Post-failure

Each failure phase implies some degree of geomechanical properties with critical transition from soil/rock mechanics into fluid mechanics depending on the type of mass movements and the material involved

Challenges for the geotechnical discipline (Nadim 2009; Nadim and Locat 2005)

- 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

$R_{(prop)} = P_{(L)} \times P_{(T:L)} \times P_{(S:T)} \times V_{(prop:S)} \times E$

Overall approach to tsunamigenic submarine slide risk assessment

$$R_t = \mathrm{S}\, H\, E_i\, V_i$$

R: Risk
H: Hazard (slide)
E: Element at risk
V: Vulnerability

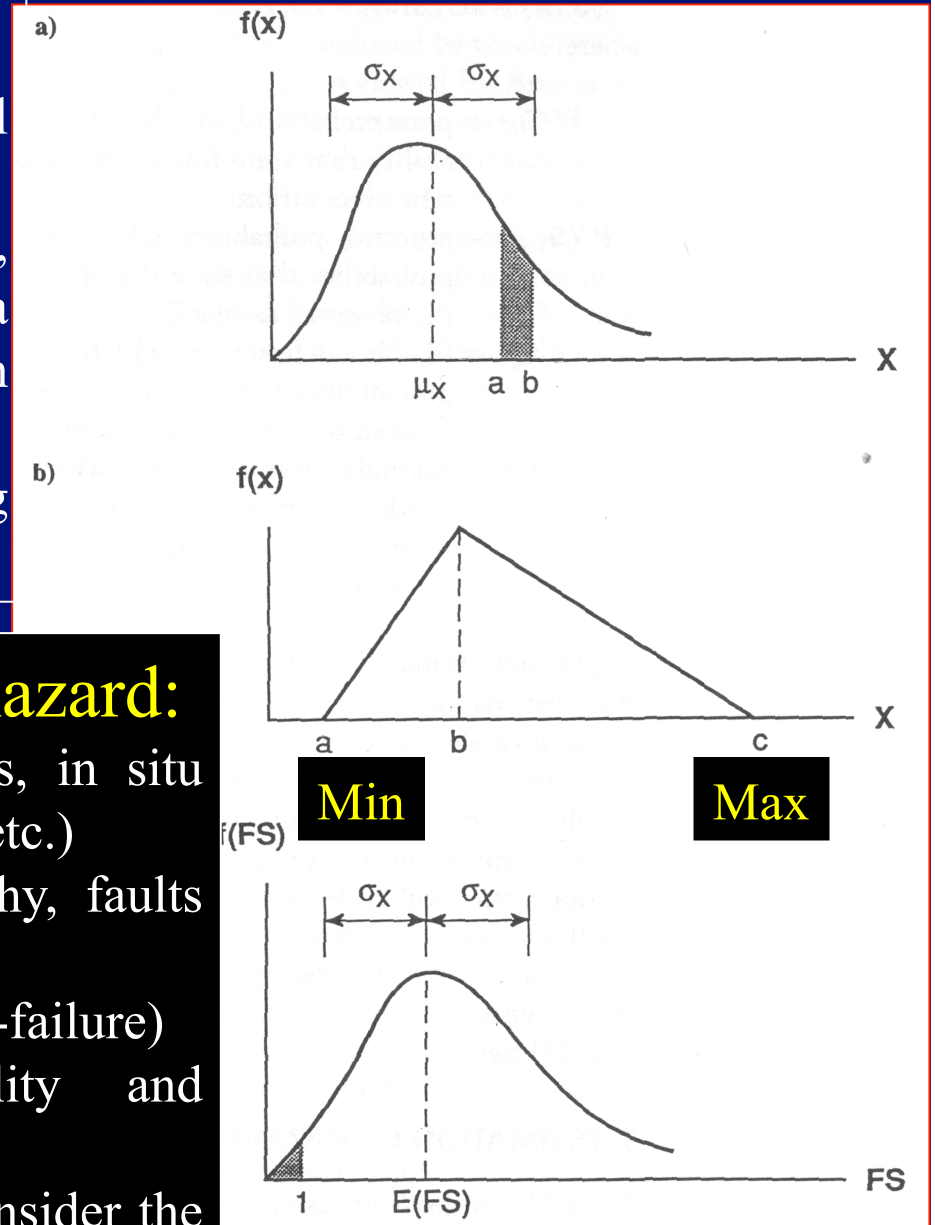
Uncertainty on the variables ?

Qualifying uncertainty:

- Tendancy from the conventional approach to use conservative numbers.
- From a probabilistic approach, uncertainty is a variable ‘x’ defined as a density function (f(x)) (a) or as a mean (m_x) and its standard deviation (s_x)
- Opinion: subjective probability (!) using best estimate (b)

Sources of uncertainty for the hazard:

- Environmewntal conditions (earthquakes, in situ pore pressures, gaz hydrate dissociation, etc.)
- Regional or site conditions : stratigraphy, faults etc.)
- Type of mass movement (failure and post-failure)
- Material properties (sampling quality and representation, experimental errors)
- Possible omission (human): failure to consider the possible mode of failures and factors that could affect performance (reduced by experience)



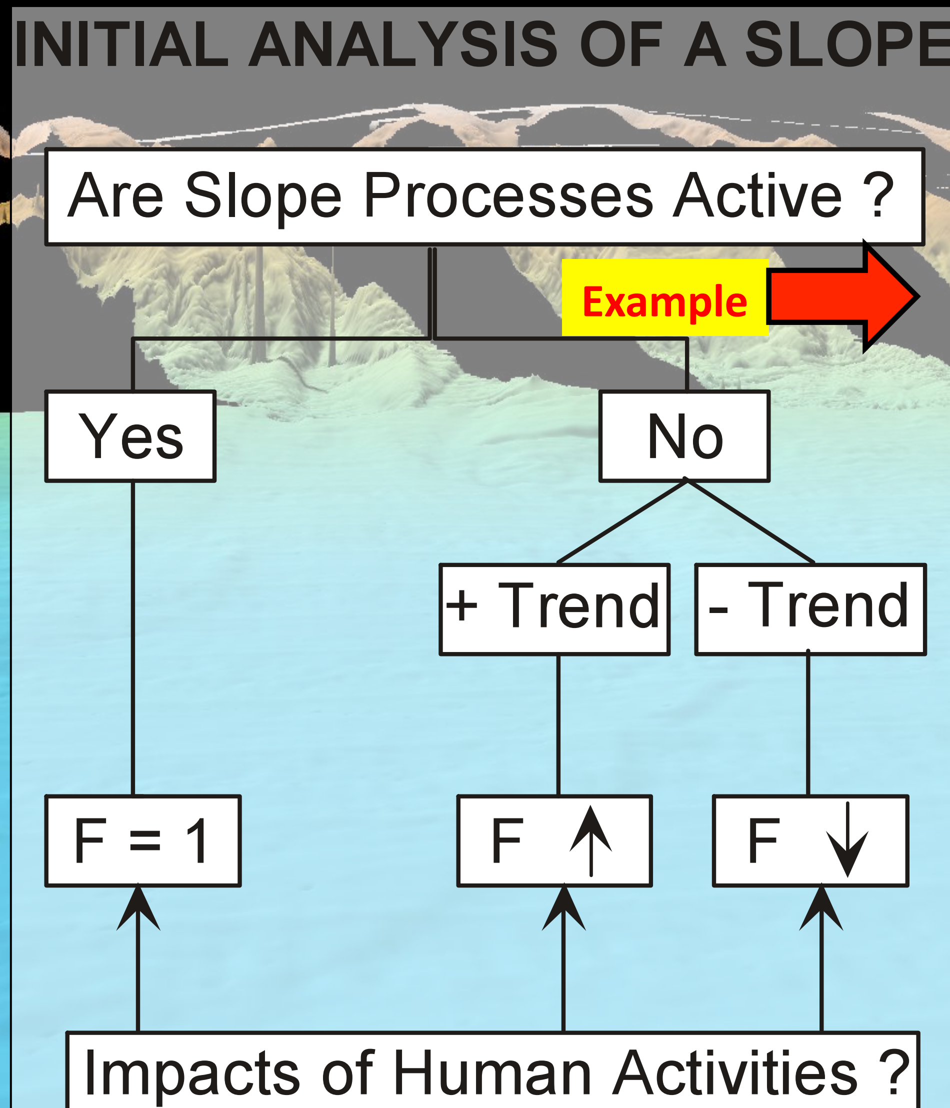
Turner and Schuster 1996

Using geomorphology to reduce uncertainty on strength and failure dynamics:

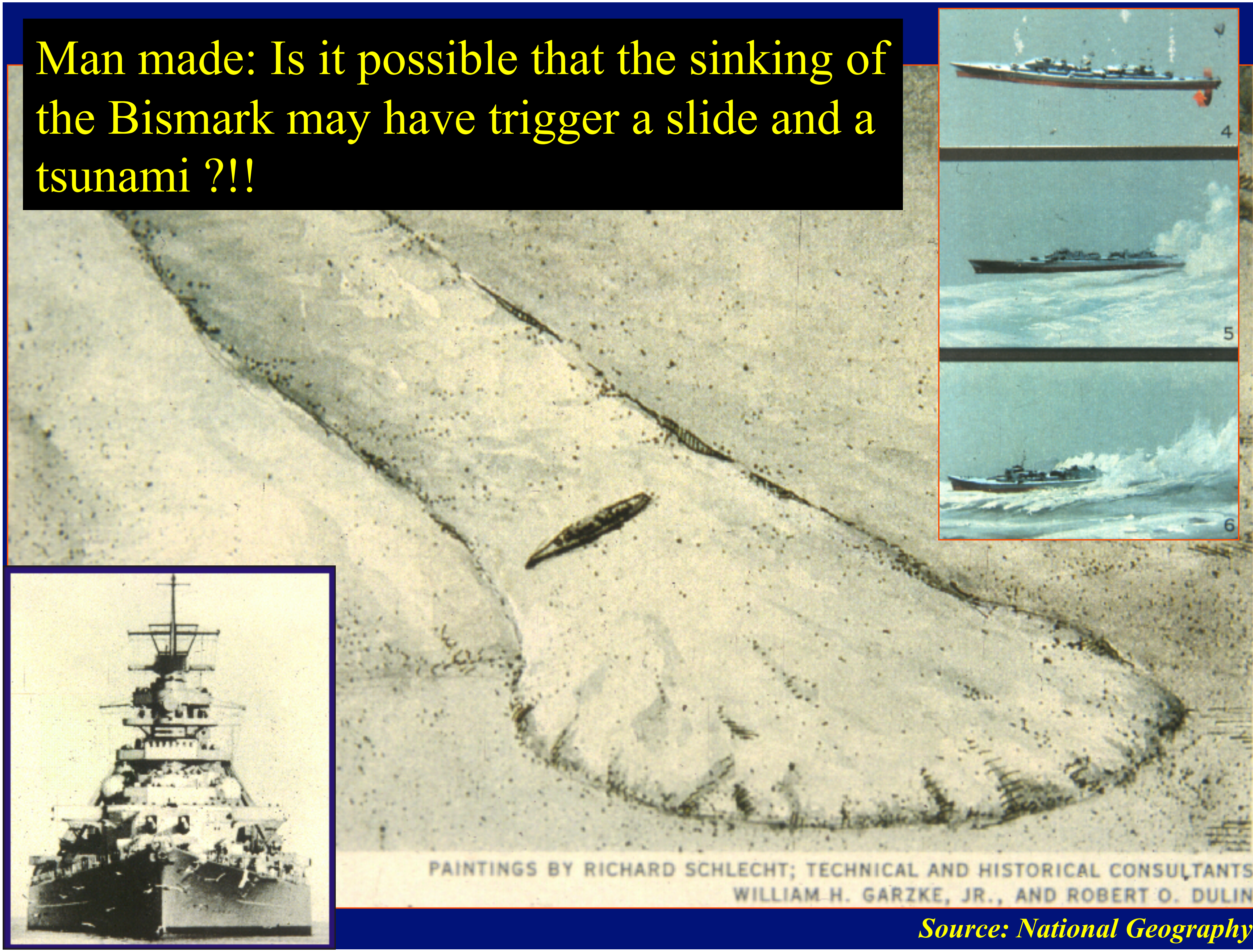
- ❑ Slope morphology
- ❑ Mobility analysis

What can we say about the factor of safety (*F*) of a natural slope ?

