# Geological Perspective on Submarine Landslide Tsunami Probability

By

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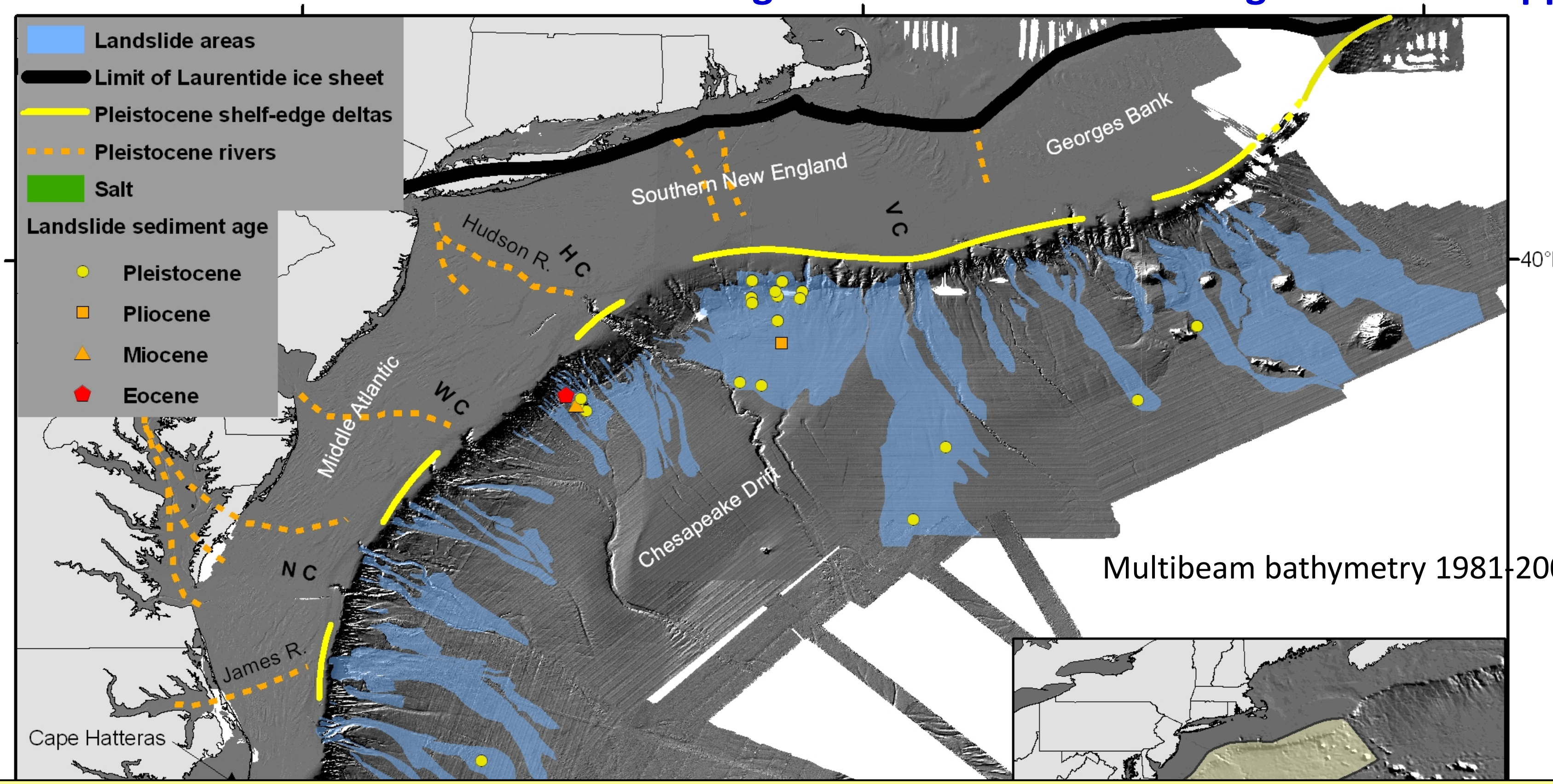
Is landslide distribution uniform in space?
Is landslide distribution stationary?
How are tsunamis generated from landslides?

# Is landslide distribution uniform in space?

## Landslides are concentrated off shelf-edge deltas where there is large sediment supply

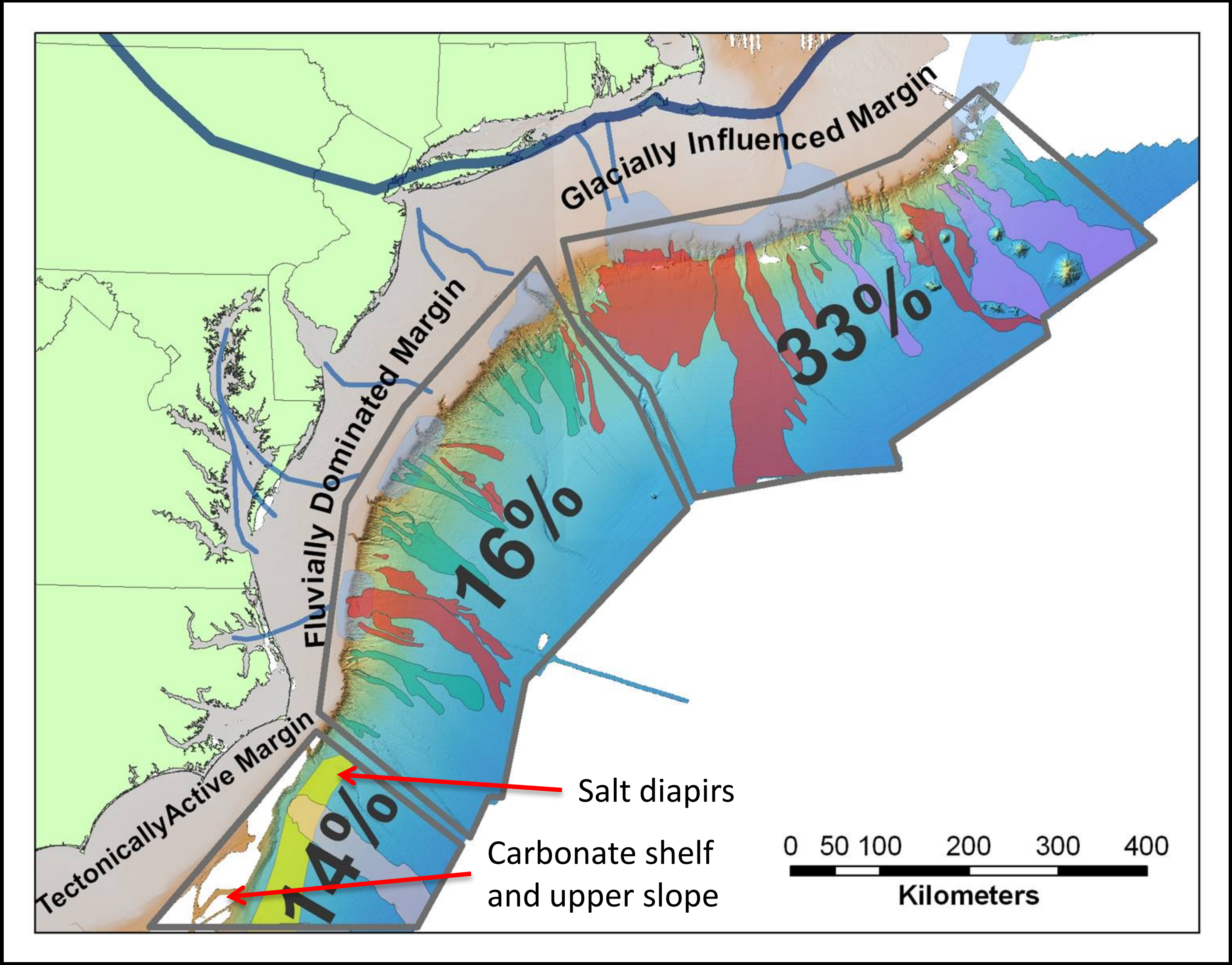



If landslides depend on available sediment that are on the verge of failure, would areas that have already failed, not fail again until more sediment is supplied to the margin?

Are large landslides predicted in margins, such as S. California, where tectonic activity may outpace sediment supply?

