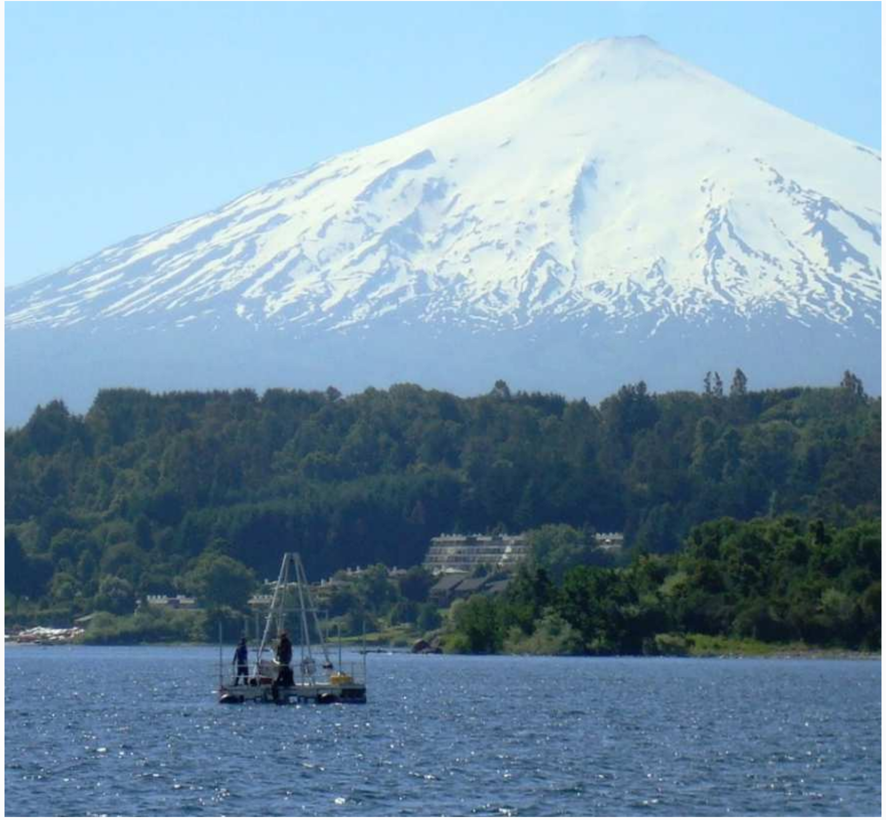
Seismic strengthening of diatom-rich sediments: A comparison of slope sediments from Chilean lakes and the Japan Trench margin



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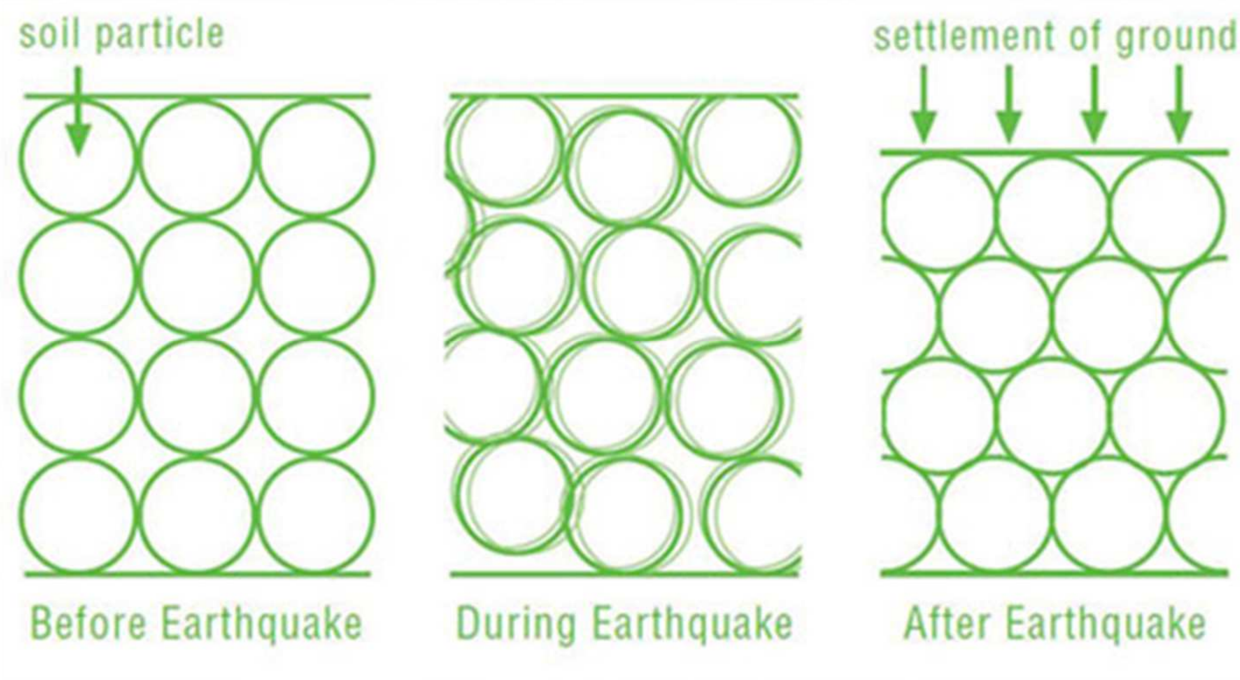
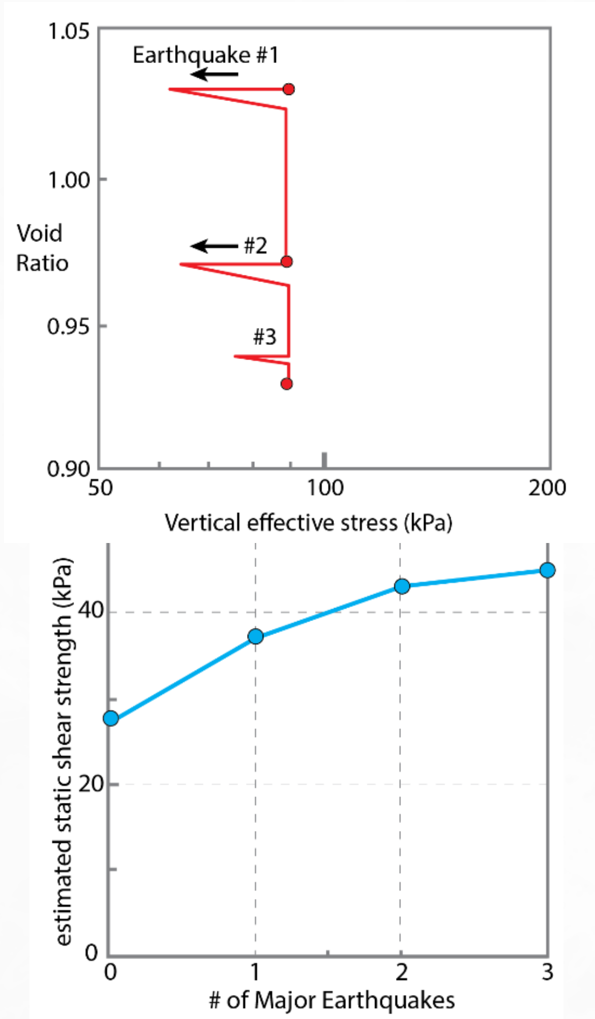
Seismic strengthening: i) earthquake shaking induces excess pore pressure, but is insufficient to induce failure of slope sediments. **ii)** the subsequent dewatering and inherent compaction of the sediment enhances the shear strength of sedimentary slopes.