- Its morphology results from geological processes: e.g. sedimentation, accumulation, erosion…
- Evolution or trend, e.g., if a canyon is active, erosion may increase slope height with angle adjustment: *F* ~ 1 (Locat 1999).
- If a canyon is being filled, *F* > 1 (local slope height is reduced).
- The same could be said about tectonic activity, sea level changes and changes in stresses along slopes or the strength of the sediments.
- On a geological scale, the angle of a natural slope is at equilibrium with processes.
- Equivalent to the '*Angle of Ultimate Stability*' of Hutchinson (2001) which he sees as a basic unit of the landscape, and considers that this angle is close to the residual friction angle.

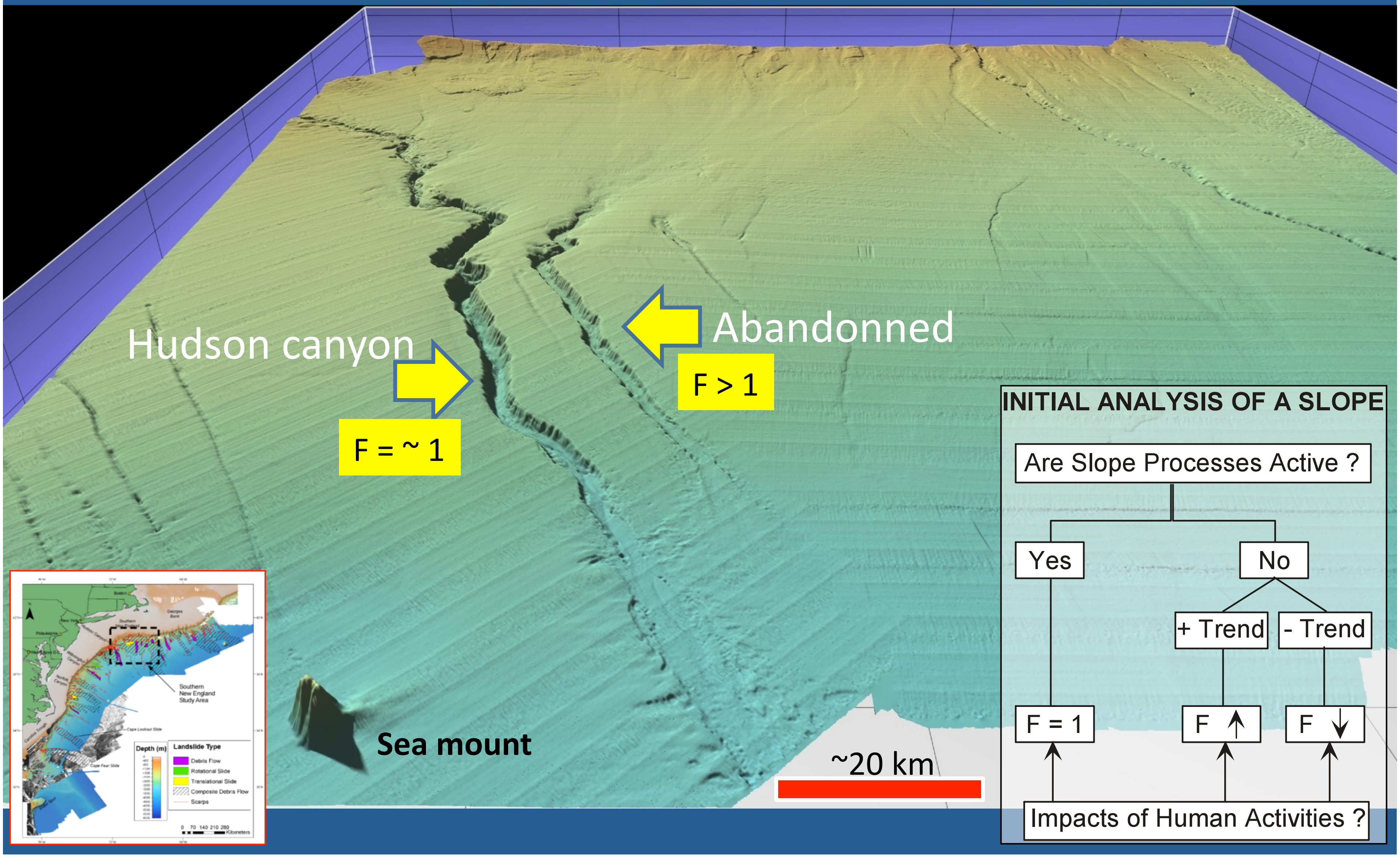


Man made: Is it possible that the sinking of the Bismark may have trigger a slide and a tsunami ?!!

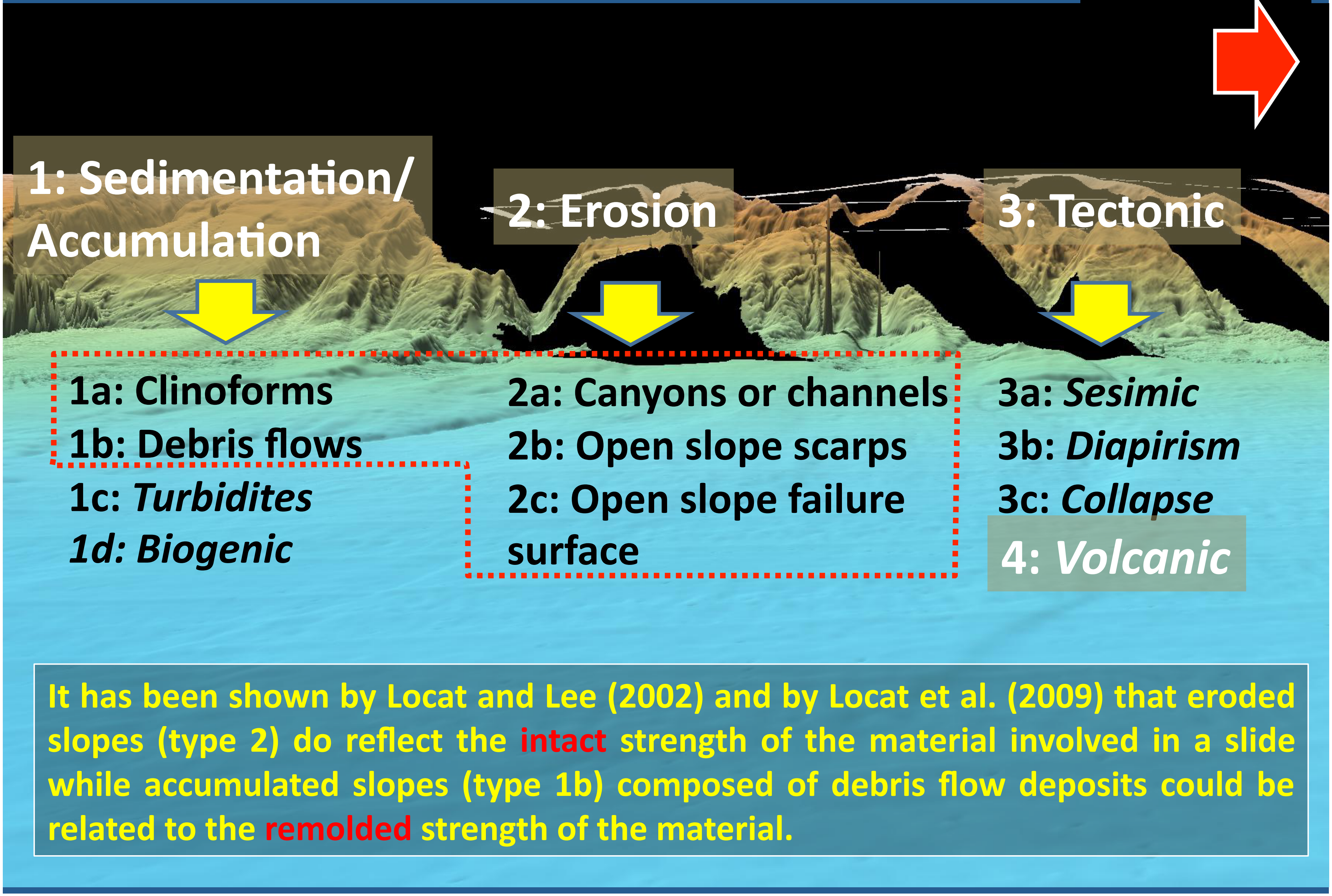


Source: National Geography

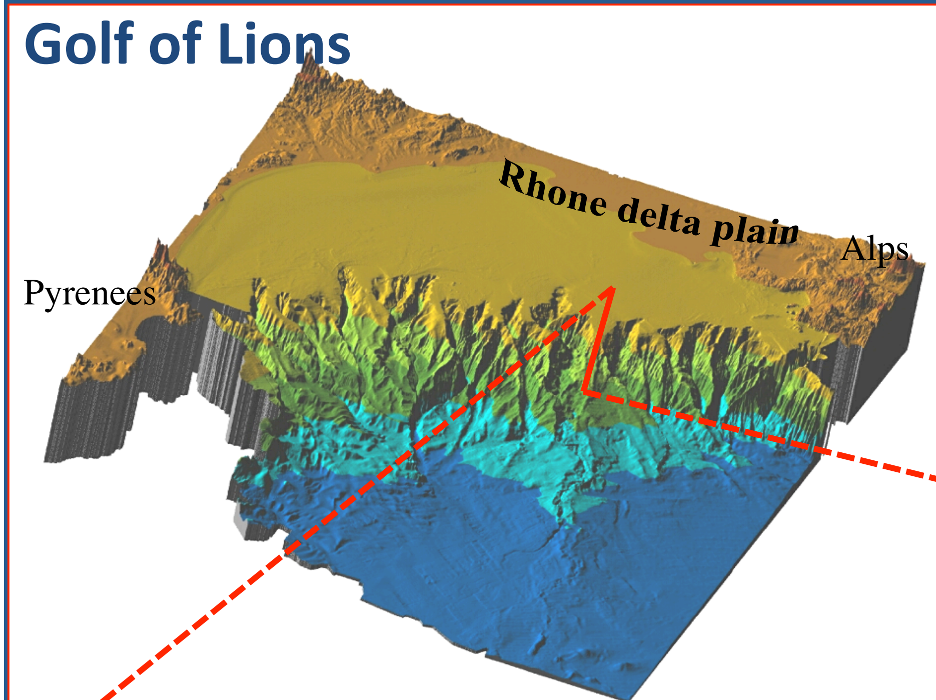
An example of deposition and erosion environment: *Active and inactive canyons*



