

When [...] we hear the loud boom of a waterfall, we know that the stream is descending a precipice. If a heavy rumble and roar, then we know it is passing over a craggy incline. [...] The young river speaks and sings all the smaller characters of the smooth slope and downy hush of meadow as faithfully as it sings the great precipices and rapid inclines, so that **anyone who has learned the language of running water will see its character in the dark.**

– John Muir (*Mountain Thoughts*)

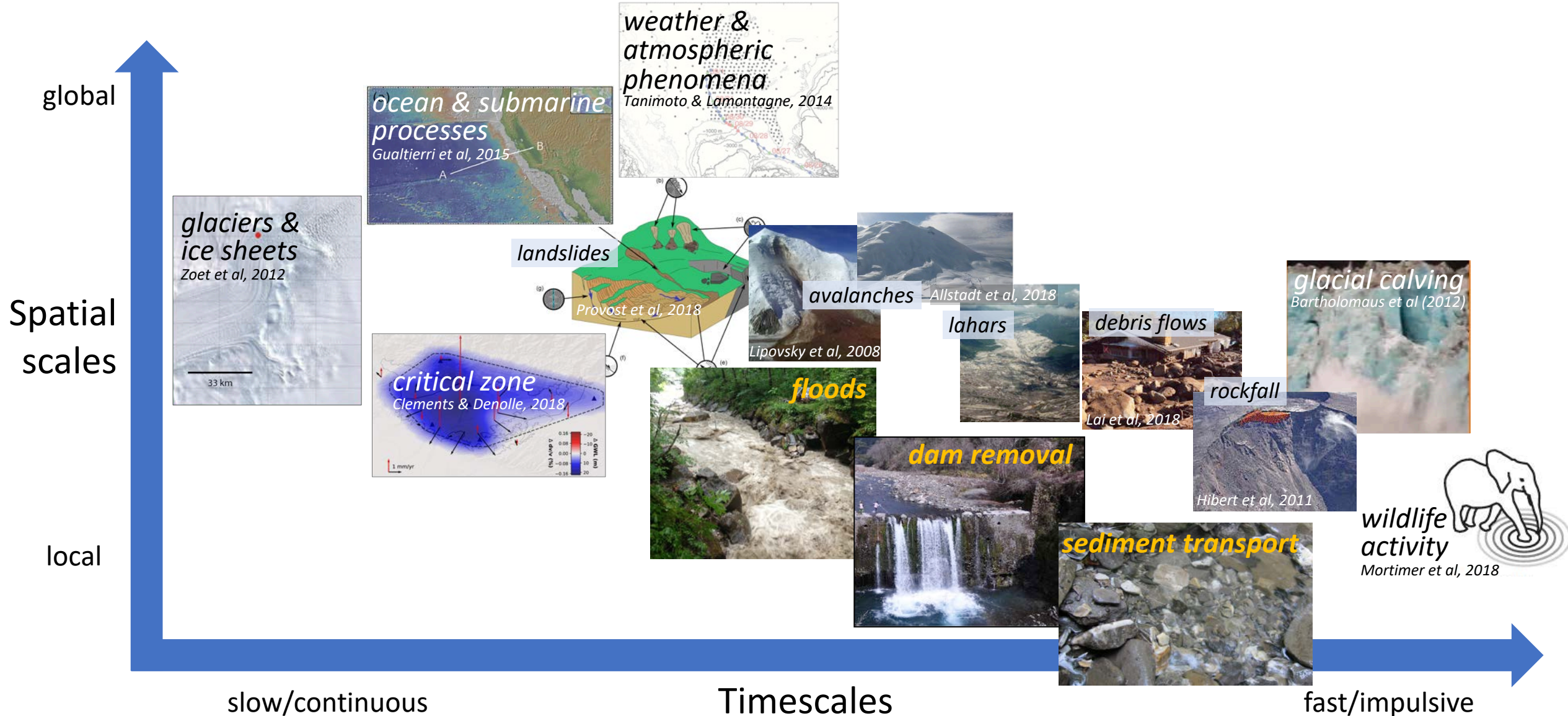
The Language of Water

New insights into river processes from seismic signals

Danica Roth

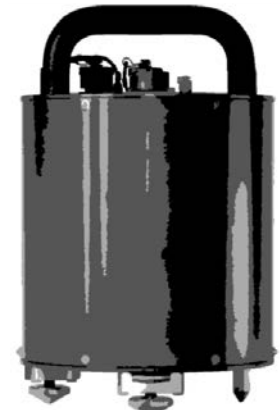
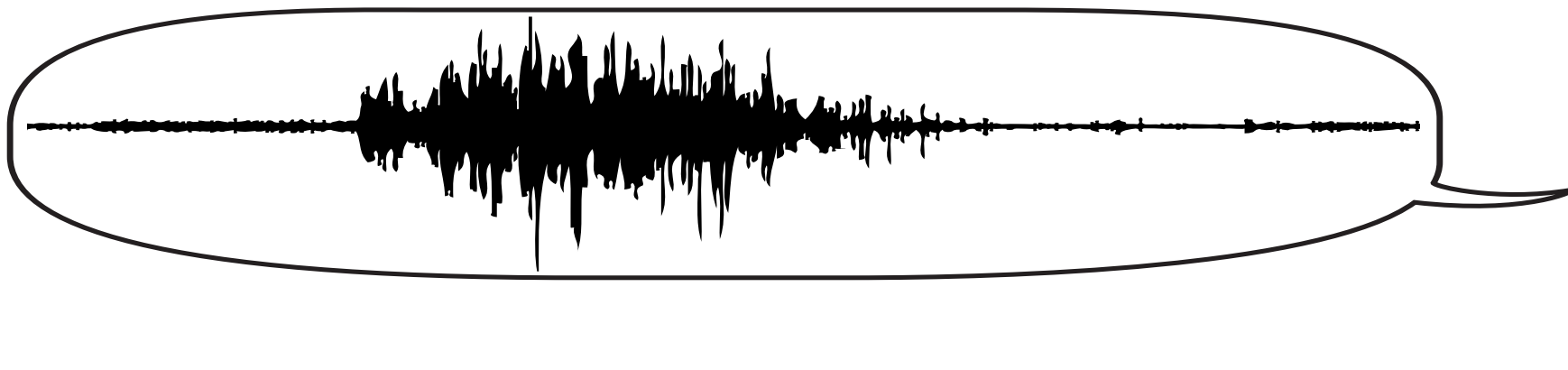
Colorado School of Mines

Seismic data is providing new insights on urgent issues in environmental and Earth surface processes



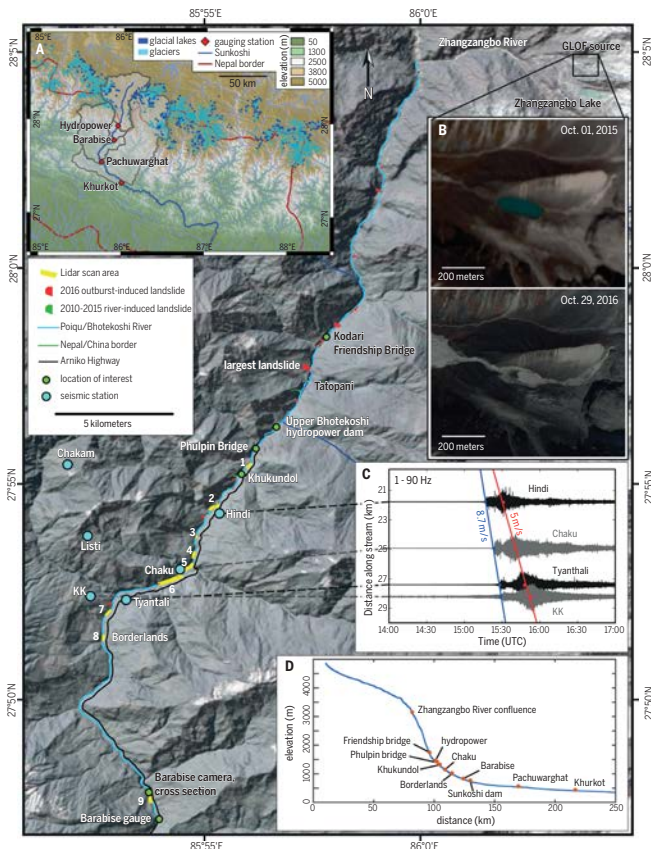
Environmental seismology offers unique advantages and opportunities for research across many fields

- Process monitoring and event detection
- Characterization of near surface materials and properties
- Links to energy transfer and budgets
- Insights into process coupling and cascades



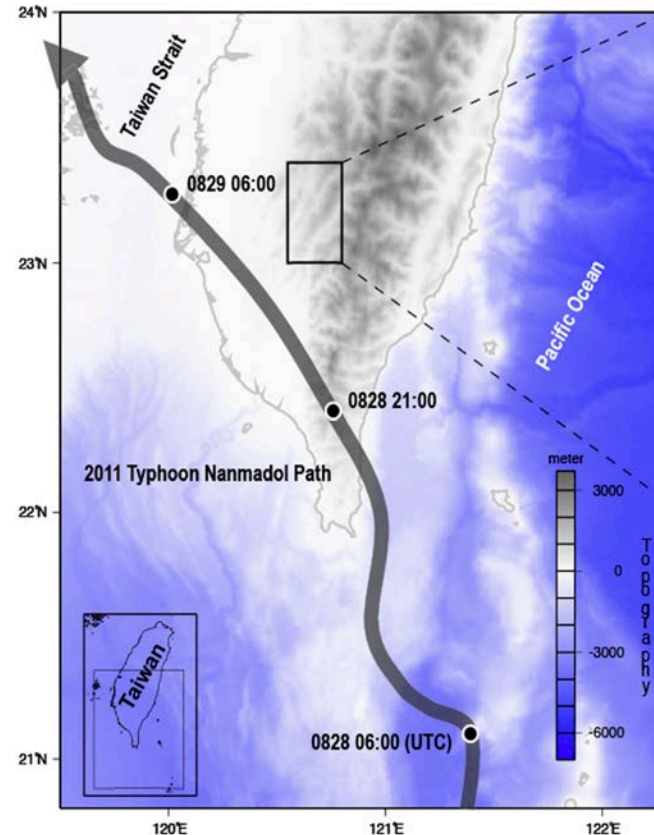
New fluvial insights from seismology

Glacial lake outburst floods, rather than precipitation, mobilize channel-stabilizing boulders and may drive long-term fluvial erosion in the Himalaya.



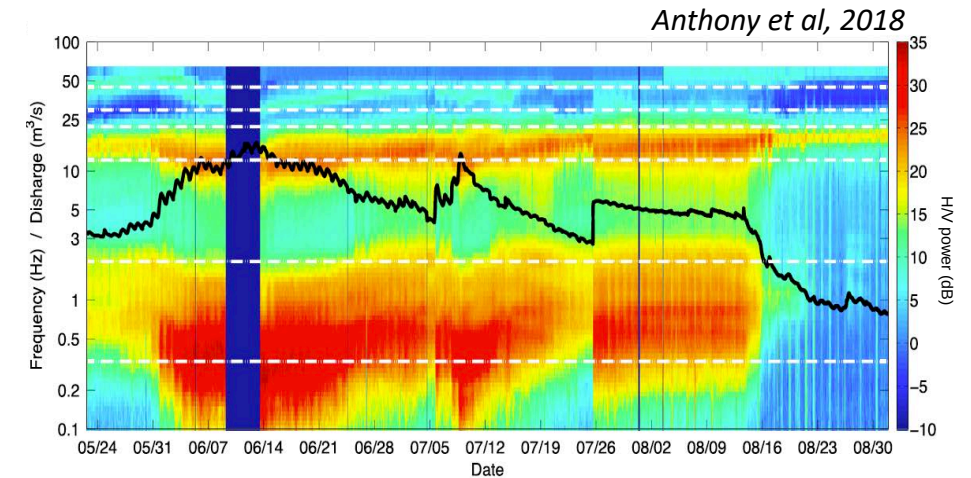
Cook et al, 2018

Seismic records reveal seasonal transitions in sediment supply driven by typhoon-induced landslides in Taiwan.

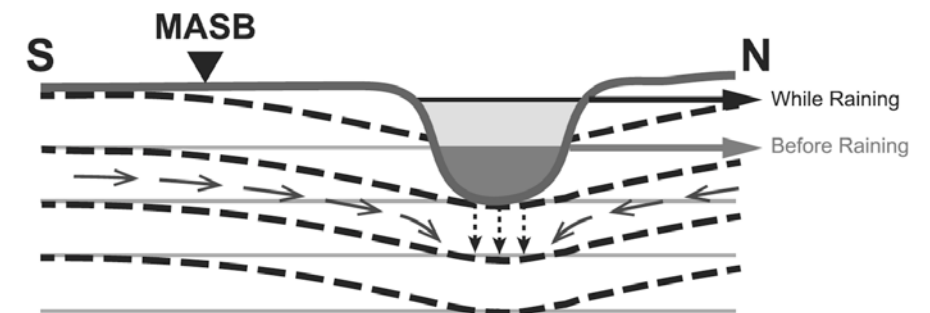


Chao et al, 2015

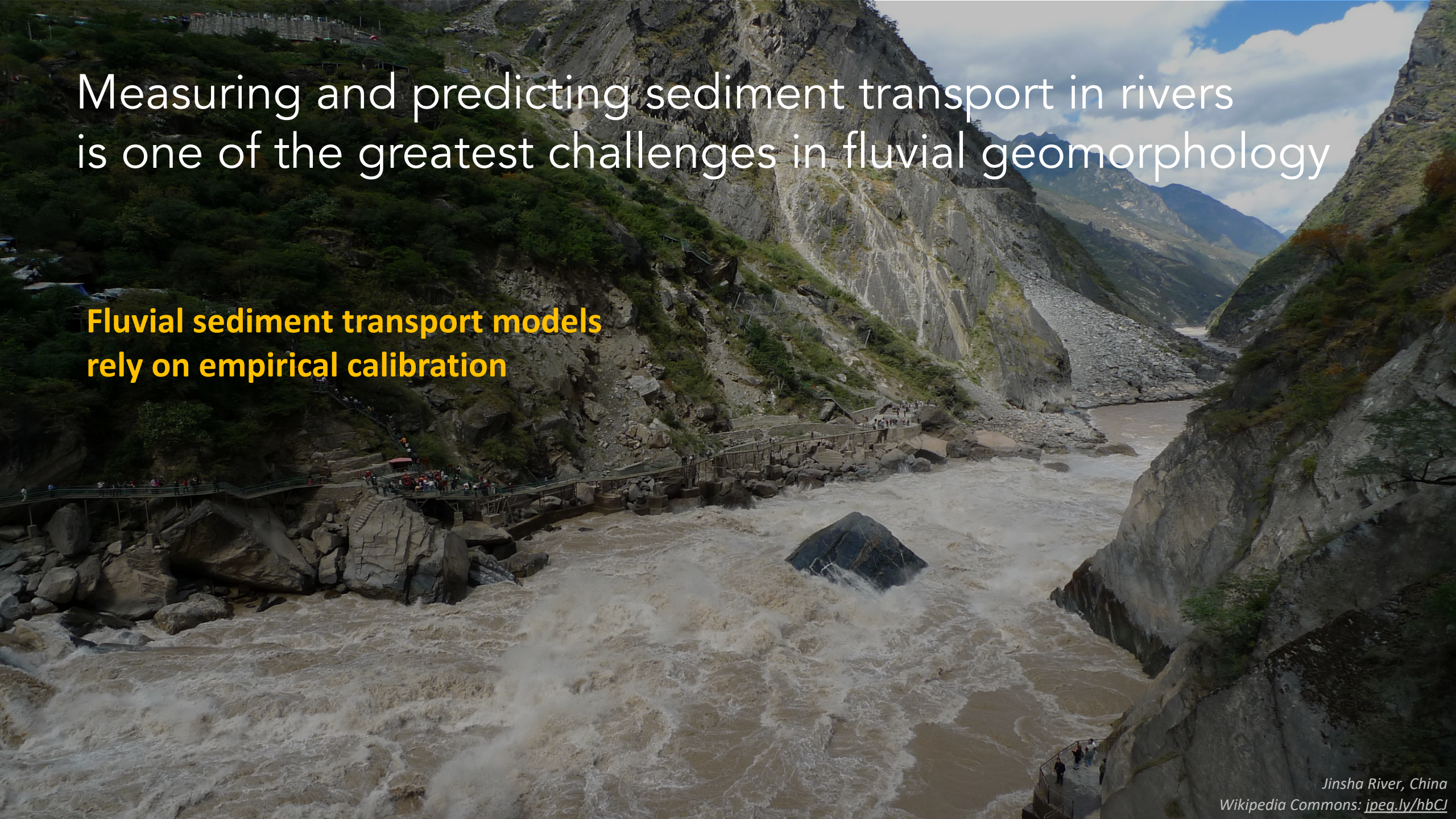
Low frequency horizontal ground motion (tilt) may reveal surface deformation due to precipitation loading, or fluctuating pressure on streambanks linked to turbulent eddy dynamics.



Anthony et al, 2018

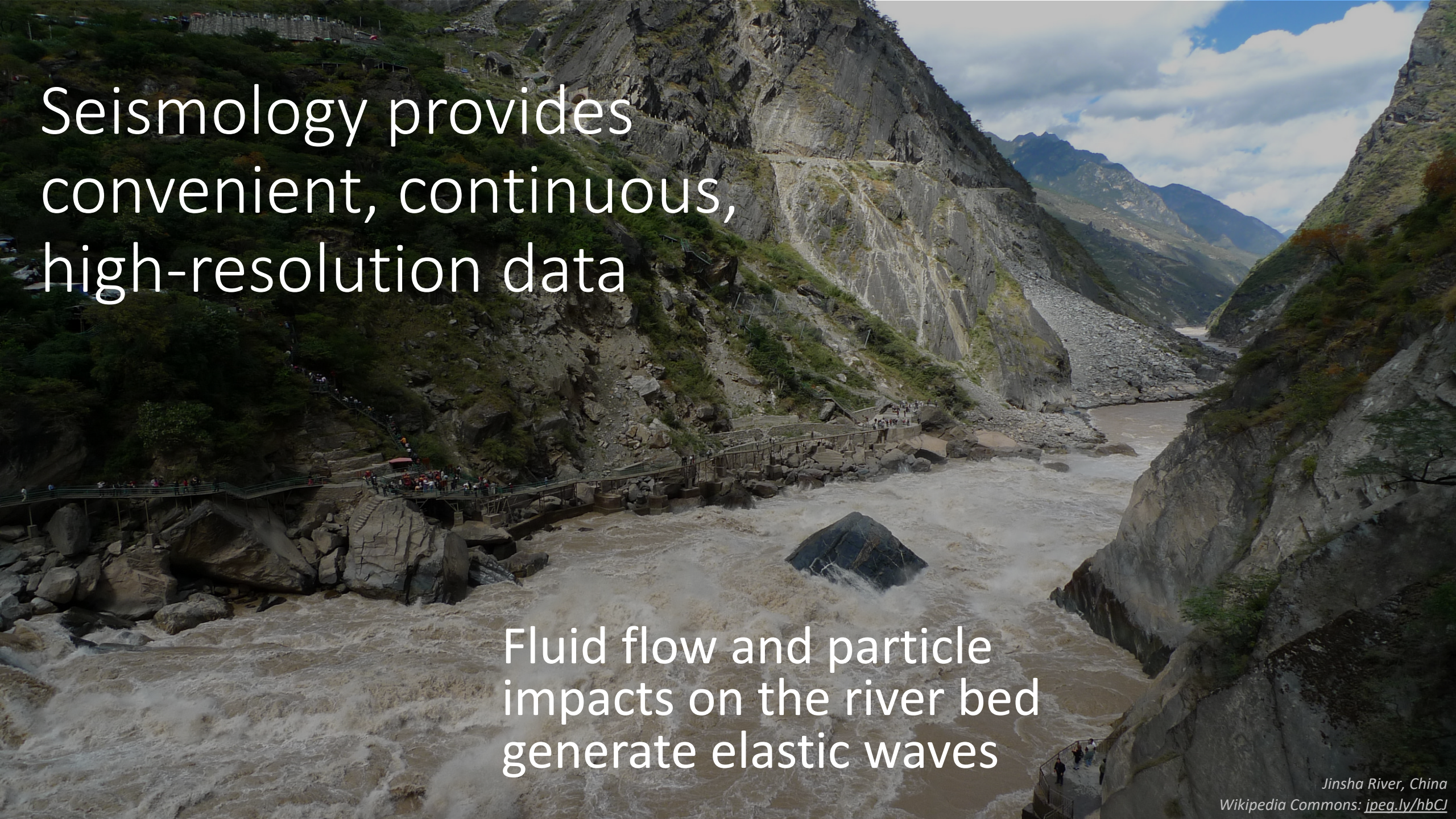


Yang et al, 2018



Measuring and predicting sediment transport in rivers
is one of the greatest challenges in fluvial geomorphology

**Fluvial sediment transport models
rely on empirical calibration**



Seismology provides
convenient, continuous,
high-resolution data

Fluid flow and particle
impacts on the river bed
generate elastic waves

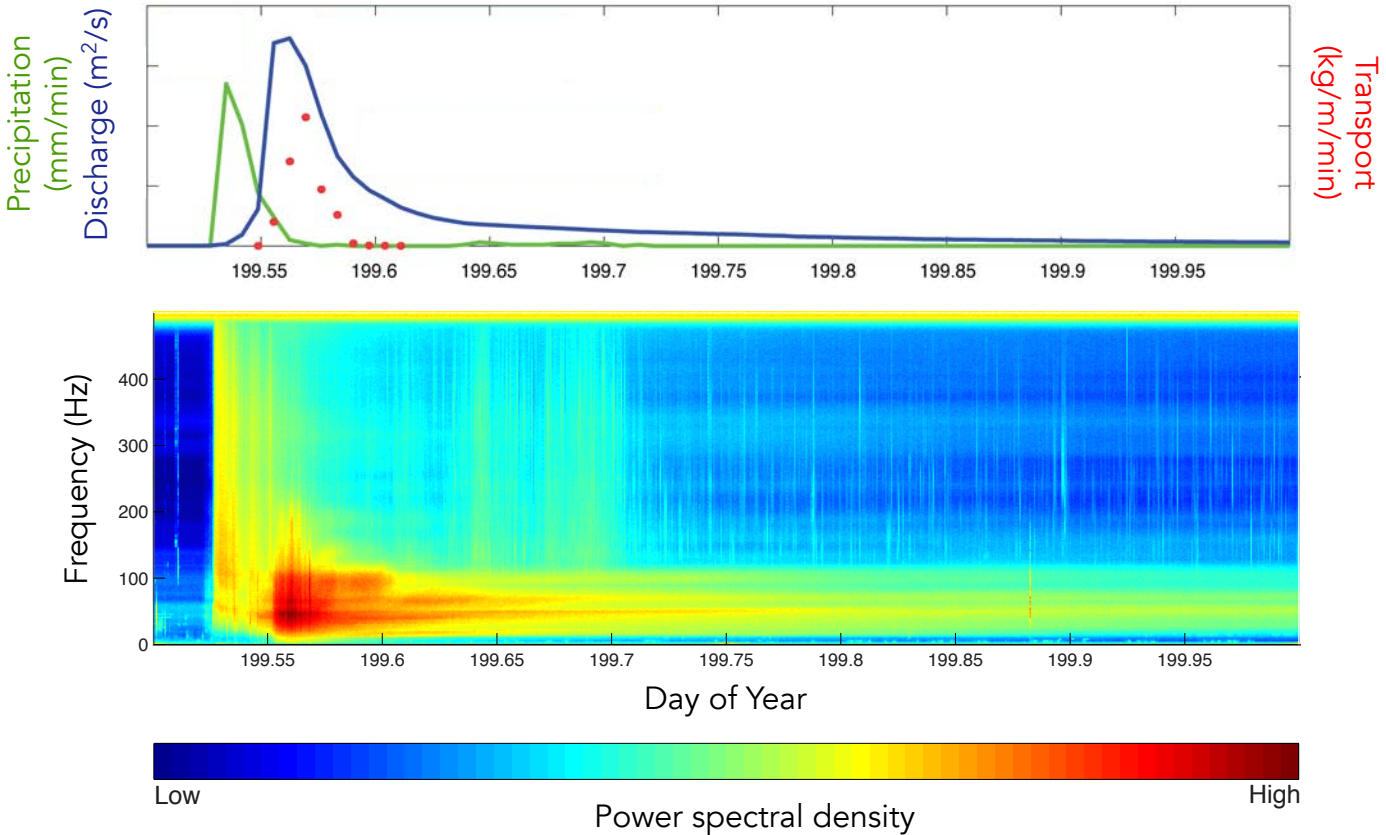


Erlenbach,
Switzerland

What can we learn about the spectral signatures of distinct fluvial processes?