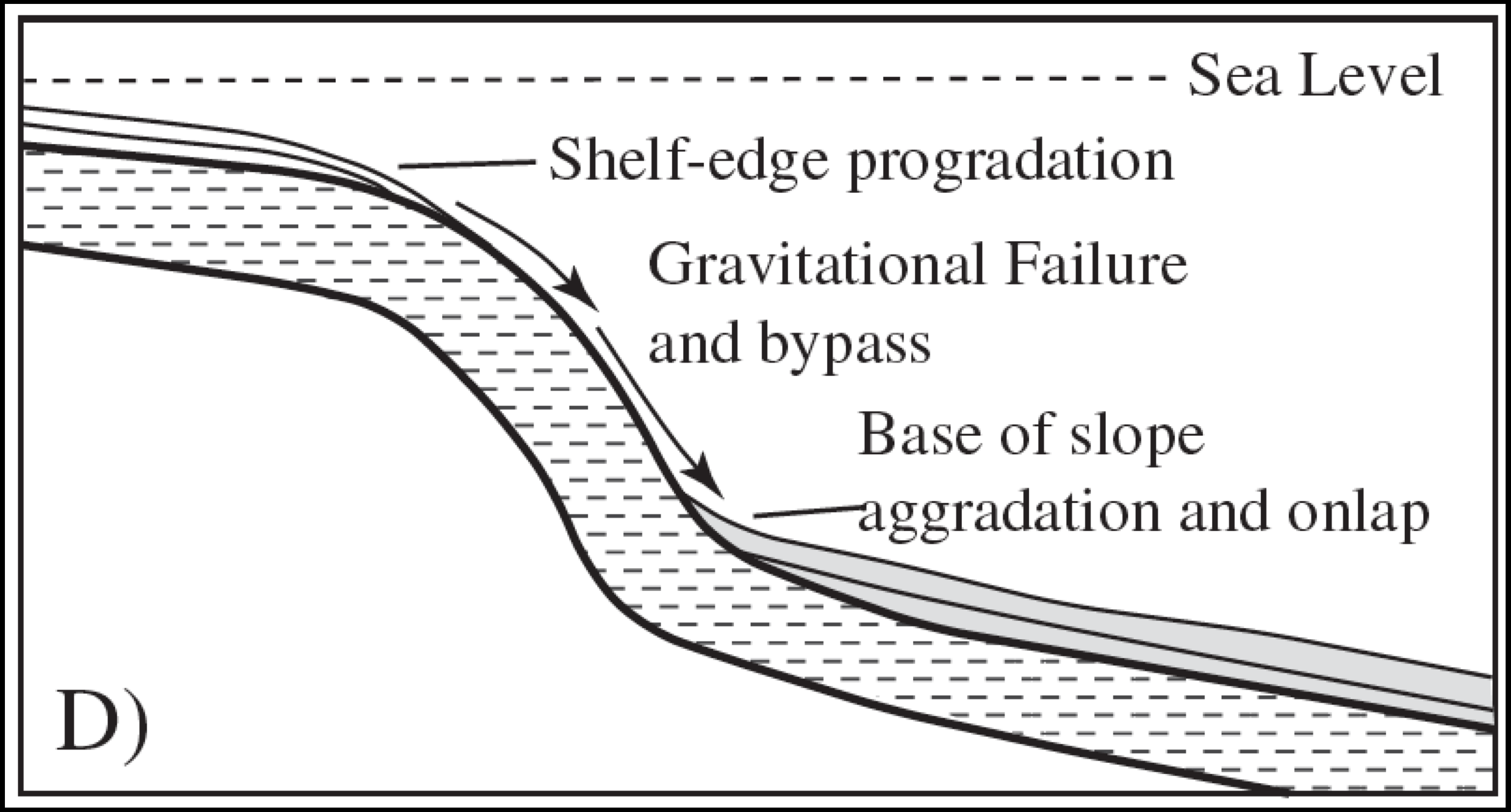
# Geologic Control on Landslides

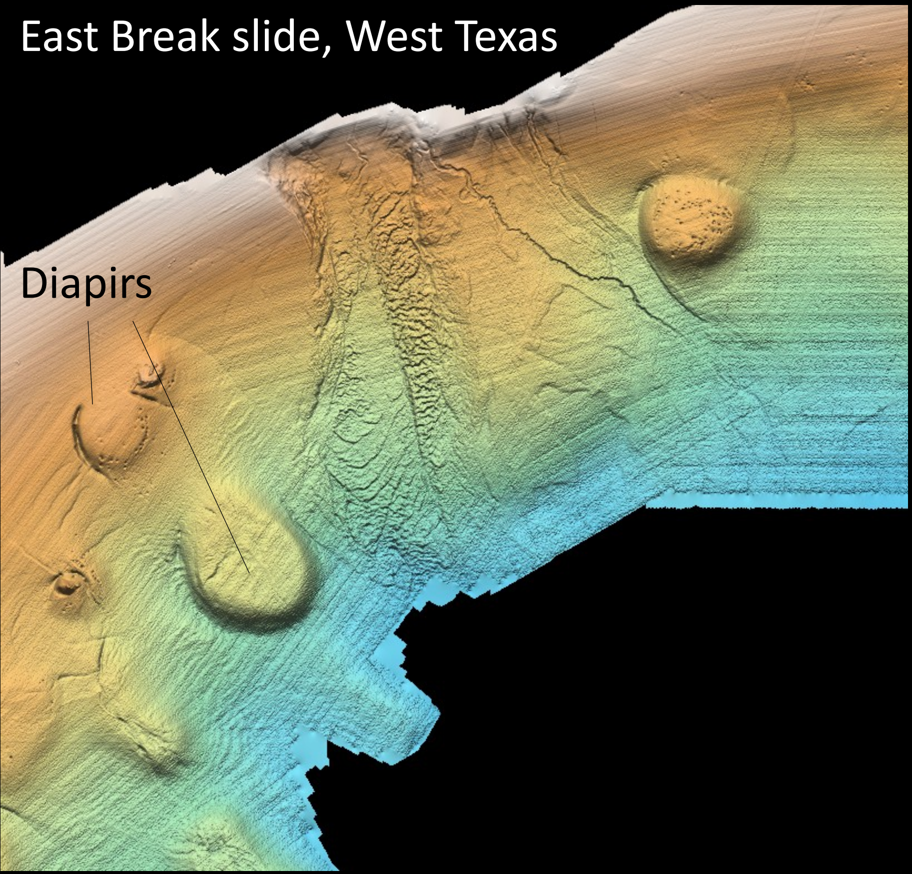
## Margin types

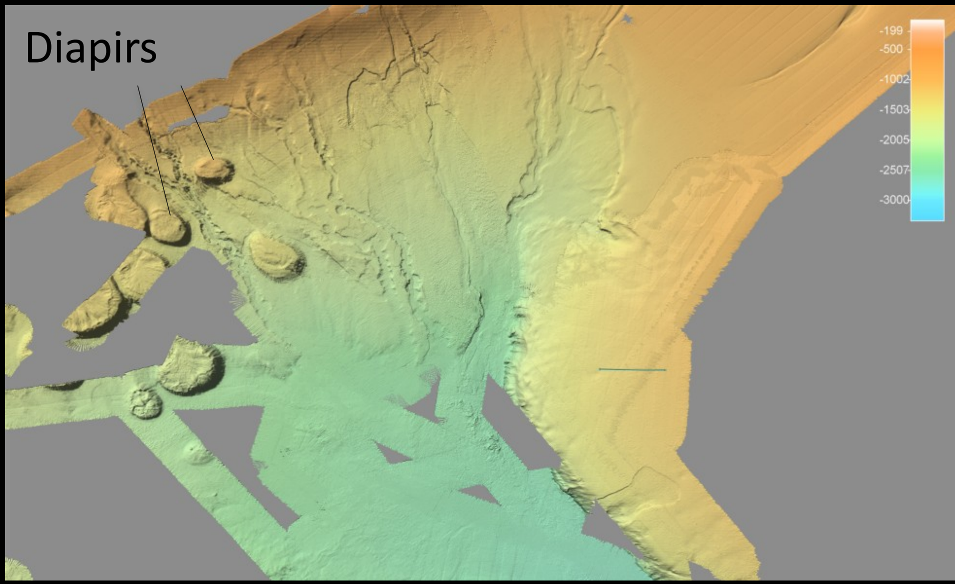



*Twichell et al., 1999*

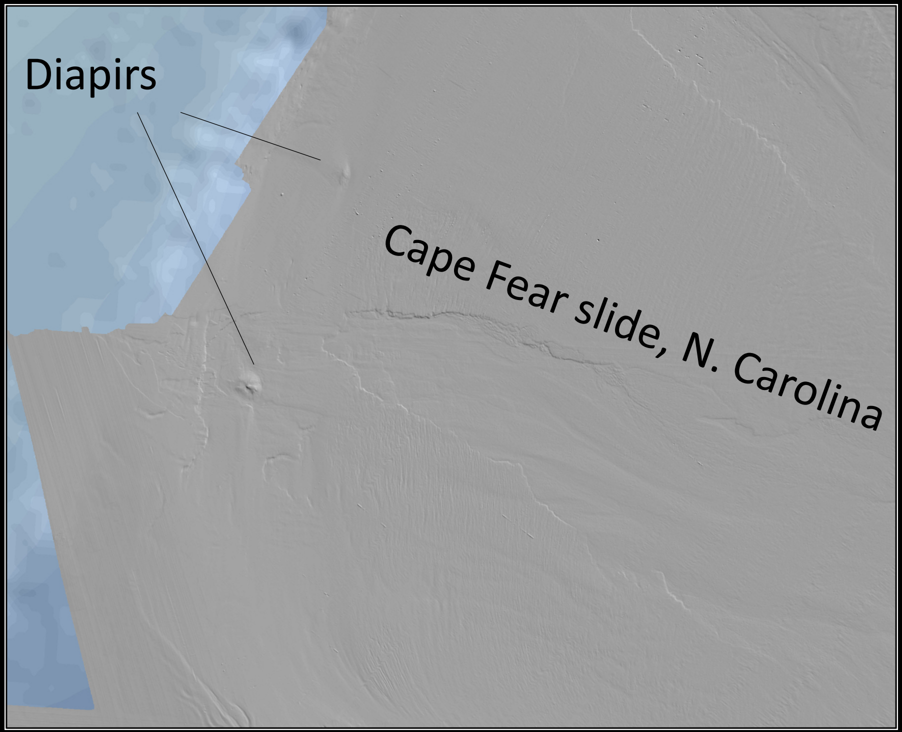
# Are higher slopes more susceptible than lower slopes?






De Soto slide, NW Florida

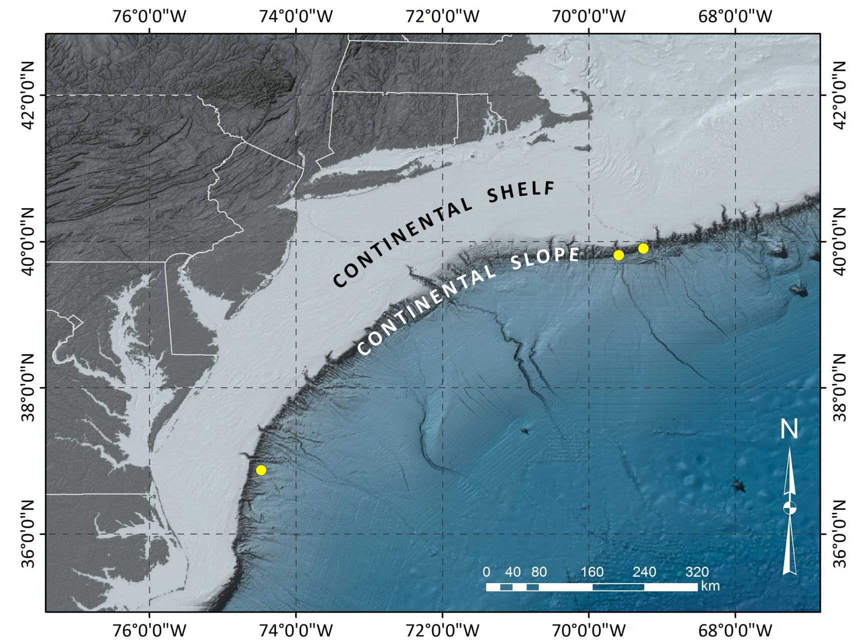


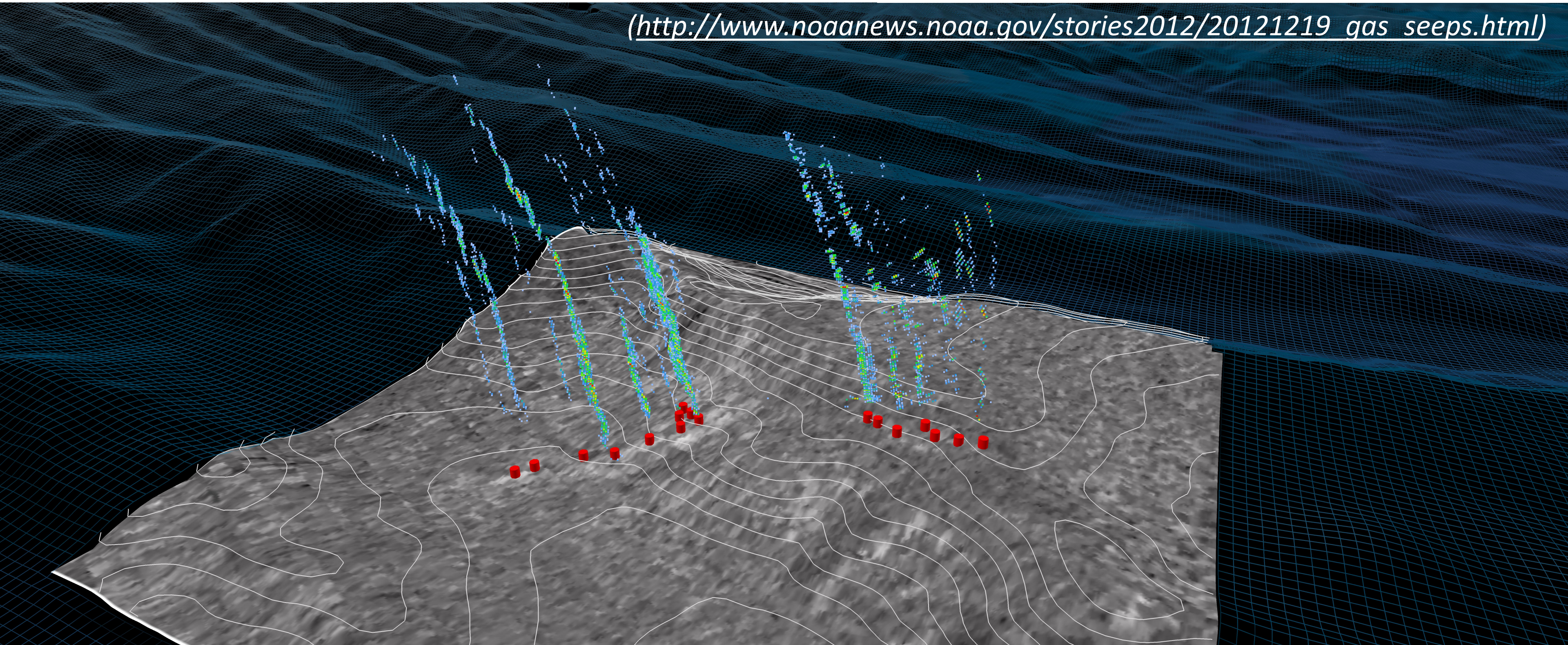

# Landslides in salt diapir environments

Rising salt changes the slope, but quantifying the rise rate is difficult

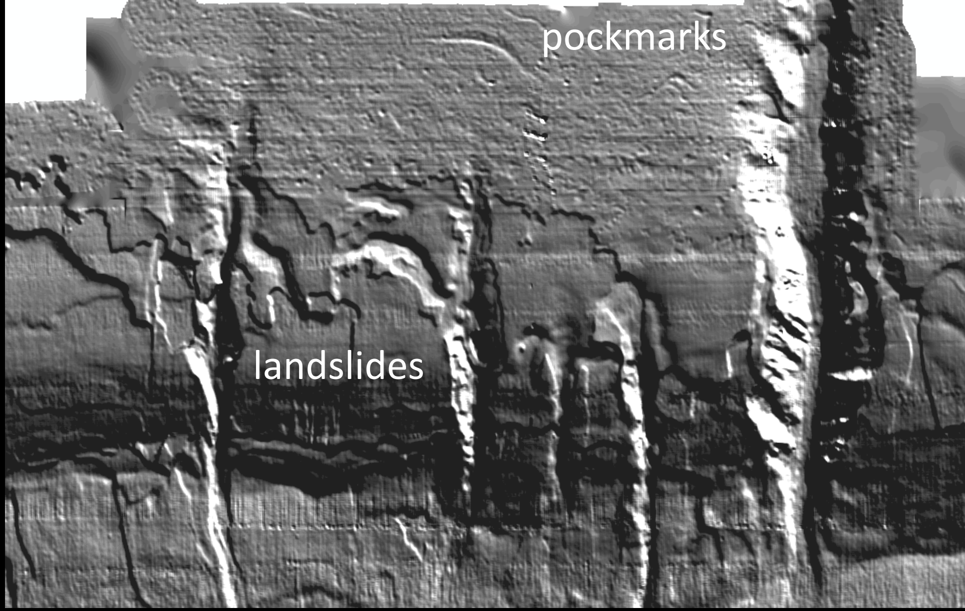
## Excess pore pressure due to:

1. biogenic and thermogenic gas
2. water release by Opal CT to quartz transformation
3. sediment loading of offshore aquifers
4. gas hydrate dissociation