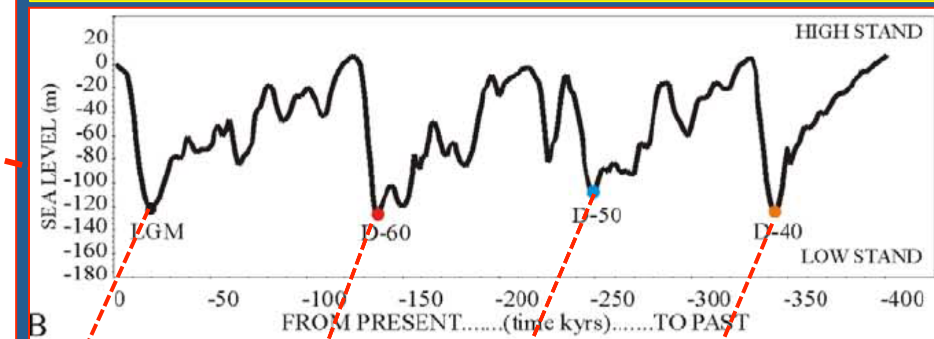
Most slopes are generated by natural proce Examples

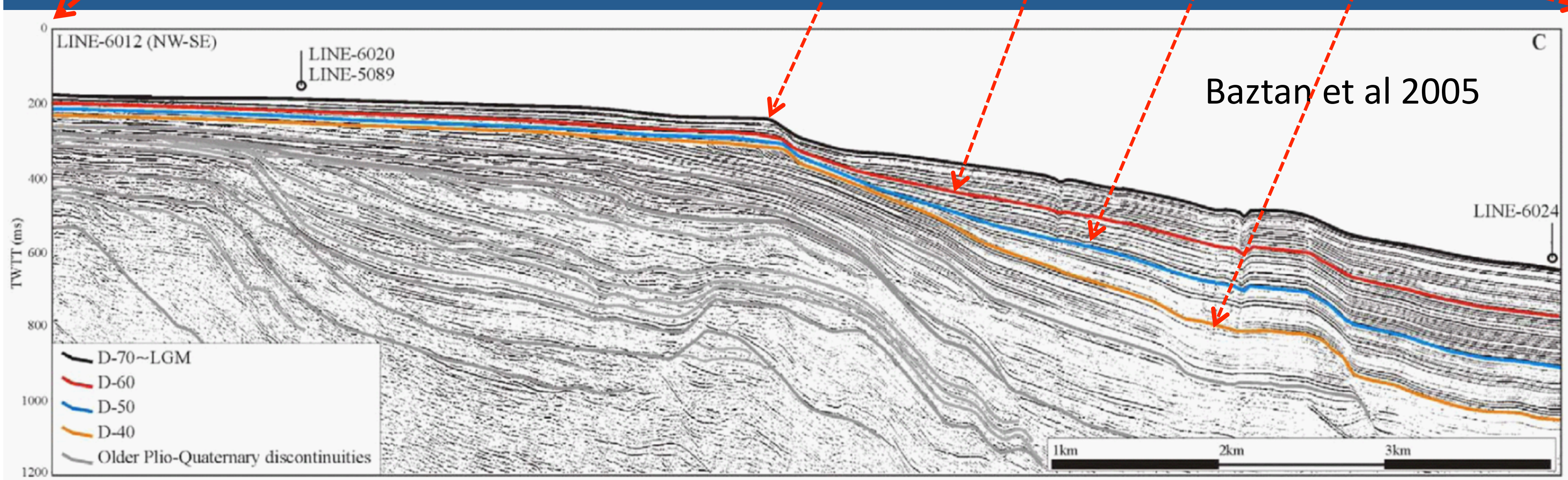


Example of clinoforms sedimentation since 350 ky



Interesting to note that a 100 m of sea level change implies a variation of 1 MPa in total stresses in the sediments with sea level recovery being much faster than lowering





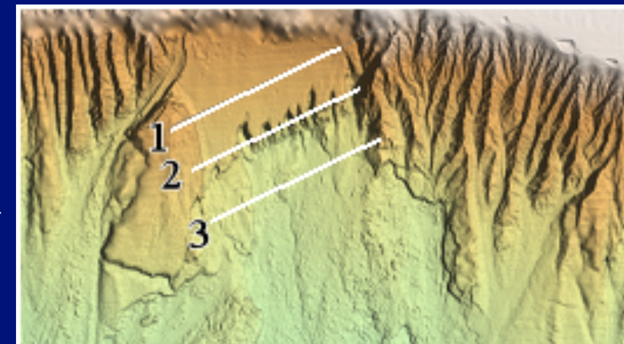
Continental slope, the Currituck slide area:

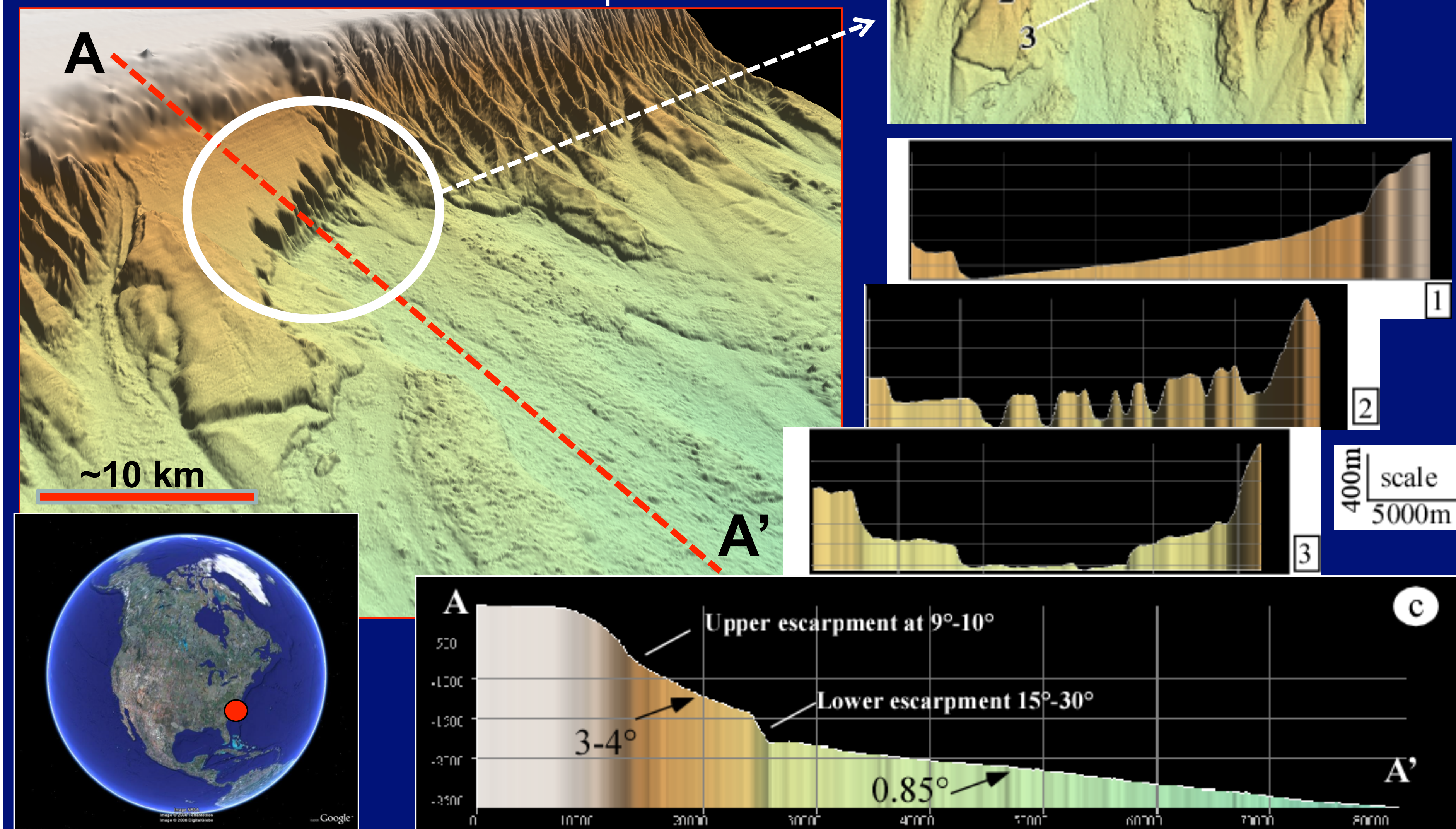
Overal slope at about 5° with canyon slope between 10 and 30°

Scarp and canyon slopes up to 30°

Failure surface slopes at about 4° (dip slope)

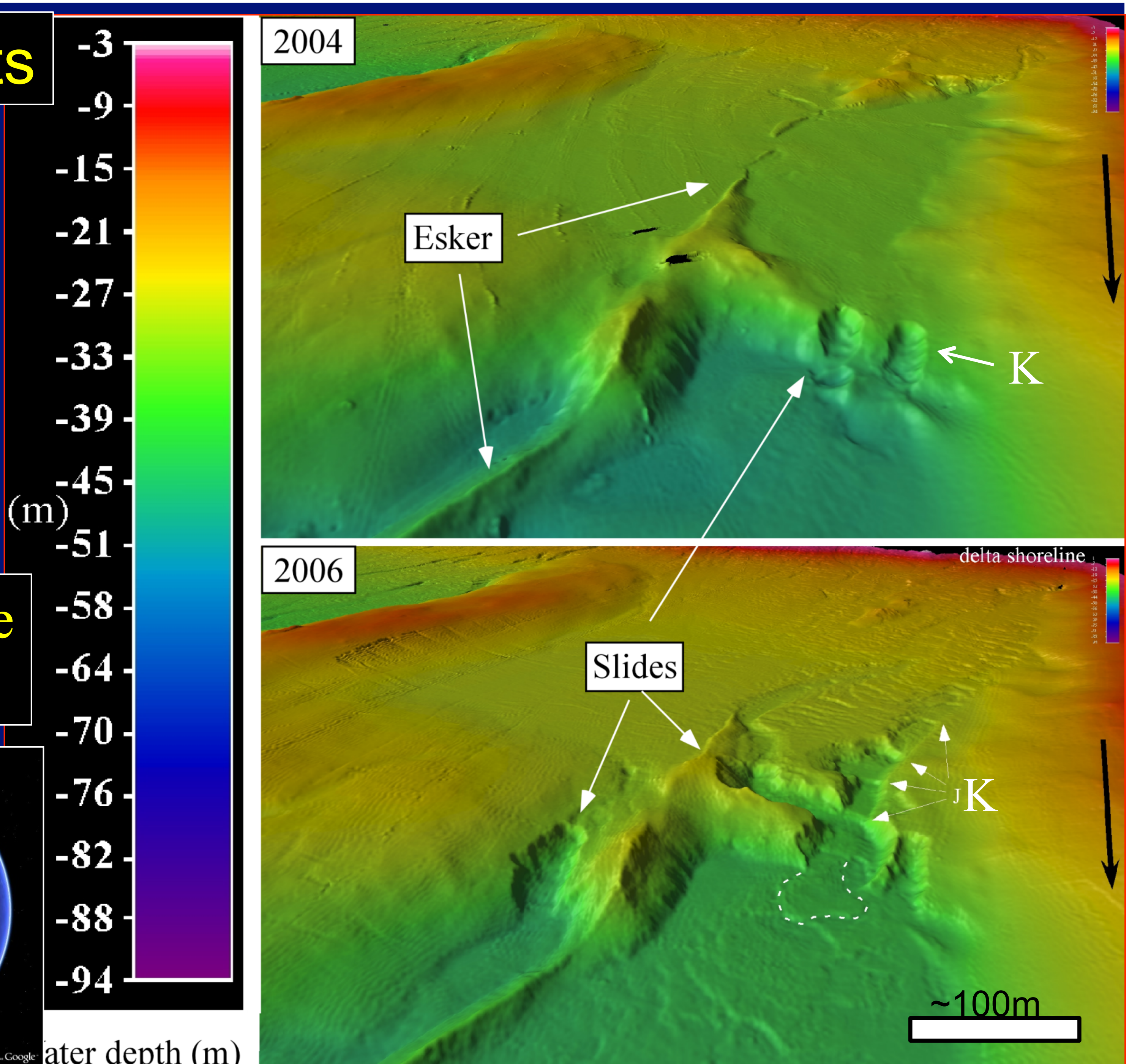
And accumulated debris flow slope at 0.85°





