

Which Factors Modulate Earthquake-Triggered Soft Sediment Deformation? Moving Towards Quantitative Lacustrine Paleoseismology



Ariana Molenaar*, Maarten Van Daele, Thomas Vandorpe, Gerald Degenhart, Marc De Batist, Roberto Urrutia, Mario Pino, Michael Strasser, and Jasper Moernaut

*ariana.molenaar@uibk.ac.at

Why?

Earthquake-induced soft sediment deformation structures (SSDS) can be used to resolve earthquake recurrence rates, but also to provide more quantitative information on past earthquake shaking intensities. Thorough understanding of the interplay between *i) different ground motion characteristics, ii) sediment properties, iii) slope morphology* is paramount for full exploitation of the paleoseismological potential of subaqueous SSDS records. However, we lack comparative studies investigating different SSDS records related to well-documented earthquakes, varying sediment types and site morphologies. Here, we present our recent publication and preliminary results comparing SSDS with different ground motion parameters, slope angles and sediment characteristics.

Ground Motion Characteristics
Slope Morphology



[Molenaar et al., 2021](#)
[\(Sedimentology\)](#)

Sediment Characteristics



Work in progress

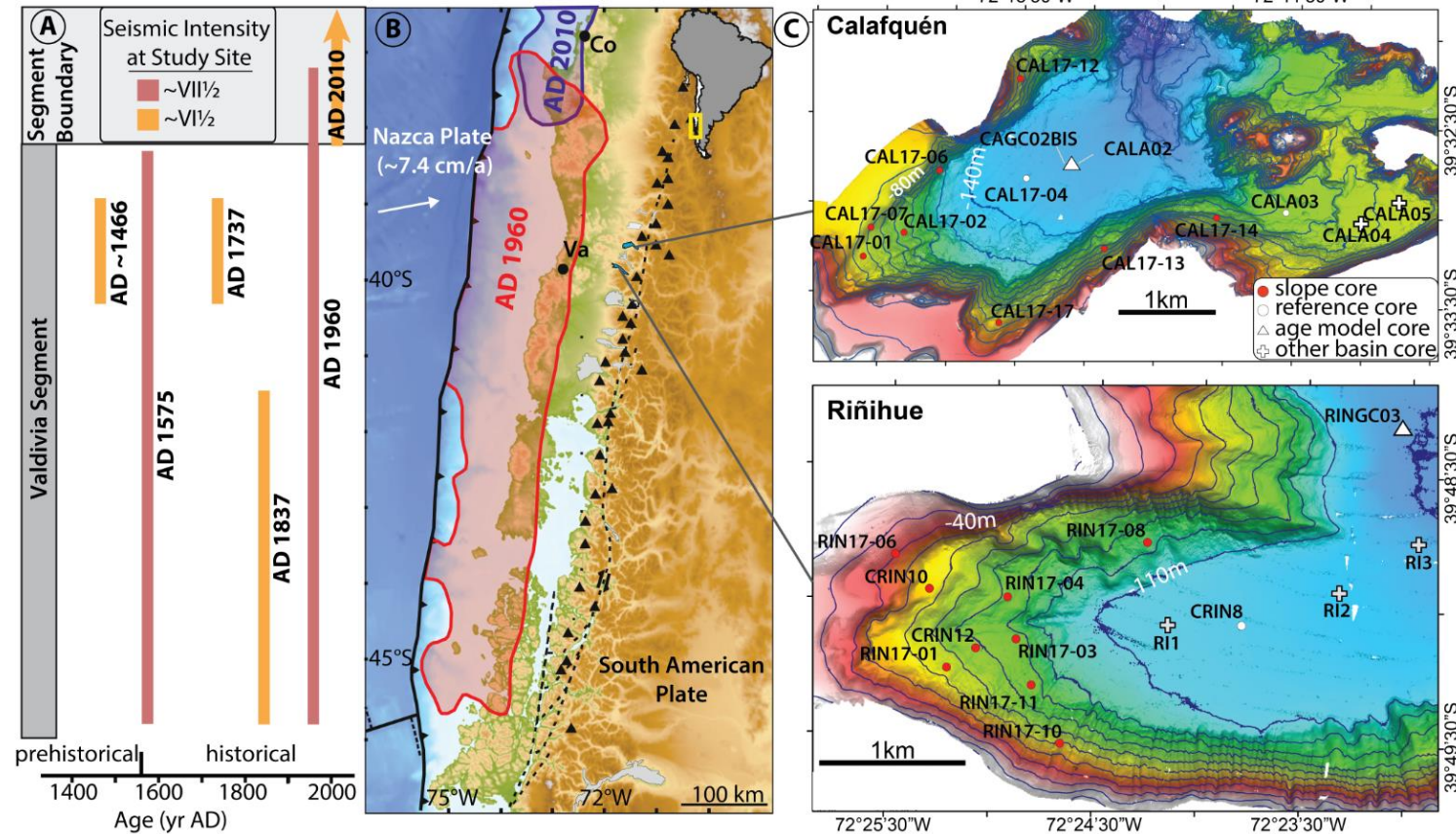
Where?