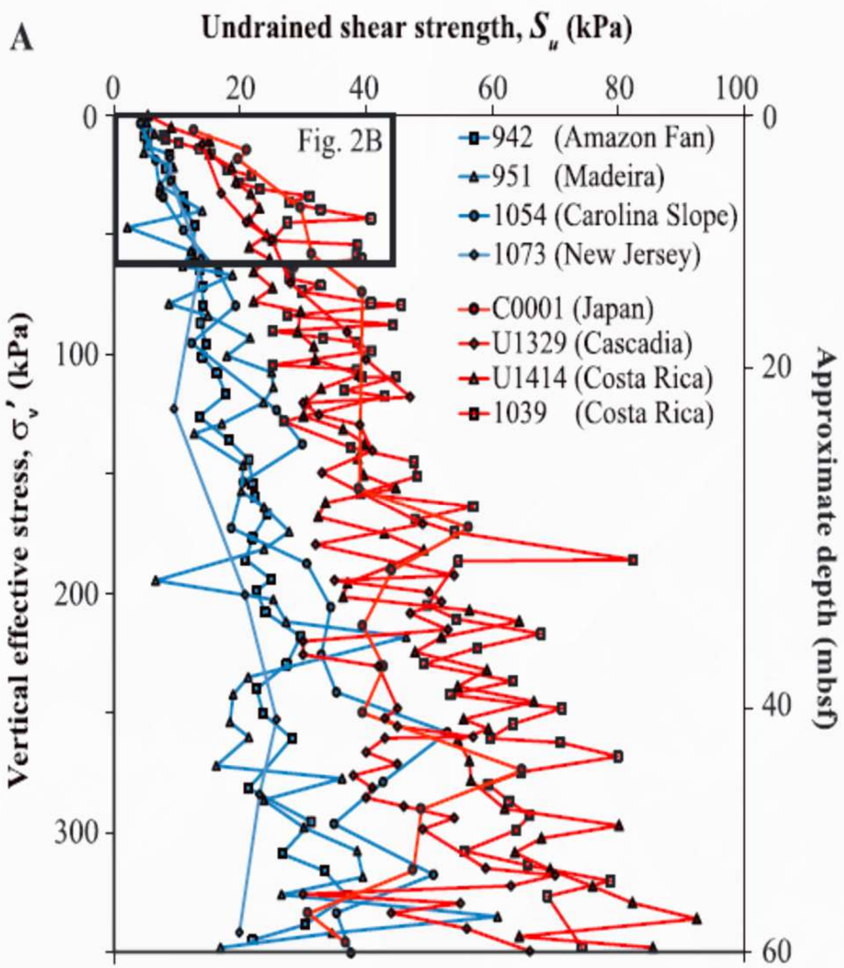


In lab experiments:



Boulanger et al. (2000)

Seismic strengthening: Active margins show significantly higher undrained shear strength (s_u) than passive margins *(Sawyer and Devore, 2015 – JGR)*



Sawyer and Devore (2015)

<u>Normally consolidated sediment</u>

S_u/σ_v' ~ 0.2–0.4

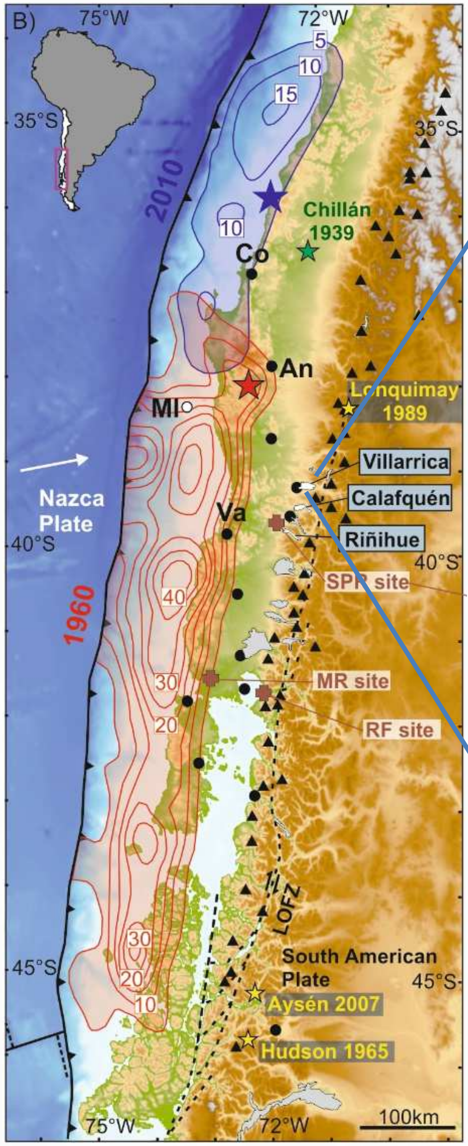
S_u = undrained shear strength

σ_v' = effective overburden stress

Seismic strengthening may explain the observed paucity of submarine landslides on active margins when compared to the short recurrence of strong earthquakes in such settings.

We investigate the possibility of seismic strengthening by documenting s_u in the upper 5m of slope sequences in **Chilean lakes and along the Japan Margin**. Moreover, with geotechnical lab test we aim at better understanding the role of lithology for this process.