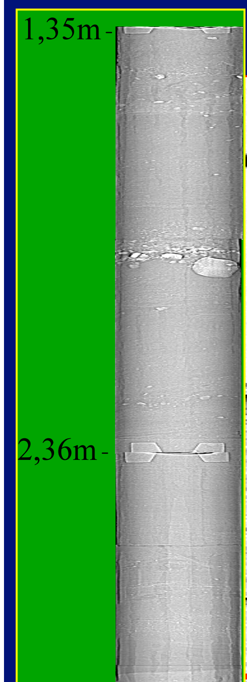
Knickpoints

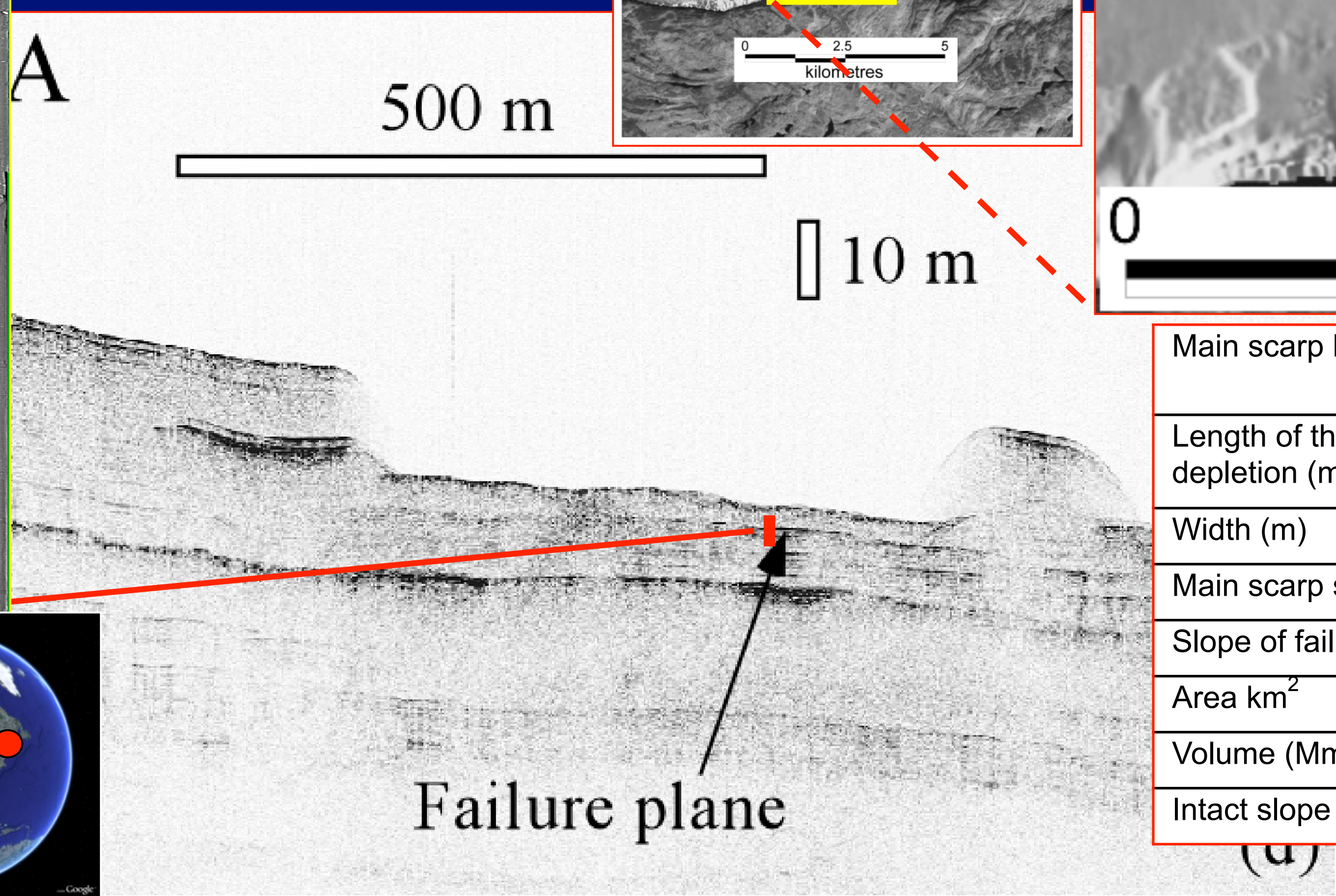
Coupling both hydrodynamic and gravitational forces

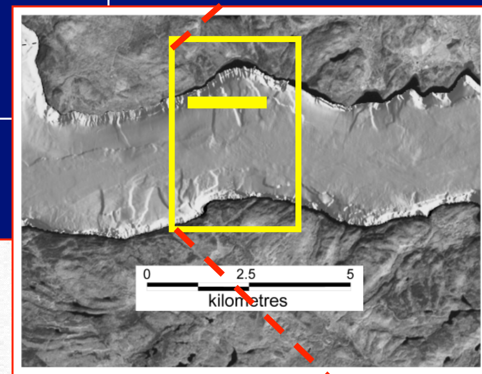


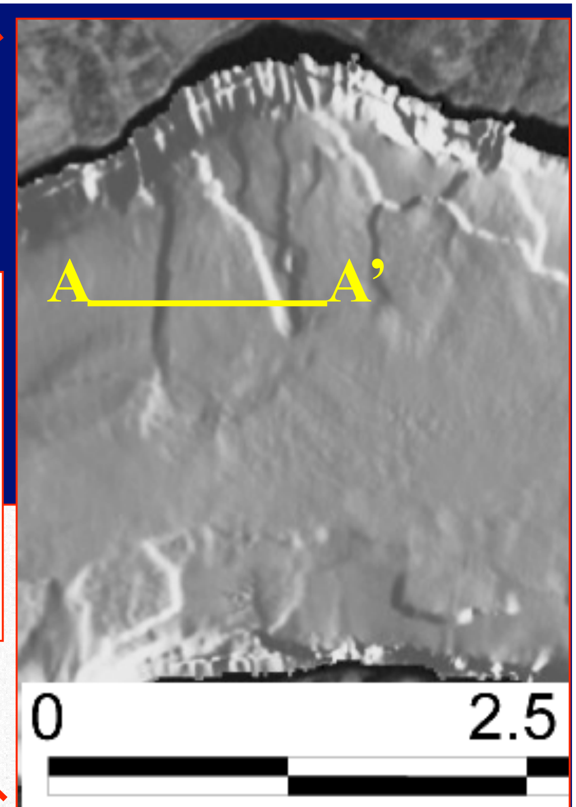
Wabush Lake
Labrador

Slopes in an earhquake triggered flow slide in Saguenay Fjord



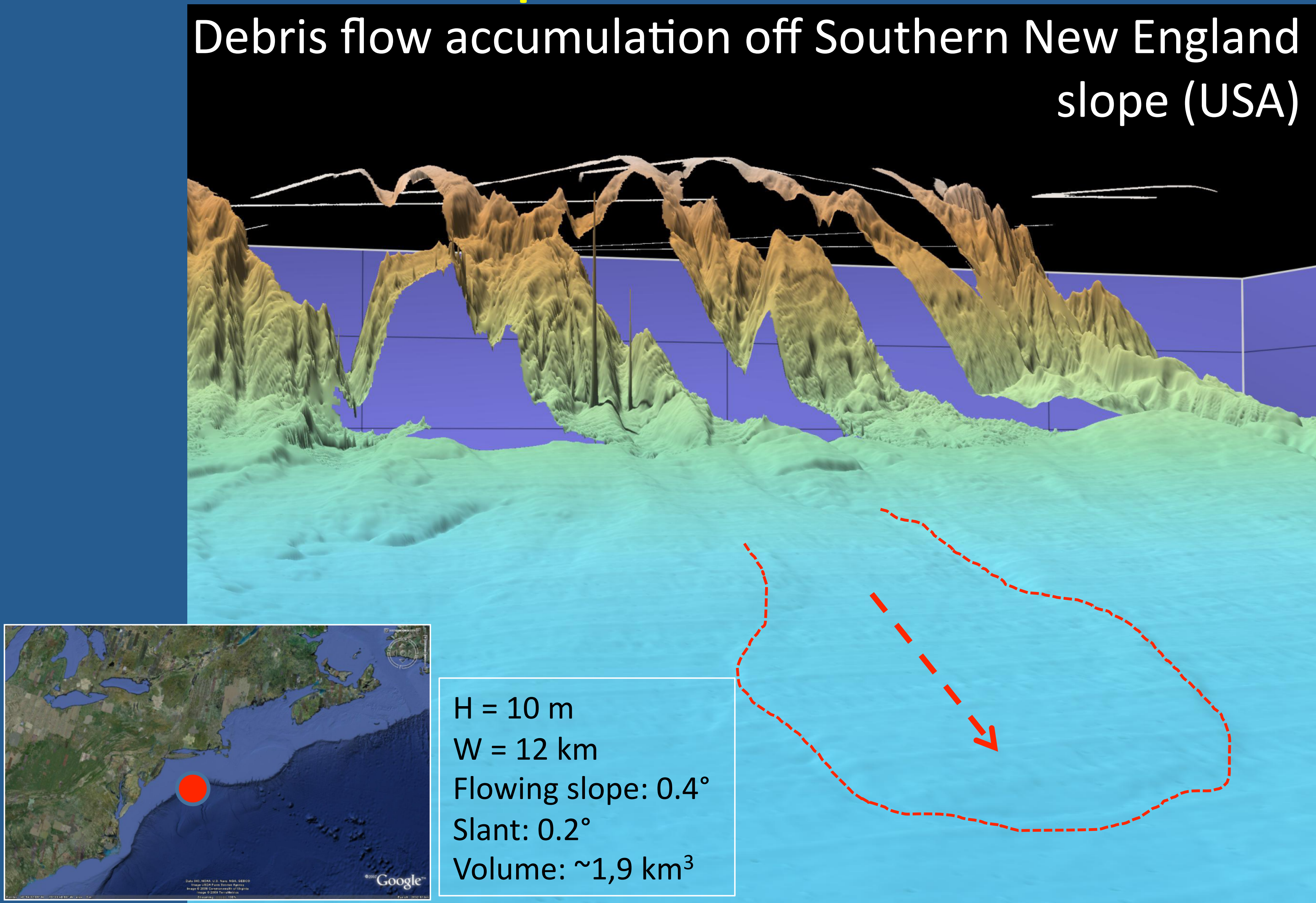






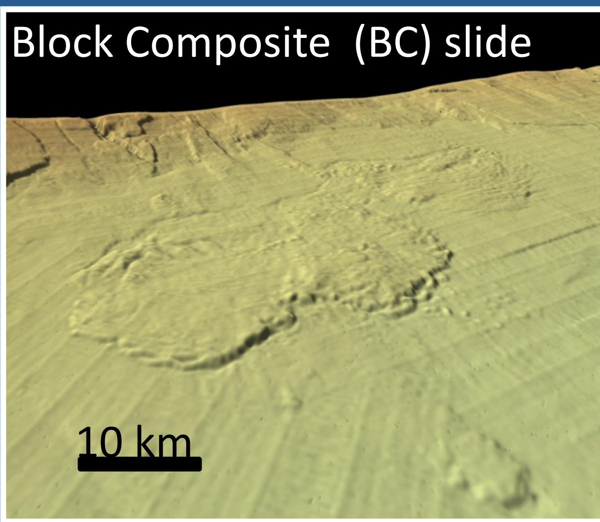
Main scarp height (m)	20
Length of the zone of depletion (m)	1150
Width (m)	510
Main scarp slope (°)	13
Slope of failure plane (°)	3
Area km^2	0.58
Volume (Mm^3)	9.04
Intact slope (°)	5

