# Elastic bracing and its effect on seismic waveforms in reservoir injection zones

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# Acknowledgments

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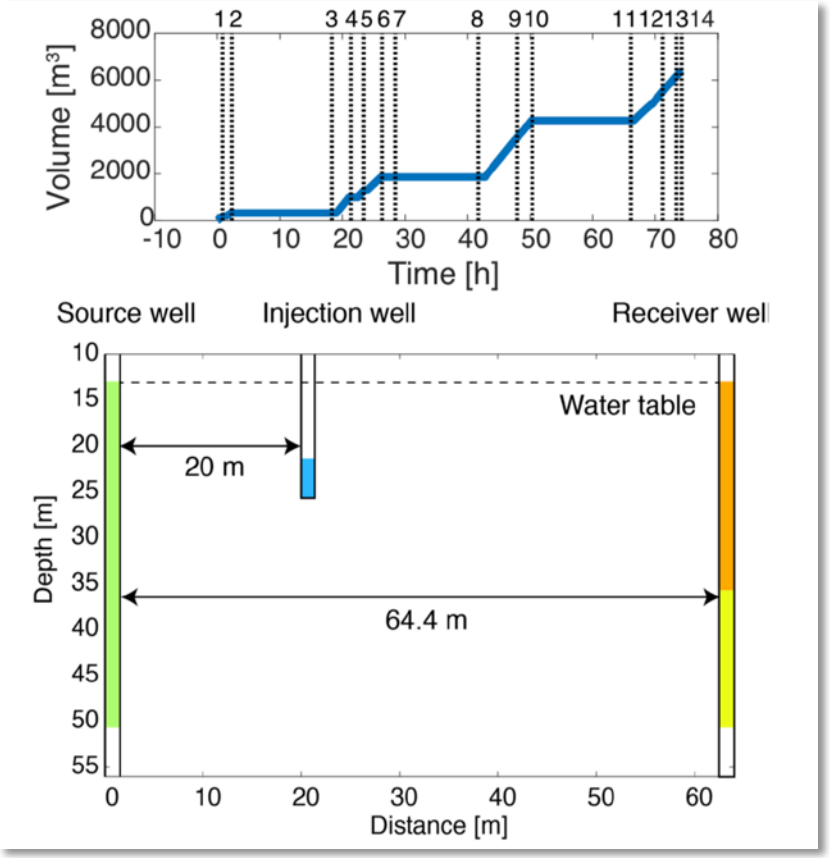
CMC RESEARCH INSTITUTES

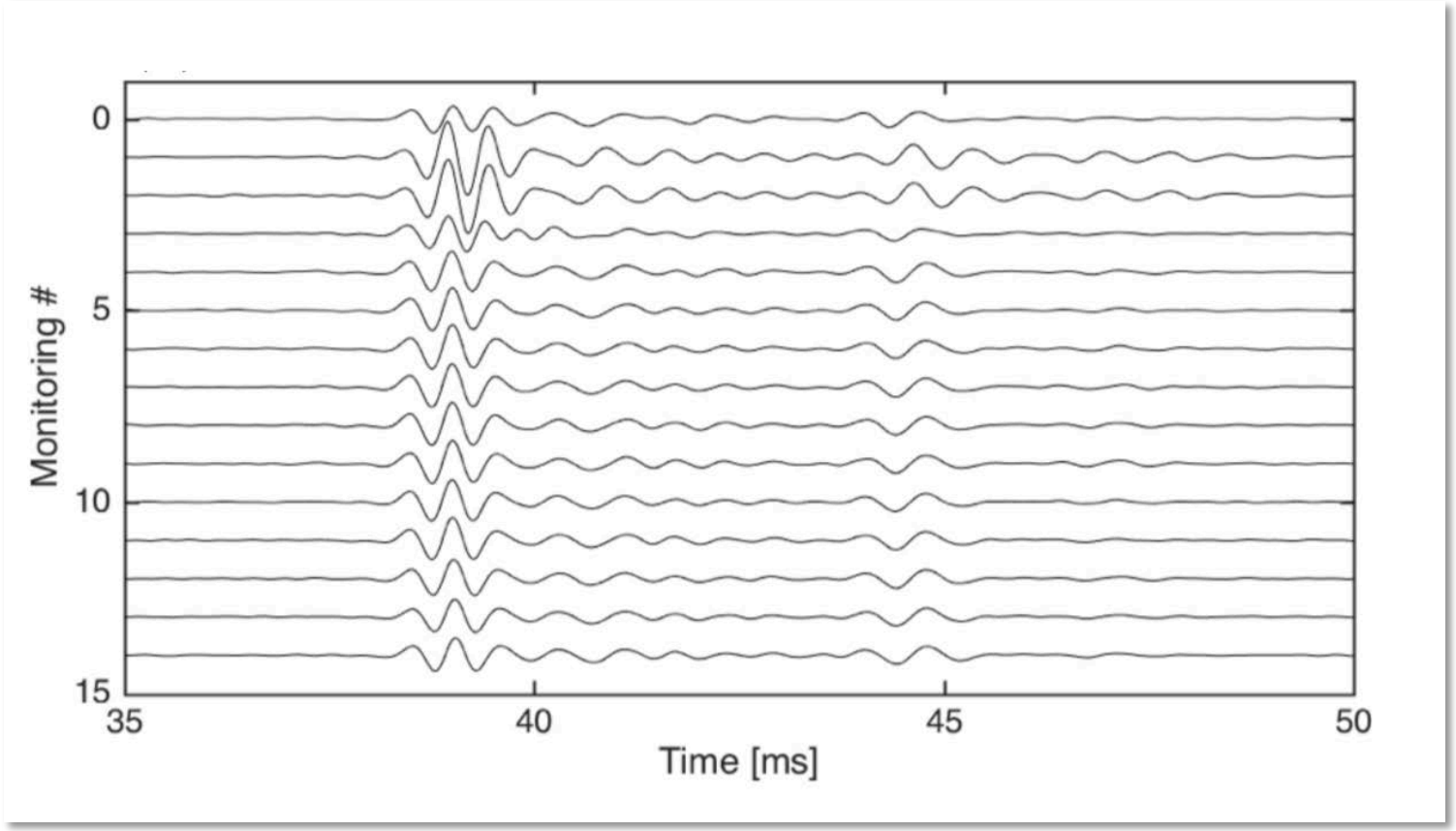
JOGMEC (A. Kato, T. Mouri, I. Kurosawa), R. Kamei

# Two experiments

## JOGMEC 2016-17 microbubble water injection monitoring experiment




Injection and model details (from Kamei et al., 2017; used by permission)




Time-lapse variation of once s-r pair (from Kamei et al., 2017; used by permission)

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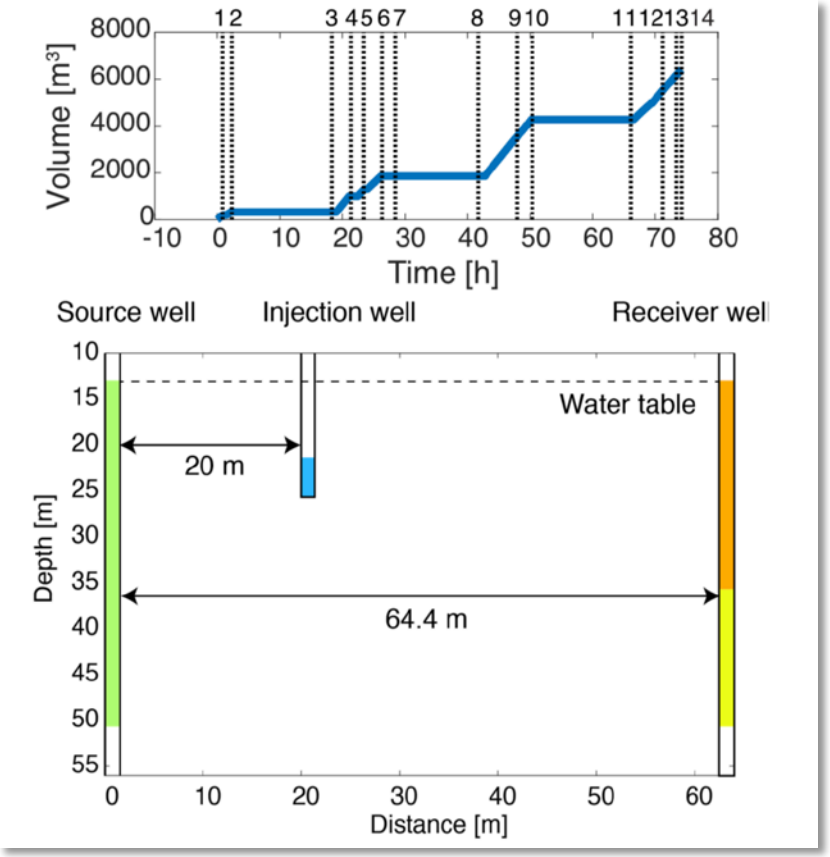