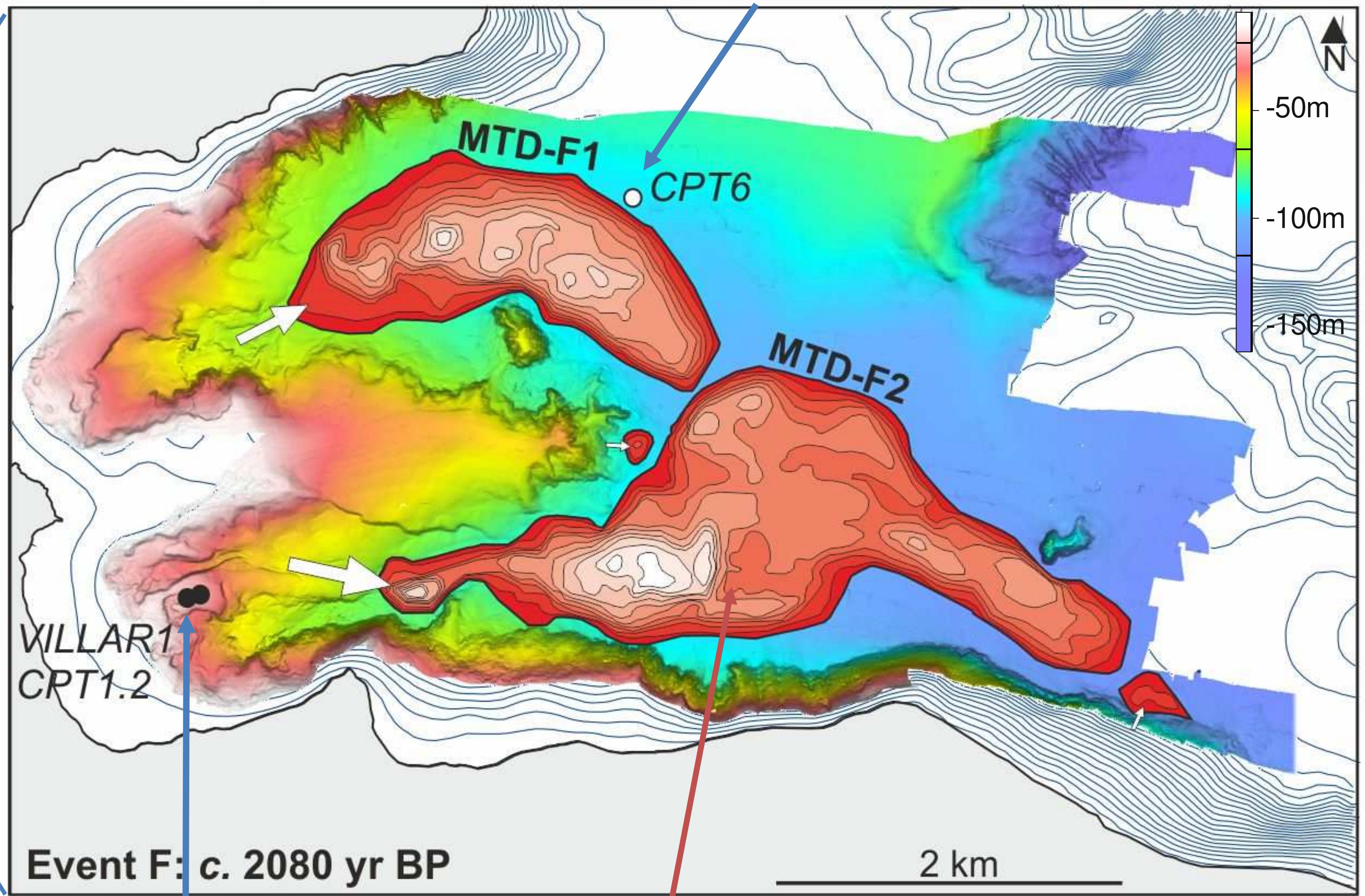
Chilean lakes: Villarrica



Moernaut et al., 2014 (JGR)

Contours: coseismic slip of major megathrust earthquakes (1960, 2010)