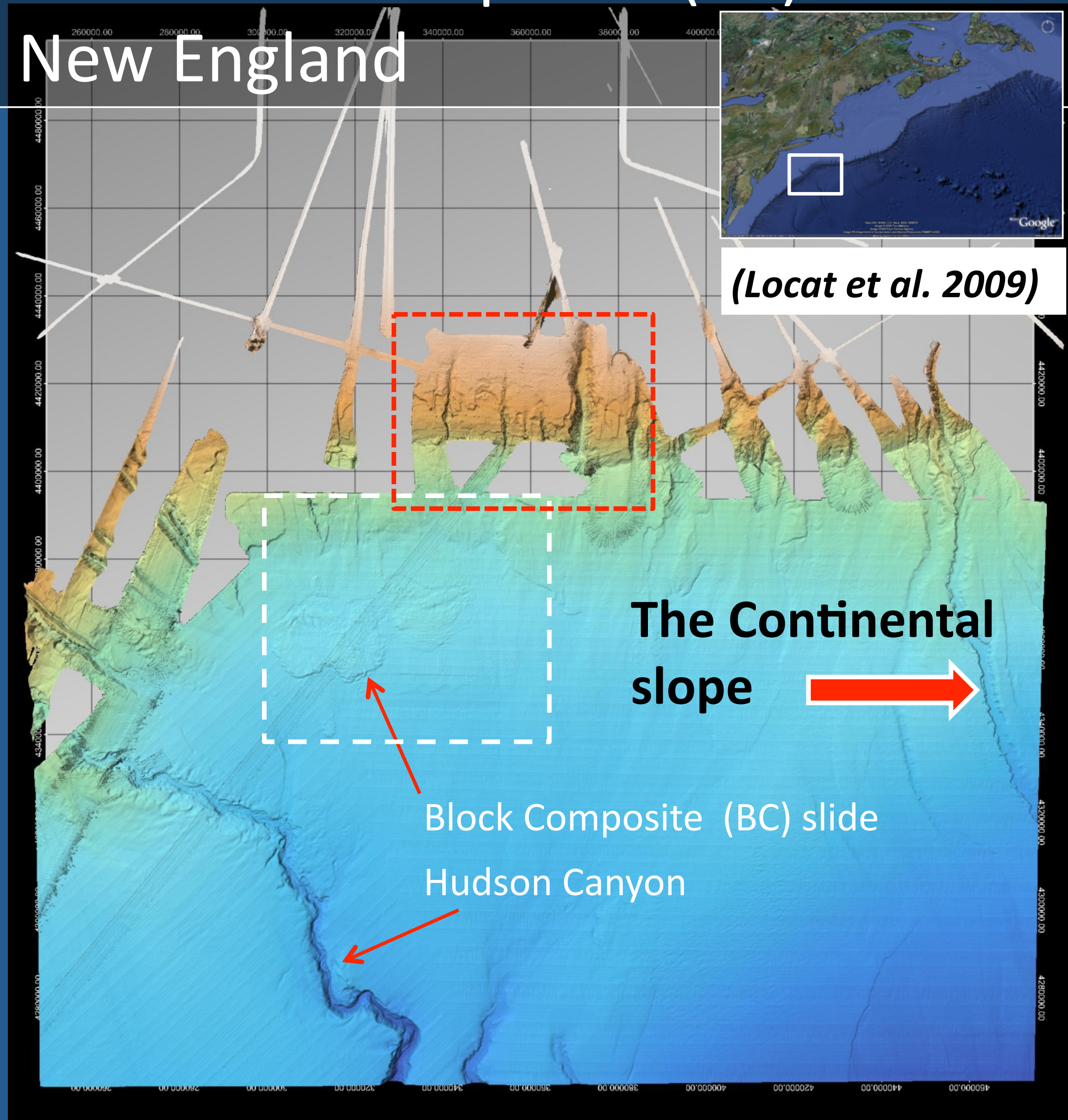
Debris flow slope



Example: Slopes of the Block composite (BC) slide area off Southern New England

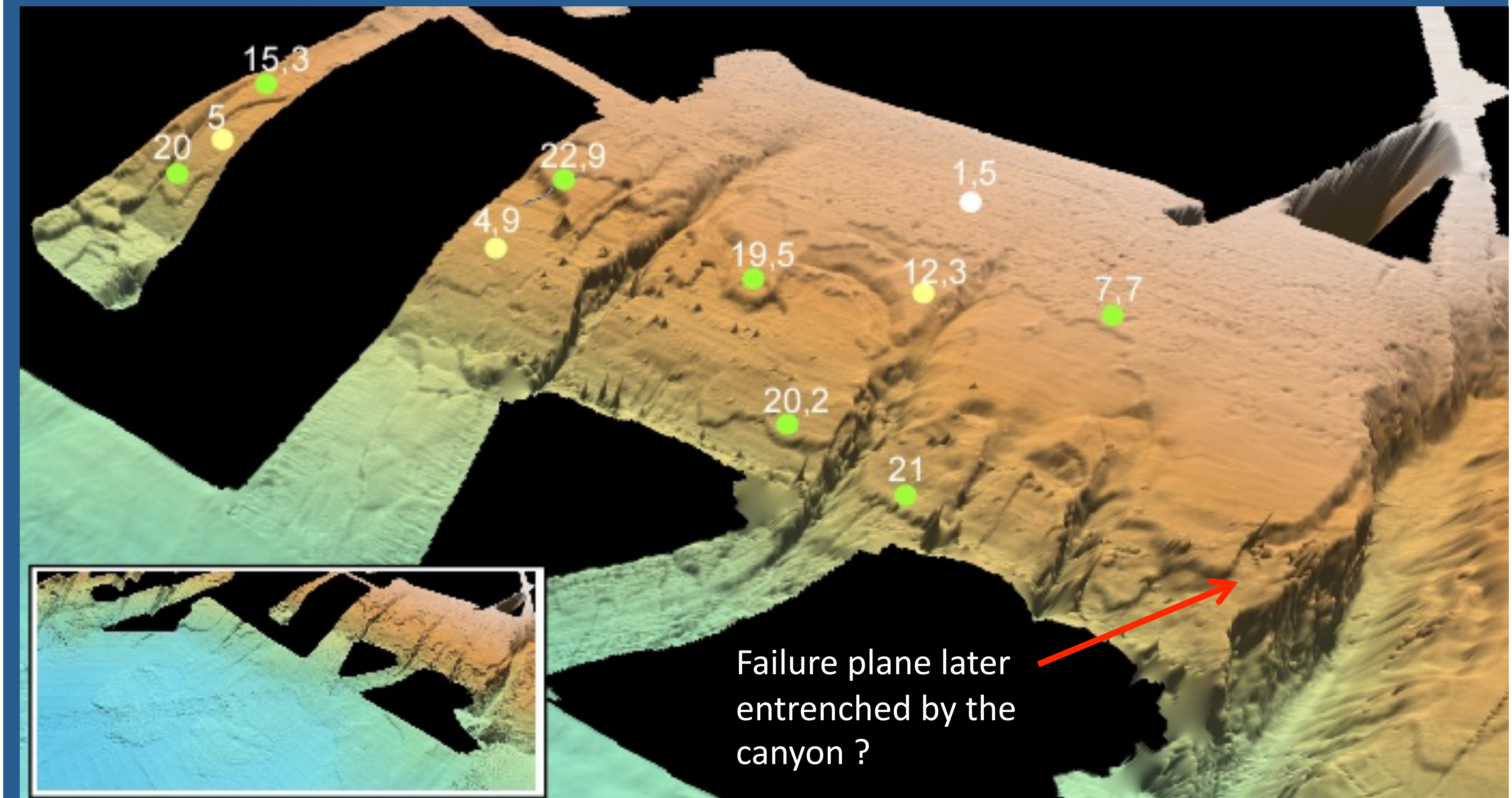
Types of slopes:
- Unfailed
- Canyon
- Scarp slopes
- Failure plane slopes