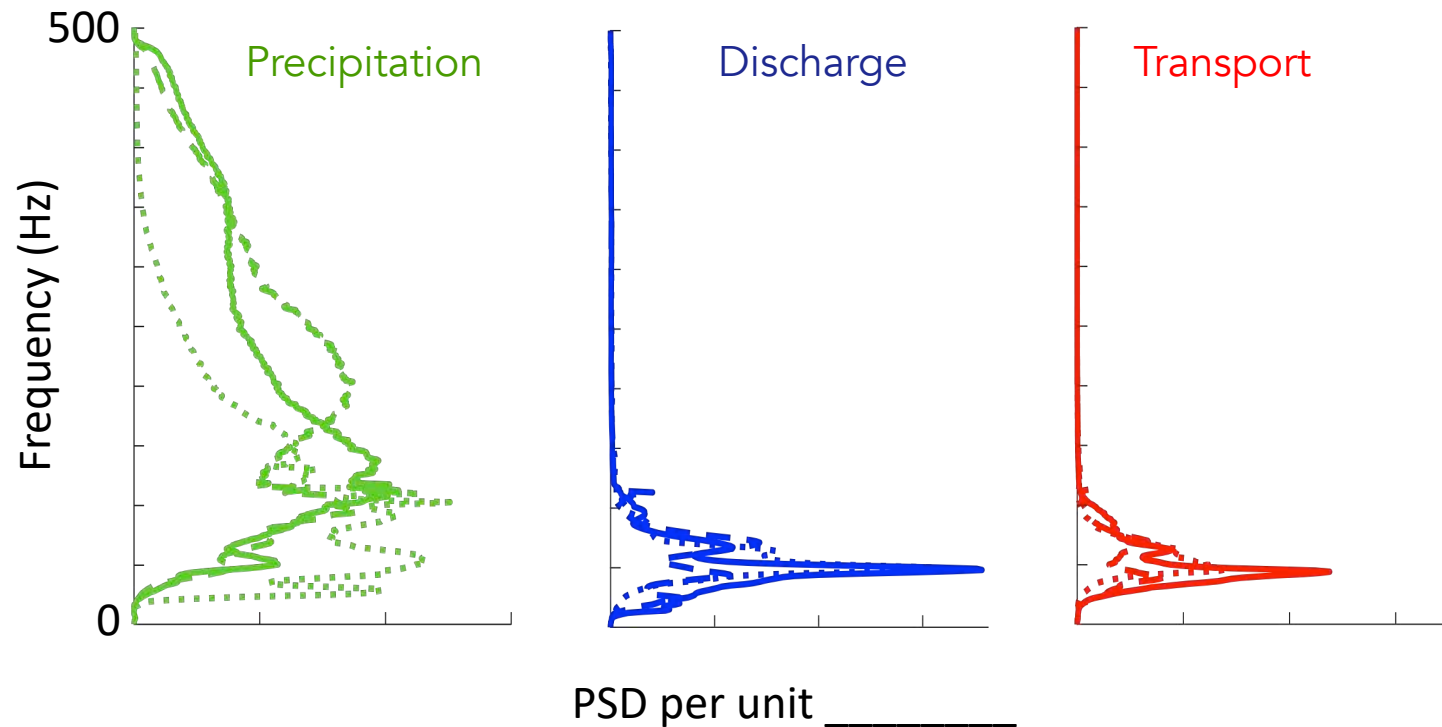


Sediment transport rates independently constrained by in-bed geophone system



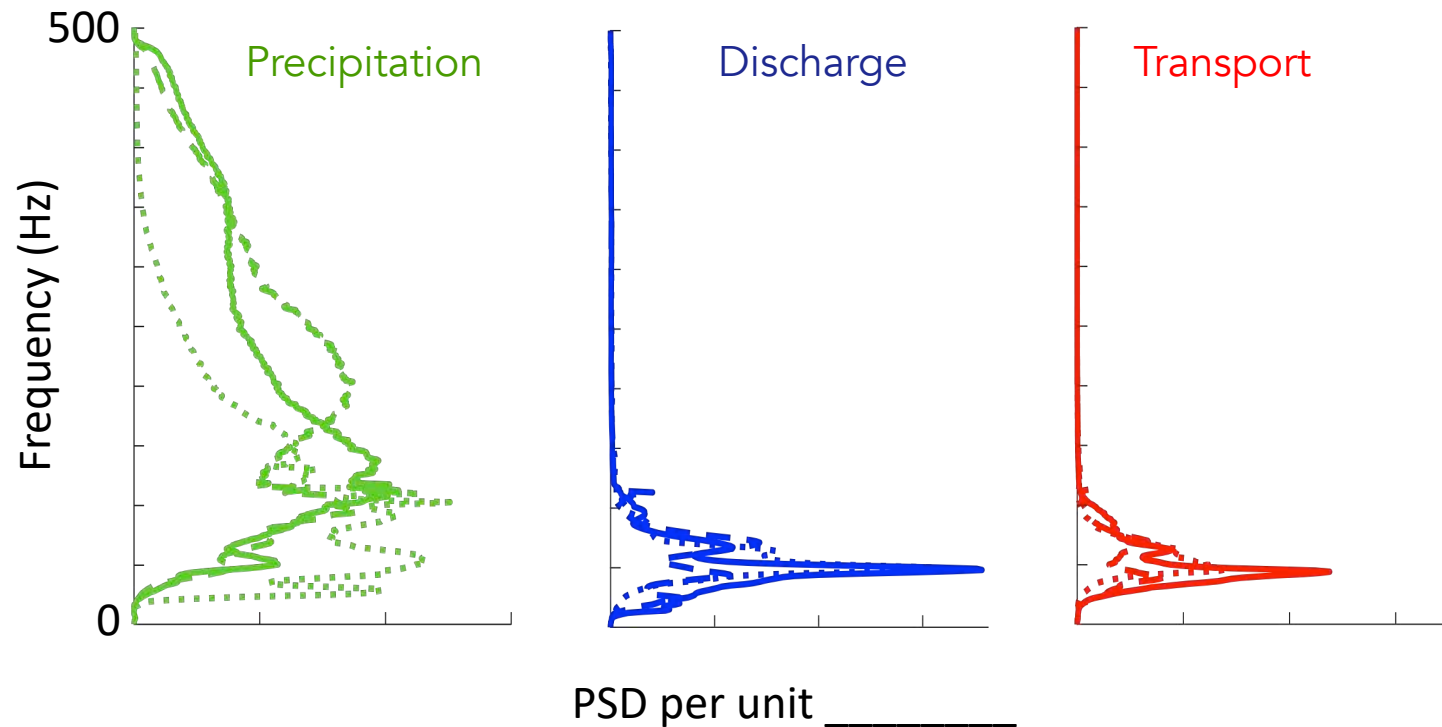
Process rates are recoverable from seismic spectra... with enough independent constraints

*Least squares regression of PSD at each frequency
identifies the spectral contributions from each process*

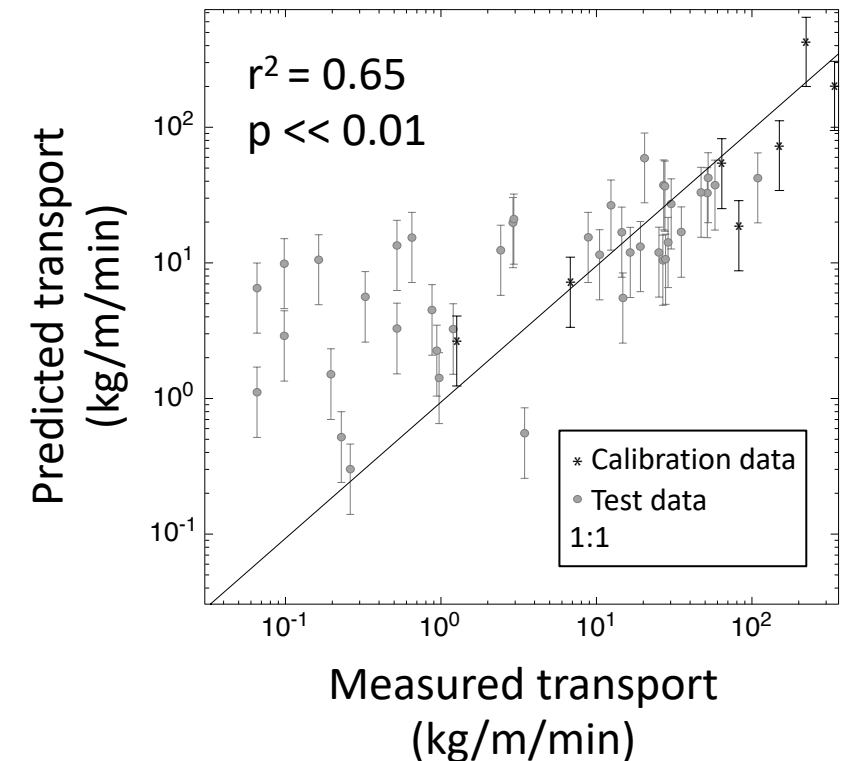


Process rates are recoverable from seismic spectra... with enough independent constraints

*Least squares regression of PSD at each frequency
identifies the spectral contributions from each process*



*Measured discharge,
precipitation and PSD
can then be inverted to
predict transport*



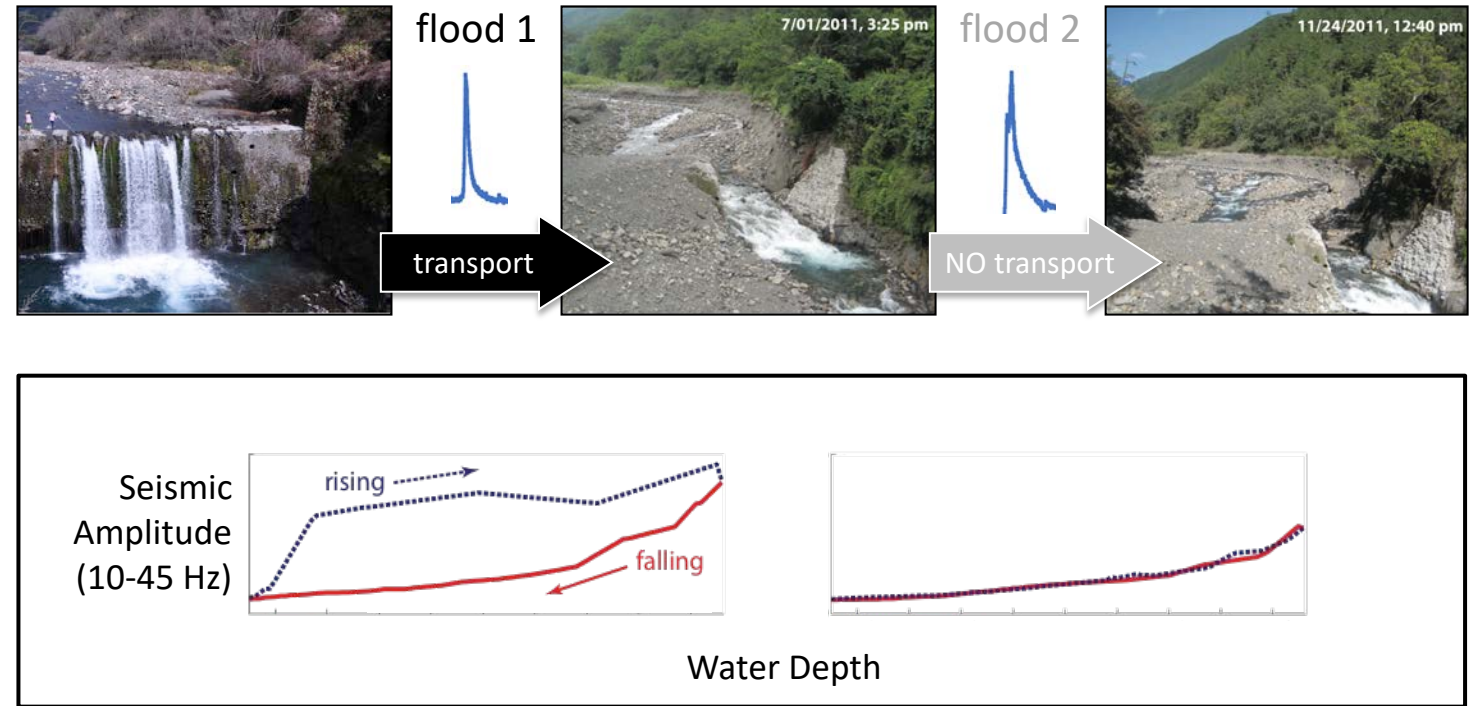
Without independent constraints, seismic data offers qualitative insights on sediment transport

Roth et al, 2014



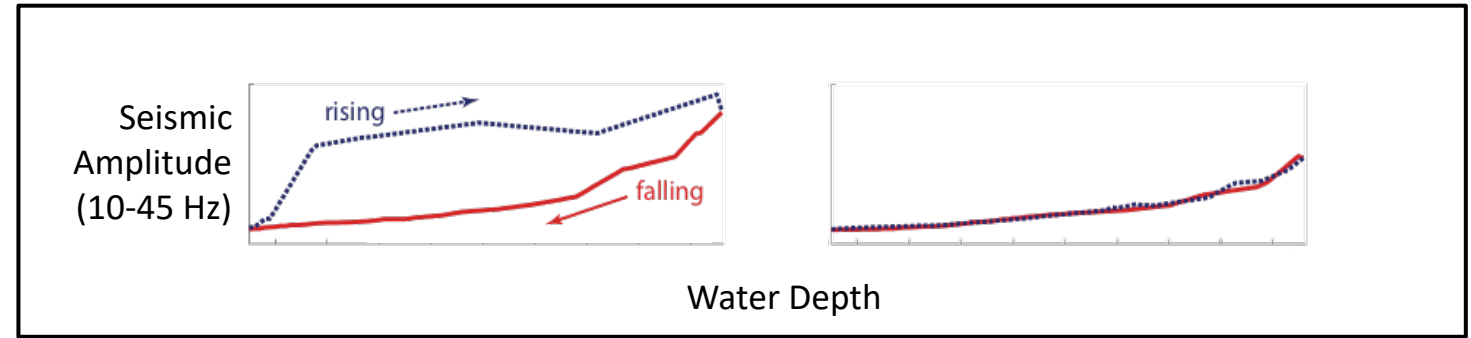
Without independent constraints, seismic data offers qualitative insights on sediment transport

Roth et al, 2014



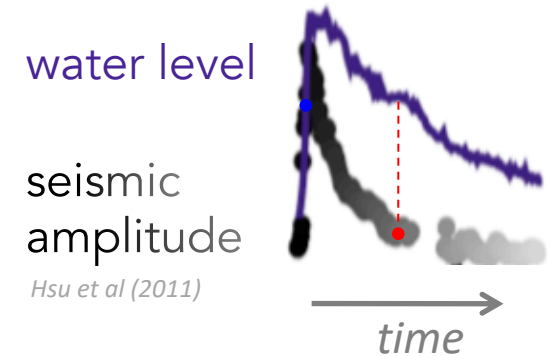
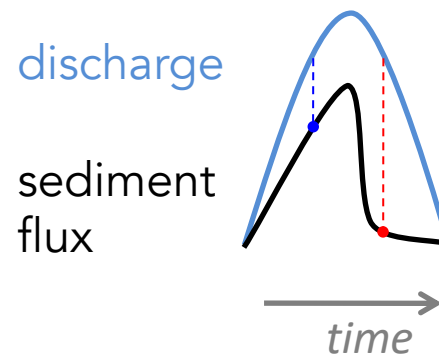
Without independent constraints, seismic data offers qualitative insights on sediment transport

Roth et al, 2014



Hysteresis in both sediment transport rates and seismic signals are commonly observed over discrete flood events.

e.g., Burtin et al., 2008; Hsu et al., 2011; Schmandt et al., 2013; Roth et al., 2014; Díaz et al., 2014; Chao et al., 2015



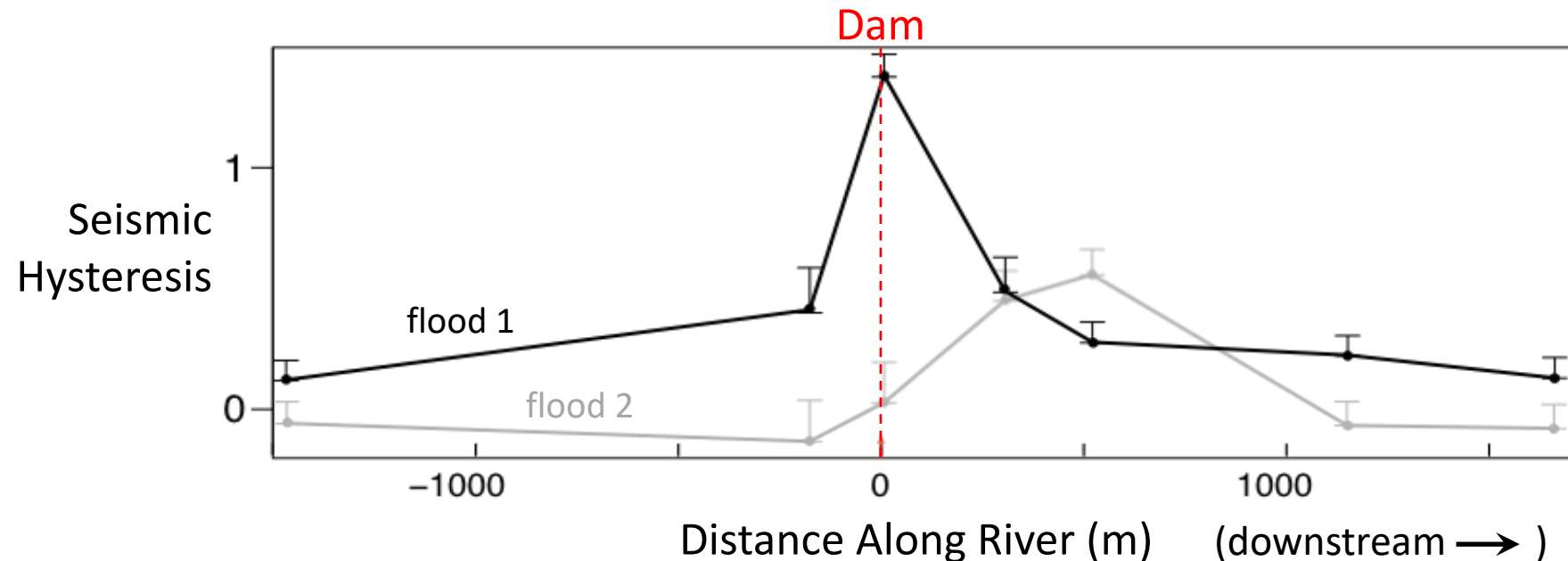
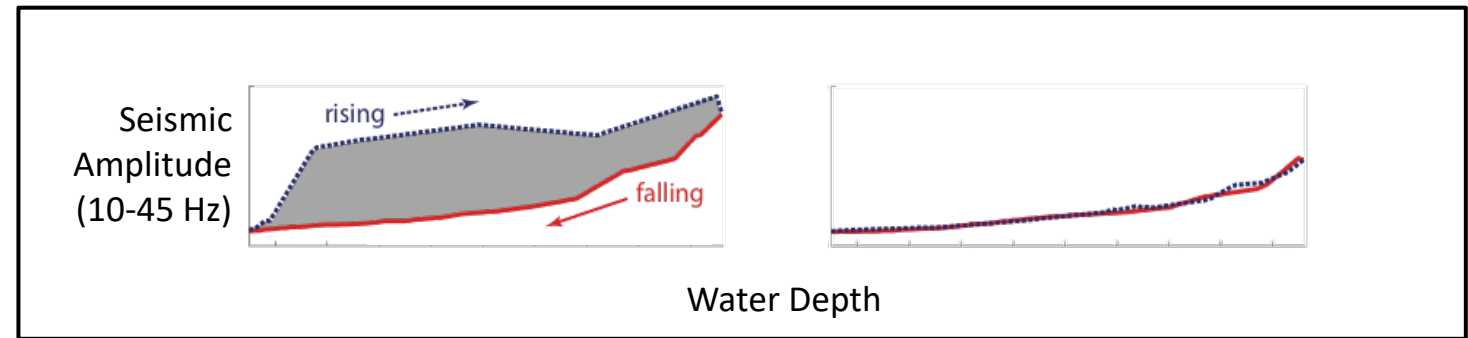
Hsu et al (2011)

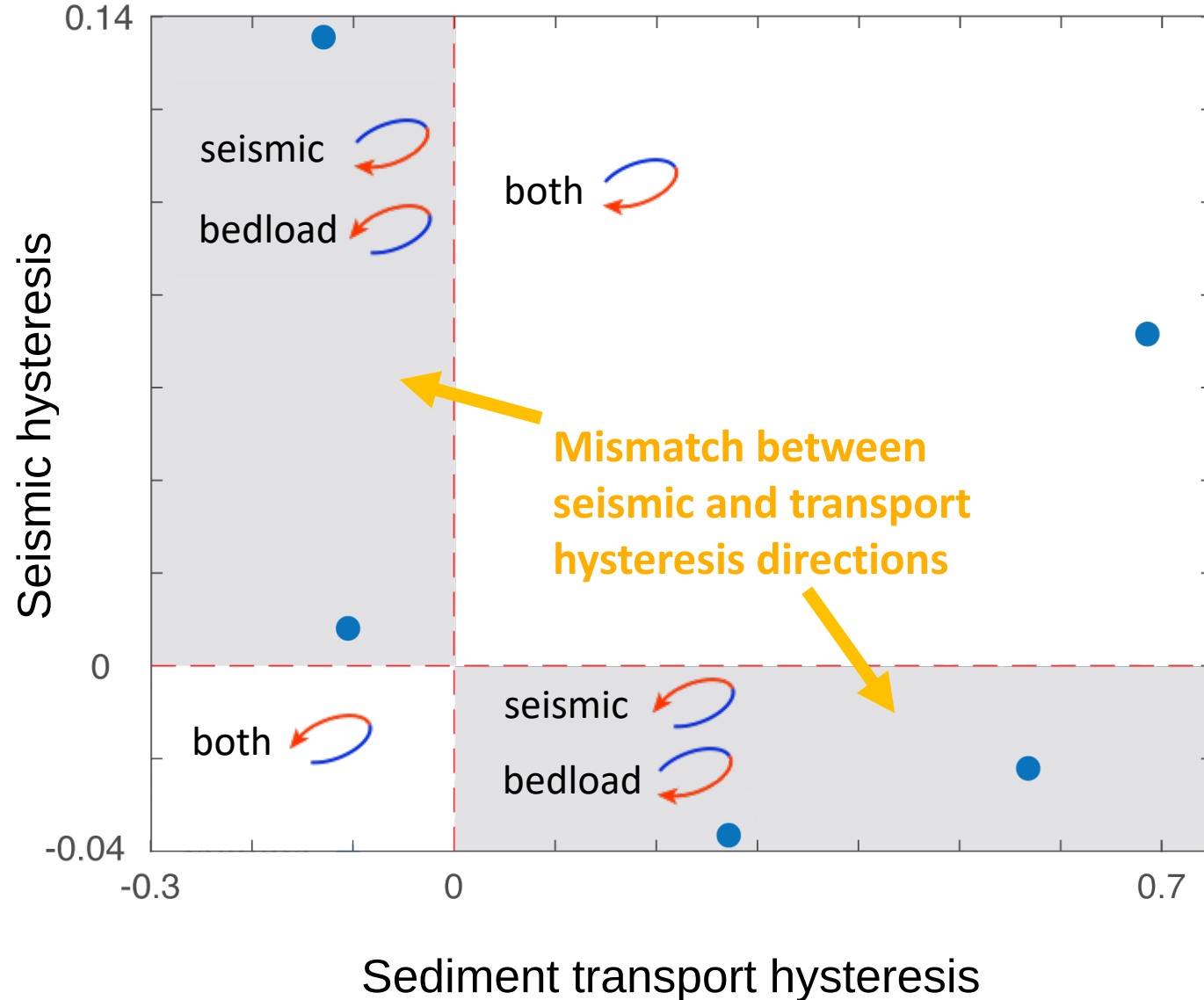
Without independent constraints, seismic data offers qualitative insights on sediment transport

Roth et al, 2014

Seismic hysteresis tracks sediment transport patterns after dam removal

Hysteresis at each seismic station over subsequent floods shows downstream advection and dispersion of a sediment pulse released from behind the dam.

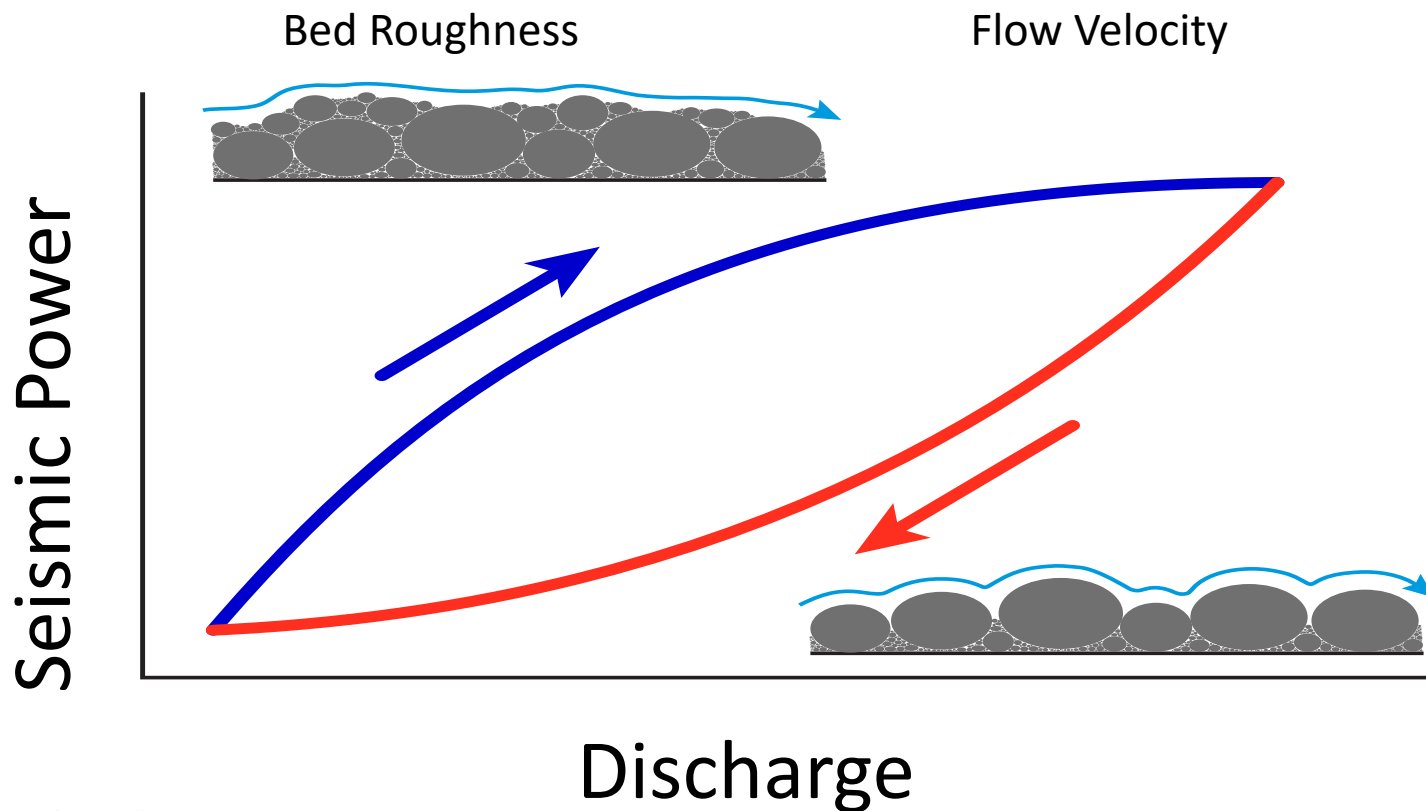
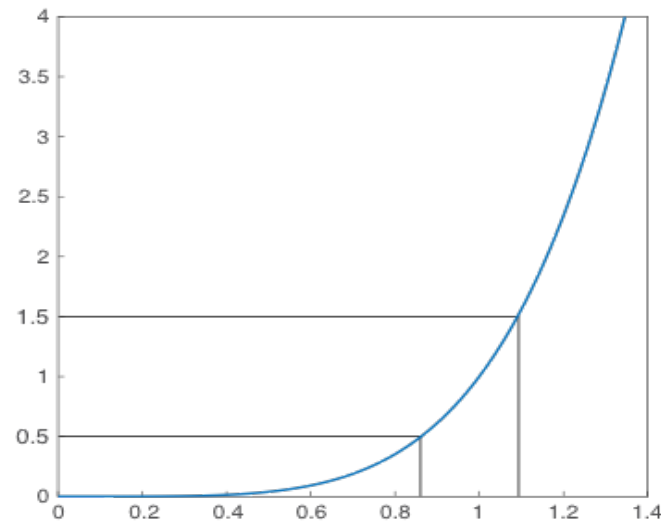
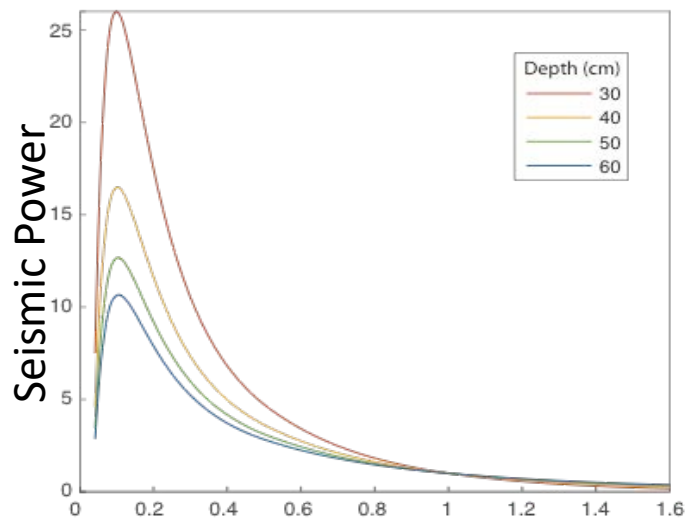




Hysteresis in seismic signals
and sediment transport rates
do not match

Roth et al, 2017

**Seismic power is higher when
transport is lower for 4 out of
5 flood events!**



Seismic sensitivity to water turbulence both a major challenge and an opportunity

The bed surface fundamentally controls water turbulence—**hysteresis due to changes in *sediment flux* versus the *turbulent boundary layer*** cannot be distinguished without additional data

Can seismic signals provide new information on turbulent flow dynamics and bed organization?