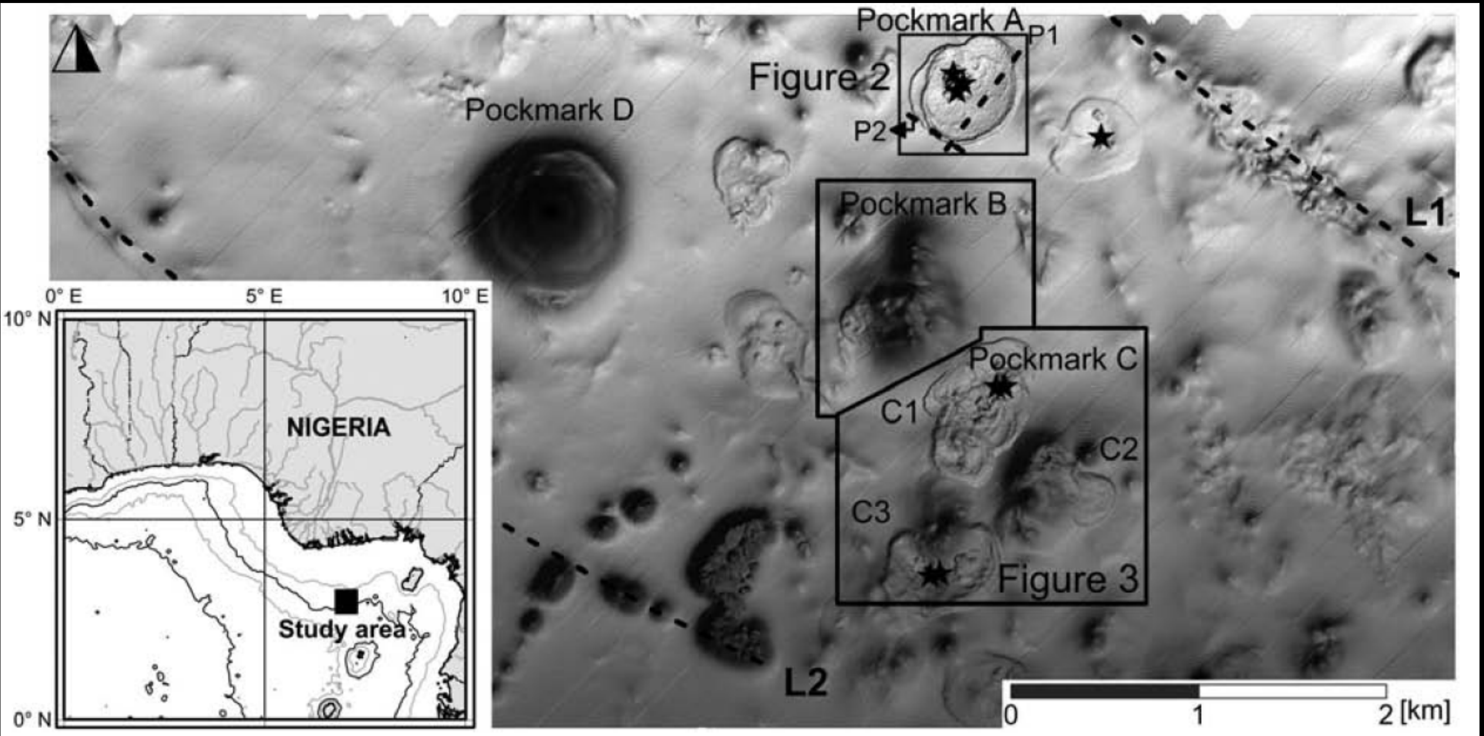


# How large are the patches of elevated pore pressure?



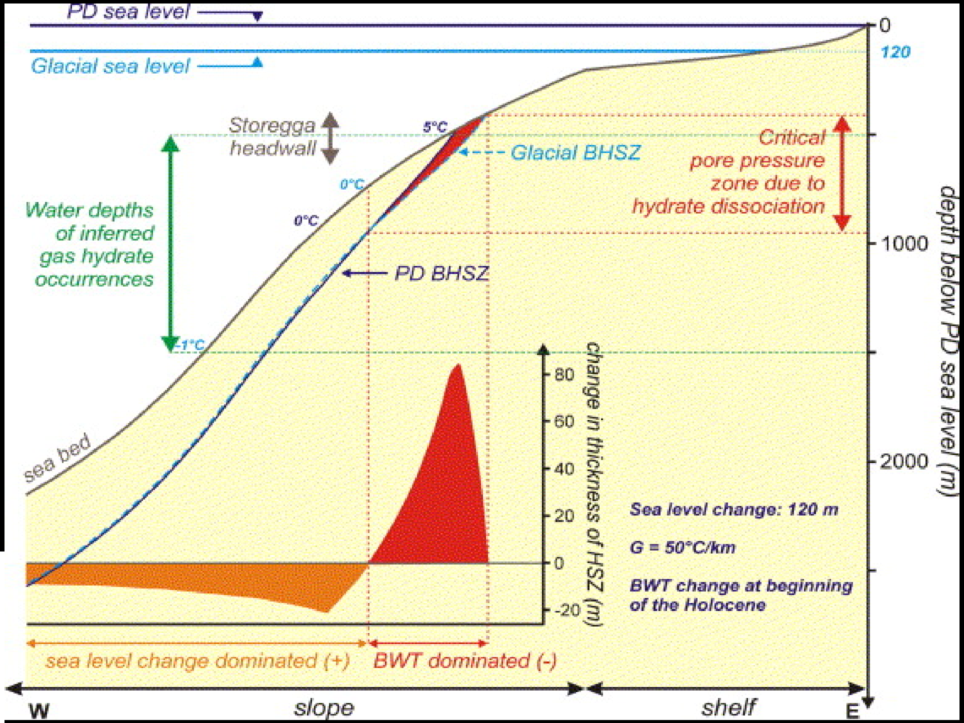

Gas/fluid venting through pockmarks all along the shelf edge (right) and mid-slope (bottom)

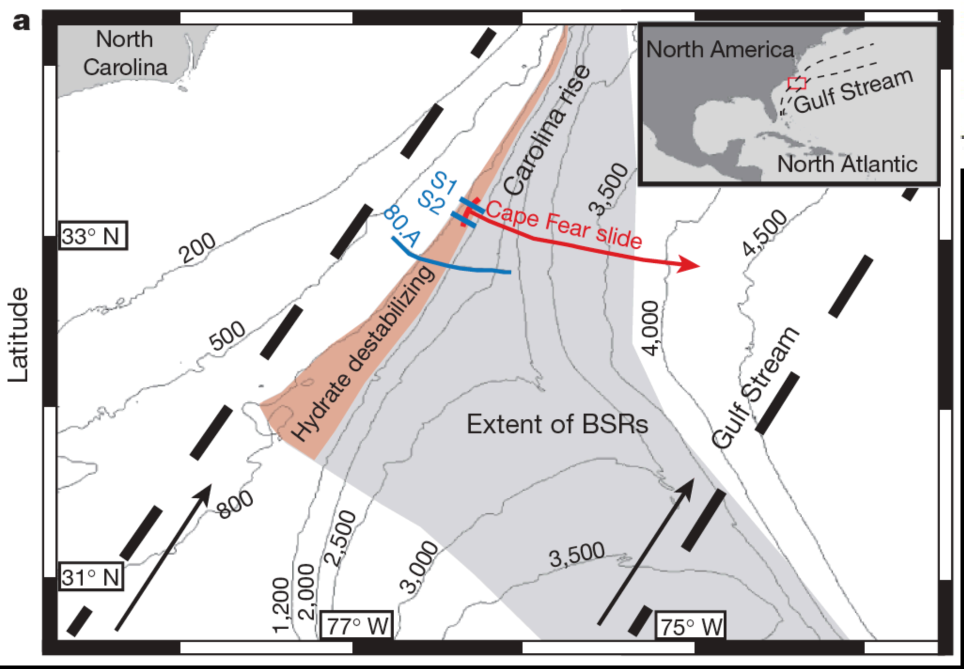



*(Sultan et al., JGR, 2010)*

# Are landslides being generated by gas hydrate dissociation?

Gas hydrate dissociation during sealevel rise can only happen if bottom water temperature rises

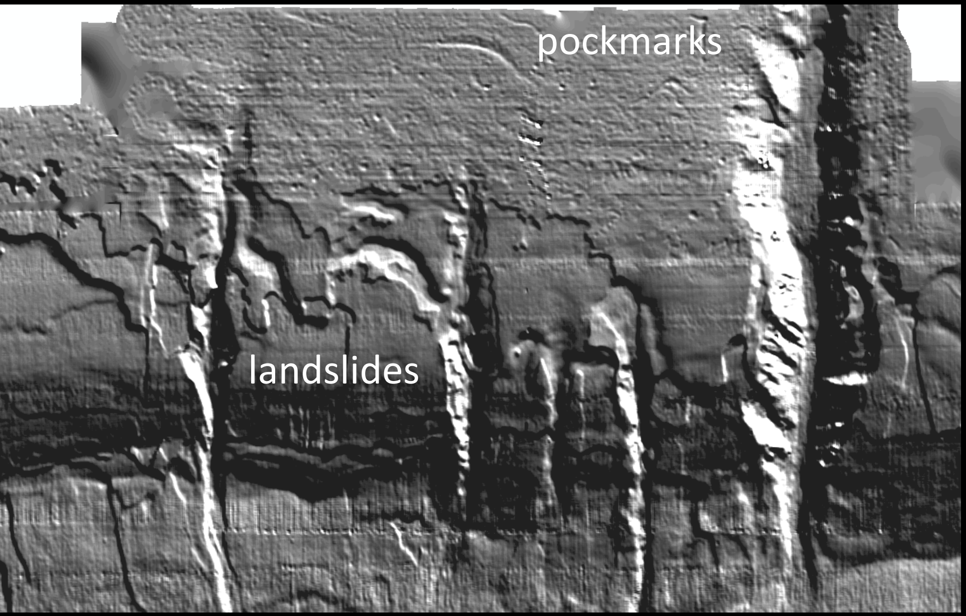


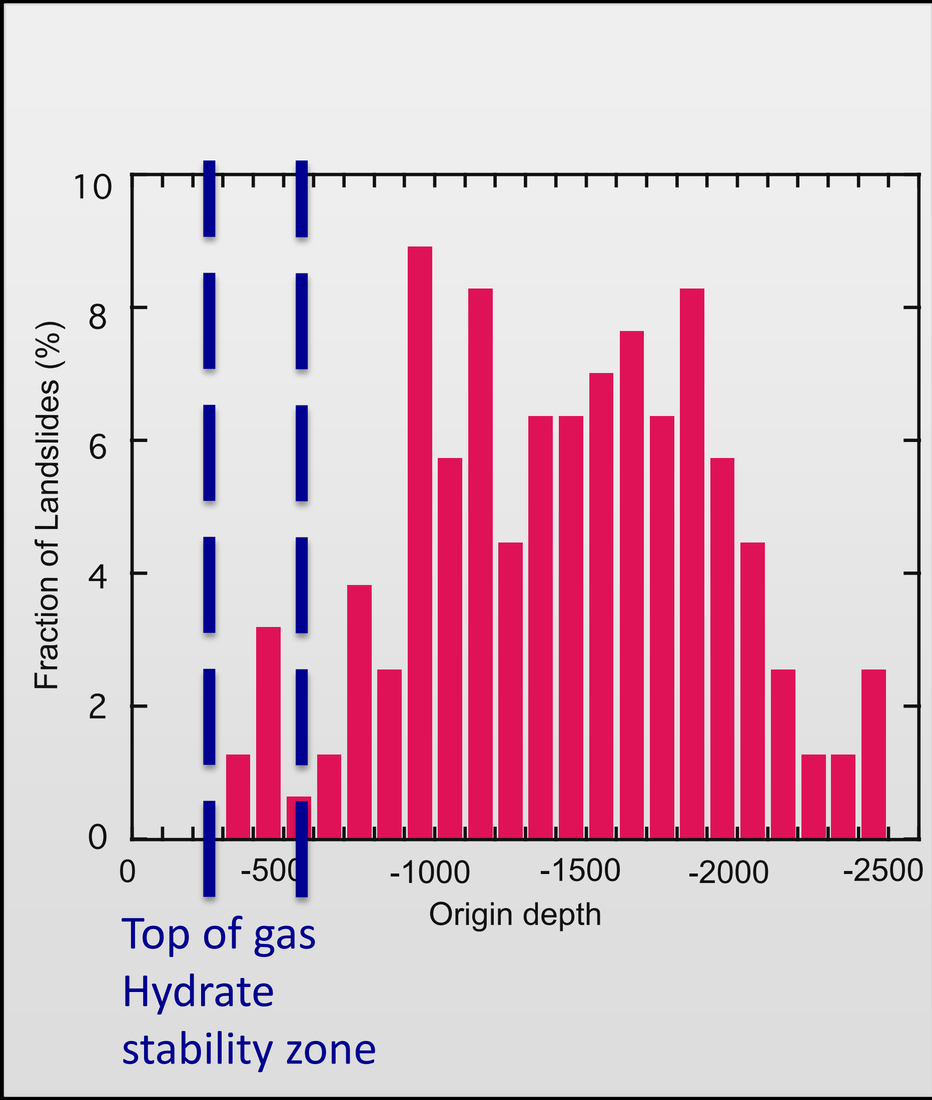

Bottom water temperature increased (BWT ) by 5°C about 12.5-10 Kyr ago.
But age of Storegga slide is 8.1 Kyr .
(Meinart et al., Mar. Petrol. Geol. 2005)

Gulf Stream hugs the shelf edge (Phrampus and Hornbach, Nature, 2012)