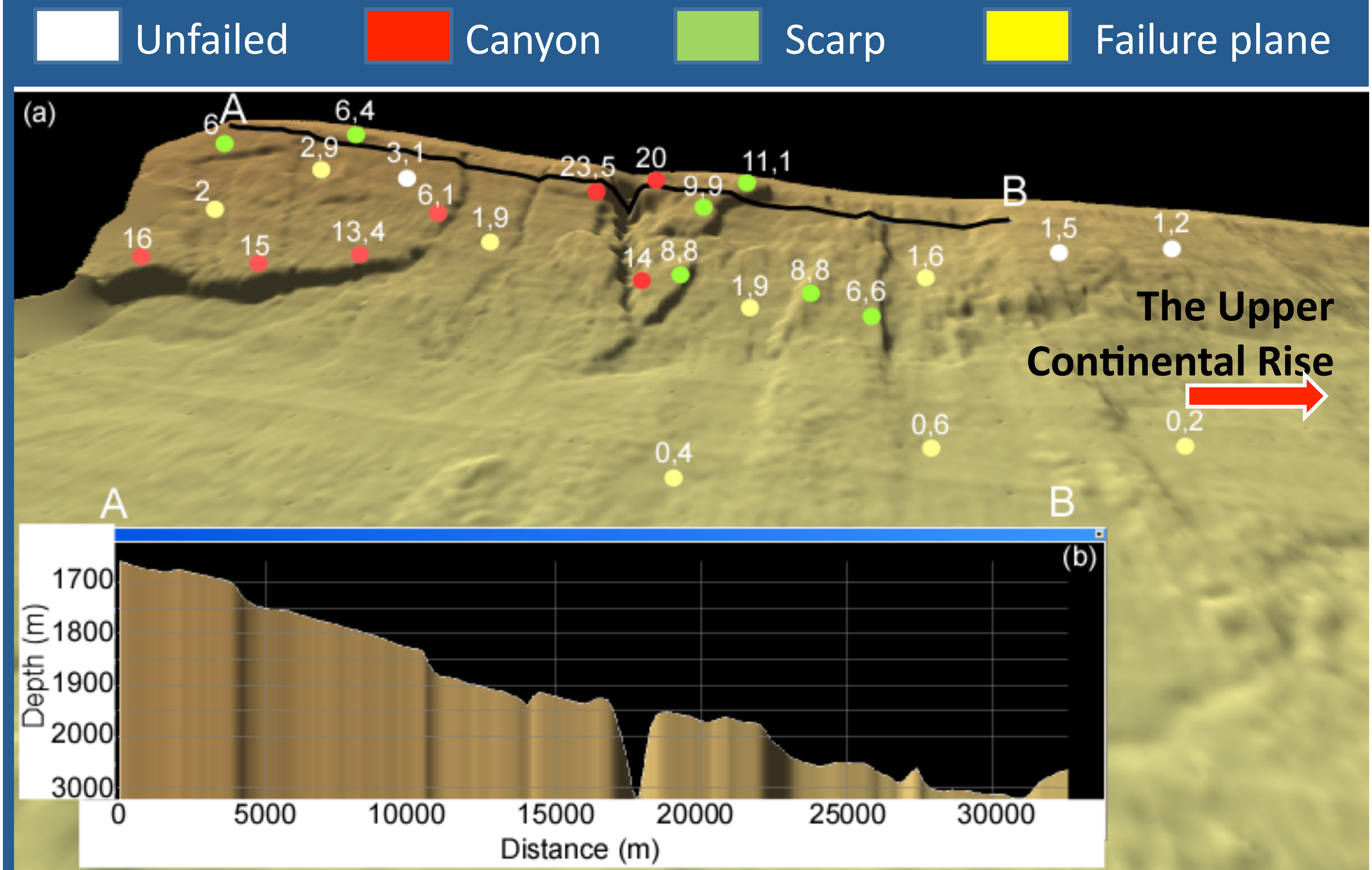


Slope angles on parts of the Upper Continental Slope

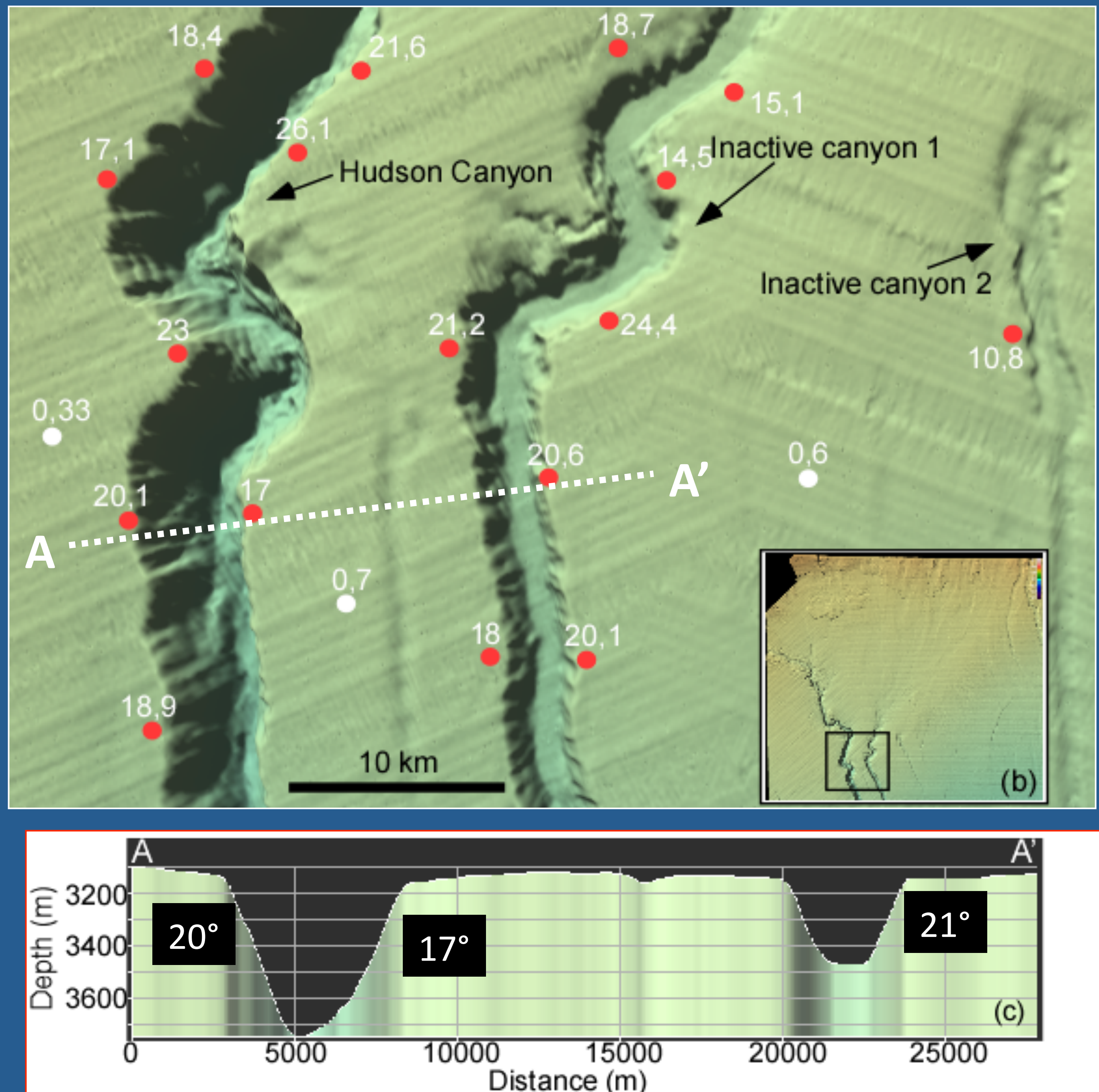
Unfailed | Canyon | Scarp | Failure plane



Slope angles on the Lower Continental Slope



Slope angles on the upper part of Continental Rise near the Hudson Canyon



Unfailed

Canyon

Scarp

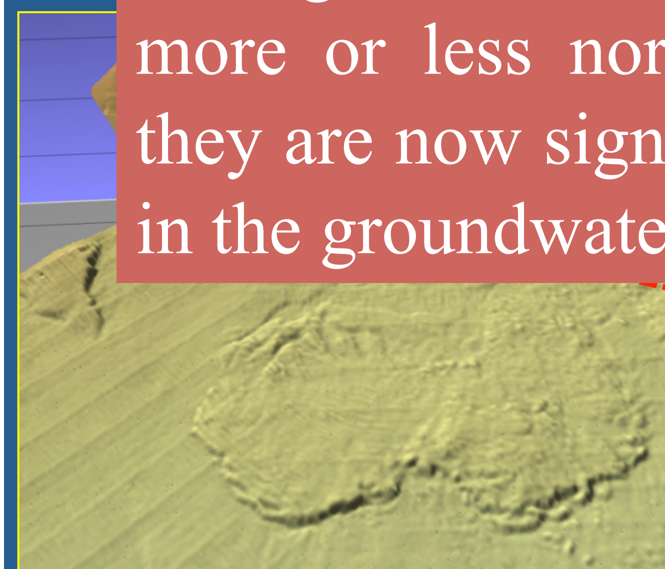
Failure plane

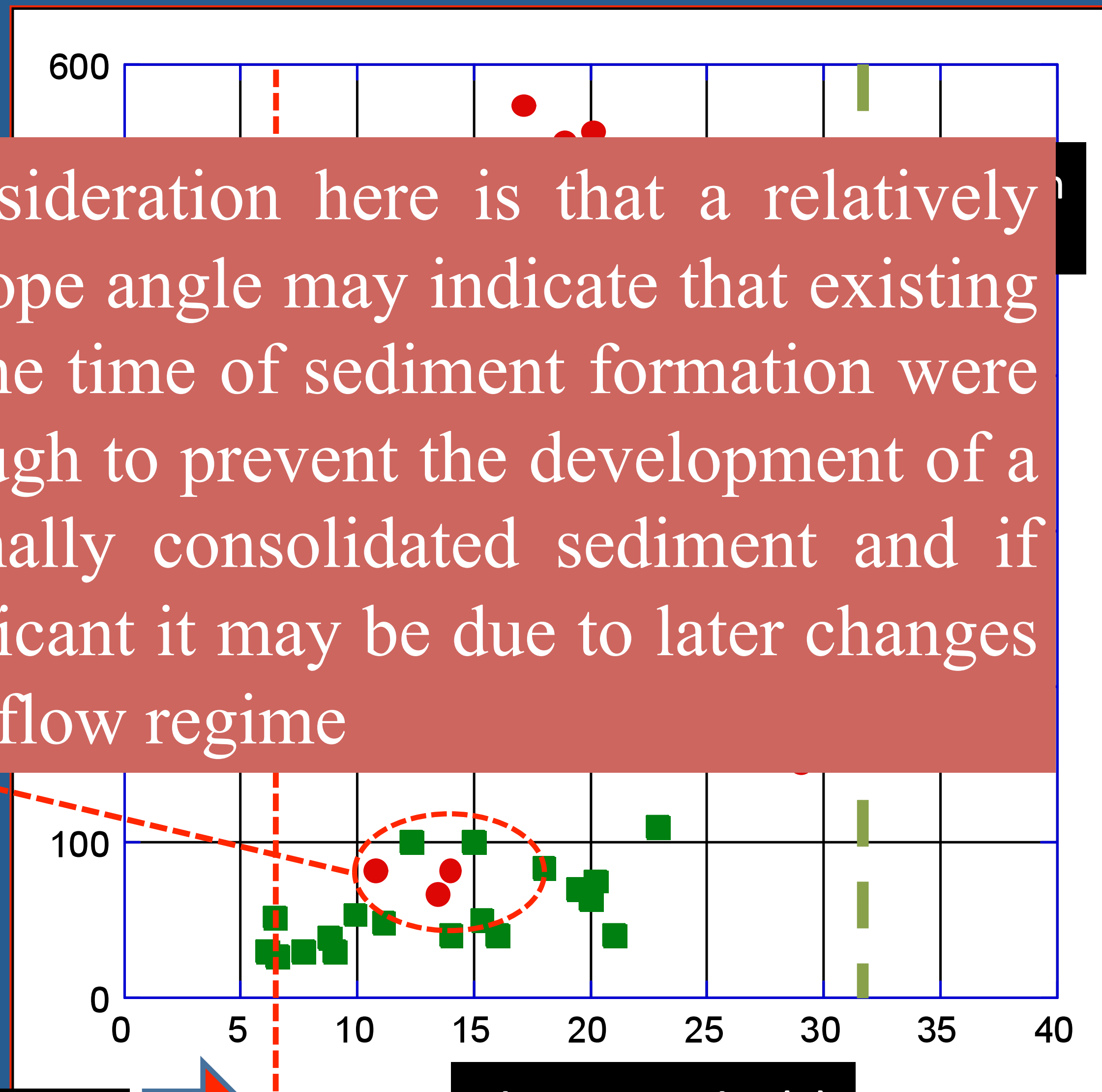
Scarps in the BC slide area

Remarks:

- Canyons active or inactive): angle steeper > 15°
- Open slope slide scarps < 25° and much lower height
- an
  fai
- Ca
  slo
  str