Undisturbed basin site



Unfailed slope sites

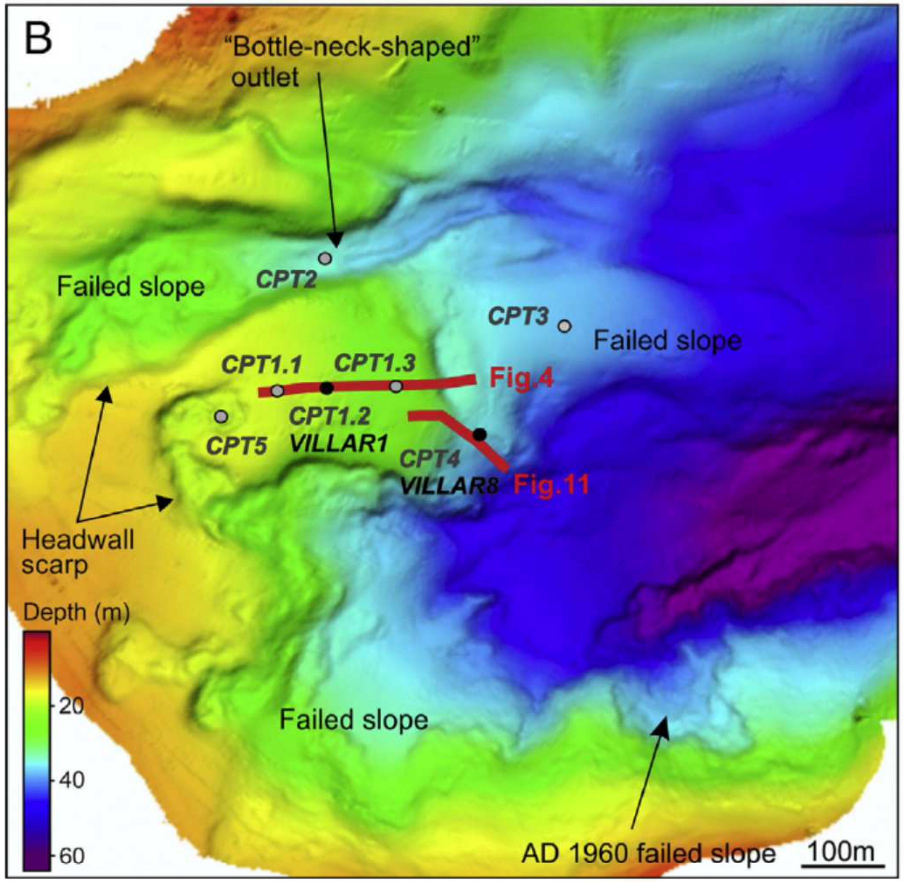
Moernaut et al., 2019

Mass-transport deposits

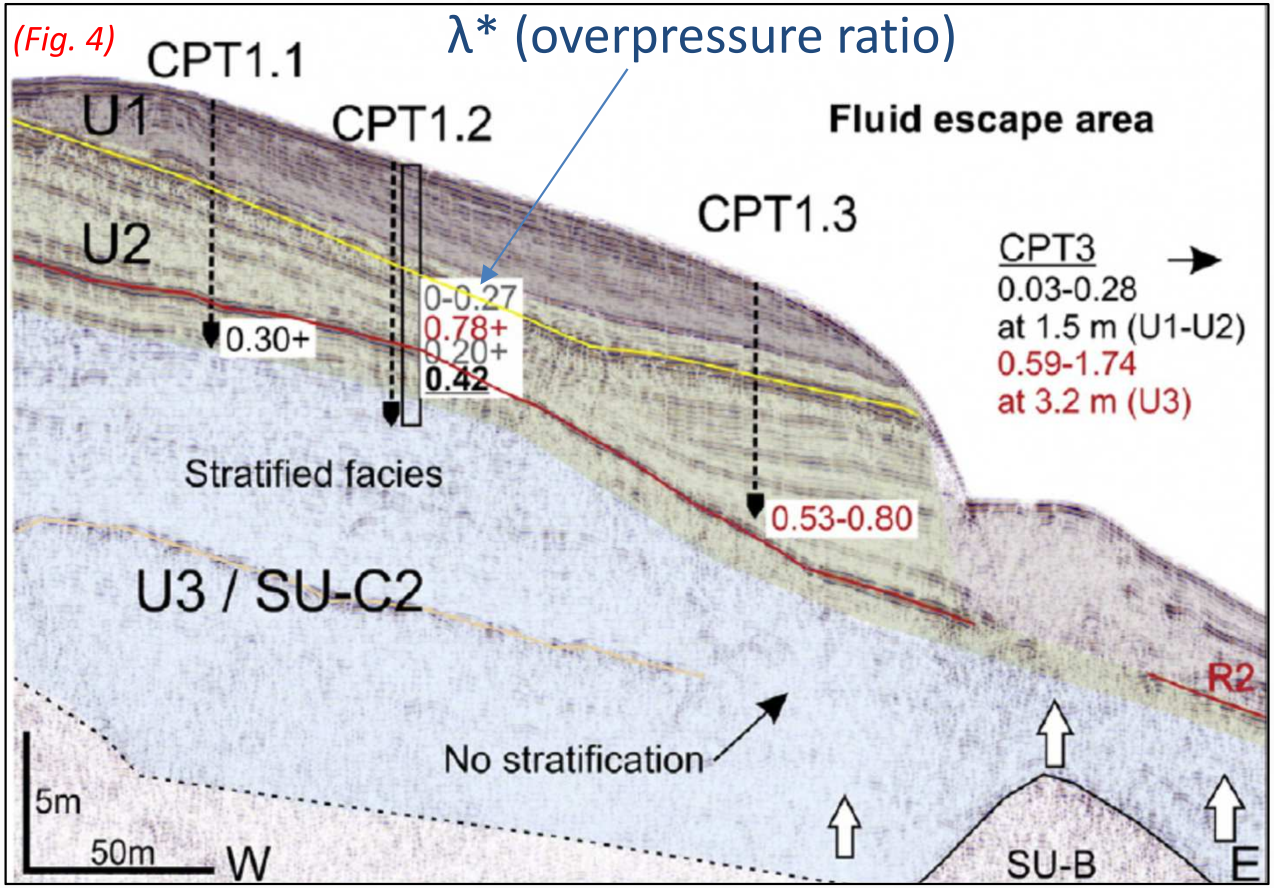
(0.5 m thickness contours)

Chilean lakes: Villarrica: CPTu transects + piston core (VILLAR1)

MARUM CPTu: (Free-fall) Cone Penetrometer with pore pressure instrument

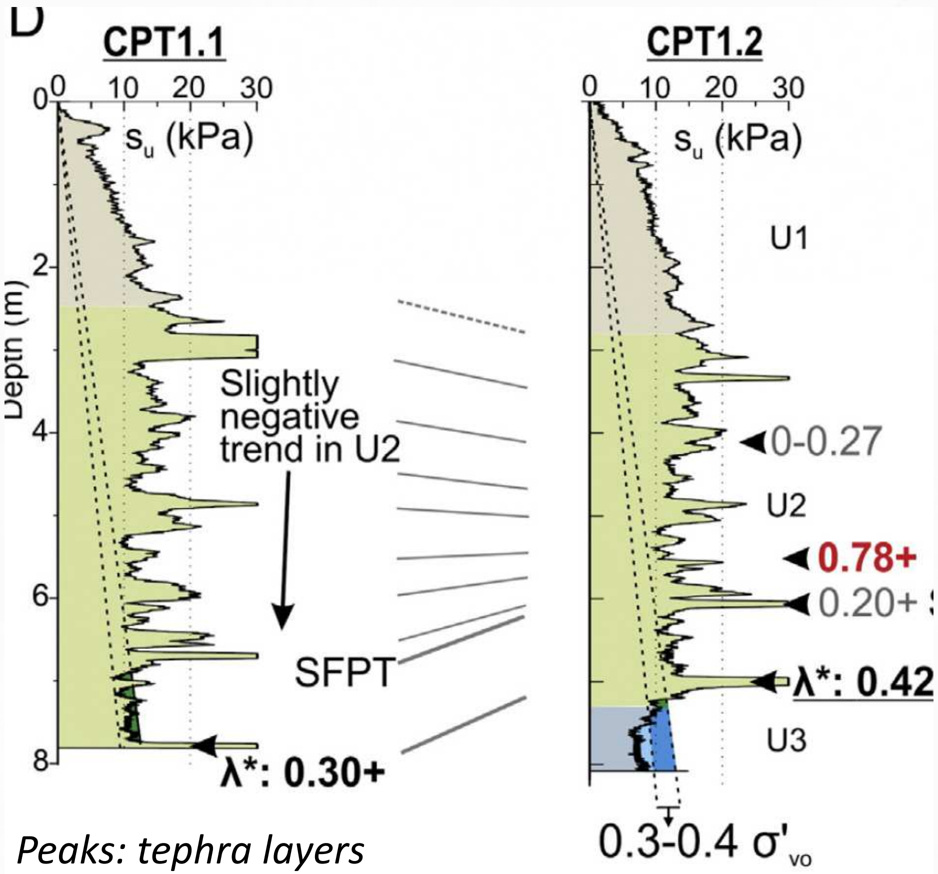


Moernaut et al., 2017



- calculate s_u during penetration
- calculate overpressure ratio λ* (dissipation tests)

Chilean lakes: Villarrica: CPT transects



Peaks: tephra layers

- Uppermost 6m are much stronger than expected from the „normal consolidation trend" (s_u/σ_v' ~0.3–0.4).
- This apparent overconsolidation is supported by oedometer tests, showing an overconsolidation ratio (OCR) of 2.0-8.1
- Below 3 m, s_u decreases slightly due to excess pore pressure (λ* 0.3-0.8) and different lithology of U3 *(Moernaut et al., 2017)*

