Sediment transport processes associated with landslides

Brothers, ten Brink, Chaytor, Flores, Andrews

Continental slope morphology and the underlying stratigraphic framework are fundamental controls on slope stability. Continental slopes evolve in response to changing sediment supply, base level and energy flux. Each of these processes, in turn, has the potential to generate over-pressures that precondition slopes for gravitational failure. Here we present a broad-scale, morphological categorization of the outer-shelf, slope and rise of the U.S. Atlantic margin and examine the relationships between landslide occurrence and morphological patterns. Four morphological slope provinces are identified: New England, Southern New England-Hudson Apron, Mid-Atlantic and Cape Hatteras. Widespread evidence for mass movements and submarine landsliding is associated with the wide, sigmoidal slopes of the Southern New England-Hudson Apron margin. Recently acquired, high-resolution seismic reflection profiles show an apparent relationship between fluid migration, faulting and landslides. These initial observations suggest fluid migration and differential pore pressures may precondition the shallowest ~100-m of slope sediment for failure. Finally, fault displacements along the lower slope have the potential to trigger landslides by seismically induced strain-weakening.

Sediment transport processes associated with landslides

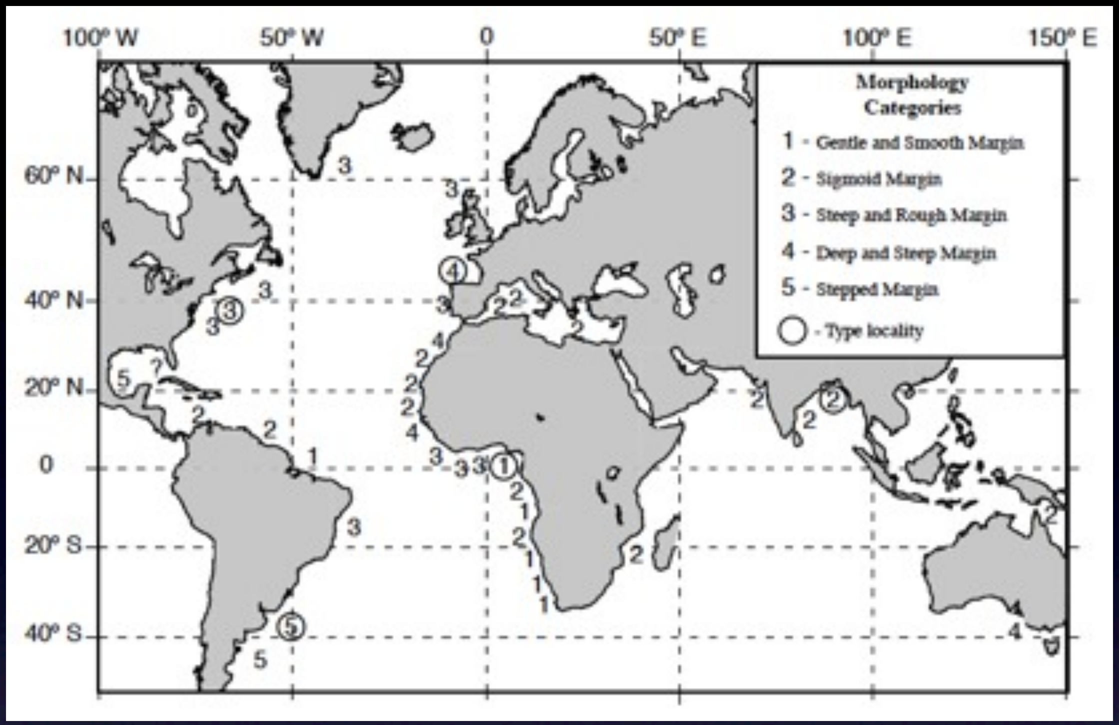
Danny Brothers
Uri ten Brink
Jason Chaytor
Claudia Flores
Brian Andrews

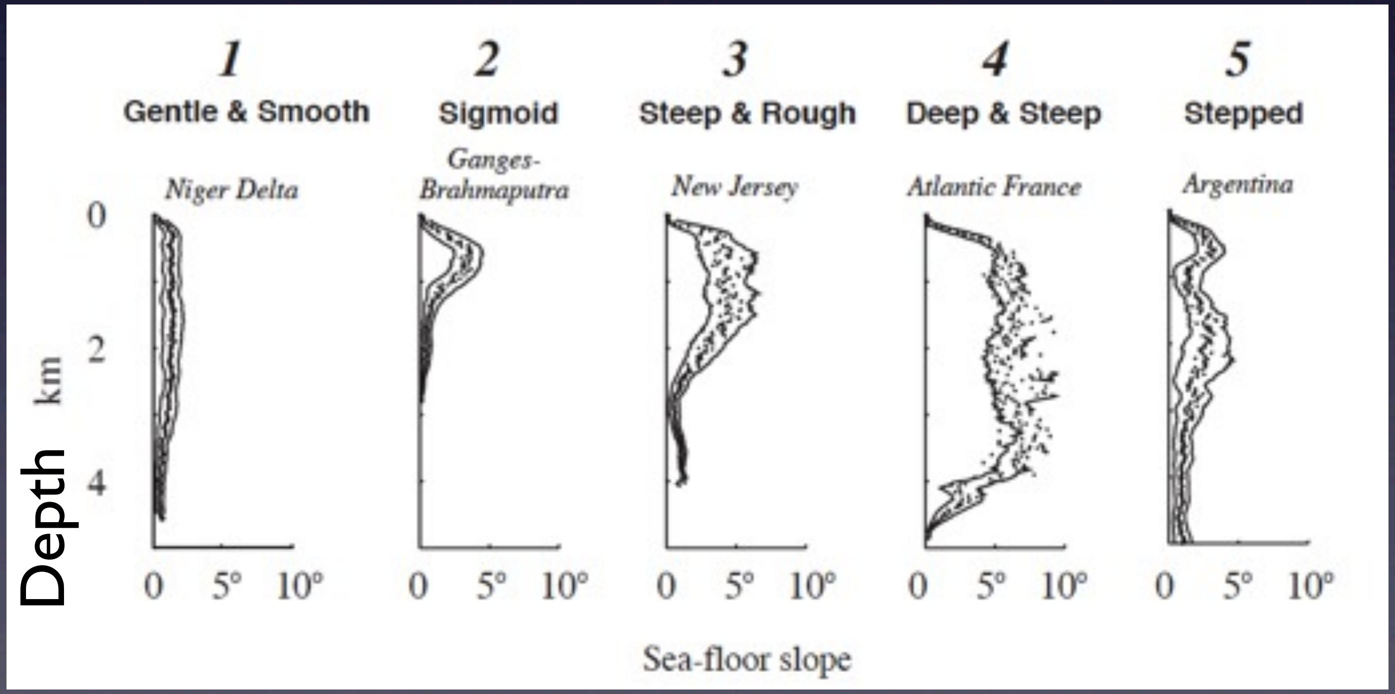
Preview

1. Atlantic Margin Morphology
   - Morphological Categories and Along-margin Variability
   - Linking Form and Process

2. Fluids, Gas, and Faulting
   - Southern New England to mid-Atlantic

Mesoscale Analysis of Continental Slope Morphology





Global study by O'Grady et al. (2000)

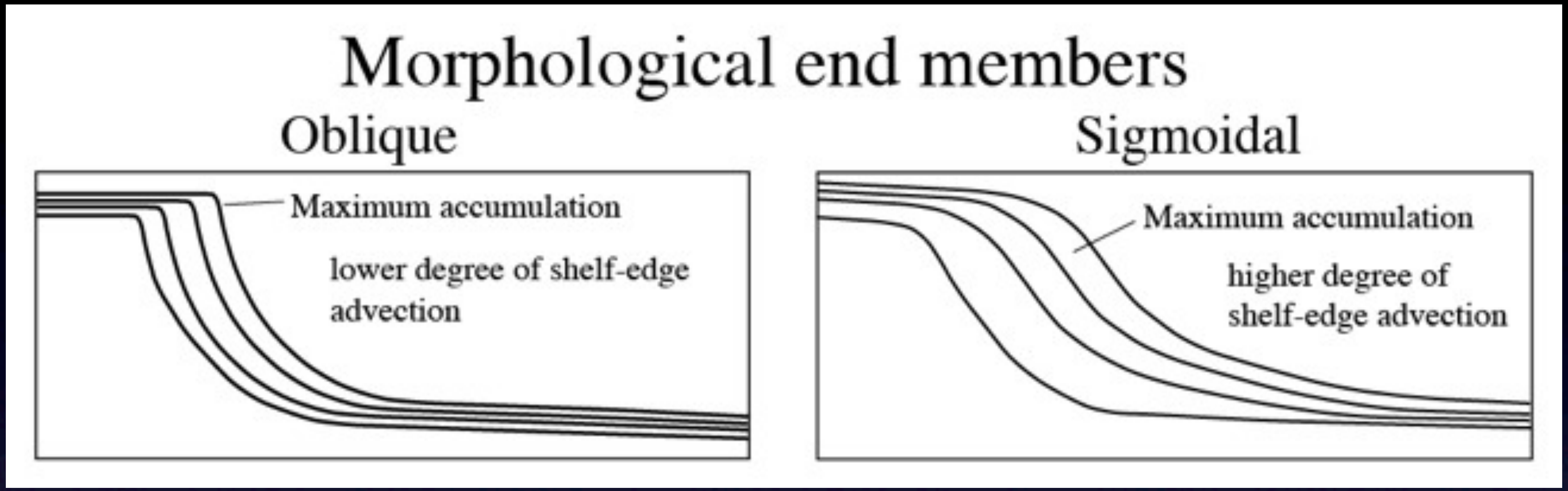
- Correlation between margin shape and stratal architecture, sediment input and degree of canyon incision
- Gentle gradients <--> high sediment input, few canyons, unstable substrates
- High gradients <--> low sediment input, many canyons, varied subsurface architecture

In the past, studies were limited by resolution of bathymetry

Can we use the margin's morphology to find areas that are potentially unstable?

Basic Assumptions of Slope Morphology

Sediment progradation has two fundamental forms



Oblique	Sigmoidal
Low energy at shelf-edge	High energy at shelf-edge
Angular shelf-edge	Rounded shelf-edge
Over-steepening and Gravitational failure of upper slope	Middle slope deposition and progradation
Often leads to sediment bypassing the middle and lower slope	Relaxed slope gradient, deposition and gravitational failure are in equilibrium

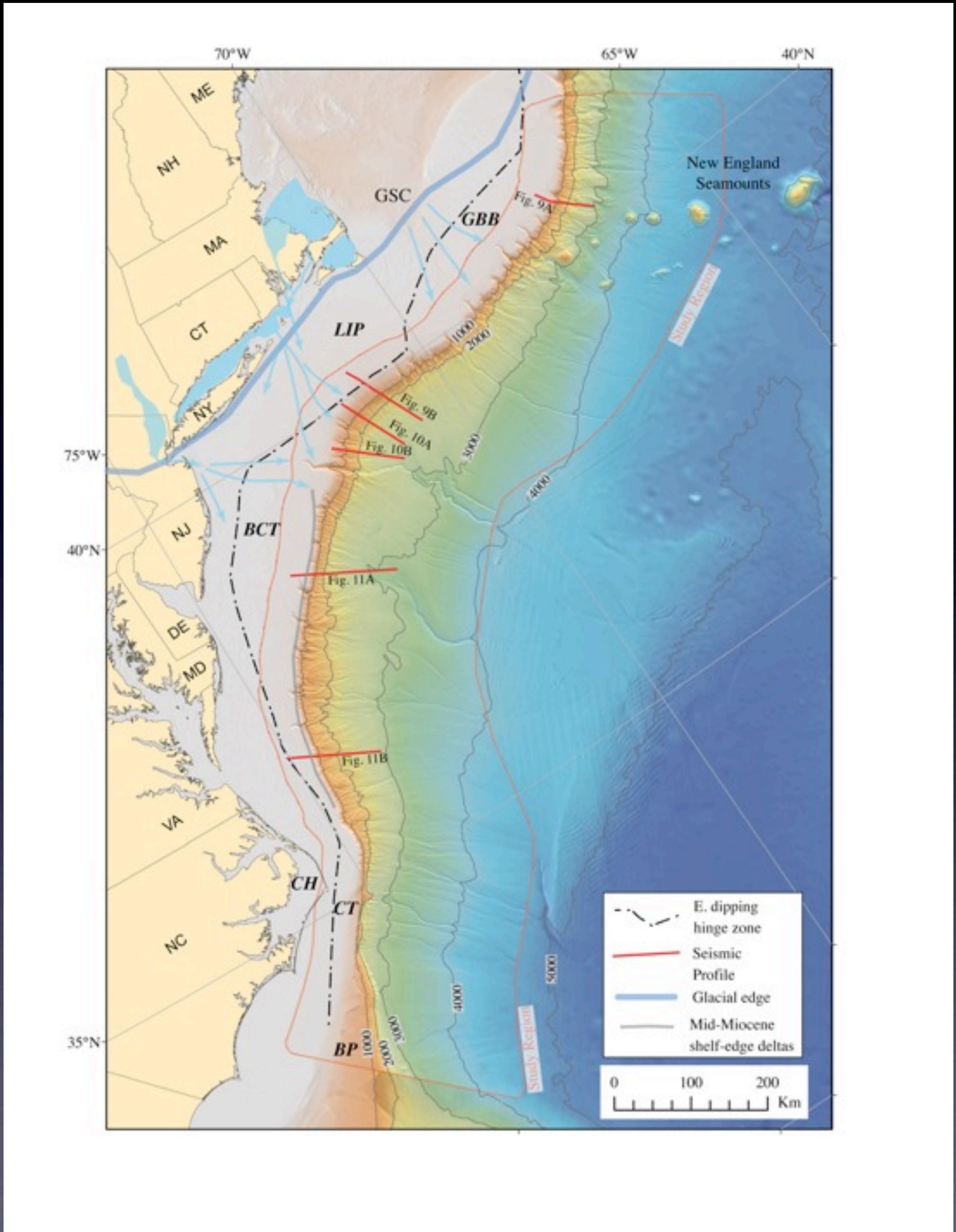
U.S. Atlantic margin

Swath Bathymetry Data

- 616,000 km² of multibeam bathymetry data from 26 cruises, including NRC funded cruise aboard NOAA Ship Ronald H. Brown.
- 100-m resolution grid merged with NOAA Coastal Relief Model
- Data Derivatives:
  - Seafloor Gradient
  - Seafloor slope direction (Aspect)
  - Smoothed Bathymetric Grid
  - Canyon Relief Grid

Seismic Reflection Data

- Thousands of line-km of legacy USGS profiles
- High resolution multichannel seismic reflection collected in 2010
- Cruise planned for September 2011



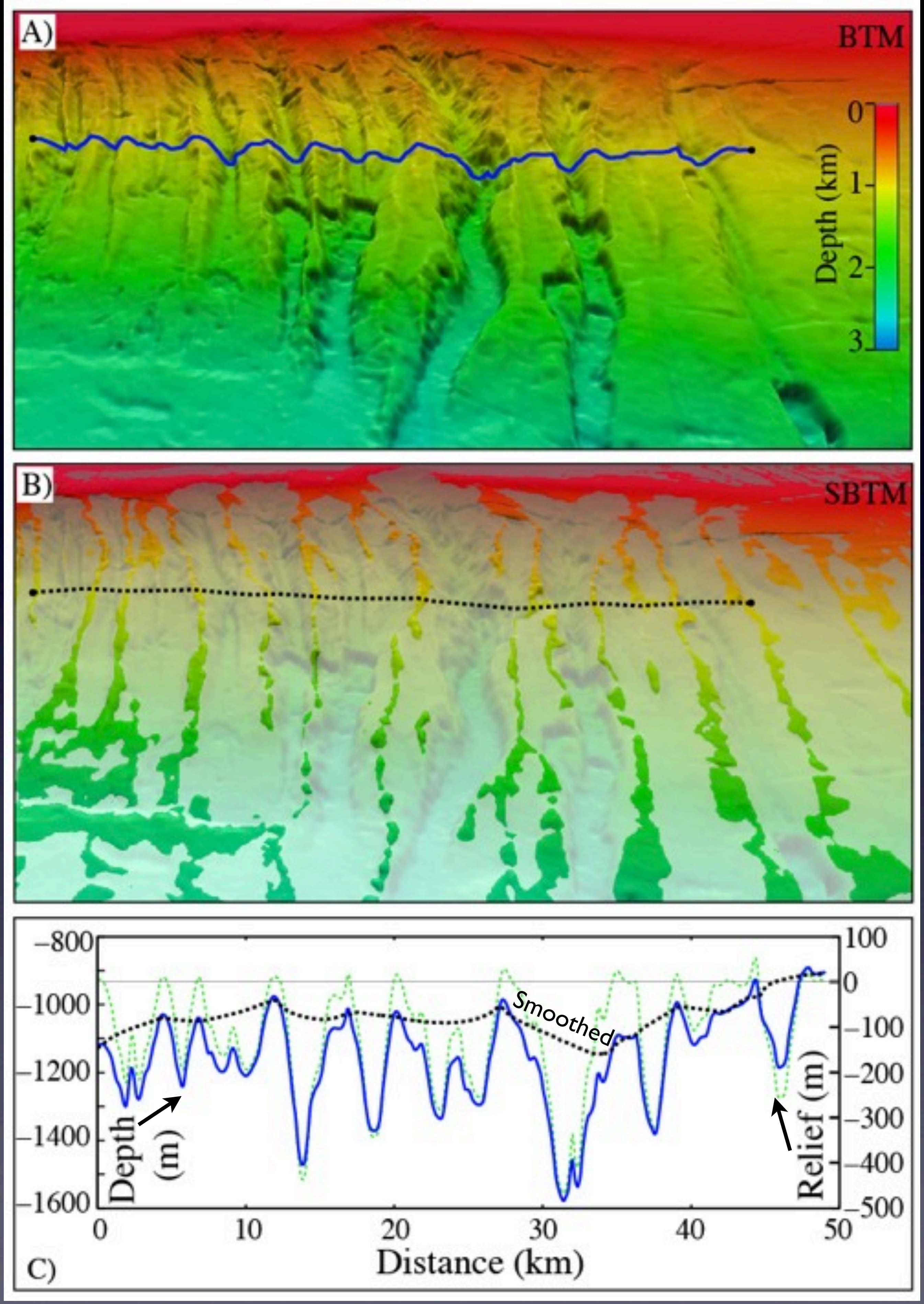
Extracting the general shape of the margin

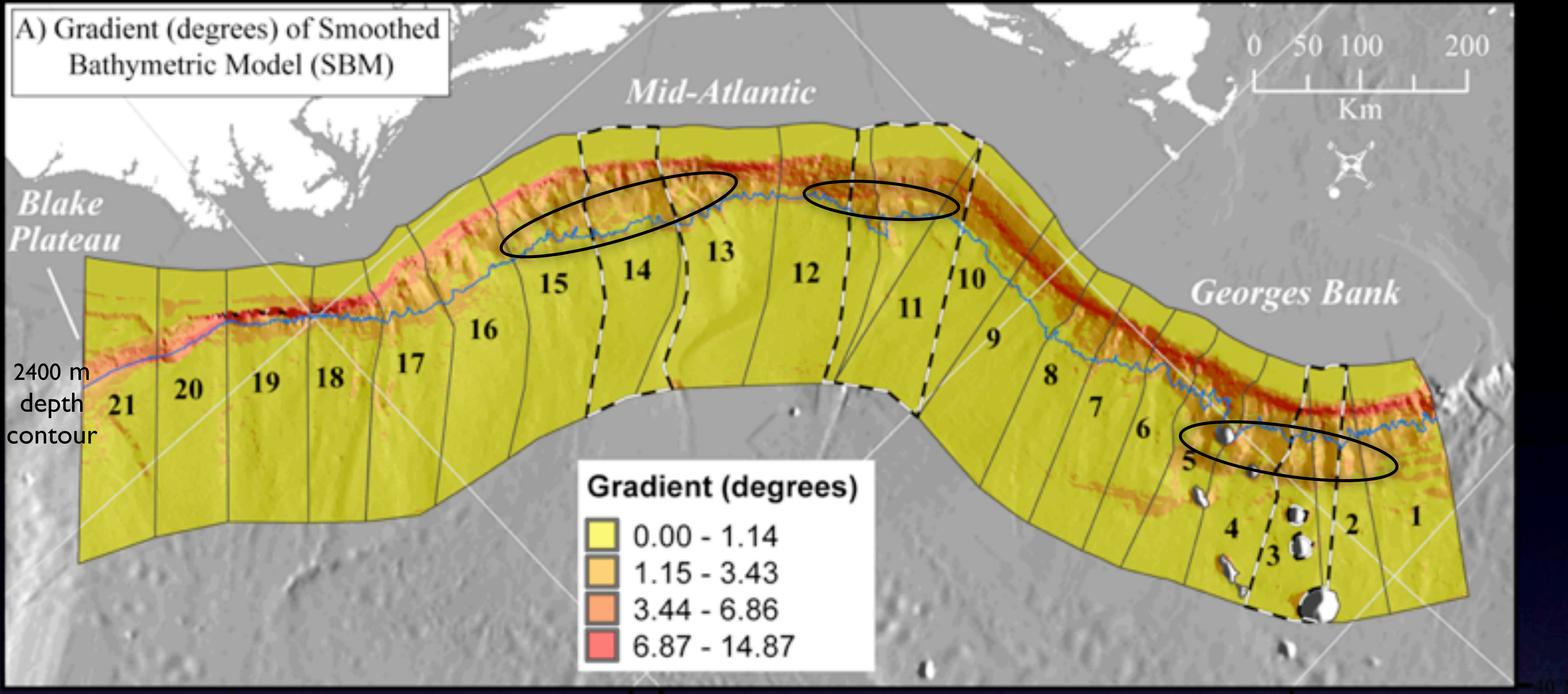
We assume unchannelized areas of the slope are the best way to look at shape of the slope