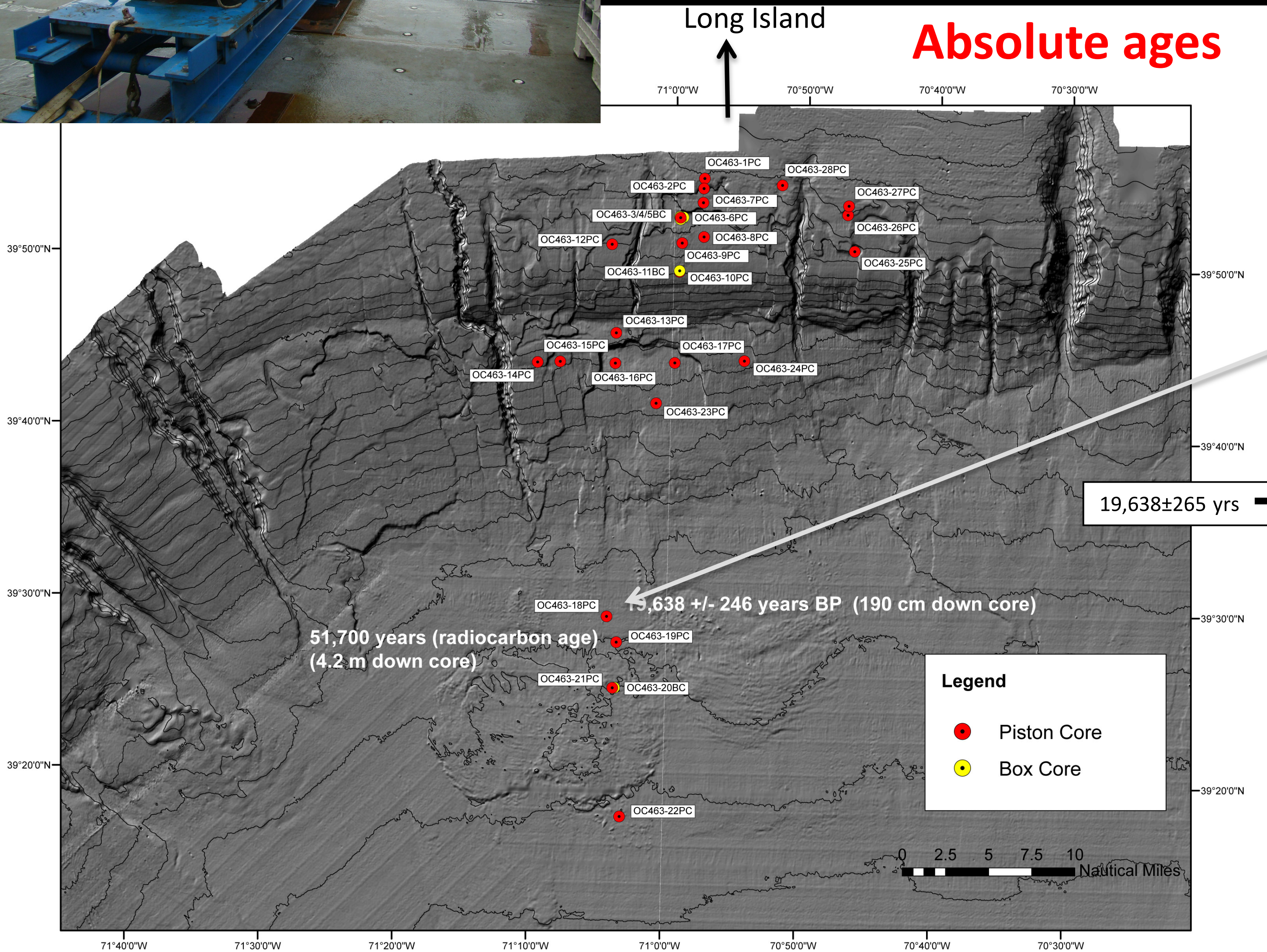
# Headwalls of most landslides are well below depth of expected gas hydrate dissociation




Gas/fluid venting through pockmarks
all along the shelf edge

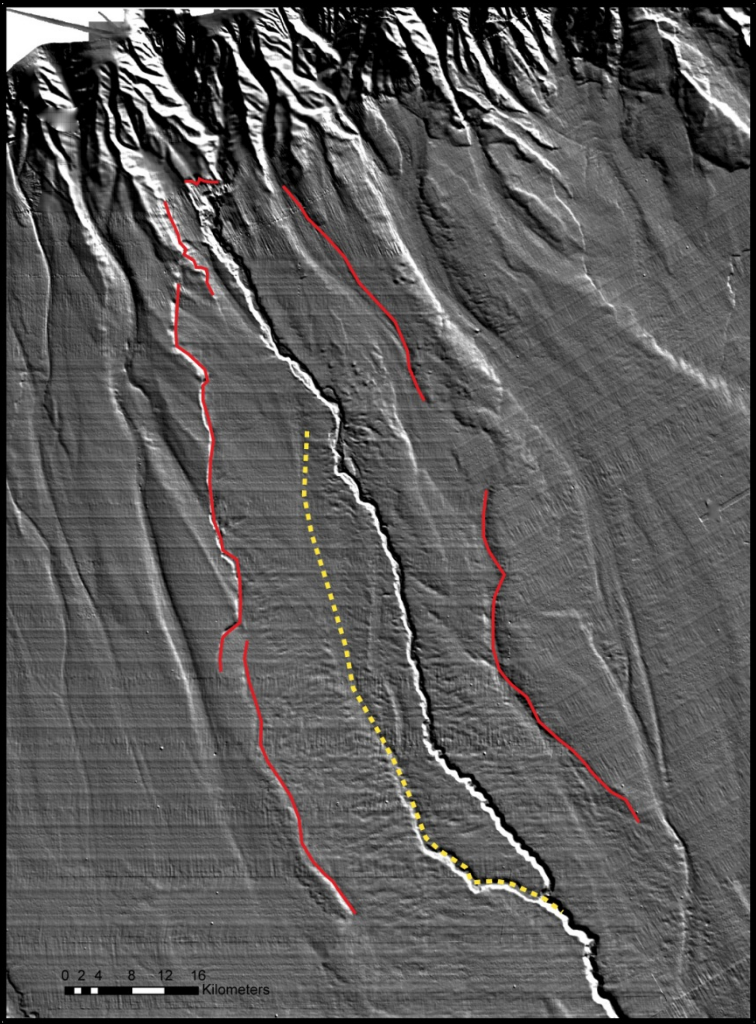


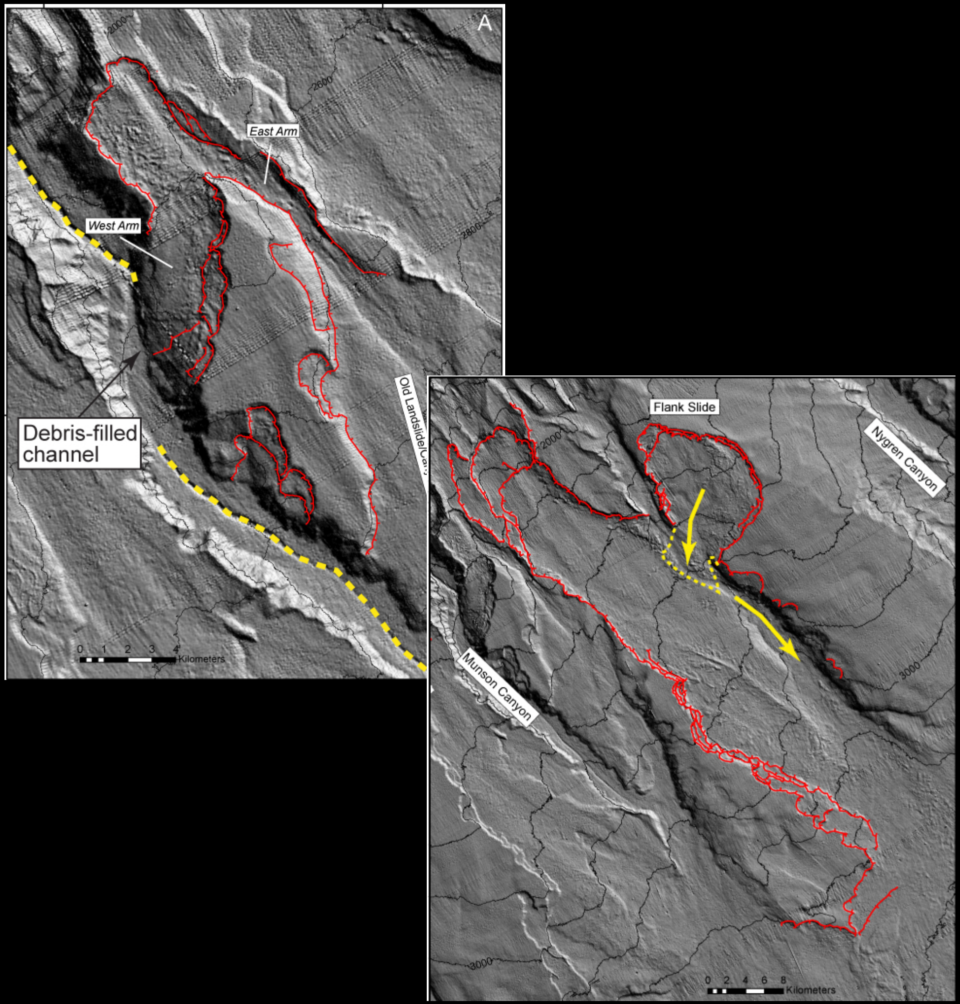
# Temporal distribution of submarine landslides




# Relative Dating

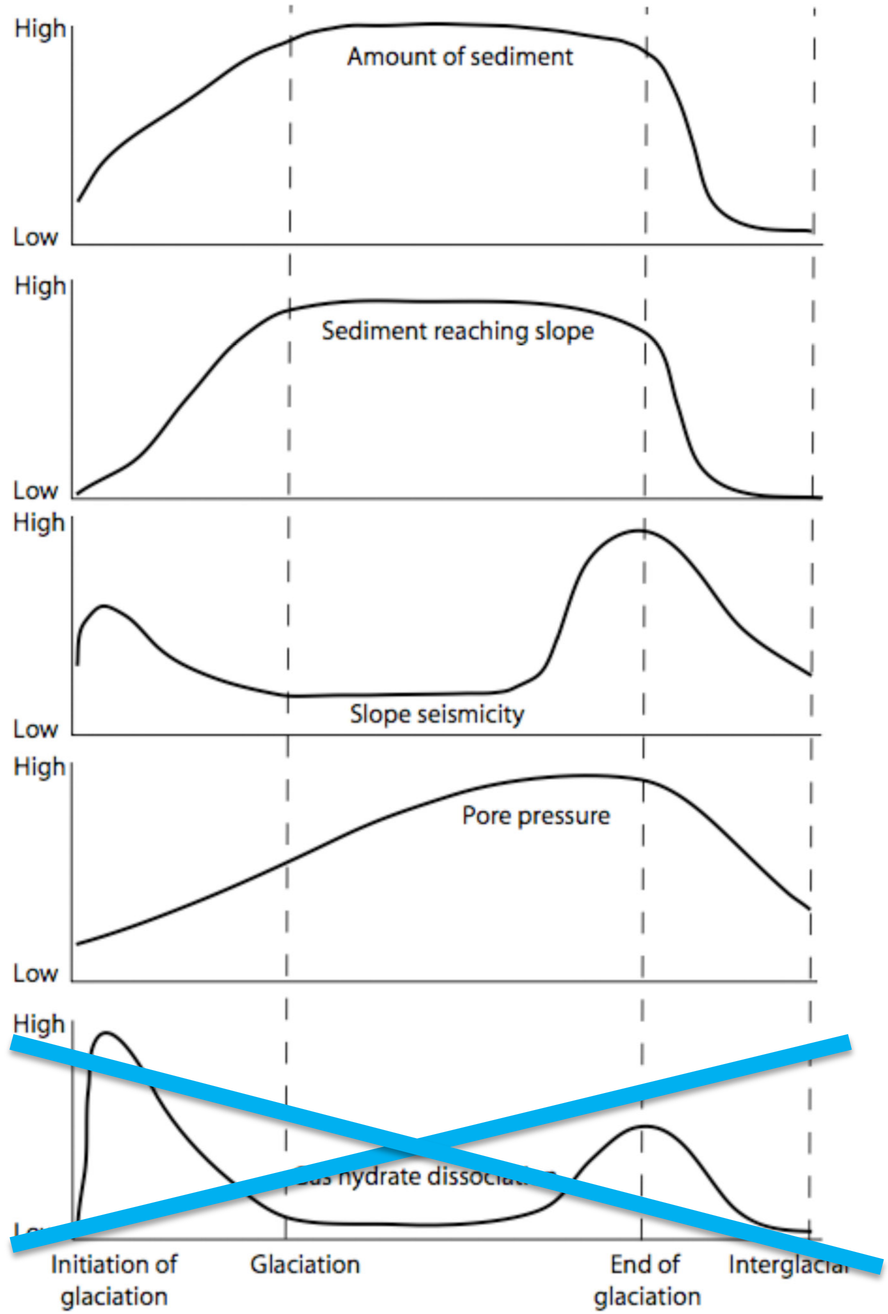
- Cross-Cutting Relationships – Scarp/debris & Canyon/Debris



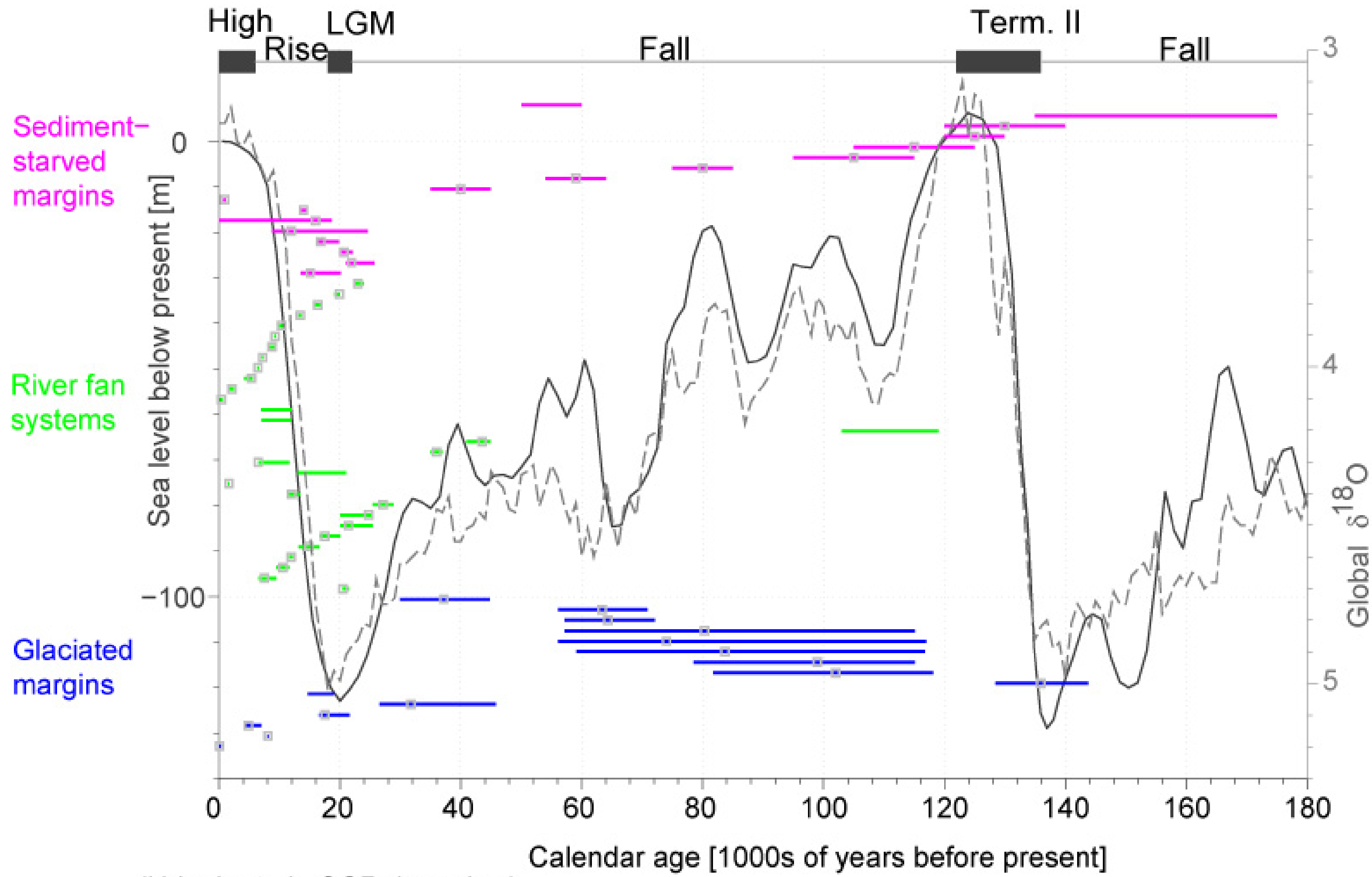
**Is landslide distribution uniform in time?**