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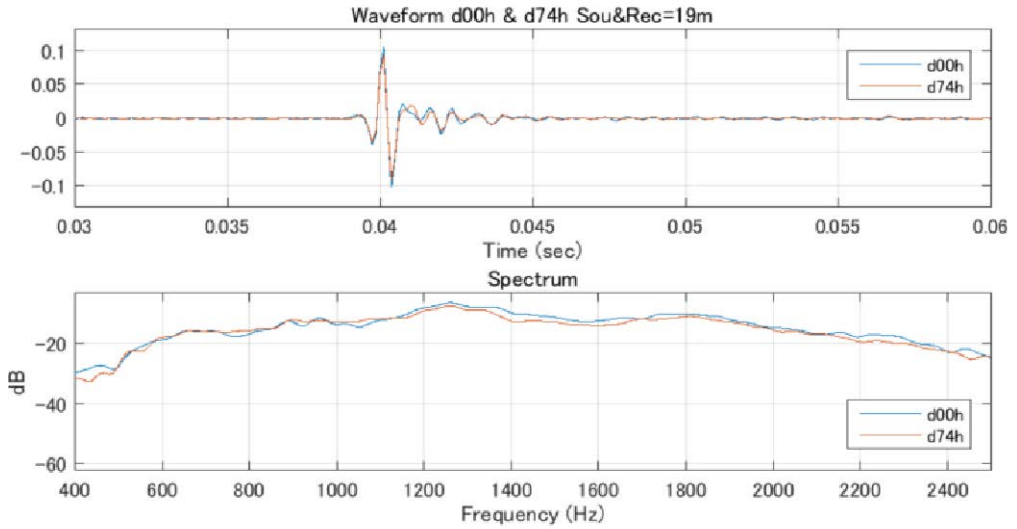


First order features:

1. Strong decay of low frequencies
2. Weak boost of high frequencies
3. Altered coda
4. Notch

Spectral changes (unpublished JOGMEC figures; used by permission)

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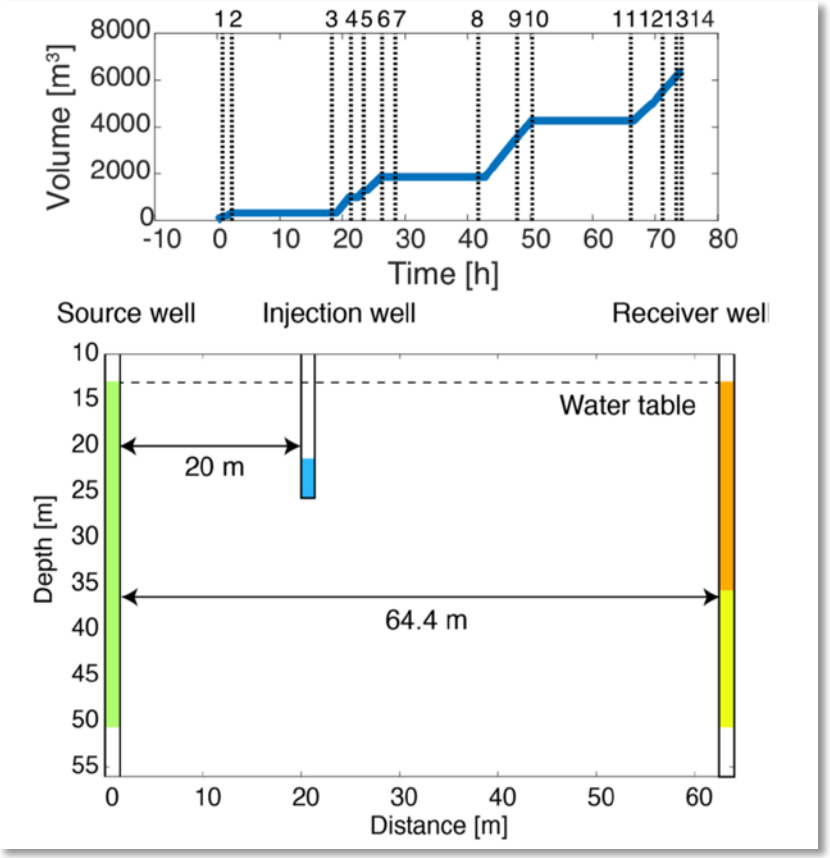


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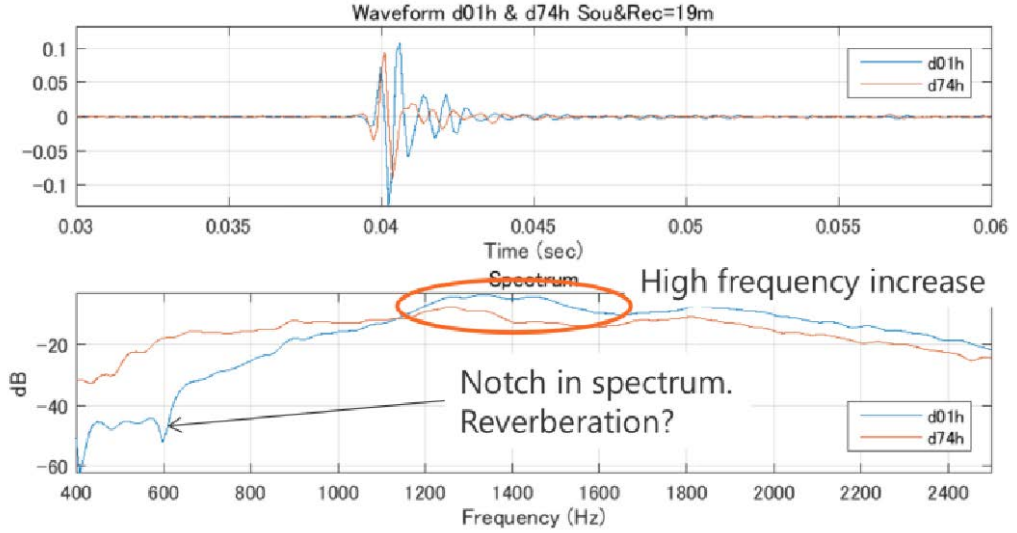