Therefore, we want to remove canyon and channel topography

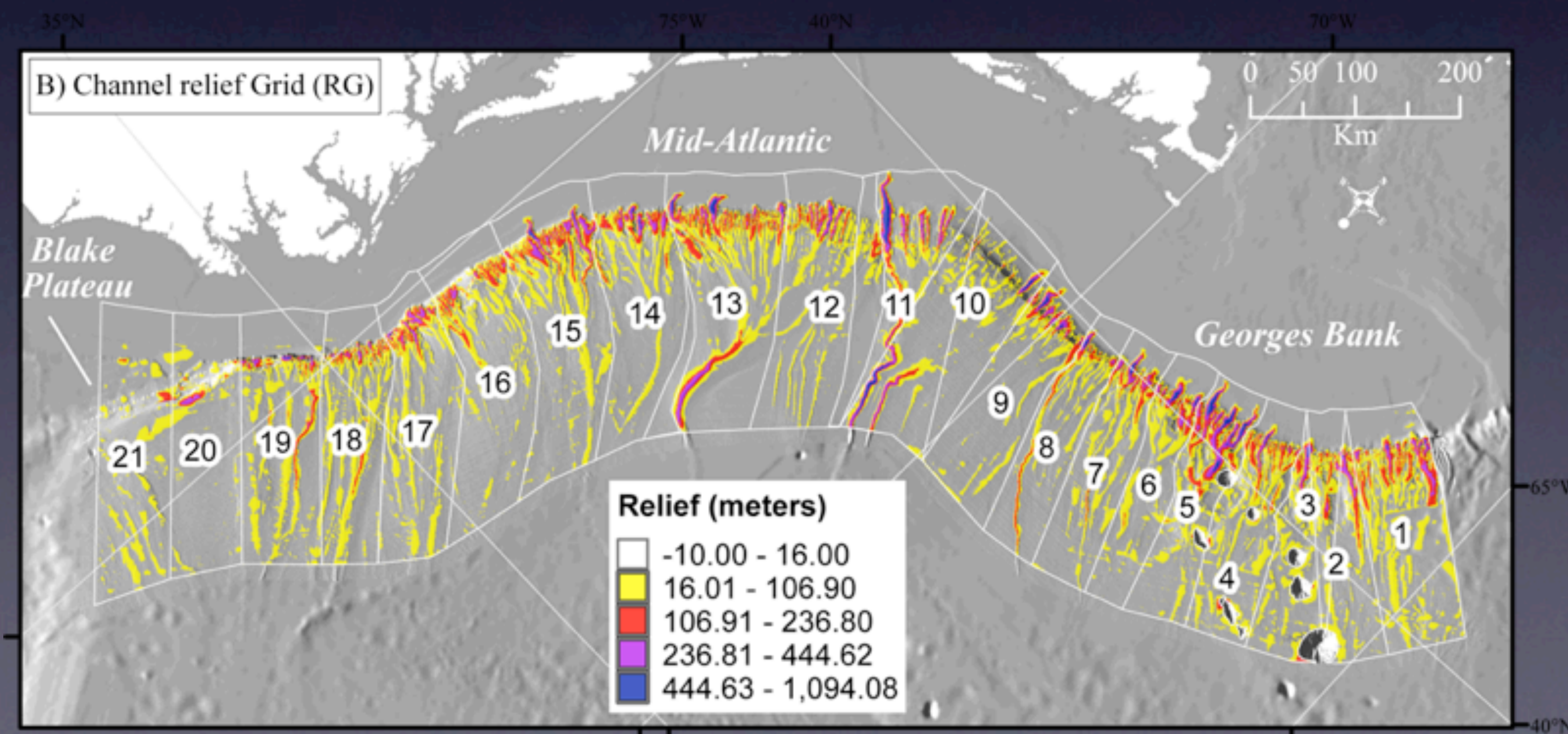
Pick ridge-crests and interpolate

Smoothed Bathymetric Terrain Model
- retains down-slope form

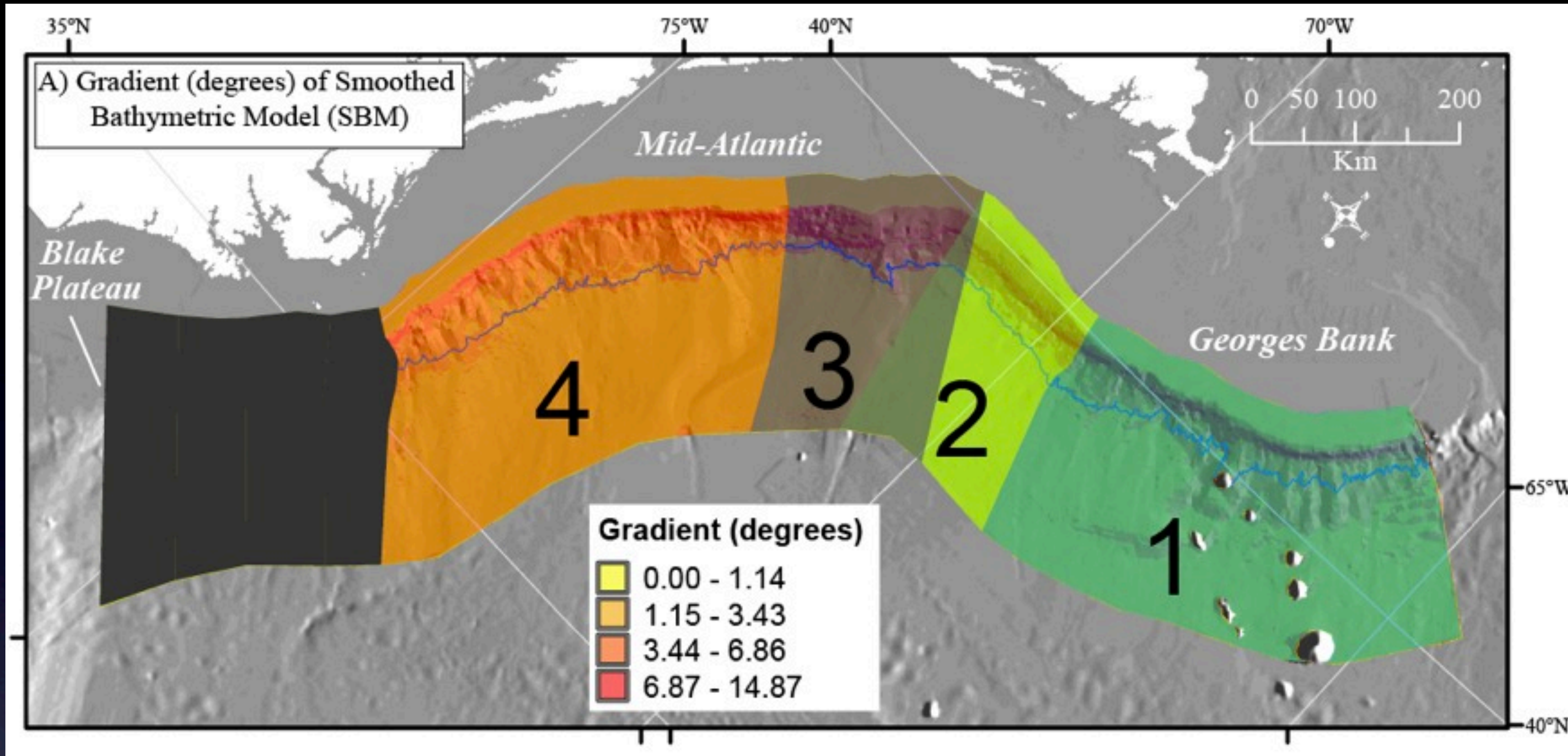




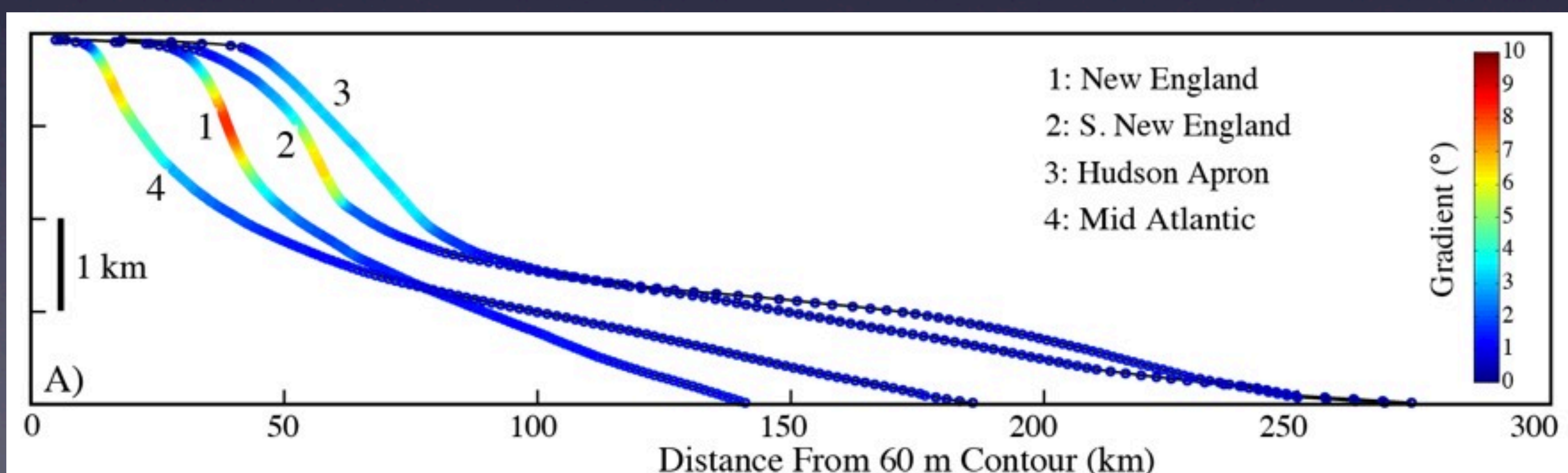
Split into 21 sub-regions divided by bathymetric boundaries



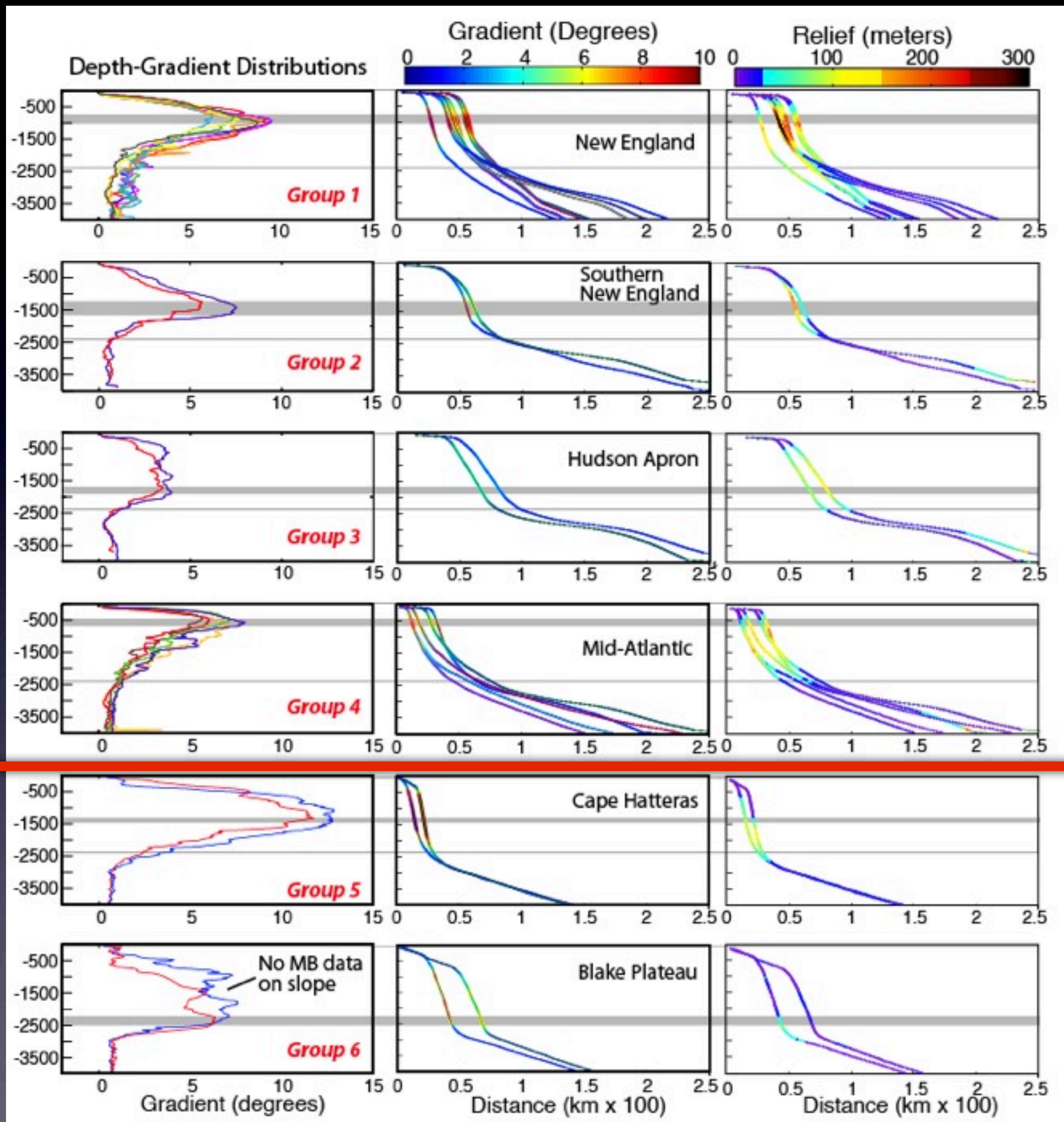
Canyon Relief Grid



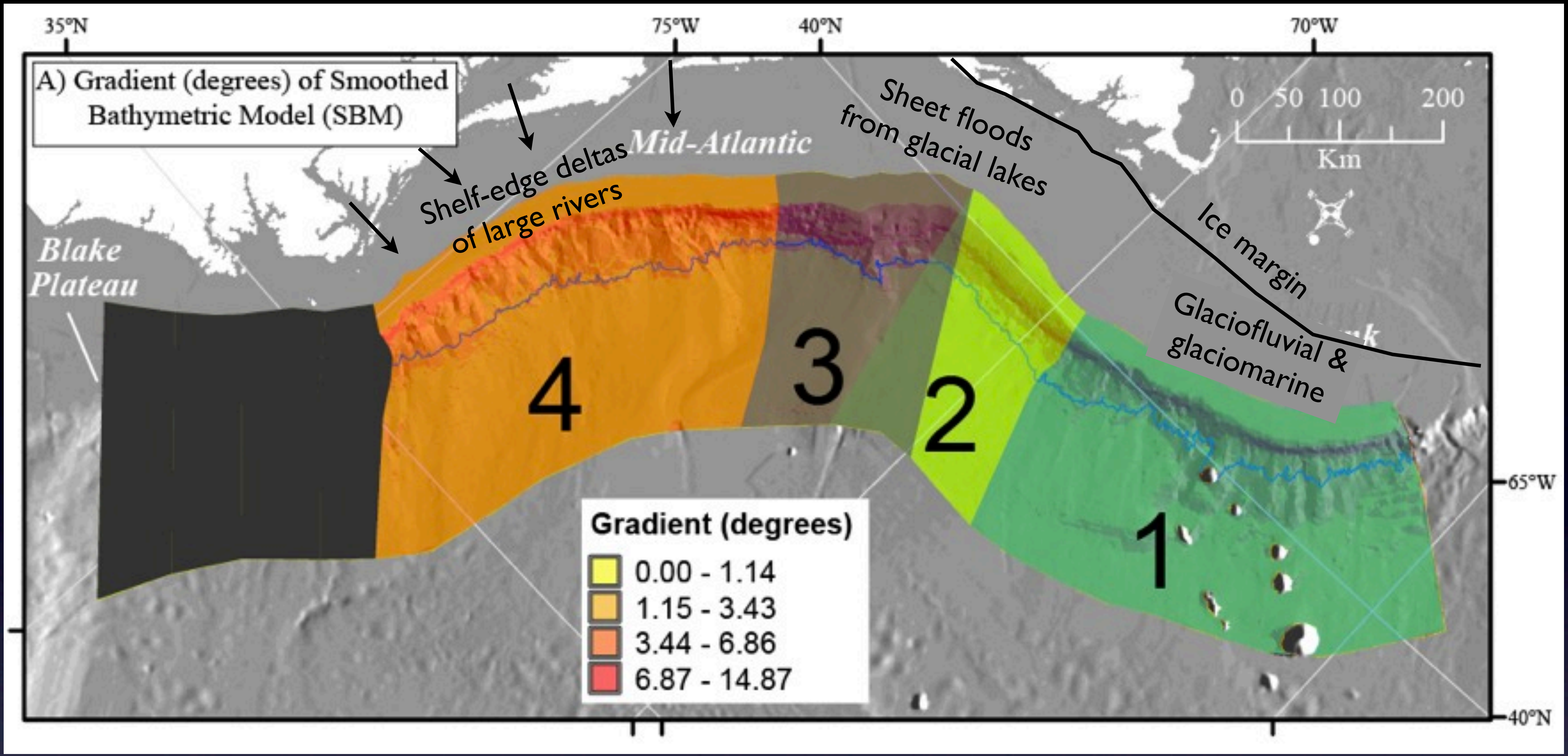
A) Gradient (degrees) of Smoothed Bathymetric Model (SBM)
Mid-Atlantic
Blake Plateau
Georges Bank
0 50 100 200
Km
4
3
2
1
Gradient (degrees)
0.00 - 1.14
1.15 - 3.43
3.44 - 6.86
6.87 - 14.87
35°N
75°W
40°N
70°W
65°W
40°N

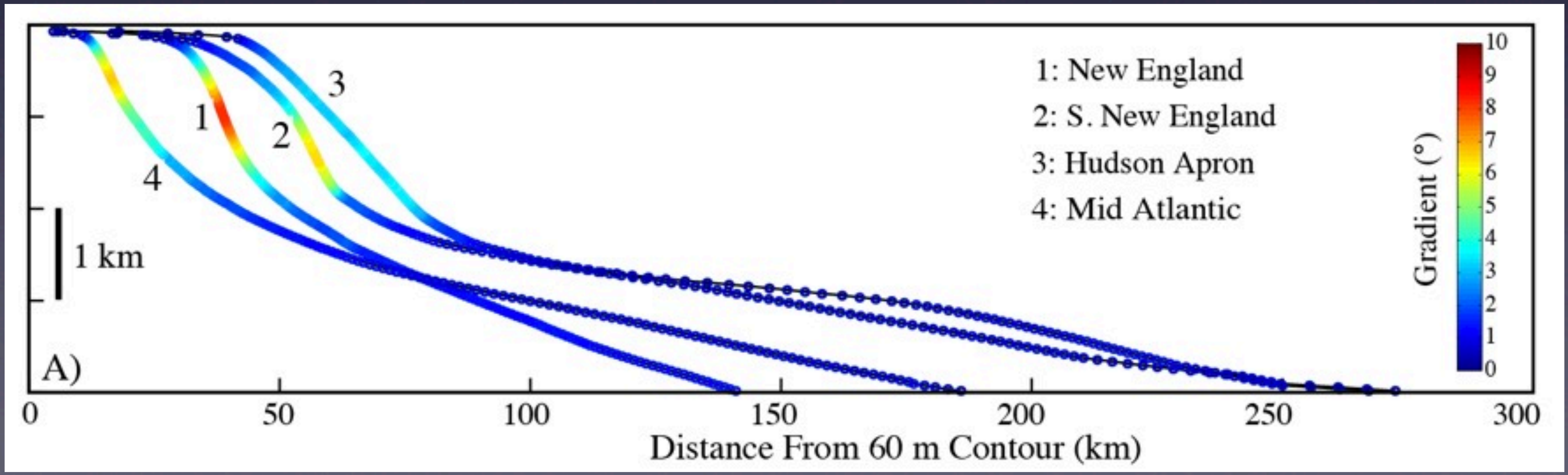


1: New England
2: S. New England
3: Hudson Apron
4: Mid Atlantic
1 km
A)
Gradient (°)
0 1 2 3 4 5 6 7 8 9 10
0 50 100 150 200 250 300
Distance From 60 m Contour (km)



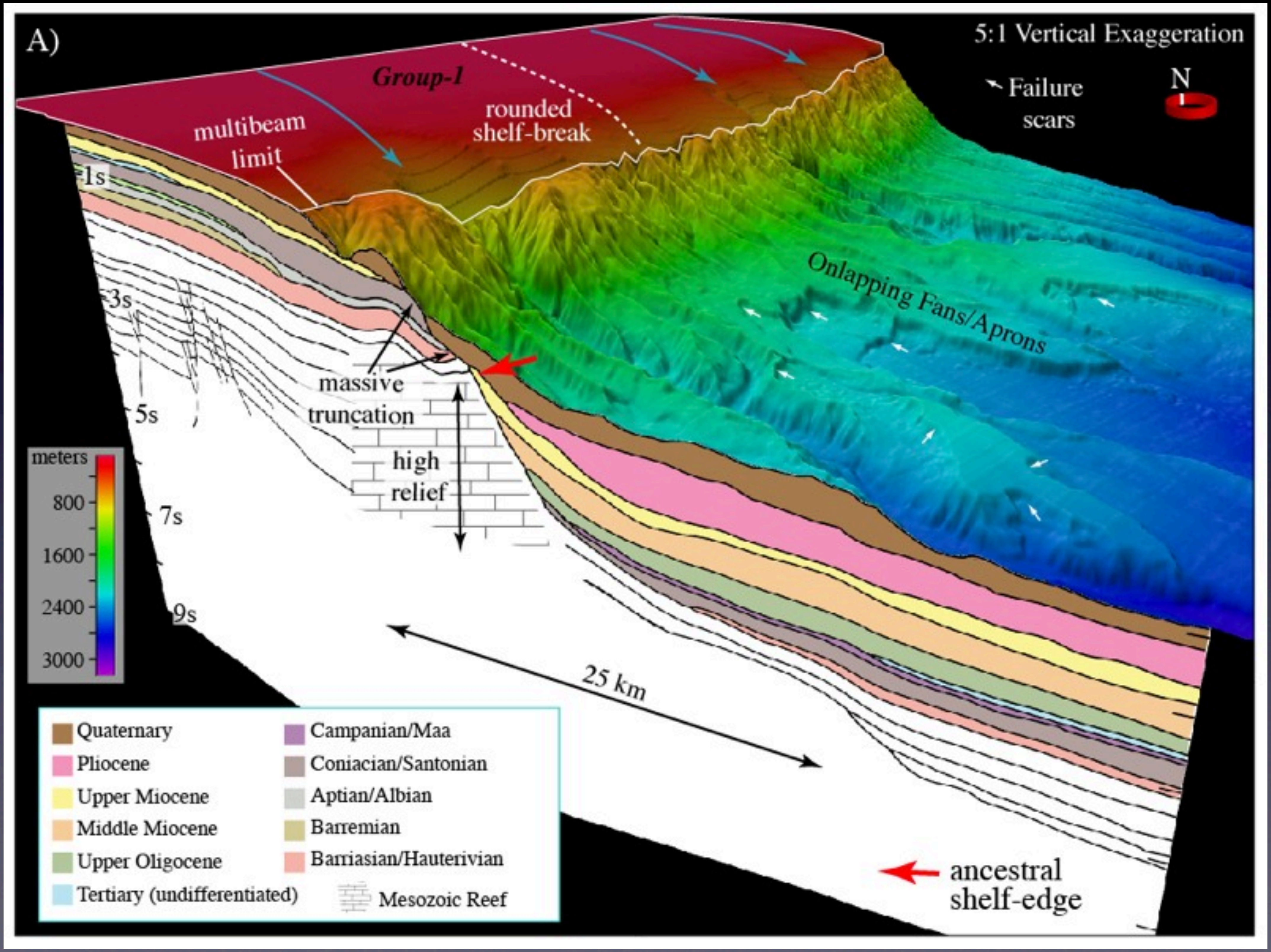
Depth-Gradient Distributions
Gradient (Degrees)
Relief (meters)
New England
Group 1
Southern New England
Group 2
Hudson Apron
Group 3
Mid-Atlantic
Group 4
Cape Hatteras
Group 5
Blake Plateau
No MB data on slope
Group 6
Gradient (degrees)
Distance (km x 100)
Distance (km x 100)


35°N
75°W
40°N
70°W
A) Gradient (degrees) of Smoothed Bathymetric Model (SBM)
Mid-Atlantic
Shelf-edge deltas of large rivers
Sheet floods from glacial lakes
Ice margin
Glaciofluvial & glaciomarine
Blake Plateau
0 50 100 200
Km
4
3
2
1
65°W
40°N
Gradient (degrees)
0.00 - 1.14
1.15 - 3.43
3.44 - 6.86
6.87 - 14.87

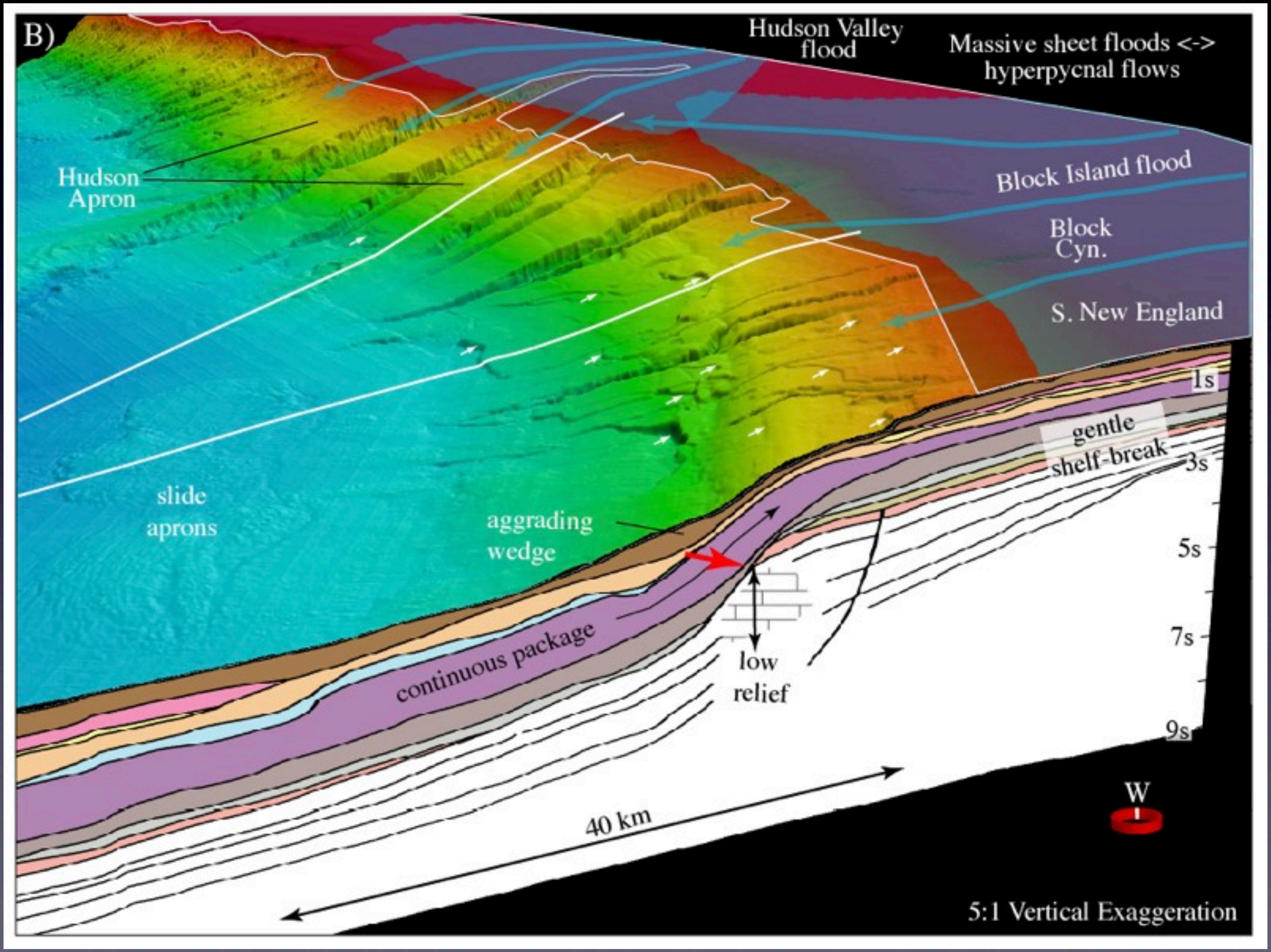

1: New England
2: S. New England
3: Hudson Apron
4: Mid Atlantic
1 km
A)
1
2
3
4
0
50
100
150
200
250
300
Distance From 60 m Contour (km)
Gradient (°)
0
1
2
3
4
5
6
7
8
9
10