Theoretical model advances are closing the gap between seismic observations, flow characteristics and sediment transport theory

Several models developed for theoretical bedload and water turbulence spectra

(*Tsai et al, 2012; Gimbert et al, 2014, 2016*)

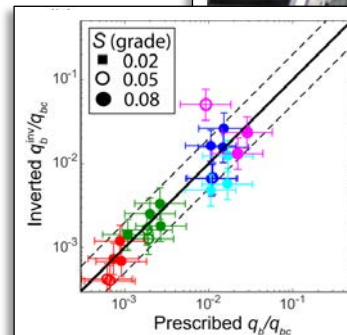
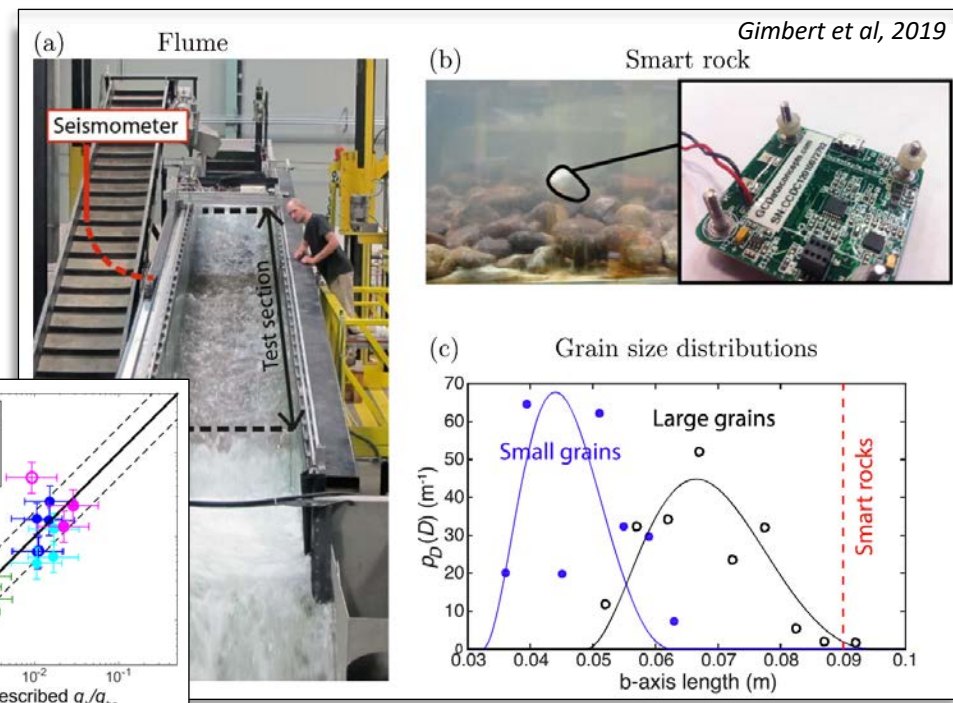
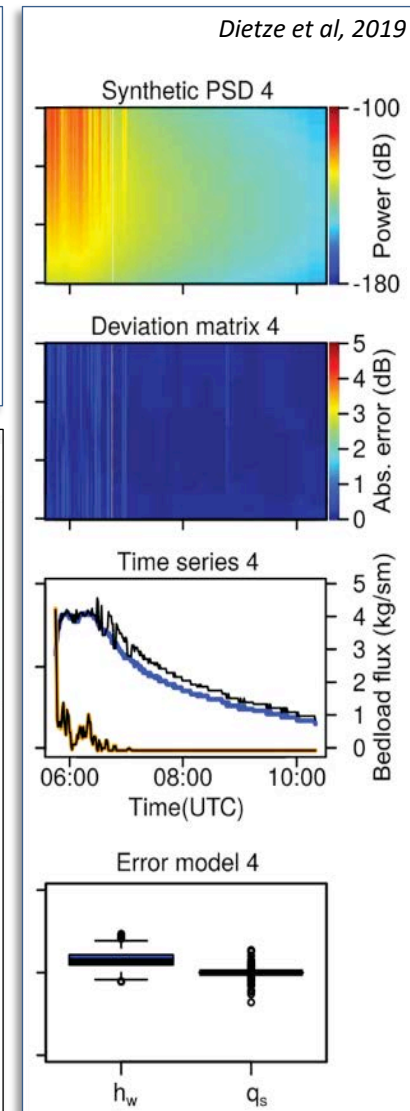
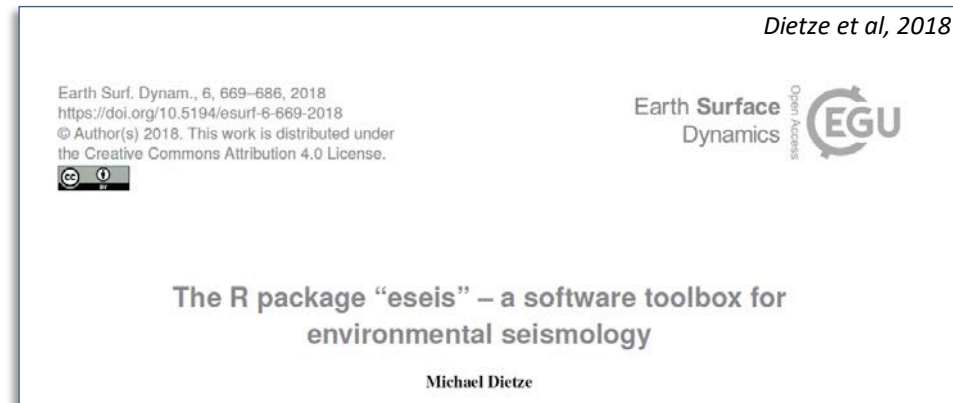
Inversion of observed spectra to estimate transport requires site-specific parameters and is complicated by overlap of spectra

Recent computational advances are providing new tools for optimizing parameters

(*Dietze et al, 2018*)

Model validation remains a major challenge, requires more controlled studies with well-constrained parameters and variables

(*e.g., Gimbert et al, 2019*)



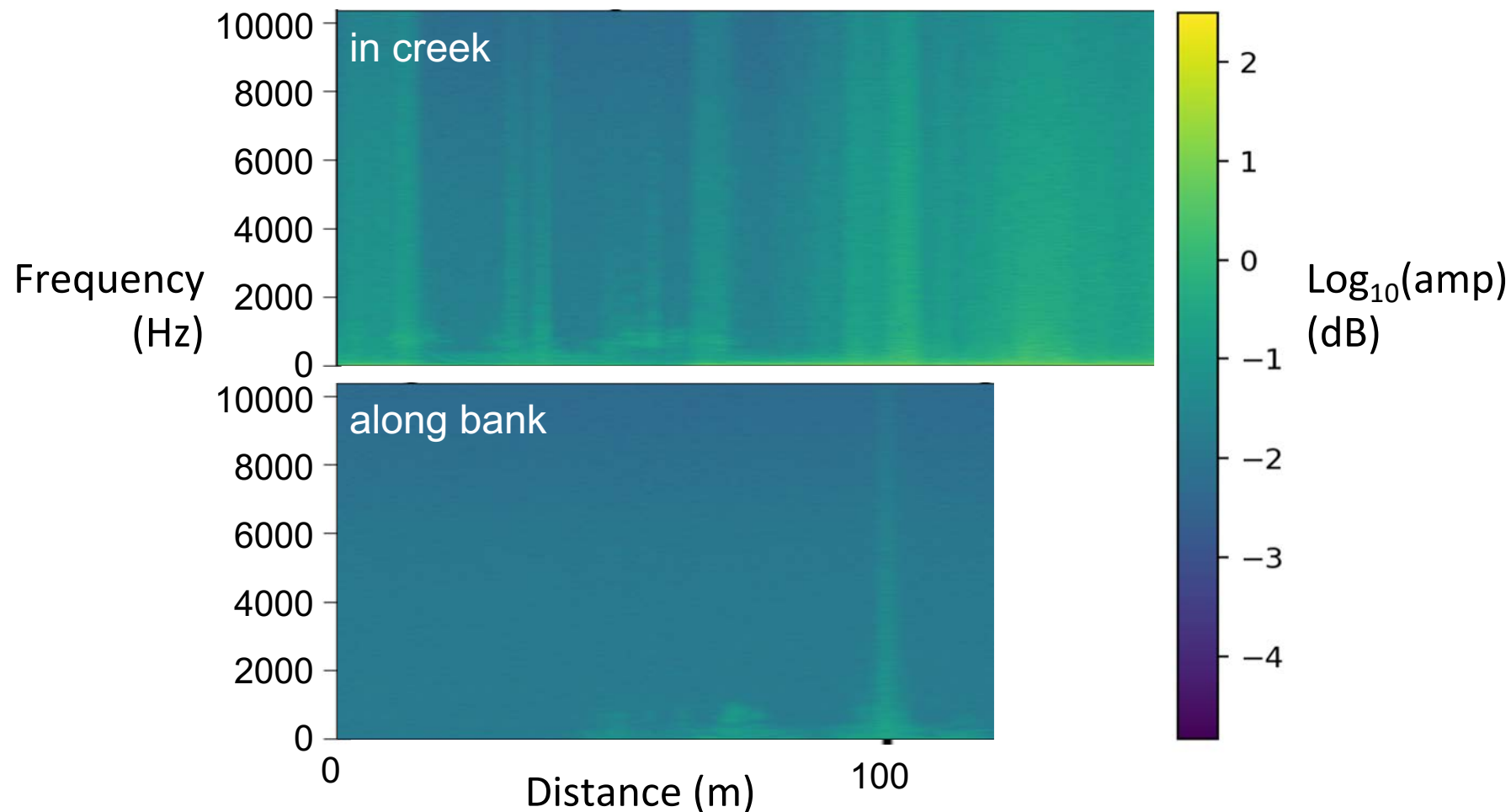
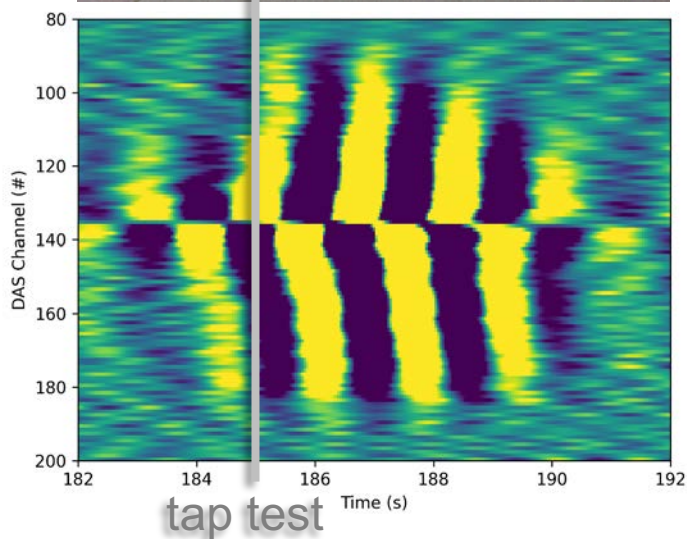
Distributed acoustic sensing (DAS) Dec. 2020, Clear Creek, CO

*Collaboration with Jin Ge, Aleksei Titov, Matt Siegfried
(not pictured: Claire Masteller, Luke Zoet)*

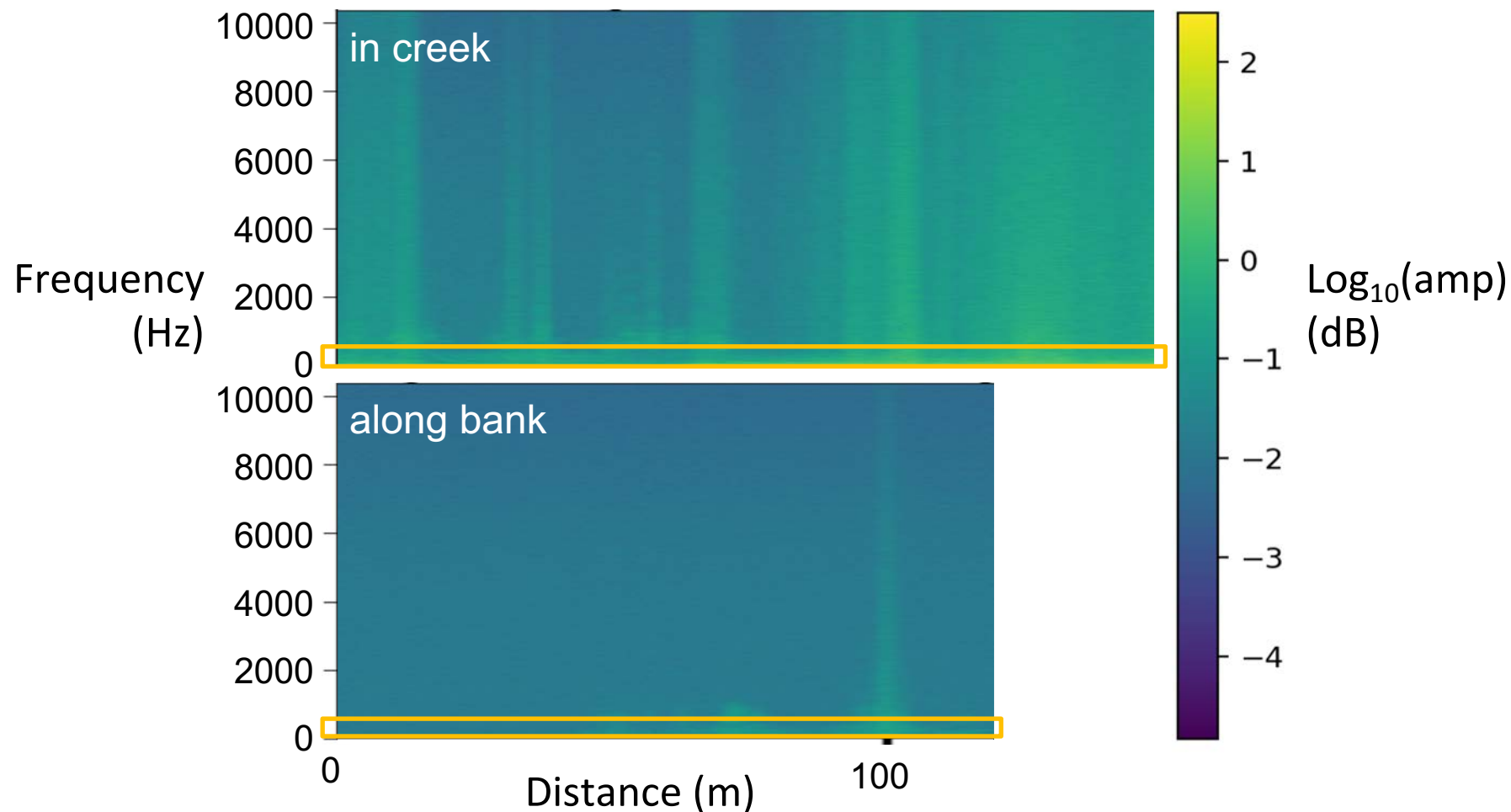
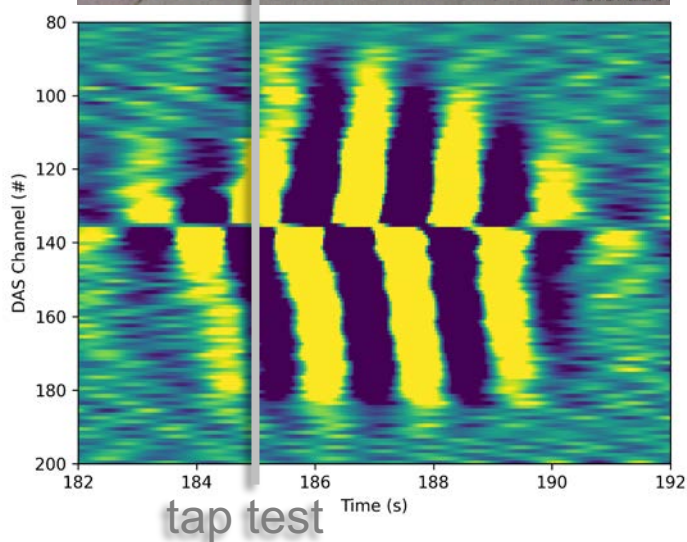


Collaboration with Jin Ge, Aleksei Titov, Matt Siegfried (not pictured: Claire Masteller, Luke Zoet)

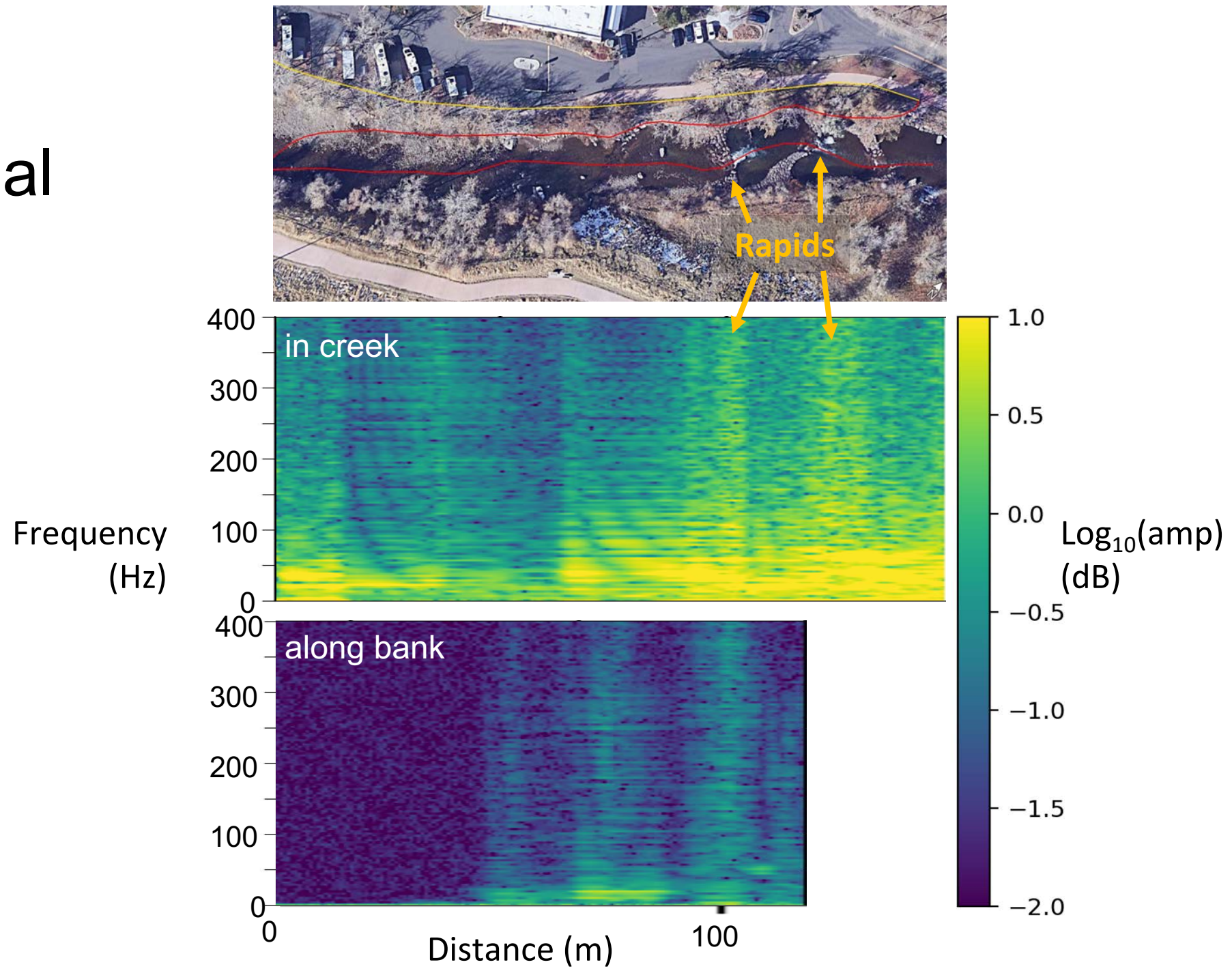
Polarity reversals created by "tap tests" identify DAS channels at key positions



Polarity reversals created by "tap tests" identify DAS channels at key positions



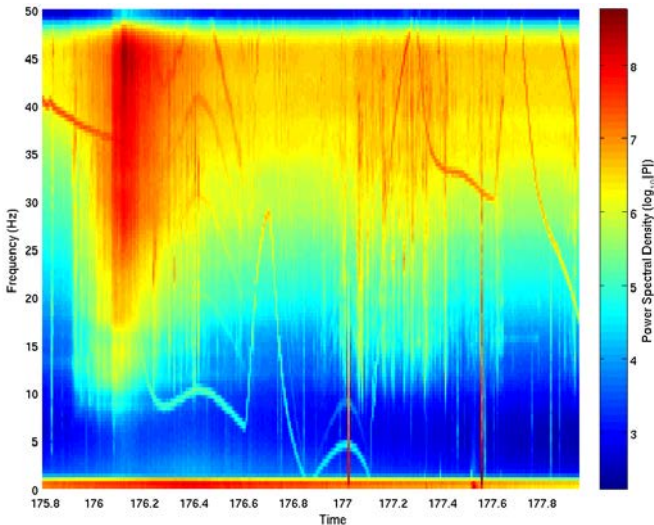
Isolated water turbulence signal



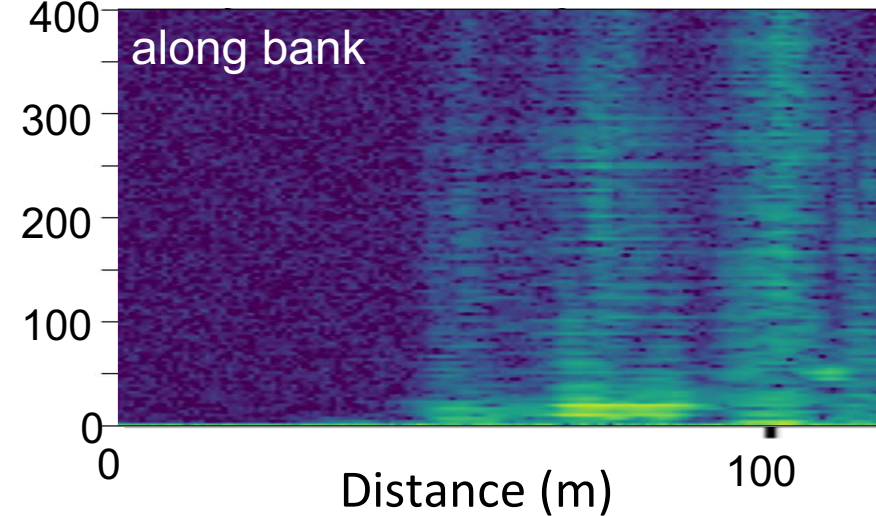
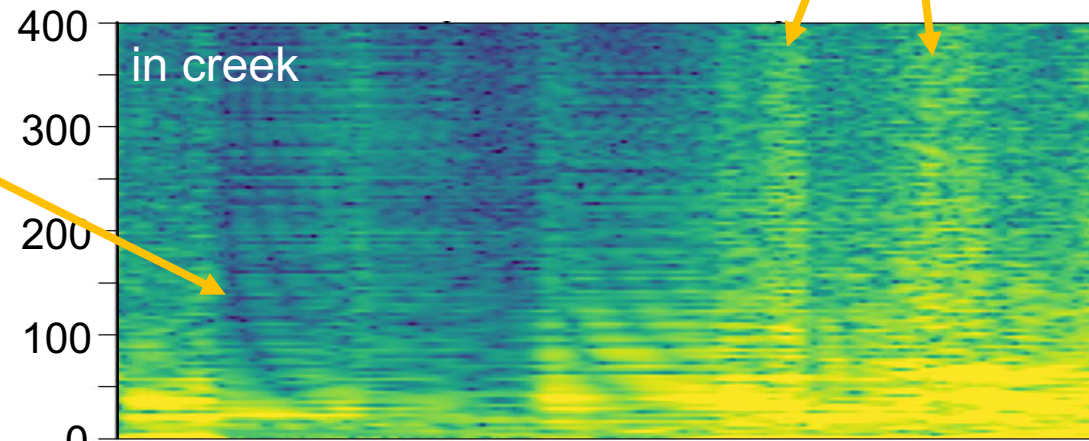
Isolated water turbulence signal

Frequency shifts due to changing flow depth or channel width?