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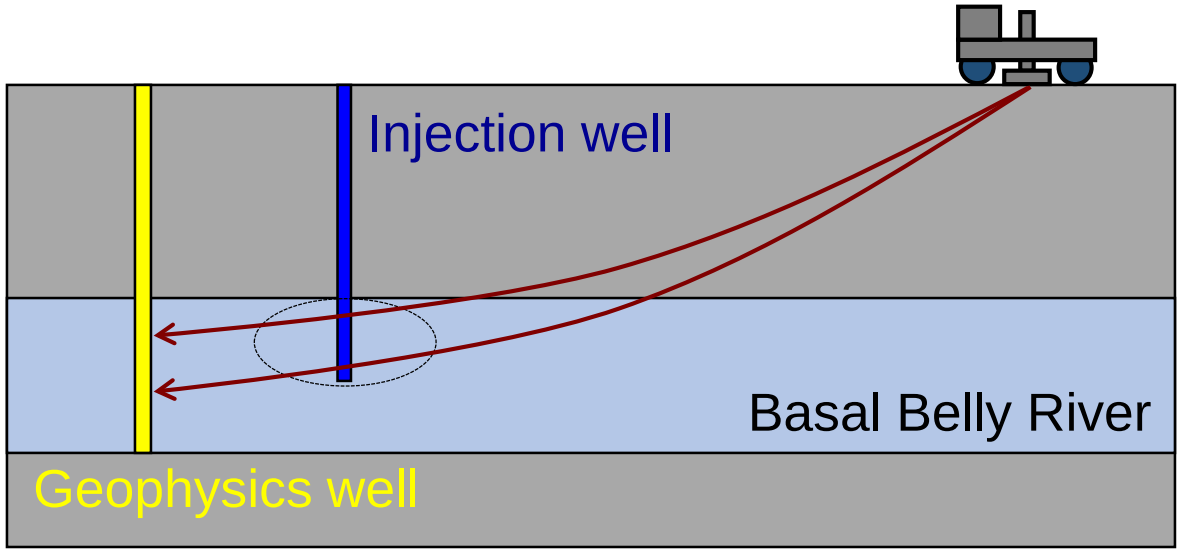
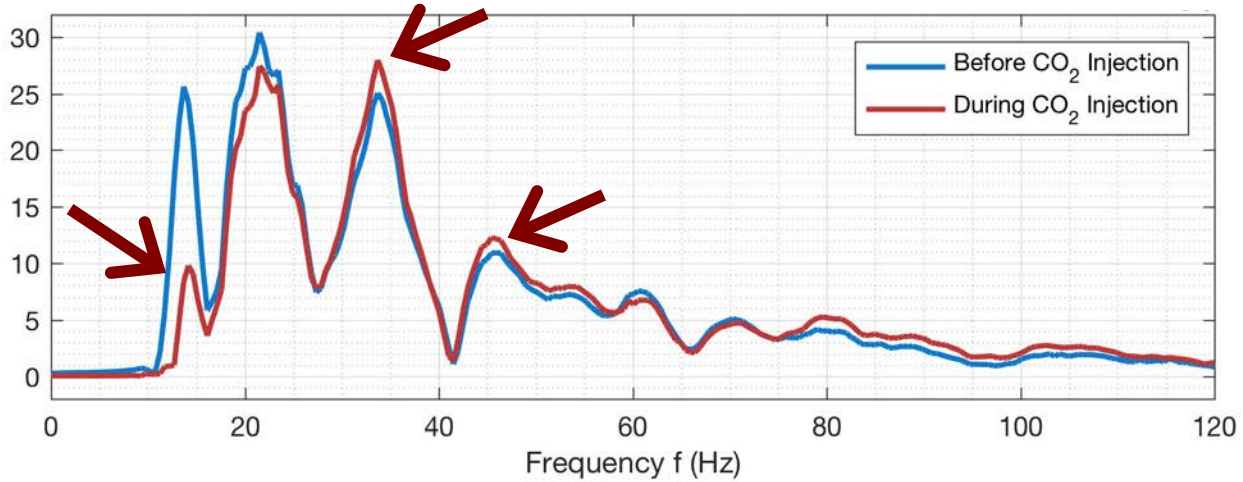
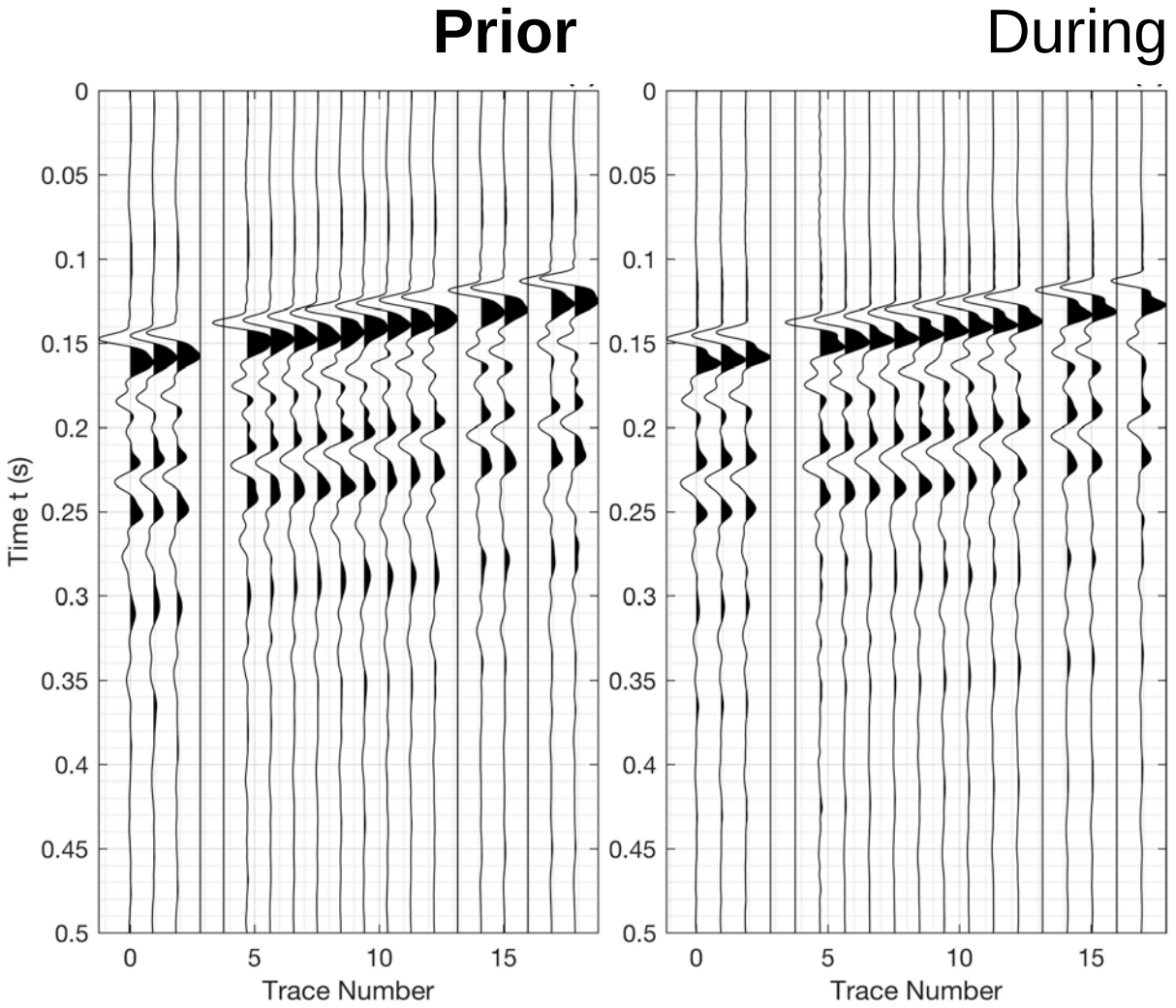
## CaMI CO2 injection testing Nov 2018