The role of the underlying geology in margin morphology

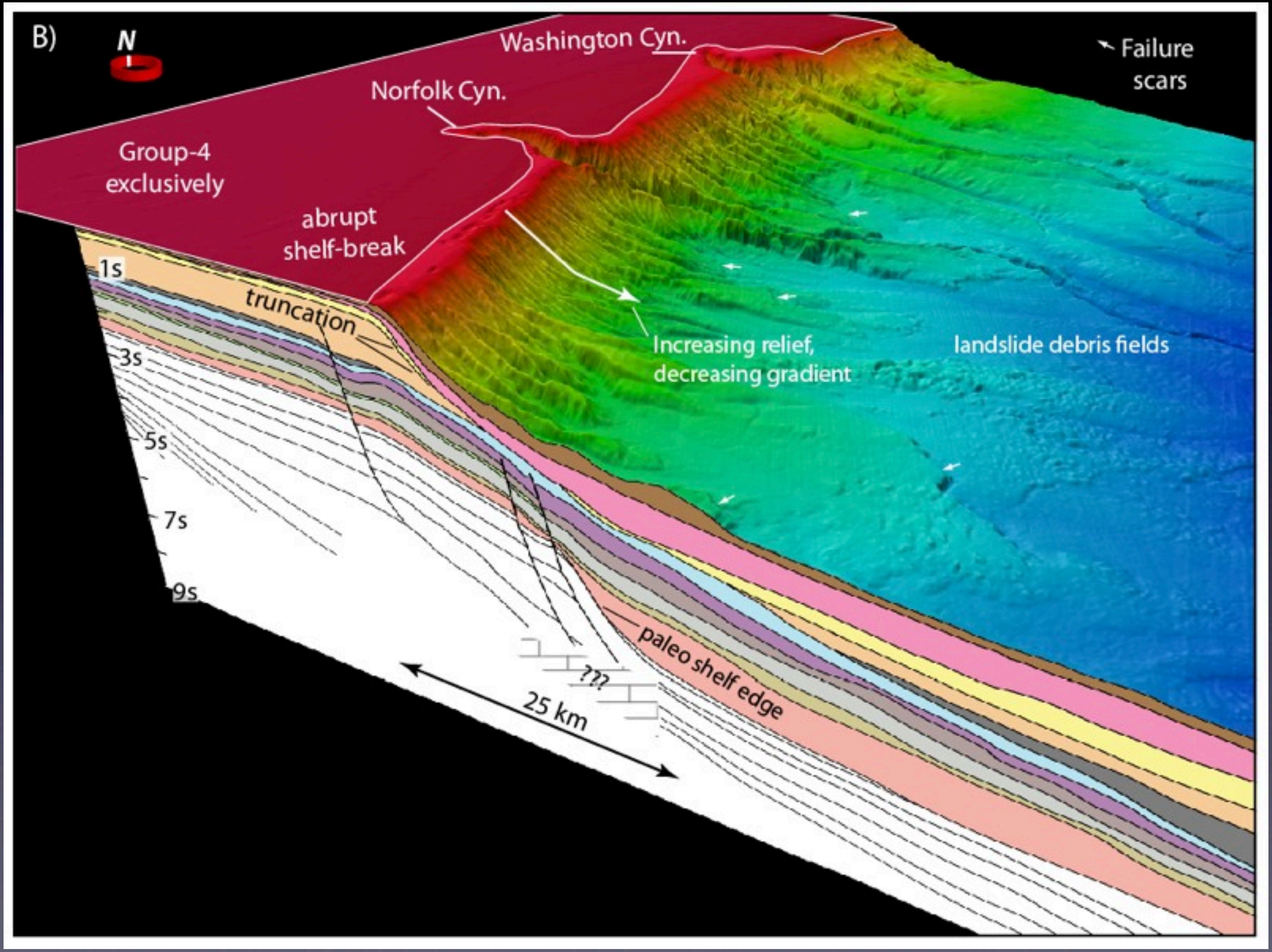
1. New England



2 & 3. Southern New England and Hudson Apron



4. Mid-Atlantic

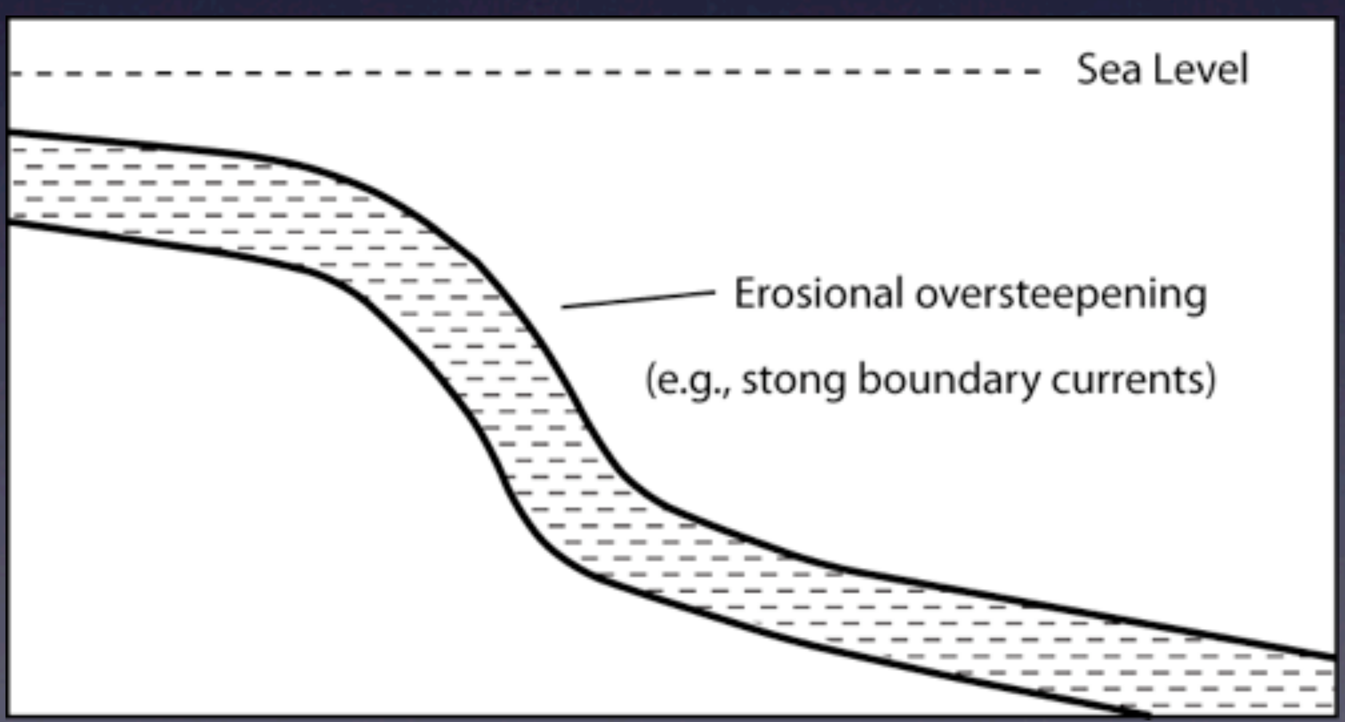


Slope Readjustment Model and the Importance of Basin Physiography

(Ross et al., 1994)

Upper slope progradation acts in concert with sediment gravity flow processes to deposit sediments on the lower slope and upper rise

Any change to basin shape away from an "equilibrium profile" will cause erosion and/or deposition in attempt to return to equilibrium condition



Bathymetric escarpments trigger slope readjustment:

1. Mass wasting on upper segment
2. Bypass to base of slope
3. Onlap and upbuilding at base of slope to lower gradient
4. Return to equilibrium and upperslope progradation

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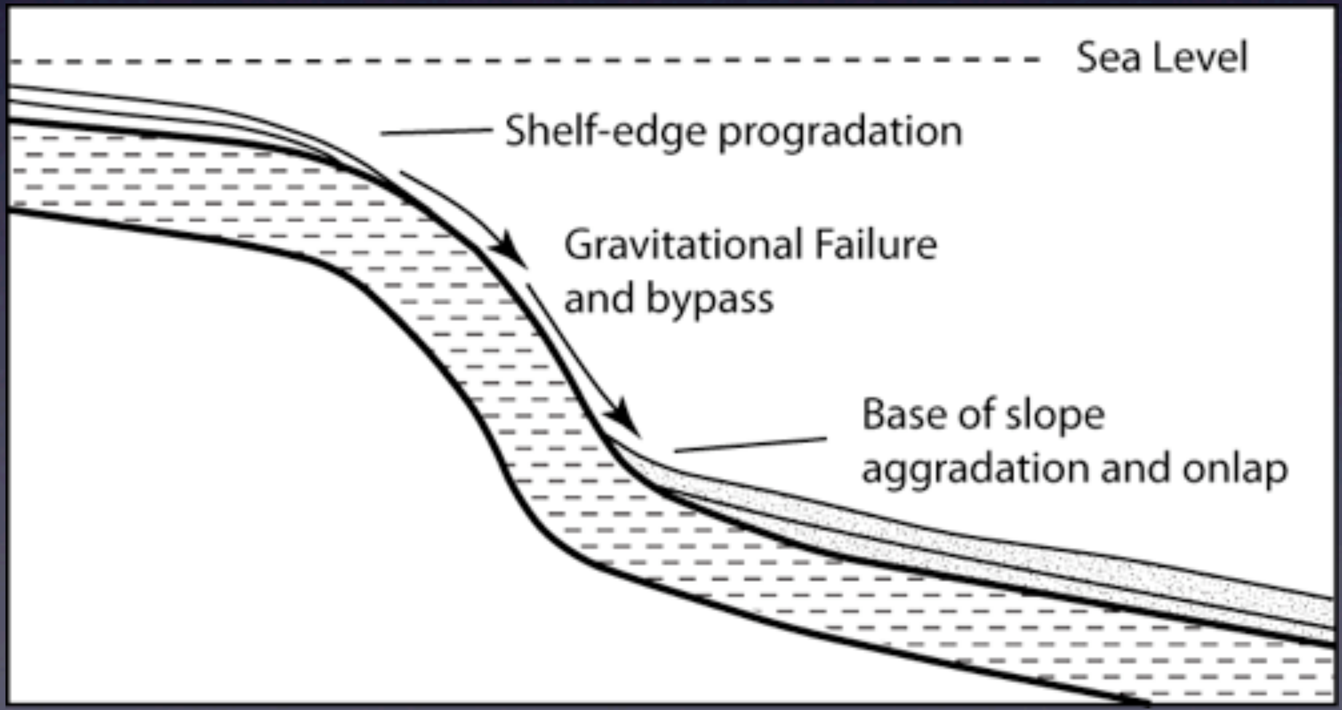

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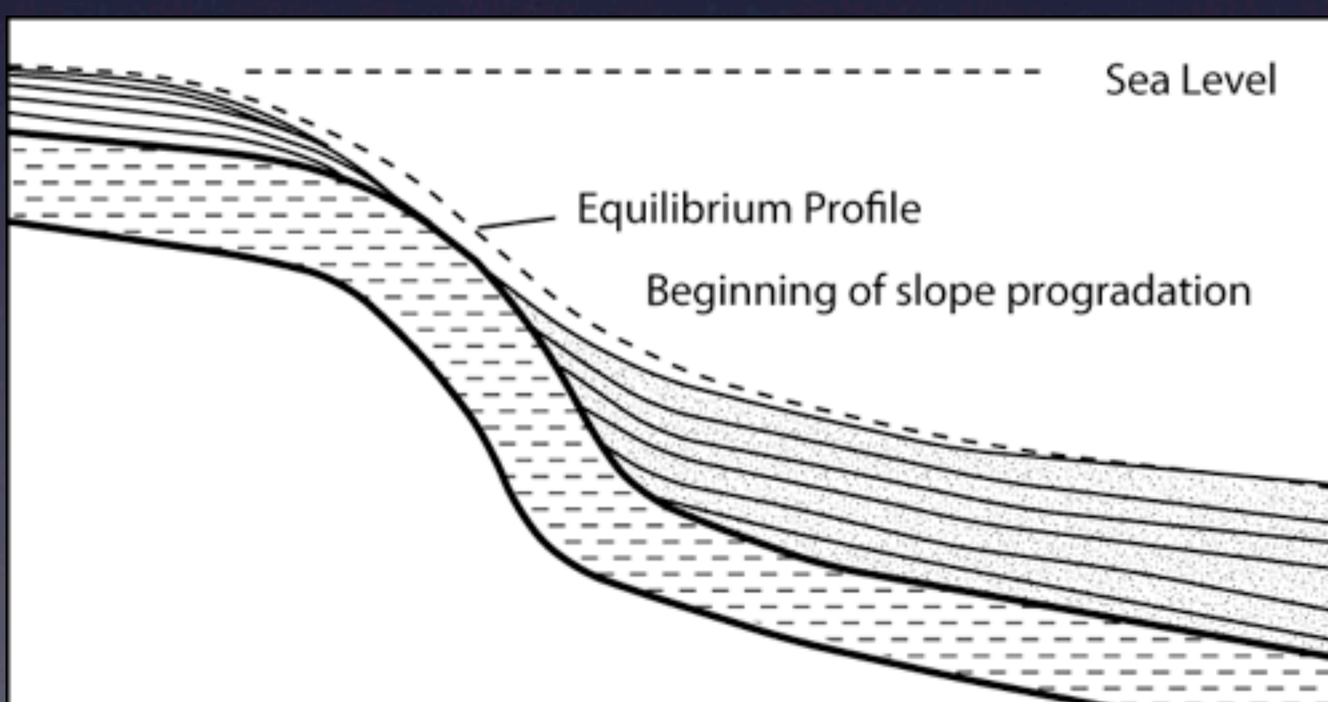

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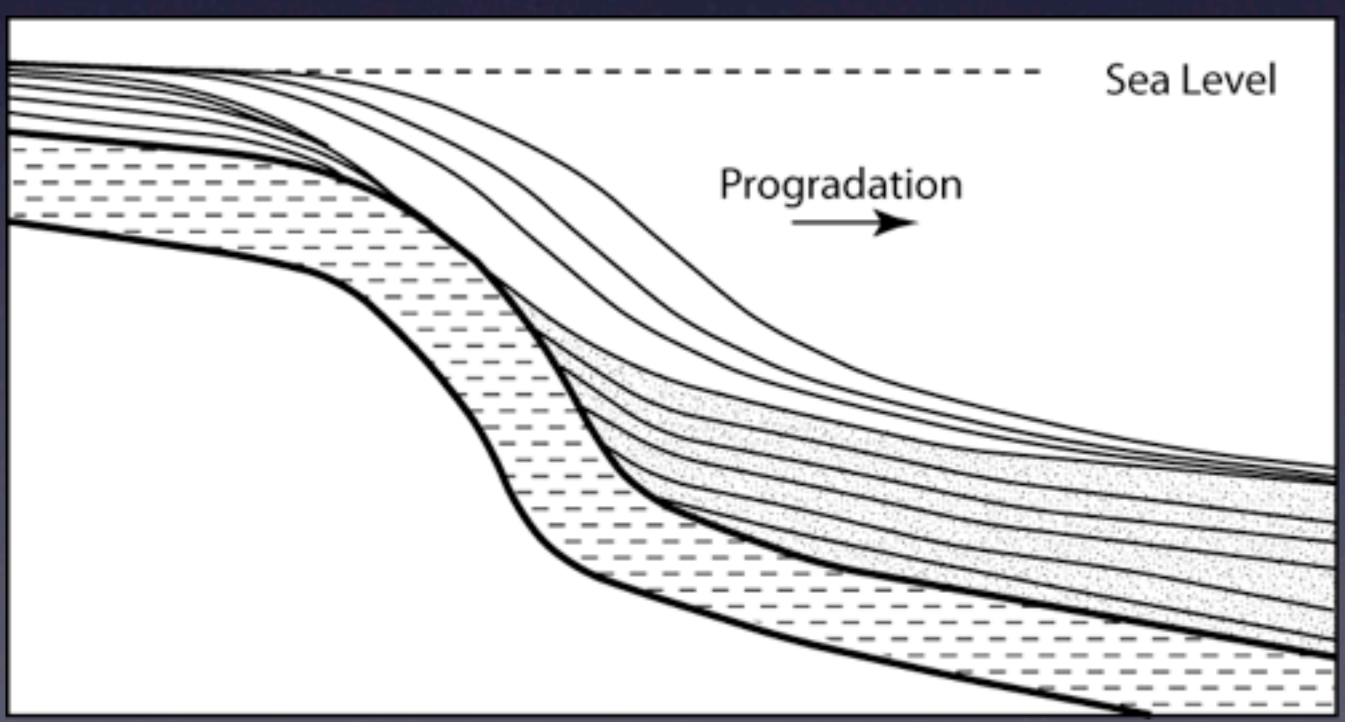

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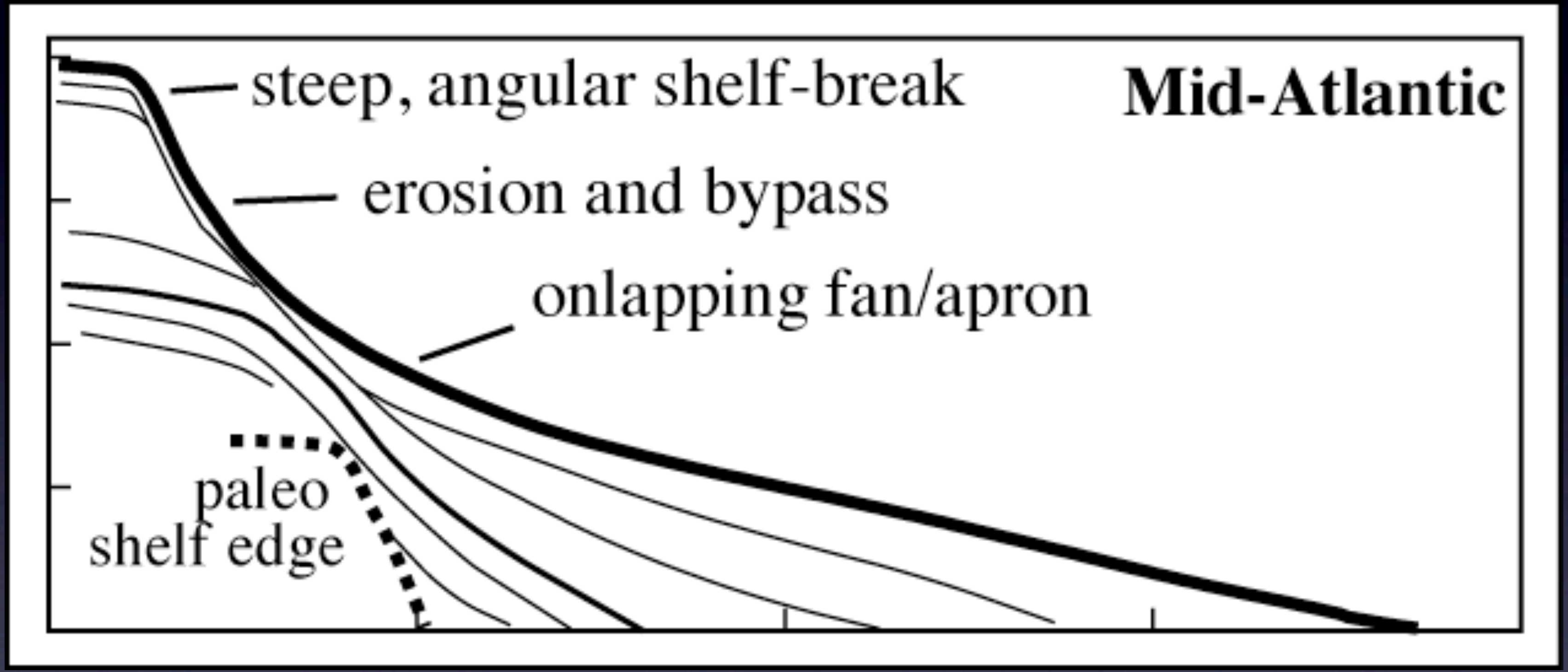
Each region is trying to build an equilibrium profile

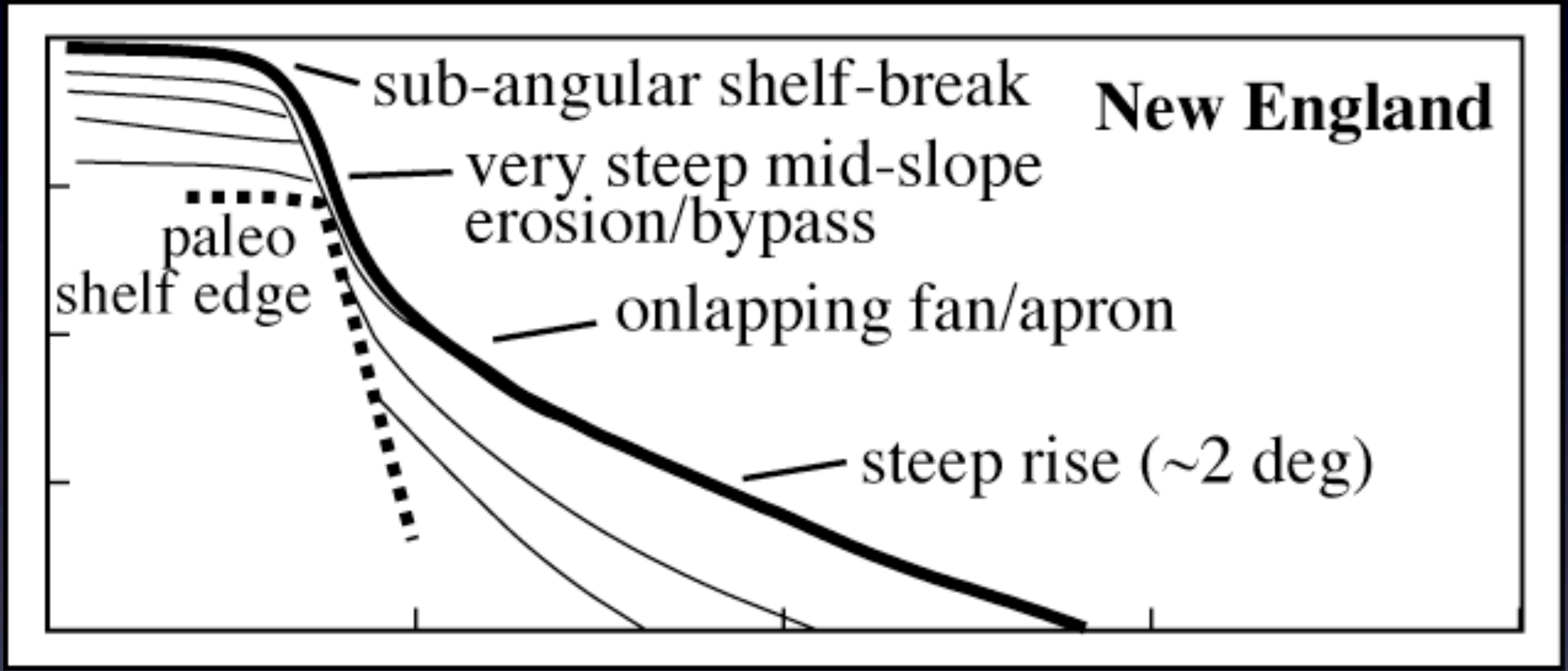
Average Slope Gradient: 3.7°



Oblique/Erosional

Each region is trying to build an equilibrium profile

Average Slope Gradient: 4.5°

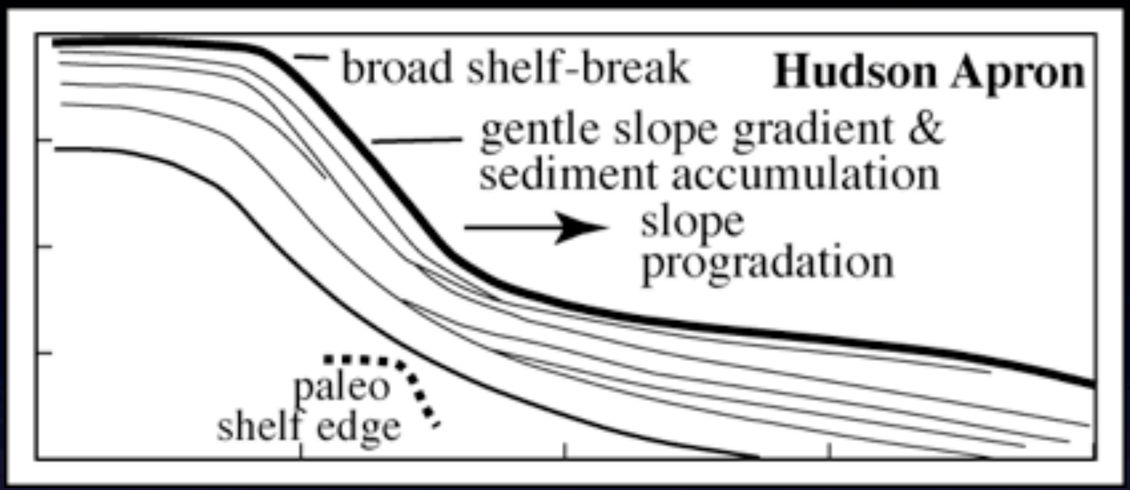


Oblique/Erosional

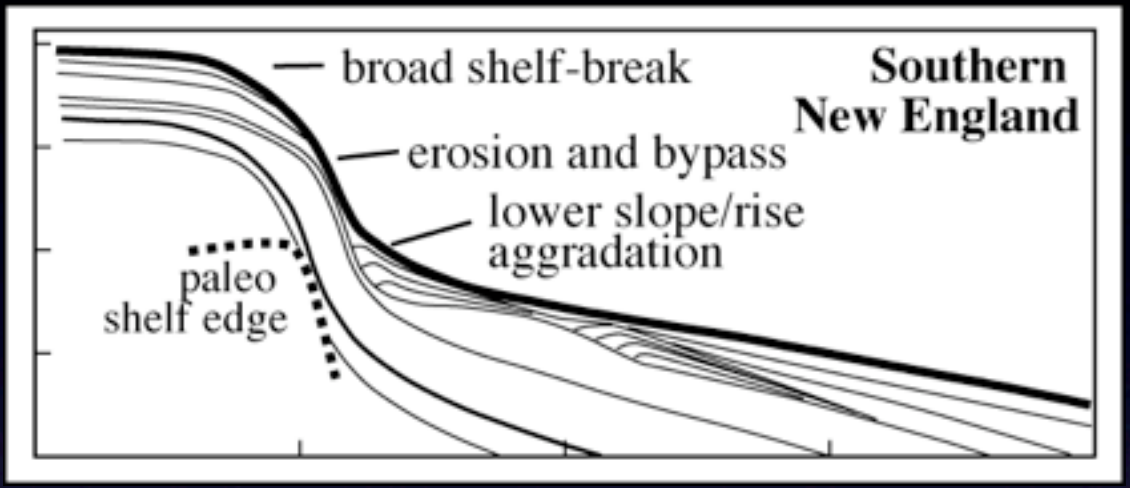
Each region is trying to build an equilibrium profile

