October 10th 2024

# Aquifer **permeability** and **shear modulus** evolution inverted from tidal signals: lessons about shallow **fractured aquifers**

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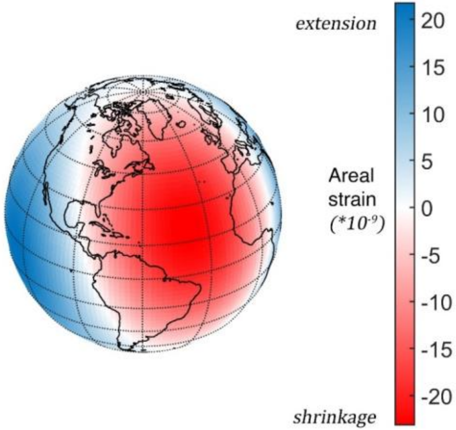
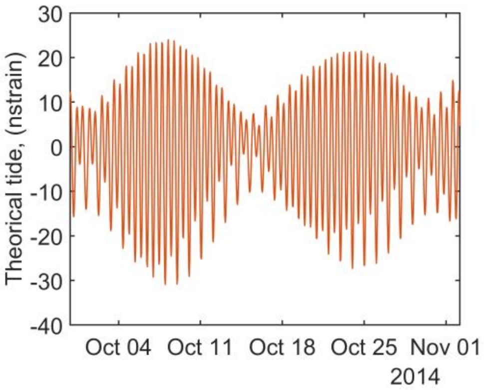
# Physics of tides

**Earth tide**:




Snapshot of the tidal areal strain (-) $\boldsymbol{\varepsilon_{\theta\theta}} + \boldsymbol{\varepsilon_{\varphi\varphi}}$ computed by the ertid function of program SPOTL (Agnew, 2012) on February 1st 2024 at midnight.

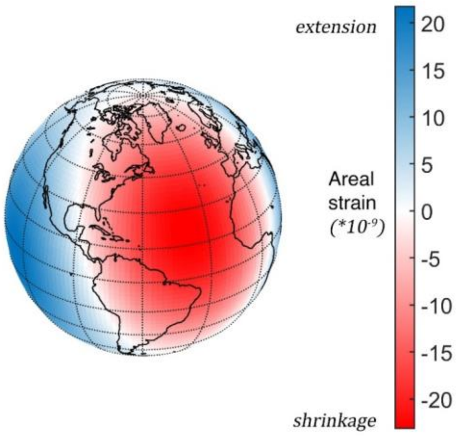



Time evolution of tidal areal strain over Martinique

- Ubiquitous but small: $\varepsilon \sim 10^{-8}$
- Computed theoretically (access to the horizontal strain only)

# Physics of tides

**Earth tide**:

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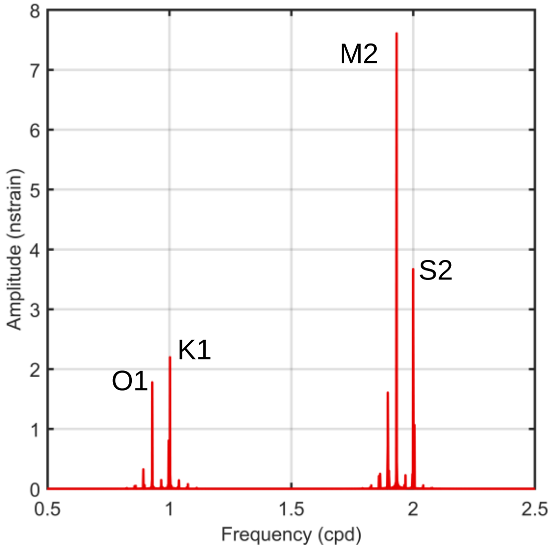
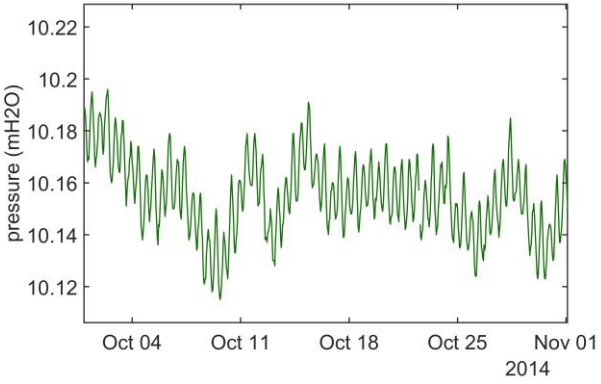