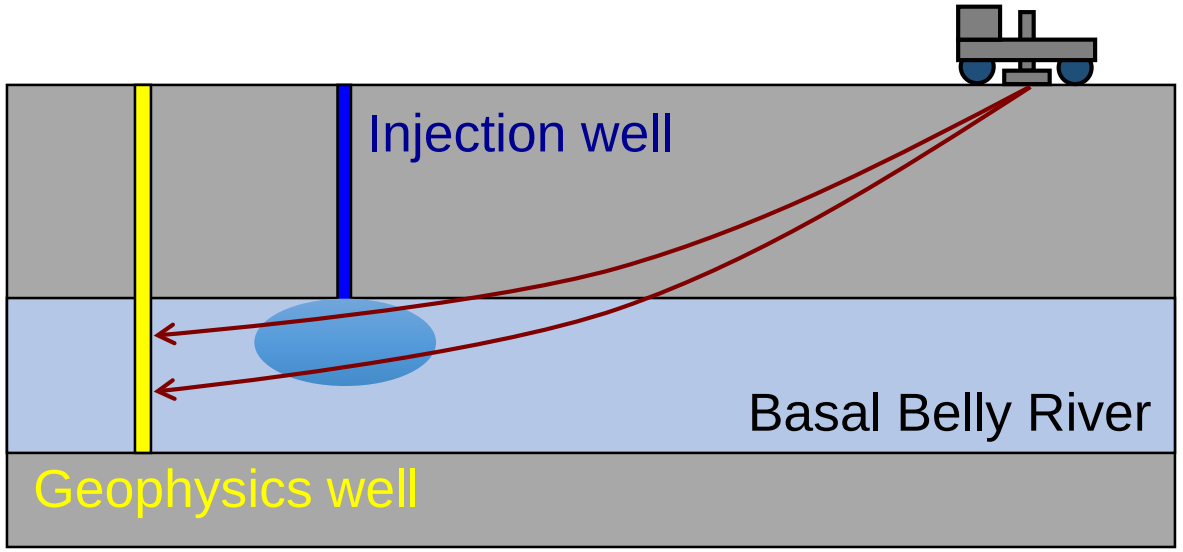


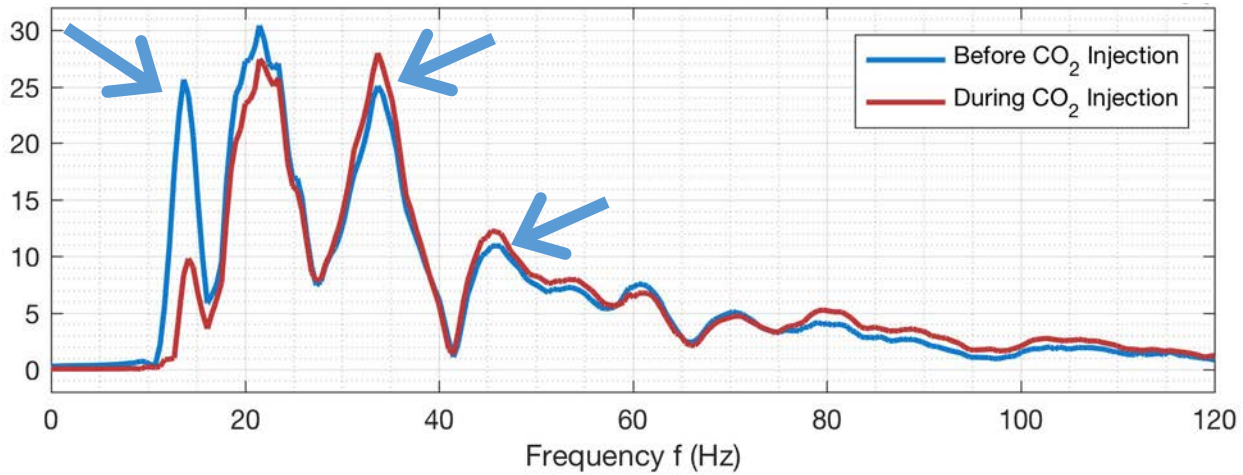



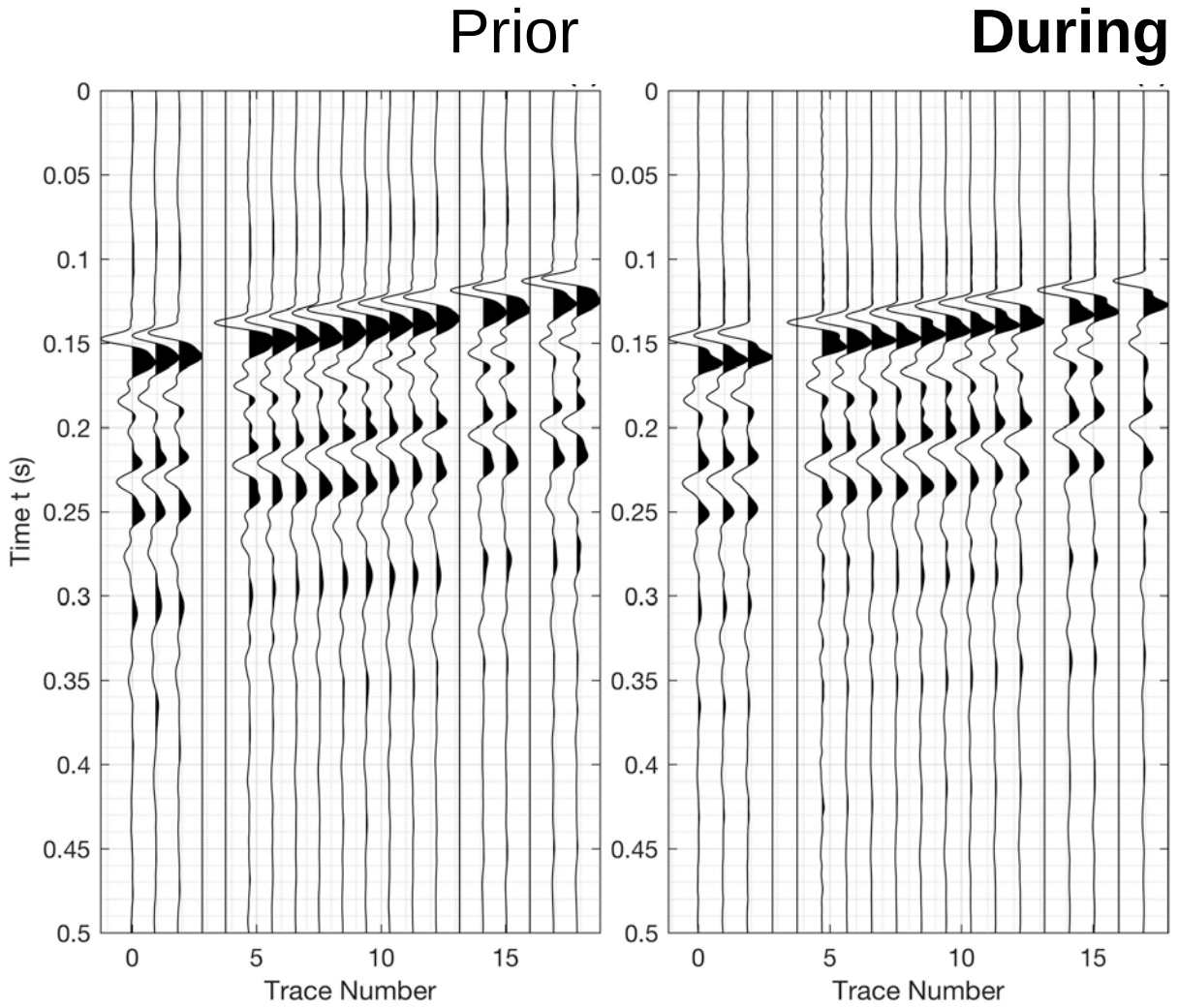



# Two experiments

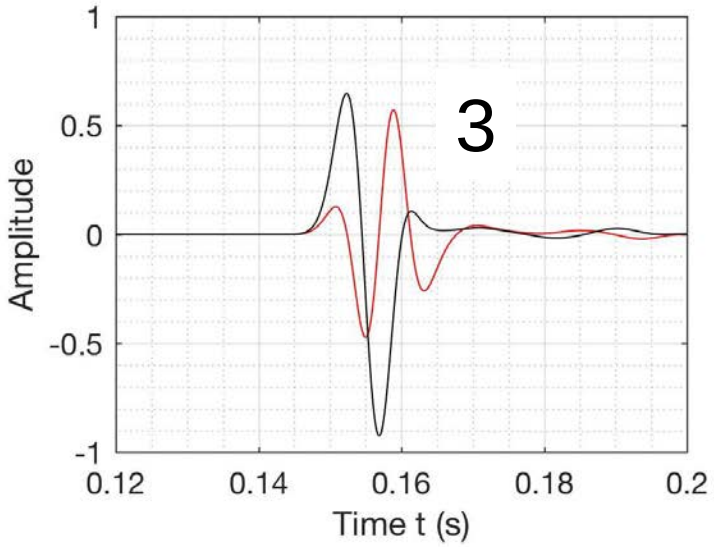
## CaMI CO2 injection testing Nov 2018

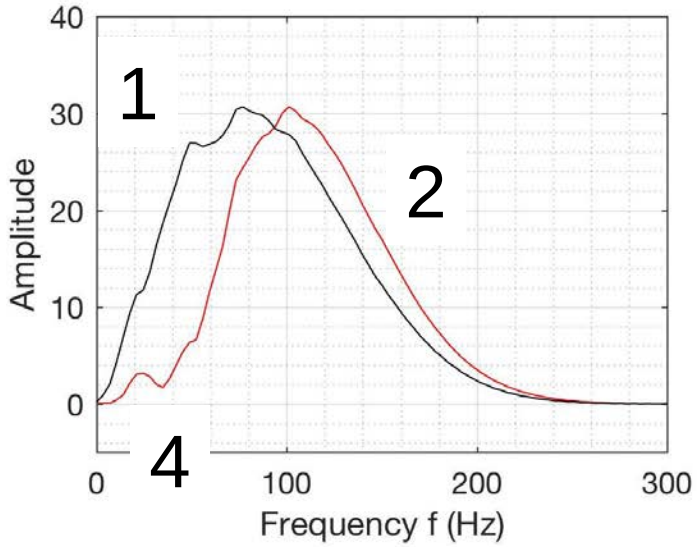