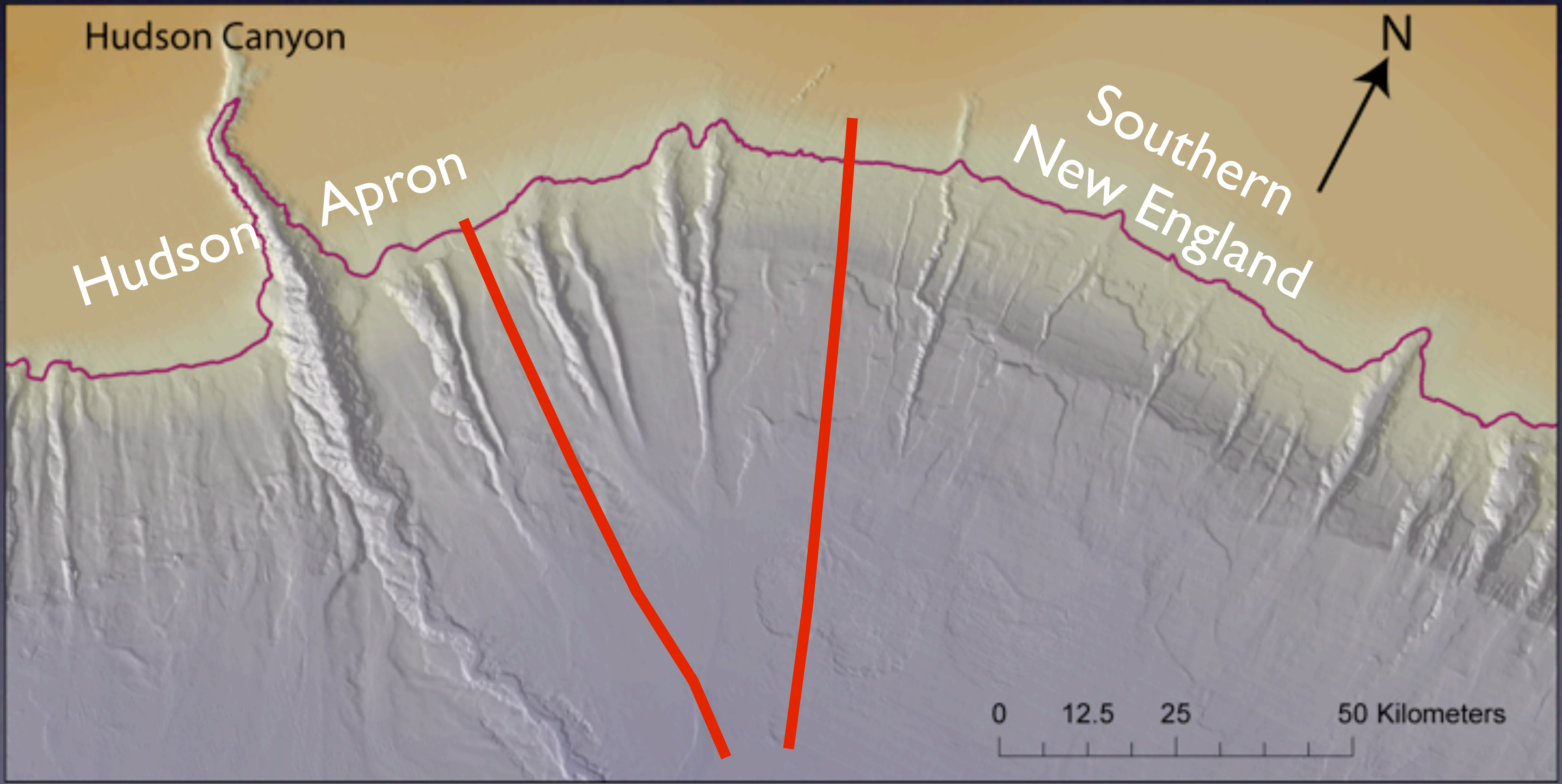
Southern New England and the Hudson Apron

Average Slope Gradient: 2.9°

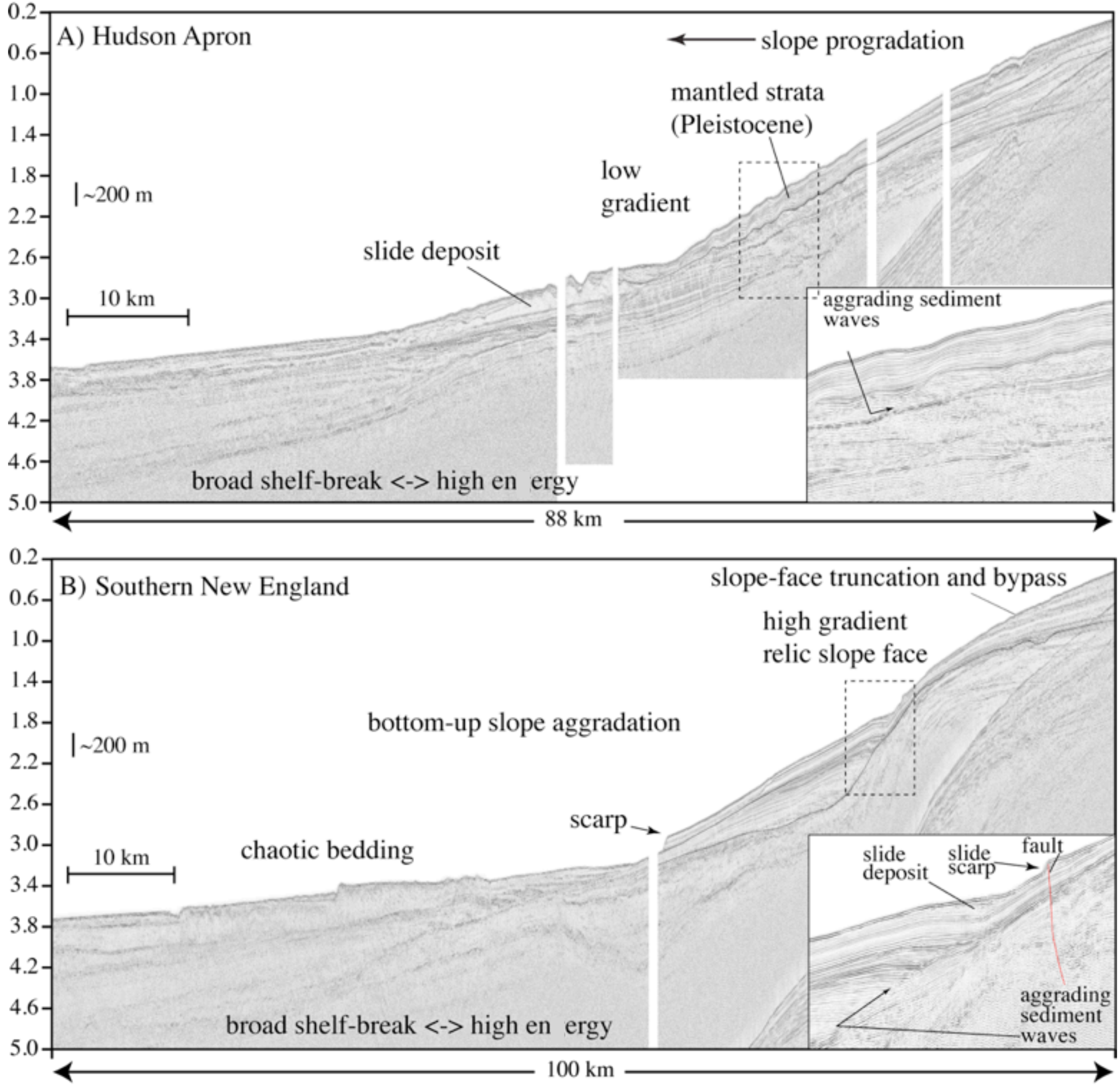


Average Slope Gradient: 3.3°





2010 seismic survey



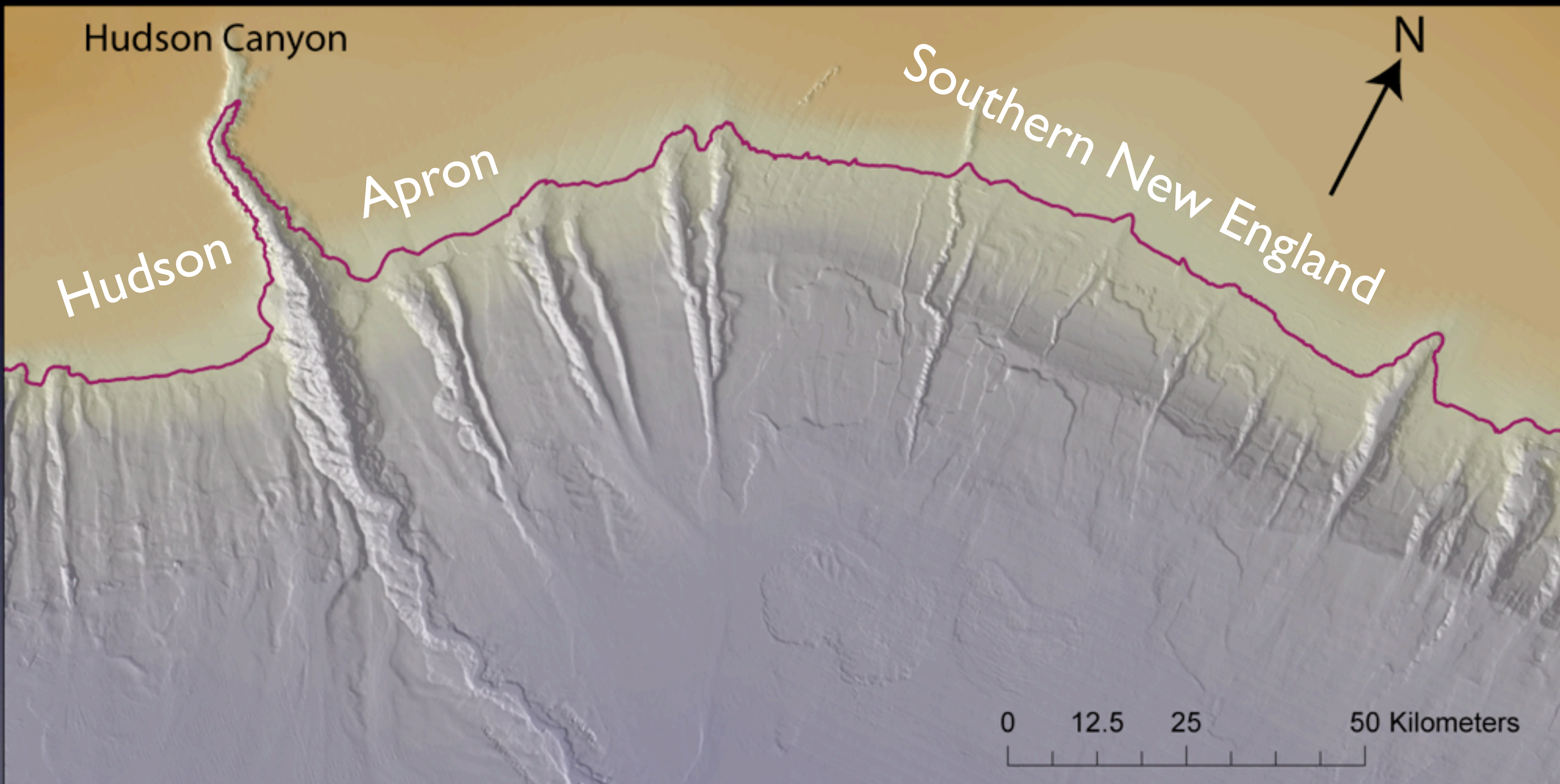
Where sediment is deposited is a function of gradient (among other factors)

Steep slopes - bypass zones, result of erosion

Relaxed slopes - accumulation zones

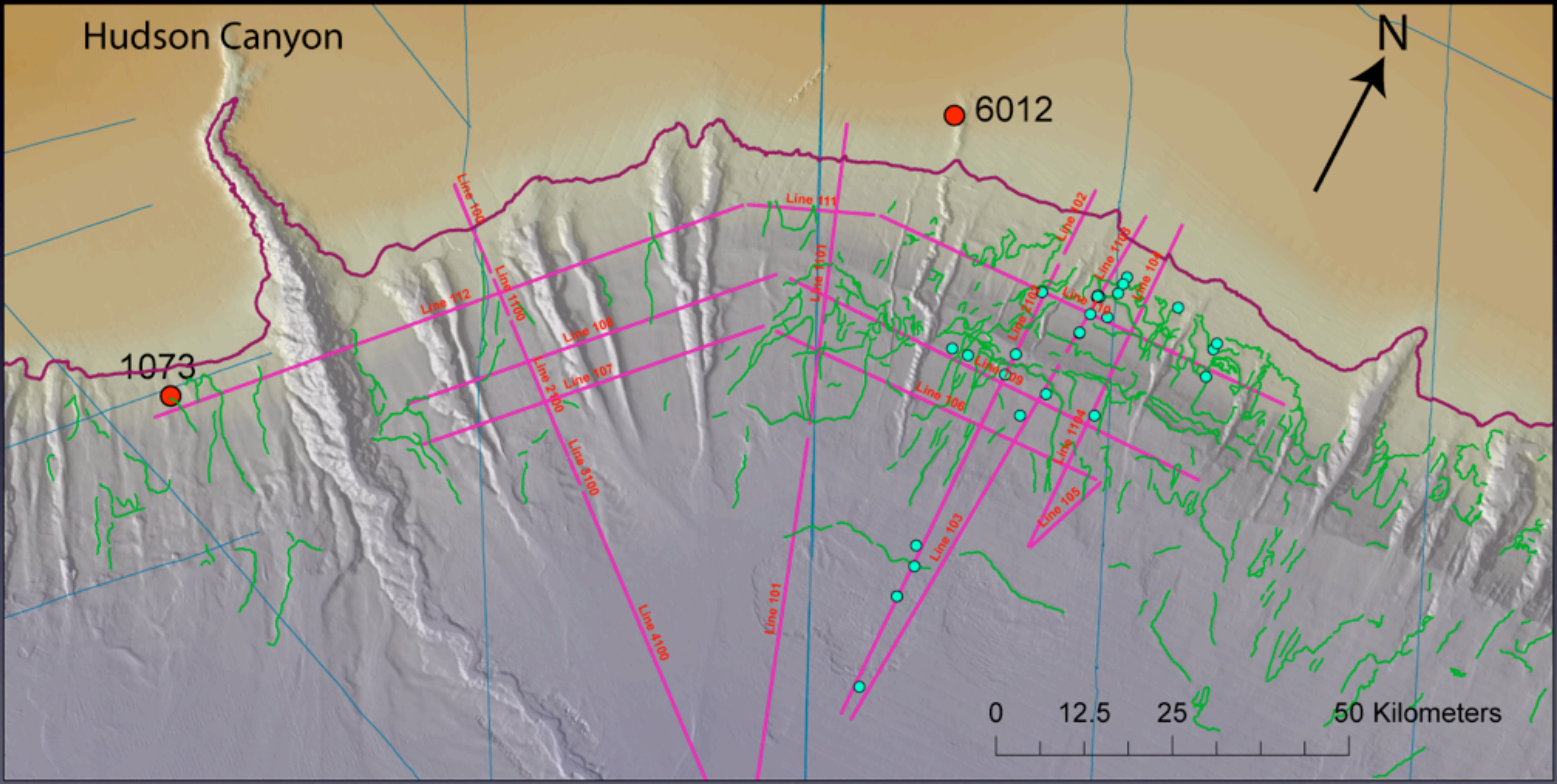
Thick unconsolidated sediments in the accumulation zone are susceptible to failure

Slope Stability: Gas, Fluids, and Faults

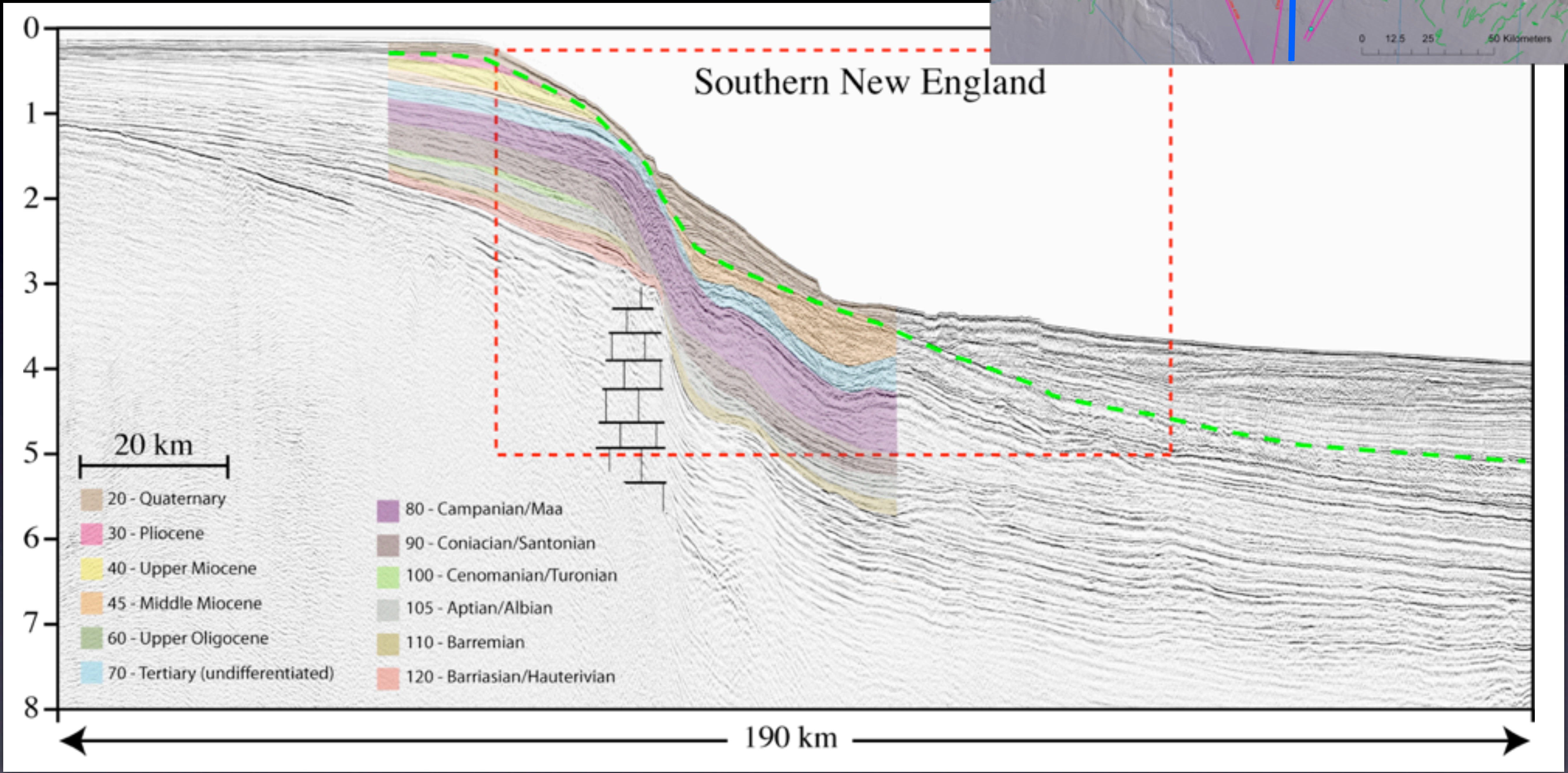


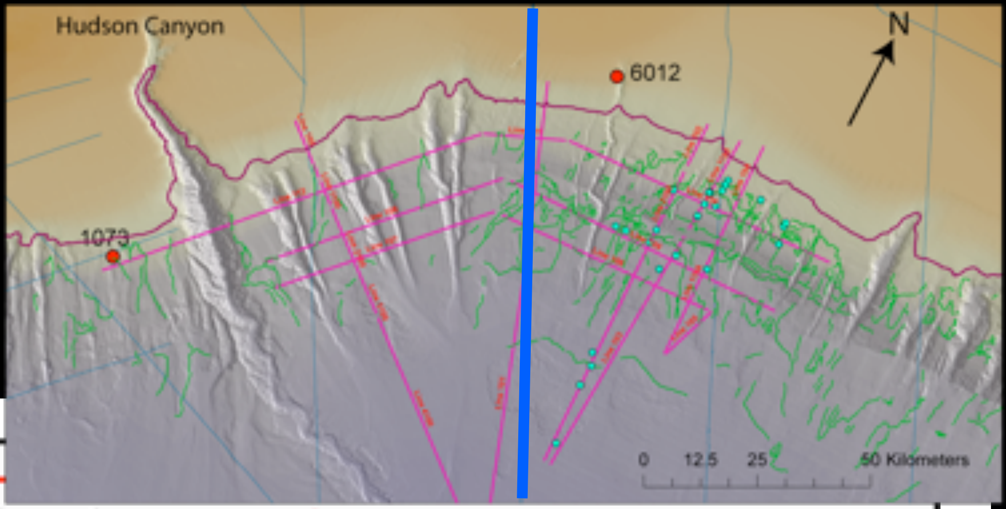
New High-Resolution Multichannel Seismic Reflection and Sediment Cores