**A qualitative approach**




*(Lee, 2009)*

# Can we use the ergodic assumption? (age distribution around the world = rate of landslide occurrence in a specific location)

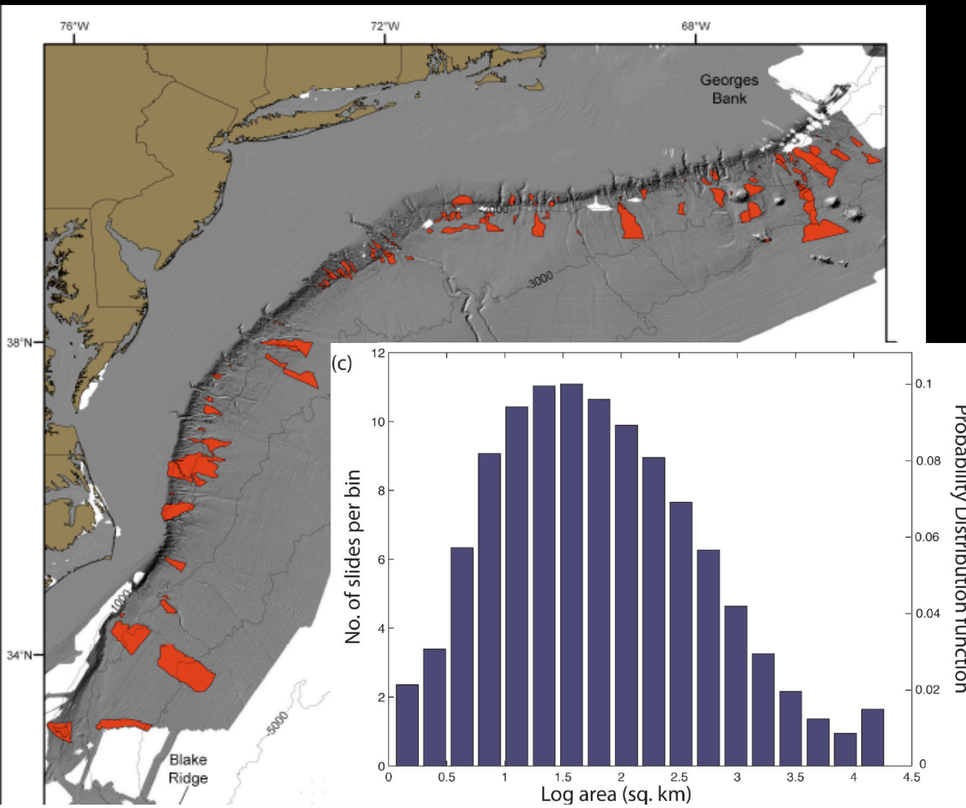


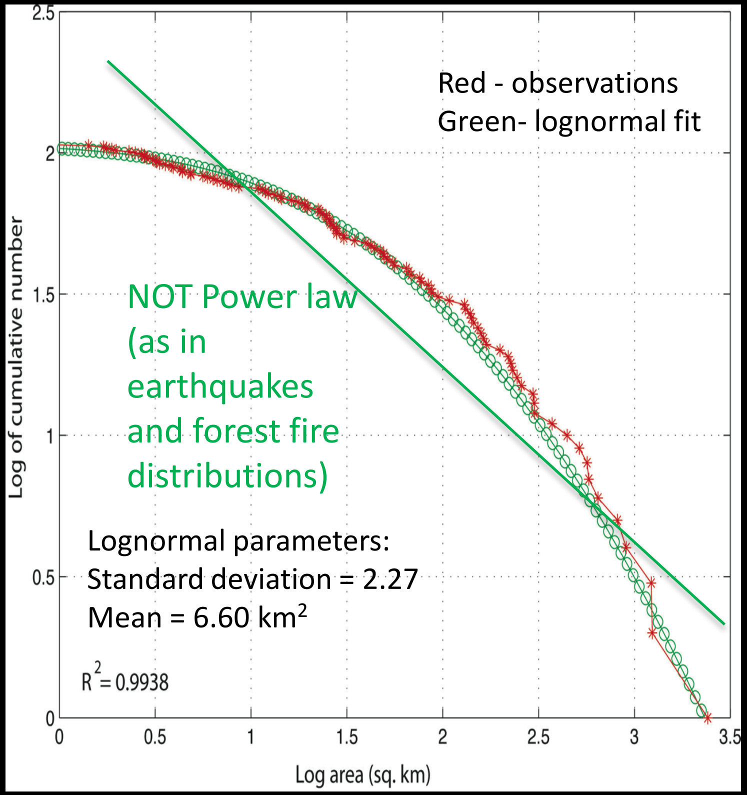

*(Urlaub et al., QSR, in review)*

Global compilation of landslide ages superimposed on sea level curve for the last glacial cycle

**Caveat: Newer landslides may erase evidence of older landslides**

# Another approach:
# Relating landslide distribution to earthquake recurrence



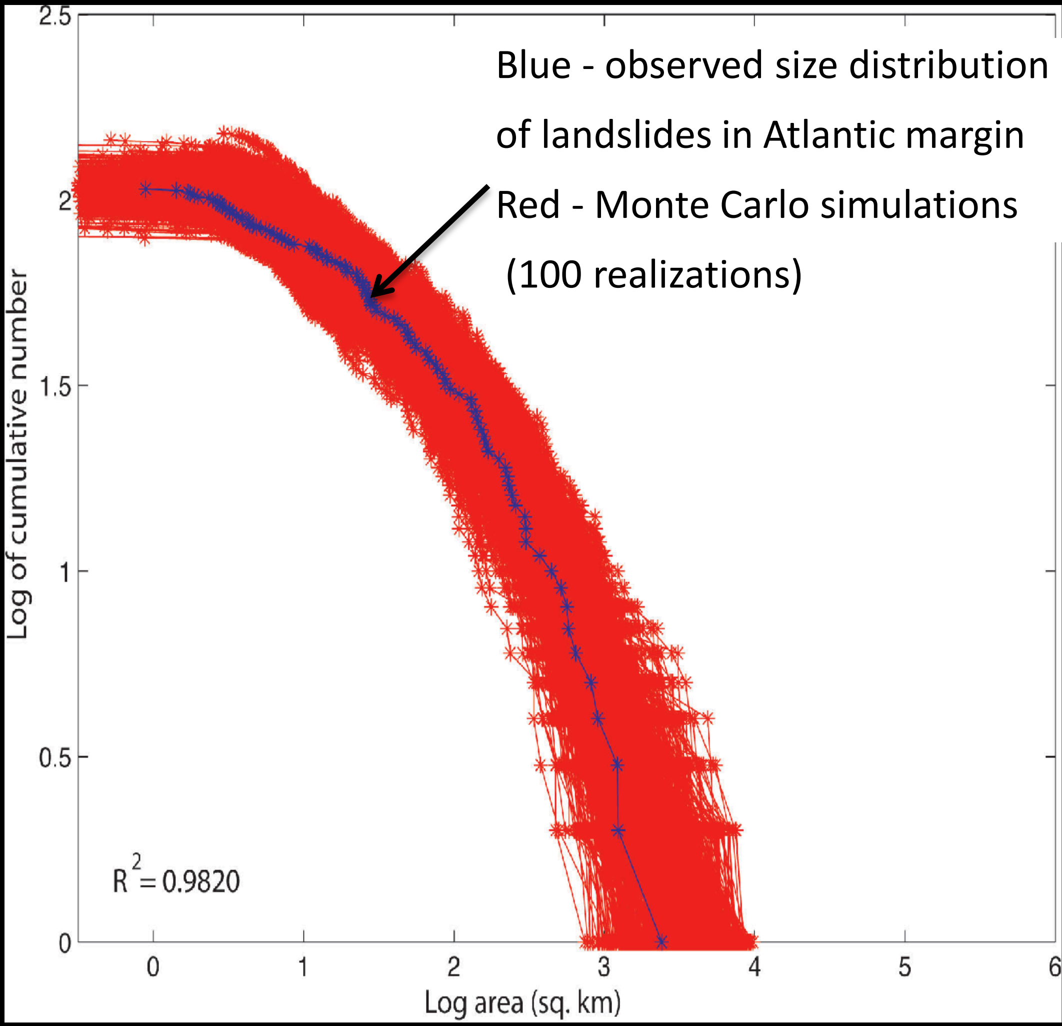




Size distribution of landslides on the Atlantic continental slope is lognormal:

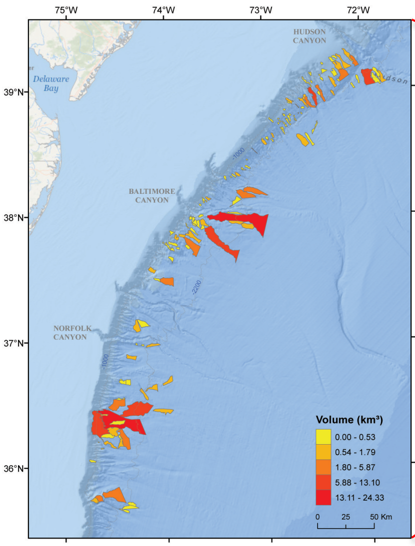
Most landslide areas are between 10-100 km$^2$, fewer larger and smaller landslides

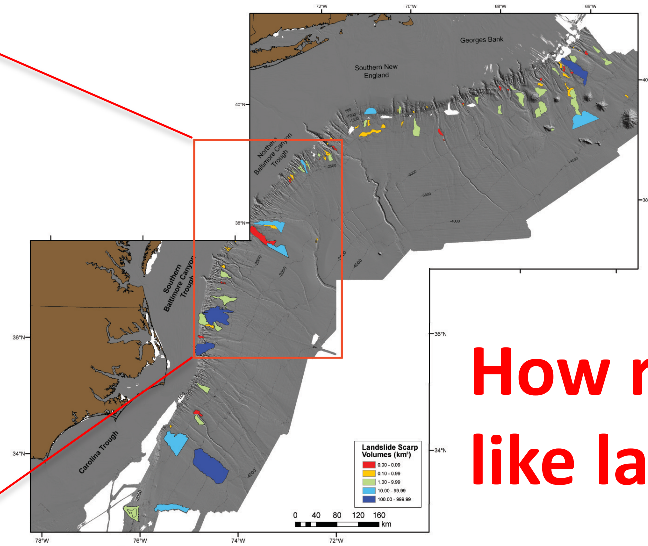
Lognormal-like landslide distributions can be generated by Monte Carlo simulations by assuming that the area of slope failure is a function of

1. Earthquake magnitude (via horizontal acceleration and attenuation)
2. Slope stability.



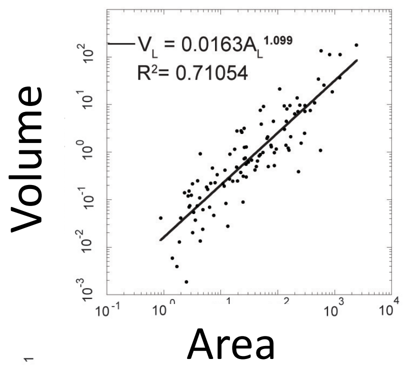

**If correct , we can predict landslide size (and tsunami probability) from earthquake probability.**

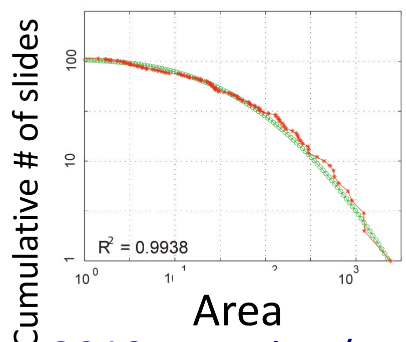


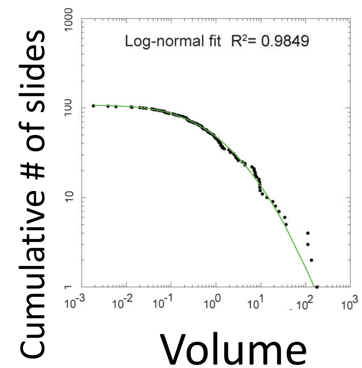




# How robust is the lognormal-like landslide distribution?

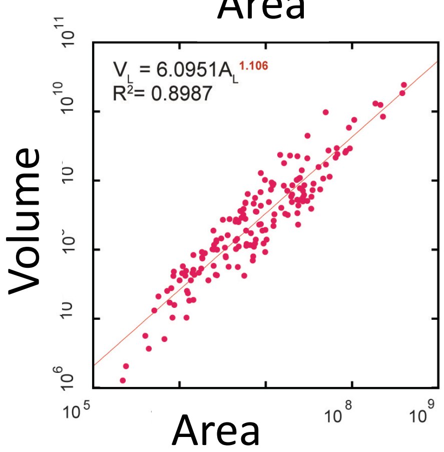
## 2009 mapping (n=106)