# Hypothesis



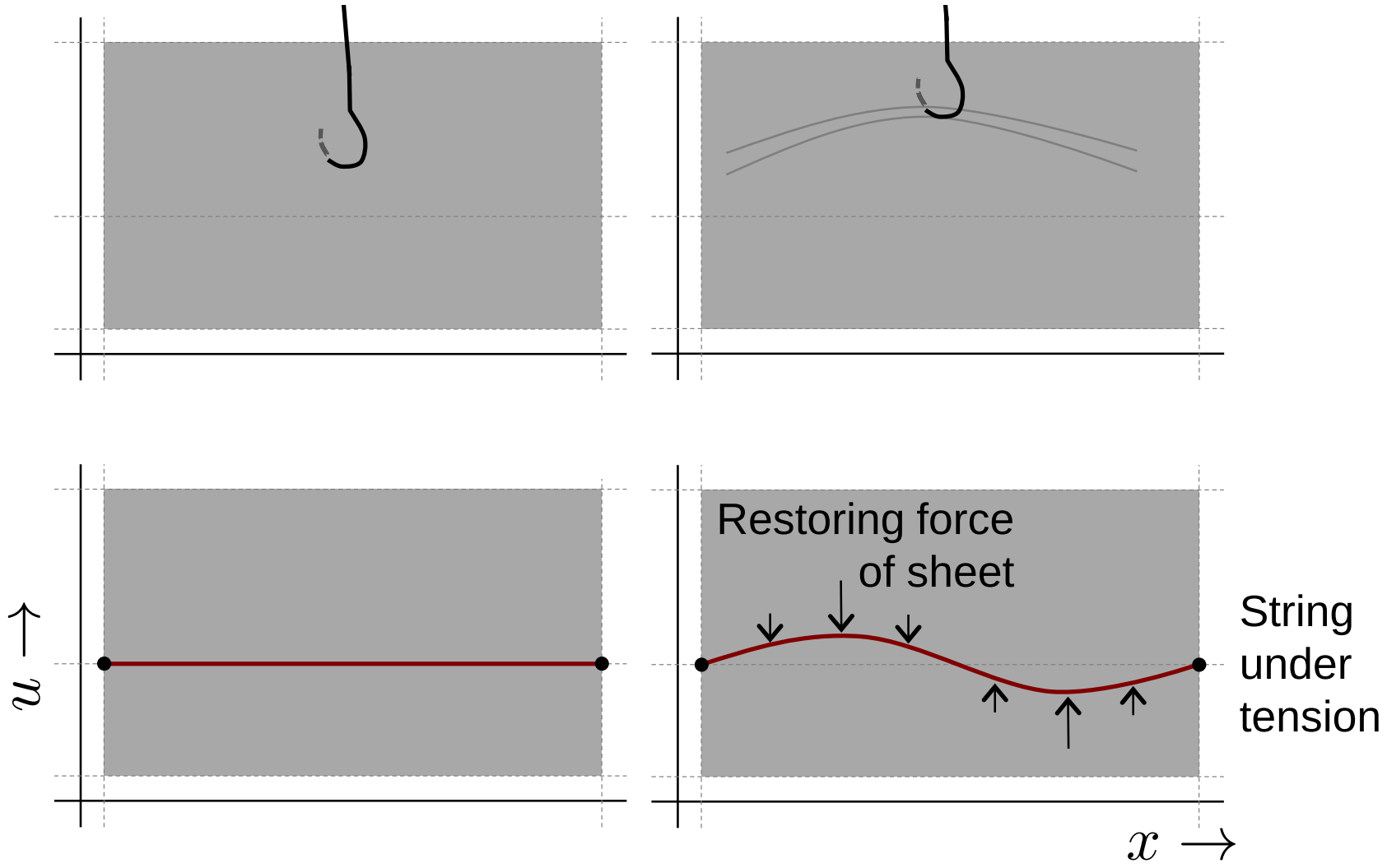




1. *Suppression of low f*
2. *Boost of high f*
3. *Coda*
4. *Notch*

## Hypothesis:

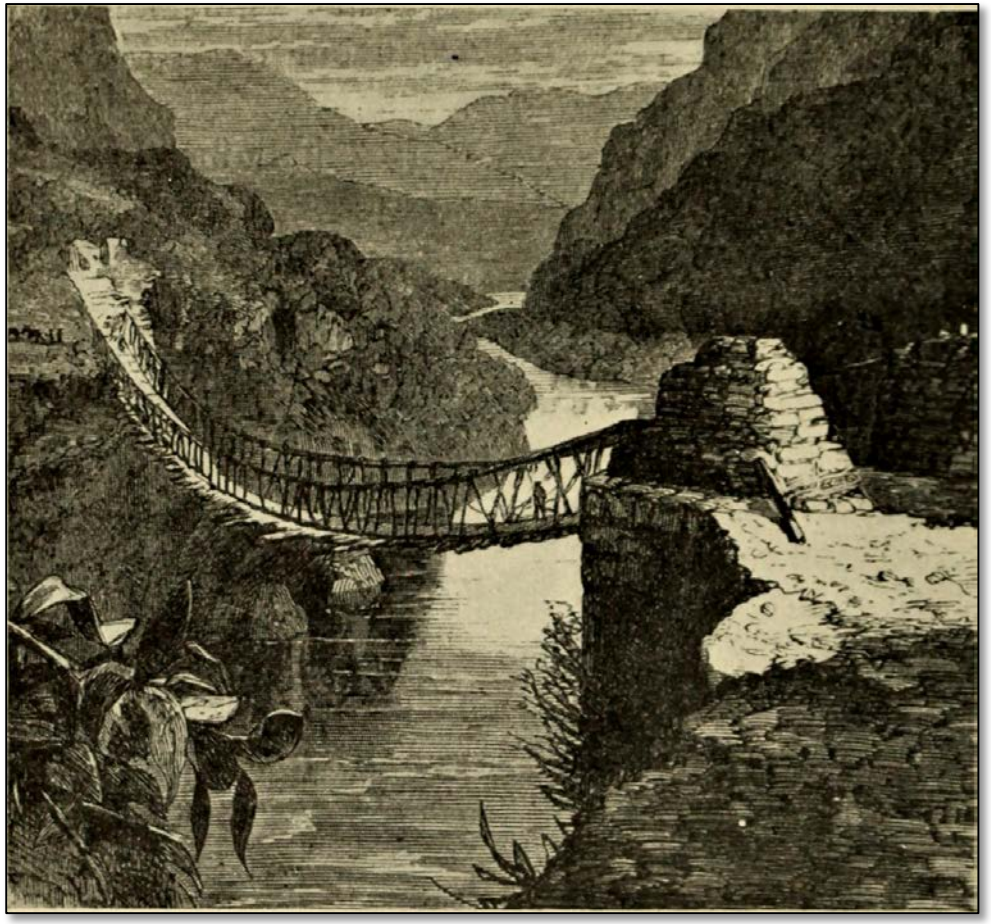
The seismic wave in the presence of recently injected microbubble / $CO_2$ is acting as if it were experiencing “elastic bracing”.