<u>Oedometer data (compression test)</u>

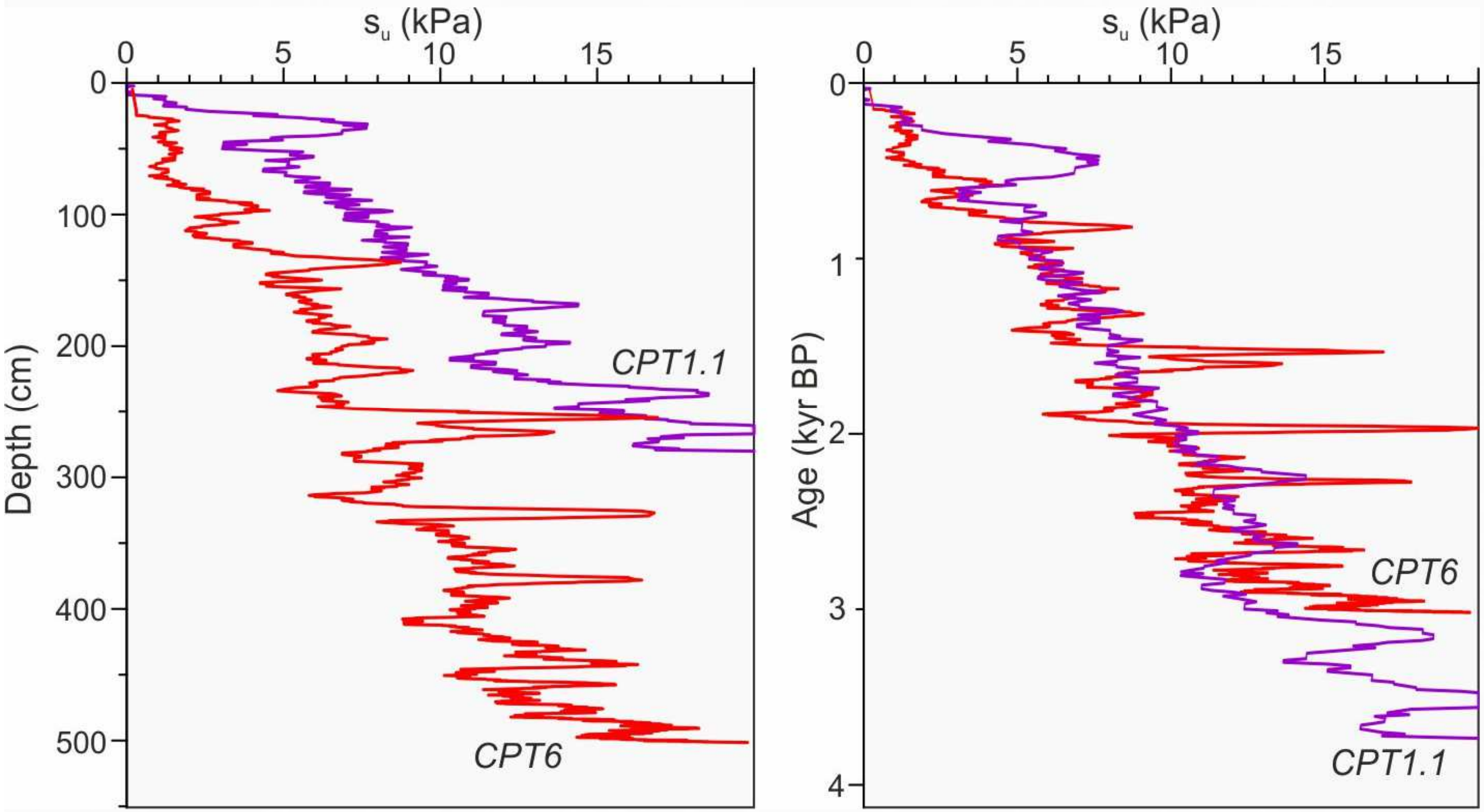
<u>Site 1.2:</u>

OCR 8.1 at 2.9m depth (U1)

OCR 2.0 at 6.4m depth (U2)

Wiemer et al (2015)

If seismic strengthening is a dominant mechanism, s_u should mainly depend on age (nr. of earthquakes), not on depth!



- *Data of U1 (base = 4.0 ka BP)*
- *Peaks: tephra layers / lahar deposits*

Quantification of trends: CoV of slopes of trendlines (through 0,0)