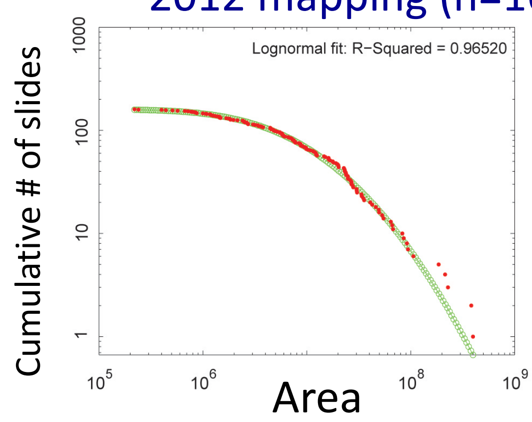


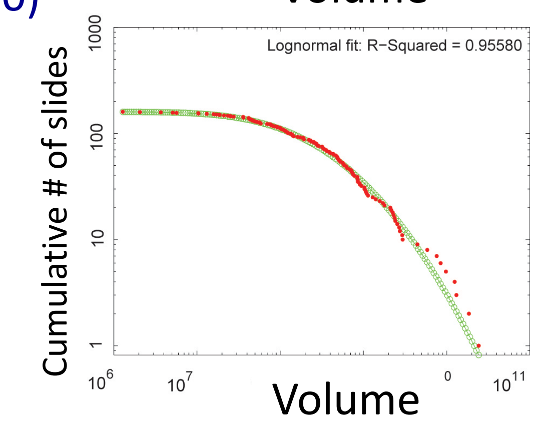



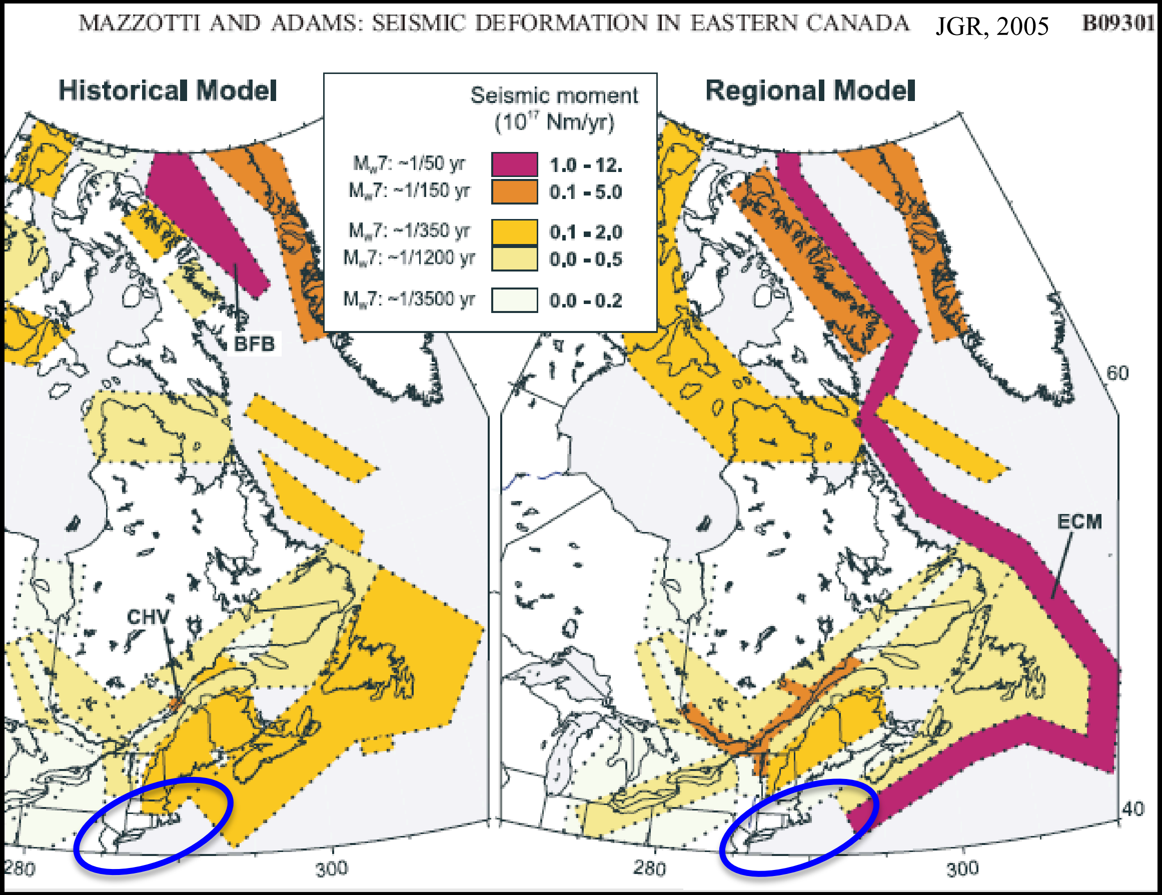

## 2012 mapping (n=160)



# Transfer the problem of probability of landslide recurrence along the Atlantic margin to probability of earthquakes along that margin

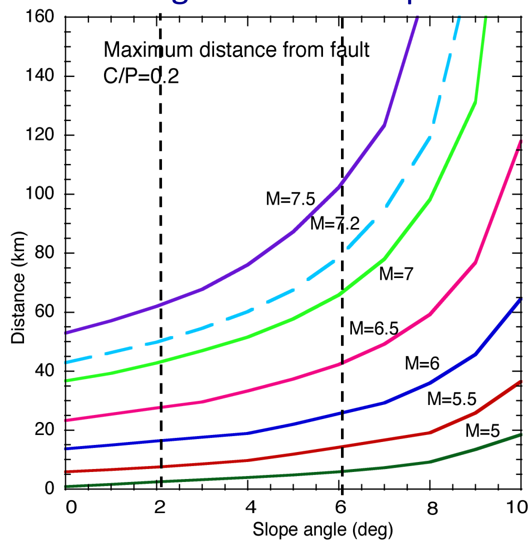



Average annual seismic release along the 6000-km-long continental slope of eastern Canada = 2-10x$10^{17}$ Nm/yr or equivalent to M7 every 40-200 y (Mazzotti and Adams, 2005).

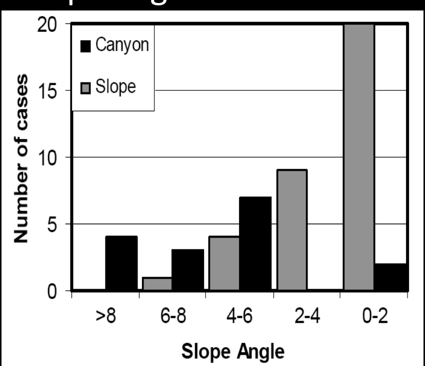
If same regional model extends to the 400-km-long New England, an equivalent M7 is expected off New England every 600-3000 y.

# A guide to tsunami warning assuming that earthquakes and landslides are related

Calculated maximum distance to failure, $r_{max}$ as a function of earthquake magnitude and slope

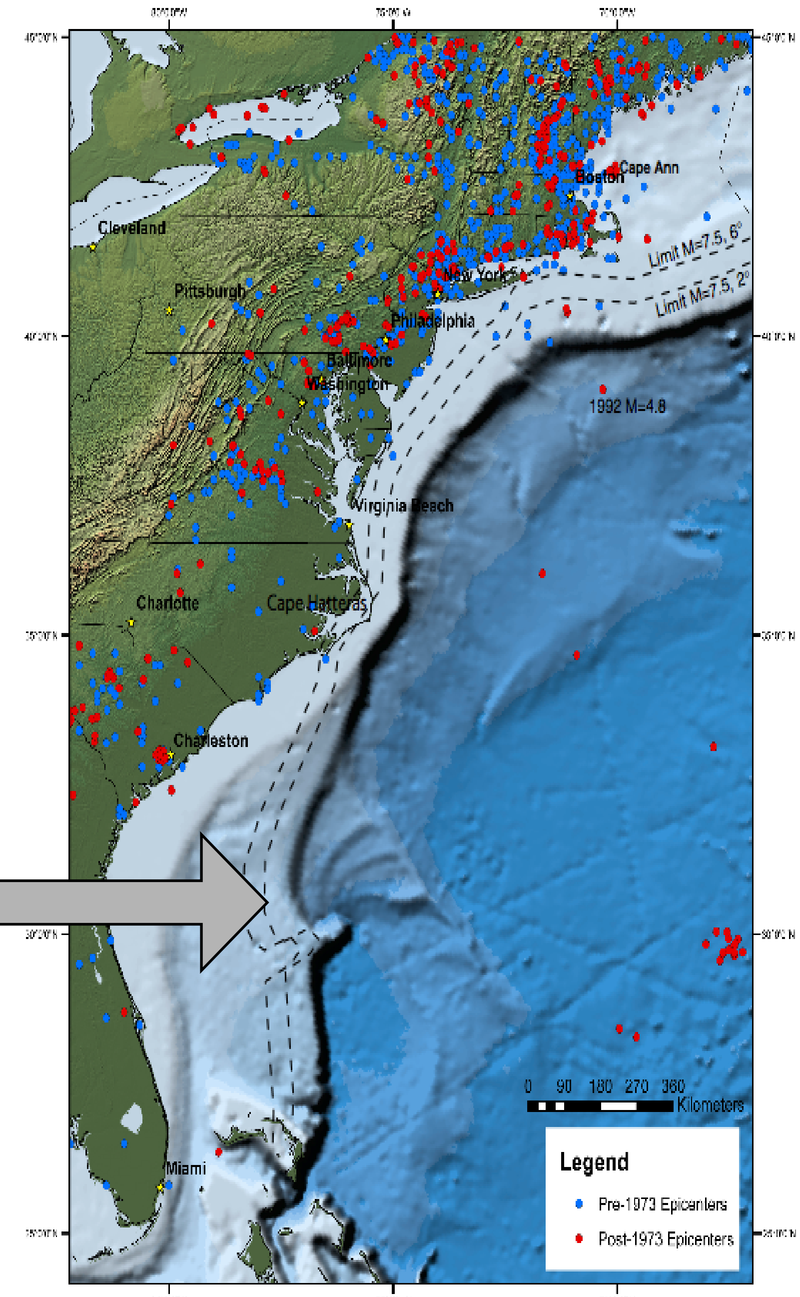



Slope angle of landslides

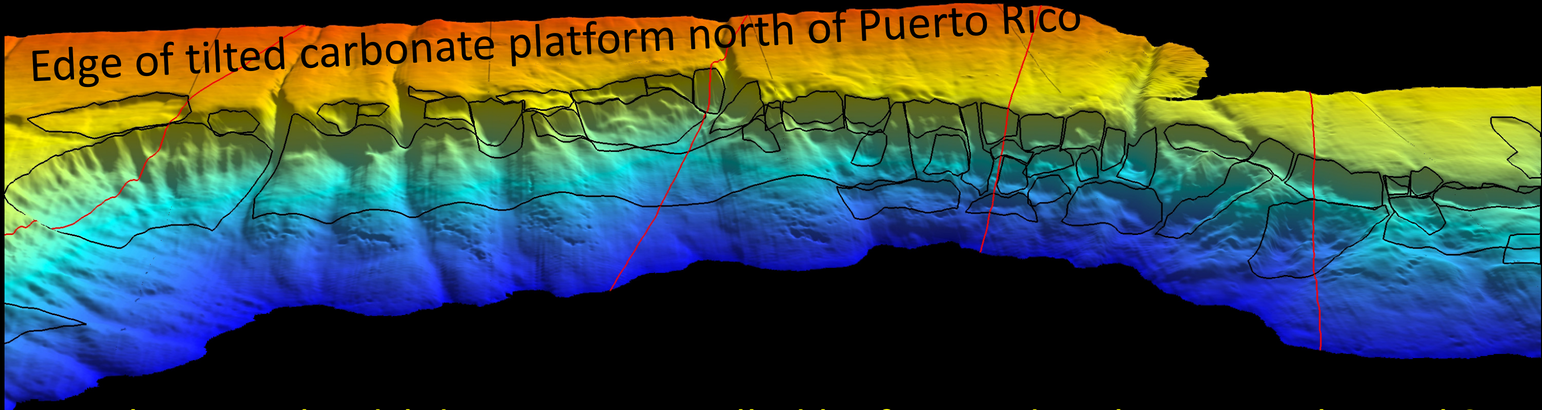



**Earthquake region that can generate landslide tsunamis is limited to outer shelf and slope**

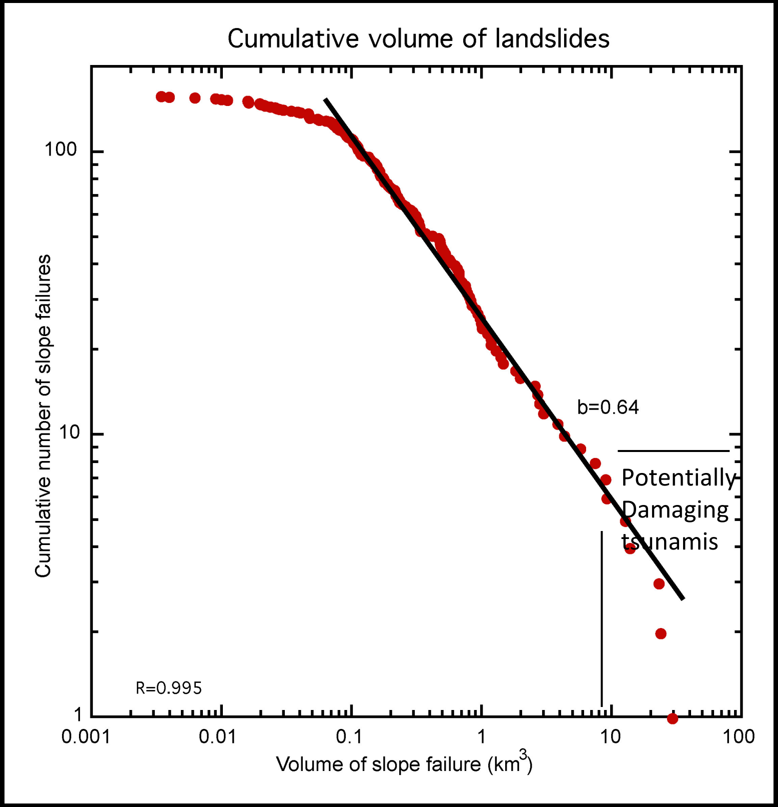
Earthquakes in the East Coast of the U.S.