Frequency spectrum of tidal areal strain over Martinique

- Ubiquitous but small: $\varepsilon \sim 10^{-8}$
- Computed theoretically (access to the *horizontal* strain only)
- Well defined frequencies linked to the ephemerides

# Physics of tides

**Atmospheric tide**:

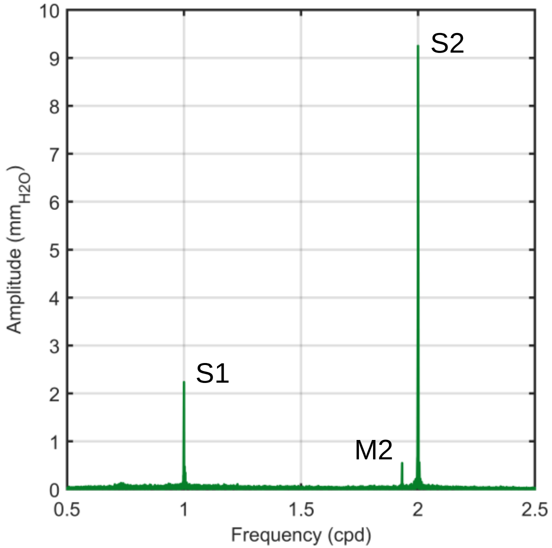




Time evolution of atmospheric pressure over Martinique

- $P_{atm} \sim 3\ cmH_2 0$
- Measured locally
- Similar frequencies (but dominance of the solar influence)

# Physics of tides

**Atmospheric tide**:




Frequency spectrum of atmospheric pressure over Martinique

- $P_{atm} \sim 1\ cmH_2 0$
- Measured locally
- Similar frequencies (but dominance of the solar influence)

# Tides in the subsurface

Noting the state variables of an aquifer $(\sigma, \varepsilon, p, \zeta)$

$$p = -BK_u\varepsilon \quad \& \quad p = \gamma P_{atm}$$

With

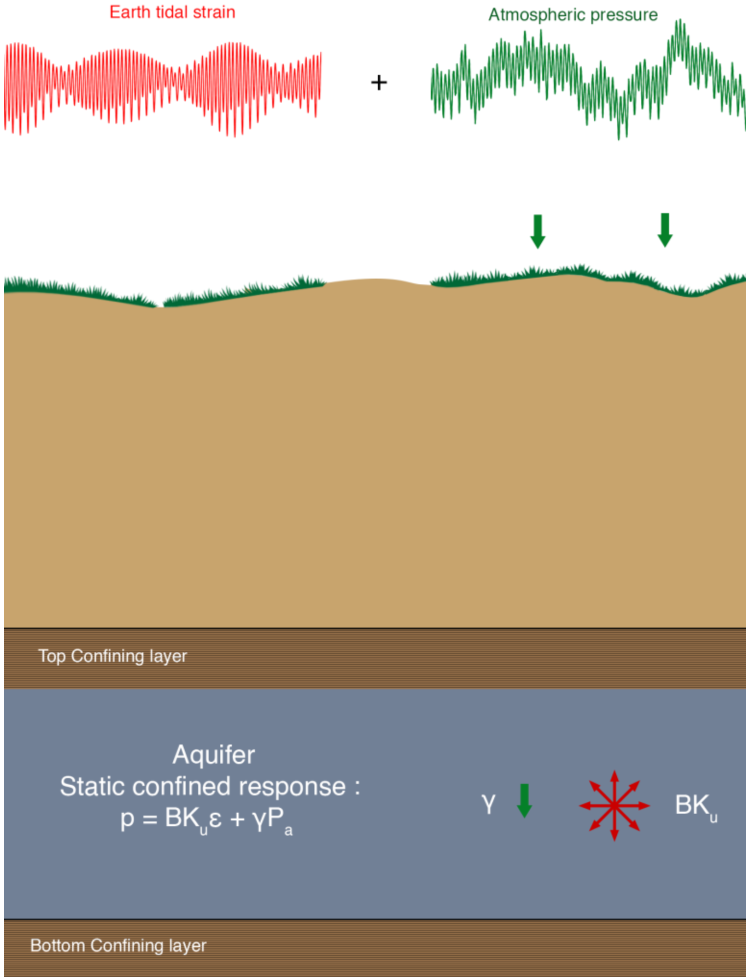
$\gamma$: Loading efficiency $\left.\frac{\delta p}{\delta \sigma_{zz}}\right|_{\zeta=0}$

$K_u$: undrained bulk modulus (Pa)

