Seismic Hazard in Passive Margin Frontier Basins: Geological Estimates of the Frequency of Large Earthquake-Triggered Submarine Landslides in Orphan Basin, Offshore Canada*

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Abstract

Seismic hazard assessment for engineering design is important but challenging in frontier basins with low seismicity, such as the Canadian east coast offshore. Here the instrumental record of past earthquakes is short, and seismological estimates of recurrence suggest a Mw > 7 earthquake every 3 ka per 100 km length of continental slope, an estimate incorporated in the 2005 Building Code of Canada. Such estimates appear much higher than the frequency of slope failure in the same area. For example, near the 1929 Mw=7.2 Grand Banks earthquake and landslide, submarine landslides of similar size have occurred every 150-200 ka. Order of magnitude differences in estimates of seismic hazard are a cause for concern.

Ultra-high resolution seismic reflection profiles from the continental slope in the highly prospective Orphan Basin, off Newfoundland, reveal a stratigraphic record of large submarine slope failures back to 0.1 Ma. C-14 dating of Heinrich and ash layers in many piston cores provided chronology of seismic markers at ~3 ka resolution after 40 ka and ~5 ka resolution prior to 40 ka. Slump-generated turbidites on the basin floor have a distinctive petrology, sedimentology and distribution, with ~1 ka chronologic resolution. Large slope failures occurred synchronously over margin lengths of 50-330 km. In the past 0.1 Ma, 5 failures affected a >120-km-long sector of the slope and 15 failures were large enough to be recognised in seismic and/or cores. We present arguments that the widespread failures were earthquake triggered: other mechanisms for triggering laterally extensive synchronous failure do not apply.

Triaxial shear measurements on cores from the continental slope show a c/p ratio of typical sediment of 0.48, implying considerable stability. The c/p ratio falls to as low as 0.25 at some weak layers based on shear vane measurements. Relationships between seismic

acceleration and c/p are examined for the 1929 Grand Banks earthquake and compared with recent data from the US Atlantic margin. This indicates that the larger Orphan Basin slope failures represent earthquakes ranging from Mw ~6.5 to ~7.5 with a mean recurrence interval for "large" earthquakes of 20 ka. This compares with the seismological estimate of a 1.5 ka recurrence interval for a Mw = 7 earthquake somewhere in this sector of the continental margin. This study demonstrates a methodology for seismic hazard assessment in other passive margin petroleum basins.

Selected References

ten Brink, U.S., R. Barkan, B.D. Andrews, and J.D. Chaytor, 2009, Size distributions and failure initiation of submarine and subaerial landslides: Earth and Planetary Science Letters, v. 287/1-2, p. 31-42.

Mazzotti, S. and J. Adams, 2005, Rates and uncertainties on seismic moment and deformation in eastern Canada: Journal of Geophysical Research, v. 110/B9.

SEISMIC HAZARD IN PASSIVE MARGIN FRONTIER BASINS:

Geological estimates of the frequency of large earthquake-triggered submarine landslides in Orphan Basin, offshore Canada

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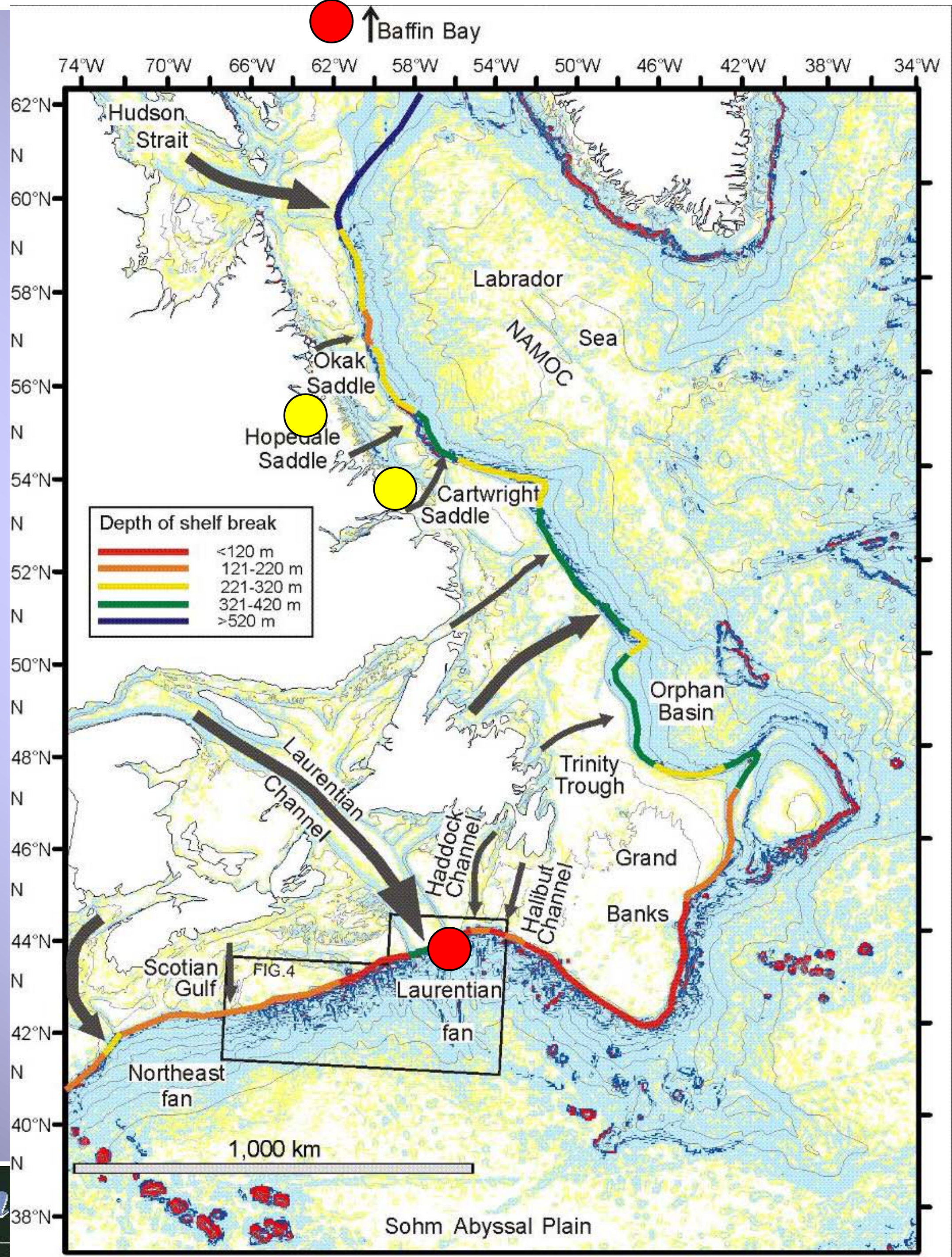
Seismic hazard assessment in basins with low seismicity

- needed for risk assessment and engineering design
- in the Canadian east coast offshore, only a short instrumental record
- seismological estimates of a Mw>7 earthquake every 3 ka per 100 km length of continental slope
- this appears inconsistent with the geological record

Passive margin earthquakes

- 1931 Baffin Bay Mw = 7.3
- 1929 Grand Banks Mw = 7.2
- 1809, 1836 felt on Labrador coast, epicentre unknown



In this study, we show:

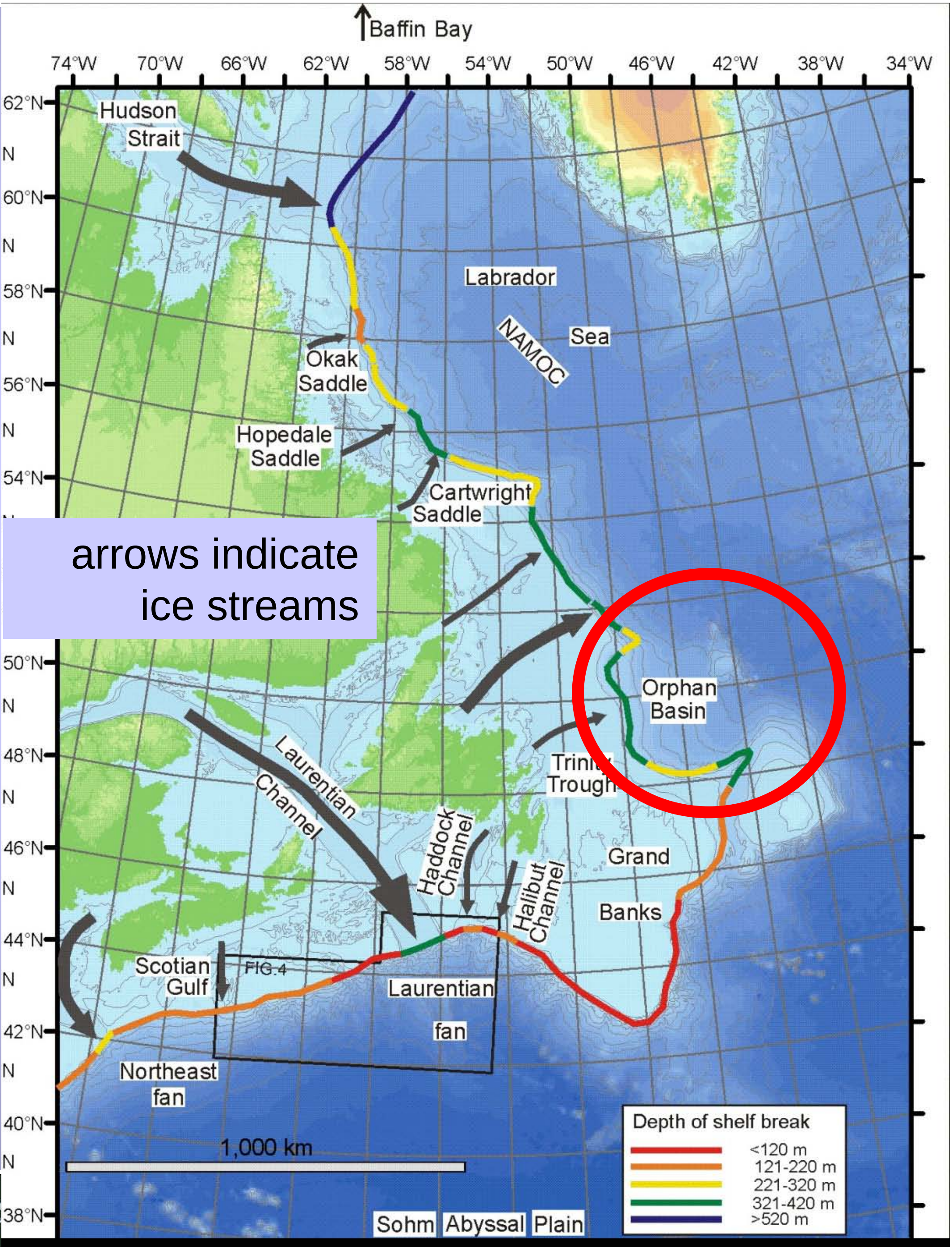
- high-resolution chronology of failures in the past 0.1 Ma
- several failures are synchronous over tens to hundreds of kilometres of slope
- such failures are interpreted as earthquake triggered: they show no clear correlation with other potential forcing factors
- earthquake magnitudes can be estimated from failure length by comparison with 1929
- they imply an order of magnitude lower seismic risk compared with the Canada Building Code

The take-home message

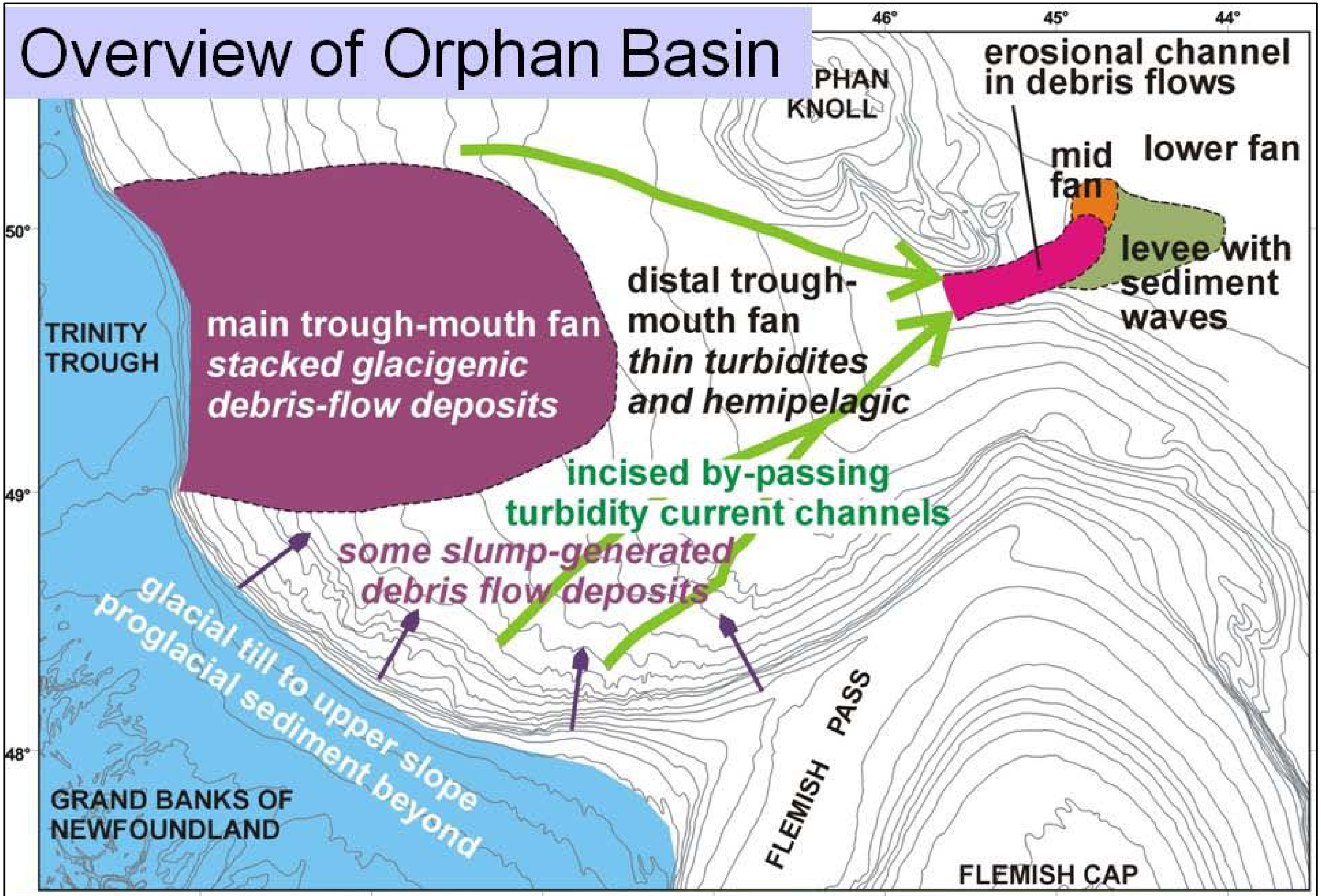
Orphan Basin

- one wildcat well in 2006-07
- another to be drilled this year
- ~ 2500 m water depth