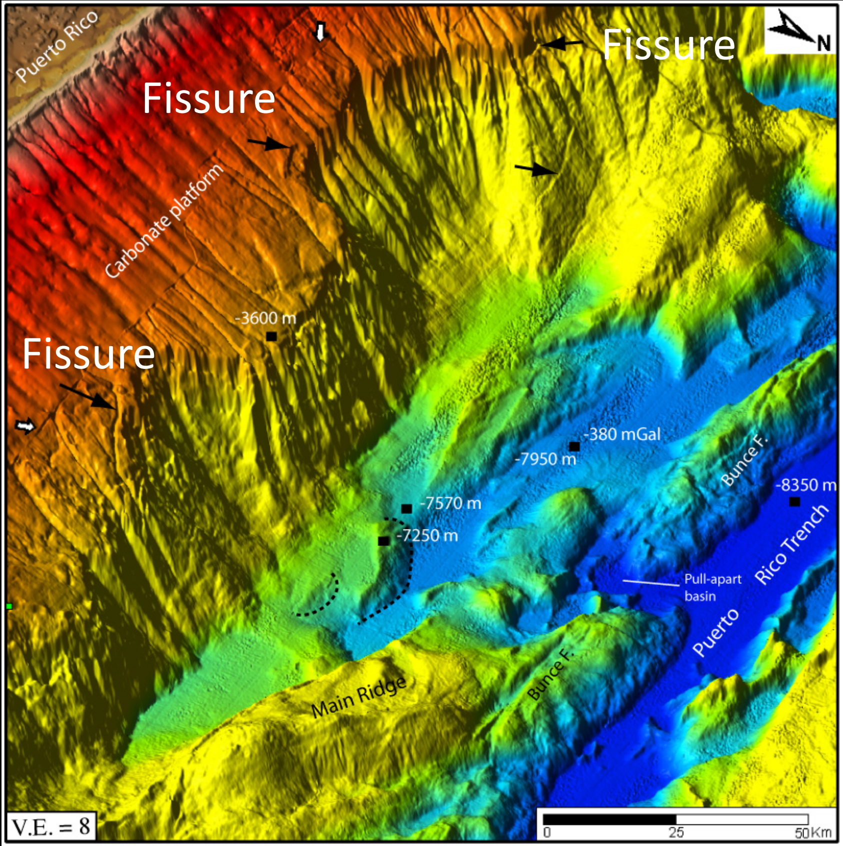


# Landslide distribution in carbonate margins (Florida, Puerto Rico)



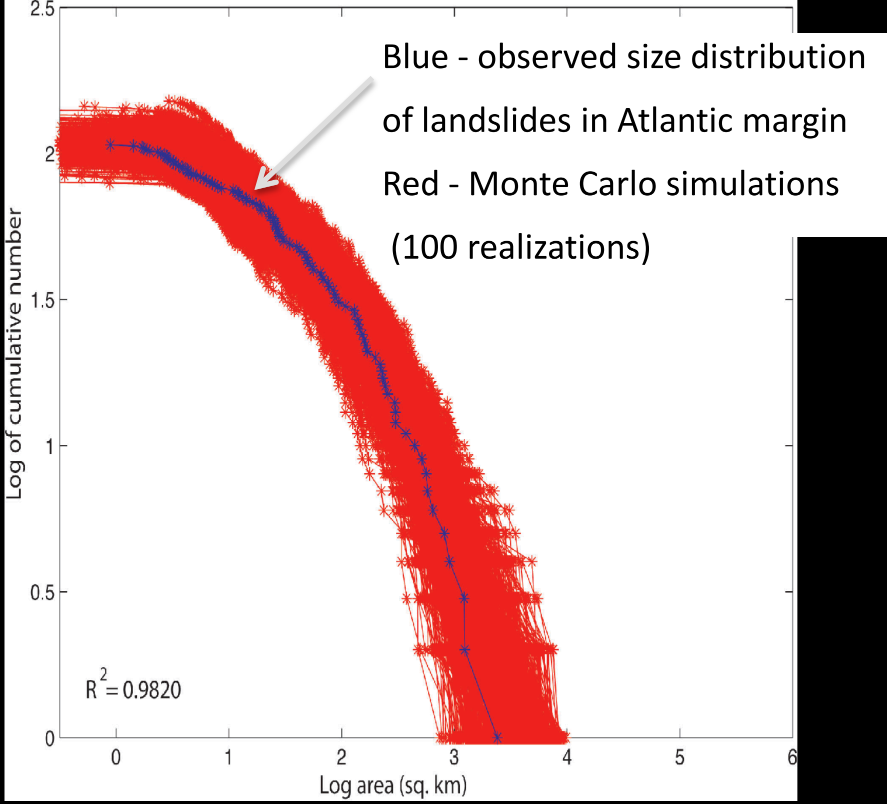

Power-law distribution because landslide size is controlled by fissure distribution in the rock?



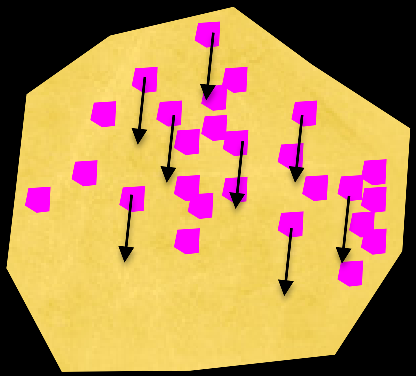



# HOW IS A TSUNAMI GENERATED FROM A LANDSLIDE?

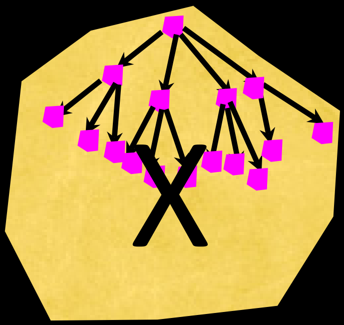
Log-normal landslide distributions can be generated by Monte Carlo simulations if we assume that the area of slope failure is a function of earthquake magnitude! And slope stability.




In other words: In sand & shale margins, failure occurs <u>simultaneously</u> over the area affected by horizontal ground shaking



Unlike other natural hazards, such as earthquakes and forest fires, failure does NOT cascade from one or a few nucleating points.



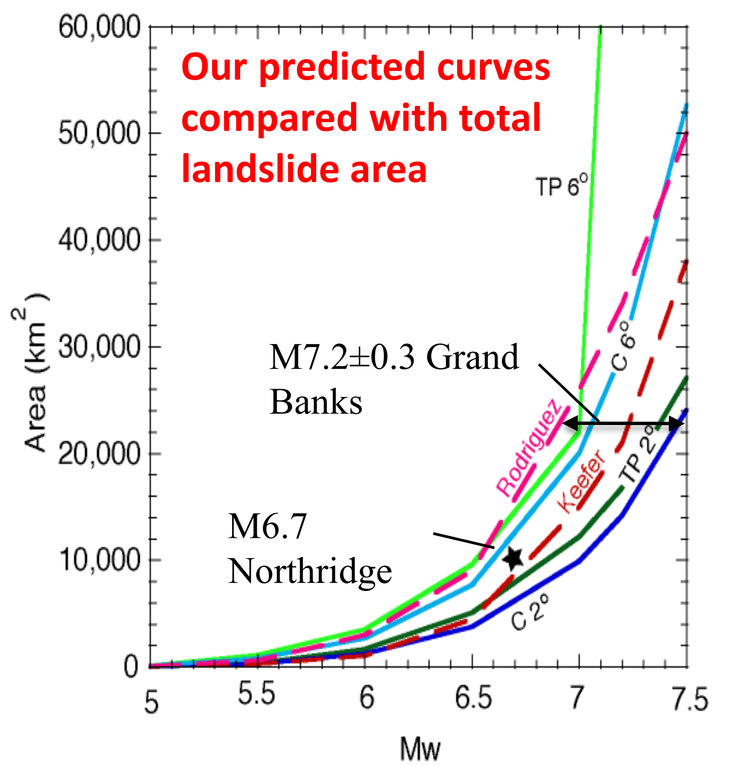
# Qualitative evidence for simultaneous failure over a large area and against a cascading avalanche process

## Seismological record

No double-couple earthquakes during large Landslides

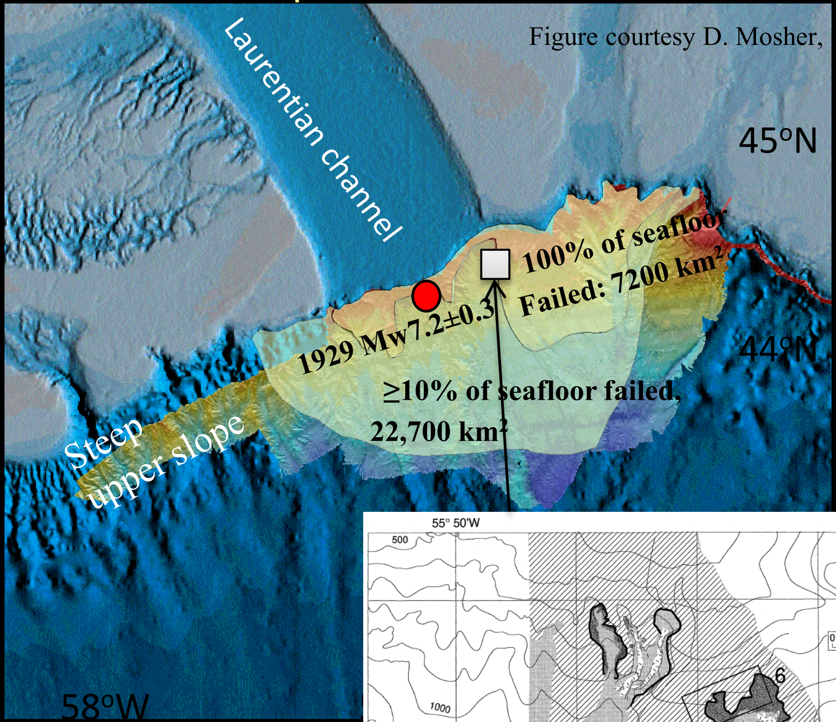
## Geological record

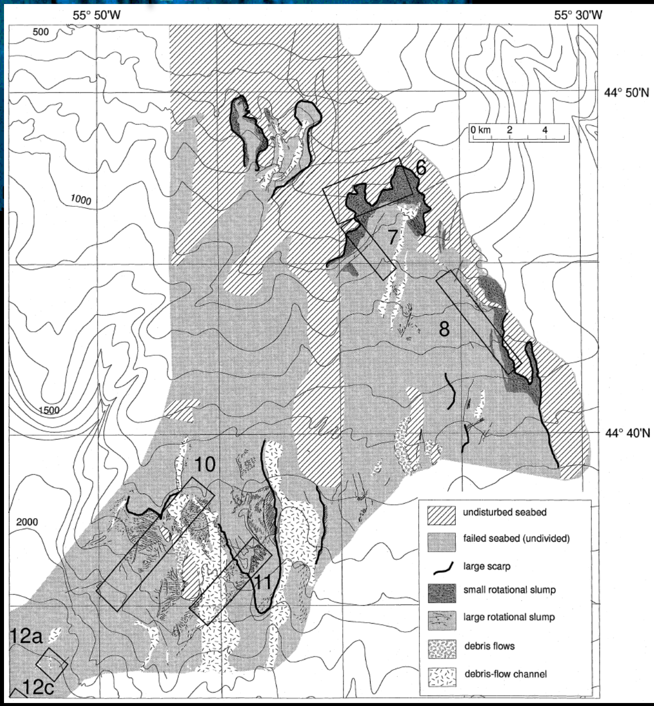
On land many small independent landslides can be observed over the area affected by earthquake shaking




## 1929 Grand banks earthquake and landslide

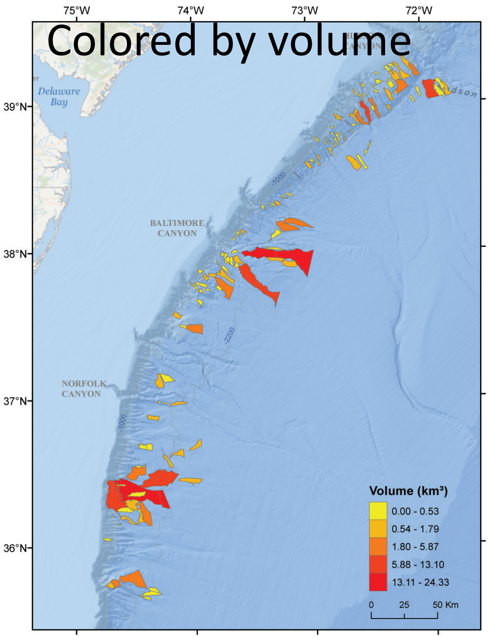
In 2/3 of area: Patchy failures with intervening areas showing no sign of failure. No single massive slump.