# “Elastic bracing” – e.g., string embedded in a rubber sheet



# Elastic bracing and the Klein-Gordon equation

## “Elastic bracing” – e.g., the rope bridge model



Old Civilizations of Inca Land (1924)

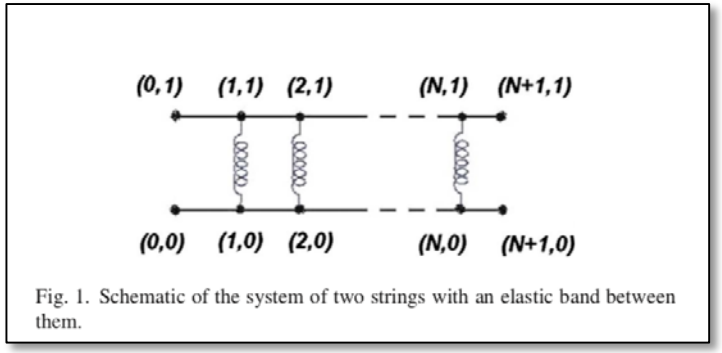



Fig. 1. Schematic of the system of two strings with an elastic band between them.

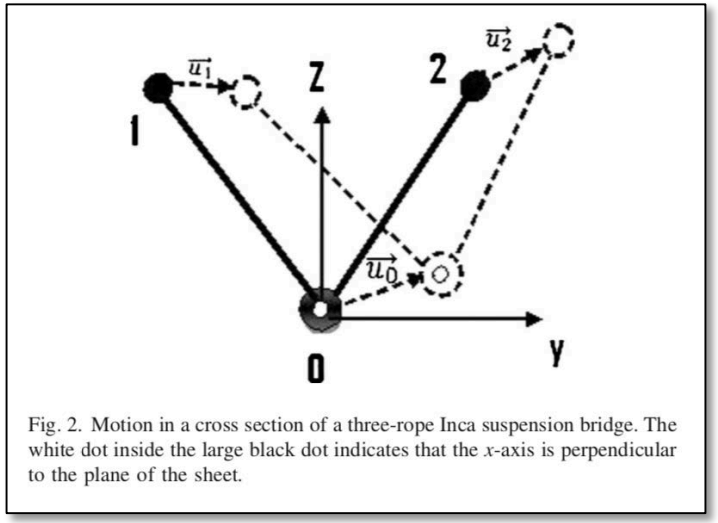



Fig. 2. Motion in a cross section of a three-rope Inca suspension bridge. The white dot inside the large black dot indicates that the $x$-axis is perpendicular to the plane of the sheet.

Gravel and Gautier (2011)

# Elastic bracing and the Klein-Gordon equation

E. Schrödinger (Wikipedia)

$$i\hbar\partial_t u = -\frac{\hbar^2}{2m}\partial_{xx}u + Vu$$

Time dependent Schrödinger equation
... nonrelativistic

O. Klein
(Wikipedia)

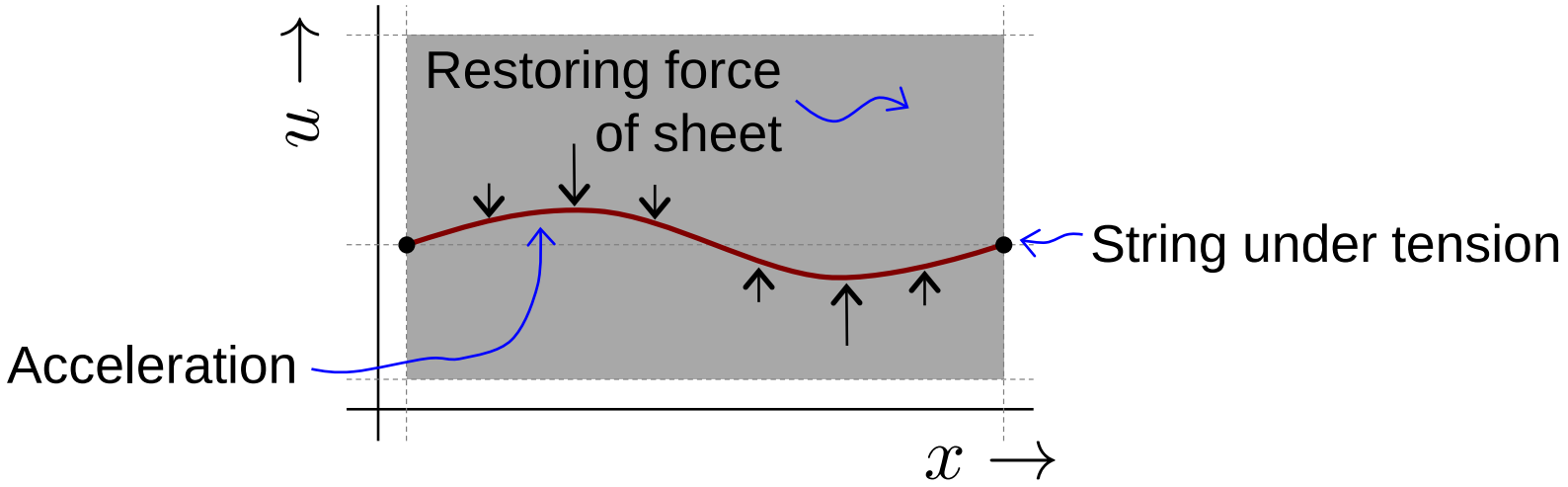
No photo available

W. Gordon

$$\partial_{tt}u - c^2\partial_{xx}u + \left(\frac{mc^2}{\hbar}\right)^2 u = 0$$

Relativistic Klein-Gordon equation

# Classical interpretation of the KG equation




$$\partial_{tt}u - \beta^2\partial_{xx}u + \alpha u = 0$$

Acceleration

String under tension

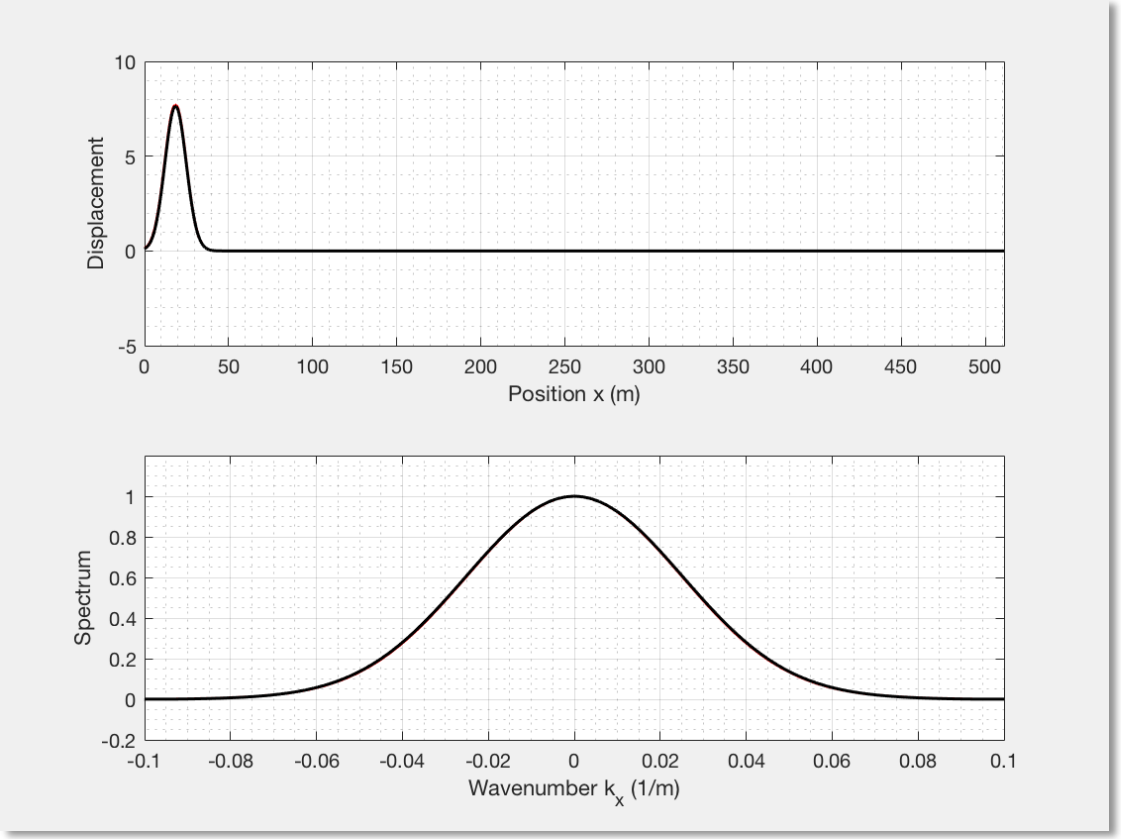
Restoring force of sheet

# Elastic bracing and the Klein-Gordon equation

$$u_i^{n+1} = 2\left[1 - \left(\frac{c\Delta t}{\Delta x}\right)^2 - \alpha\right] u_i^n + \left(\frac{c\Delta t}{\Delta x}\right)^2 \left[u_{i-1}^n + u_{i+1}^n\right] - u_i^{n-1}$$