An interesting consideration here is that a relatively high intact scarp slope angle may indicate that existing seepage forces at the time of sediment formation were not significant enough to prevent the development of a more or less normally consolidated sediment and if they are now significant it may be due to later changes in the groundwater flow regime





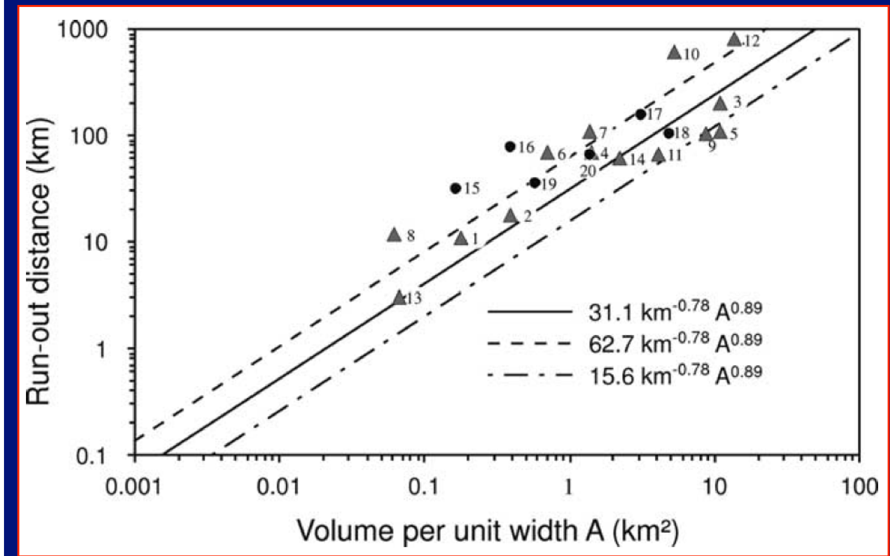
Open slope failure planes <5°

Comments on BC slide area

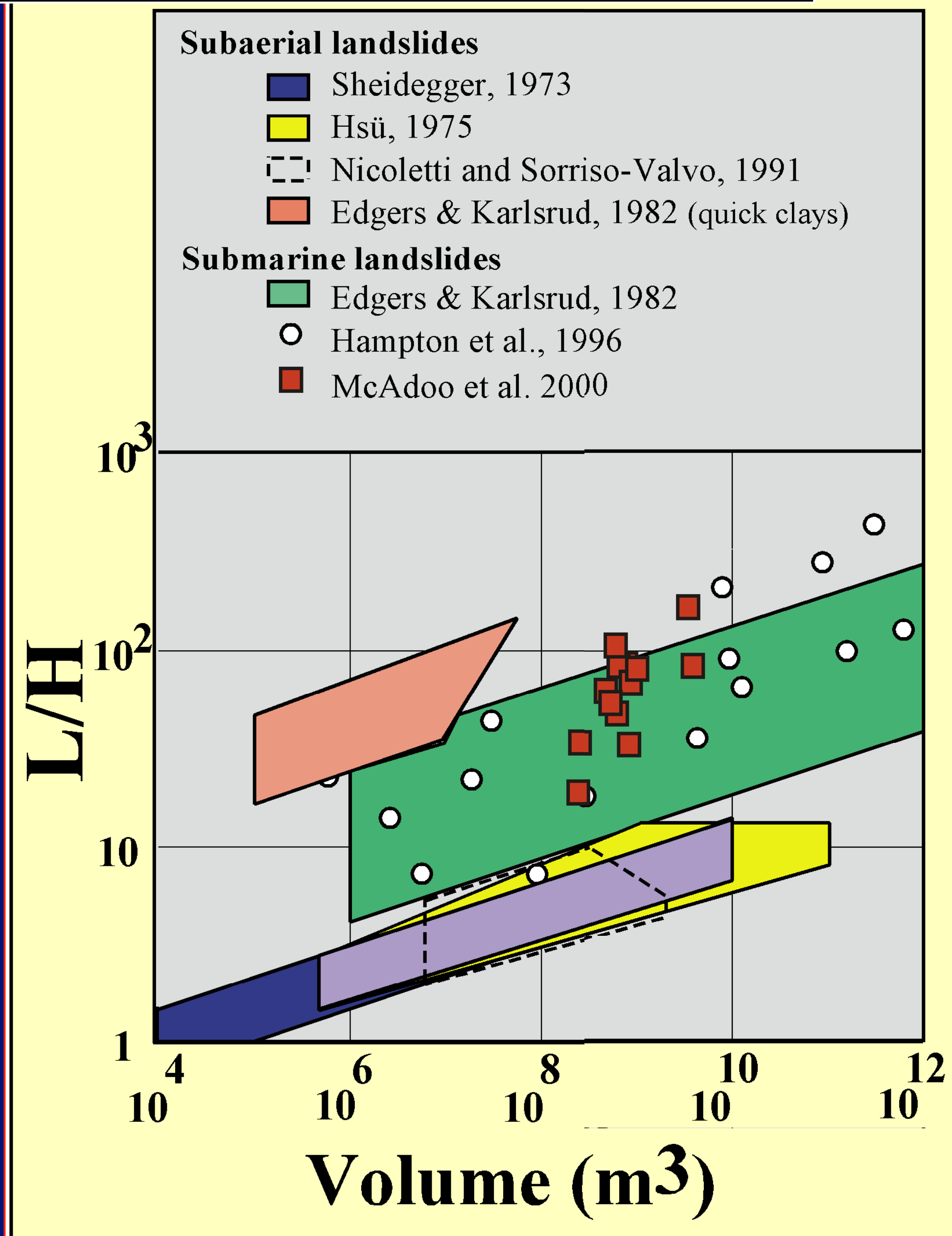
- Slopes scarps, on both canyon and open slope, can be steep (close to 30°)
- Sliding **(circular ?)** is the main failure mechanism observed in canyons.
- Failure plane slope **on open slope** appears to follows statigraphic layer and type of failure can be complex but must include some sort of flow failure with most of the amphitheatre empty of disturbed sediments (no remnants of spread failures if any)
- Cannot determine if open slope scarps results from **multiple failures, so timing is important.**
- Canyon incision came after most of the open slope failures ???
- When canyon incision takes place in clinoforms the steepness of the local slope may results from the fact that the slopes are cut in a direction perpendicular to the bedding inclination.

Morphology (Potential Energy) and Mobility

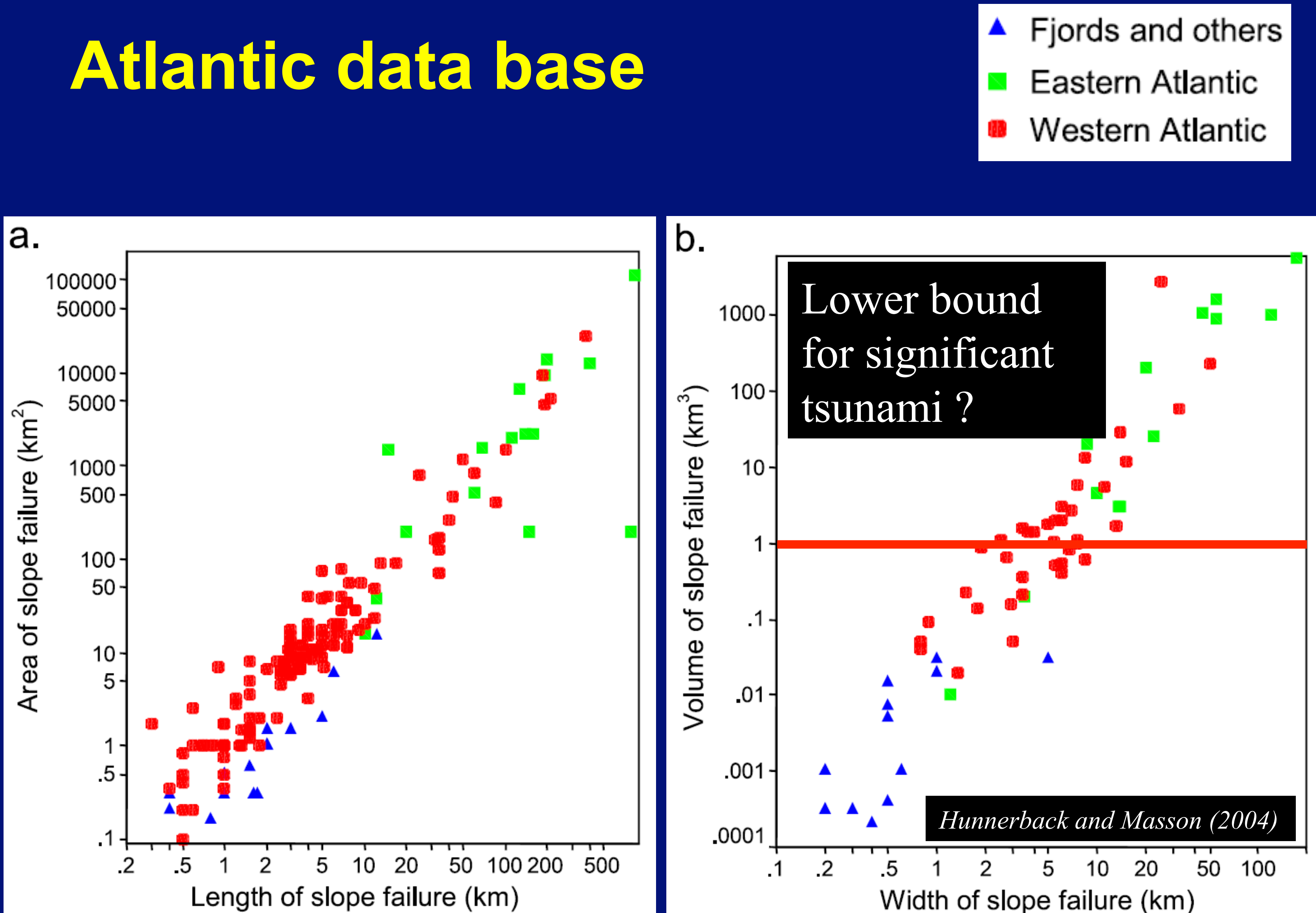
The derivation of flow properties using empirical relationship based on volume or area to the run out distance should always make a distinction between channelizd and non-channelized flows.