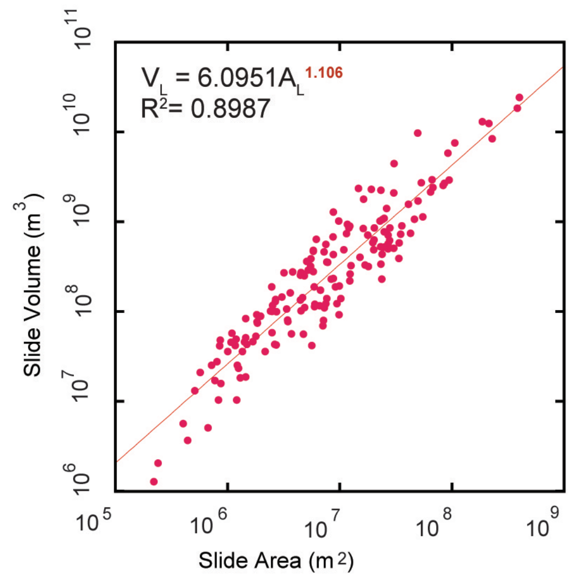


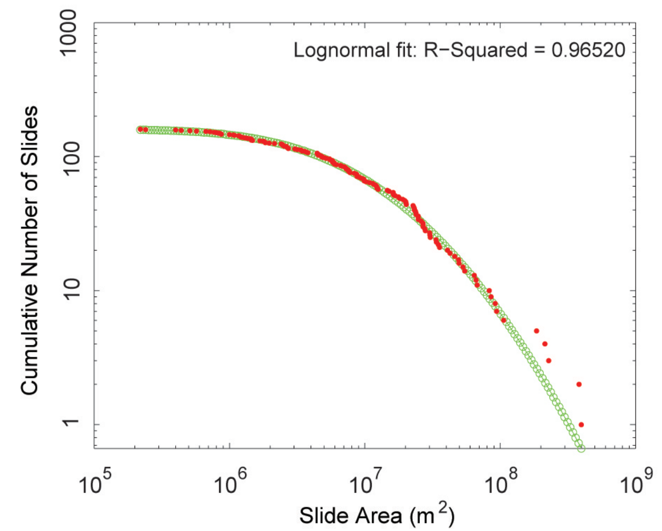

*Piper et al., 1999*

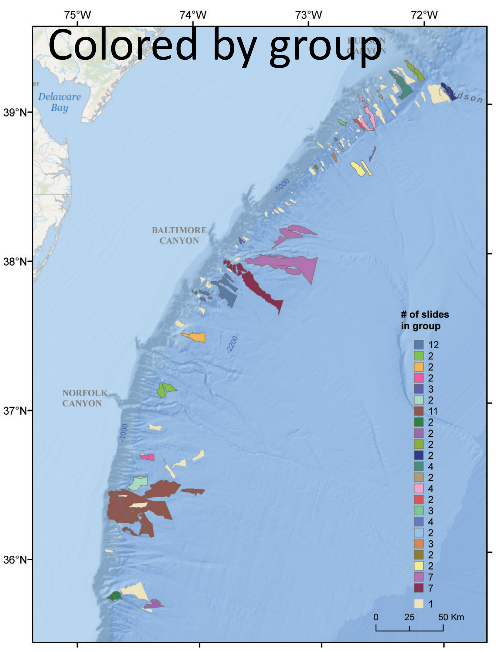
# Area-volume distribution indicates that several independent landslide scars were formed by the same event



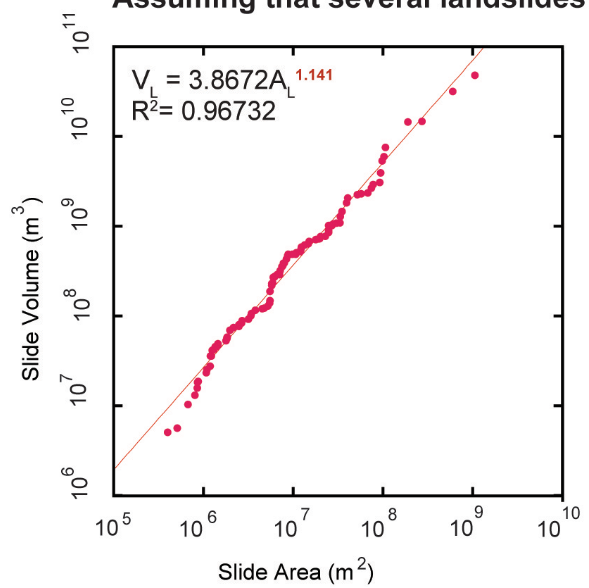



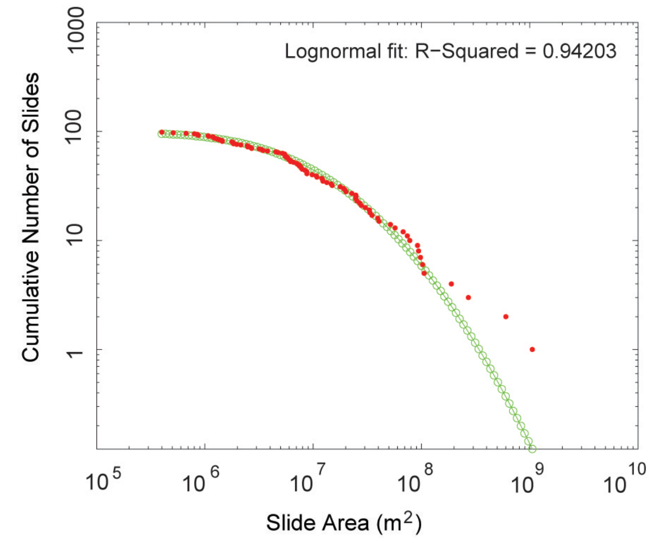

## All landslides in Mid-Atlantic: This study (n = 160)

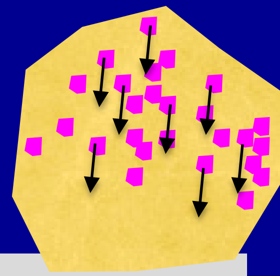


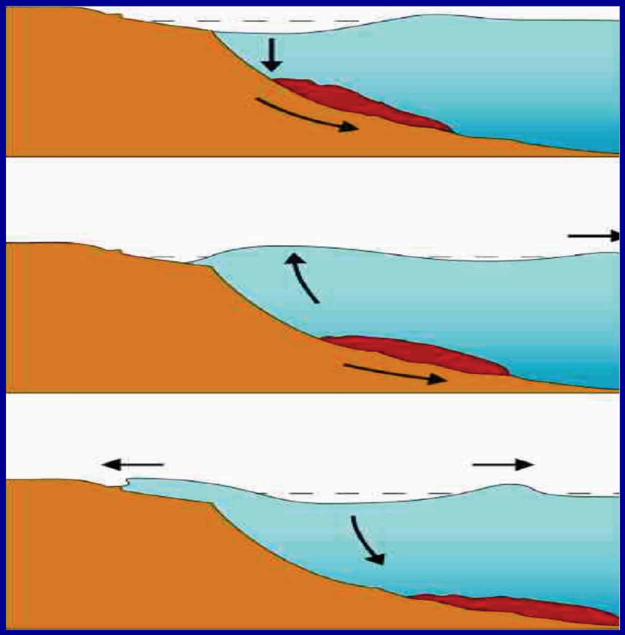

## Assuming that several landslides failed simultaneously during a single event (n = 98)



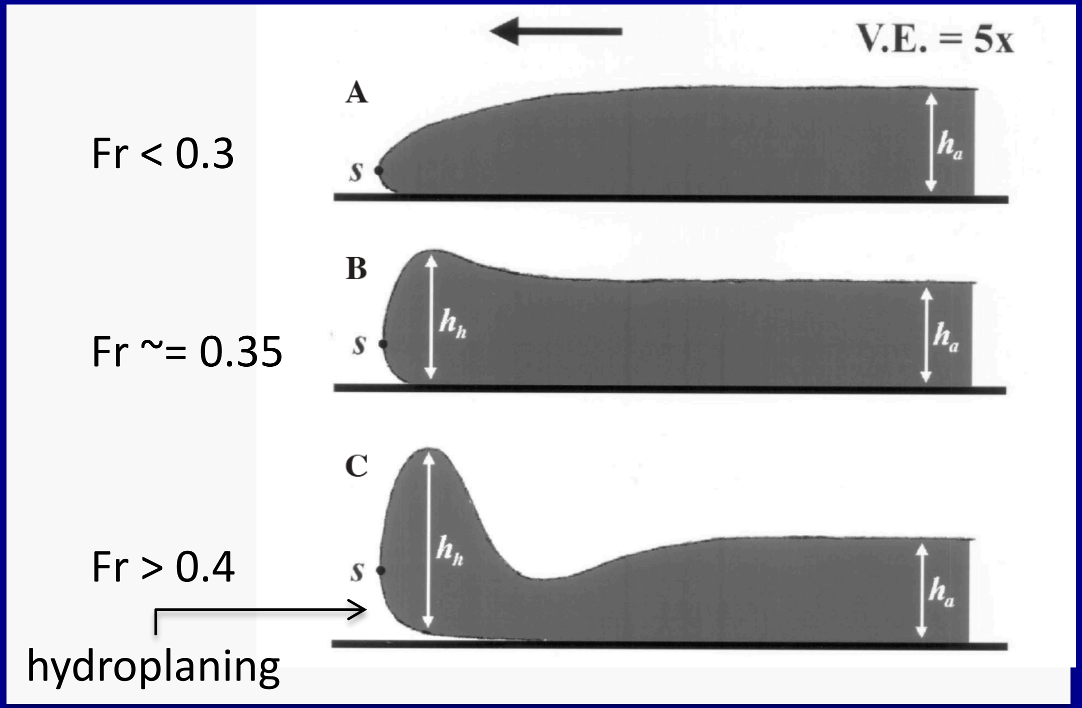





Puzzle:
How does a landslide generate a tsunami?
By constructive interference of many small failures? or by convergence of thick debris flows, which ‘ignite’ turbidity flows?



*Grilli et al., 2009*




*Mohrig et al., 1998*

# Conclusions

1. Future probabilistic assessment of landslide tsunamis should account for possible non-uniform distributions of landslides in time and space and for several landslides failing simultaneously.

2. Sediment supply and composition and pore pressure affect the spatial distribution of landslides.

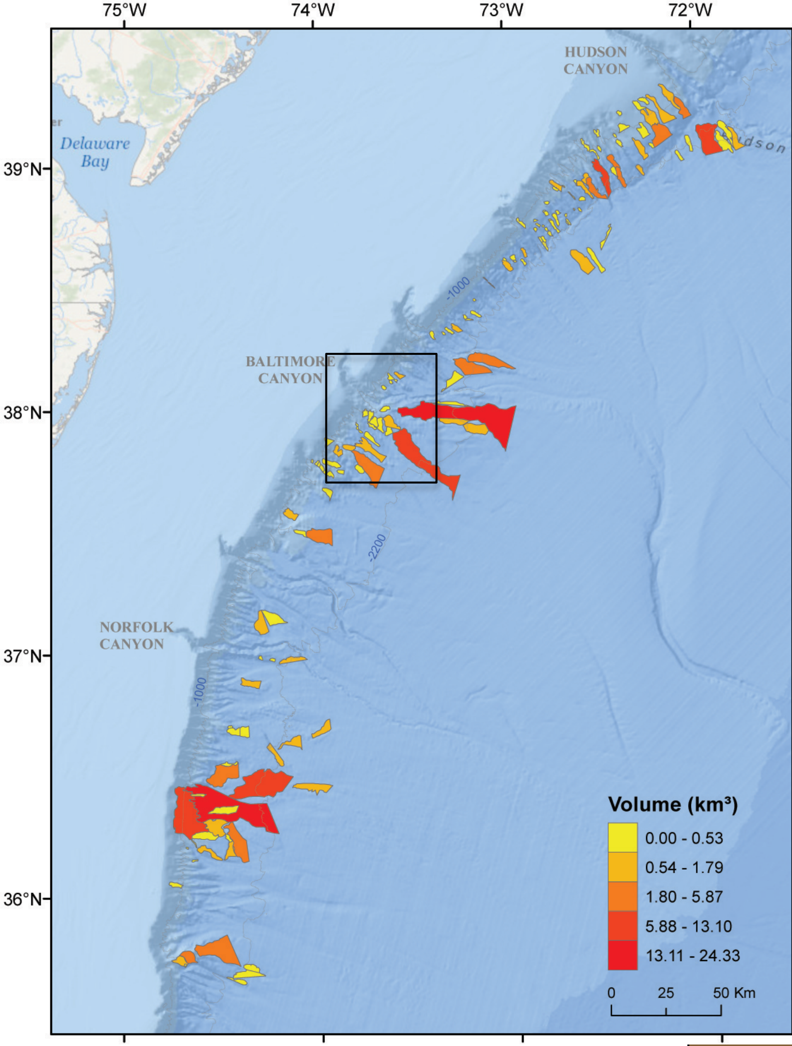
1. Dating landslides remains a challenge.

2. Landslide size is a function of earthquake magnitude, hence probabilistic assessment of landslide tsunamis can utilize earthquake probability.

3. Power law distribution of landslides in carbonate margins may reflect fissure distribution, not earthquake magnitude.

4. How are tsunamis generated by landslides?

# Spatial distribution of submarine landslides




2012