	Vs depth	Vs age
Villarrica	0.545	**0.007**

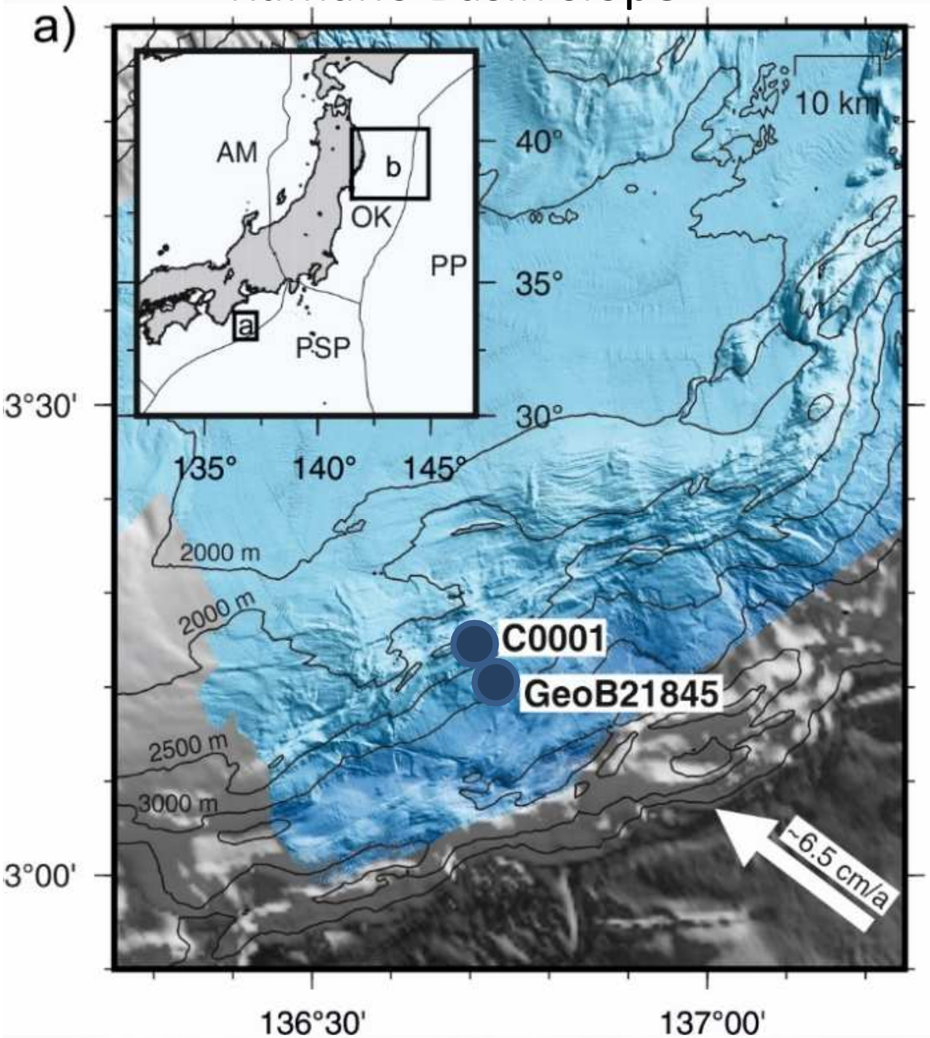
CoV = standard deviation / mean

Very good match when plotting s_u vs. age

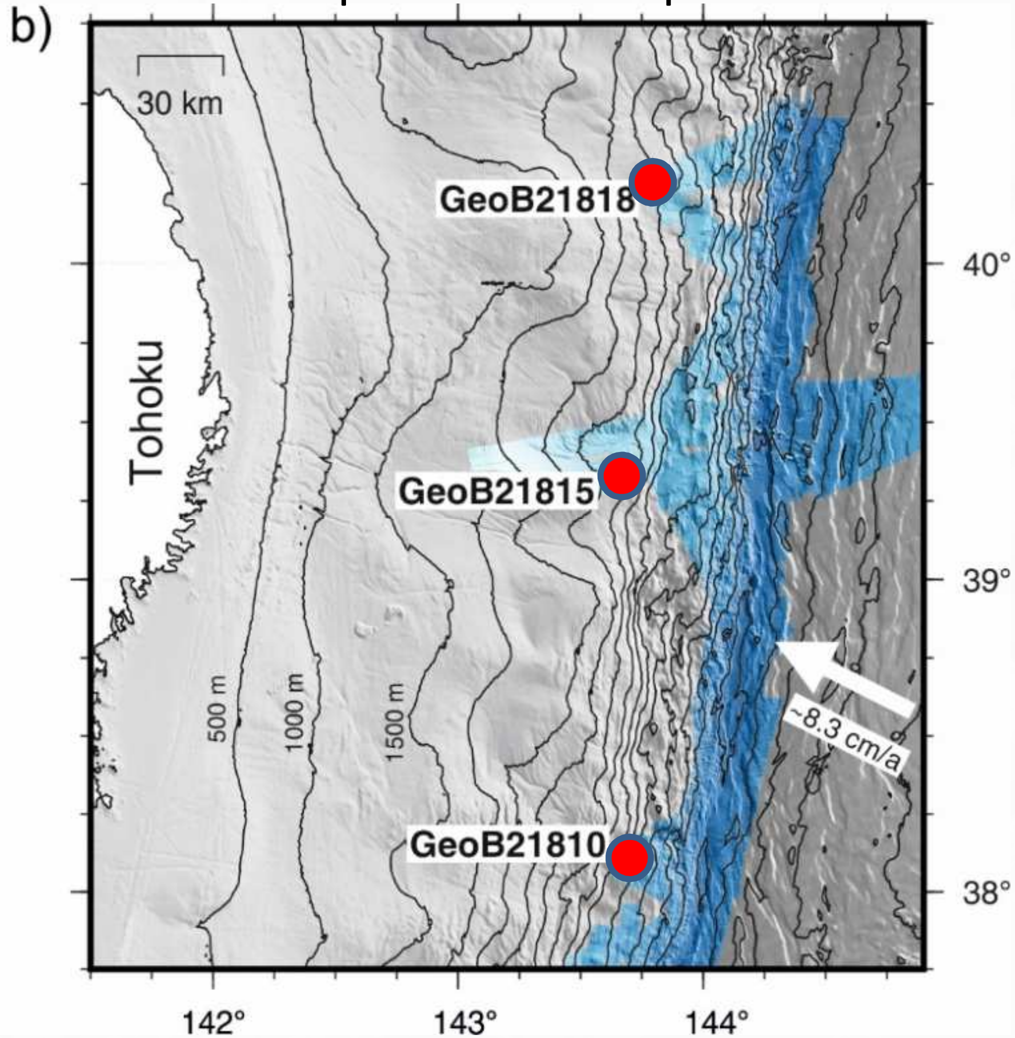
Offshore Japan *Wu et al. (submitted)*

Vane shear data on sediment cores

Kumano Basin slope

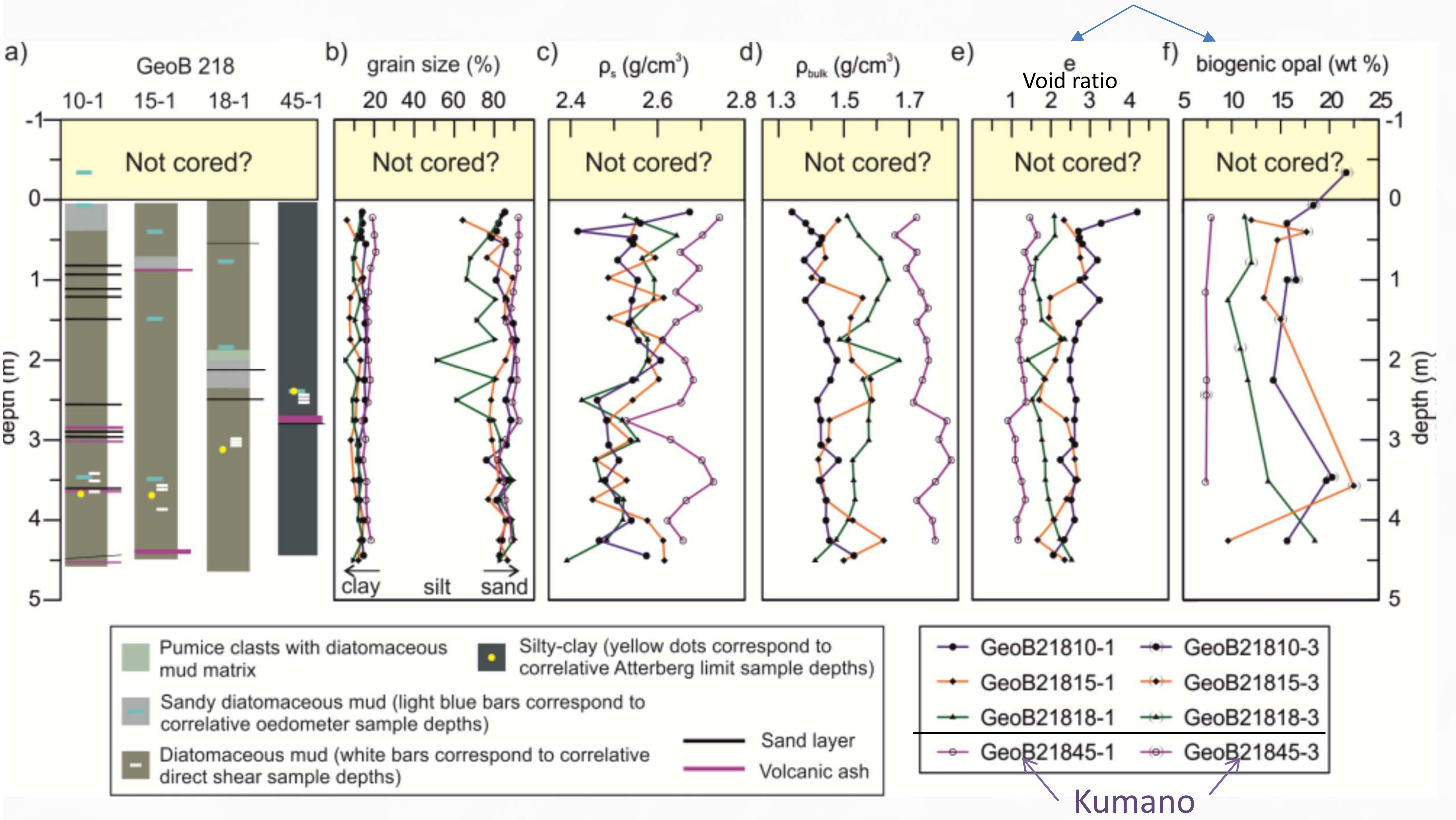