arrows indicate ice streams



Overview of Orphan Basin

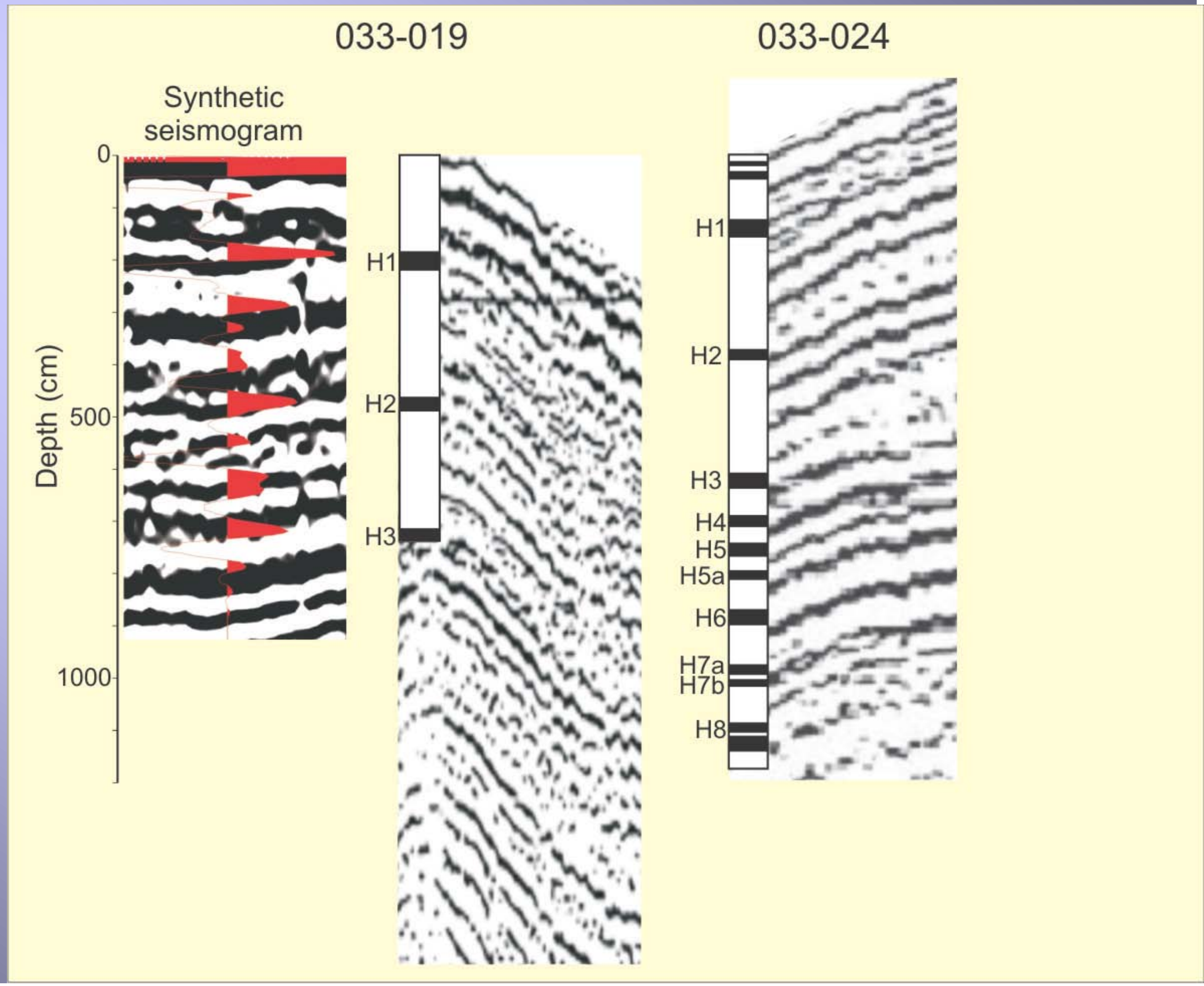


Geological Survey of Canada
A T L A N T I C

Notes by Presenter: Reddish bars show area of next two slides.

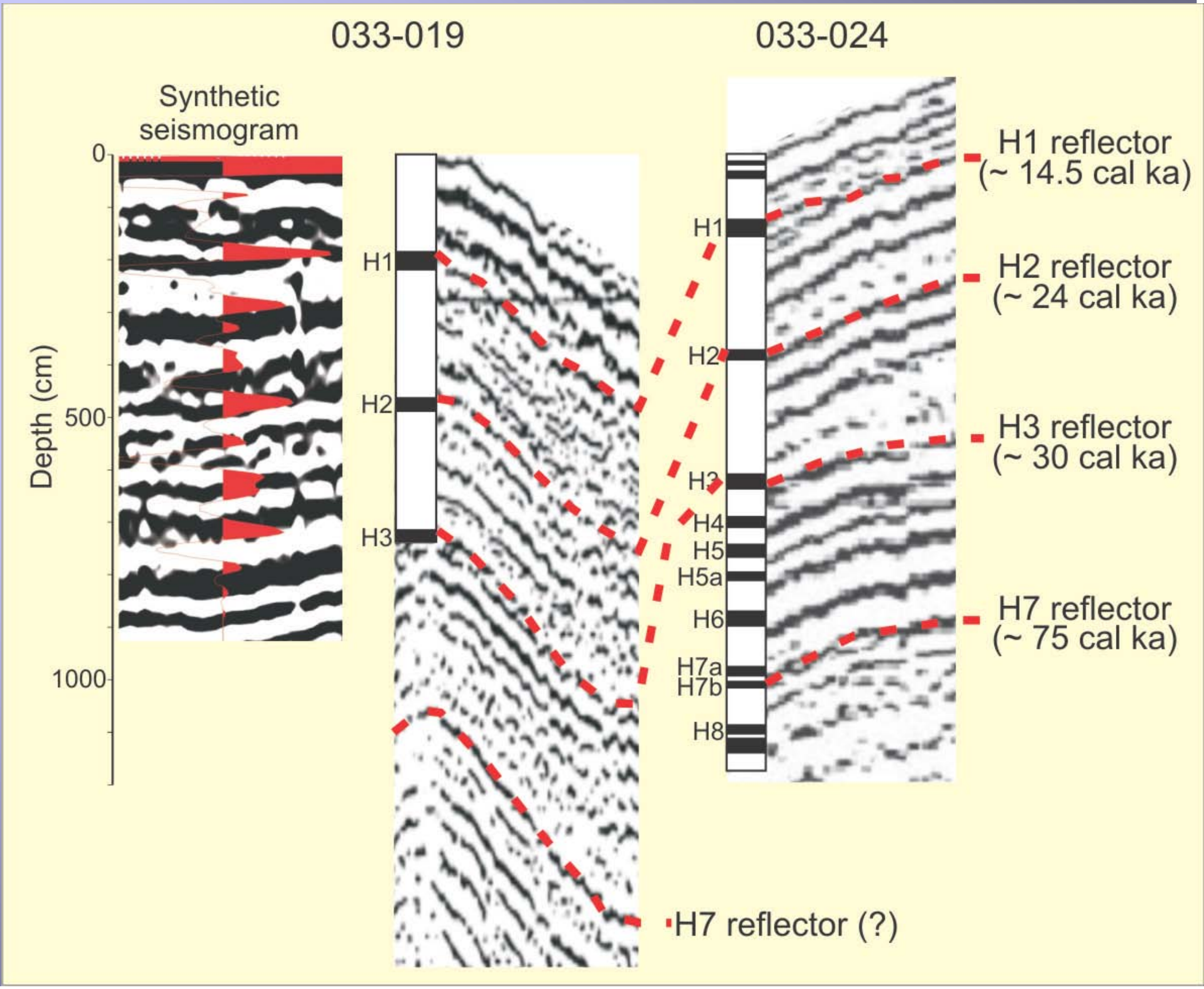
Superb stratigraphic control

- Huntec ultra-high resolution sparker profiles, resolution better than 1 m



Superb stratigraphic control

- Heinrich layers every 7 ka in late Pleistocene; high detrital carbonate content gives strong impedance contrast