May explain similar observations in less well-constrained data, e.g., after dam removal:



Frequency (Hz)



Distance (m)



Opportunities

- Continuous record of existing data in many places
- Identification of rare events, forcing/precursors and process cascades
- High spatial/temporal resolution for process monitoring (large arrays, DAS)
 - With independent calibration/data: direct estimates of sediment transport rates
 - Without independent calibration/data: tracking of qualitative patterns, relative rates
- Characterizing bed organization/evolution or energy transfer

Challenges/Needs

- Complex coupling between sediment transport, hydraulic parameters and environmental variables
- Site-specific attenuation (i.e., empirical Green's functions) – riverbeds are heterogeneous!
- Parallel development and validation of theoretical models will require controlled seismic deployments co-located with traditional instrumentation to independently measure environmental variables
 - Weather/meteorological data
 - Water level/discharge
 - Sediment transport rates
 - High resolution topography/change detection
 - Substrate characteristics (attenuation)
 - Video/time-lapse imagery



— Acknowledgements —

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PASSCAL Instrument Center, Eugene Cota-Robles
Fellowship, DOE National Nuclear Security
Administration, CSM Geophysics Department, CSM
Dean's EREP and CSM VPRTT

Collaborators/Coauthors:

Noah Finnegan, Emily Brodsky, Jens Turowski, Dieter
Rickenmann, Alexandre Badoux, Florent Gimbert, Claire
Masteller, Jin Ge, Aleksei Titov, Matt Siegfried, Luke Zoet

— Supplemental —————



<https://www.wsl.ch/en/news/2019/06/the-worlds-largest-debris-flow-measuring-system-is-back-in-operation.html>

Illgraben, Switzerland

In-bed sensor systems

Steel plate(s) embedded in engineered concrete bed

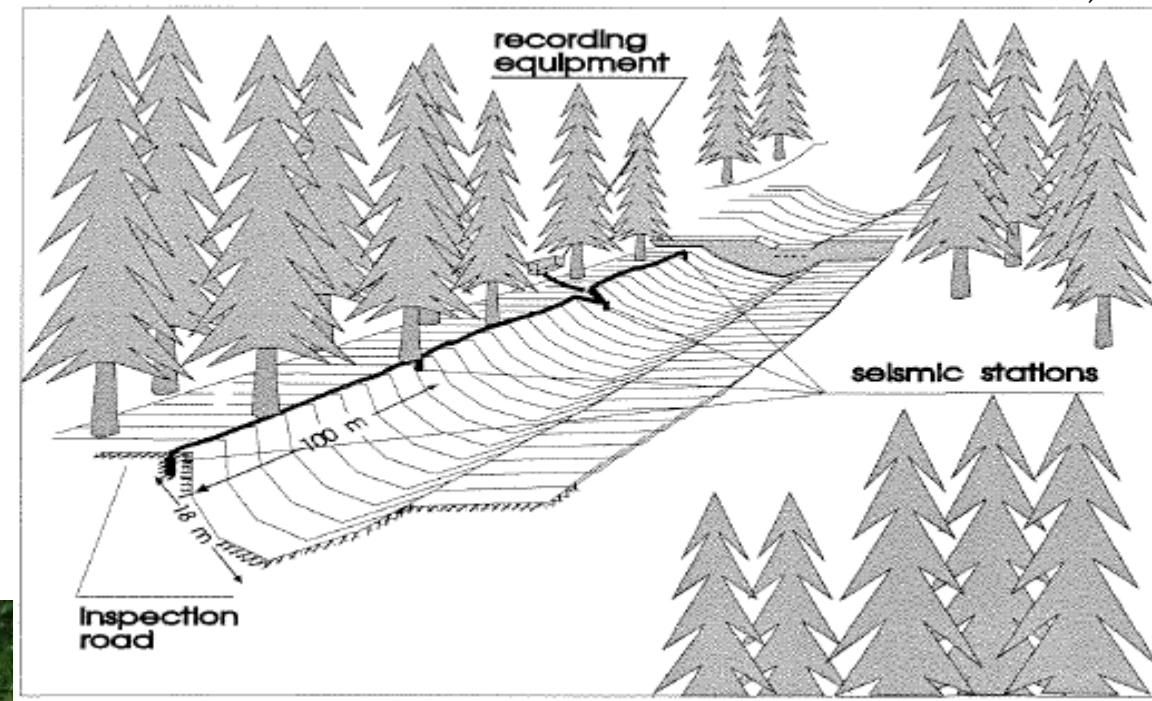
- Acceleration sensors + load cells beneath plate
- Wide range of complementary instrumentation
 - radar/laser scanners
 - video cameras
 - meteorological stations
 - discharge gages
 - retention basins
 - basket samplers
 - etc...



Erlenbach, Switzerland

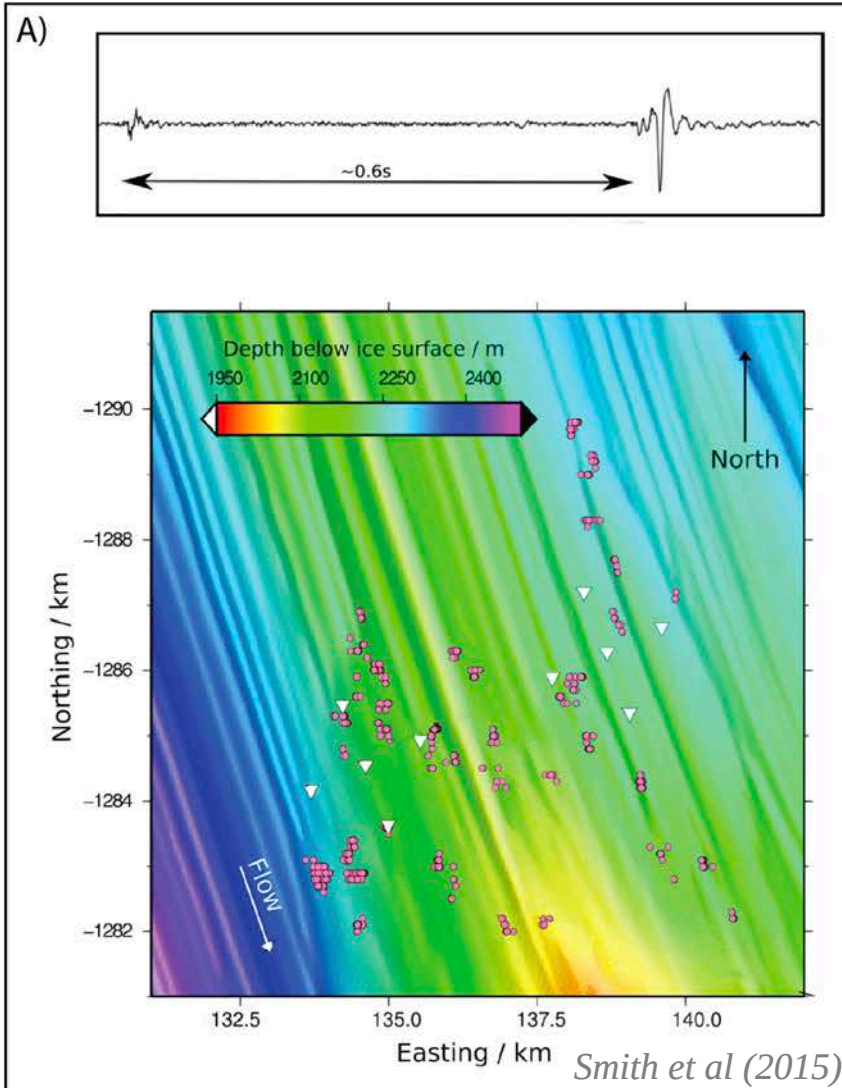
Along-stream monitoring systems

Fast and easy deployment near expected event sites

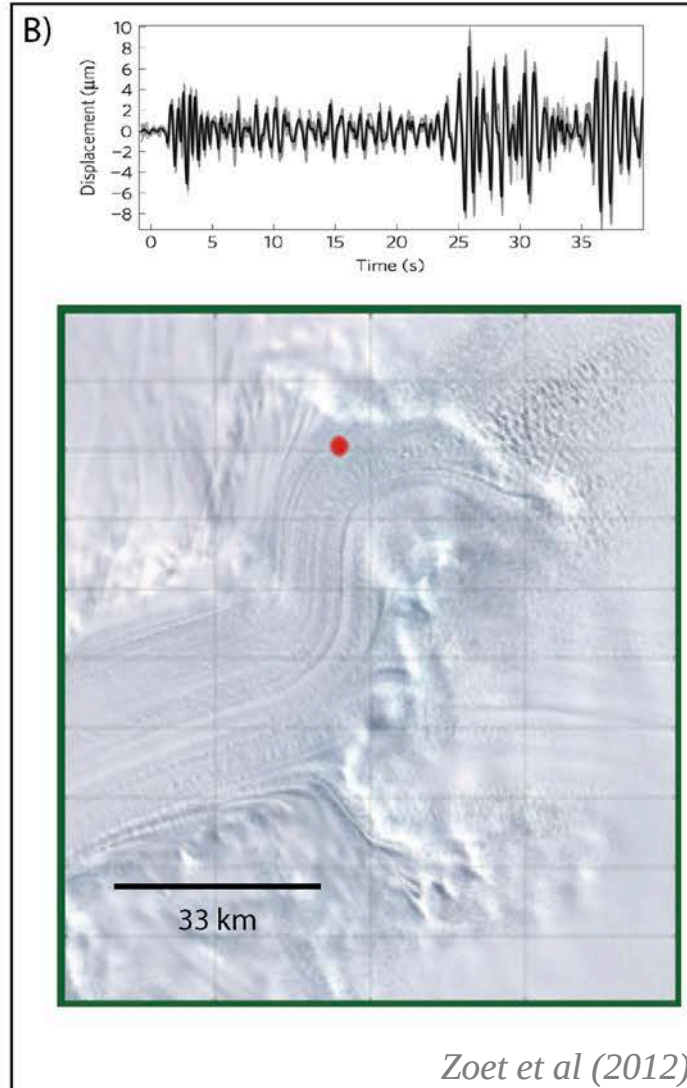


Scales of glacial stick-slip asperities from Antarctica

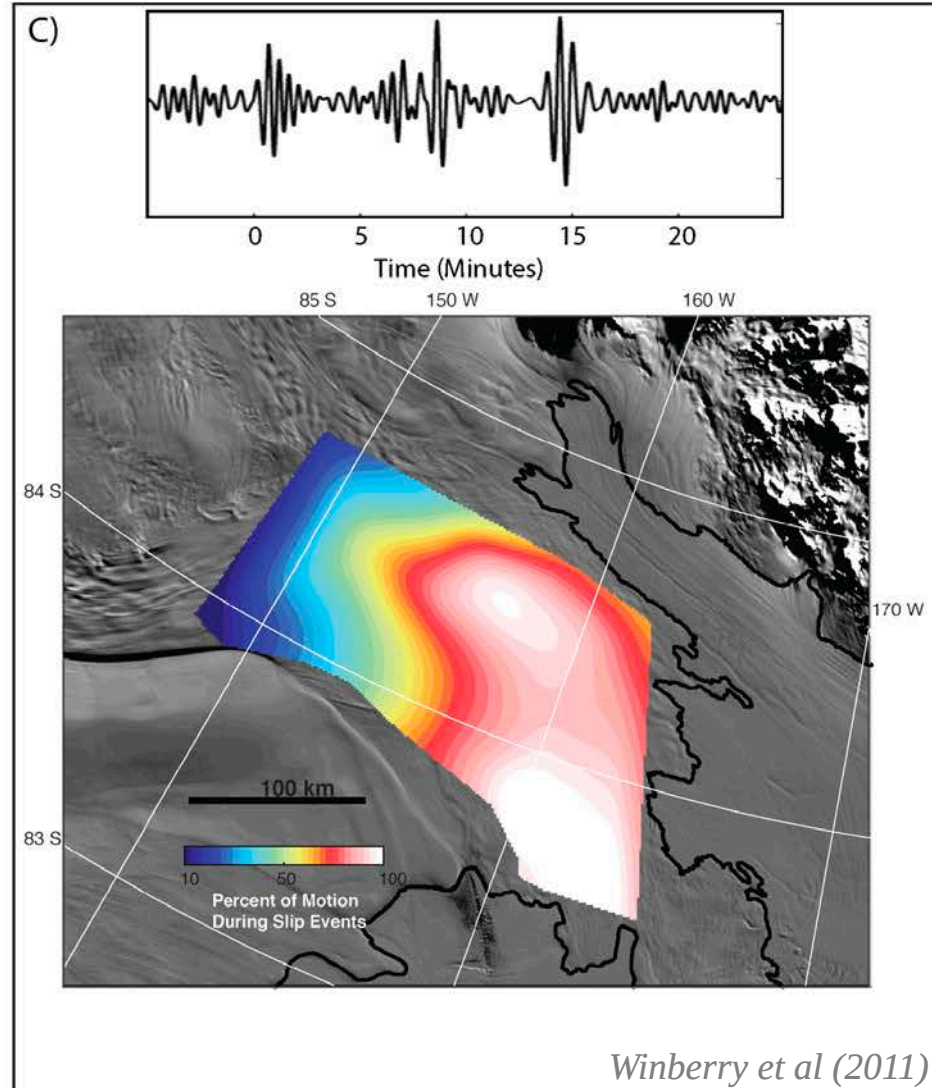
≈1 m-scale asperity



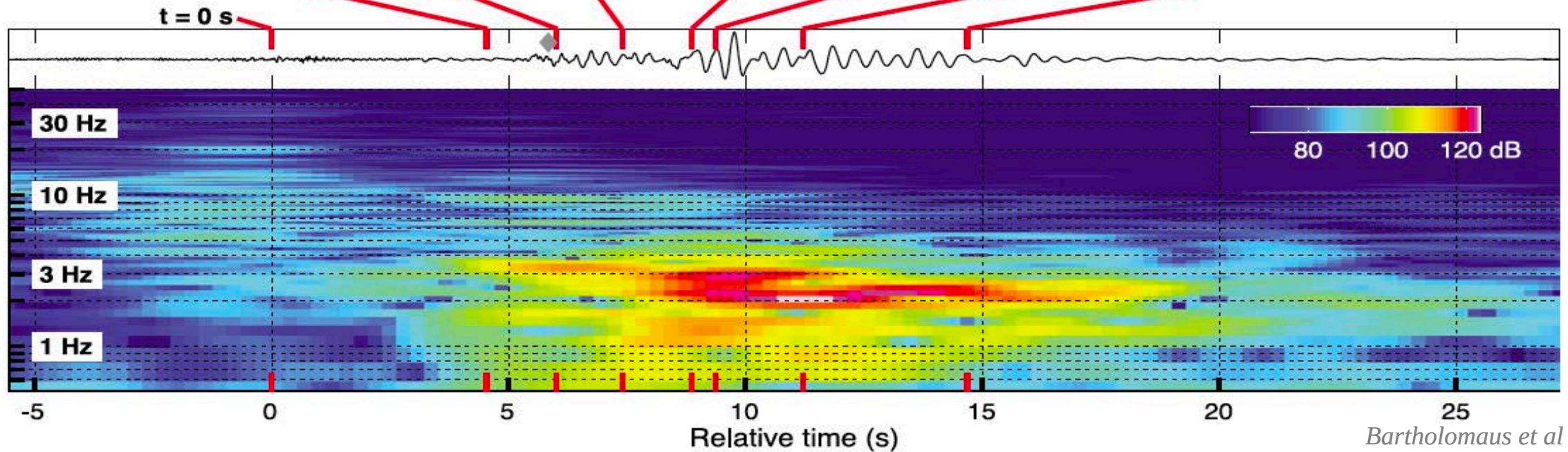
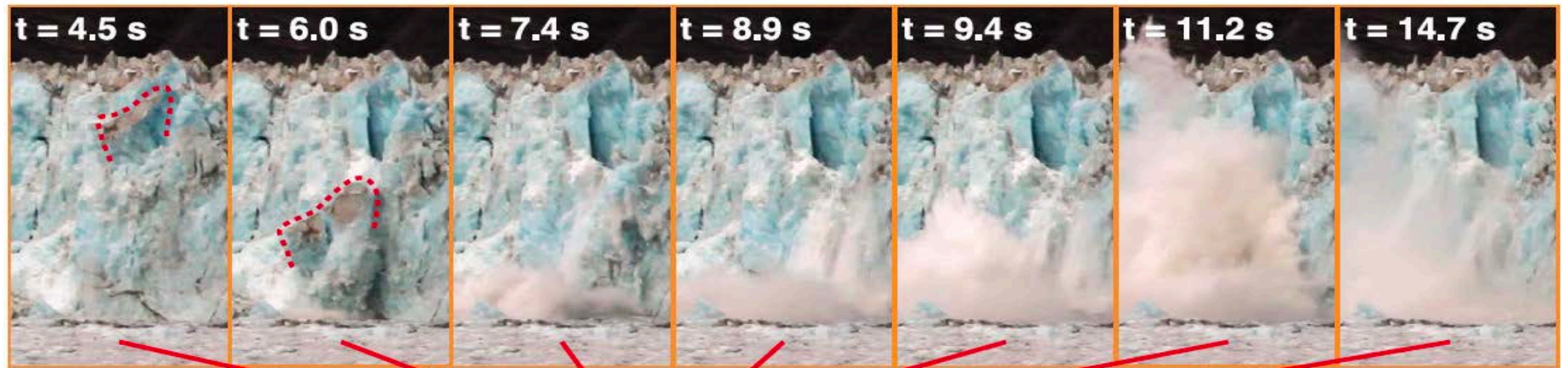
≈1 km-scale asperity



≈50 km-scale asperity

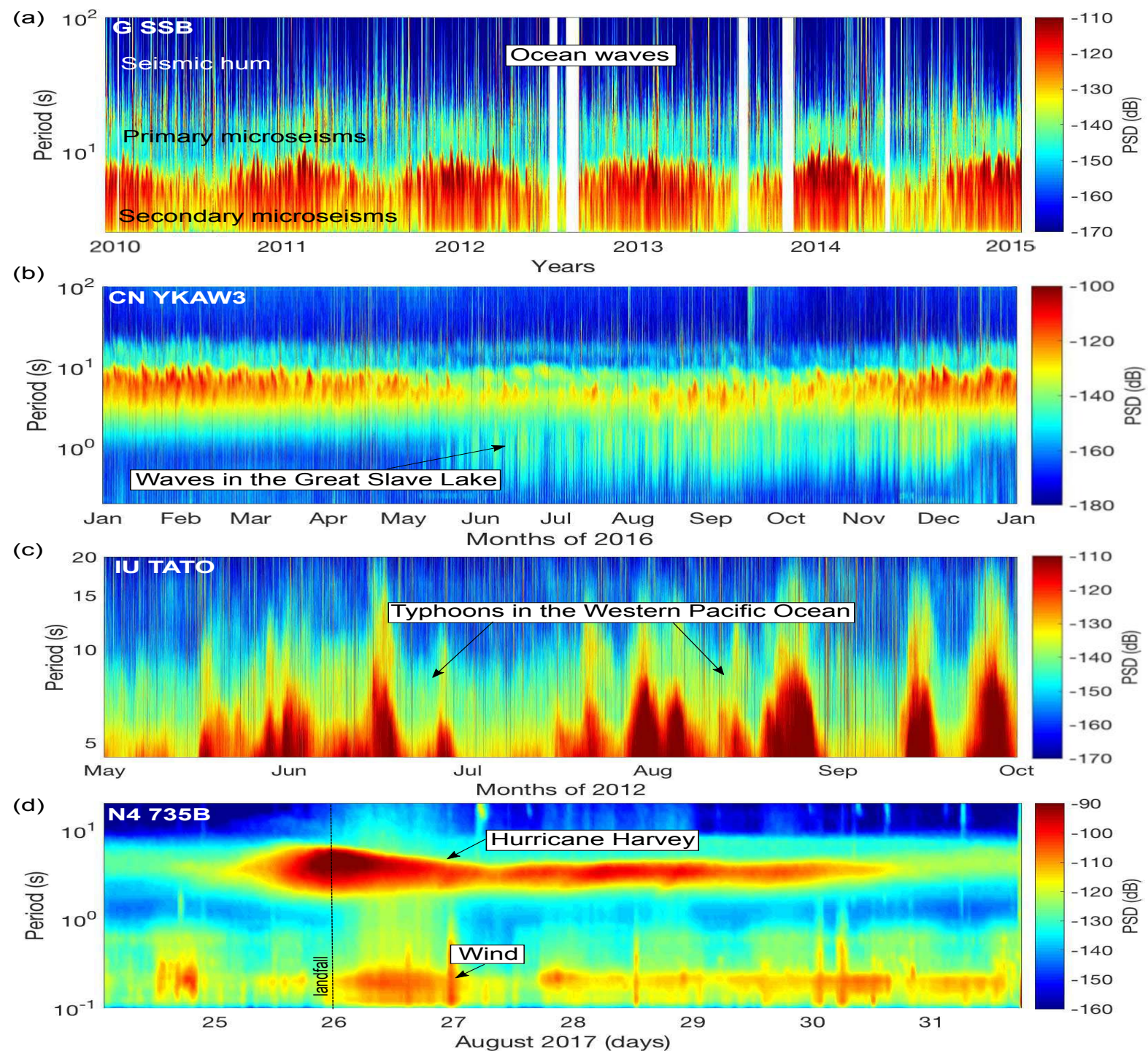


Calving event from Yahtse Glacier

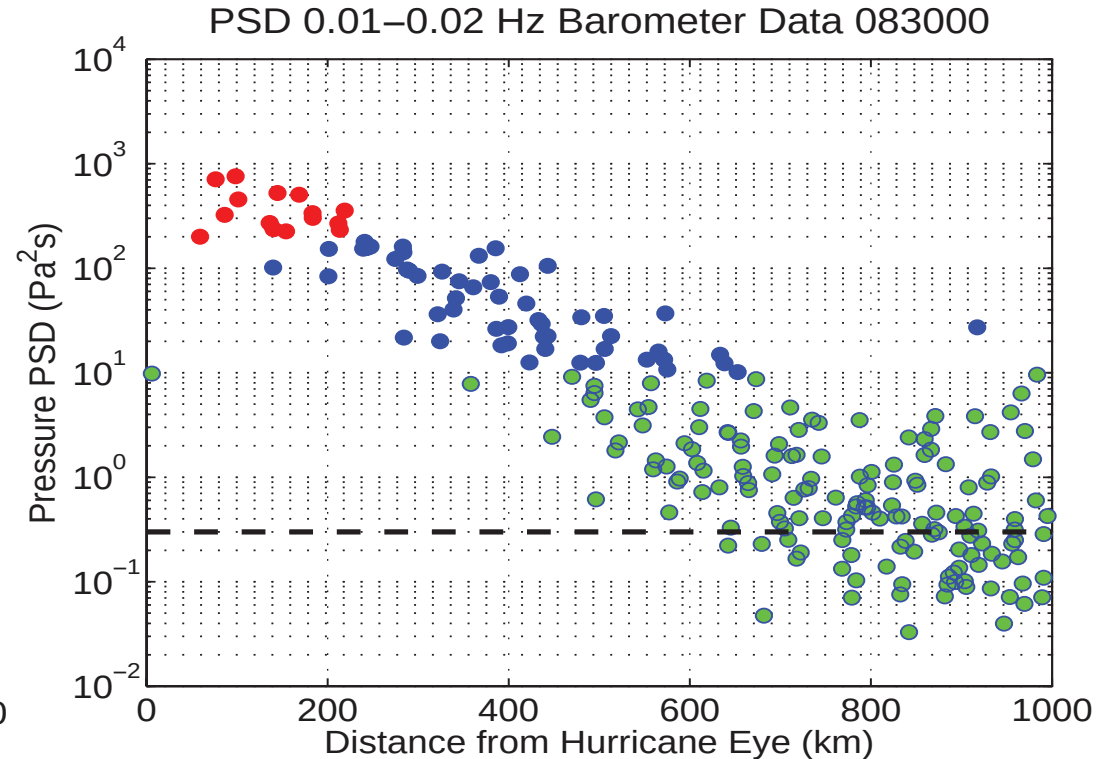
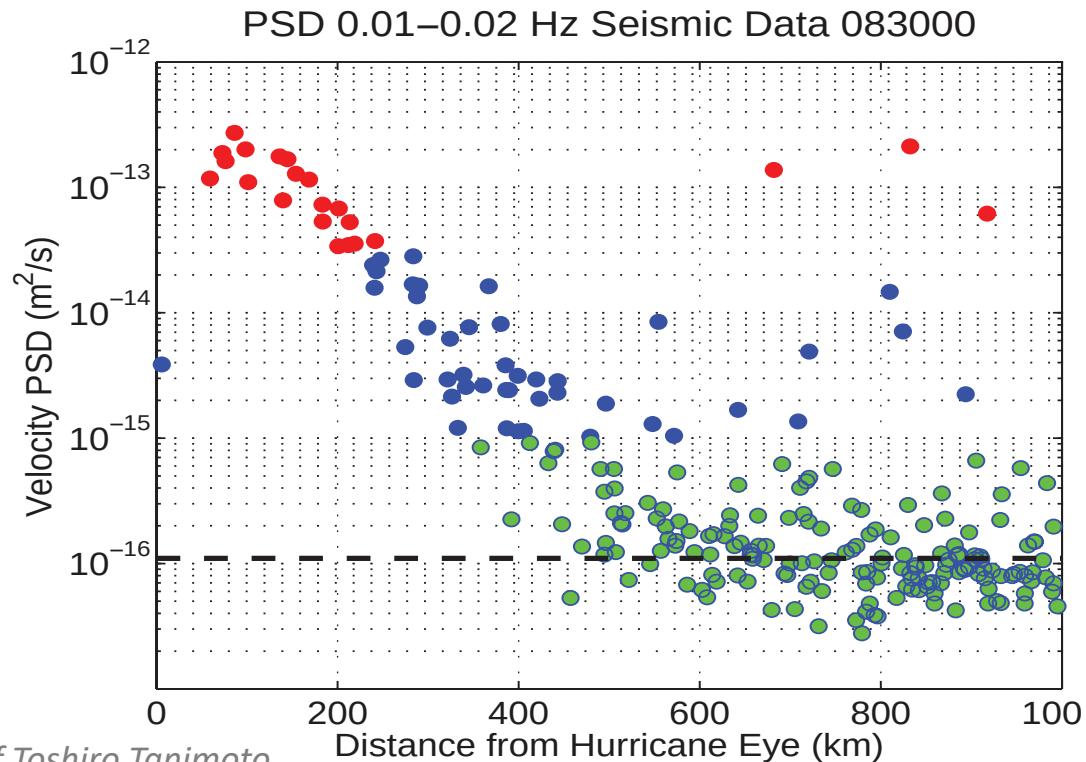
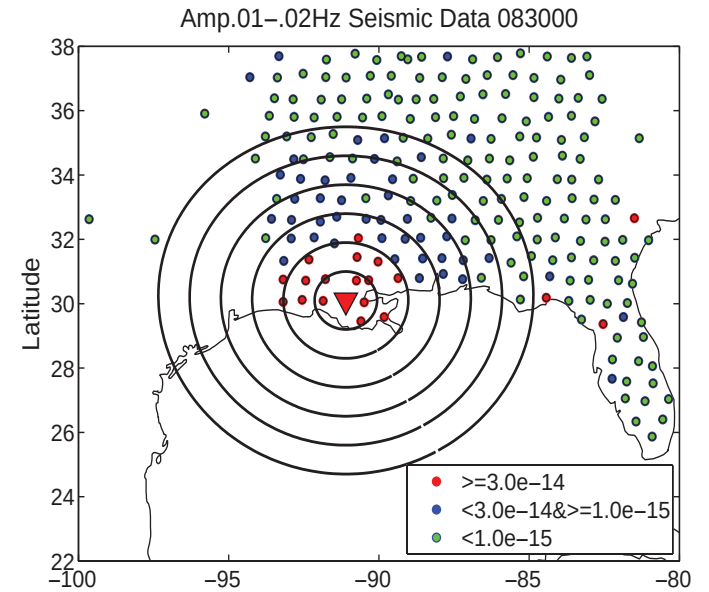
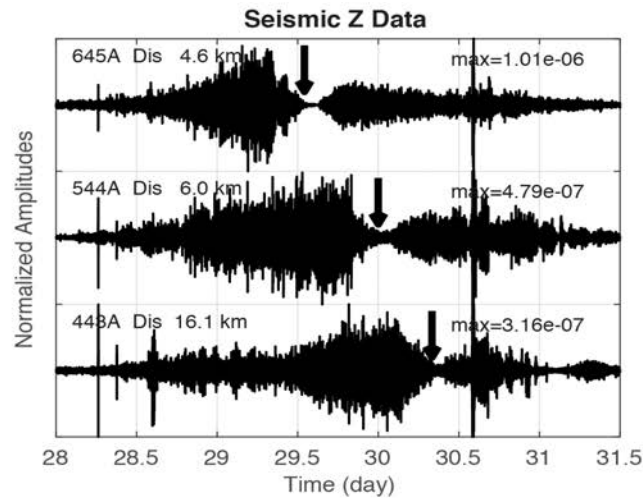