$B = \frac{\delta p}{\delta \sigma_{|\zeta=0}}$: Skempton coefficient

*-> it's not the best formulation as it uses*

$$\zeta = S_\varepsilon p + S_\varepsilon \cdot BK_u\varepsilon$$



# Tides in the subsurface

We link the state variables of an aquifer $(\sigma, \varepsilon, p, \zeta)$ in a *constitutive equation*:

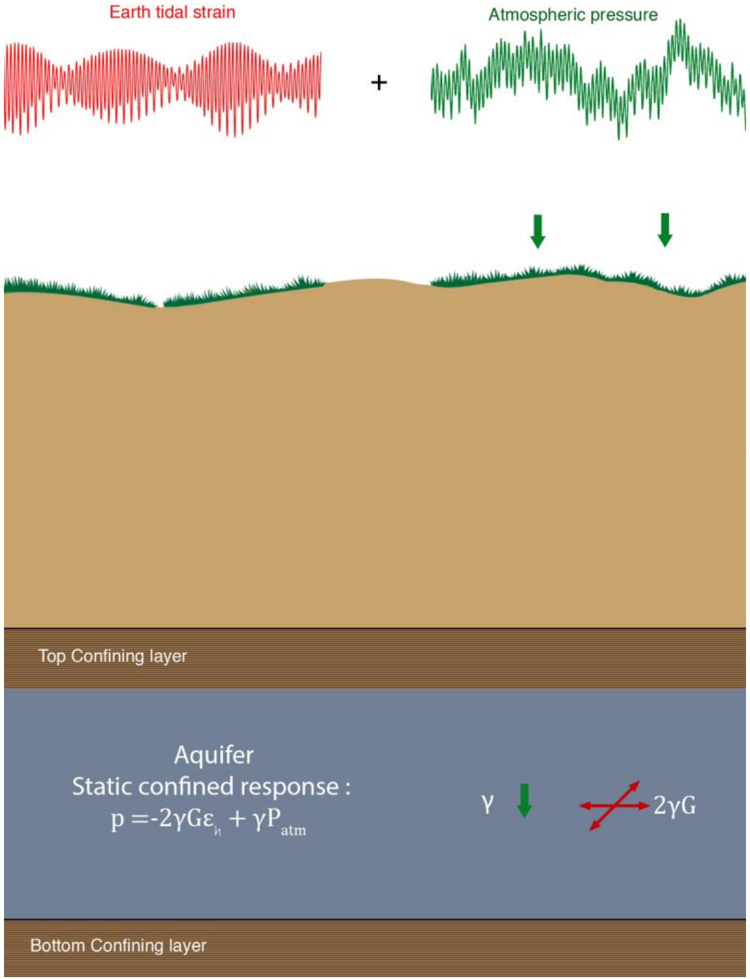
$$\zeta = S_h p + S_h \cdot \mathbf{2G\gamma}\varepsilon_h$$

With

$S_h$ : *Uniaxial* storage coef. $S_h = \frac{\delta\zeta}{\delta p}_{|\varepsilon_h=0,\sigma_{zz}=0}$ (-)

$G$: Shear modulus (Pa)

$\gamma$: Loading efficiency $\left.\frac{\delta p}{\delta\sigma_{zz}}\right|_{\zeta=0}$