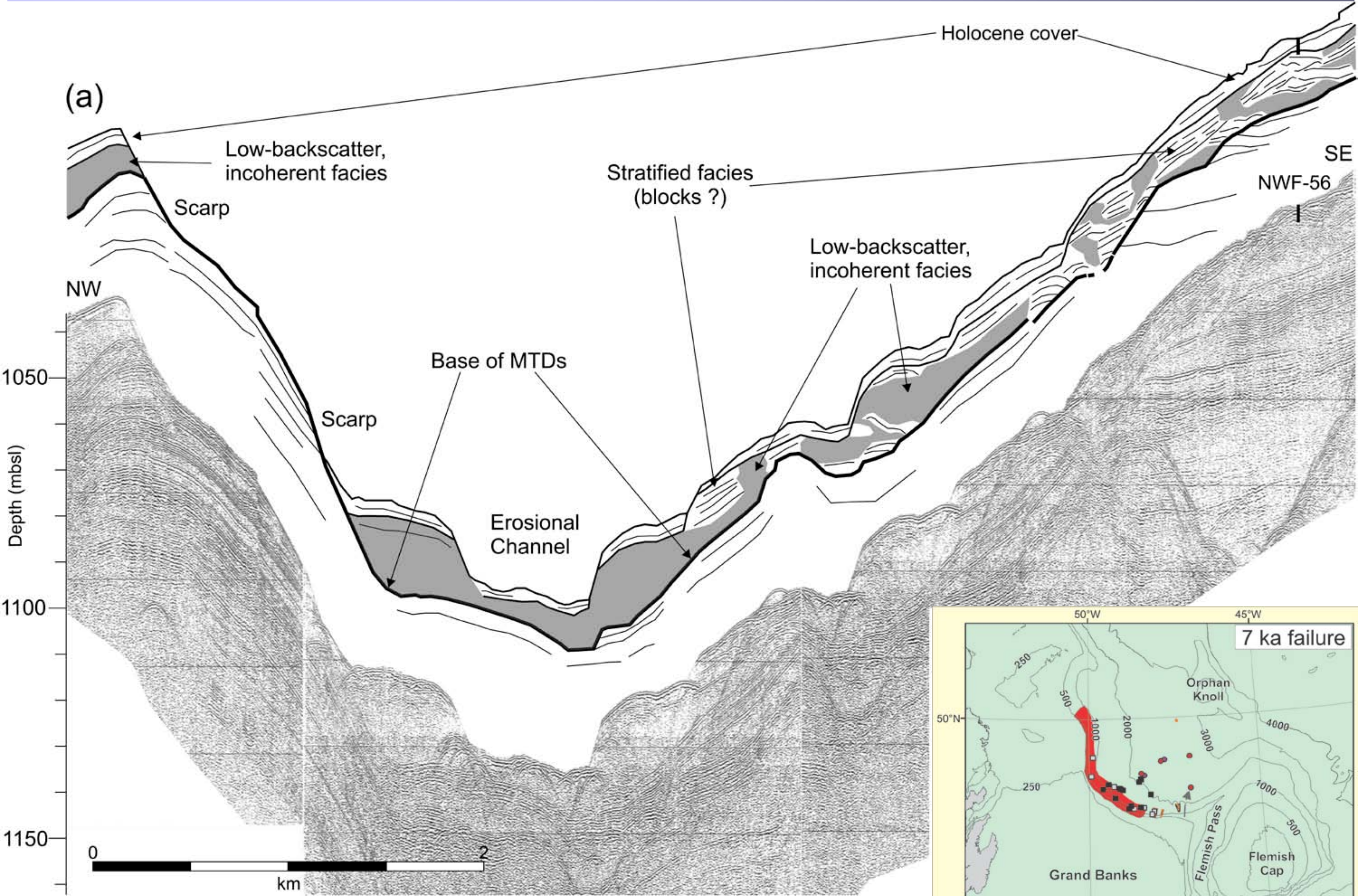
Superb stratigraphic control

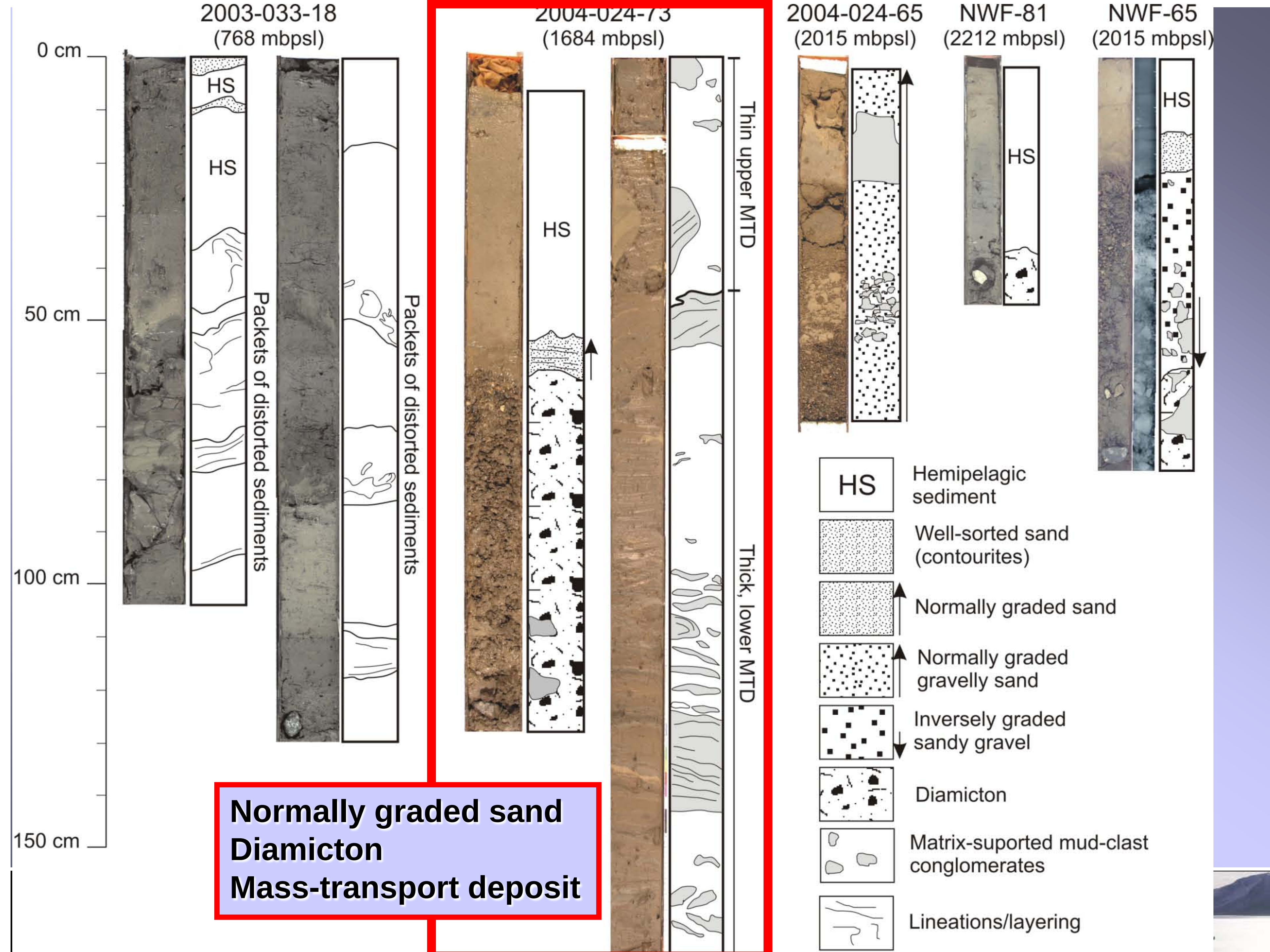
- Dating resolution better than 1 ka back to > 40 ka based on cores
- Where seismic correlation away from dated cores, age resolution estimated at < 5 ka

Evidence for large earthquakes

- widespread synchronous failure in multiple drainage systems
- characteristic turbidite deposits including gravel and diamict from retrogressive failure into outer shelf till

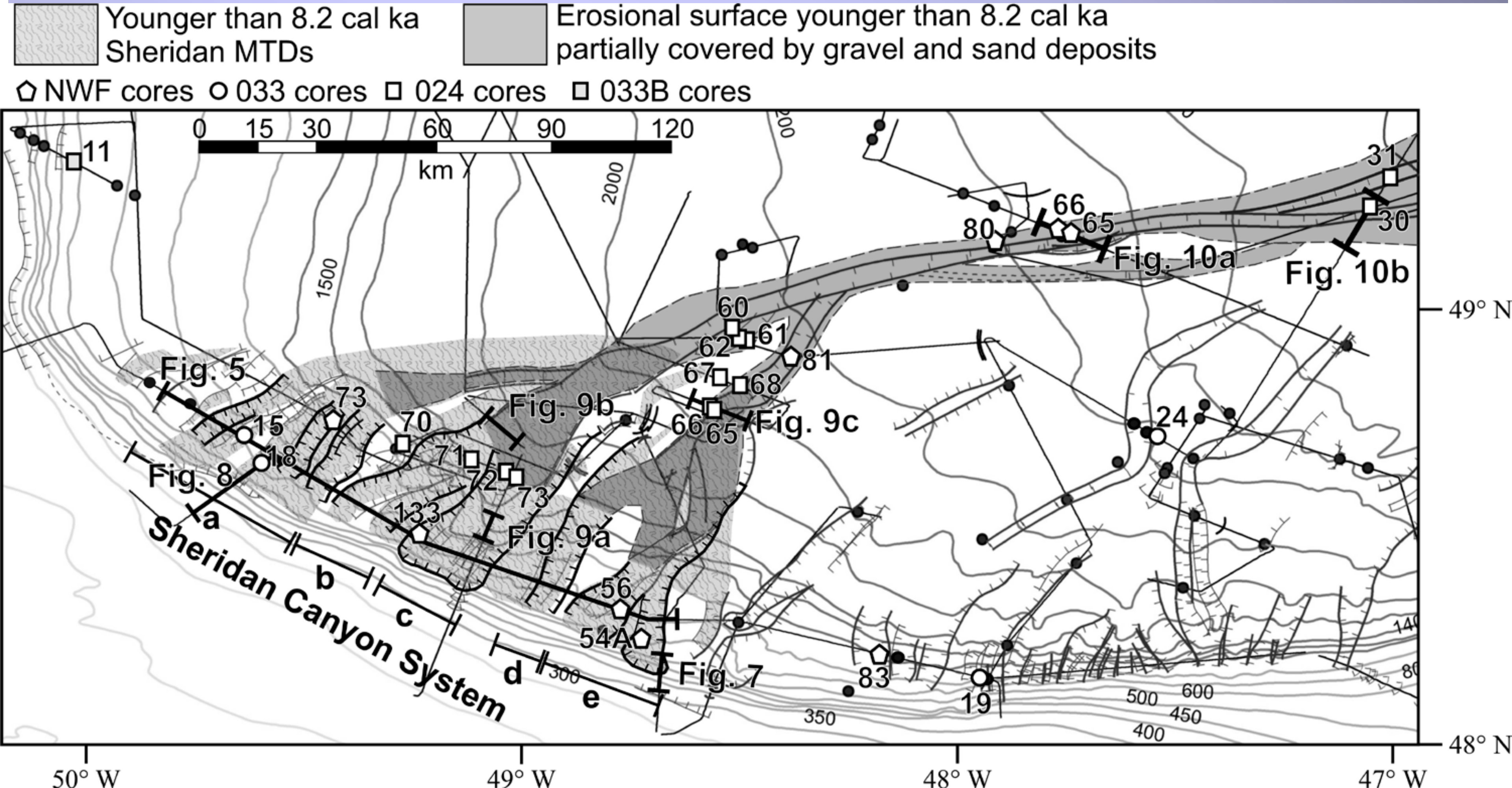
Example: the 7 ka Sheridan failure



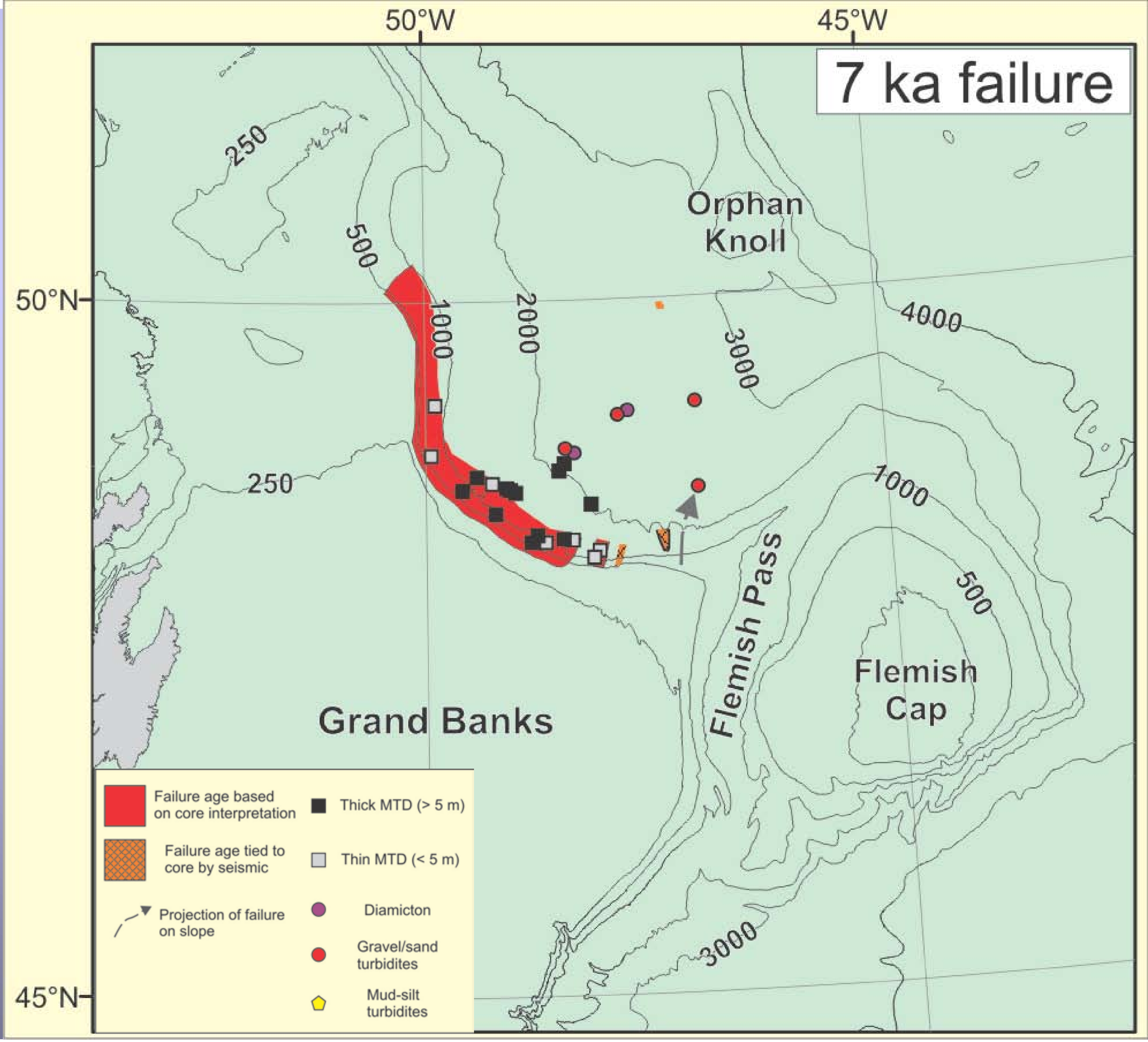


2003-033-18
(768 mbpsl)
2004-024-73
(1684 mbpsl)
2004-024-65
(2015 mbpsl)
NWF-81
(2212 mbpsl)
NWF-65
(2015 mbpsl)
0 cm
50 cm
100 cm
150 cm
HS
Packets of distorted sediments
Thin upper MTD
Thick, lower MTD
Hemipelagic sediment
Well-sorted sand (contourites)
Normally graded sand
Normally graded gravelly sand
Inversely graded sandy gravel
Diamicton
Matrix-suported mud-clast conglomerates
Lineations/layering
Normally graded sand
Diamicton
Mass-transport deposit