--> Understand stratigraphic architecture and age of landslide deposits



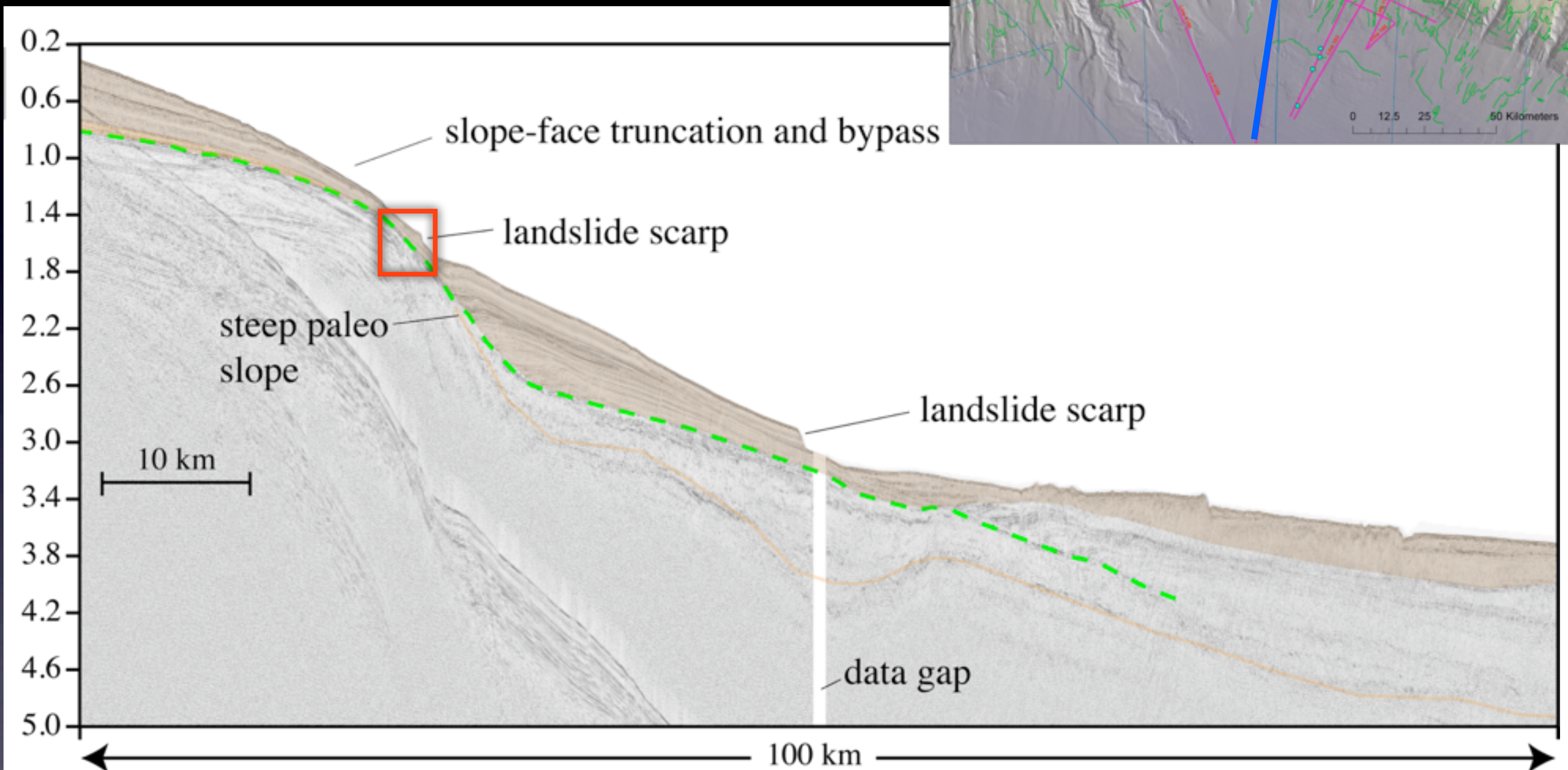
Legacy data provides geological framework

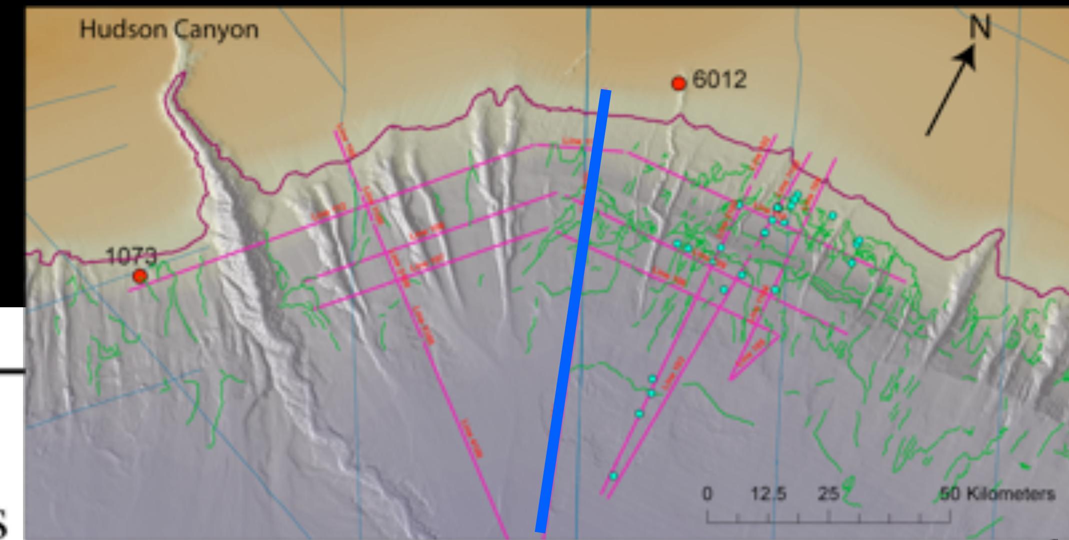




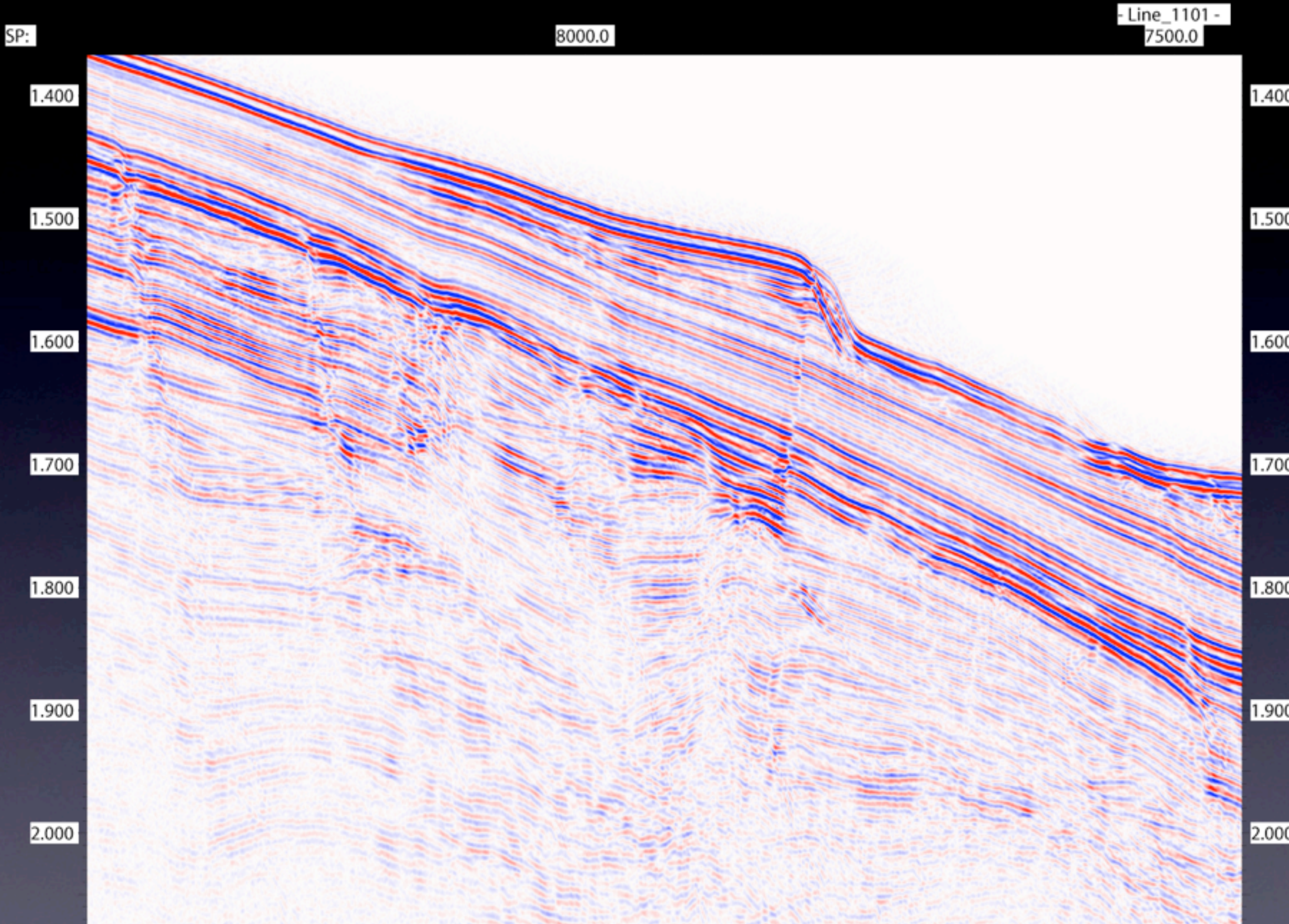
50 m maximum resolution

Modern data provides detailed resolution of the Pliestocene section

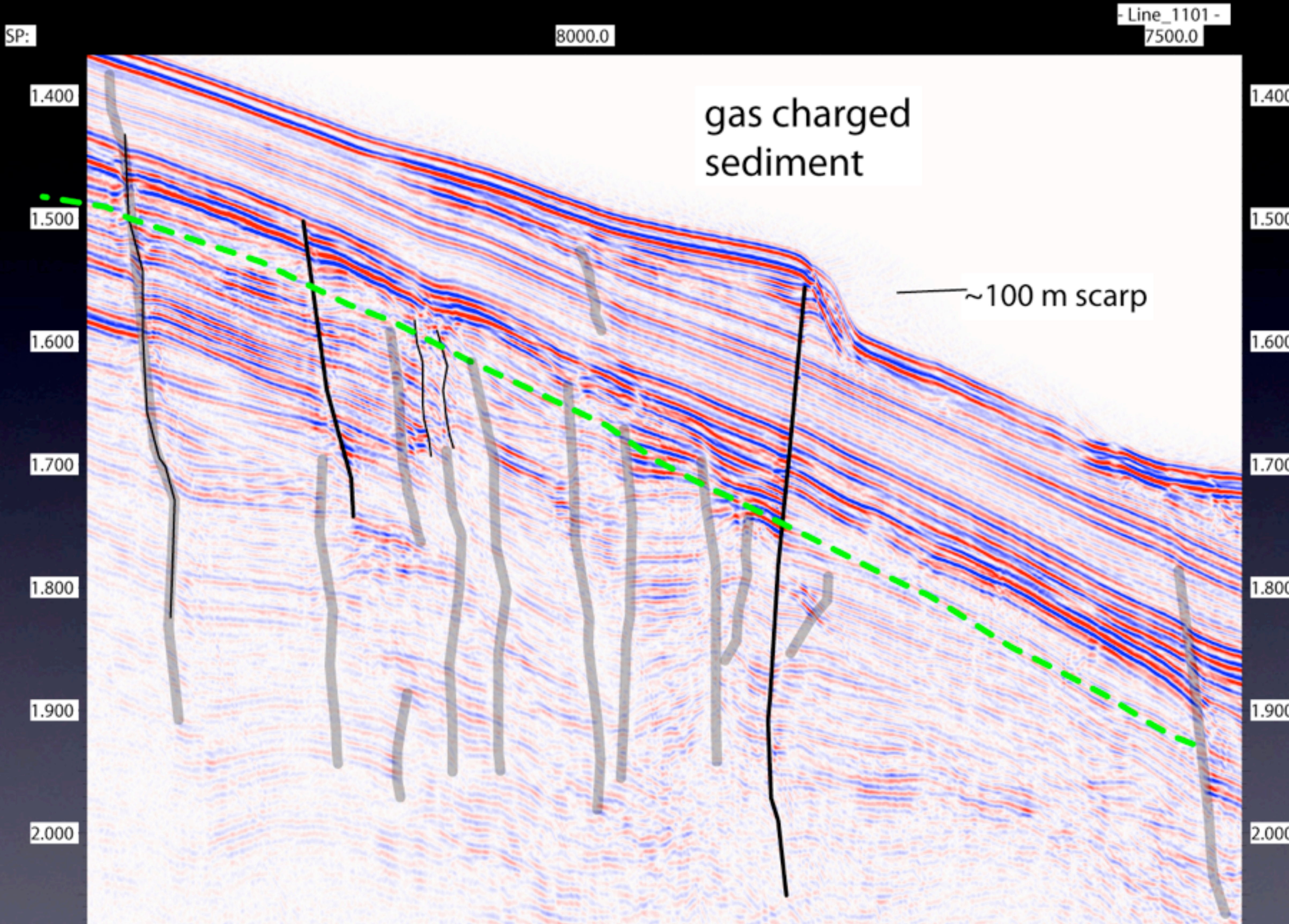




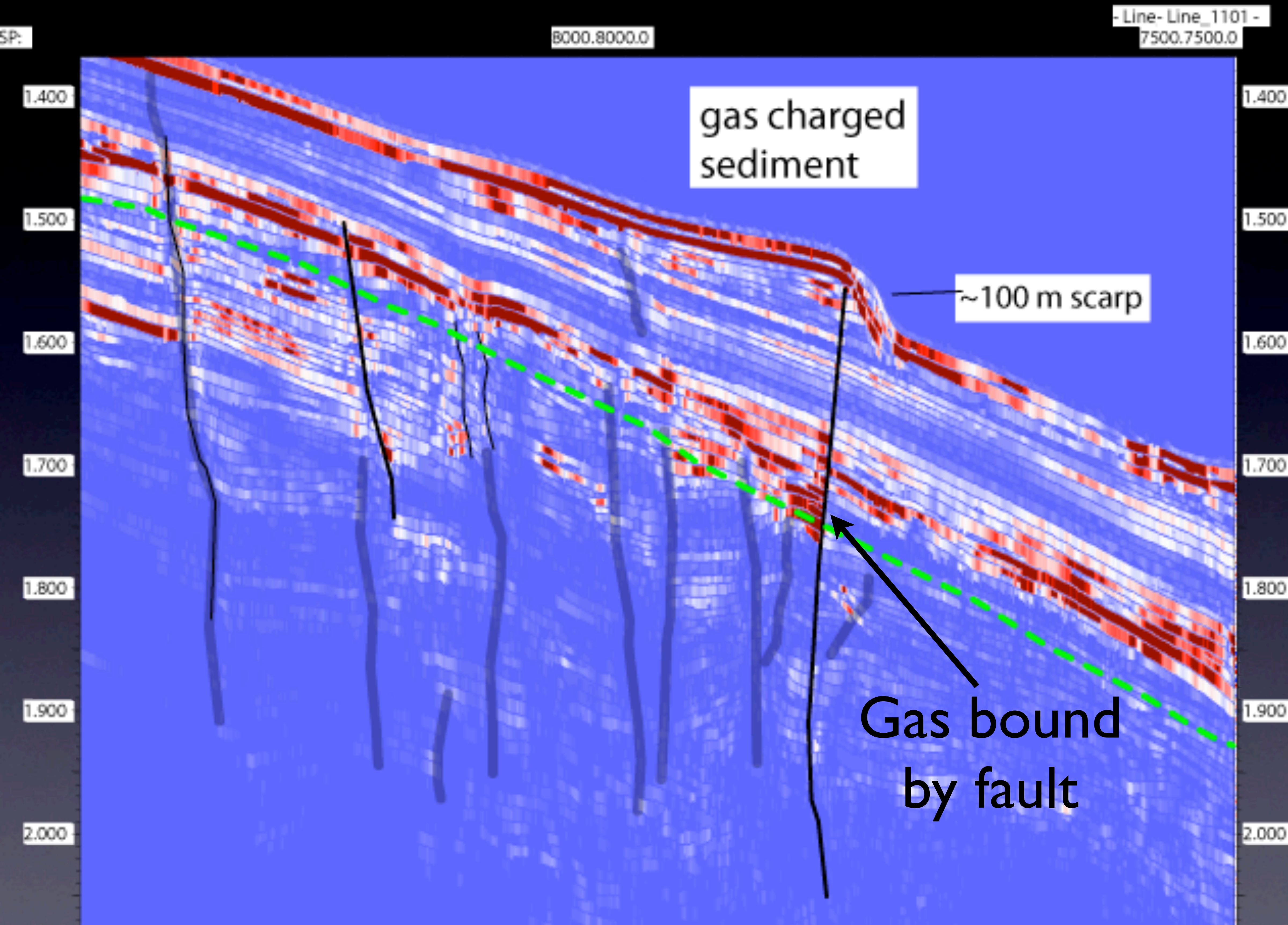
~5 m maximum resolution



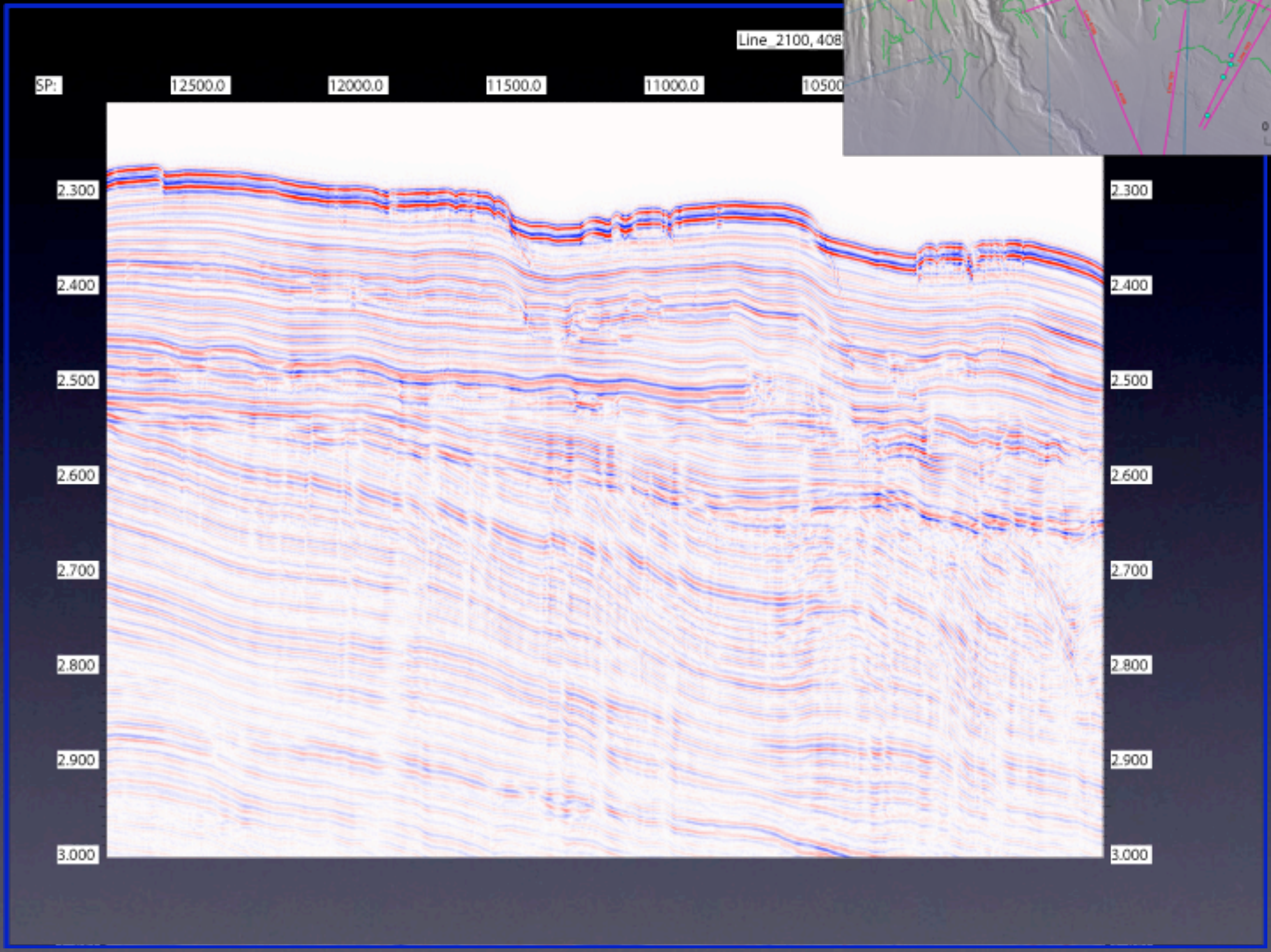
Irregular, faulted layers, gas wipe-out, enhanced reflectors



SP:
8000.0
- Line_1101 -
7500.0
1.400
1.500
1.600
1.700
1.800
1.900
2.000
gas charged
sediment
~100 m scarp



Reflector amplitude: Red - high, Blue - low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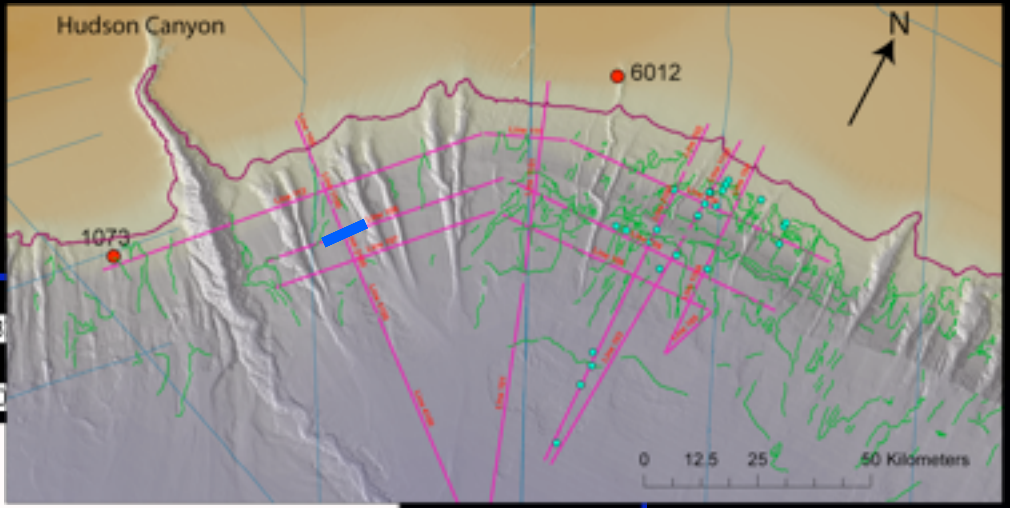
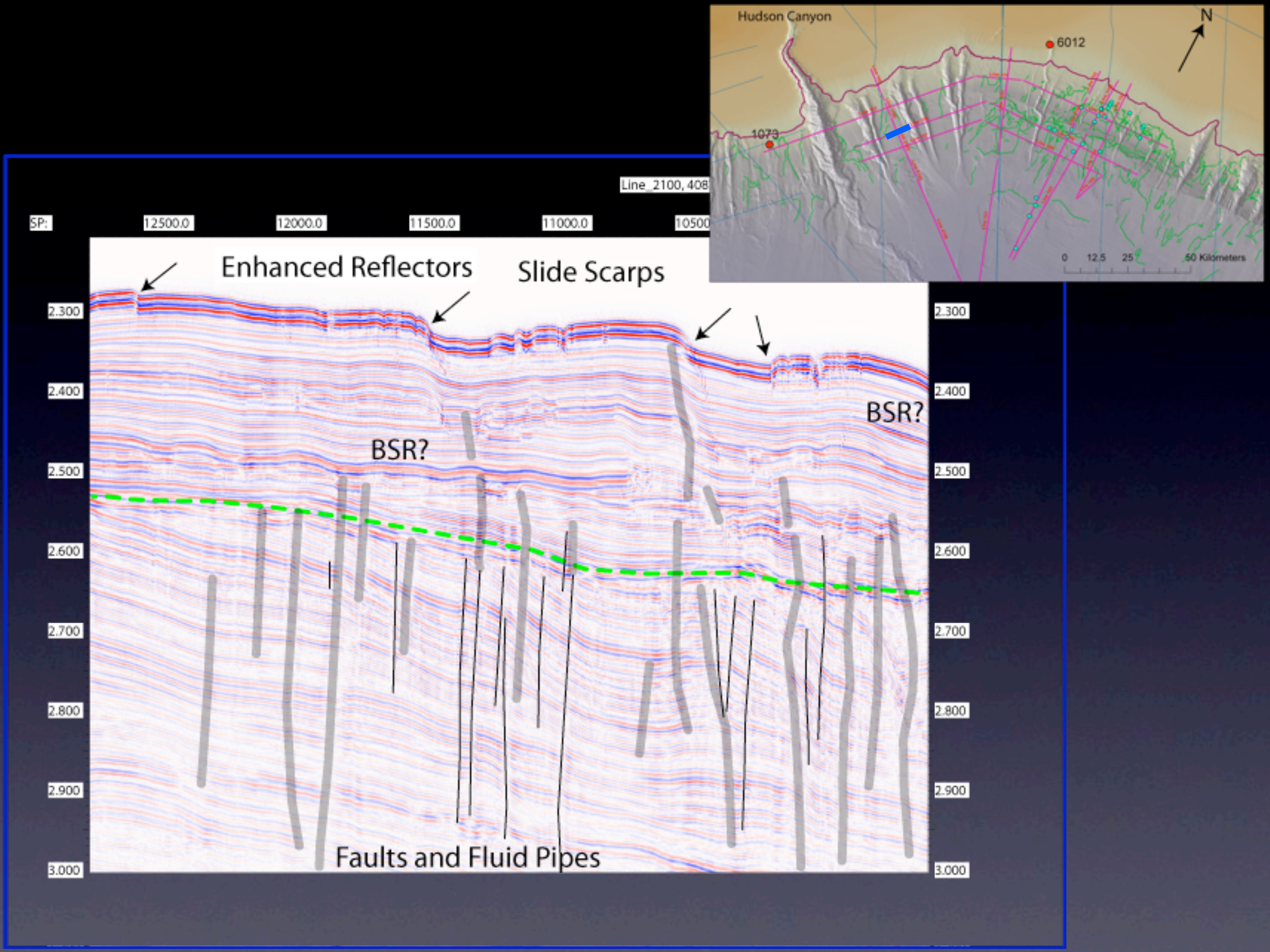