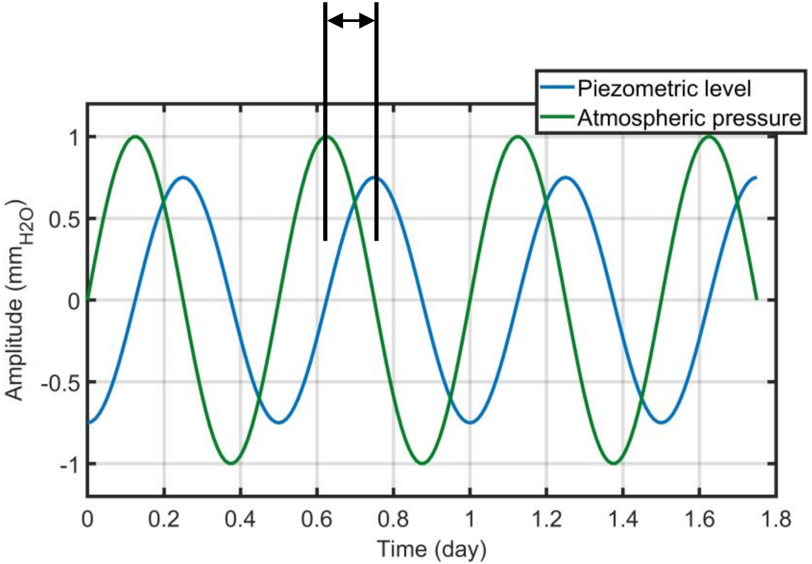


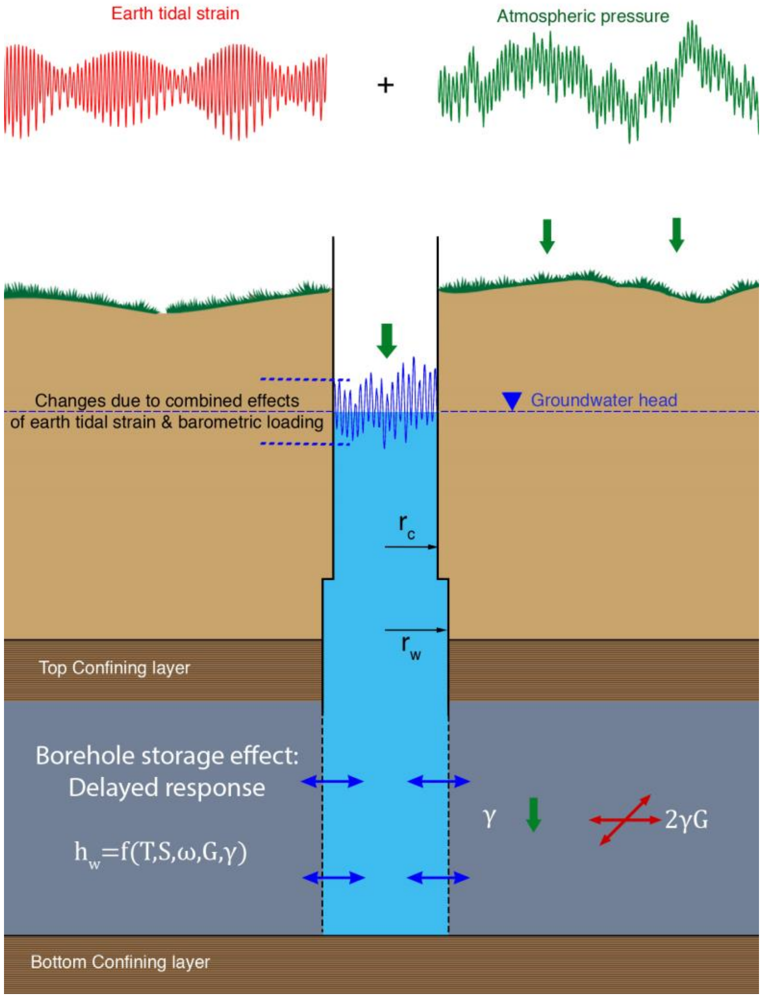
# Response of a borehole:

We do not measure pore pressure but borehole piezometric head:

→ Attenuation and phase lag

$$\Delta\varphi = -45°$$

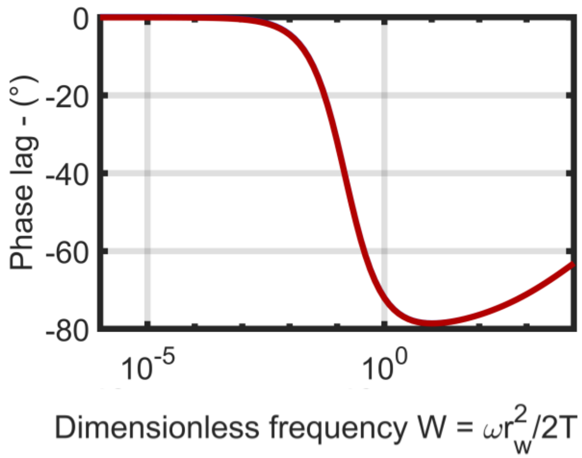


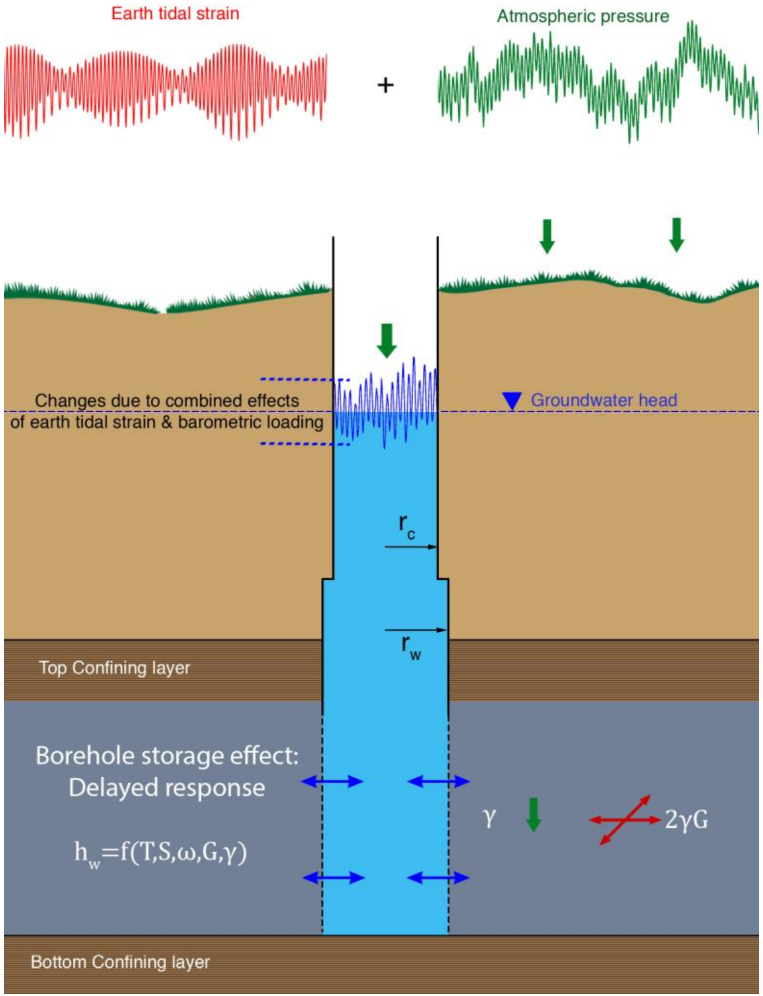



# Response of a borehole:

Borehole storage effect (Hsieh, 1988)

**phase lag** is mostly sensitive to aquifer *transmissivity*



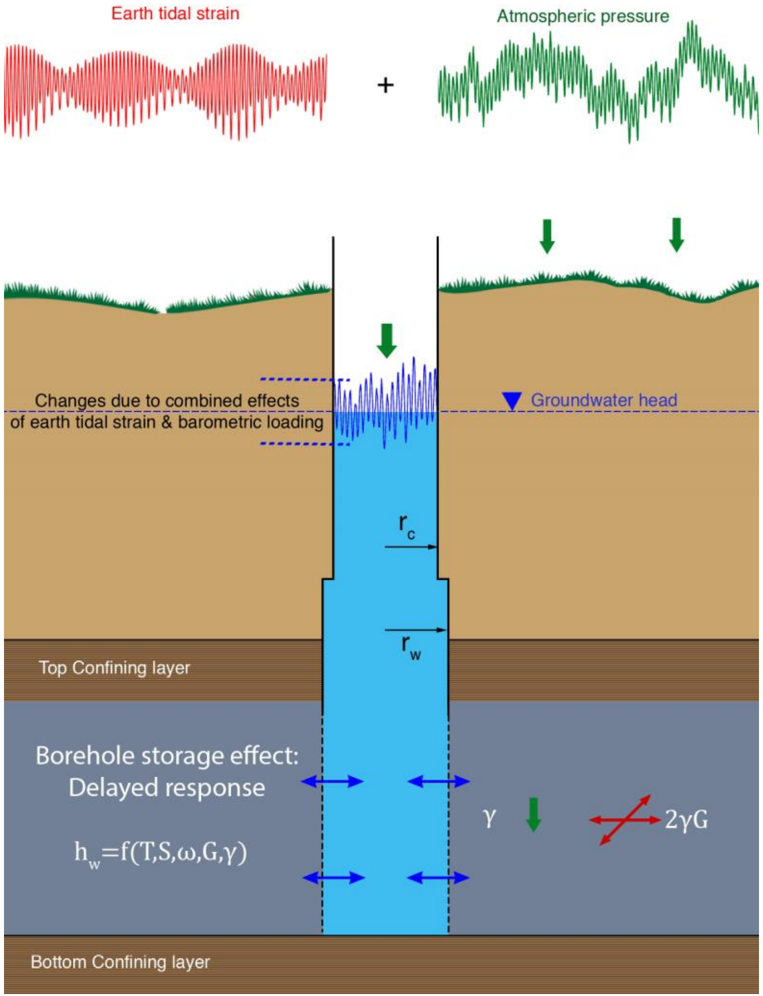
# Response of a borehole:

Borehole storage effect (Hsieh, 1988)

**Amplitudes** give you access to both

$$\gamma \ \& \ 2\gamma G$$

*-> measurment of the shear modulus evolution over time*



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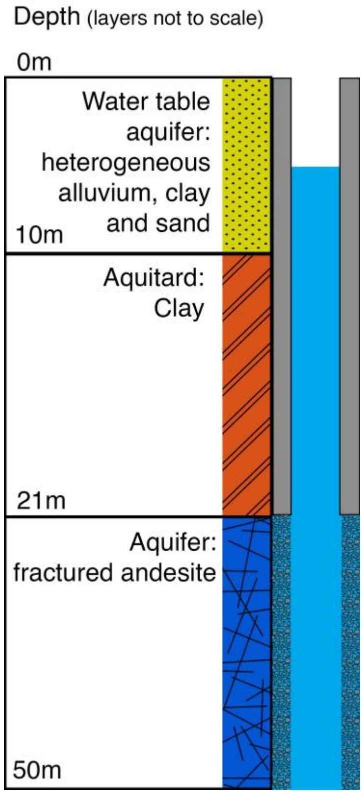
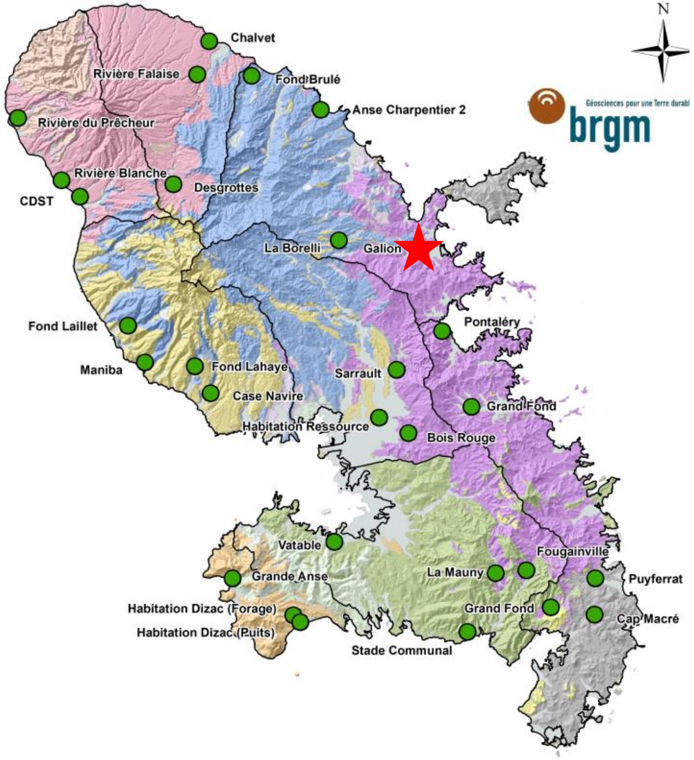
# Application in Martinique