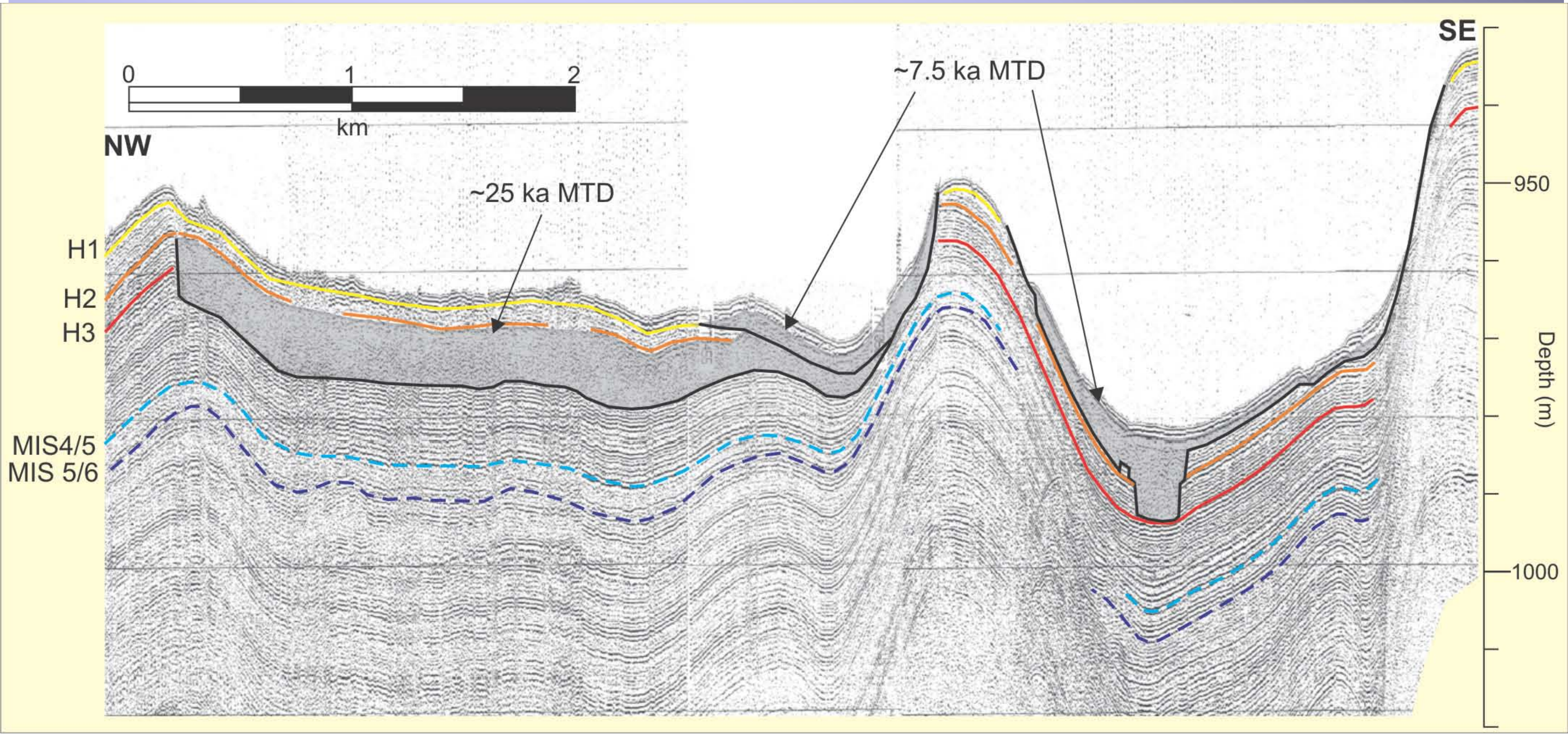
- retrogressive gullies heading at limit of till on the outer shelf
- gullies lead to channels on basin floor



- failure present along 300 km of slope
- MTDs, diamict, gravel turbidites on basin floor

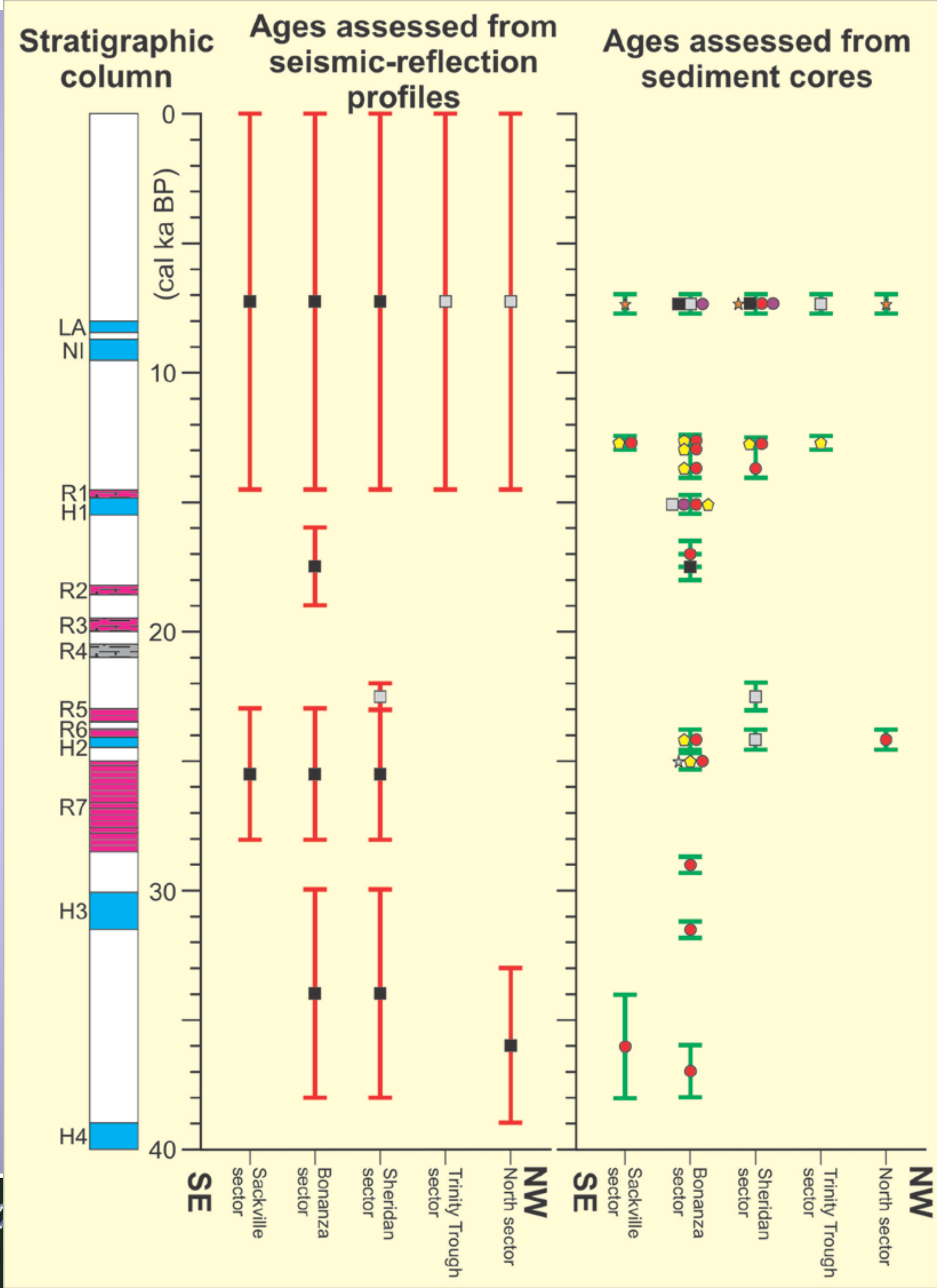


- older slope failures recognised in seismic and dated at their margins from the regional seismic stratigraphy



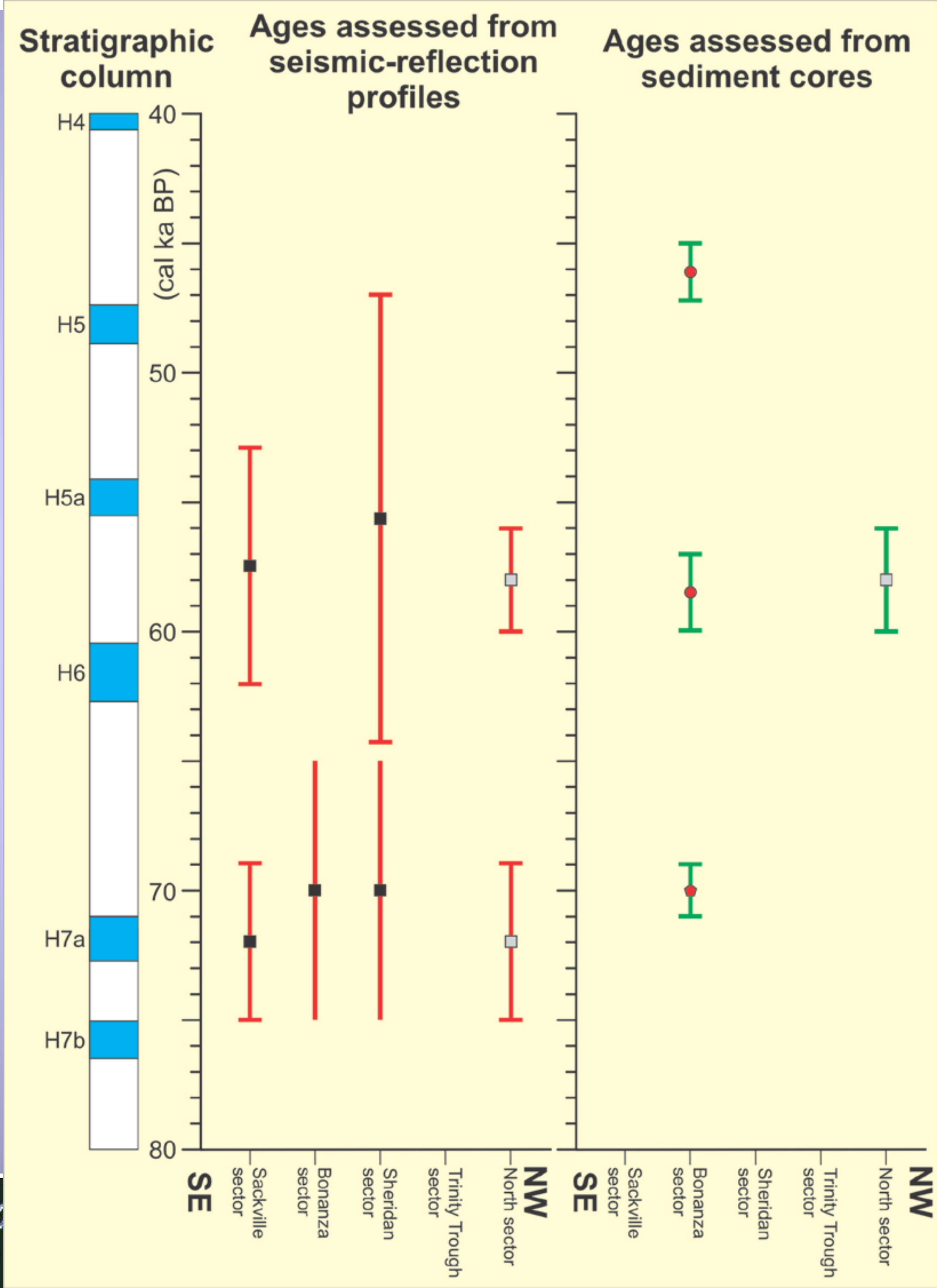
The inferred earthquake record

- we use similar data from seismic and cores to infer rare widespread failure events