- » The Chilean Subduction Zone (B)
- » Two lakes: lakes Riñihue and Calafquén (C)
- » Slope angles of 0.2-9.5° and 0.2-14.2° in lakes Riñihue and Calafquén, respectively
- » 17 slope and 3 basin sediment cores (C)

Megathrust Earthquakes:

- » 4 historical and 1 prehistorical megathrust earthquake (A):

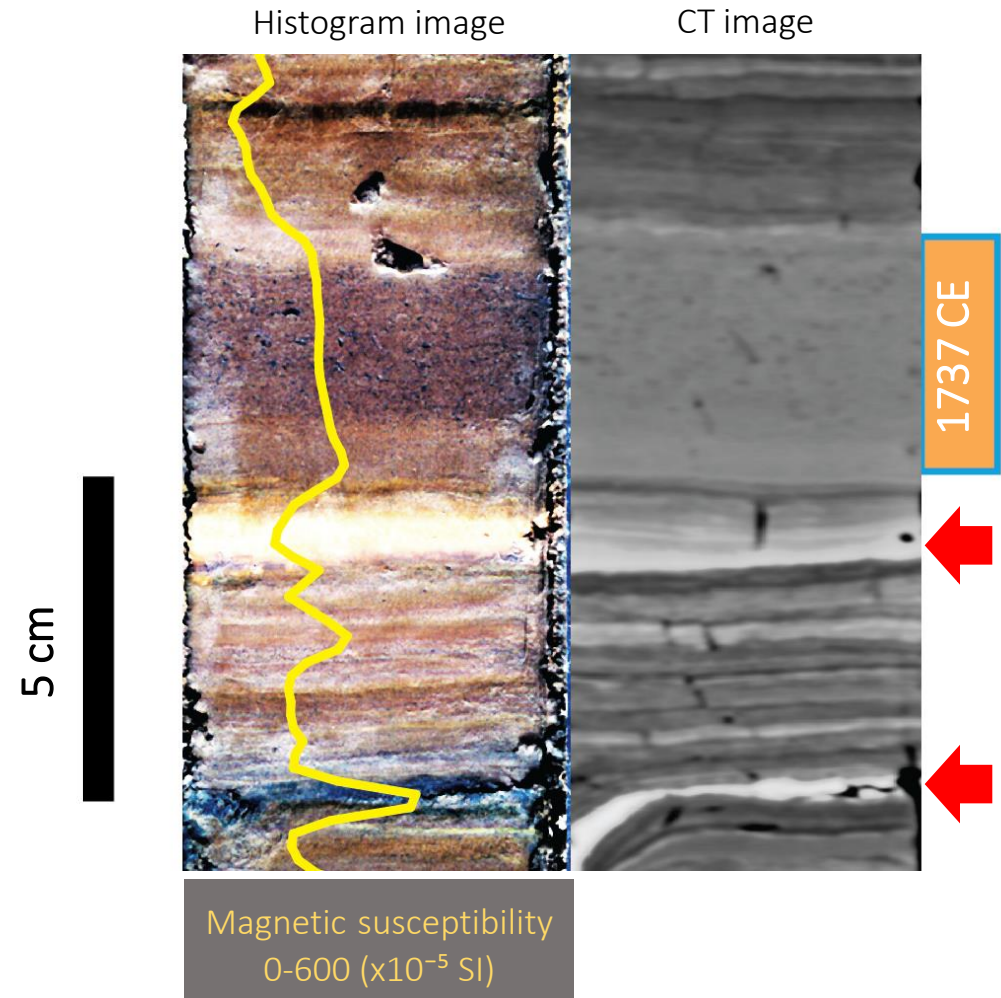
1960 CE (Mw 9.5)
 1837 CE (Mw 8.8-9.2)
 1737 CE (Mw 7.5-8.2)
 1575 CE (Mw ~9.5)
 ~1466 CE (Mw 7.5-8.2)