Japan Trench slope

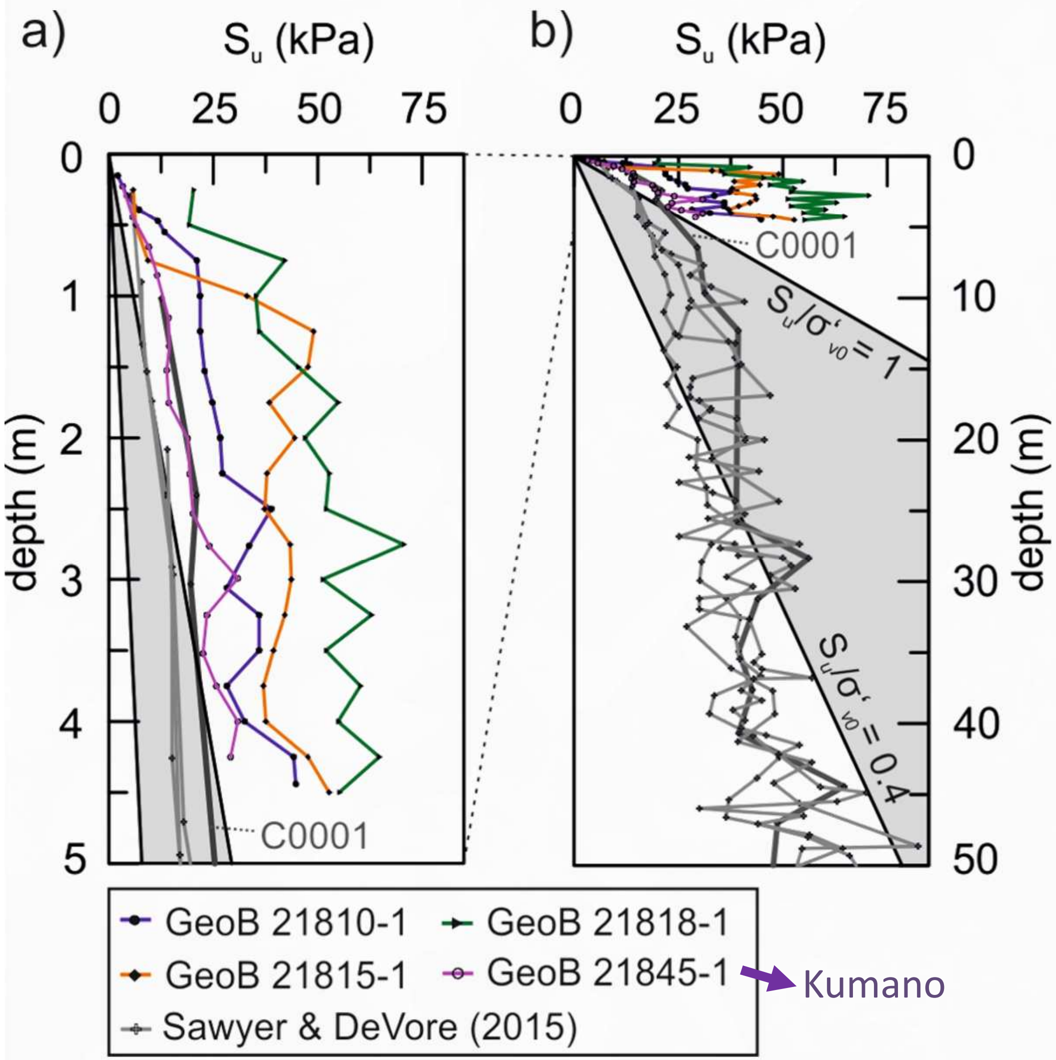


Offshore Japan: Sedimentology

Kumano slope has about half the amount of biogenic opal (diatoms + sponge spicula) than Japan Trench slope



Offshore Japan: Undrained shear strength



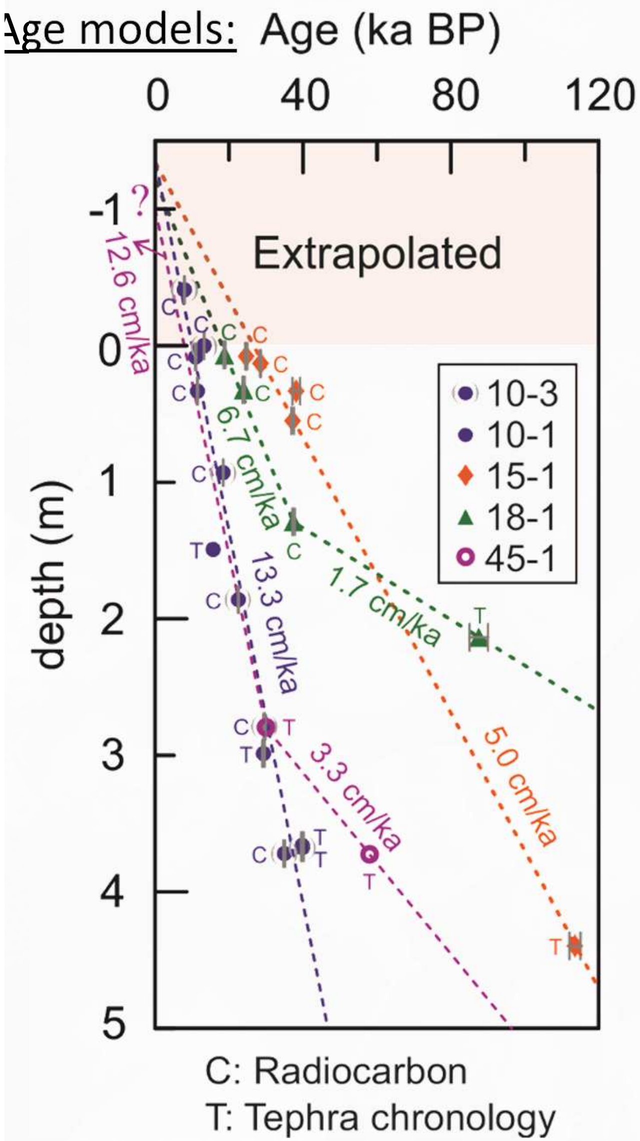
Wu et al. (submitted)