Hudson Canyon
6012
1073
N
0 12.5 25 50 Kilometers



Hudson Canyon
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0 12.5 25 50 Kilometers
Line_2100, 408
SP:
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12000.0
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10500
Enhanced Reflectors
Slide Scarps
BSR?
BSR?
Faults and Fluid Pipes
2.300
2.400
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2.600
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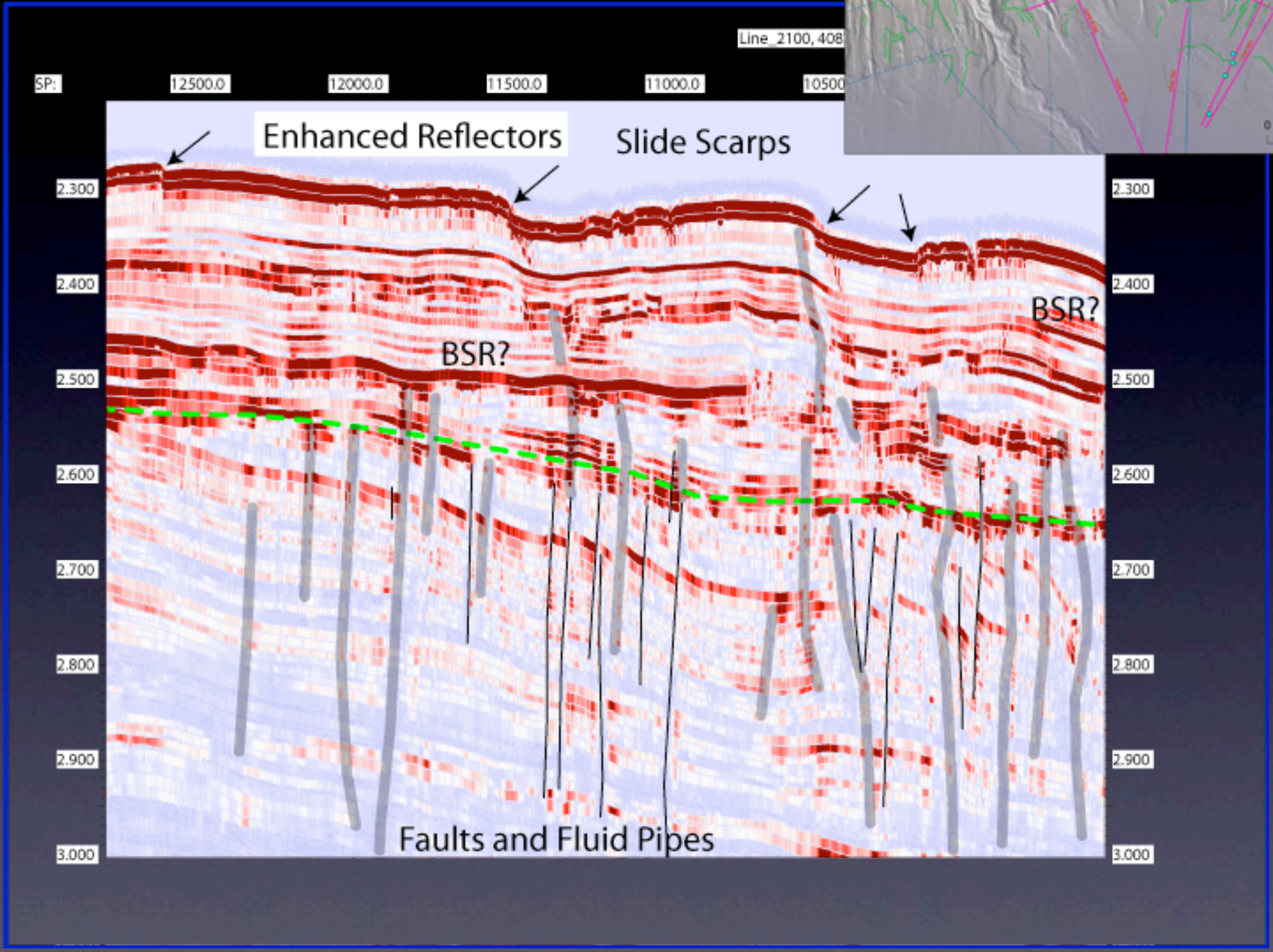
2.800
2.900
3.000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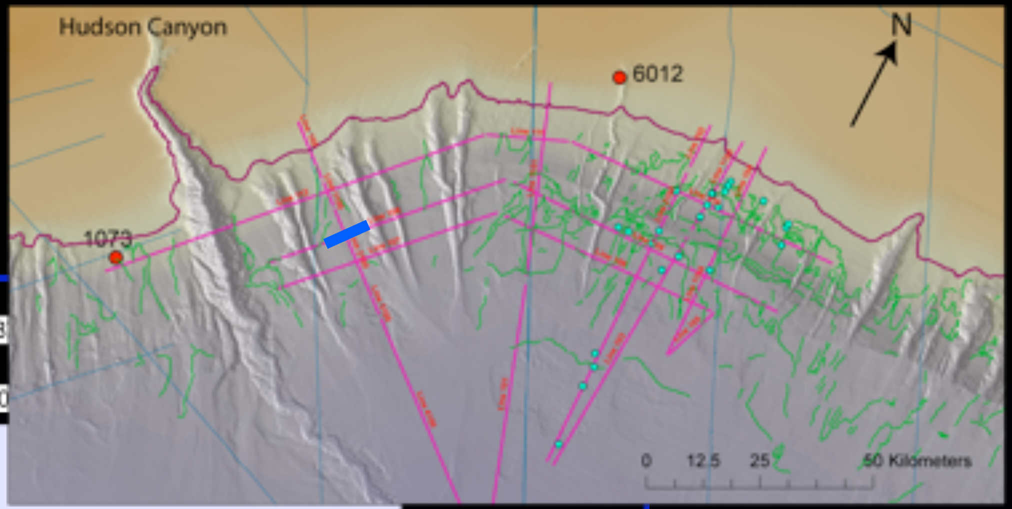
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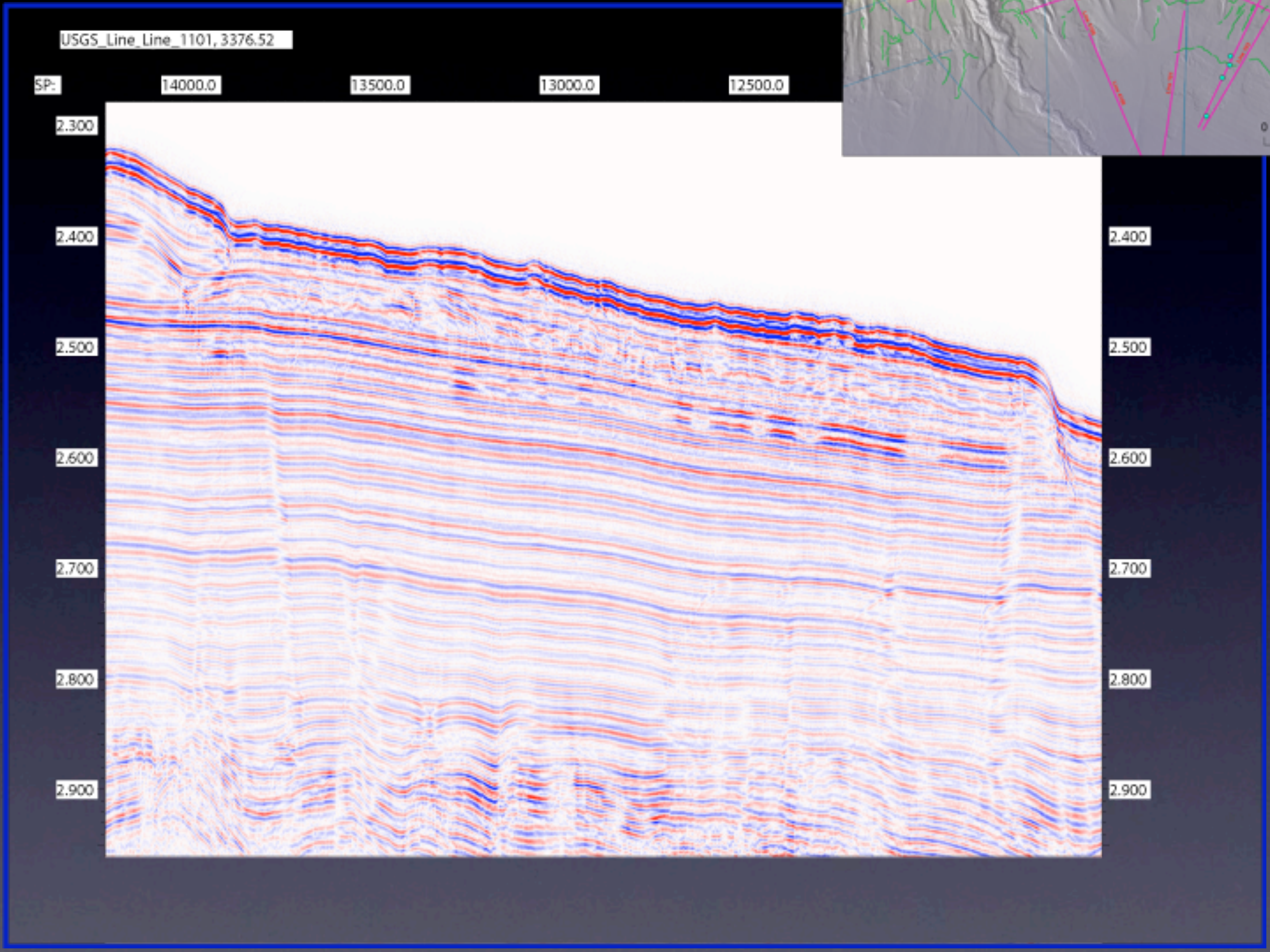
0 12.5 25 50 Kilometers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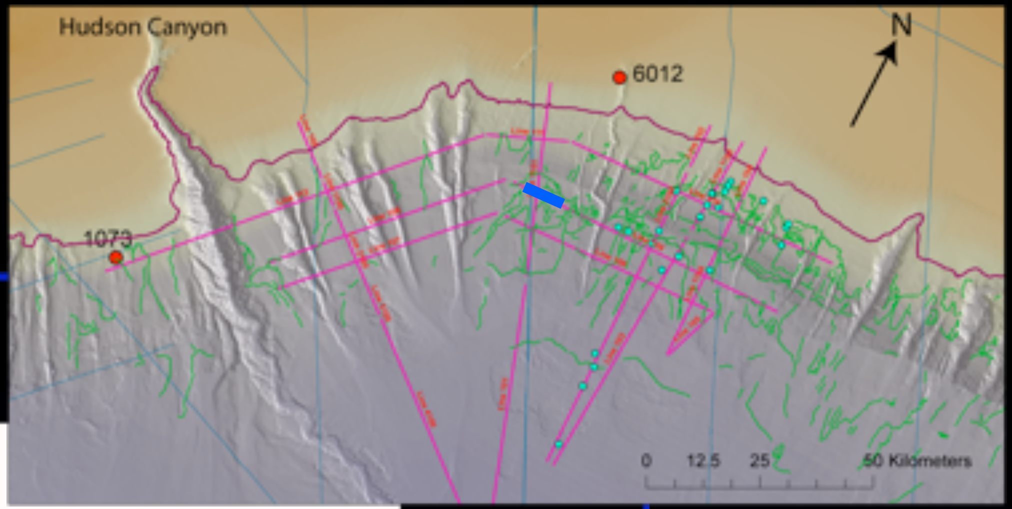
Hudson Canyon
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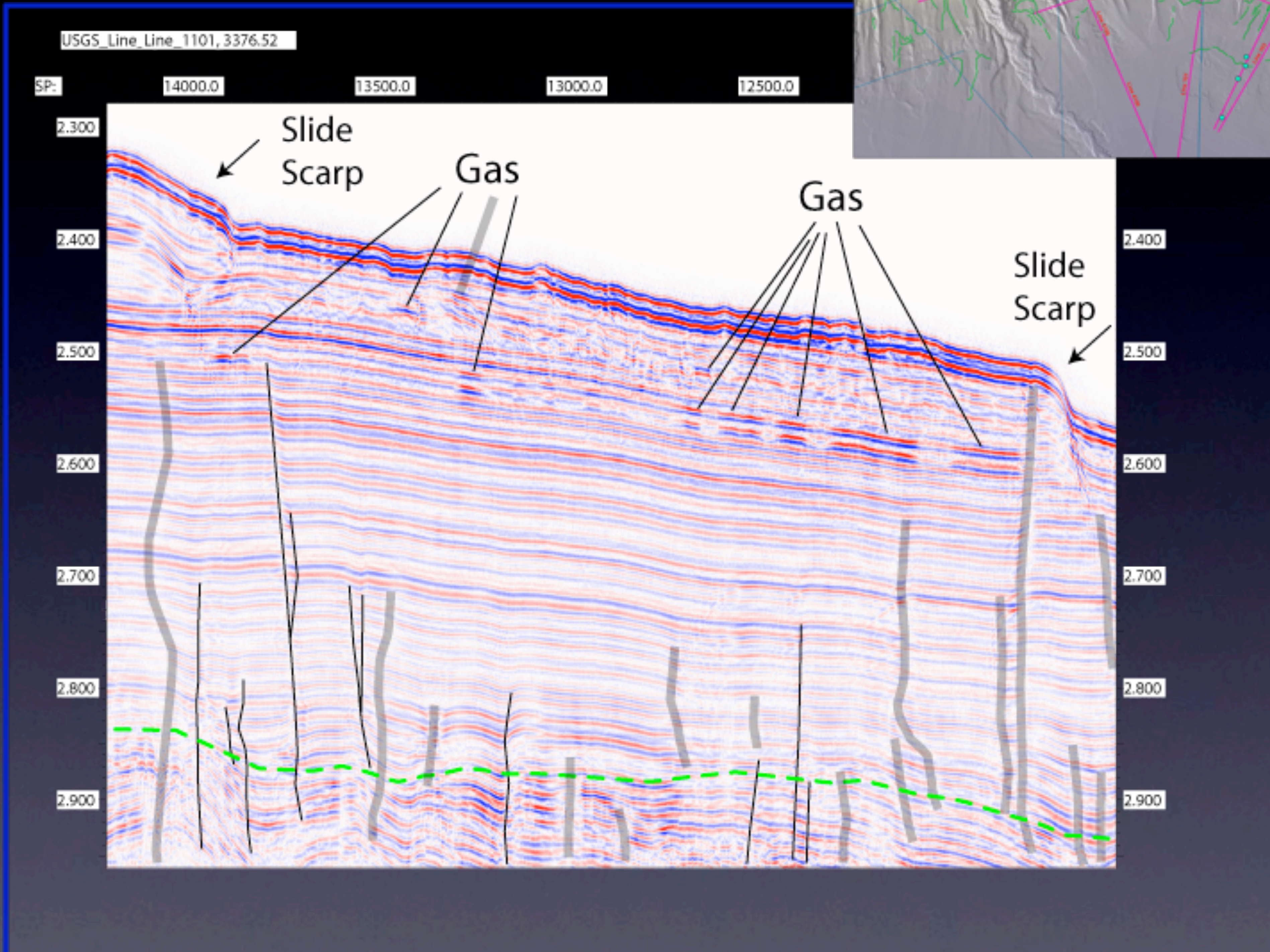
50 Kilometers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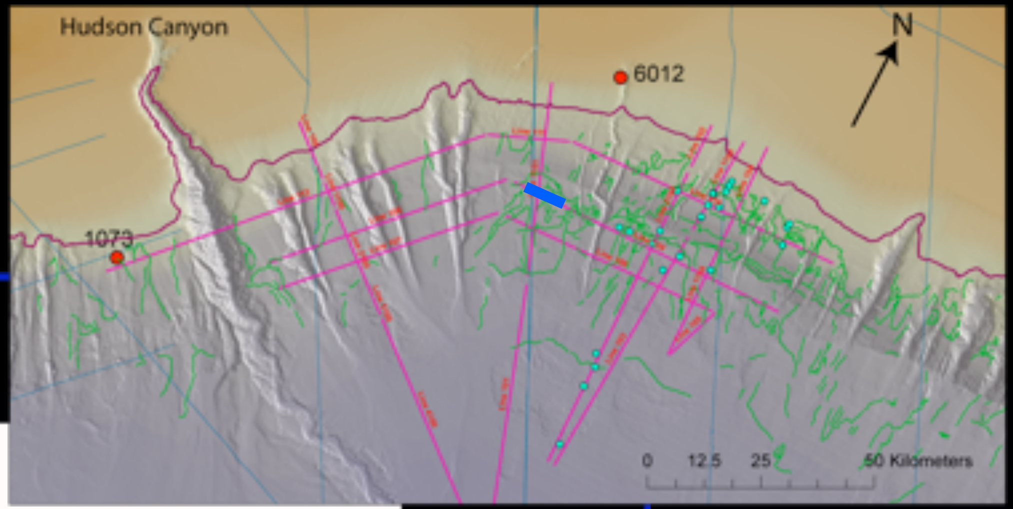
2.900
Slide Scarp
Gas
Gas
Slide Scarp

Hudson Canyon
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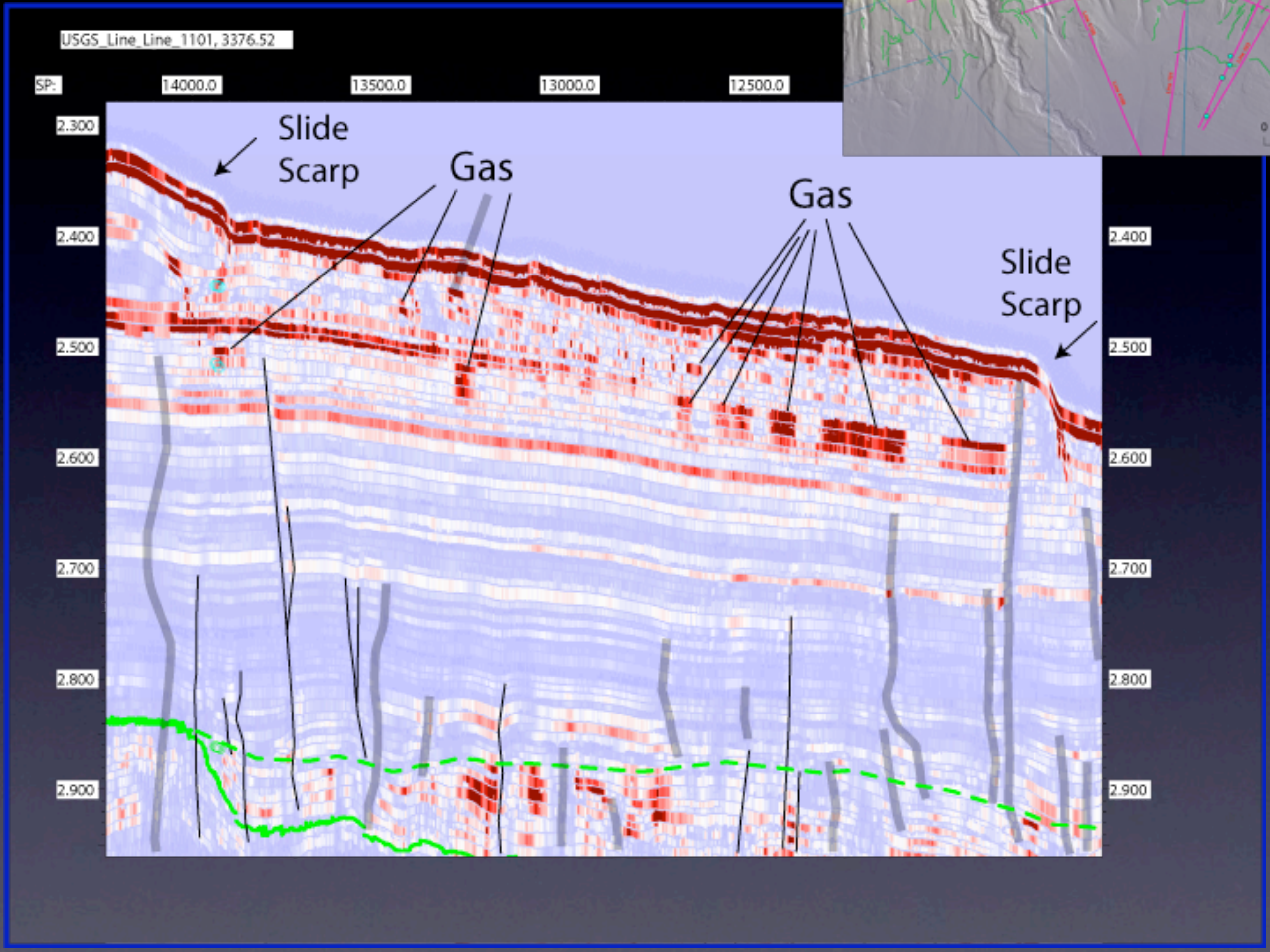
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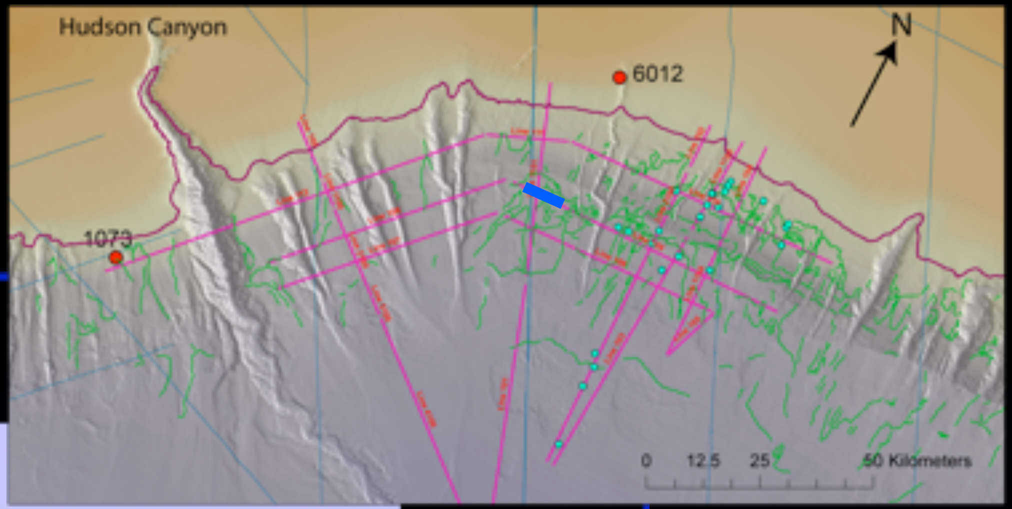
Slide Scarp
Gas
Gas
Slide Scarp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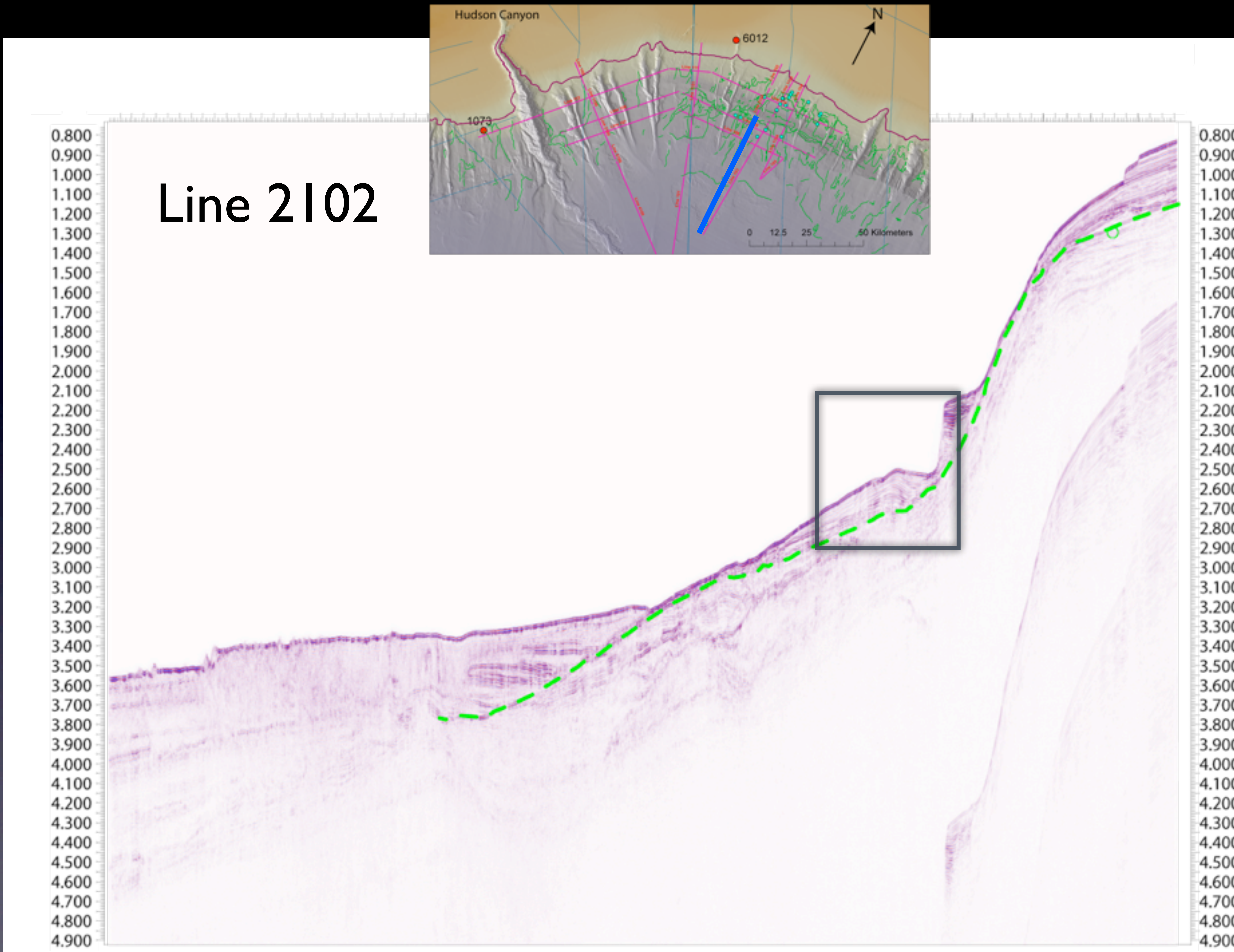