[Molenaar et al., 2021 \(Sedimentology\)](#)

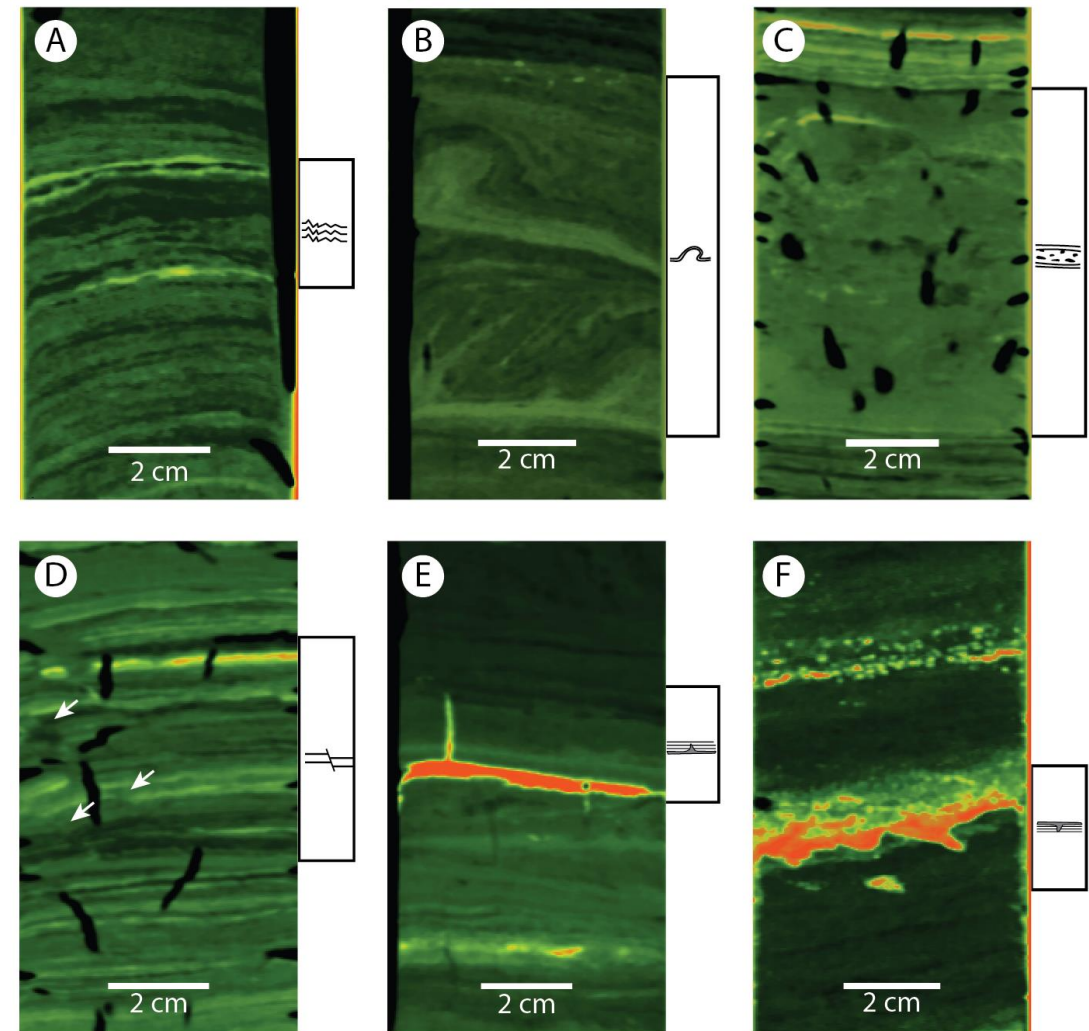
Sediment Description

- » Millimetre-scale biogenic varves: diatomaceous ooze (spring) and clay to silt sized organic-rich terrestrial material (winter)
- » Intercalated with coarse-grained tephra and fine-grained lahar deposits (**red arrows**)
- » Dated by varve counting, $^{210}\text{Pb}/^{137}\text{Cs}$ and tephrochronology (Moernaut et al. 2014, Van Daele et al. 2015).
- » Seismo-turbidites in the basin related to each of the 5 megathrust earthquakes.



Soft Sediment Deformation Structures

- » Six SSDS types:
 - A) Disturbed Lamination
 - B) Folds
 - C) Intraclast Breccia
 - D) Faults
 - E) Injection Structures
 - F) Load Structures