scalar wave field ——

KG field ——



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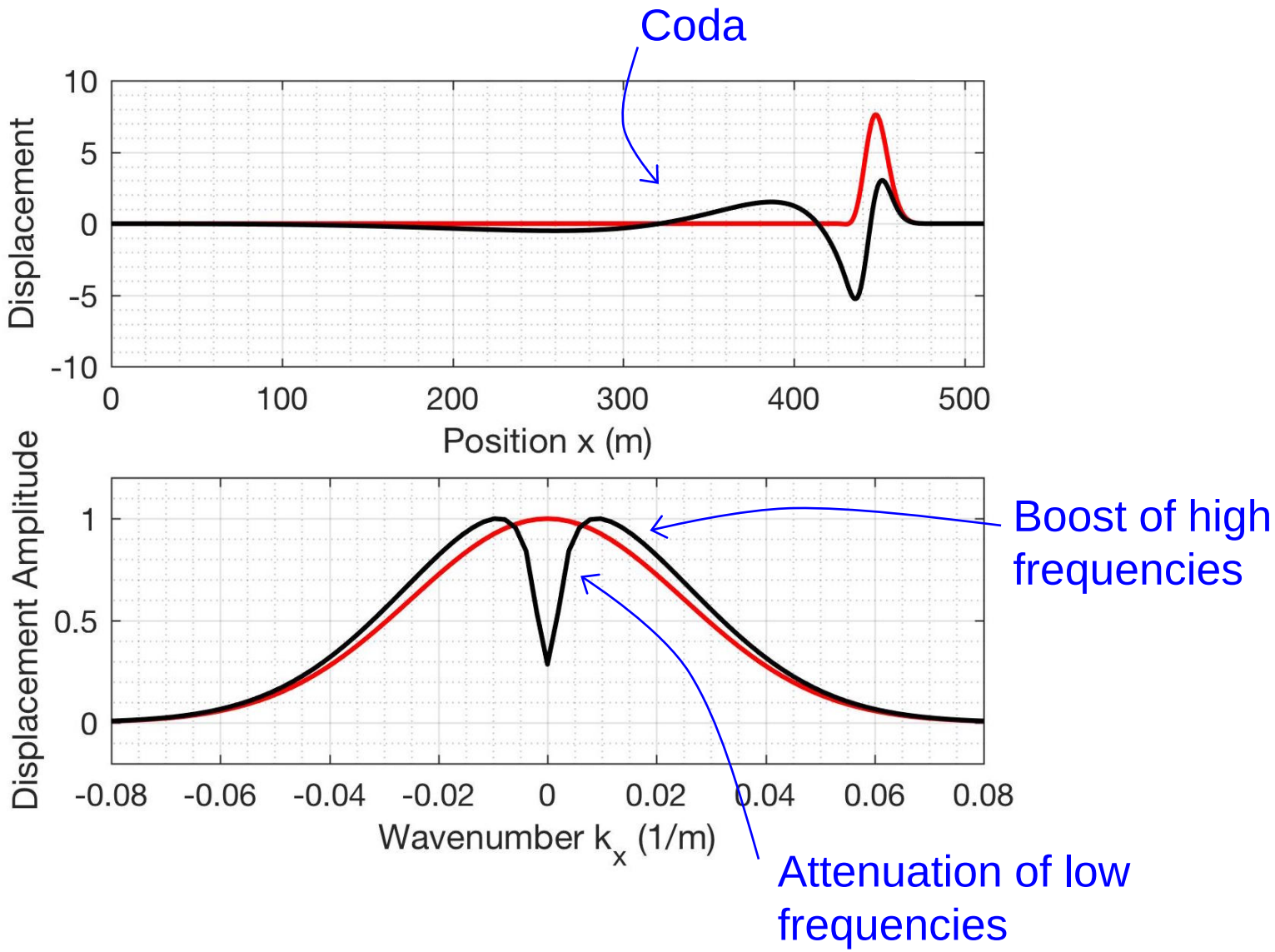

# An elastic equation with Klein-Gordon bracing

Elastic force balance receives an extra term:

$$\rho \ddot{u}_i - \sigma_{ij,j} = 0$$

...incorporated into a displacement-stress FD scheme via:

$$u_{i,j}^{n+1} = 2u_{i,j}^{n} - u_{i,j}^{n-1} + \frac{\Delta t^2}{\rho_{i,j}} \times \text{stress terms}$$

whose “2” weight is reduced locally by the amount η

# An elastic equation with Klein-Gordon bracing

Elastic force balance receives an extra term:

$$\rho \ddot{u}_i - \sigma_{ij,j} - \eta u_i = 0$$

...incorporated into a displacement-stress FD scheme via:

$$u_{i,j}^{n+1} = \left(2 - \eta_{i,j}\right) u_{i,j}^{n} - u_{i,j}^{n-1} + \frac{\Delta t^2}{\rho_{i,j}} \times \text{stress terms}$$

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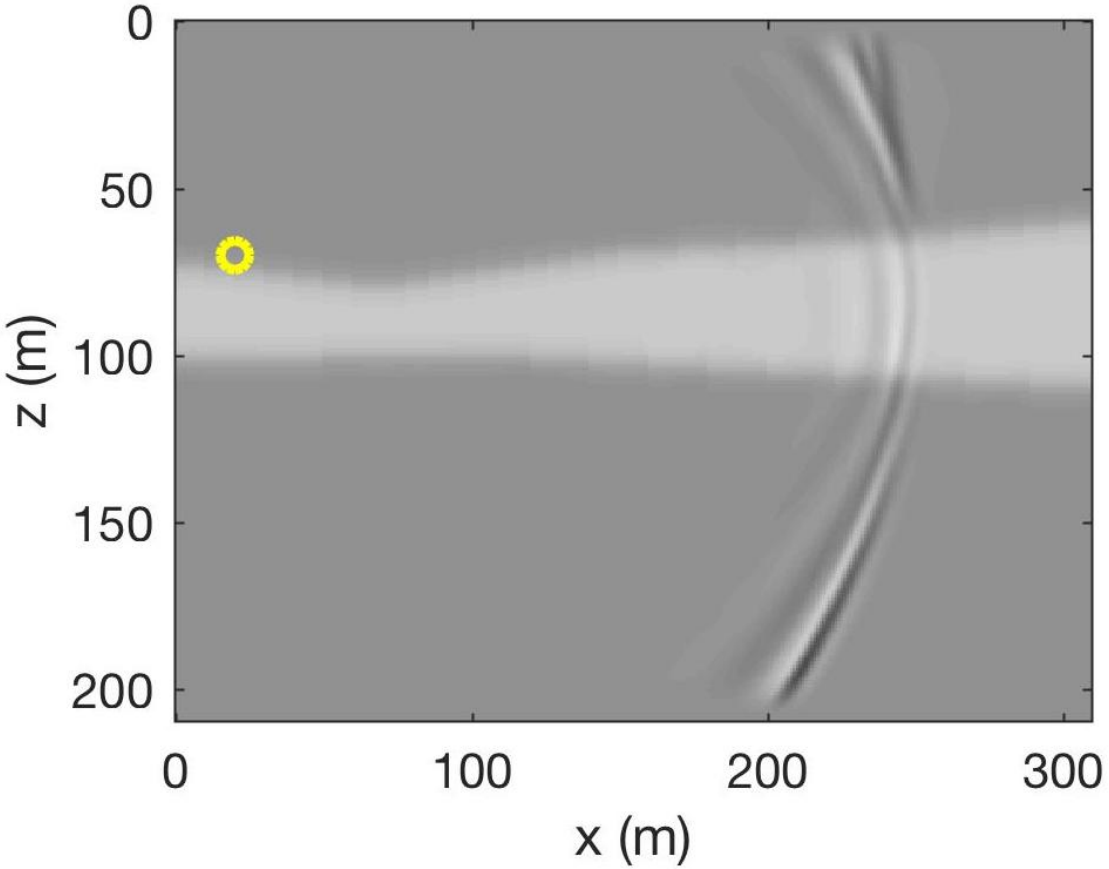