Microseisms

Oceanic and atmospheric phenomena

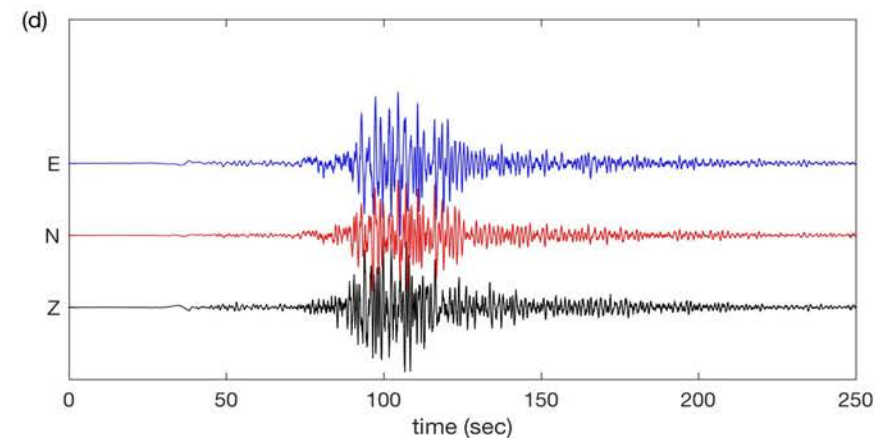
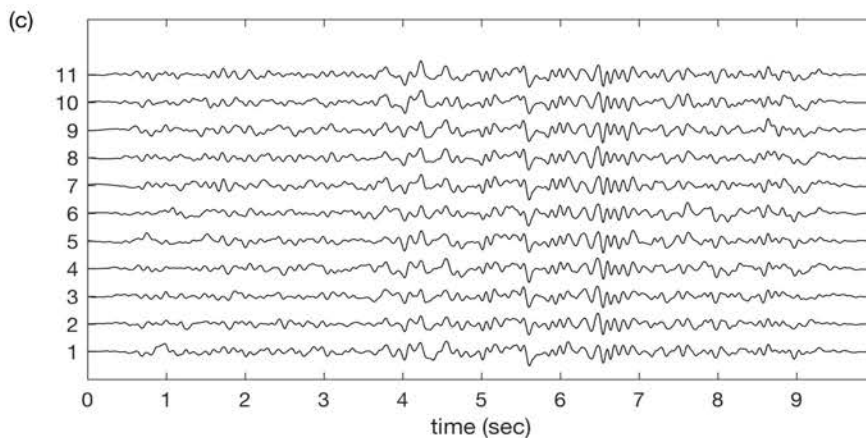
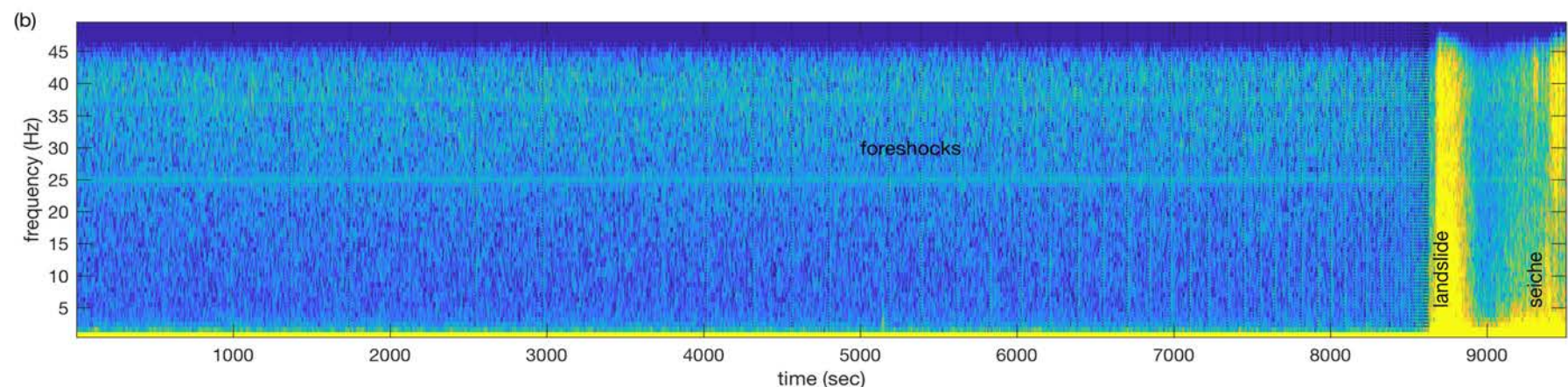
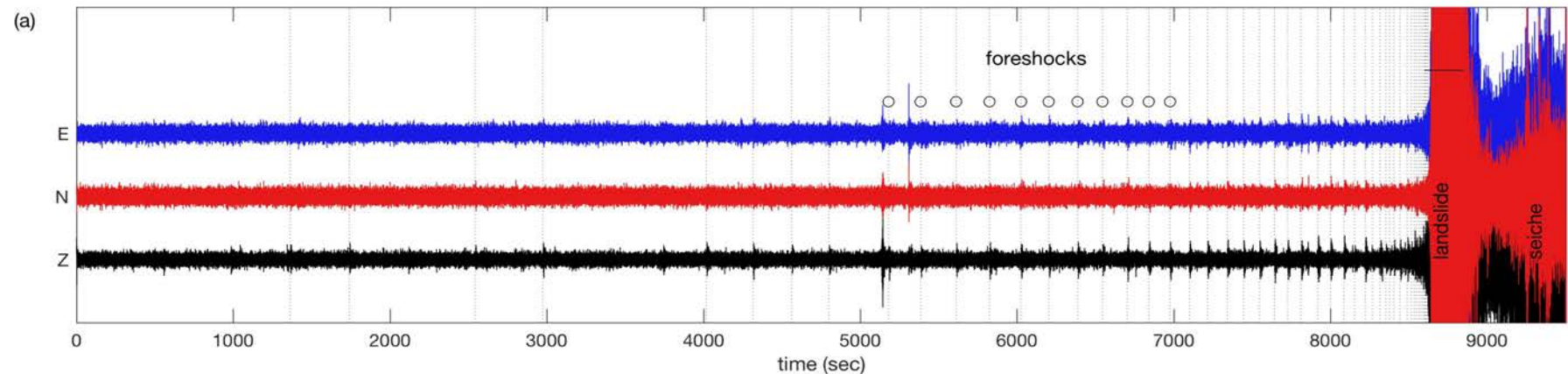
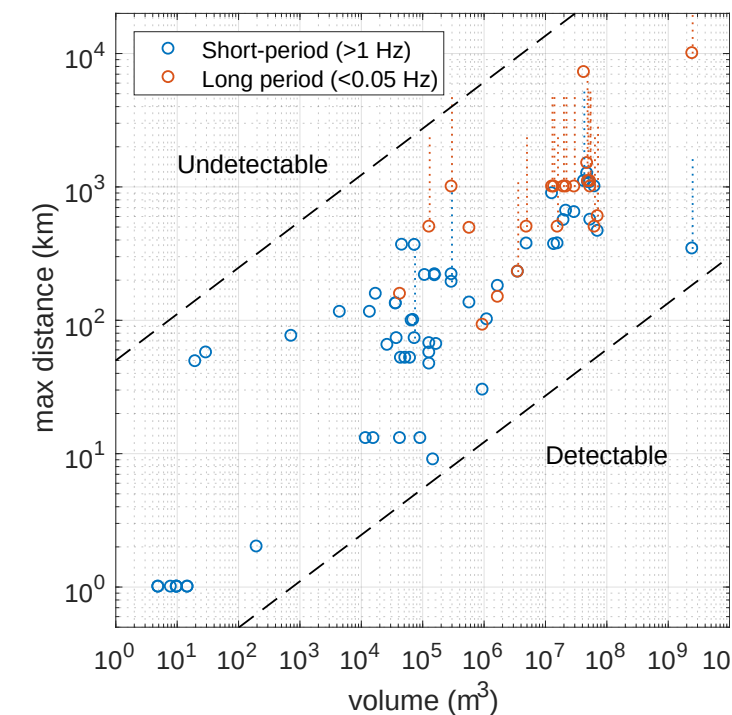


Hurricane physics observed with seismics & pressure sensors



Nuuggaatsiaq landslide, Greenland

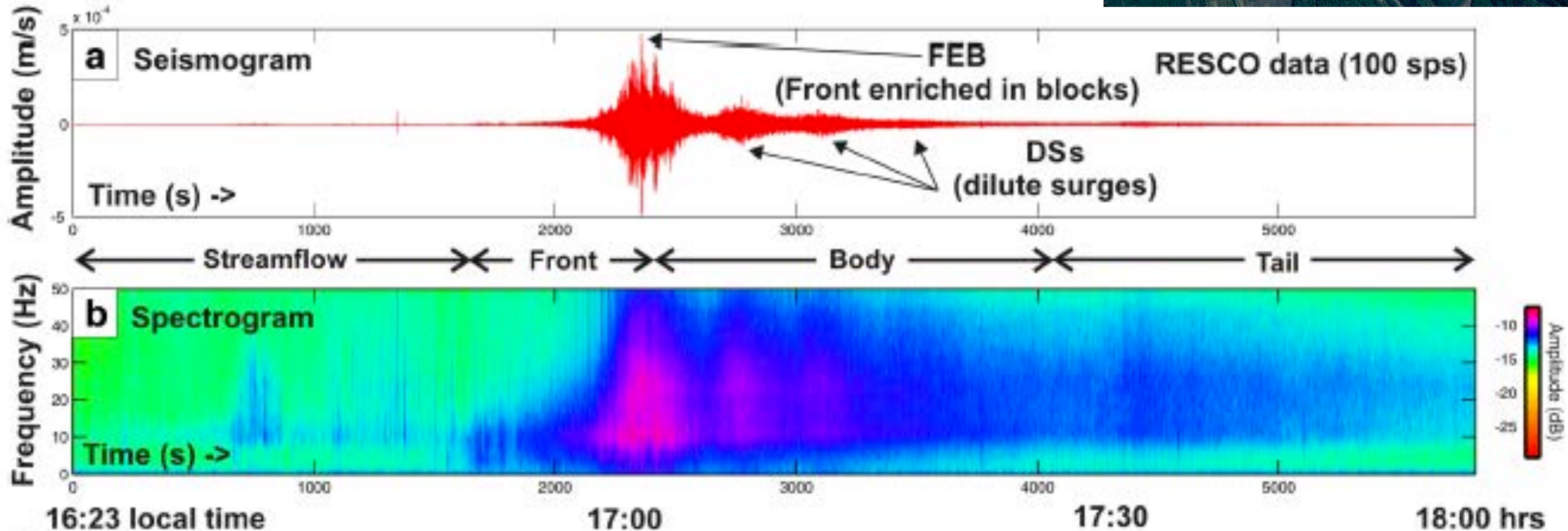
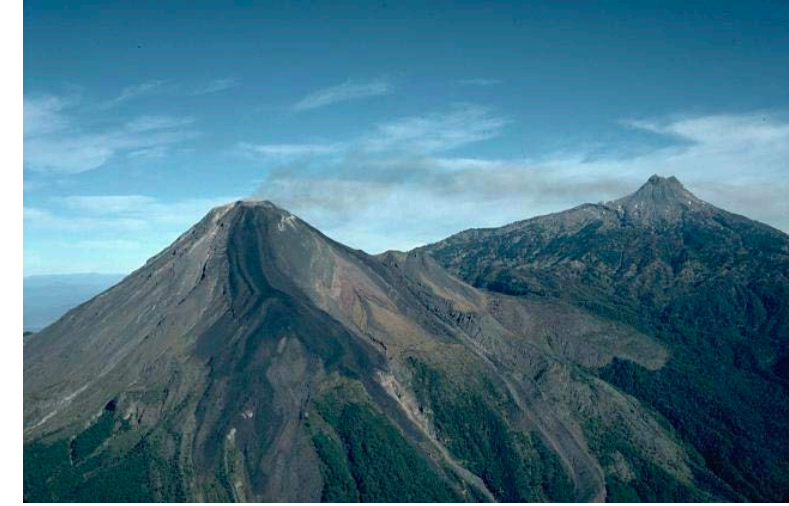
June 17, 2017



Lahar on Volcán de Colima

frequency content changes as different parts of the flow pass by the station

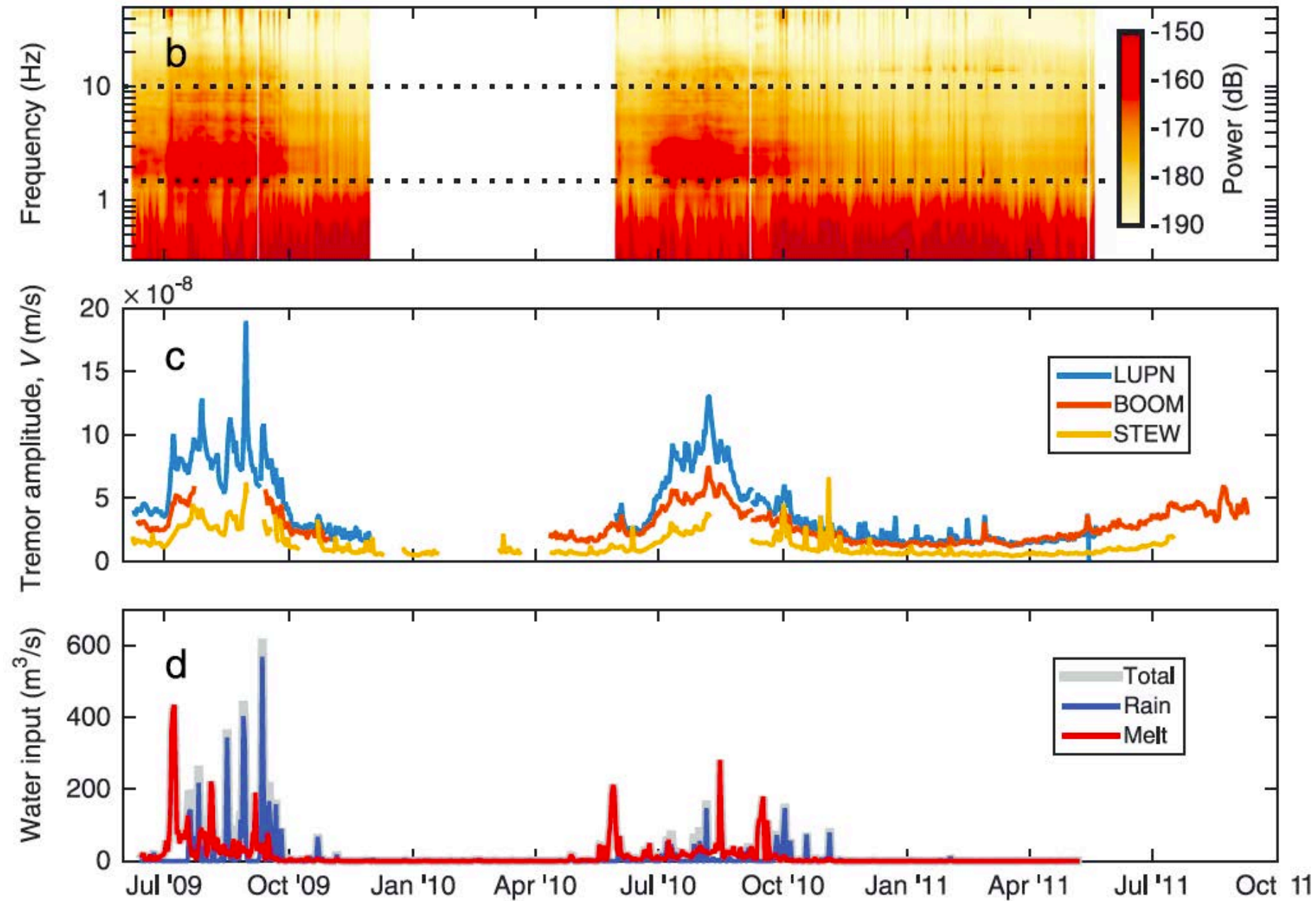
(located about 100m from the channel)



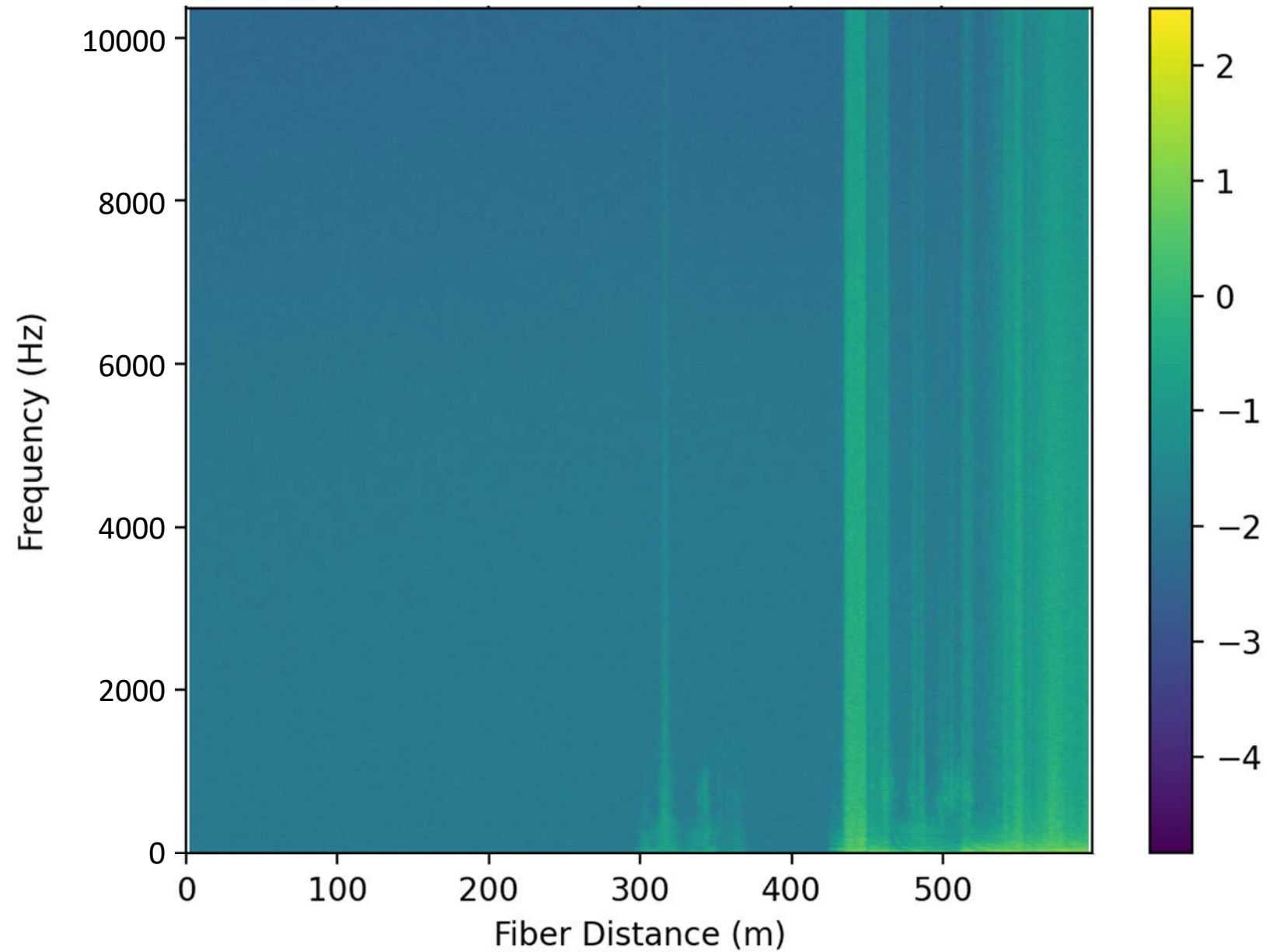
25 June 2012

(from Vázquez et al., (2016))

Seasonal
glaciohydraulic
tremor
interpreted as
subglacial flow
Yahtse Glacier, AK



Frequency Spectrum Analysis

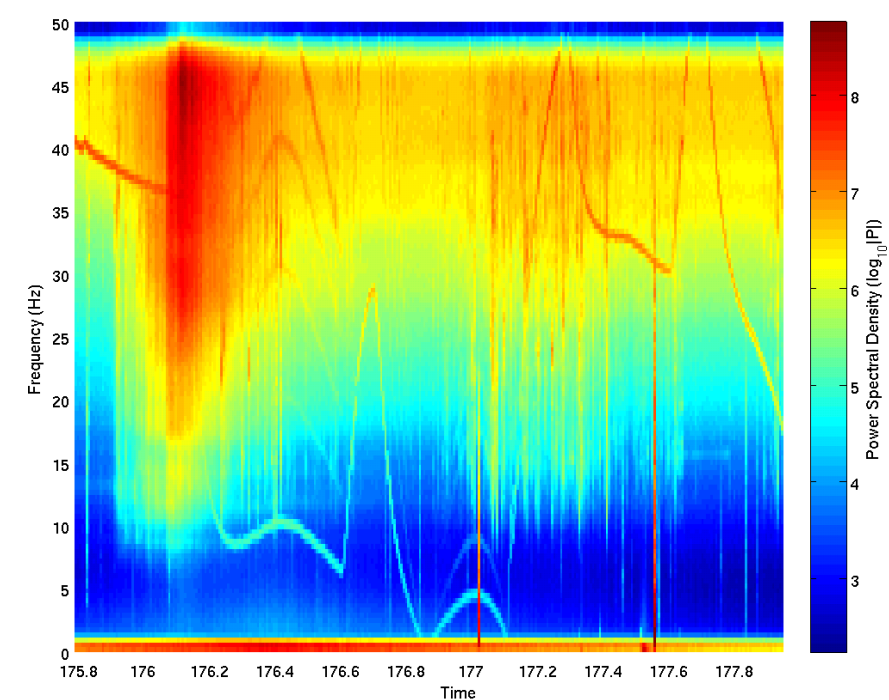


Distance:

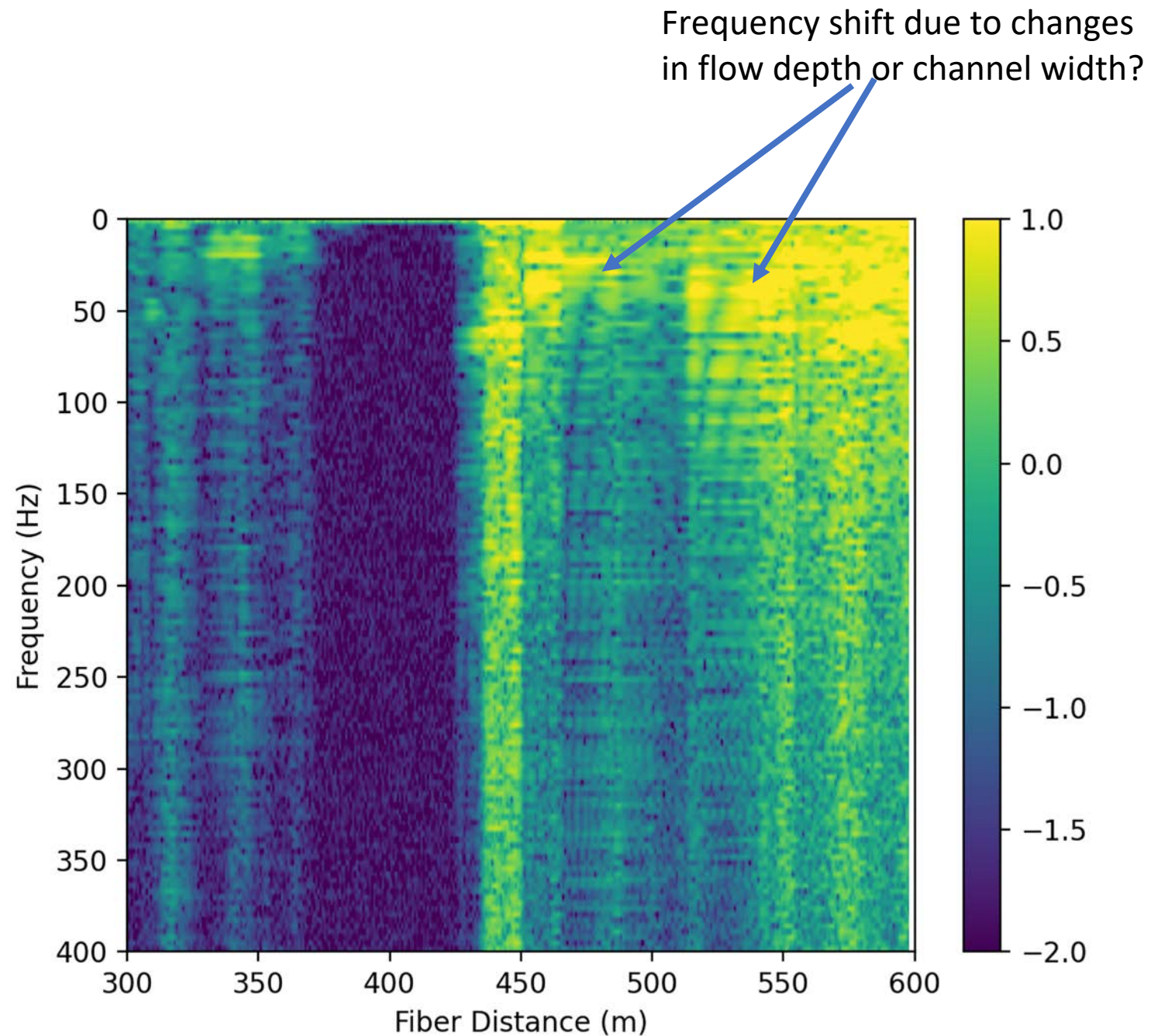
66-267: pave road

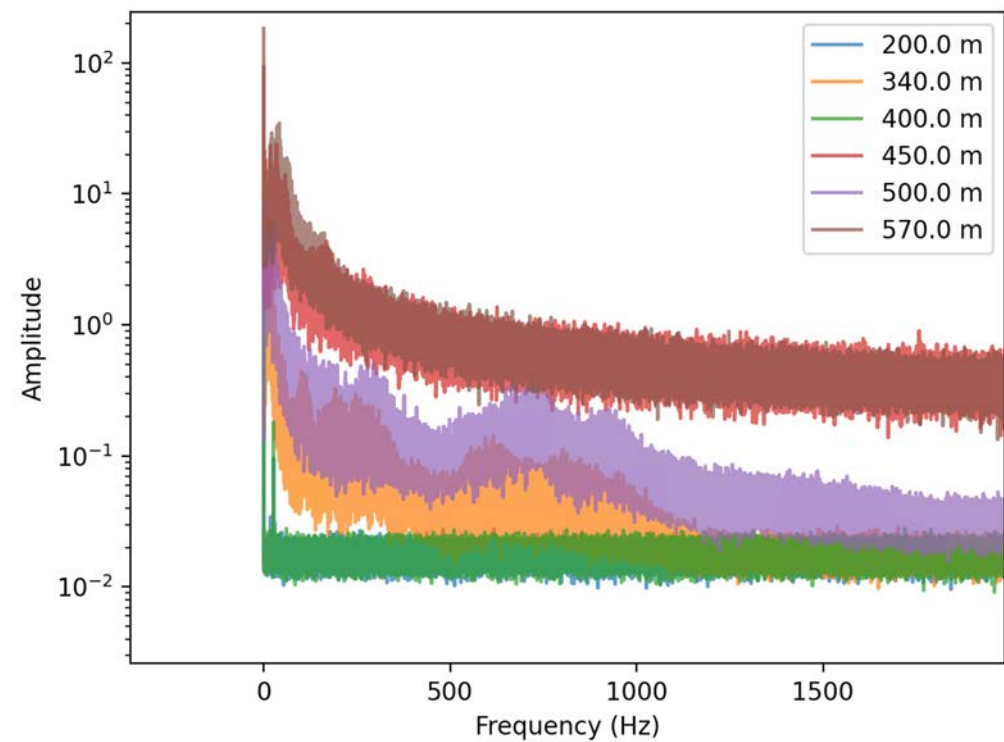
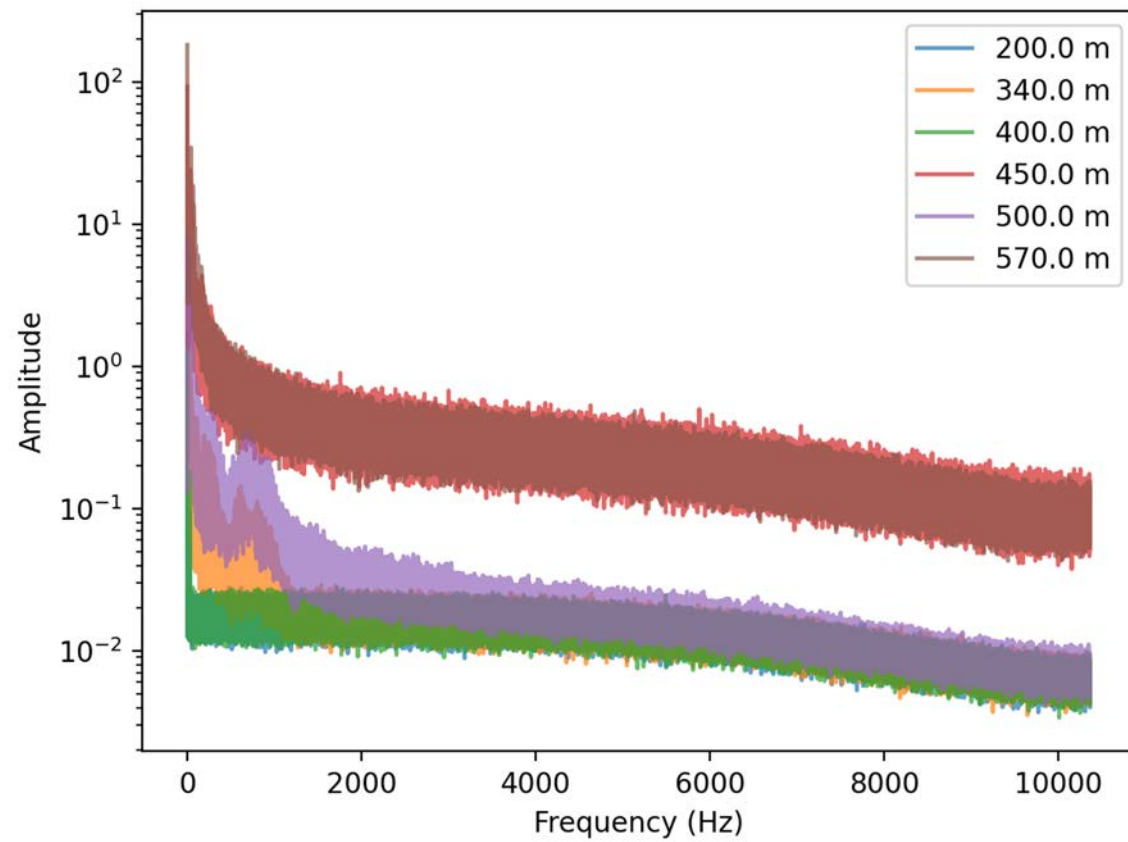
267-430: bank

437+ : in creek

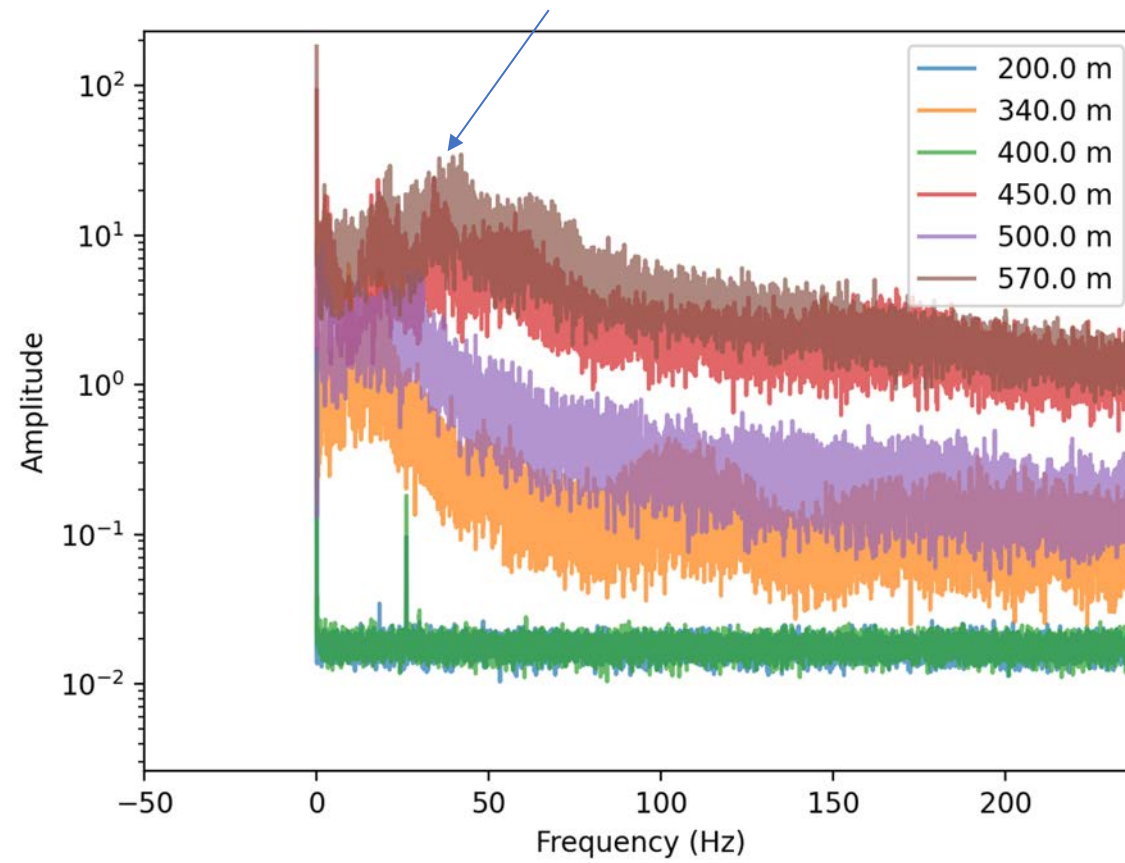


shifting frequencies during flooding events have been observed in other studies and attributed to decreases in velocity as sediment becomes water saturated (Anthony et al, 2018)

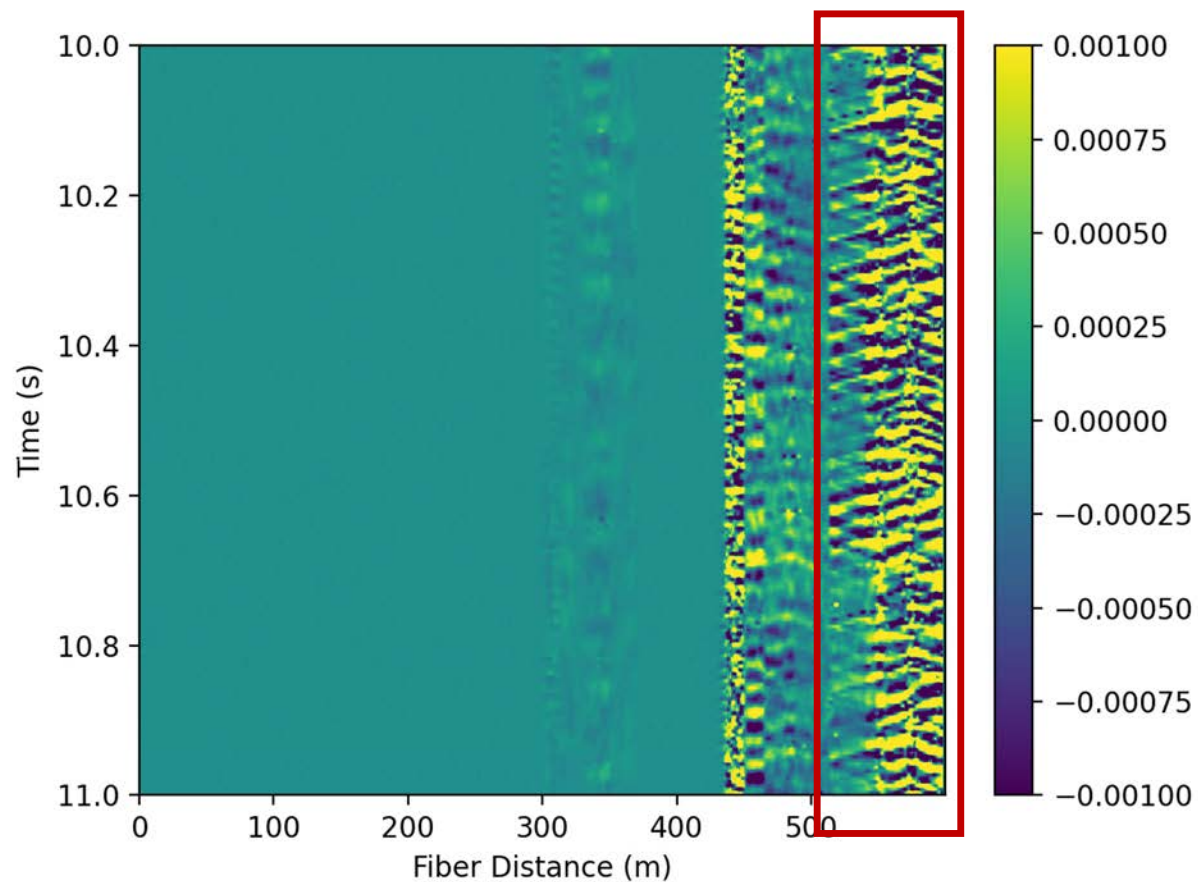




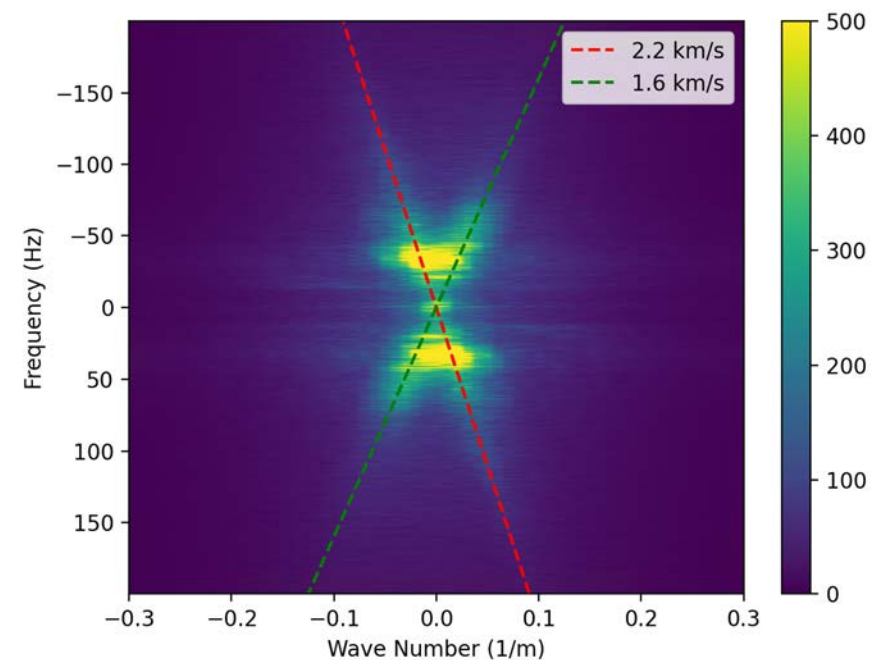
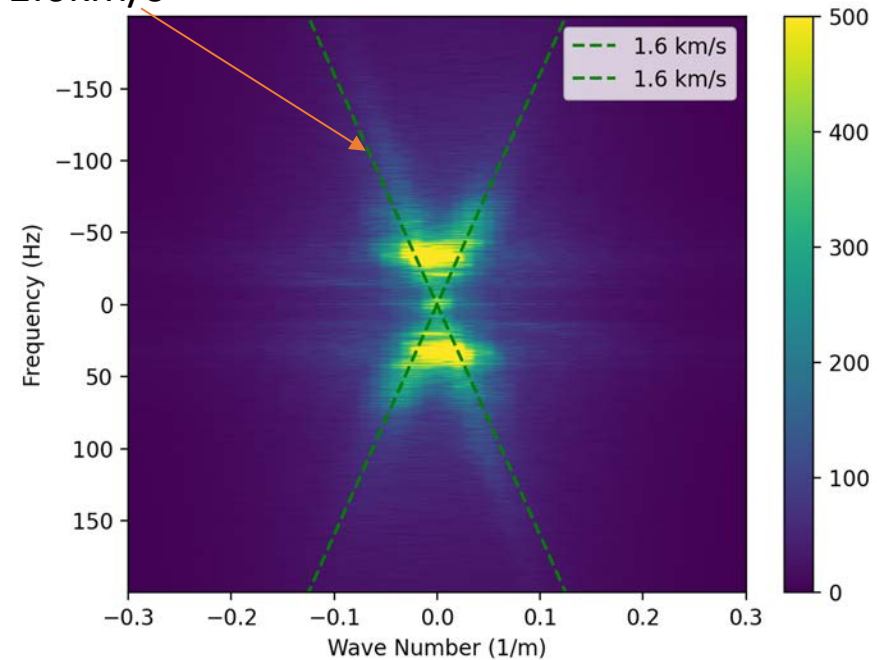
Interesting harmonics



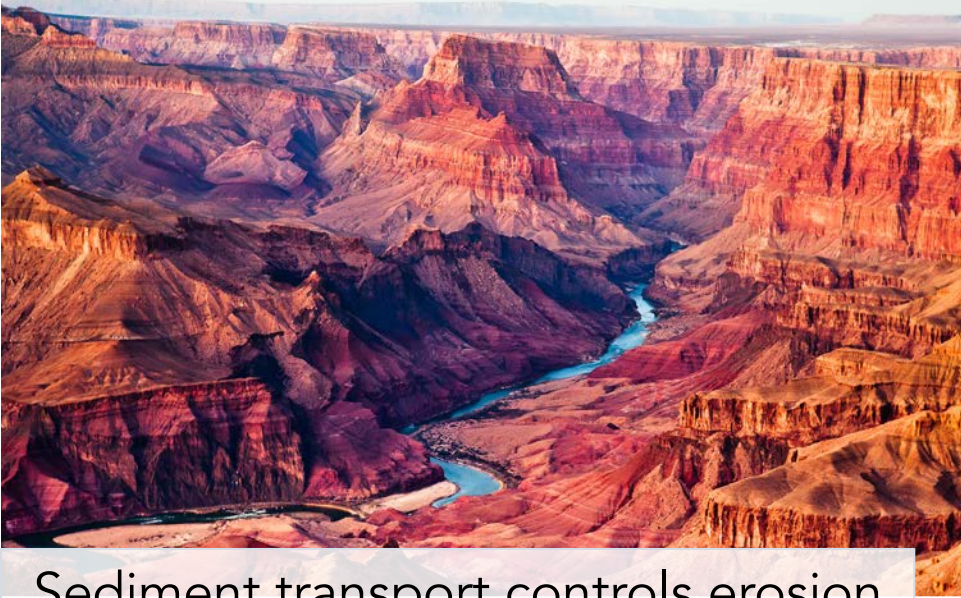
F-K analysis for velocity



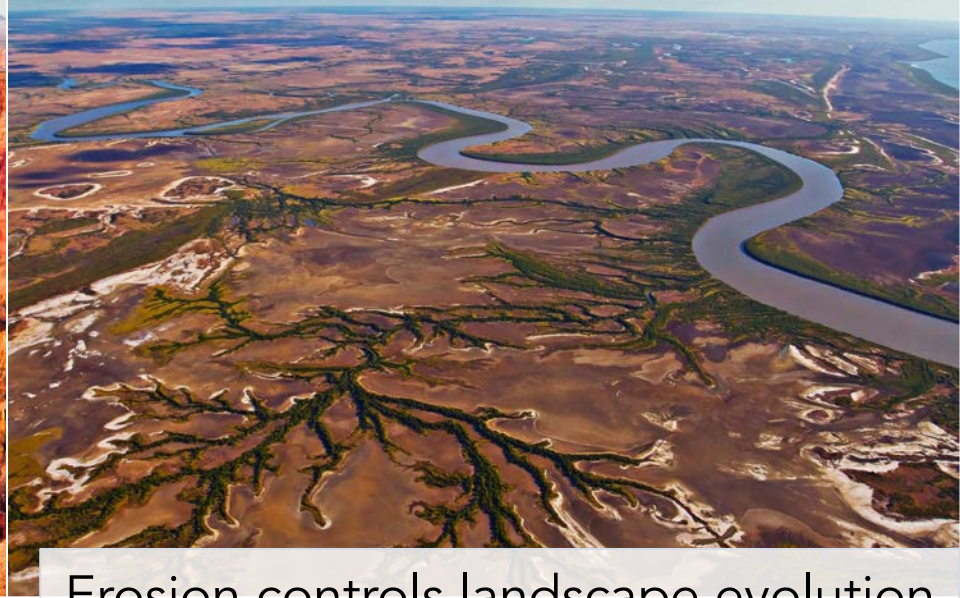
Does not fit 1.6km/s



Why do rivers matter?



Sediment transport controls erosion



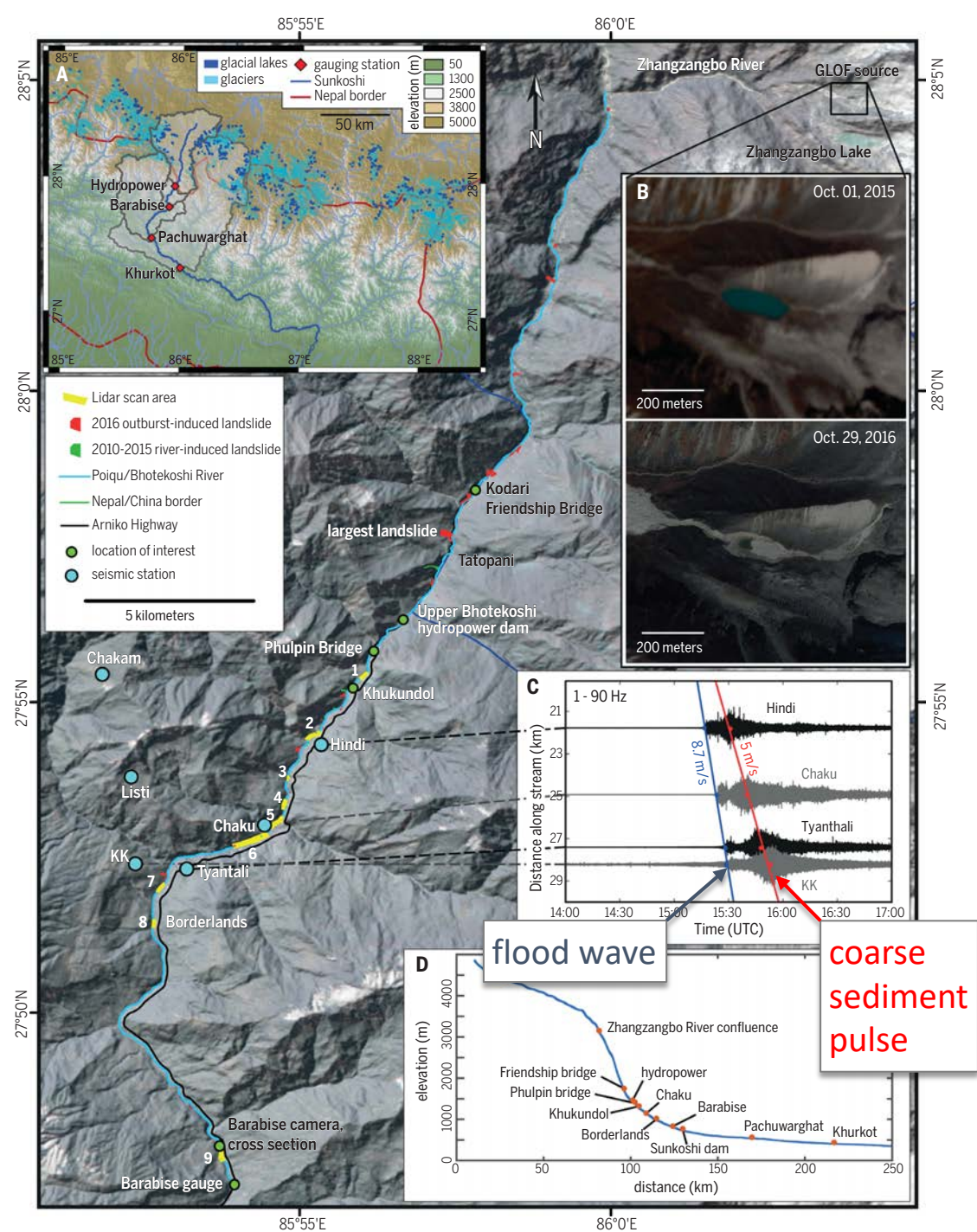
Erosion controls landscape evolution





Sediment controls rivers





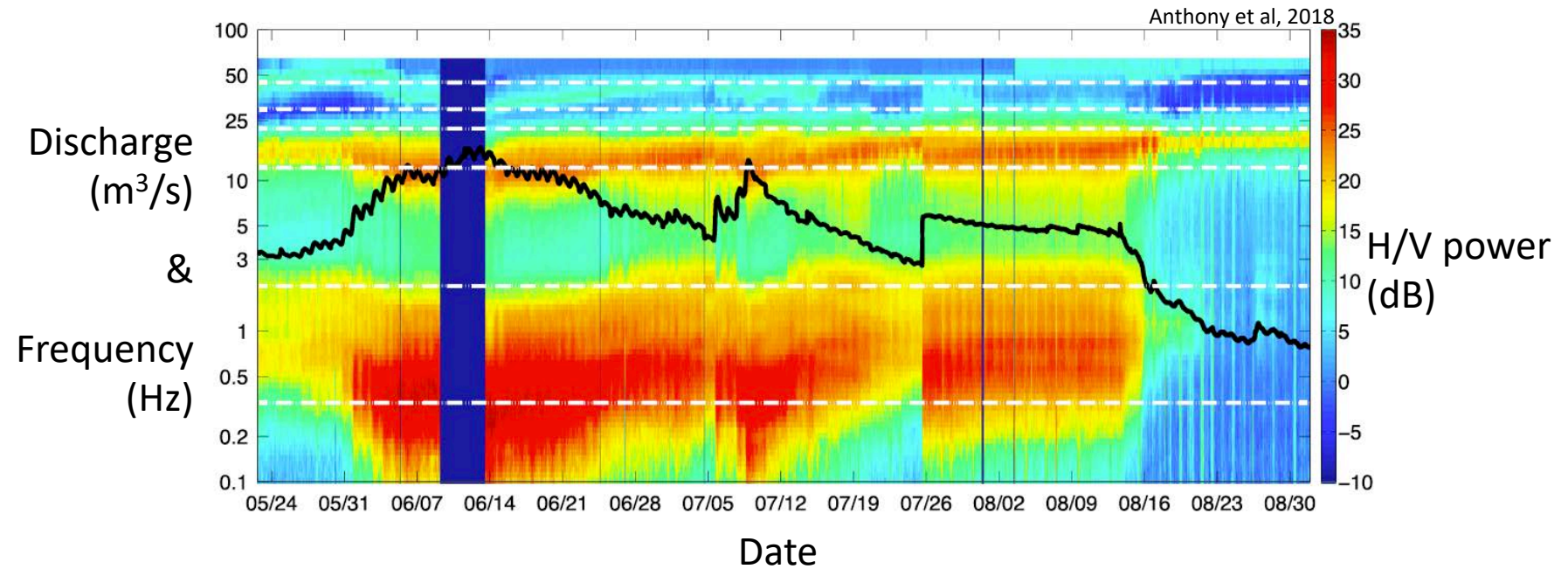
Seismic records provide new insights into glacial lake outburst flood mechanics