- » Total 49 SSDS intervals observed in both lakes (NOT linked to coring disturbance)
- » 61% can be stratigraphically correlated to one of the 5 megathrust earthquakes (page 6)
- » 68% of non-earthquake related SSDS are directly above a lahar or tephra deposit
- Non-earthquake related SSDS can be caused by (i) an unknown local prehistorical earthquake; or (ii) one of the five megathrust earthquakes, which potentially induced dewatering of a deeper tephra or lahar deposit, thereby weakening overlying sediment.



[Molenaar et al., 2021 \(*Sedimentology*\)](#)

How? The Method

1. SSDS detection:

Using X-ray computed tomography (CT) data on sedimentary sequences.

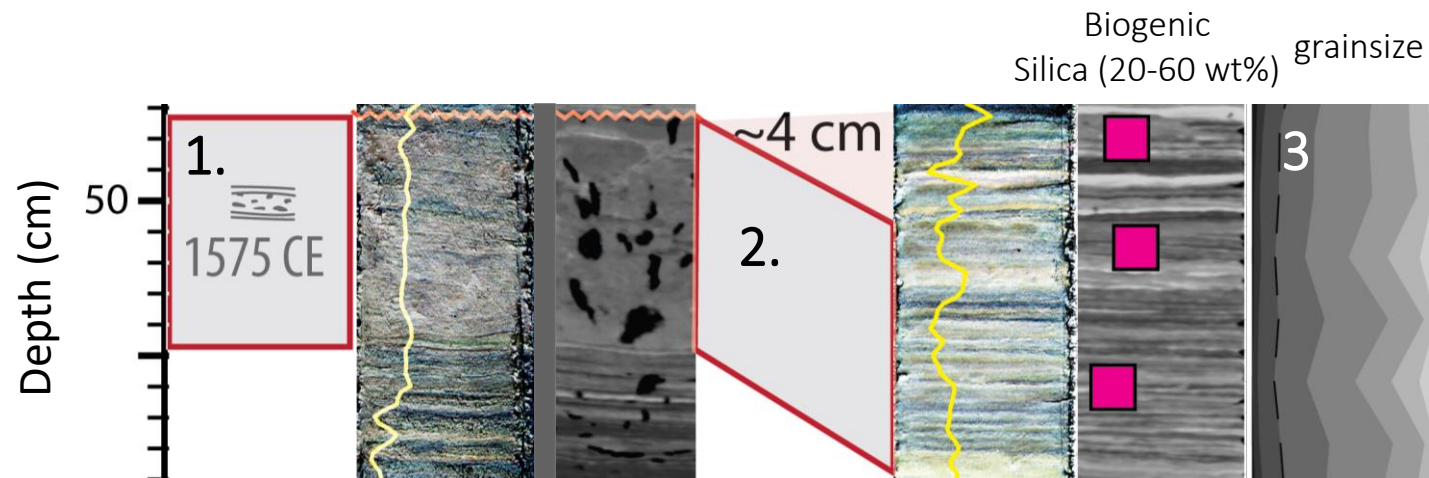
2. Determination of ground motion parameters by correlation to historical earthquake record:

SSDS are linked to megathrust earthquakes by correlating slope sequences to well-dated seismo-turbidite records.

Peak Ground Acceleration (PGA) and Bracketed Duration (BD) are calculated for each earthquake.

3. Determination of slope morphology and sediment characteristics:

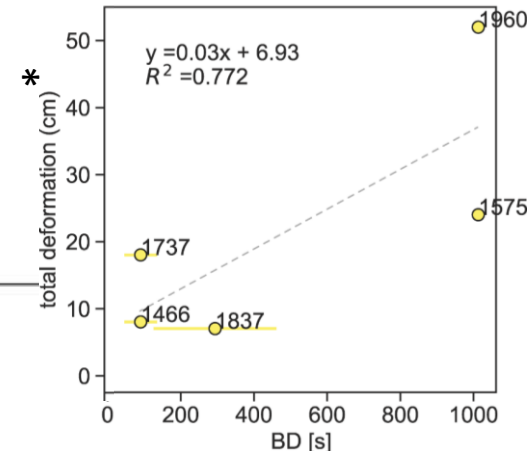
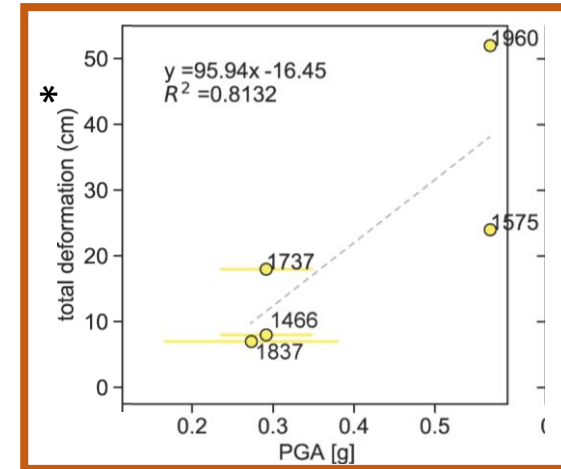
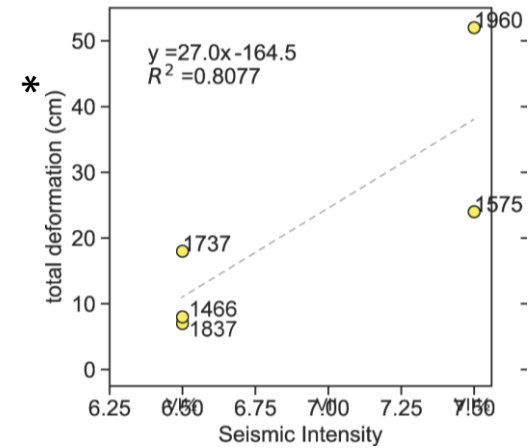
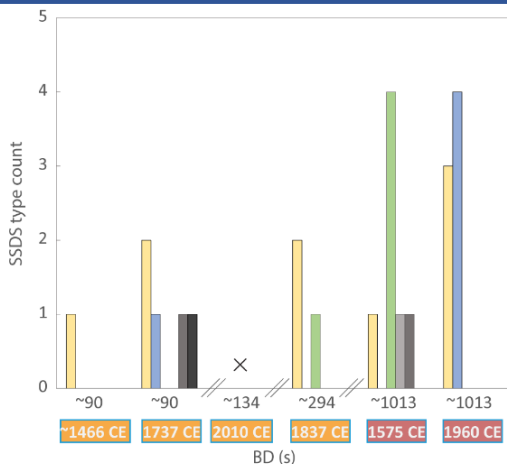
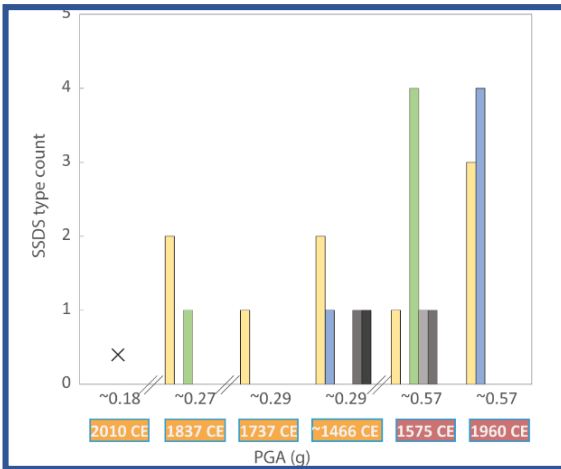
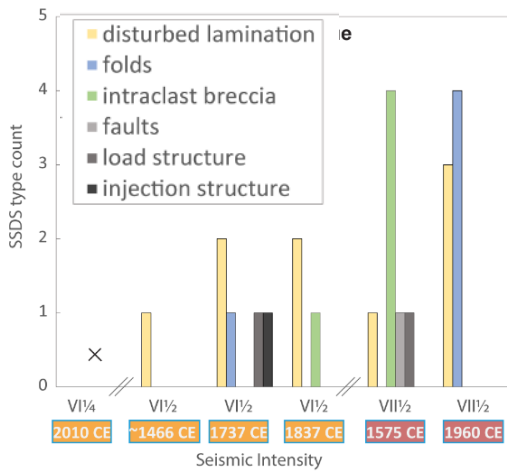
Slope morphology is determined based on bathymetric maps and sediment characteristics are projected on slope cores from basin cores.