Line 2102
Hudson Canyon
6012
1073
N
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50 Kilometers
0.800
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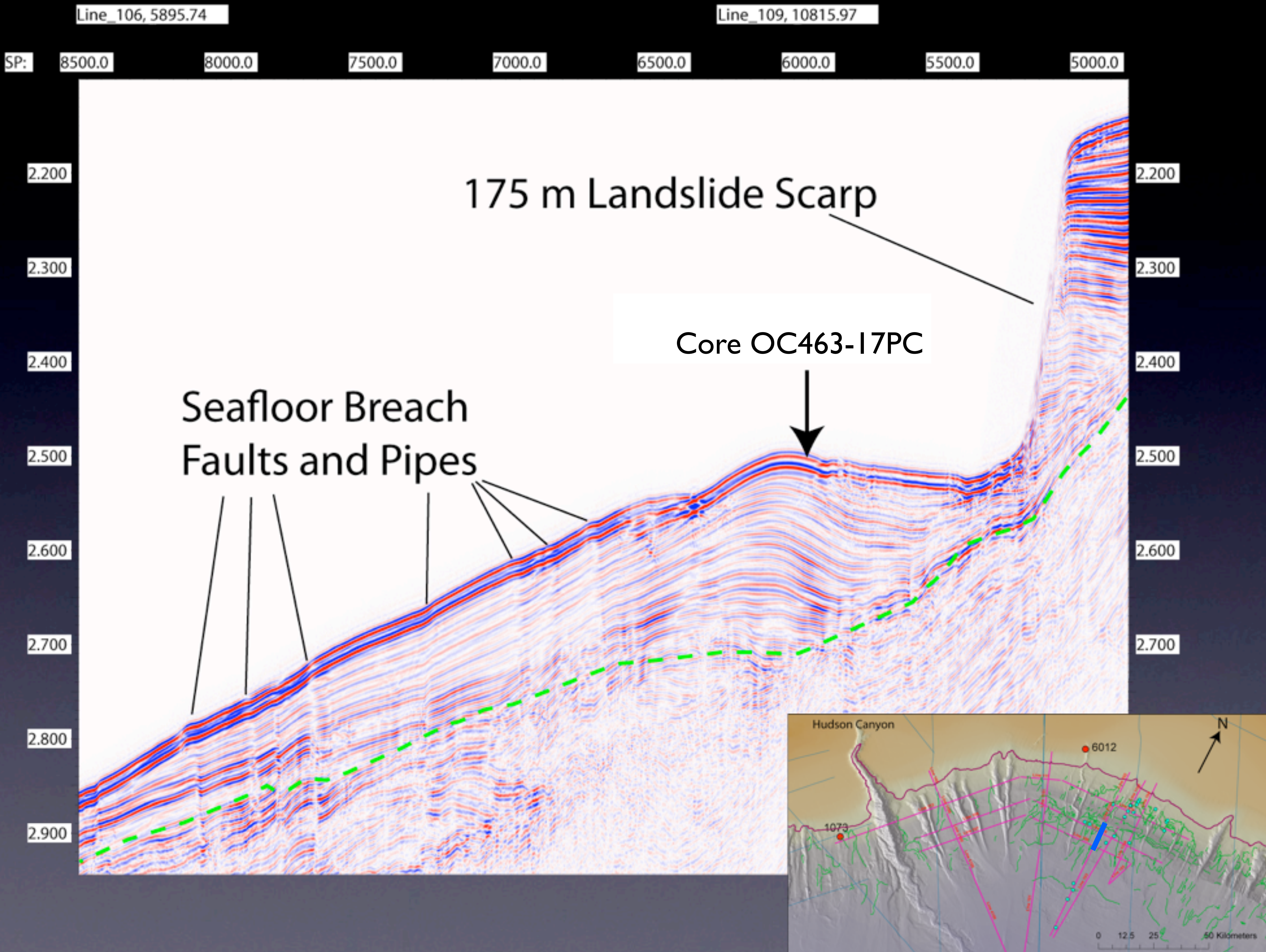
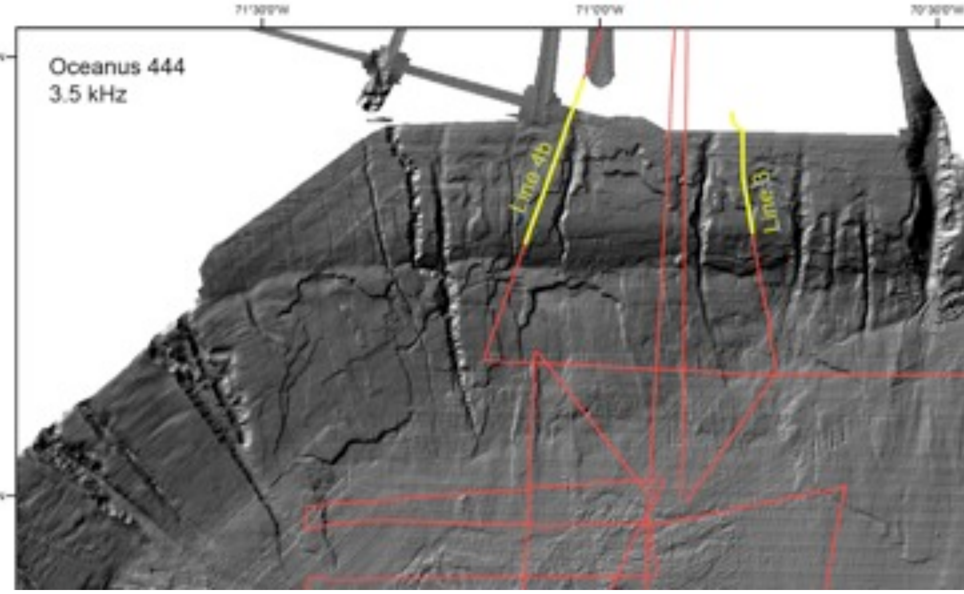
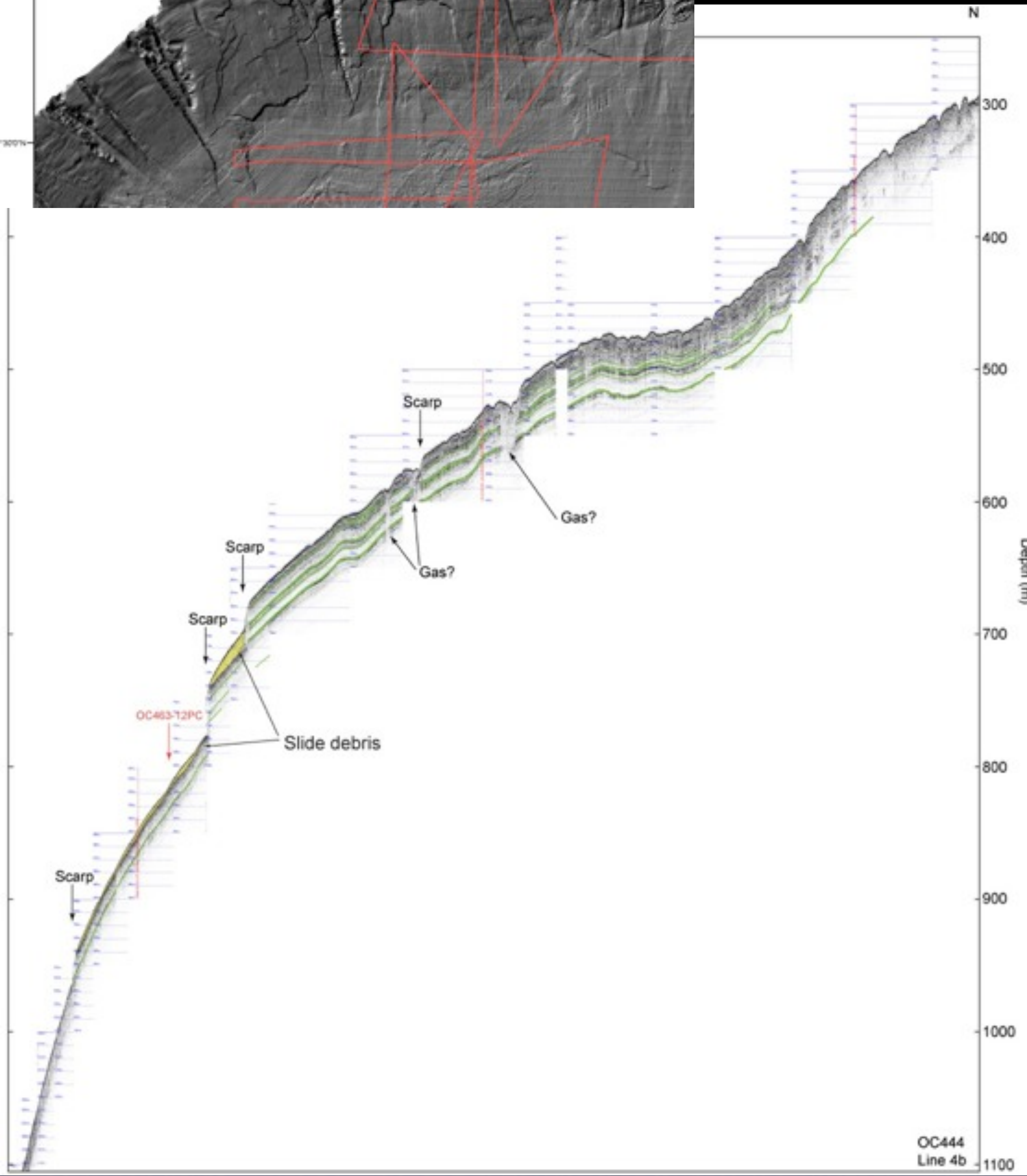
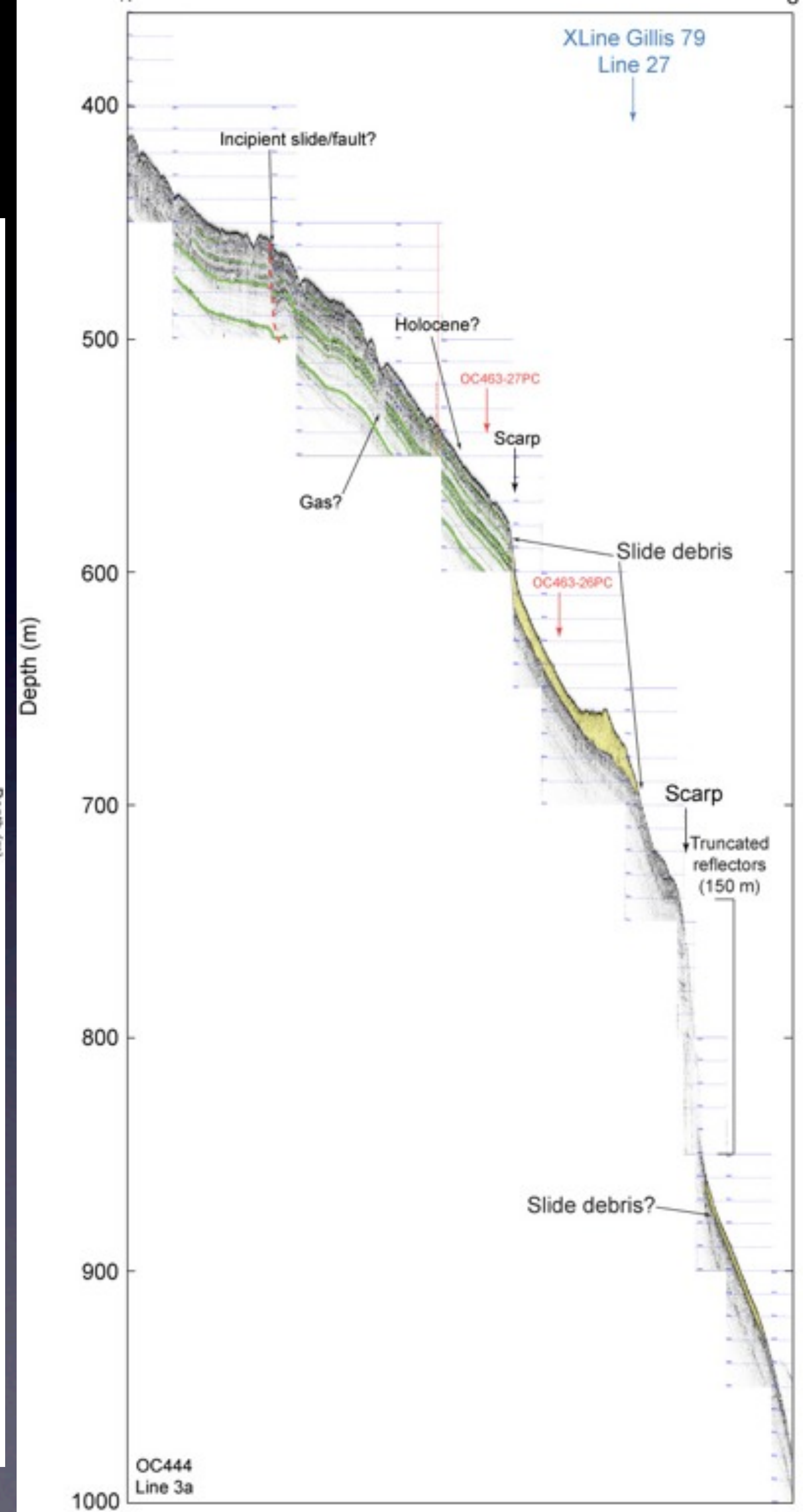
4.500
4.600
4.700
4.800
4.900


Line_106, 5895.74
Line_109, 10815.97
SP:
8500.0
8000.0
7500.0
7000.0
6500.0
6000.0
5500.0
5000.0
2.200
2.300
2.400
2.500
2.600
2.700
2.800
2.900
175 m Landslide Scarp
Core OC463-17PC
Seafloor Breach
Faults and Pipes
Hudson Canyon
N
6012
1073
0
12.5
25
50 Kilometers

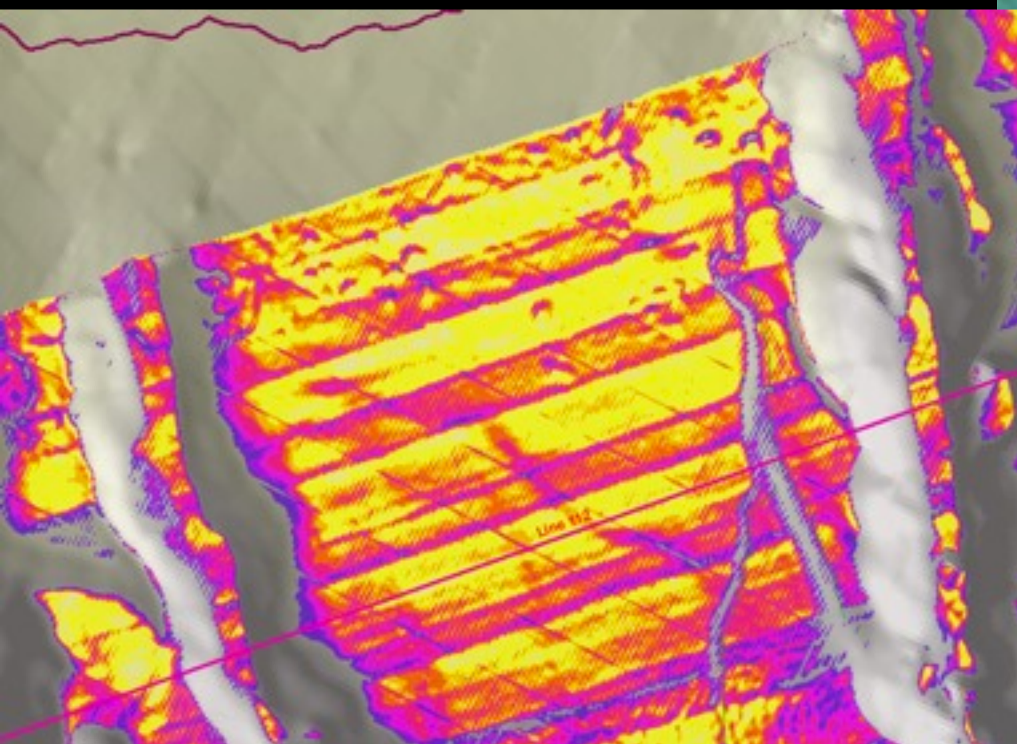
3.5 KHz seismic profiles collected aboard R/V Oceanus May 2008 in Southern New England