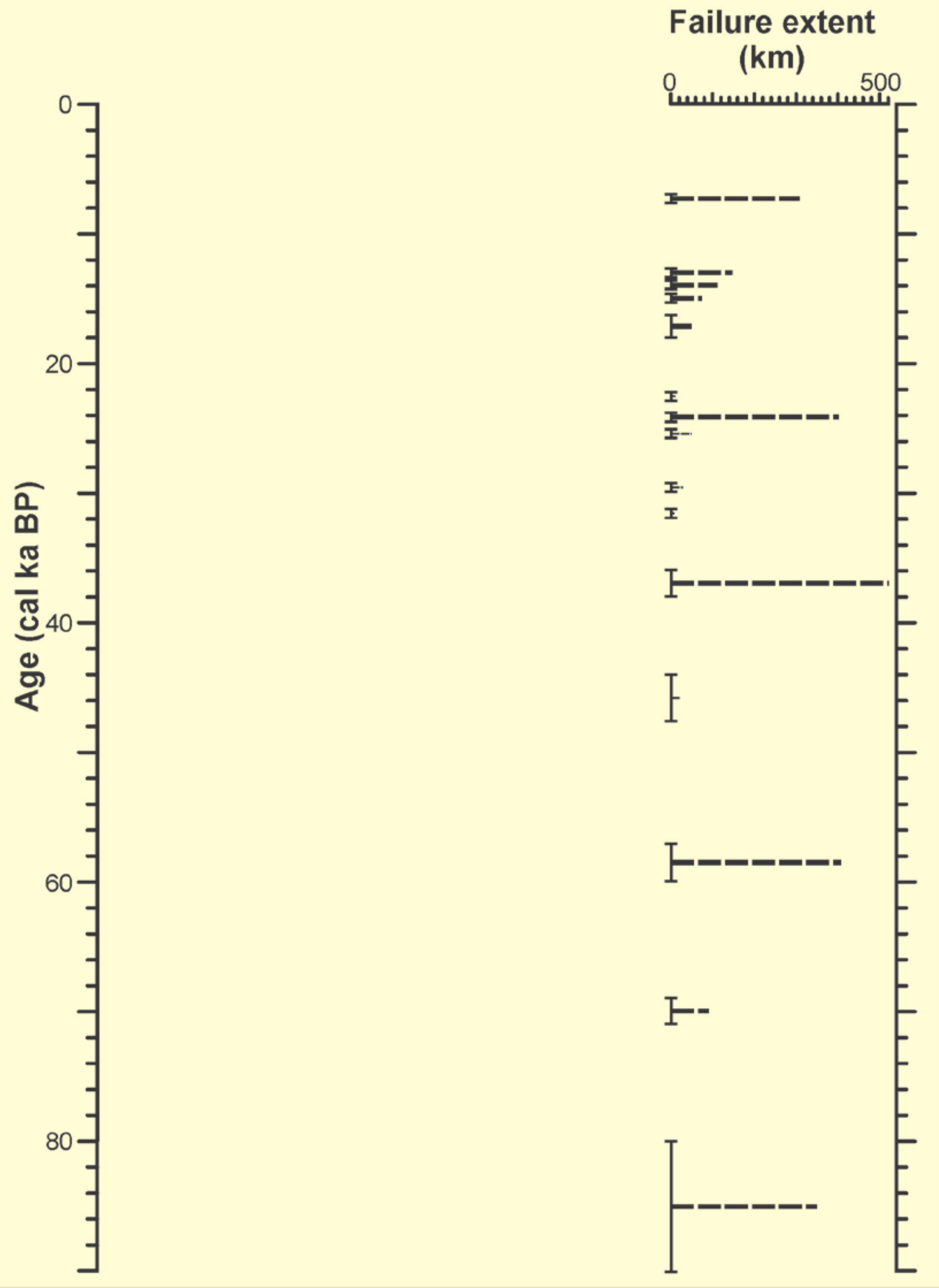
The inferred earthquake record

- the 40-80 ka record: less core control



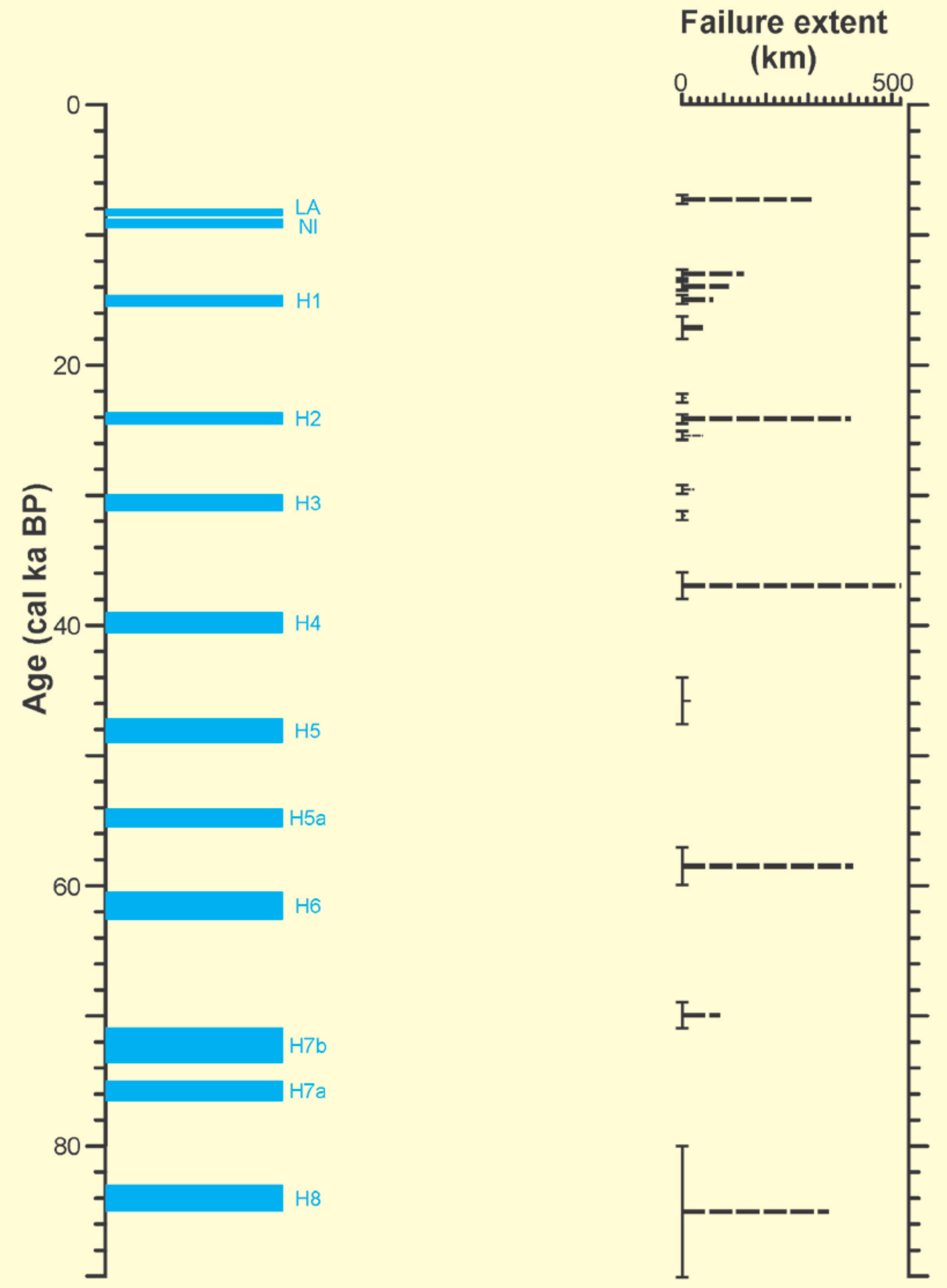
The inferred earthquake record

- age estimates and along-slope extent of failures



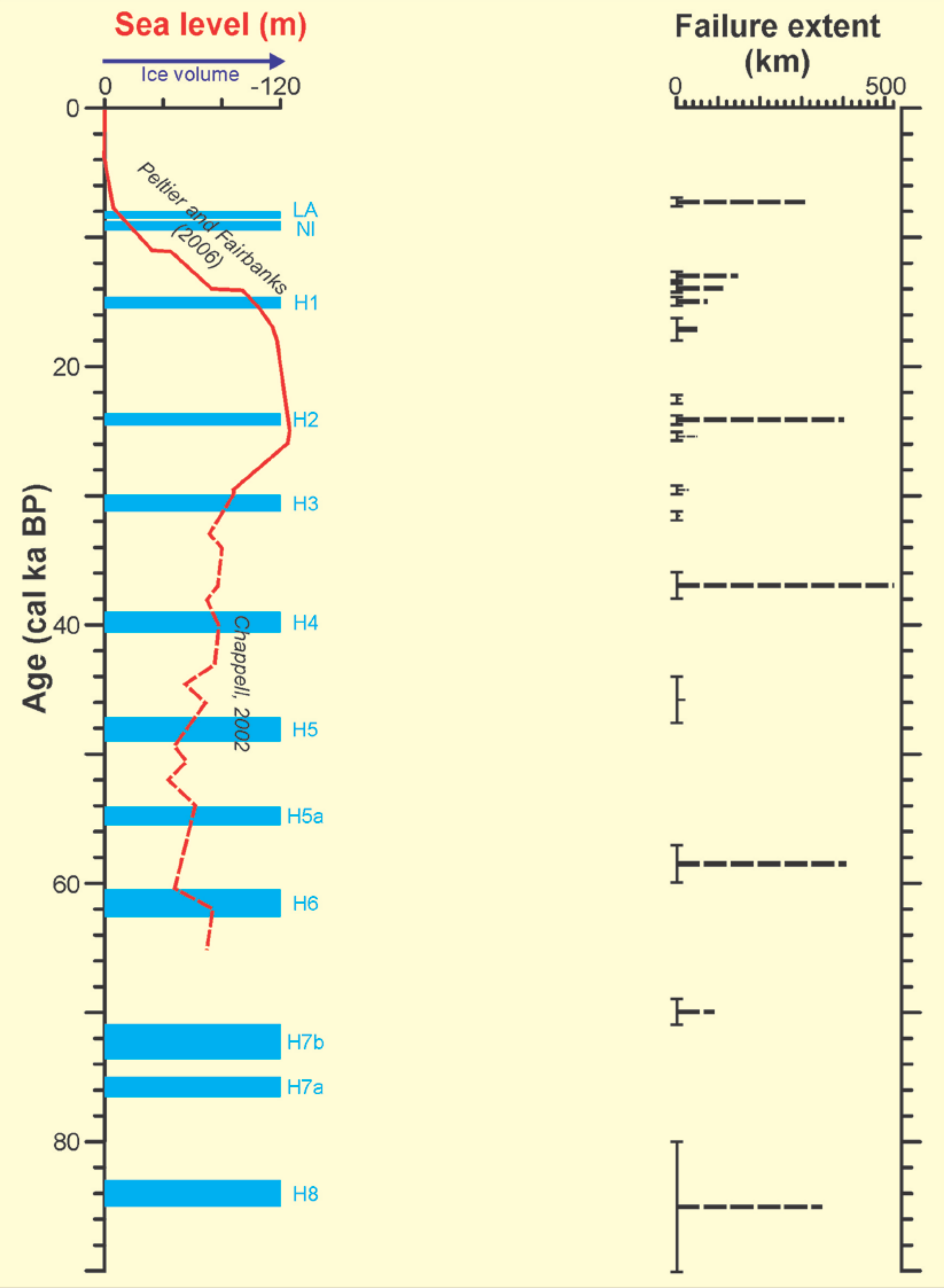
The inferred earthquake record

- in relation to stratigraphic markers
- ?? correlation with Heinrich events



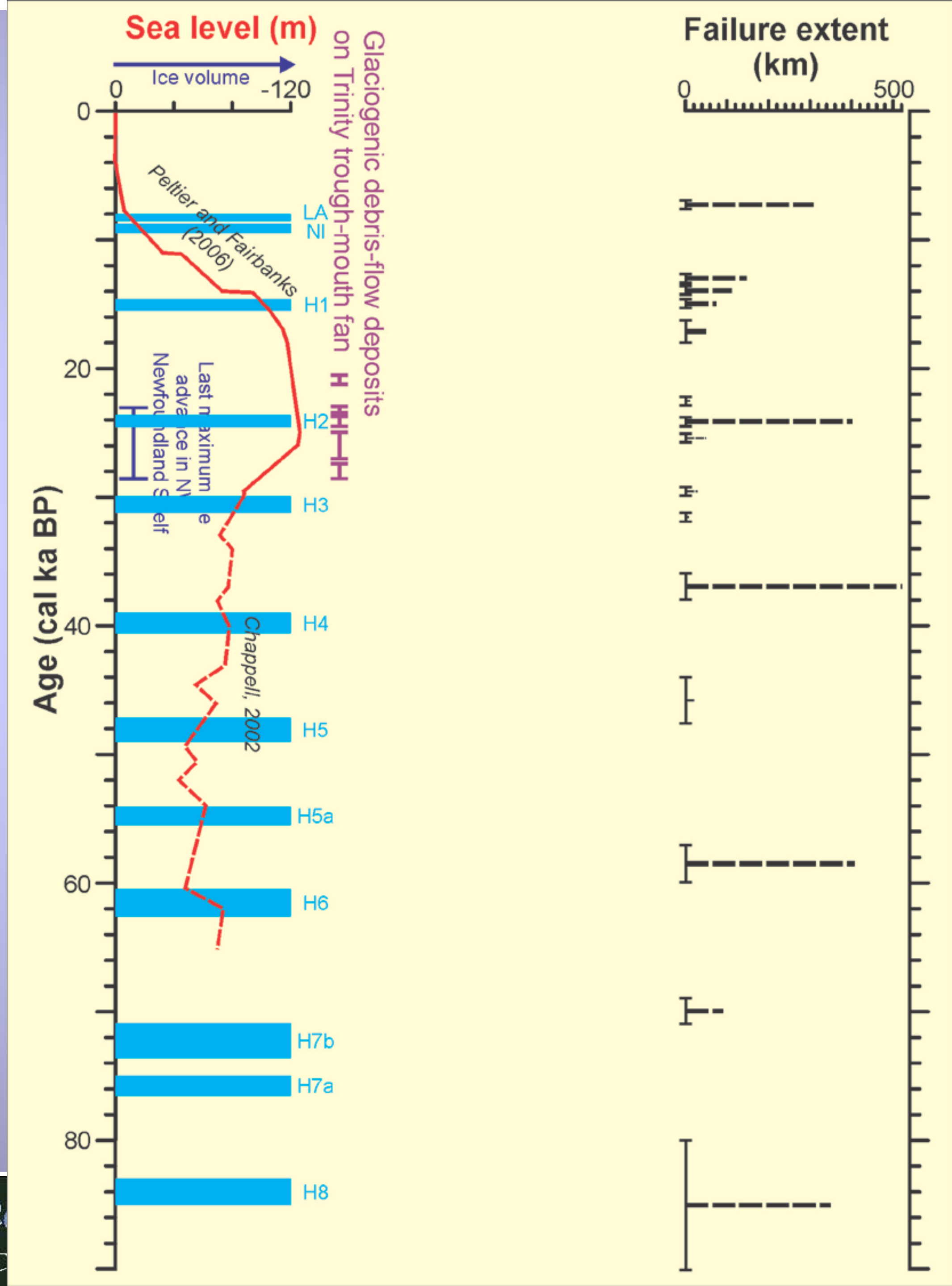
The inferred earthquake record

- no obvious relationship to sea level change



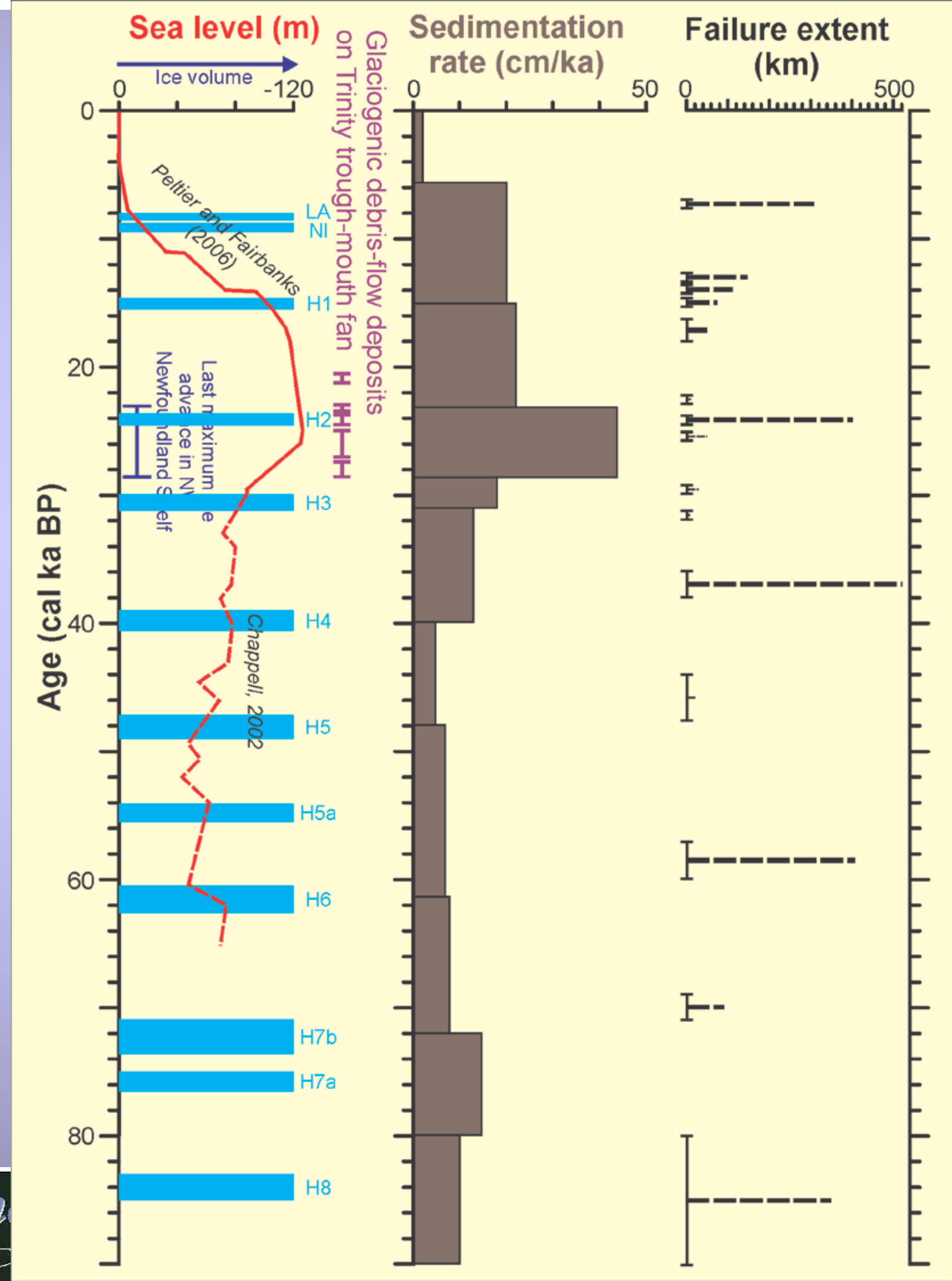
The inferred earthquake record