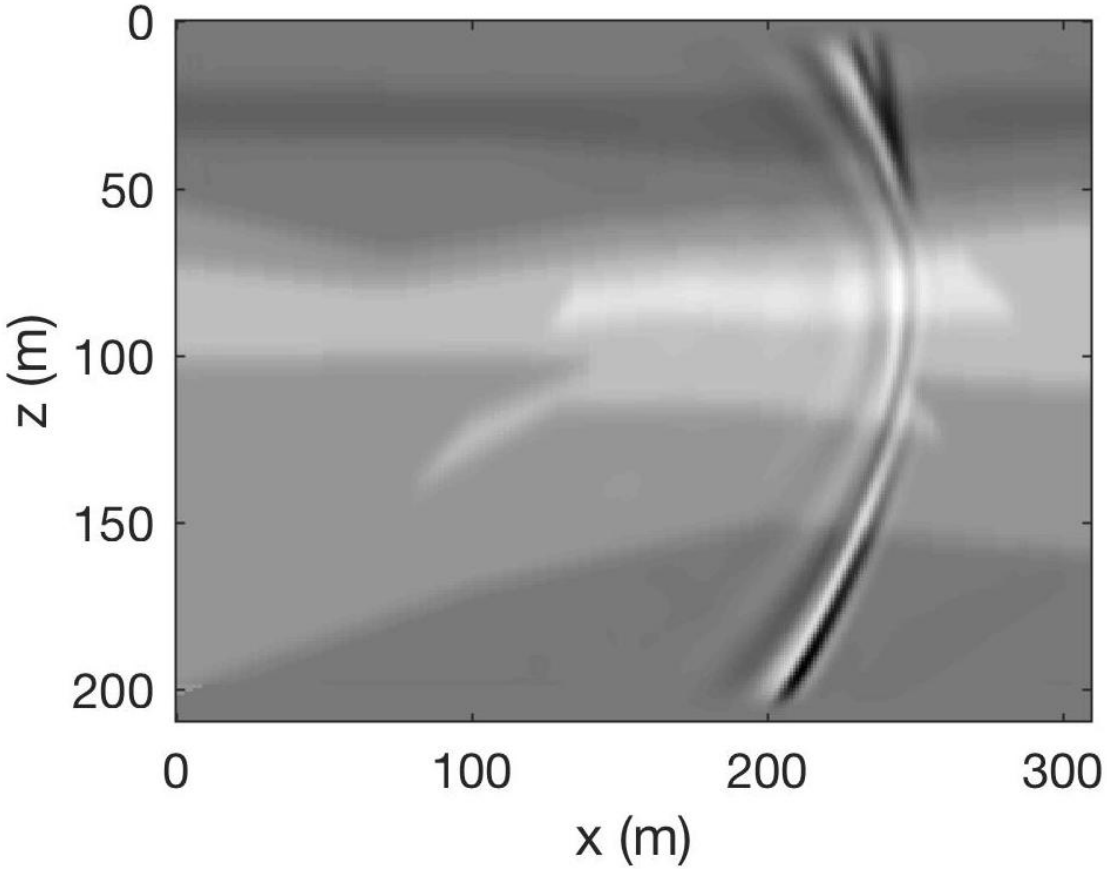


2D elastic FD code modified from J. Li

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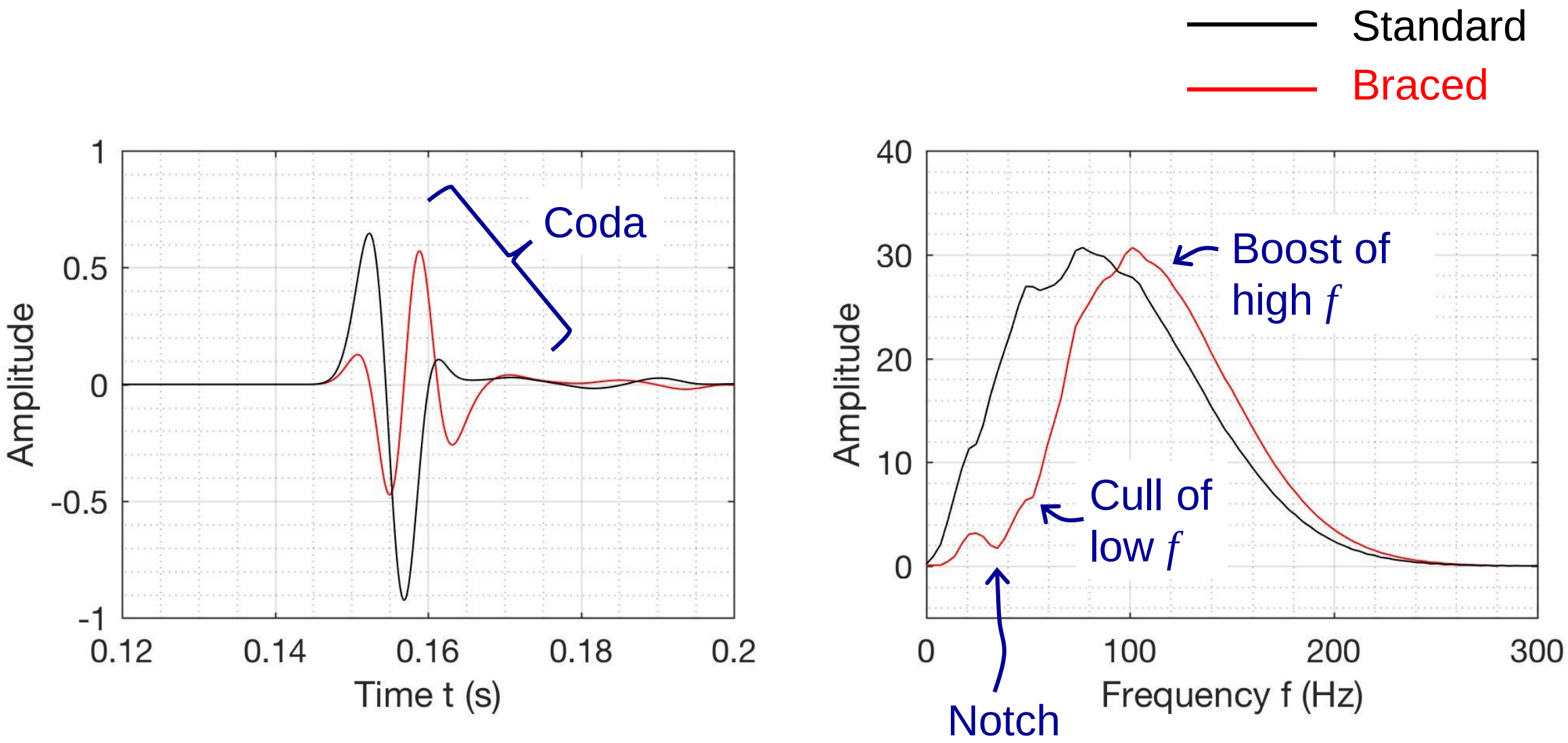

# Discussion

- Probably could have explained this with heterogeneity: case for introducing “new physics”?
- No microscopic / mechanical explanation is put forward: what is the value of a macroscopic description absent one?
- Emphasize in seismic:
    - introduction of a small number of parameters (e.g., Q)
    - constrainable with bandlimited observations
    - data – seismic model par – mechanical/petrophysical par
- Next steps:
    - confirm / falsify with more observations!
    - continue to analyze transient waveform changes in injection
    - laboratory analyses with microbubble water