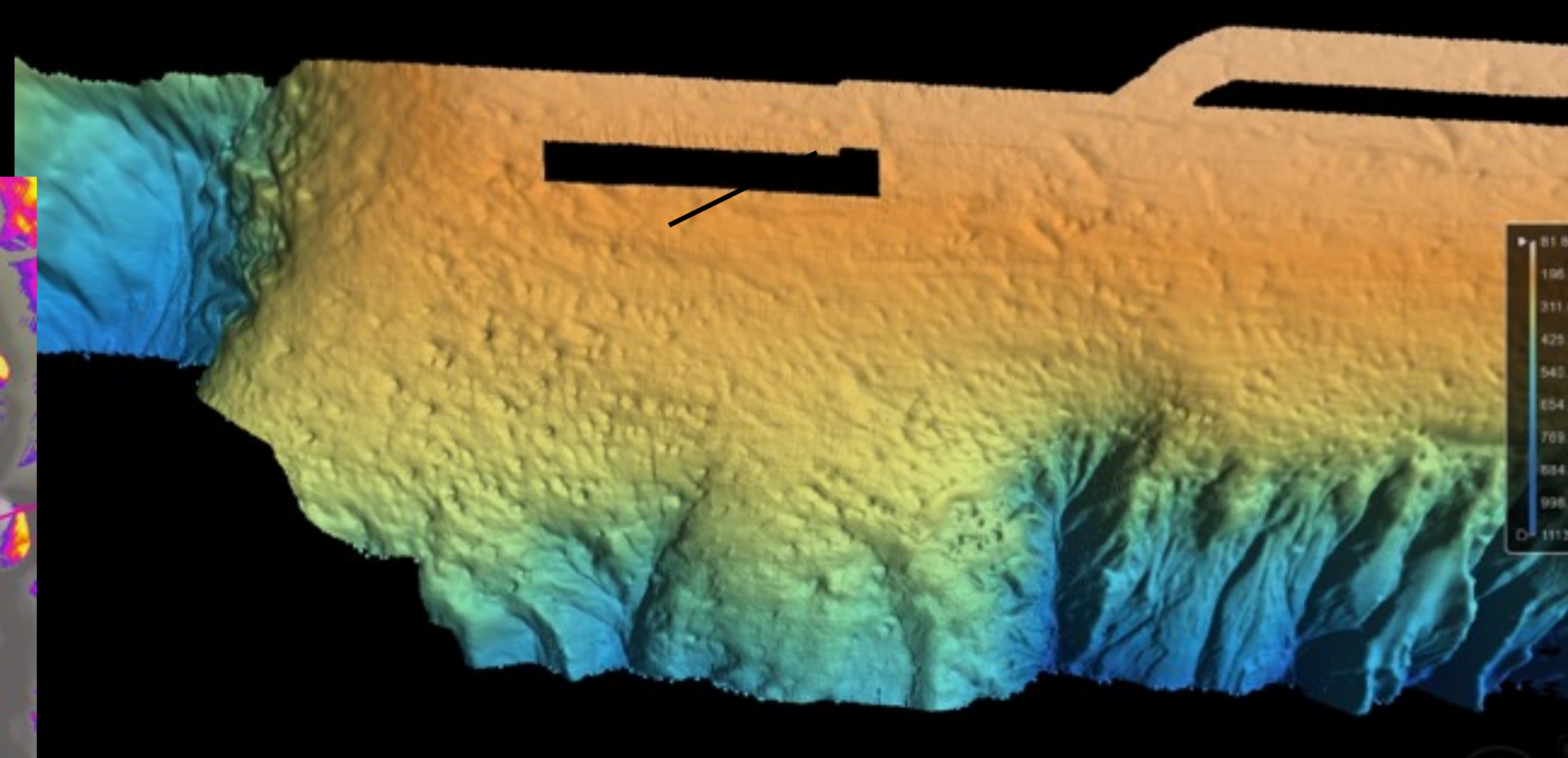




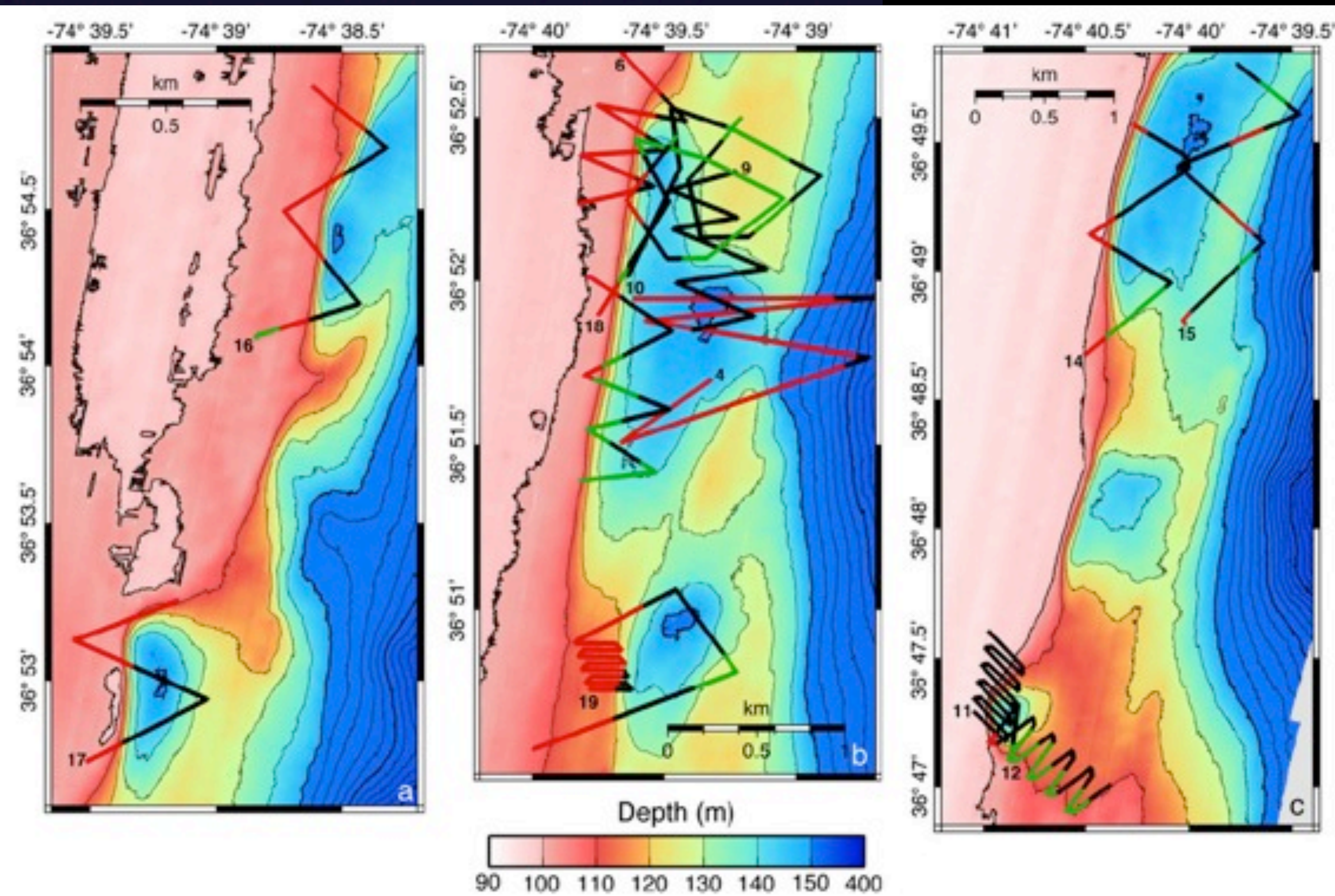


Pockmarks east of Hudson Canyon - 2009 data

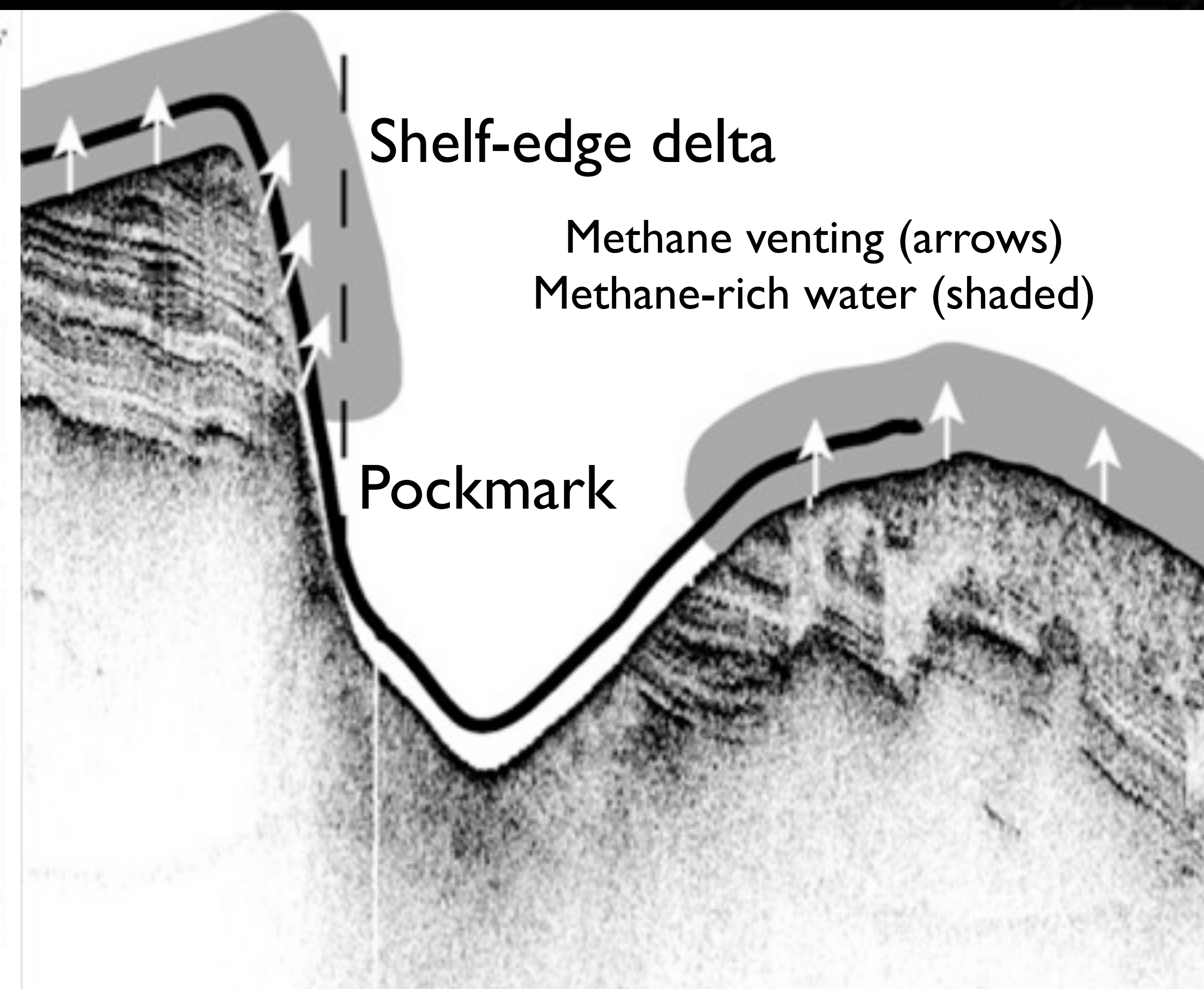




Pockmarks south of Baltimore canyons - 2011 data



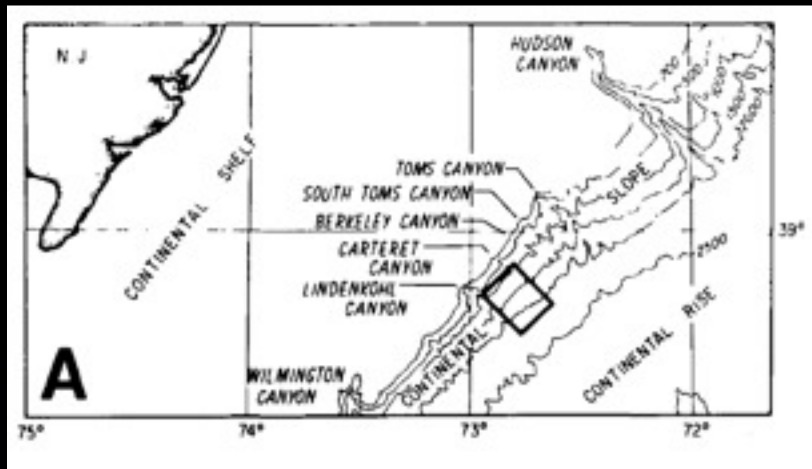
Gas concentration: Red - high, Green -intermediate, black - background

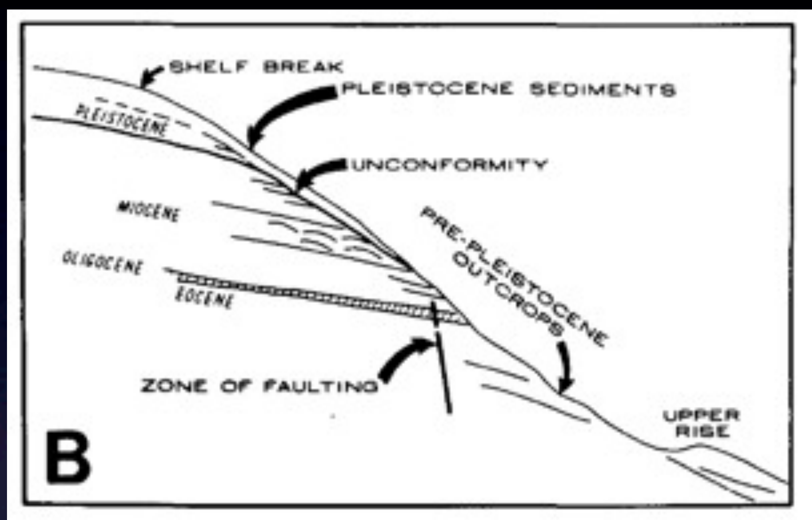


(Newman et al., EPSL, 2008)

Fresh Water Sapping off the New Jersey Slope

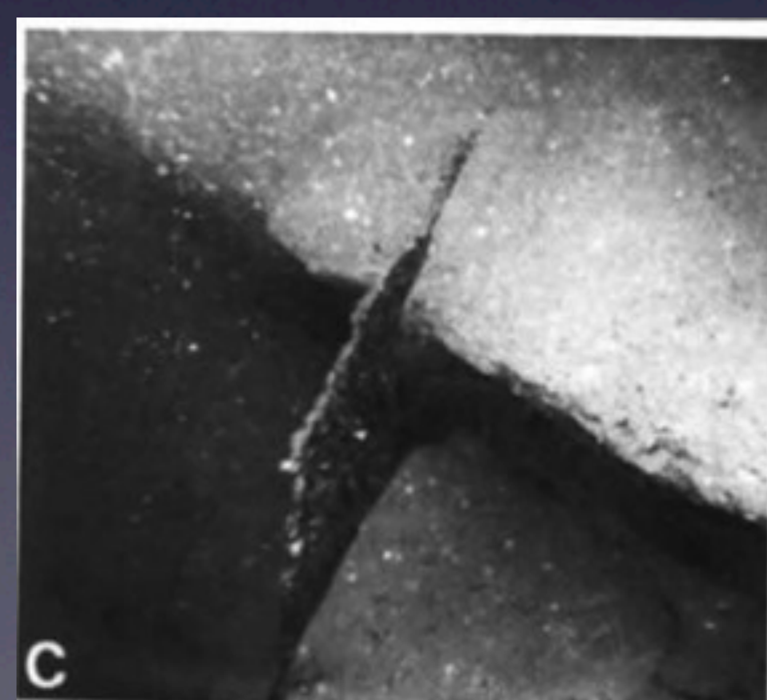
Robb et al., *Geology* 1984





Faults and Fractures

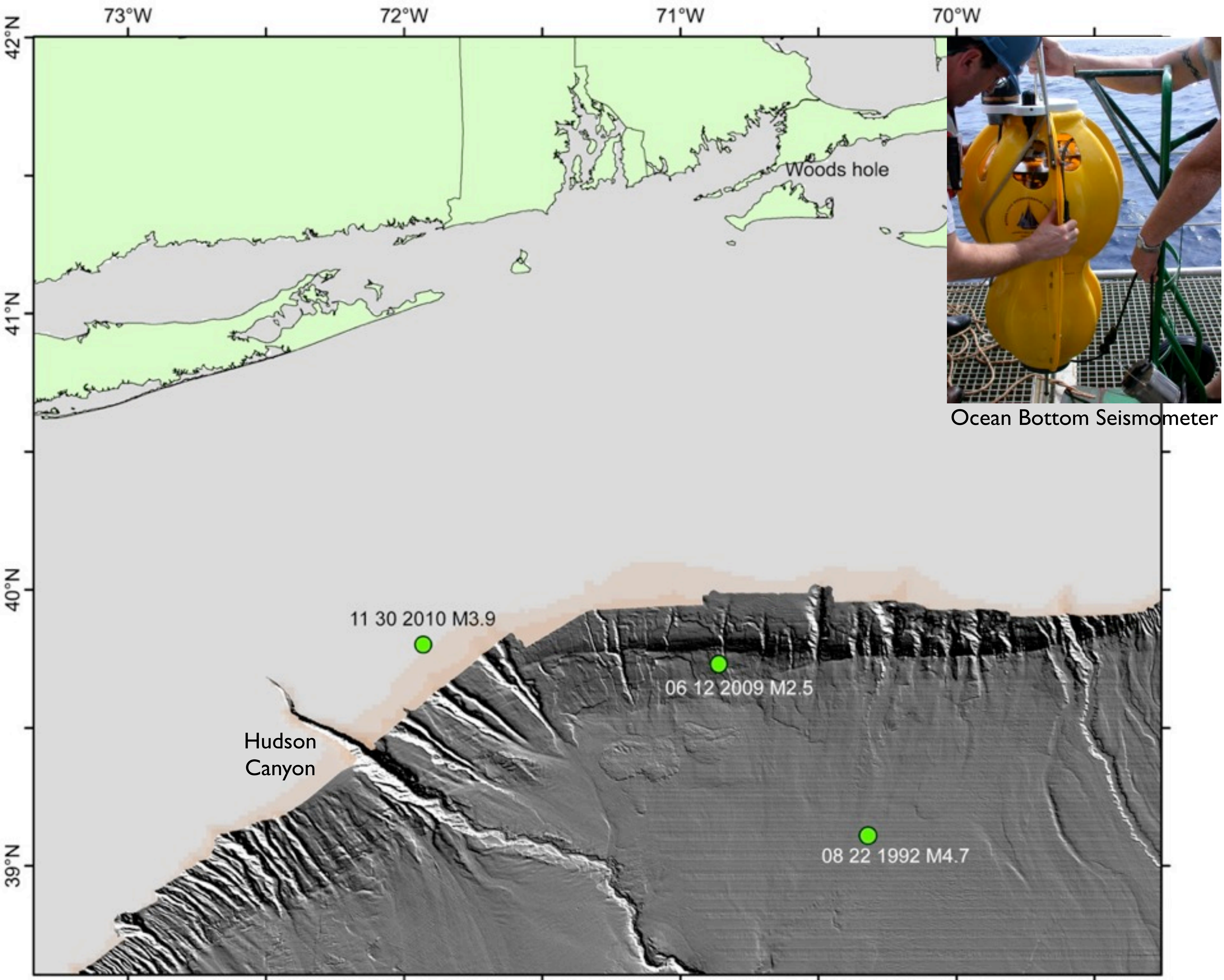
- Jointing, dissolution and fluid migration
- Displacement from differential sediment loading and pore fluid pressures



But what is the source of the gas?

Future Work

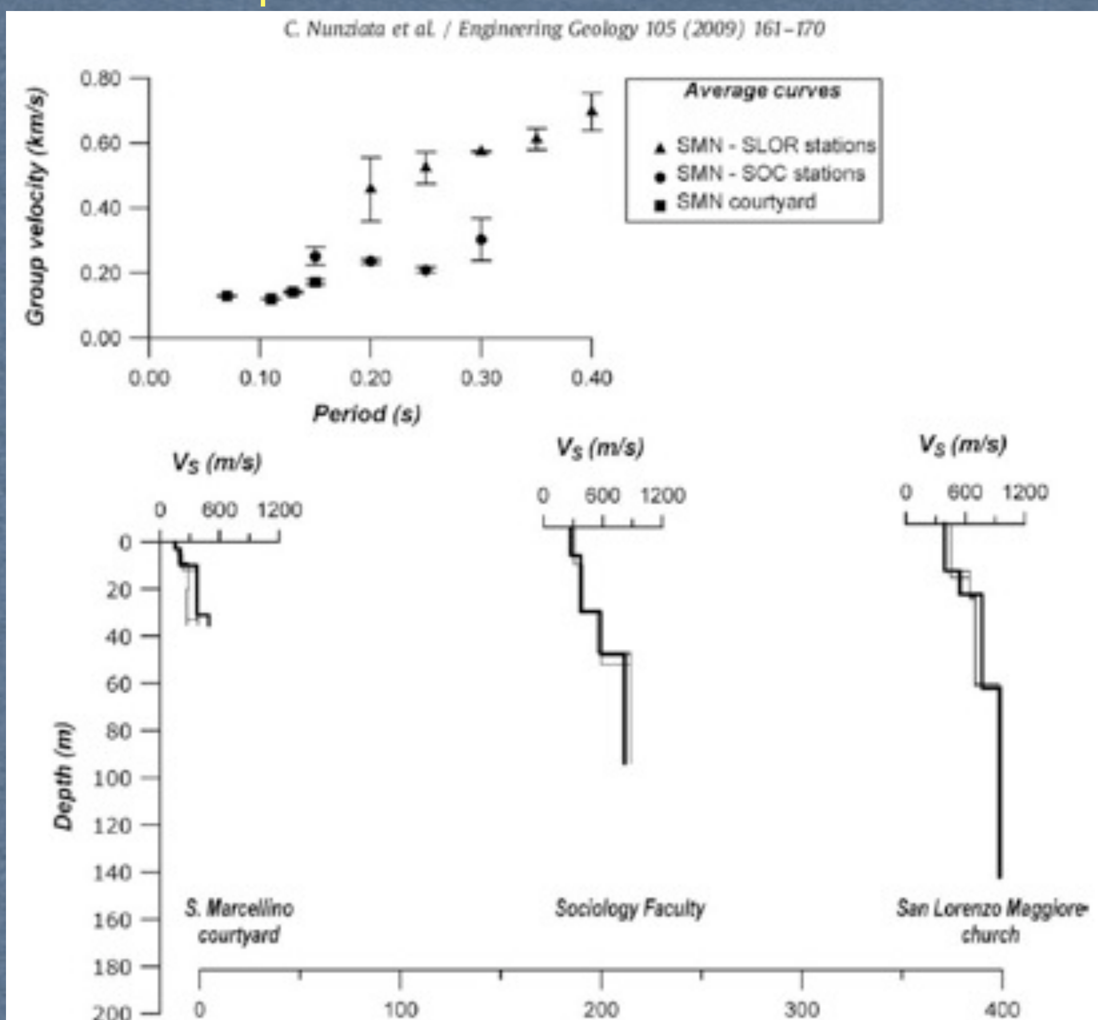
- Seismic Cruises (September 2011, 2012)
- Better age control on seismic horizons
- *Detailed mapping of fracture, fault, fluid pipe densities*
- *Multibeam mapping of pockmarks & gas blowout features*
- *Sample the fluids and identify source layer of gas?*
- Monitor micro-seismic activity with an OBS array
- Ambient-noise cross correlation to determine sediment shear velocity



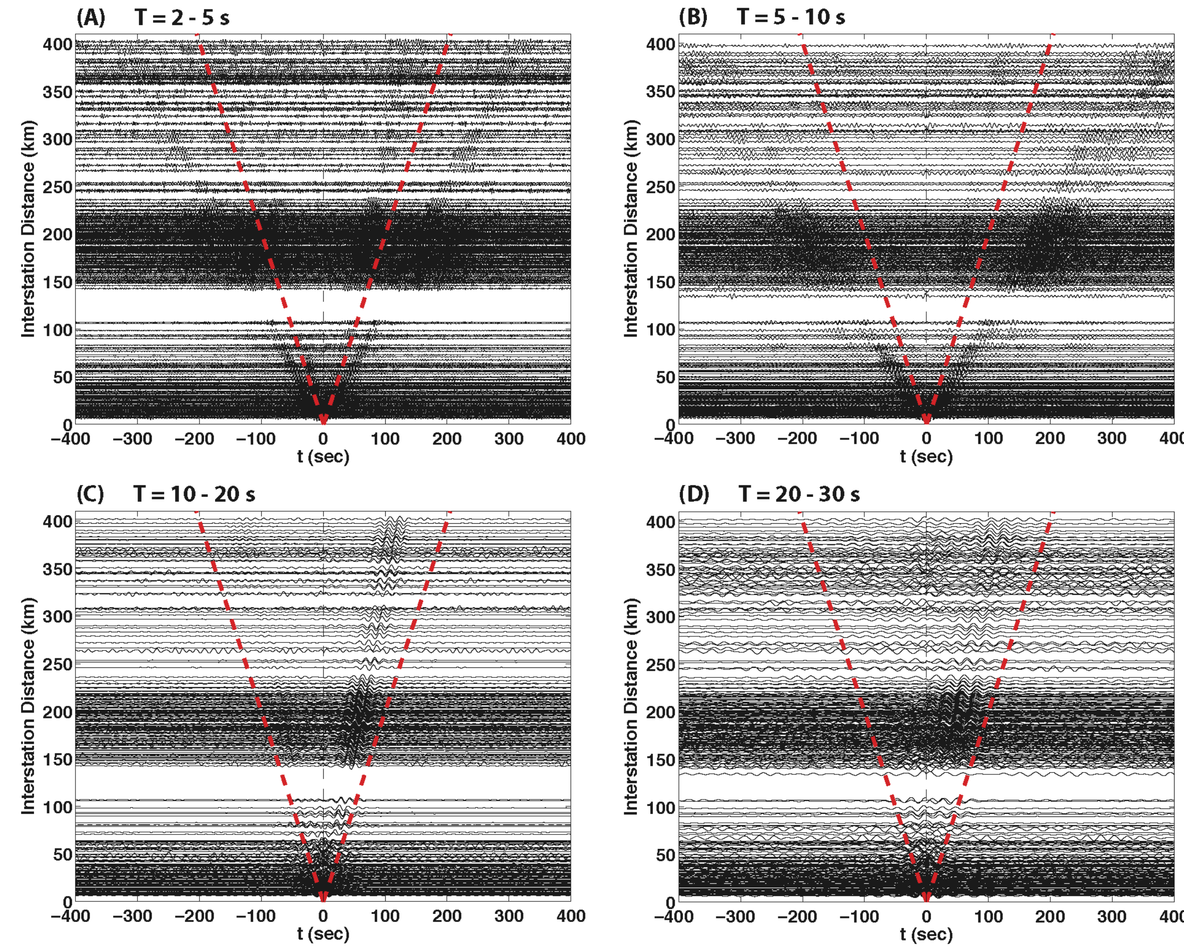
Ocean Bottom Seismometer

Inter-station cross-correlation of ambient noise

Cross-correlation results from noise recorded on land in Napoli for 1 hour and filtered at 3-15 Hz



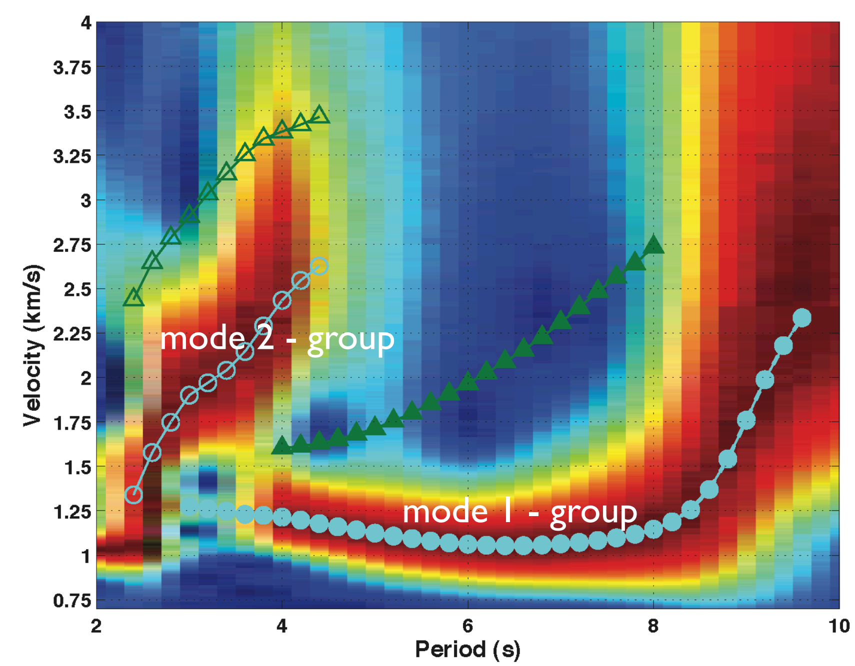
East Pacific Rise:
Year-long cross-correlation functions for all OBS station pairs



Positive time lag - noise propagation from 90°-270° azimuth.
red lines = 2 km/s propagation speed

Yao et al. (in press)

Test a new technique to map phase velocity dispersion and invert for Vs in shallow sediments in the ocean by recording noise on vertical component of ocean bottom seismometer for 1 year in Southern New England.



Spectogram for group-velocity dispersion from one OBS pair

Conclusions

- Complex interplay between pre-existing physiography and sediment delivery to the margin
- Basic Observations:
  - Smooth, simgoidal profiles contain relatively greater volume of unstable sediment on slope
  - Steep, oblique profiles contain relatively more unstable sediment on upper-slope and lower-slope/upper-rise
  - Morphological patterns can be used to identify where unconsolidated Quaternary sediment have accumulated
- Fluids may play a fundamental role in stability of the Atlantic margin (shelf edge everywhere and also on slope and rise of Southern New England?)

End