Ground Motion Characteristics

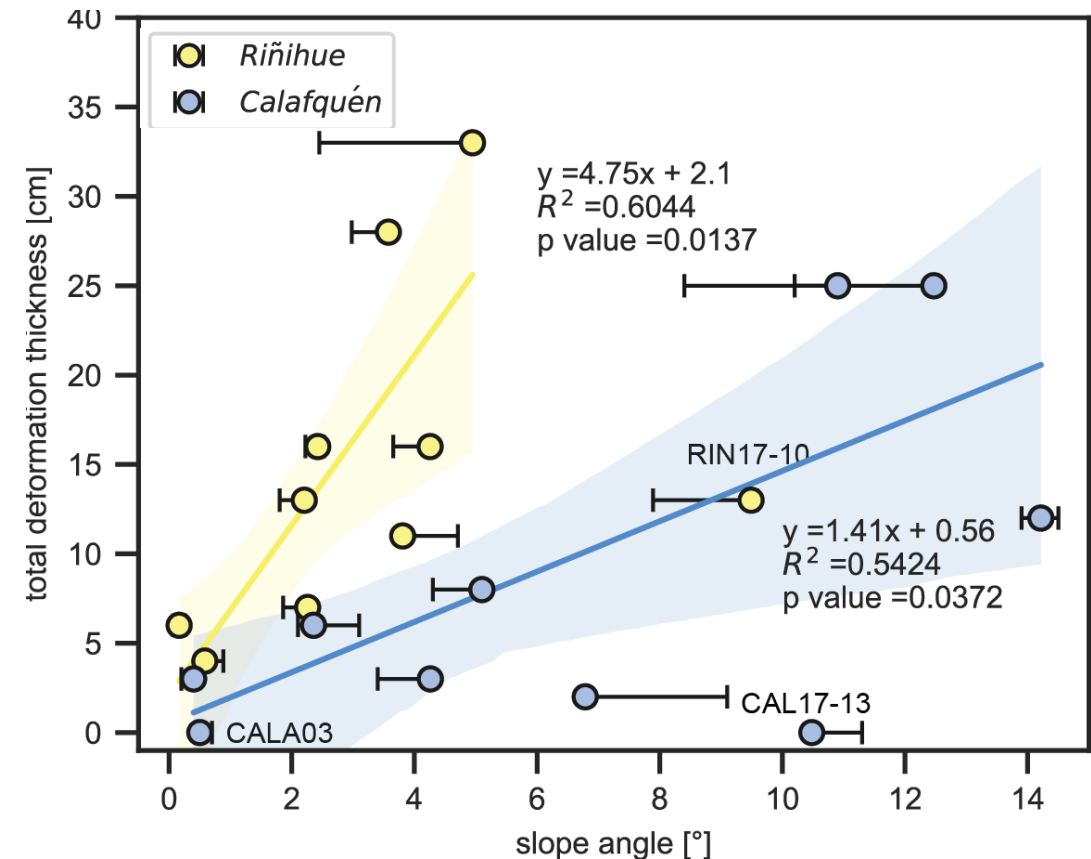
- » In lake Rinihue SSDS count and total thickness of all SSDS per earthquake* (i.e. total deformation in right graph) both link best to PGA.
- » The strongest Mw 9.5 1960 and 1575 earthquakes link to most SSDS with highest deformation intensity (i.e. folds and intraclast breccias).

- Corresponds to observations at the Dead Sea: SSDS development evolves from disturbed lamination to folds and finally intraclast breccia driven by earthquake-induced shear (i.e. Kelvin-Helmholtz Instability (KHI); e.g. Wetzler et al. 2010, Lu et al. 2020).
- Correlation with PGA suggests amplitude of ground acceleration as the main control on KHI-driven deformation.



Slope Morphology

- » SSDS can be observed already at slope angle of 0.2° in the basin
 - » Total deformation increases with slope angle in both lakes
 - » Total deformation in lake Calafquén increases less with slope angle than in lake Riñihue
- Seismically-induced shear stress alone can suffice to deform sediment
 - Even minor increases of gravitational downslope stress will ease deformation.
 - Lower sensitivity of deformation with slope angle (i.e. in lake Calafquén) could be explained by higher diatom content (average 69 versus 37 wt% biogenic silica) as diatoms enhance shear strength through high particle interlocking and surface roughness