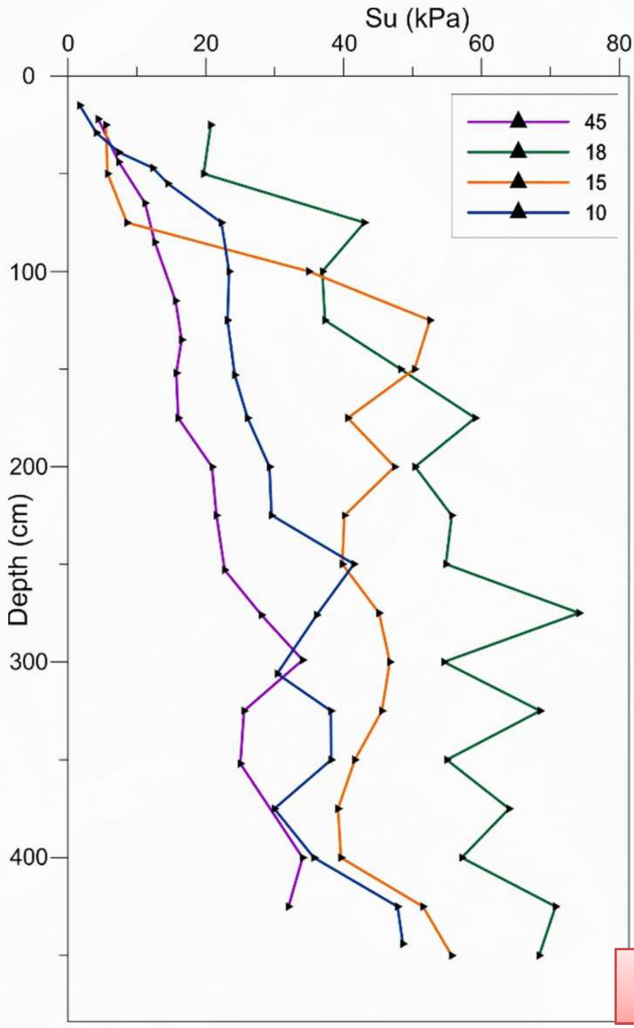
- Uppermost 4.5 m are much stronger than expected from the compilation of active margins of Sawyer and Devore (2015).
- This apparent overconsolidation is supported by oedometer tests, showing an overconsolidation ratio (OCR) of 2.7-6 at a depth of 3-4 m.
- Kumano Basin slope is relatively less overconsolidated than Japan Trench slopes.

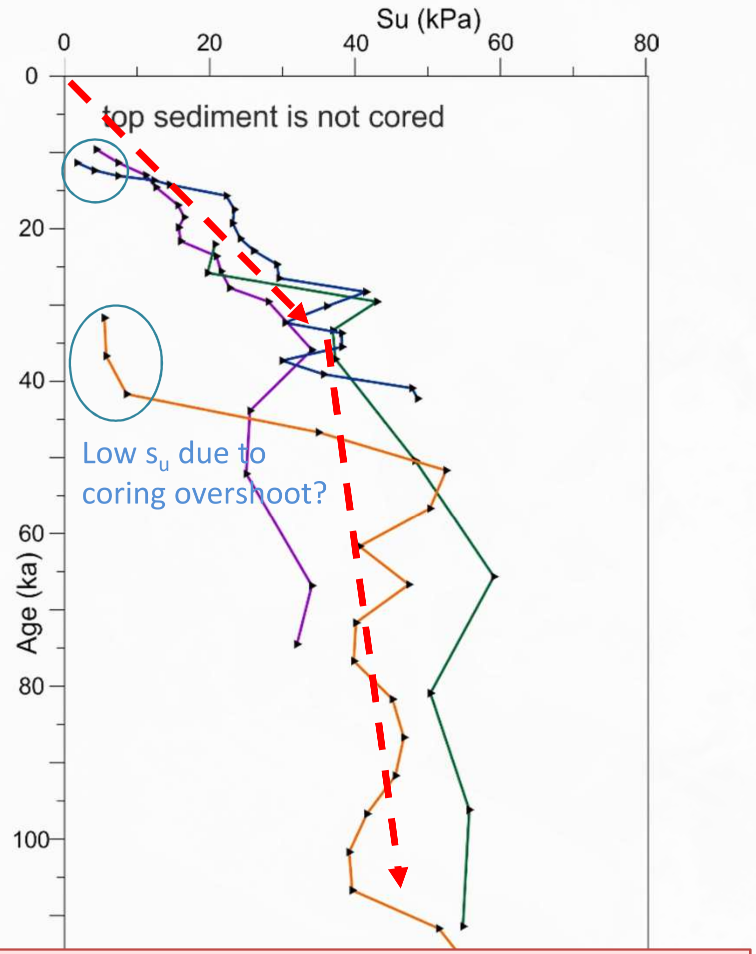
Oedometer data at 3-4 m core depth

OCR of 5.3-6 (Japan Trench slope)
OCR of 2.7 (Kumano slope)

Offshore Japan: Undrained shear strength







Decrease in trendline variability (upper part)

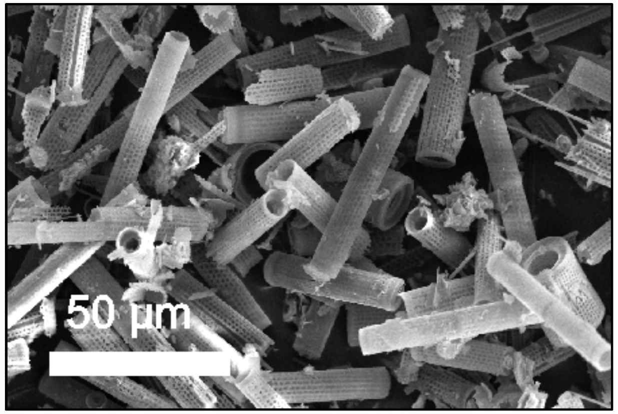
CoV trendline slope	vs Depth (first 2m)	vs Age (to knickpoint)
Japan Trench	0.300	**0.137**
JT vs Nankai	0.560	**0.127**

Role of diatoms:

Adding diatoms to a clay-silt mixture leads to higher static shear strength and lower strain-softening potential when shaken *(Wiemer and Kopf, 2017).*

Diatoms allow effective seismic strengthening (*Wu et al., submitted*):

- high particle interlocking and surface roughness may contribute to high shear strength *(Wiemer et al., 2017).*
- Diatom ooze behaves as a granular material under cyclic loading, building up excess pore pressure
- Diatom ooze has high permeability, allowing drainage of excess fluids between earthquakes
- Diatoms are crushable into smaller fractions, facilitating compression and settlement after seismic shaking



Images from Van Daele et al. (2014), Wiemer et al. (2017)

Role for submarine slope failure:

- Low bulk density due to void space in frustules

→ **Low downslope shear stress** (**low driving force**) for a given thickness

- High s_u due to effective seismic strengthening

→ **High resisting force to slope failure**

⇨ **low probability of slope failure** (unless “weak layers” are present)

Summary

- Diatom-rich slope sediments in Chilean lakes and offshore Japan are strongly (apparently) overconsolidated, with values that go beyond the expected trend for active margins proposed by Sawyer and DeVore (2015).

- The strong age dependency of undrained shear strength suggests that seismic strengthening (i.e. nr. of strong earthquakes) may be the principal cause for this overconsolidation.

- Very effective seismic strengthening may occur at the Chilean lakes and offshore Japan, because the presence of diatom frustules alters the mechanical properties of sediments. It leads to higher particle interlocking, surface roughness, and compressibility after seismic shaking. Given their hollow structure, even a modest weight % of diatoms (7% Kumano slope, 15% Japan Trench slope) takes up a considerable space in the in-situ sediment texture.

- We conclude that diatomaceous muds along active margins tend to demonstrate extremely elevated shear strength resulting in higher slope stability against submarine landslides.

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