Cook et al, 2018

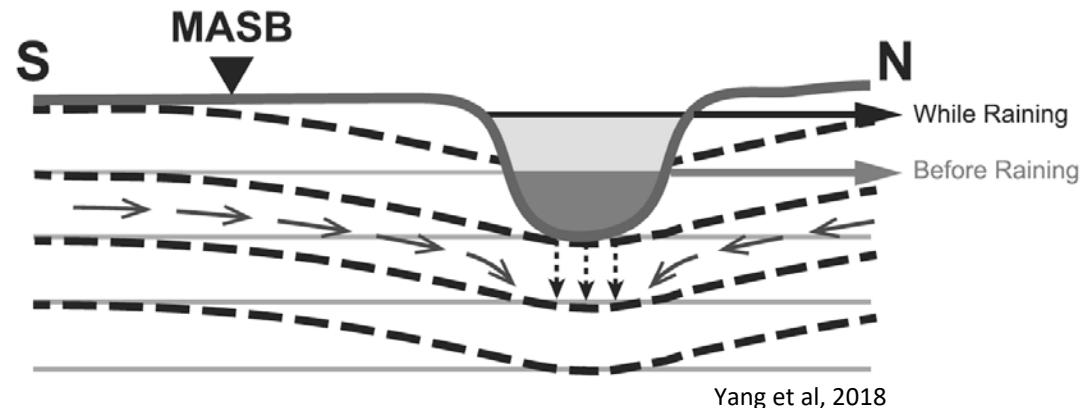
Mobilization of channel-stabilizing boulders by glacial lake outburst floods—rather than precipitation—may drive long-term fluvial erosion and valley evolution downstream of glaciers in the Himalaya.

Low frequency horizontal ground motion (tilt) may reveal turbulent eddy dynamics or precipitation loading

0.1–2 Hz H/V acceleration power interpreted as hyporheic zone deformation by fluctuating pressure on streambanks by large-scale turbulent eddies.



Low frequency horizontal seismics could enable continuous monitoring of average discharge and large eddy dynamics, estimates of average water loading over $\lesssim 10$ s of kilometers, constrain decadal rainfall records,



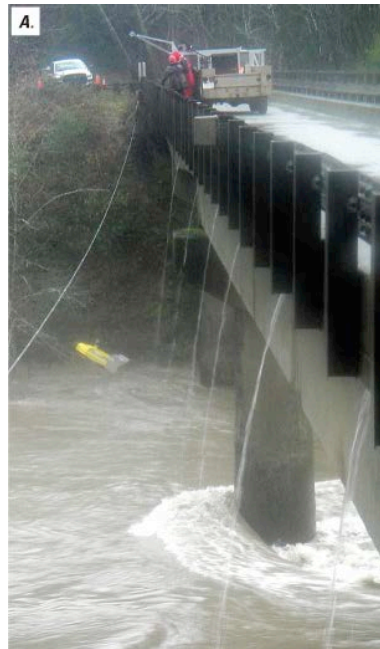
< 0.3 mHz velocities correlate with rainfall and rate of change in river flow depth.

Measuring and predicting fluvial sediment transport is a fundamental need—but extremely challenging

Fluvial sediment transport models
rely on empirical calibration



Laboratory experiments

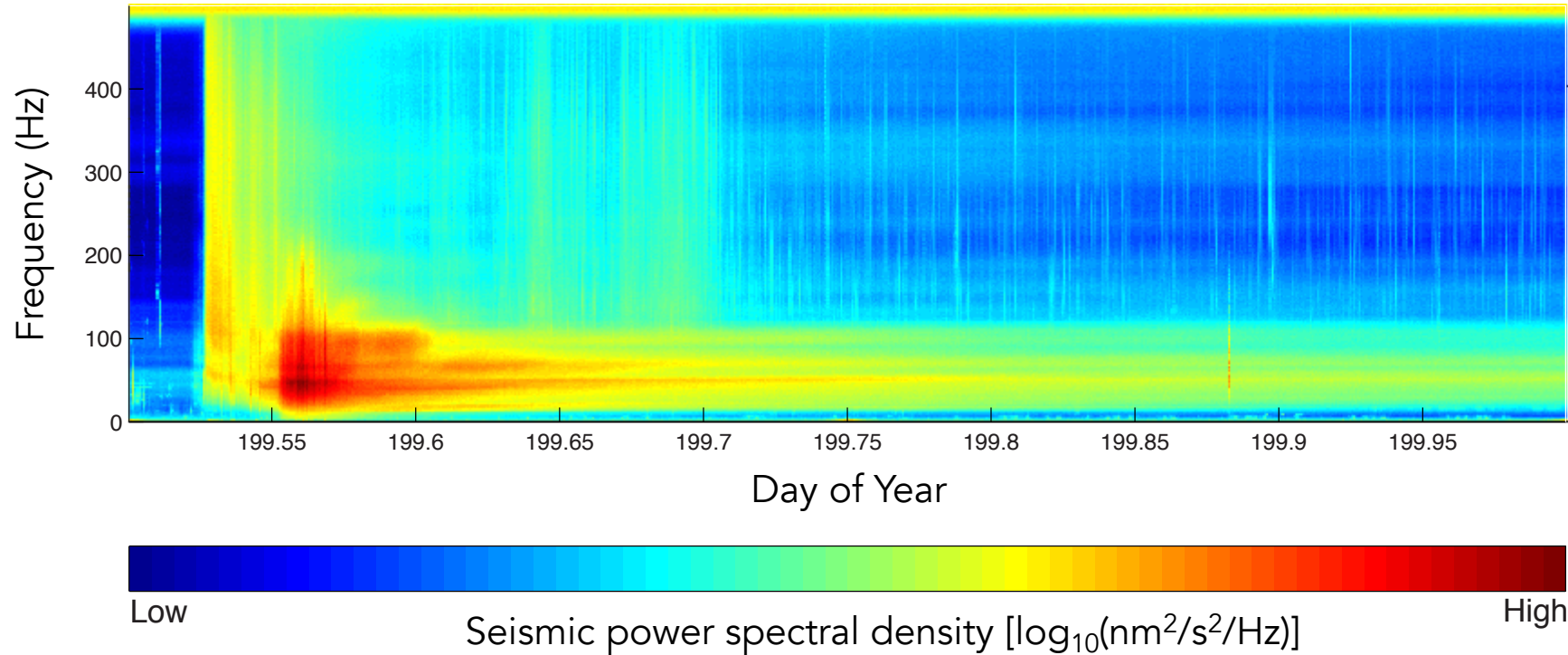
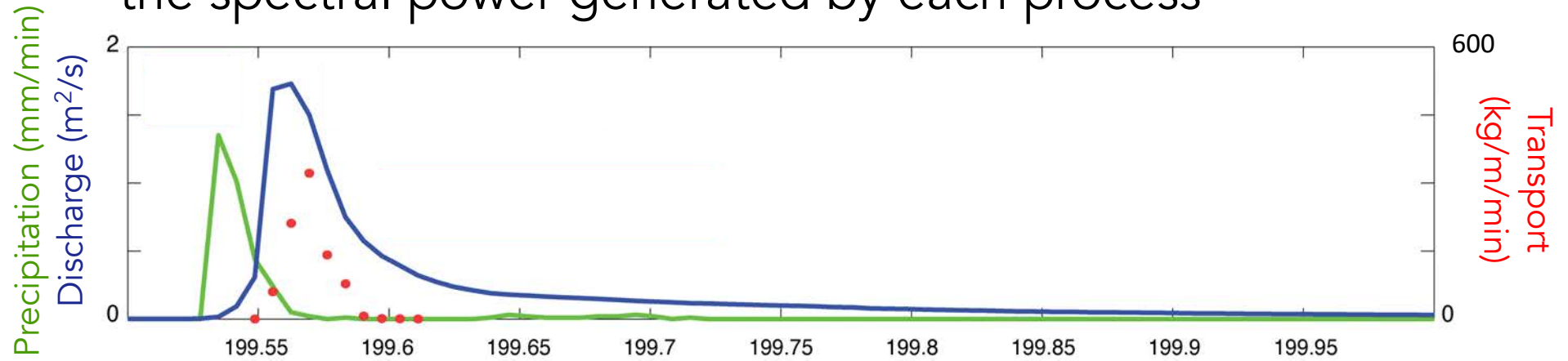


Manual
measurement

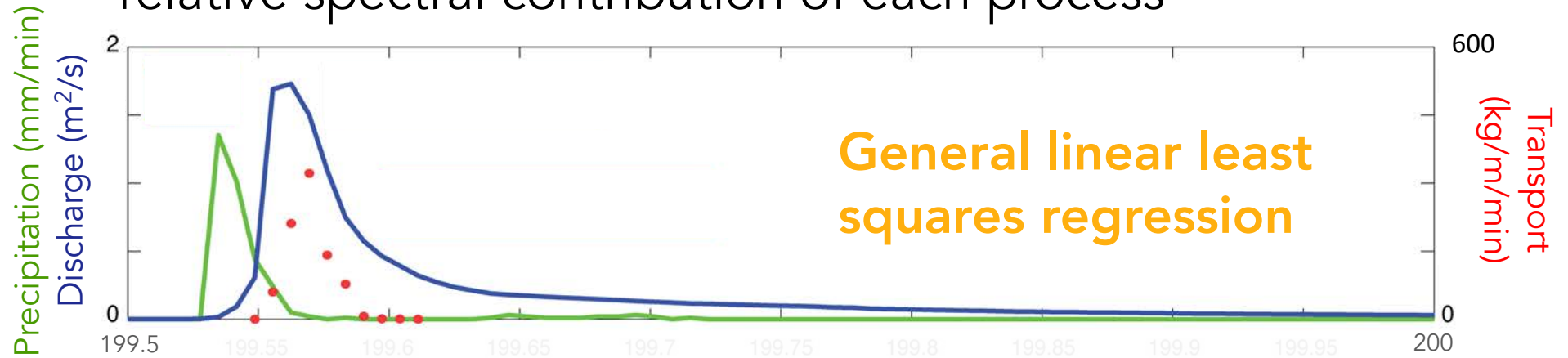


Permanent instrumentation

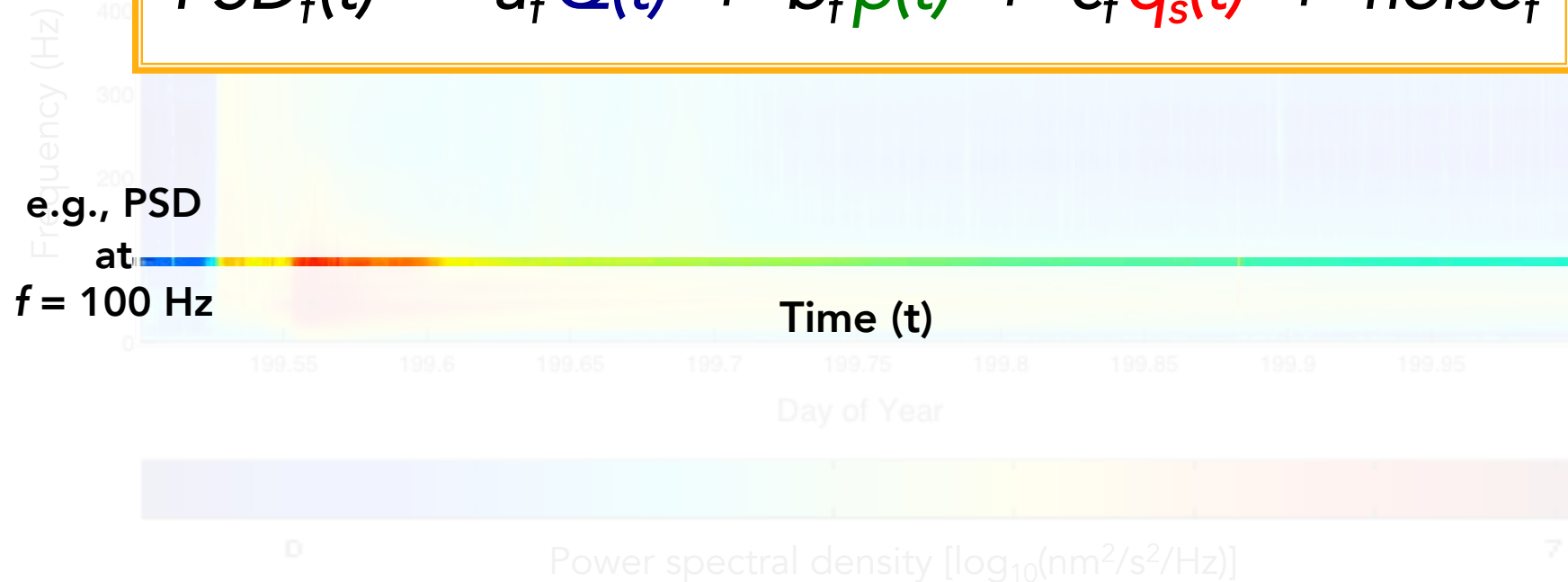
Independent measurements help to distinguish the spectral power generated by each process



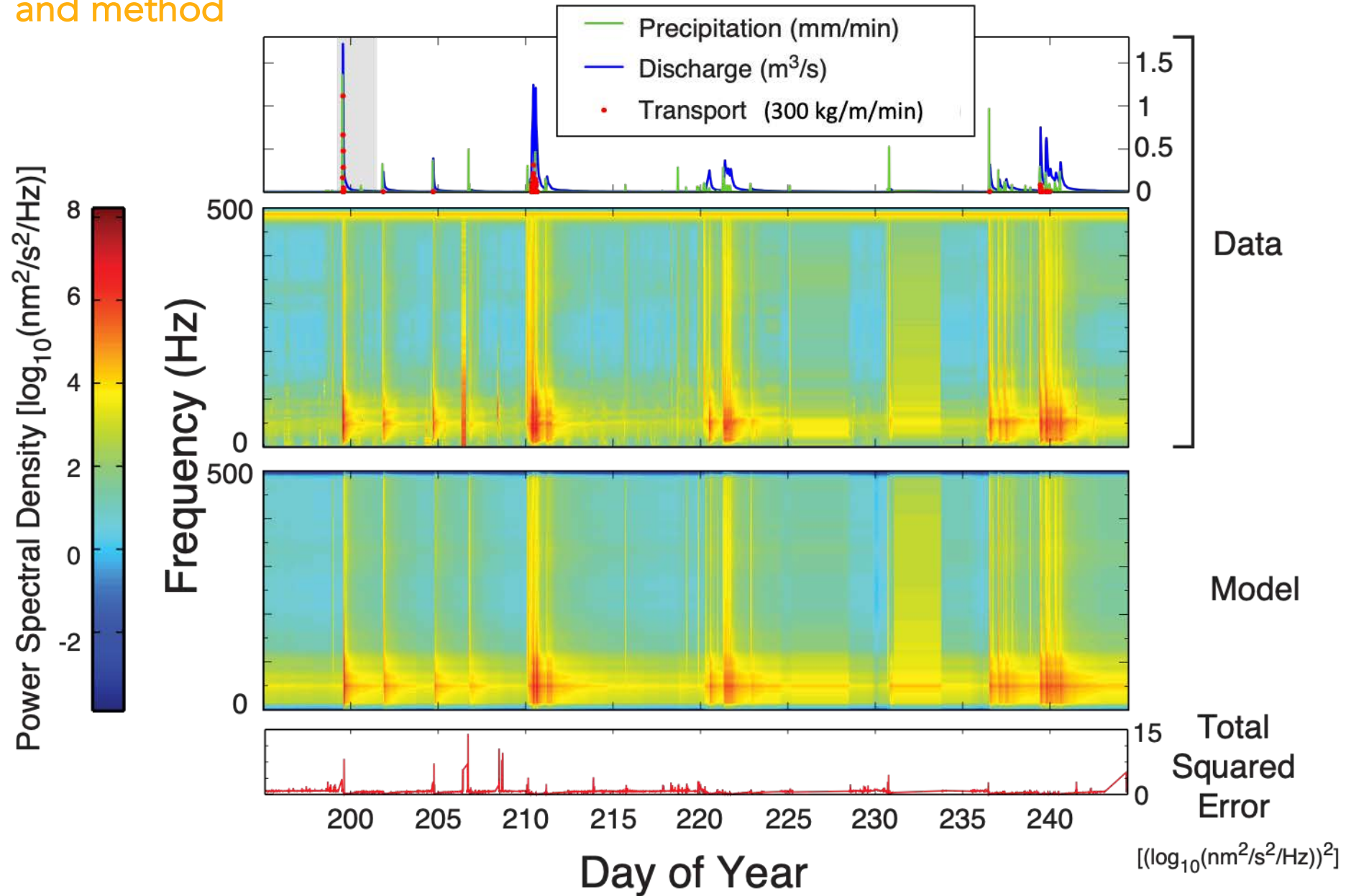
Regression for a_f , b_f , c_f at each frequency identifies the relative spectral contribution of each process



$$PSD_f(t) = a_f Q(t) + b_f p(t) + c_f q_s(t) + noise_f$$

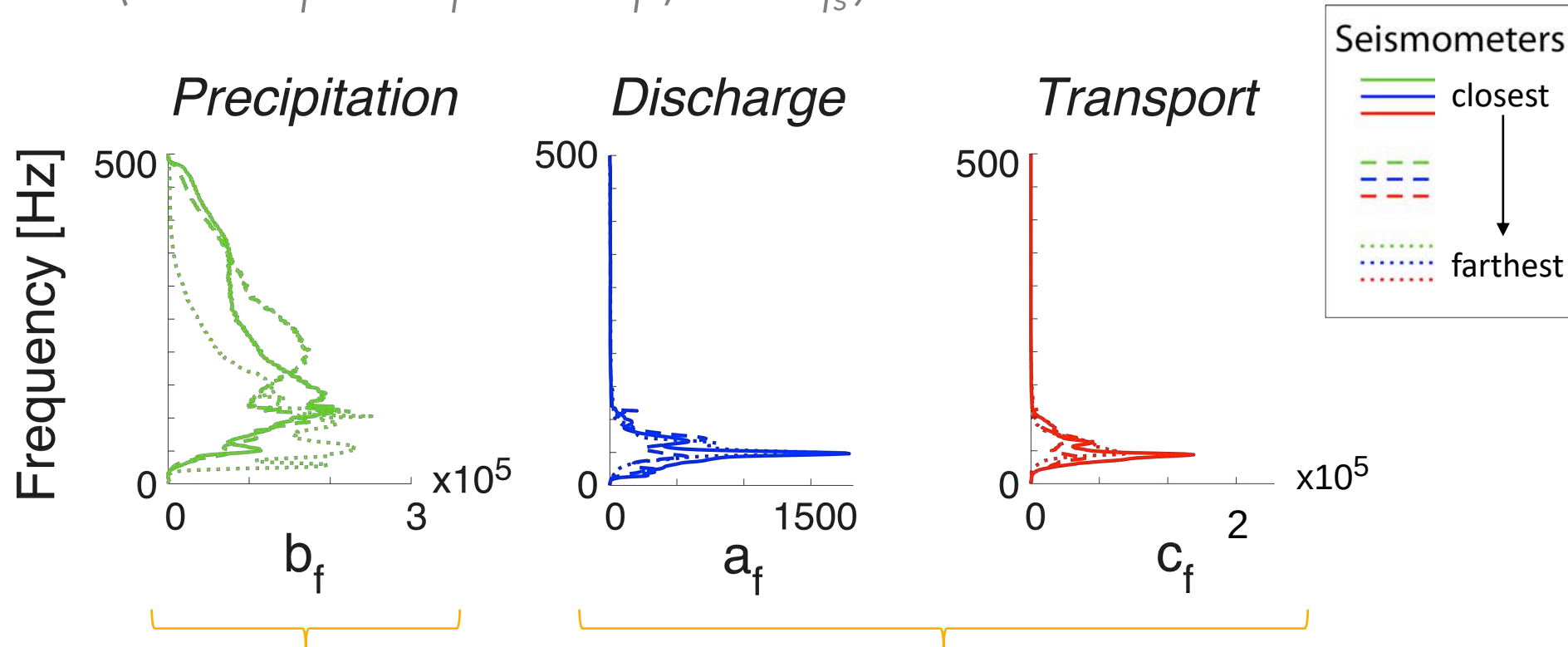


Model results validate coefficients and method



Regression coefficients represent normalized power spectra at each seismometer

(seismic power per unit p , Q or q_s)



Broadband

signal dominated by
rainfall directly above
seismometers

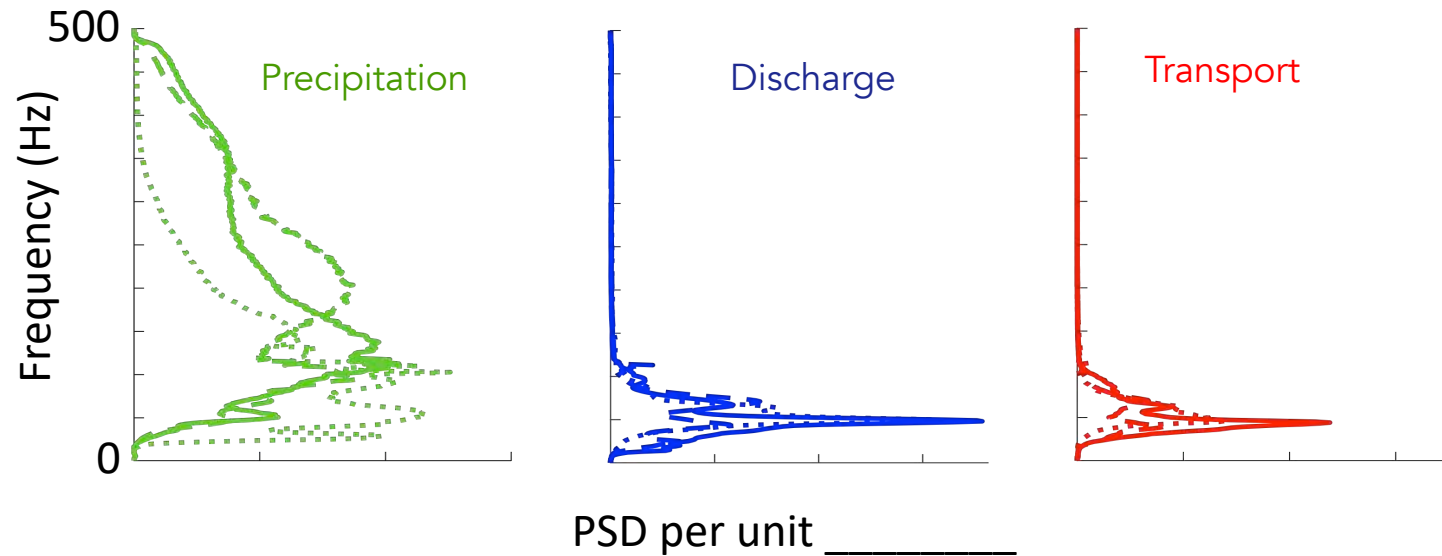
Higher frequencies attenuated

dominant signal source is more distant

Turbulence and transport spectra overlap

Process rates are recoverable from seismic spectra... with enough independent constraints

*Least squares regression of PSD at each frequency
identifies the spectral contributions from each process*