- or to shelf-edge glaciation
- small failures more common during deglaciation



The inferred earthquake record

- no obvious relationship to regional sedimentation rates
- *large events infrequent*

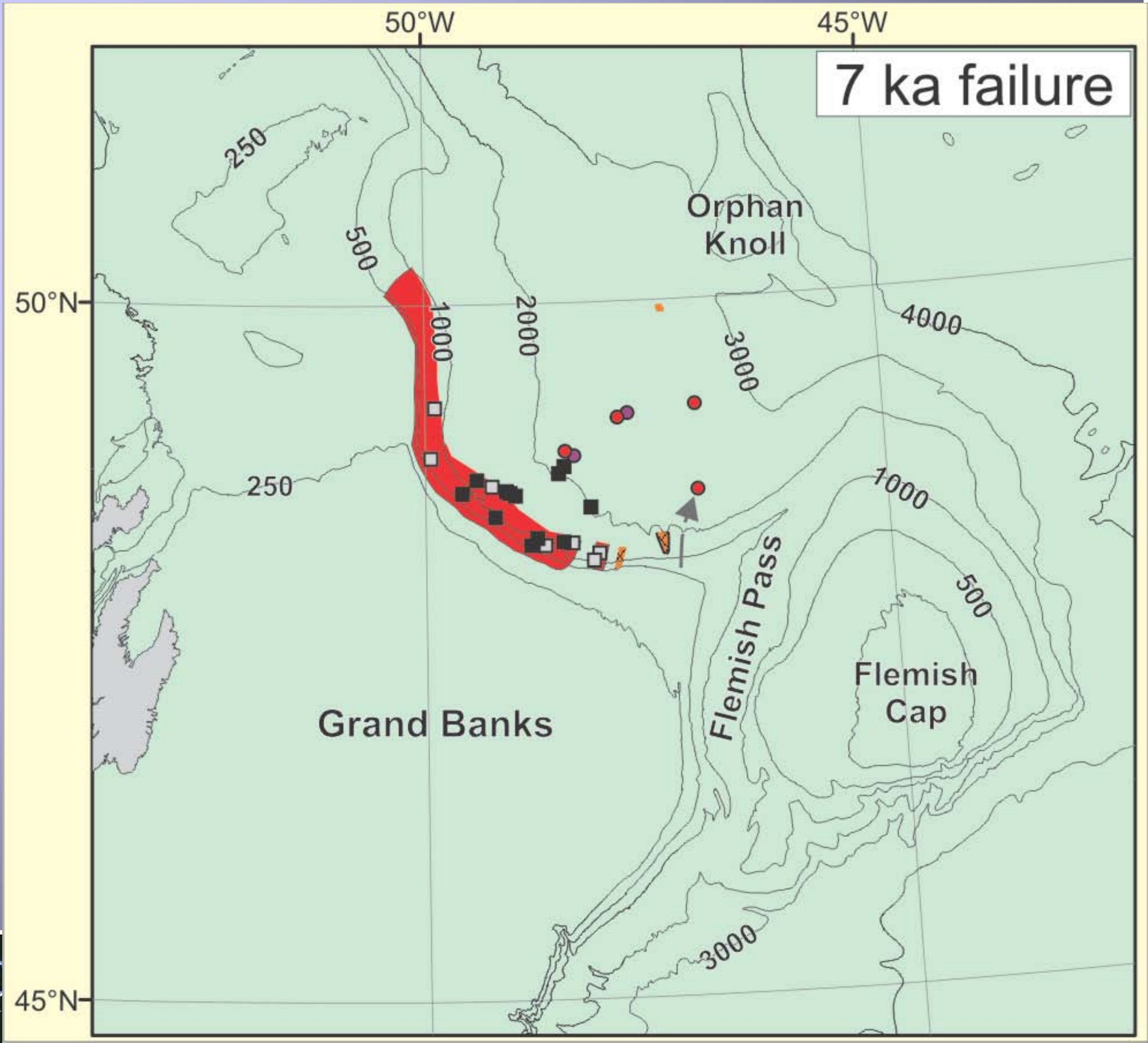


Are failures of similar age to within seismic resolution (5 ka) synchronous?

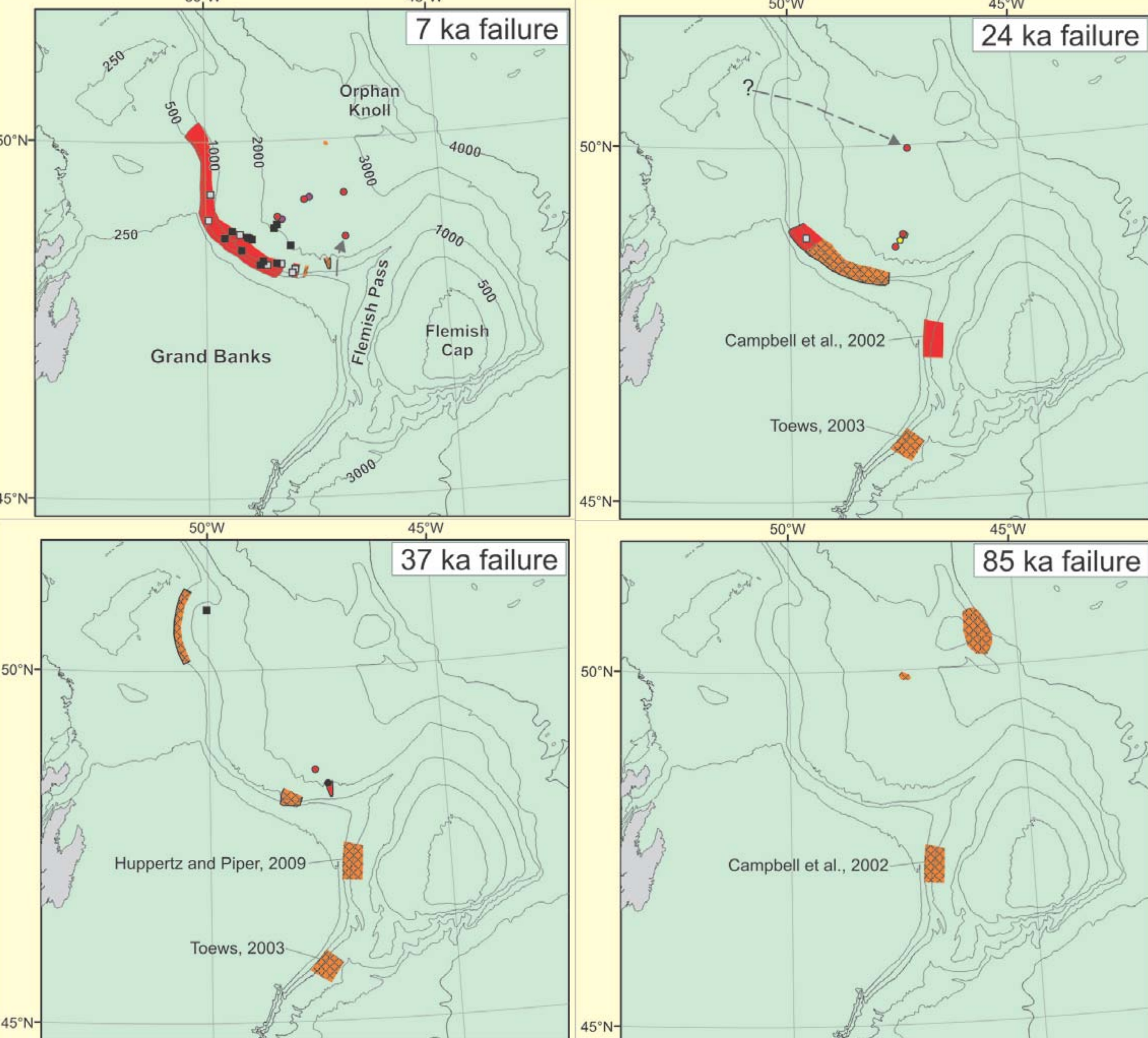
- cannot be certain
- record of both failures and failure-triggered turbidites suggests that large events are infrequent
- Occam’s Razor argues they are synchronous
- if not, our lengths of failed slope are overestimated