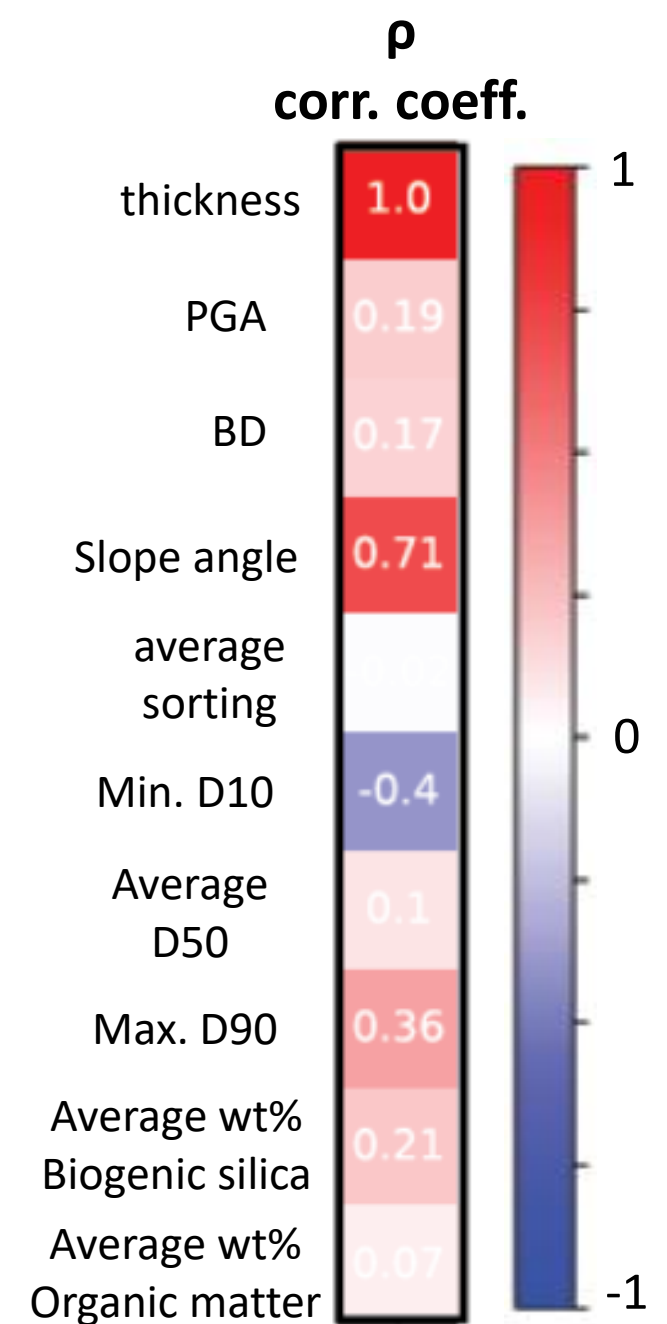
[Molenaar et al., 2021 \(Sedimentology\)](#)

Sediment Characteristics

Preliminary Results:

- » (For now) no clear correlation of individual SSDS thickness with ground motion parameters
- » Thickness of individual SSDS correlates best with slope angle.
- » Next highest correlation coefficient for minimum D10 and maximum D90.
- Lower Min. D10 and higher max. D90 could link to *higher content of lahar and tephra particles*, potentially causing *dewatering and weakening of sediment* (more detail in page 5).
- PGA: Low correlation of individual SSDS thickness, but high correlation of count and total deformation thickness per earthquake (page 7) combined with high correlation of SSDS thickness and slope angle, suggest stronger shaking amplitude can lead to deformation at lower slope angles (i.e. more sites), but not necessarily affects deeper sediment.

We evaluated linear correlation of thickness of each SSDS with ground motion parameters, slope angle, grainsize data, biogenic silica (i.e. diatom content) and organic matter content.



Outlook

In the upcoming year, we will add more SSDS to our study and create a world-wide overview of different SSDS in varying seismic settings (e.g. subduction, intraplate) and sediment types.

Conclusion

- Most SSDS intervals (61% of 49) could be linked to strong megathrust earthquakes
- Strongest earthquakes caused most SSDS and highest thickness of summed deformed sediment intervals (*page 7*)
 - Ground motion amplitude controls KHI-driven soft sediment deformation development (*page 7*)
- Earthquake-induced shear alone can suffice to induce soft sediment deformation (*page 8*)
- Minor increases of gravitational downslope stress can ease deformation (*page 8*)



ORIGINAL ARTICLE | [Open Access](#)

What controls the remobilization and deformation of surficial sediment by seismic shaking? Linking lacustrine slope stratigraphy to great earthquakes in South-Central Chile

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First published: 15 February 2021 | <https://doi.org/10.1111/sed.12856>