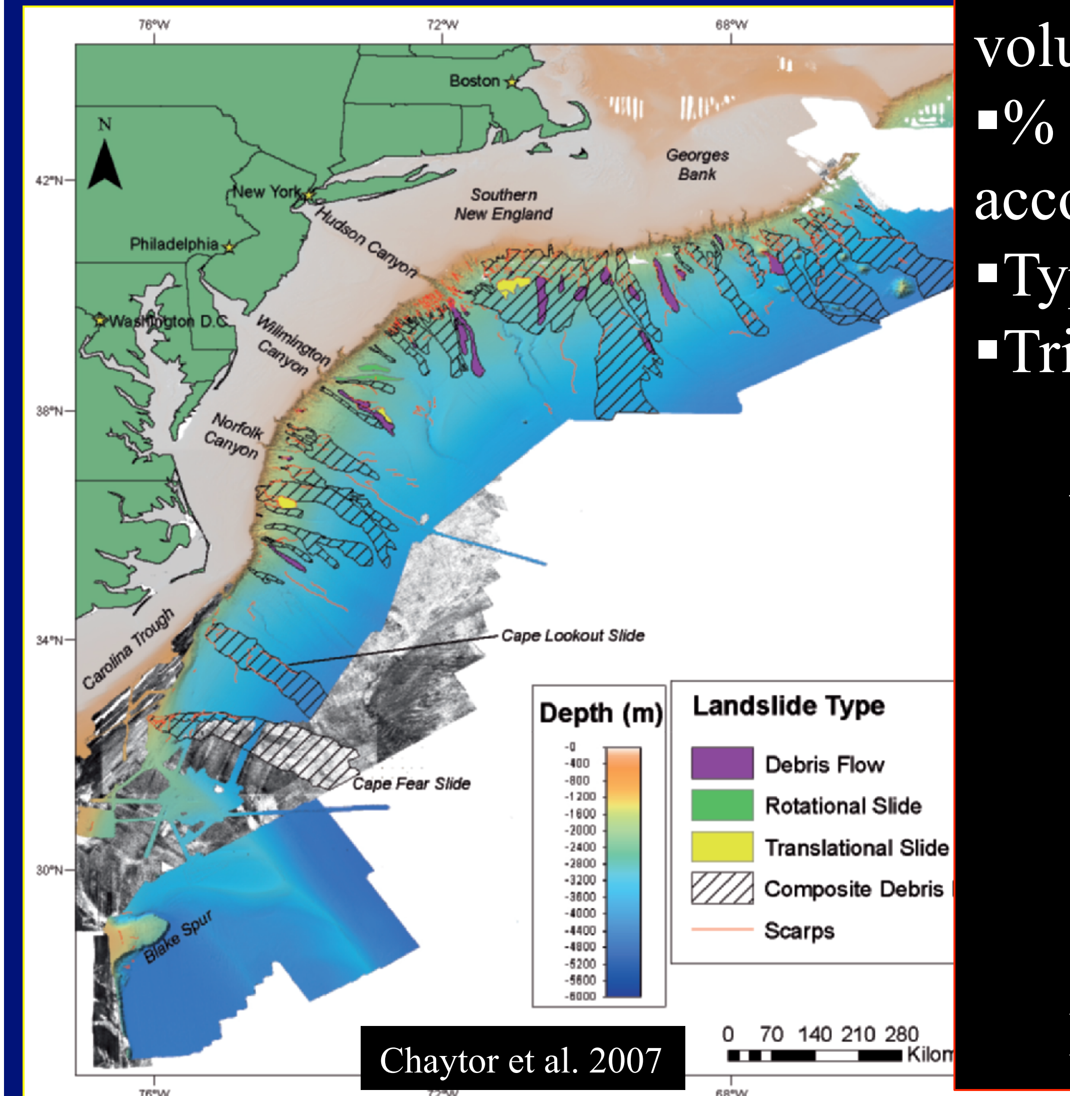
Issler (2005), using the volume per unit width (sort of normalized volume) proposes another correlation between the normalized volume of a slide and the its run-out distance.



Atlantic data base



Comments from slope morphology



Chaytor et al. 2007

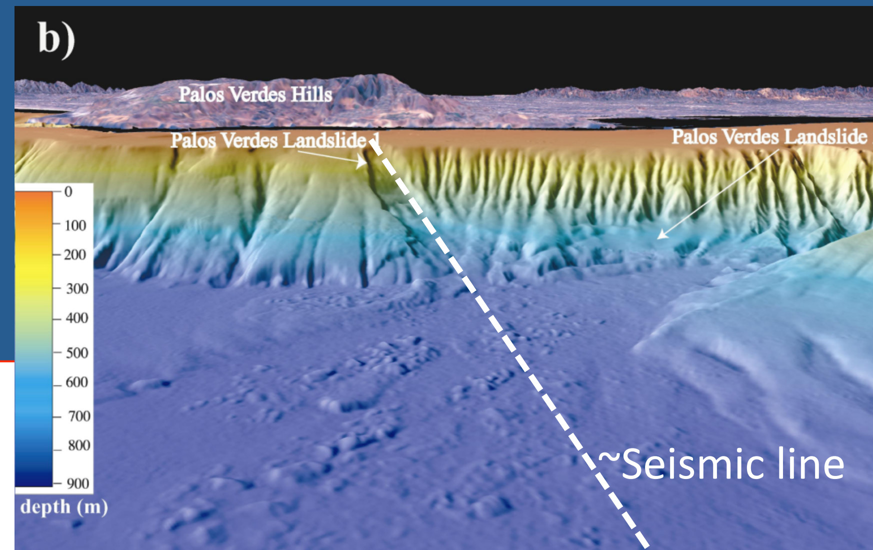
Comments for hazard assessment:

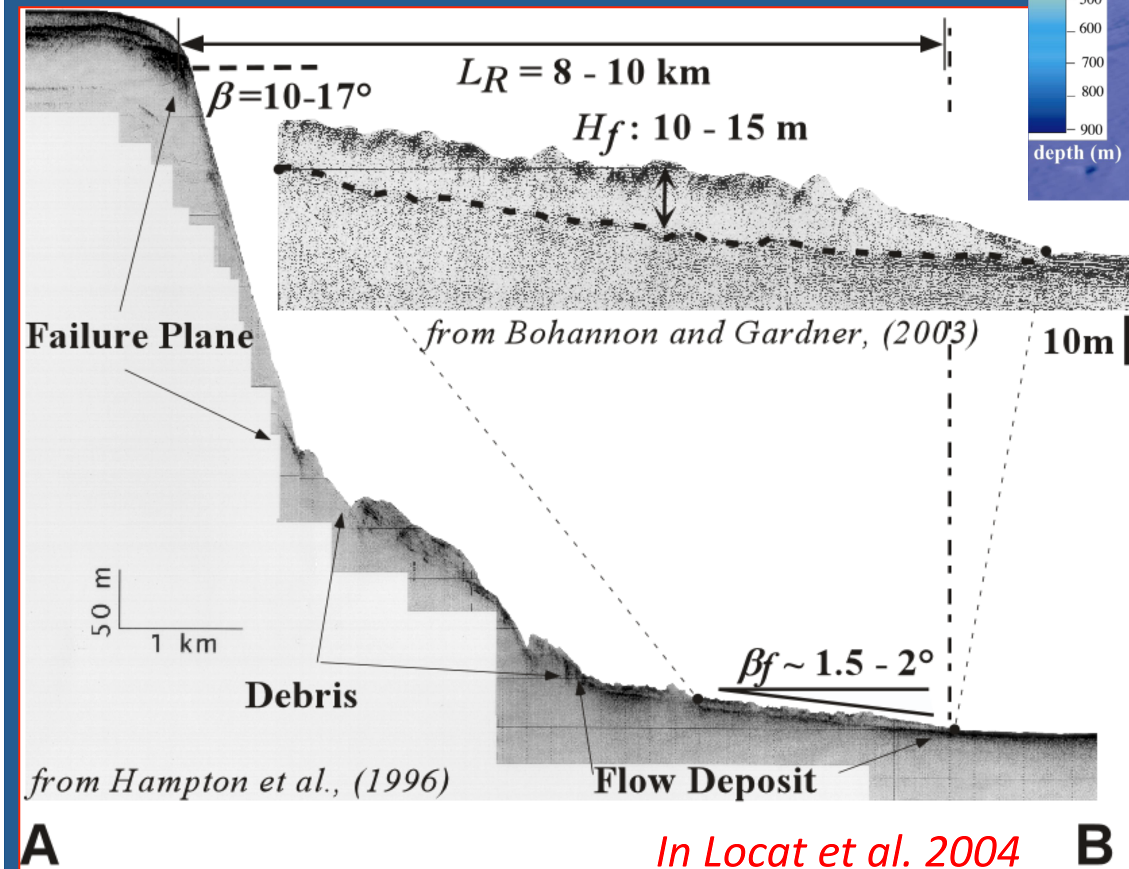
- Clear link between energy, volume, and area
- % of unfailed slopes to take into account for hazard ?
- Type of mass movement ?
- Triggers
  - sediment overloading: limited to ice age
  - gaz hydrates: too late unless significant global warming!
  - Seepage forces (GW), active
  - earthquake: still significant like
  - other tectonic forces (e.g. Diapirms) to be understood!

Mobility and Strength

Johnson (1970) and Hampton (1972) proposed a simple approach to estimate the strength and conditions for stopping the flow:

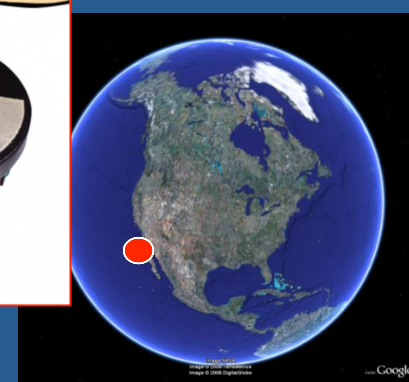
$$t_c = H_c g' \sin b_c$$



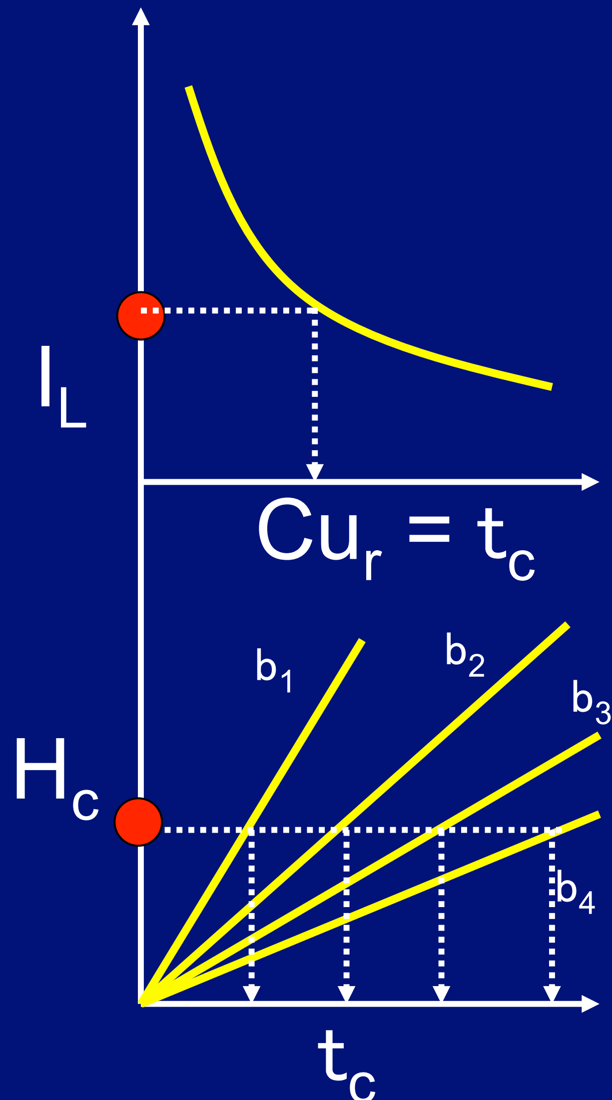


In Locat et al. 2004

The slope is the trick for the thickness of the *pancake!*



Mobility: estimating strength from liquidity index and geometry of flow deposit



$$\tau_c = \left[\frac{a}{I_L}\right]^b ; \mu = \left[\frac{c}{I_L}\right]^d$$

For clays (Bingham model): m/t_c = 0.001!

$$\tau_c = H_c \gamma' \sin\beta$$