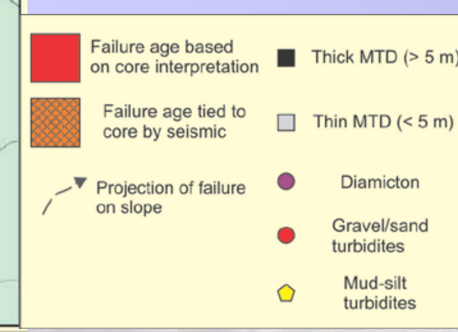
The distribution of earthquakes

- The extent of the 7ka Sheridan failure is 300 km along the margin



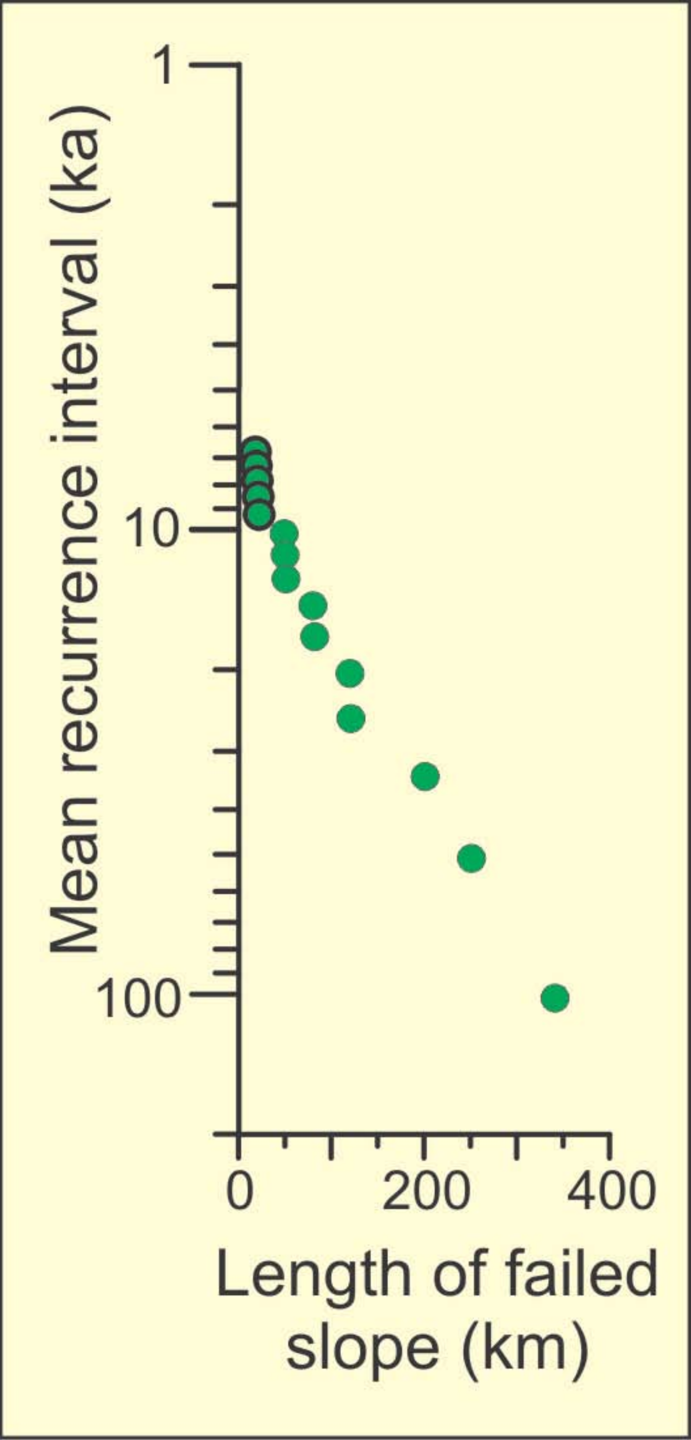
Similar lengths determined for older large failures





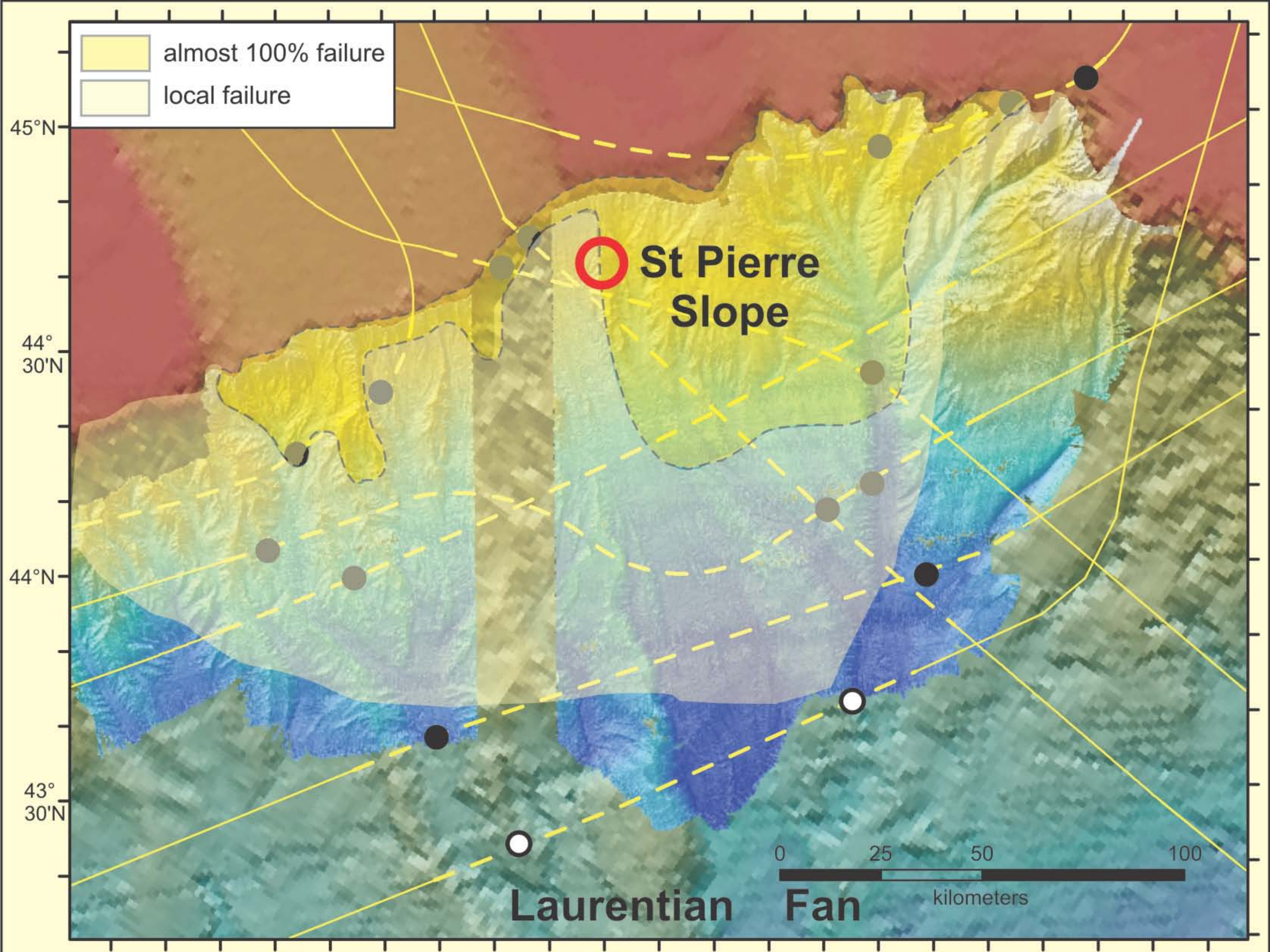
Extent of failure and recurrence interval

- by ordering length of failed slope in Orphan Basin for the past 120 ka and determining frequency, get a straight line plot



Extent of failure and recurrence interval

- can we relate the length of failed slope to the magnitude of the earthquake ?
- calibrate with the Mw=7.2 1929 Grand Banks earthquake
  - about 270 km of slope failed retrogressively
  - similar gradients and topography to Orphan Basin slopes
  - sediments may be weaker because gassier, but are similar at the margins of the failure

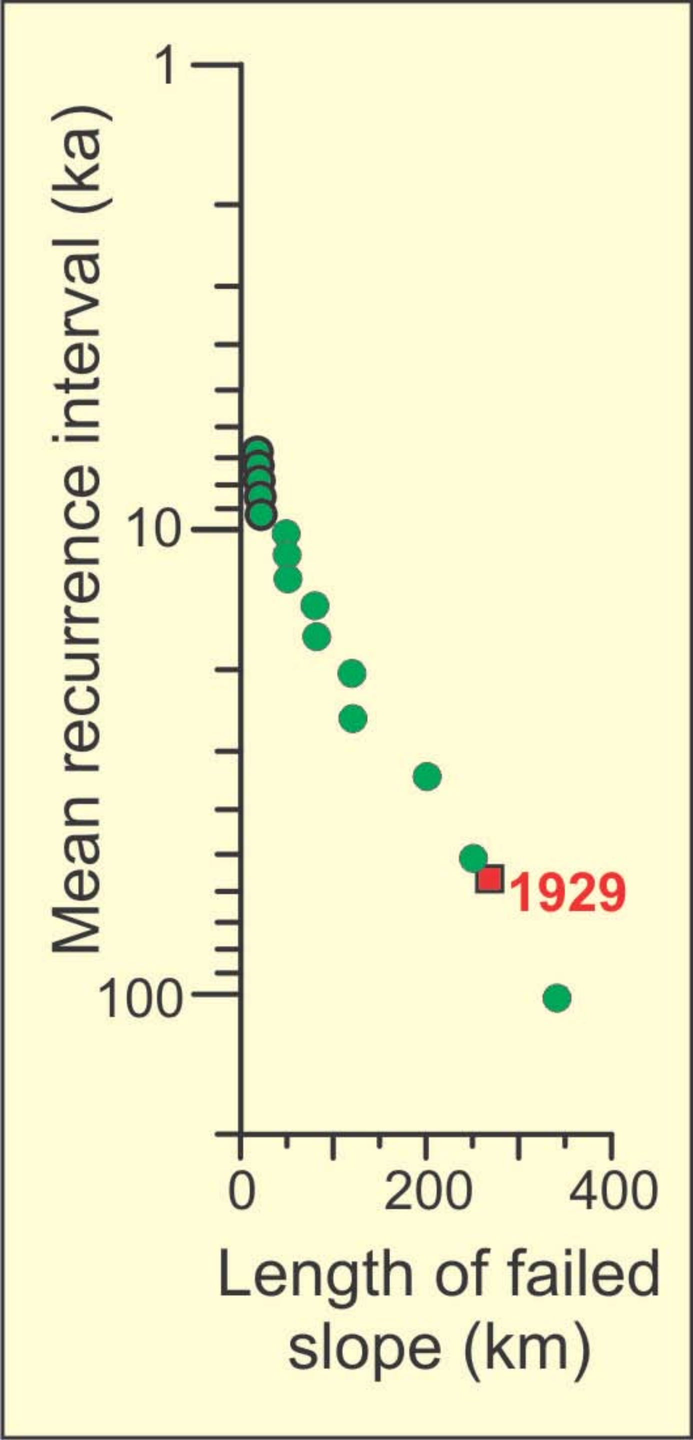


almost 100% failure
local failure
45°N
44° 30'N
44°N
43° 30'N
St Pierre Slope
Laurentian Fan
0
25
50
100
kilometers

Extent of failure and recurrence interval

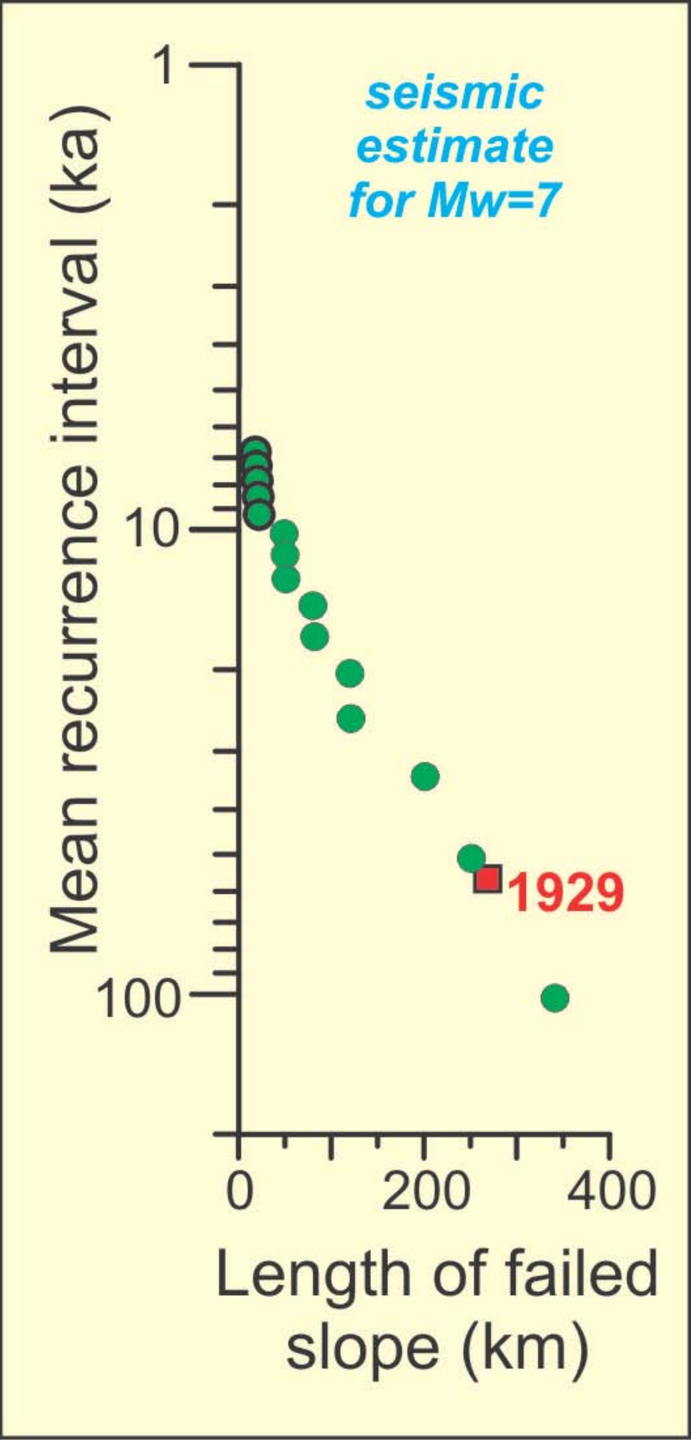
At the site of the 1929 Grand Banks earthquake

- minimum recurrence interval of 1929 is ~ 50 ka for the last 200 ka
- more like 150-200 ka recurrence over the last ~ 1 Ma
- greater role of glacial loading since MIS 7 ?