**Spectral peaks are strongly
moderated by attenuation—
site-specific parameters and
distance from channel matter!**

Broadband

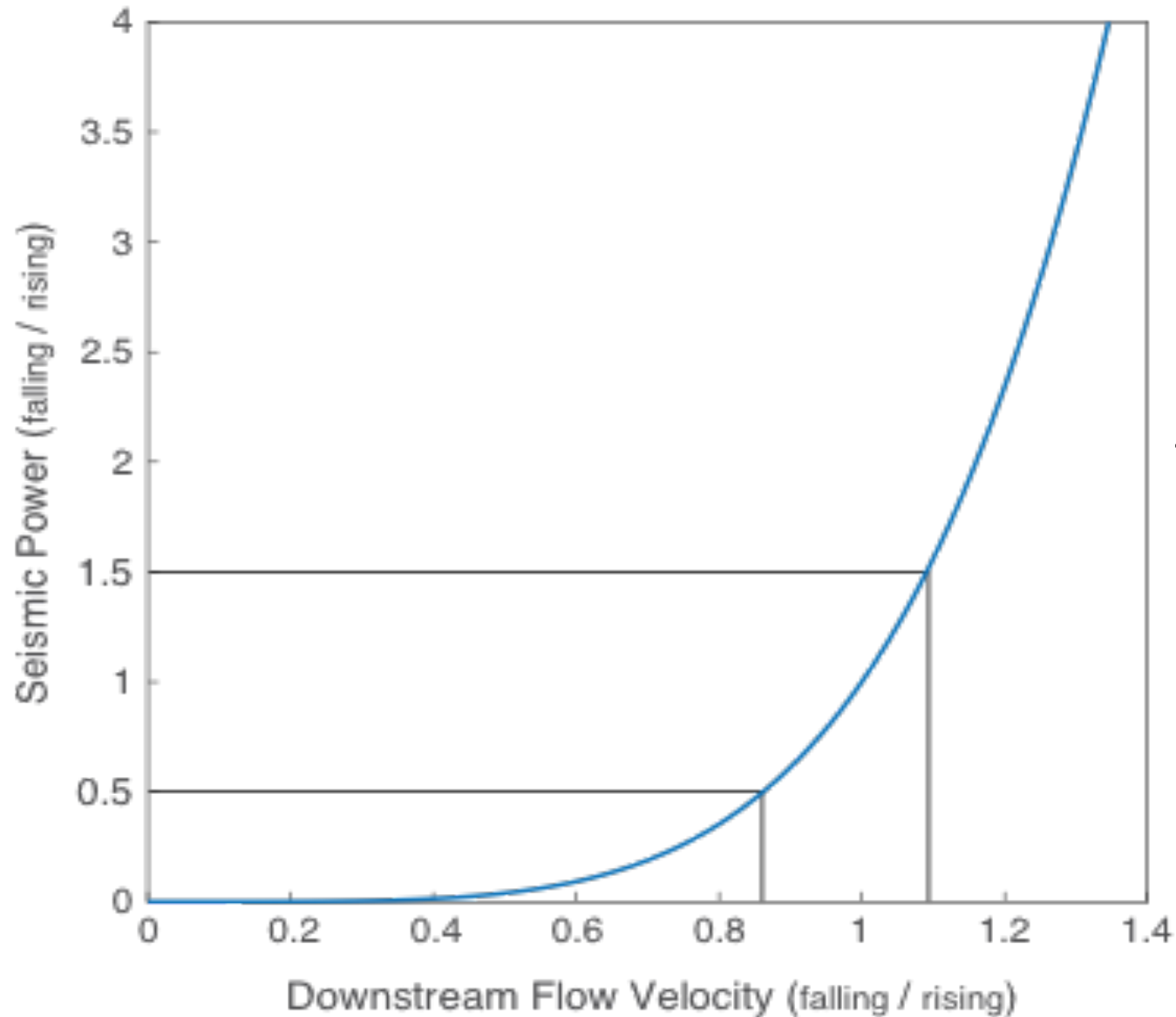
signal dominated by rainfall
directly above seismometers

Higher frequencies attenuated

dominant signal source is more distant (4-7 m)

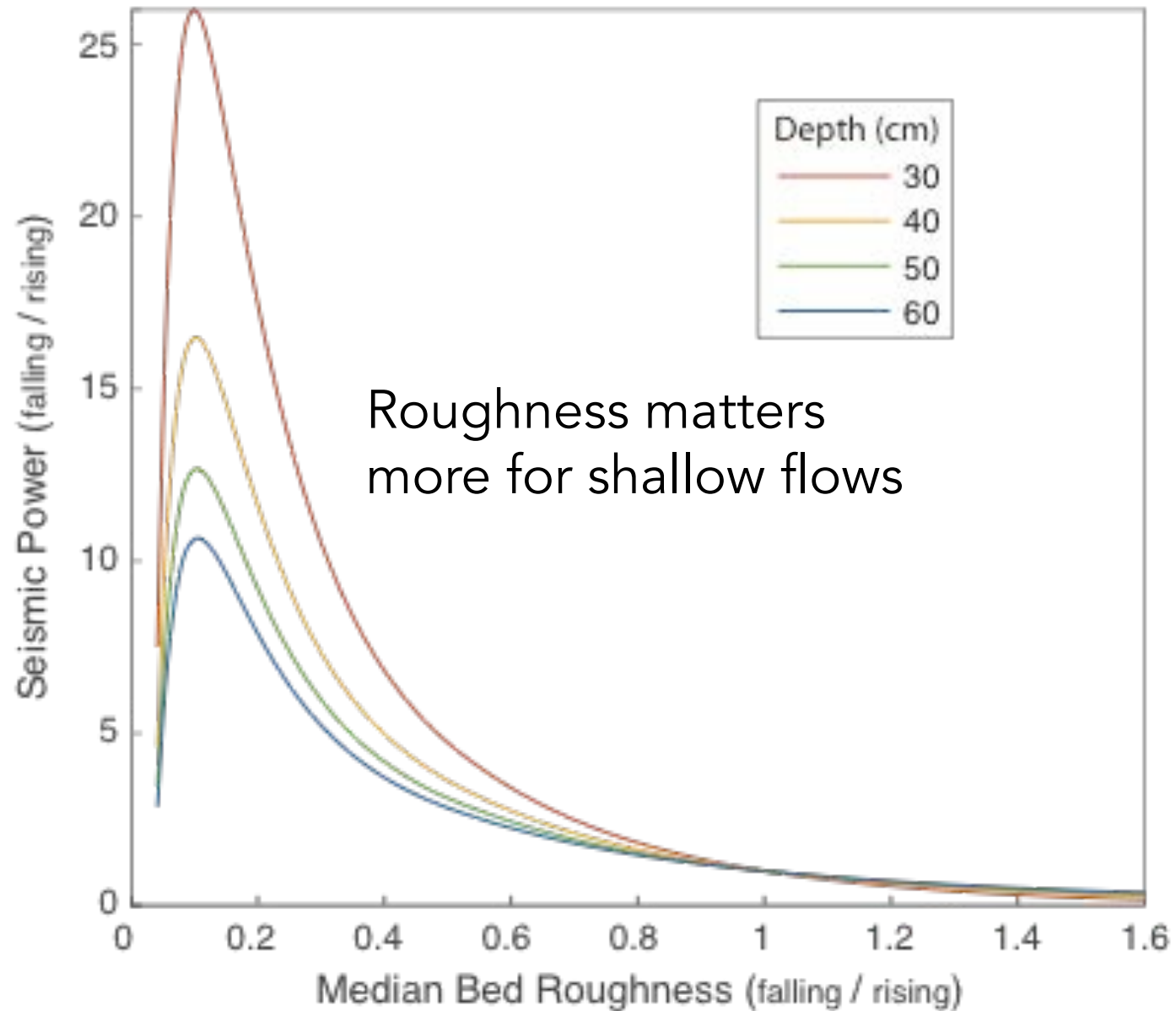
Turbulence and transport spectra overlap

Changing flow velocity by $>10\%$ accounts for hysteresis



Faster flows
generate more
turbulence

$$\text{Power} \propto \text{velocity}^5$$

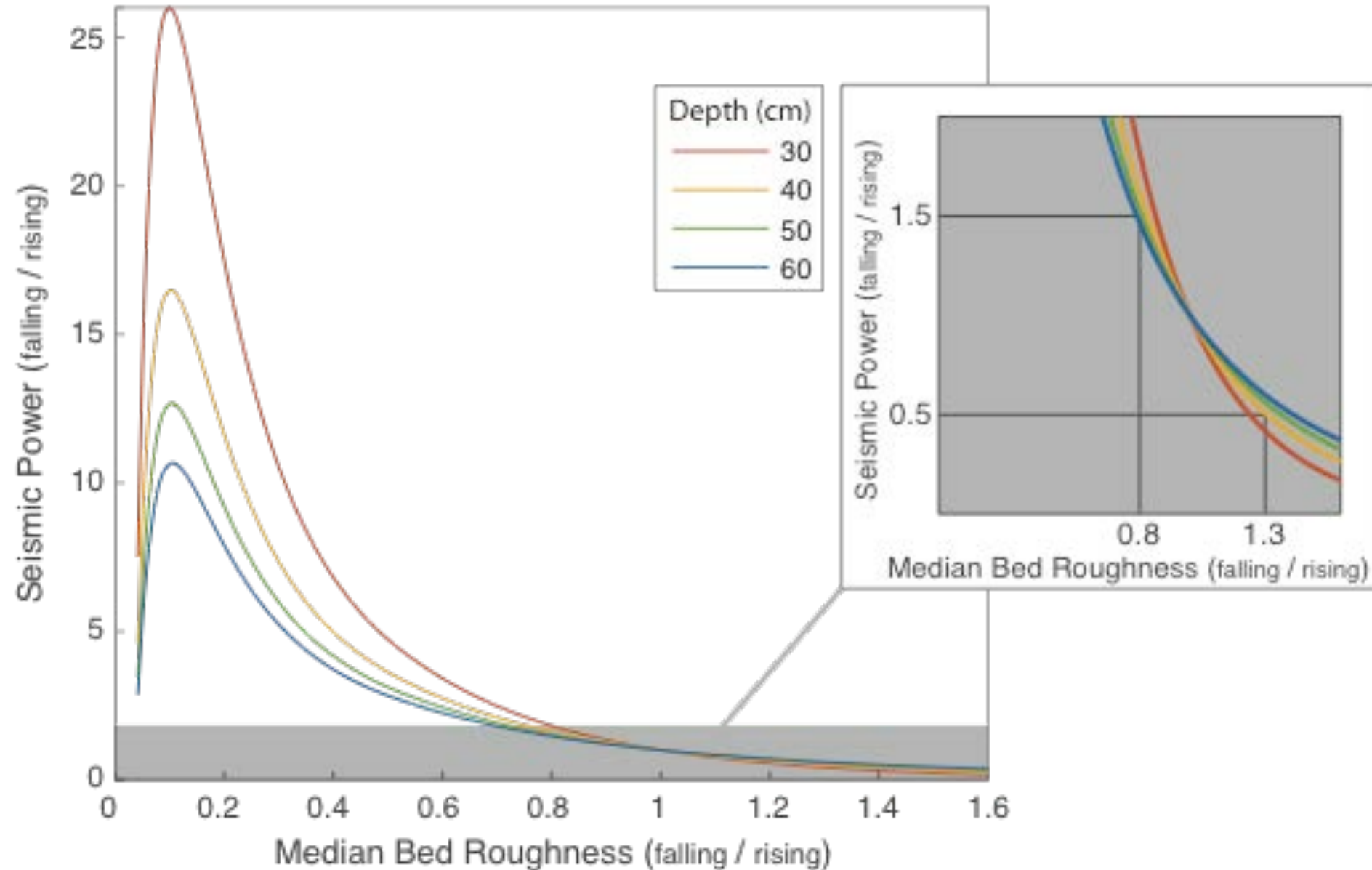


Roughness matters
more for shallow flows

Rougher beds
generate less
turbulence due
to form drag

e.g. Lamb et al., 2008

Changing bed roughness by $>30\%$ accounts for hysteresis



Calculated from Gimbert et al. (2014)

Rearrangement of grains likely causes hysteresis in both sediment transport and water turbulence

Reversal of Ψ_S and Ψ_G cannot be explained by any process that causes positively correlated hysteresis in turbulence and sediment transport

Semi-stochastic changes in shear velocity and bed roughness due to:

- Erosion/aggradation of the bed around large boulders
- Shifting of boulders



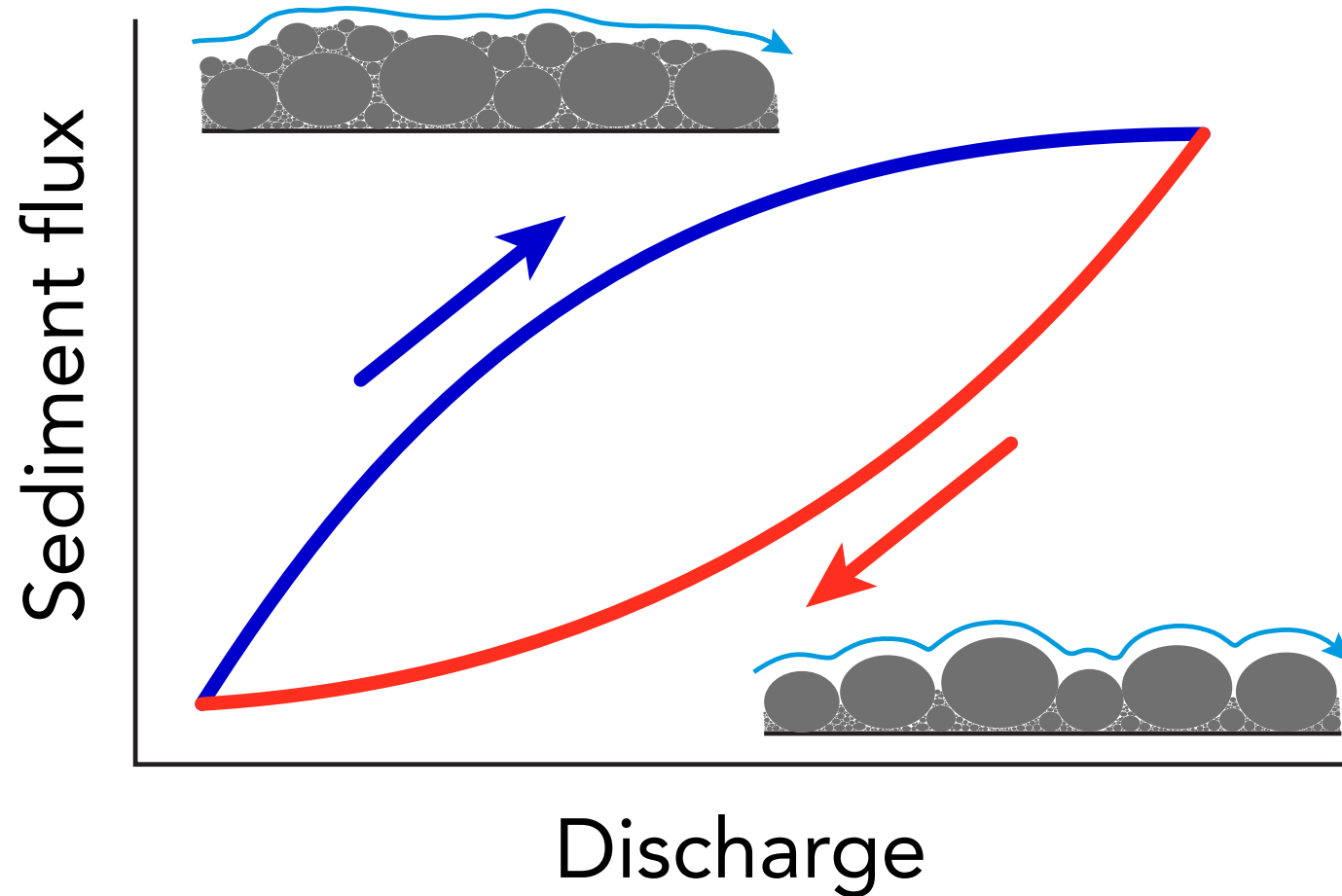
Rearrangement of grains likely causes hysteresis in both sediment transport and water turbulence

Channel hydraulics (e.g., flow depth and velocity) on the Erlenbach are highly sensitive to the degree of boulder protrusion above the bed.

Yager et al., 2007

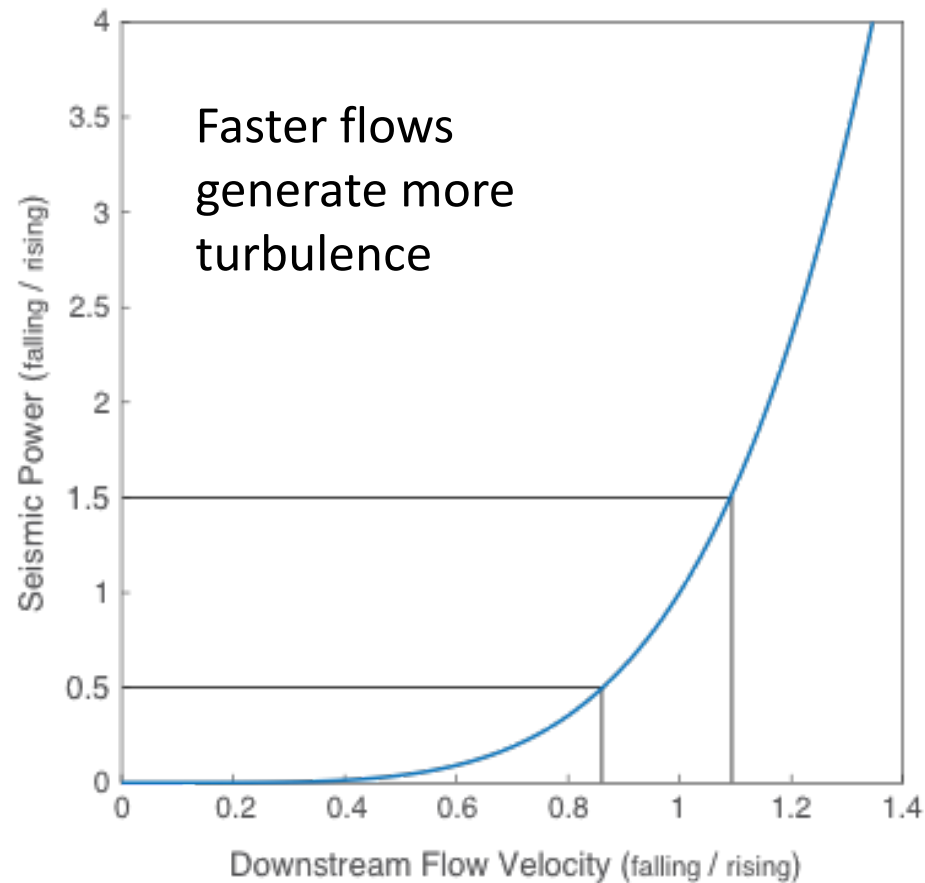
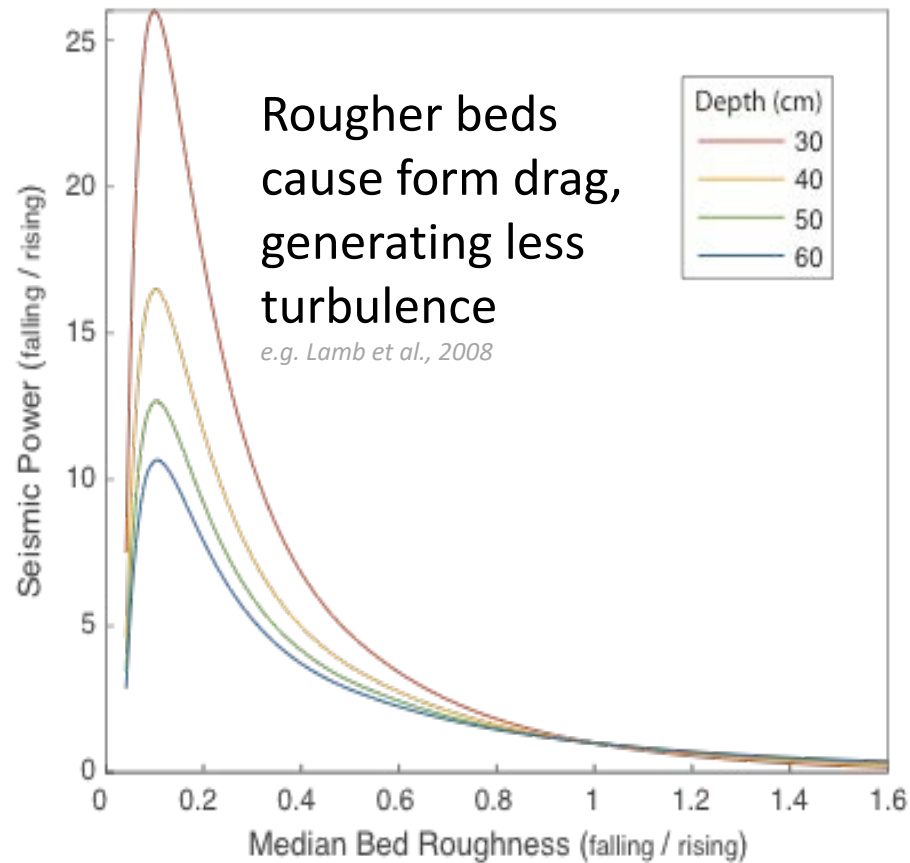


The bed surface fundamentally influences water turbulence



Does seismic hysteresis
reflect changes in the
sediment flux, or in the
turbulent boundary layer?

Seismic sensitivity to water turbulence is both a major challenge and an opportunity

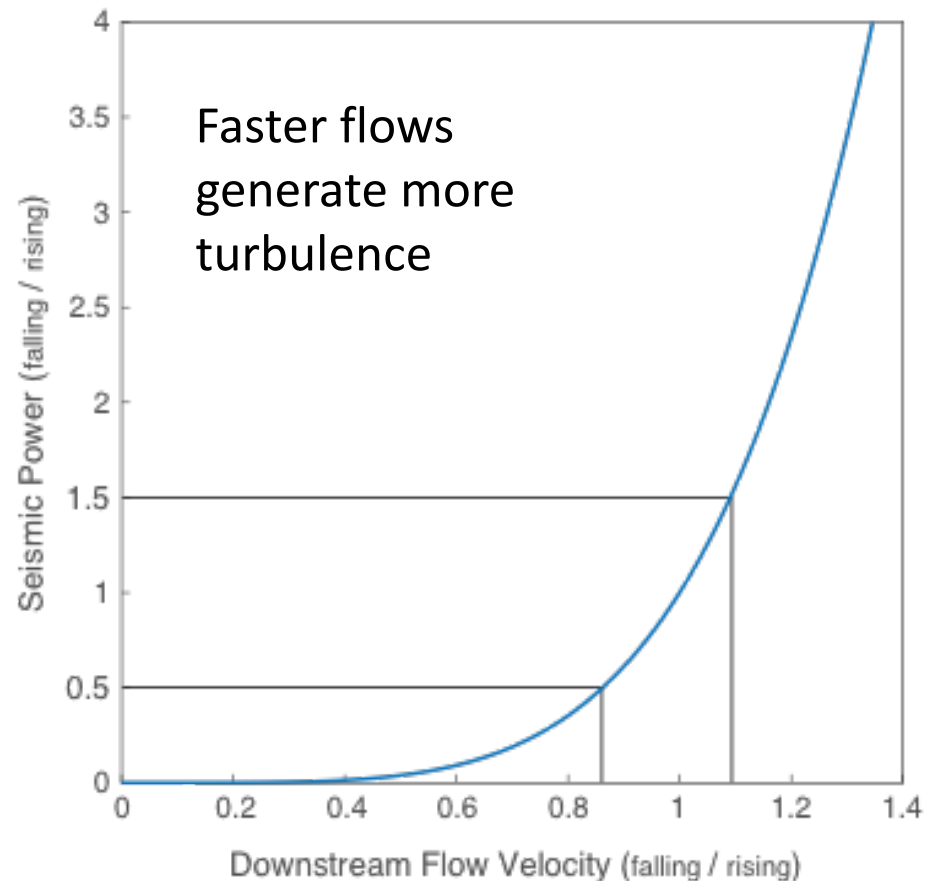
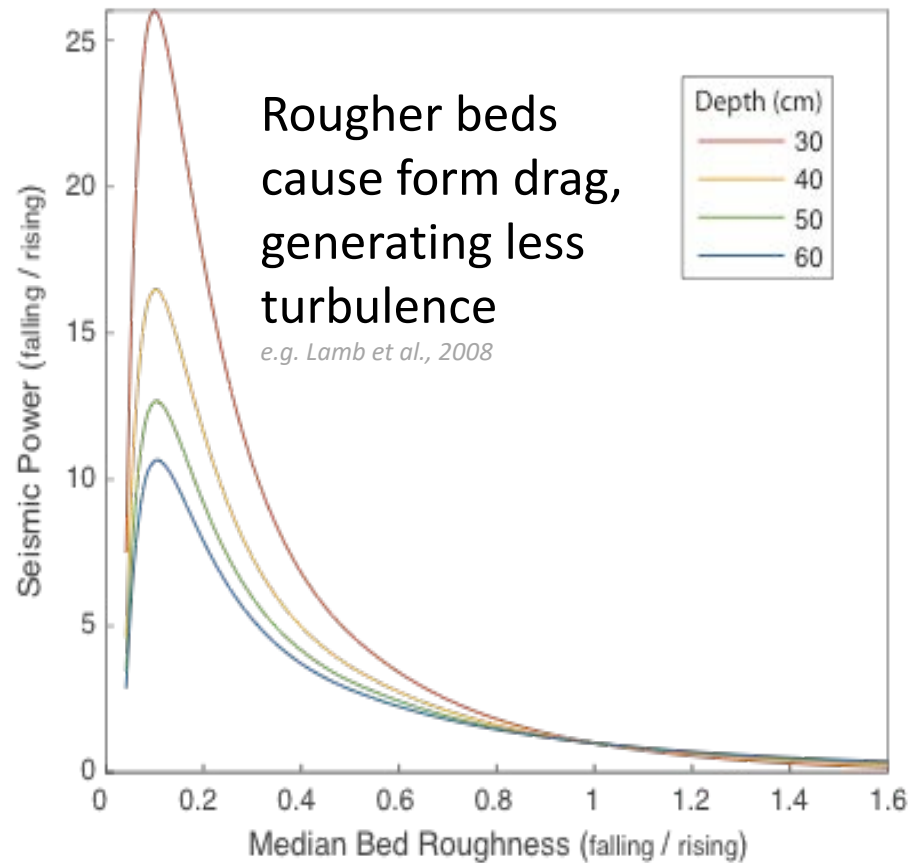


~10% change in flow velocity or
~30% change in bed roughness
could account for observed
hysteresis in seismic power



Bed reorganization around boulders
may cause semi-stochastic changes
in shear velocity and bed roughness

Seismic sensitivity to water turbulence is both a major challenge and an opportunity



Can seismic signals provide new information on turbulent flow dynamics and bed organization?



Bed reorganization around boulders may cause semi-stochastic changes in shear velocity and bed roughness