Extent of failure and recurrence interval

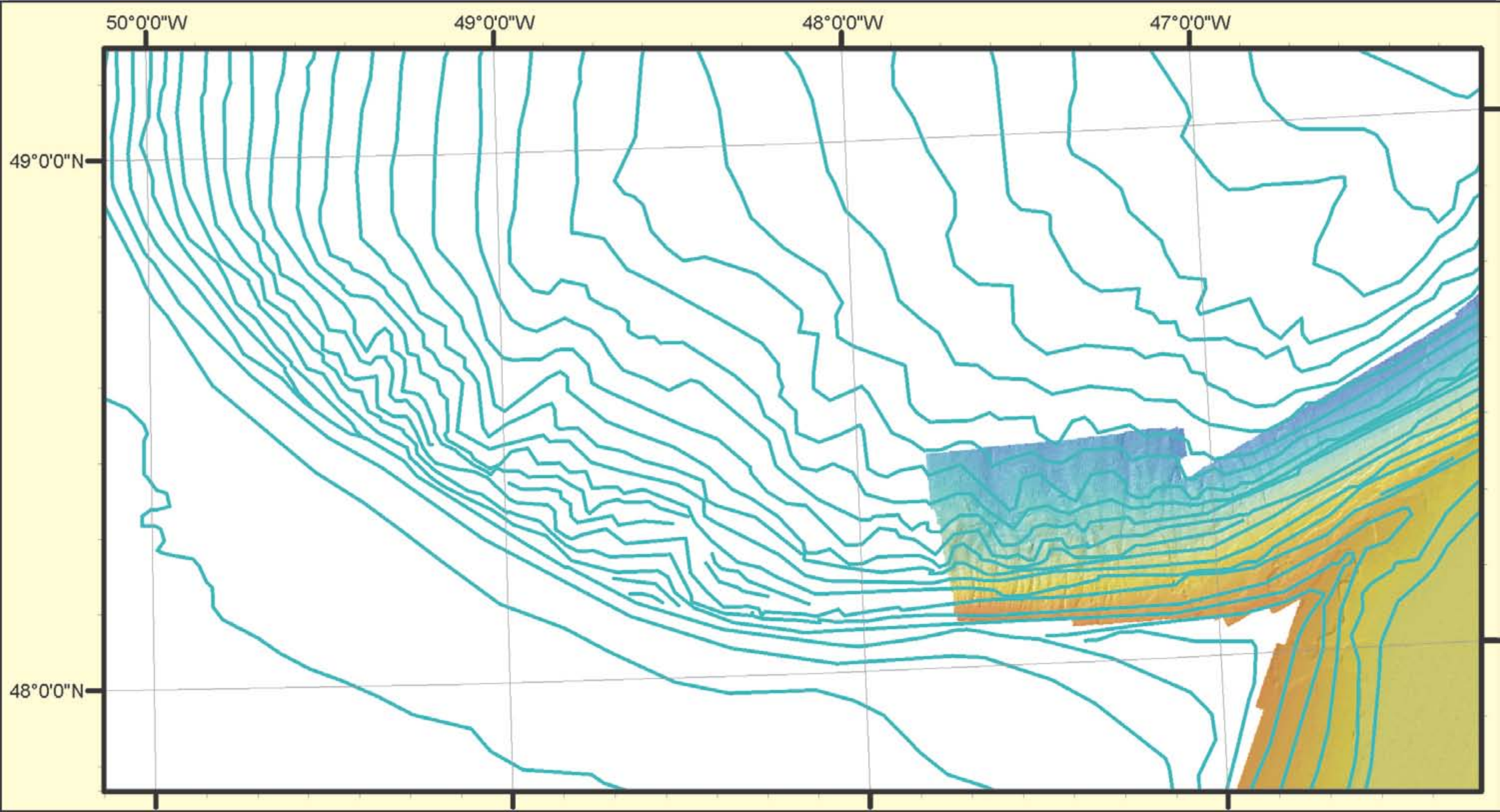
- quite different from the seismically proposed recurrence interval of one Mw = 7 earthquake per 100 km of margin every 3 ka
- even though we have no precise way of calibrating magnitude from failure length



Earthquakes, failure, and sediment strength on the continental slope

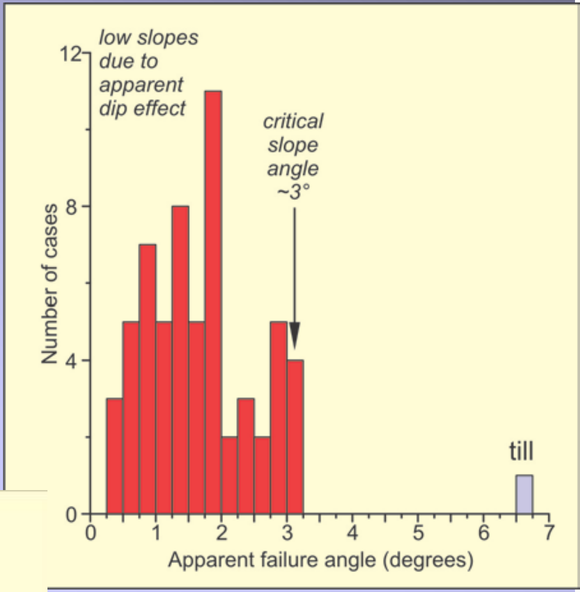
- Failure is essentially a consequence of:
  - gradient
  - magnitude of seismic acceleration
  - sediment strength

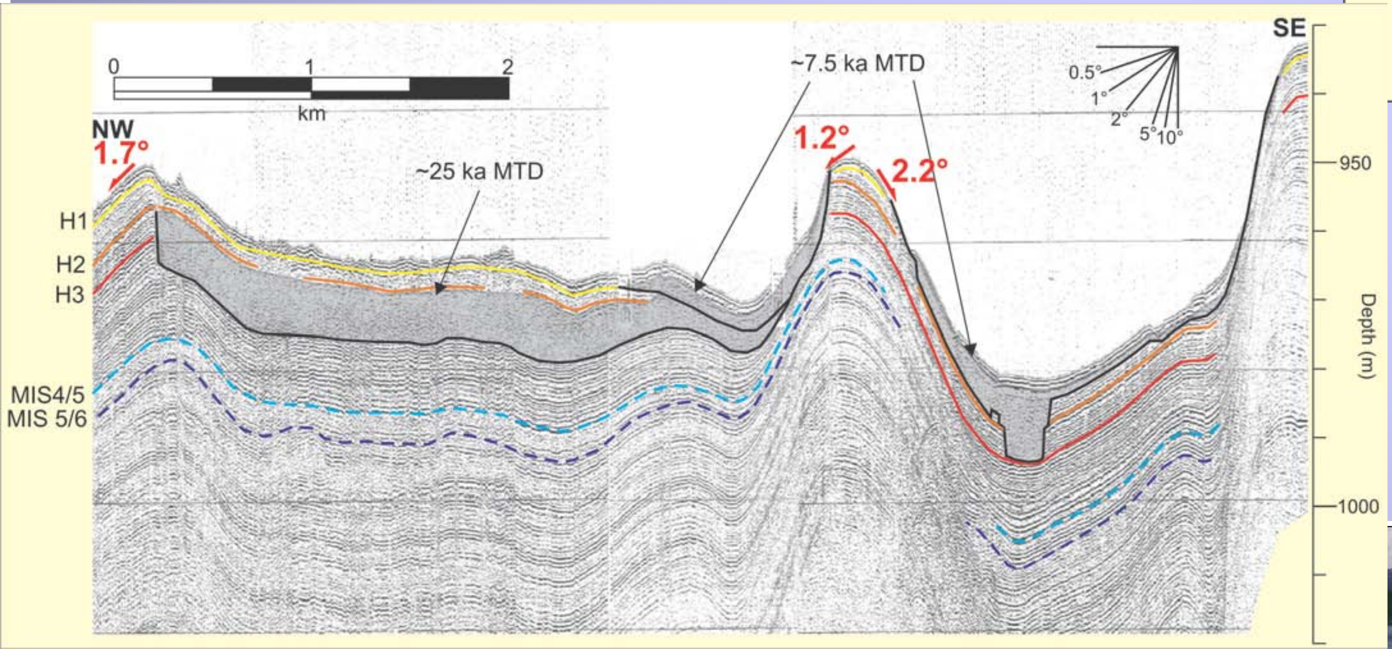
- Gradient variable: mean slope is < 3° but gradient on canyon/valley walls much steeper
- Local gradients steep enough to initiate failure with 10% seismic acceleration (Mw > ~ 6.5), widespread potential for retrogression



Earthquakes, failure, and sediment strength on the continental slope

- Apparent slope angle at which retrogressive failure ends (based on seismic profiles)

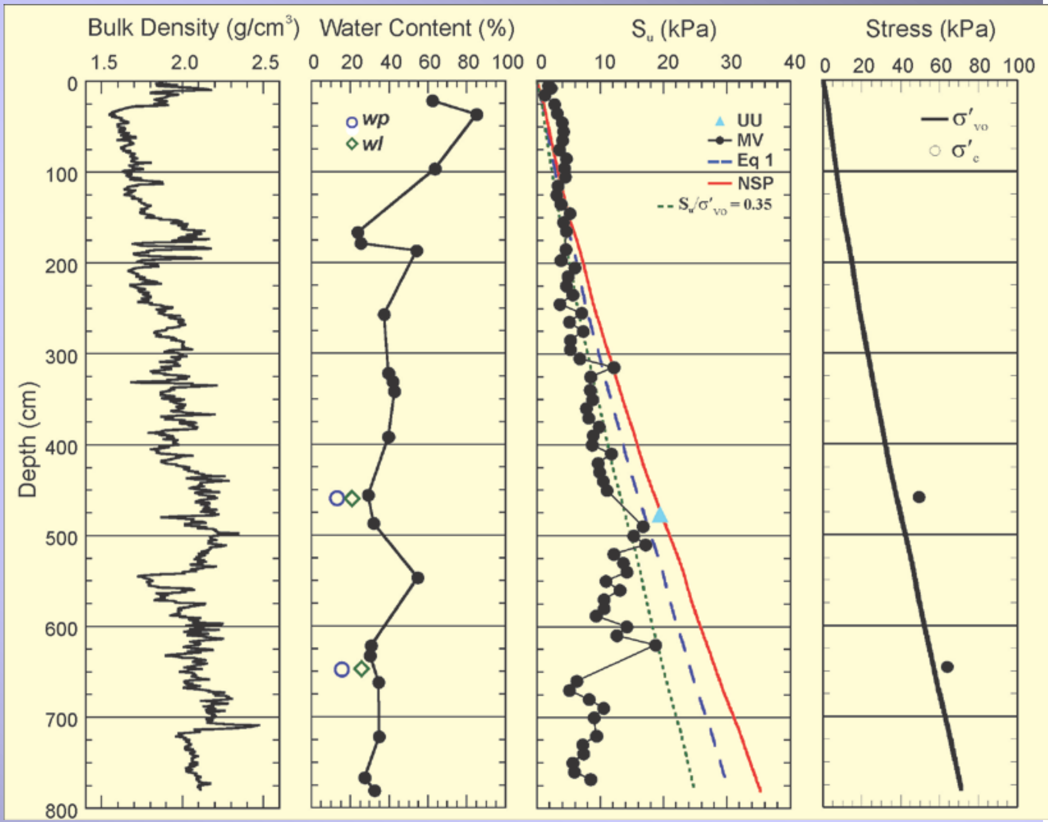




- Critical angle 3° for end of retrogression

Earthquakes, failure, and sediment strength on the continental slope

- Strength properties in Orphan Basin are in no way unusual
- *Su/σ′ᵥ* (ratio of undrained shear strength to vertical overburden stress) averages 0.35 from miniature shear vane, 0.48 from CIU tests
- compares with values of 0.33-0.40 within the outer failure zone from 1929



Earthquakes, failure, and sediment strength on the continental slope

- Based on ten Brink et al. (2009), a 100 km length of failure corresponds to:
  - M = 6.8 for $Su/\sigma'_v = 0.2$
  - M = 7.5 for $Su/\sigma'_v = 0.3$
  - M = 6.4 based on comparison with the 1929 failure
- Maximum possible magnitude on Canadian margin M = 7.6 (Mazzotti & Adams 2005)
- a 2 point change in magnitude (e.g. M = 5.6 to M = 7.6) is equivalent to a 10-fold increase in failure length (ten Brink et al. 2009).
- this is probably the range represented in Orphan Basin

Earthquakes, failure, and sediment strength on the continental slope

- mean recurrence interval of 20 ka for earthquakes of Mw > 6.5 to 7 in Orphan Basin
- compare with estimates of 1.5 ka for Mw > 7 based on seismological criteria
- why the discrepancy ?
  - failures underestimate seismicity: inconsistent with seismic accelerations in Mw = 7 earthquakes
  - seismic strengthening (Lee, 2004): not supported by geotechnical measurements
  - seismological estimates too high

In conclusion

- The seismic risk estimated from major submarine landslides is an order of magnitude less than the risk estimated from the short historical record of seismicity