# The Galion borehole

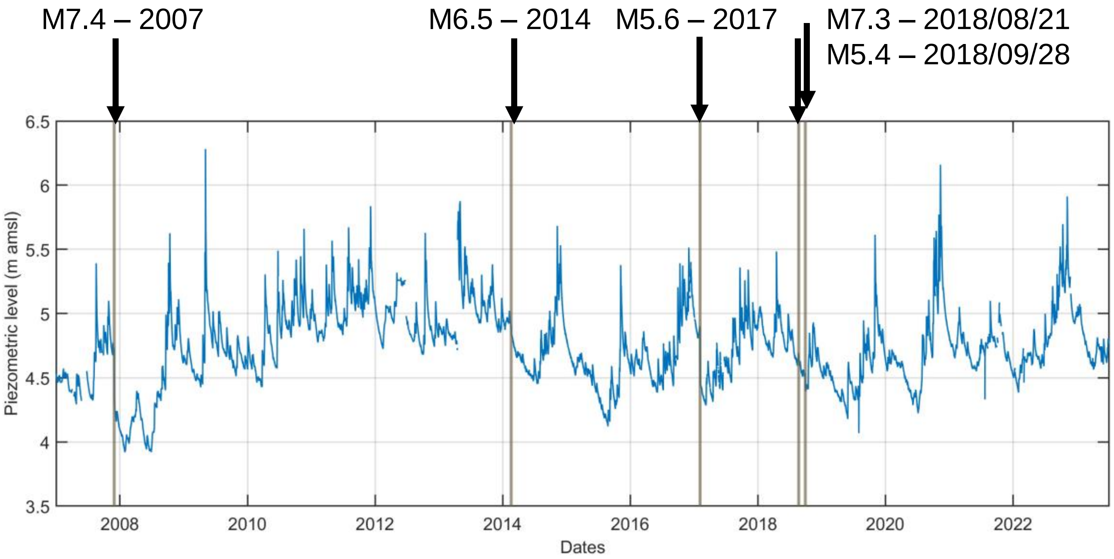


# Practically:

**Input data**

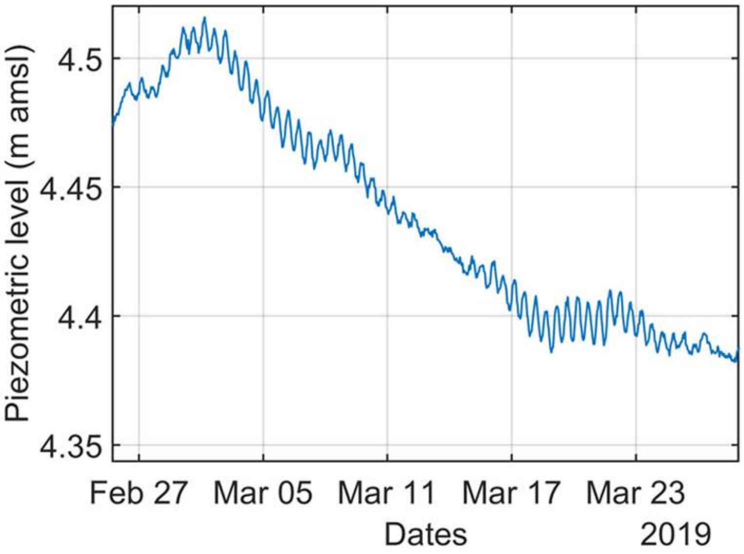
- Piezometric level at an *hourly sampling rate*



# Practically:

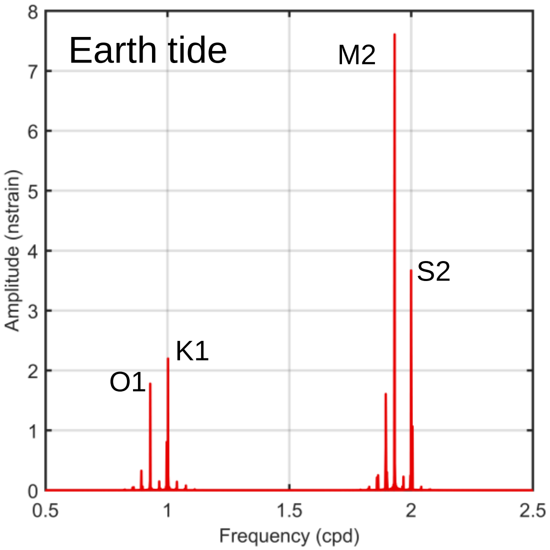
**Input data**

We are interested in the tidal oscillations around 1 & 2 cycles per day

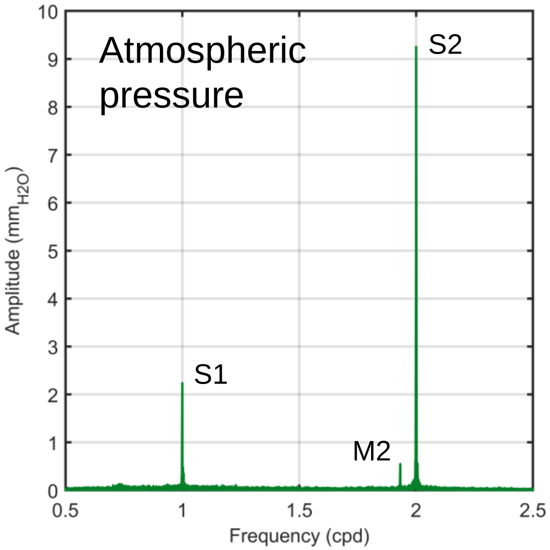


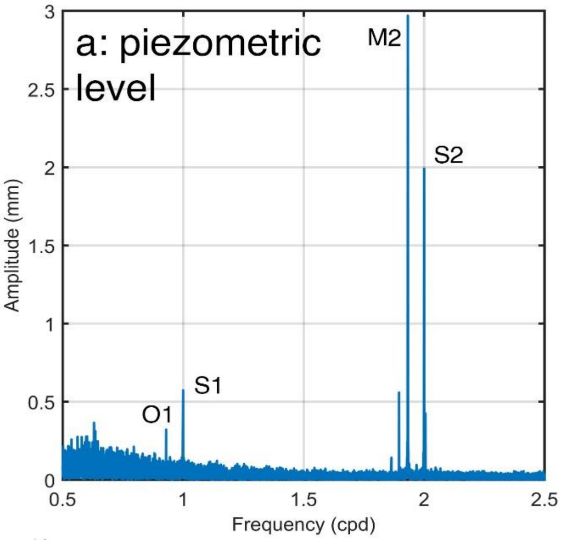
# The tidal analysis workflow:

**Data processing:**



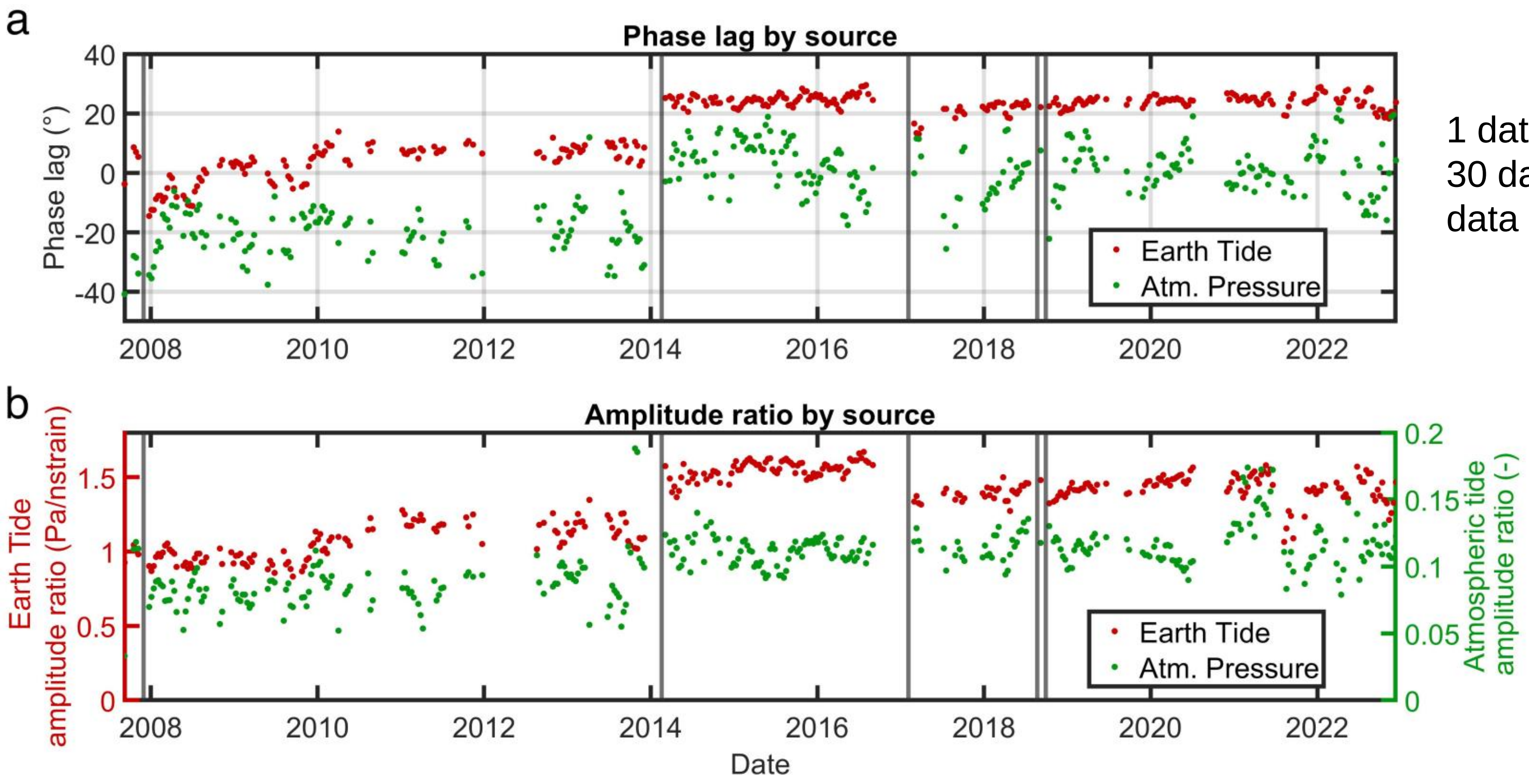

+



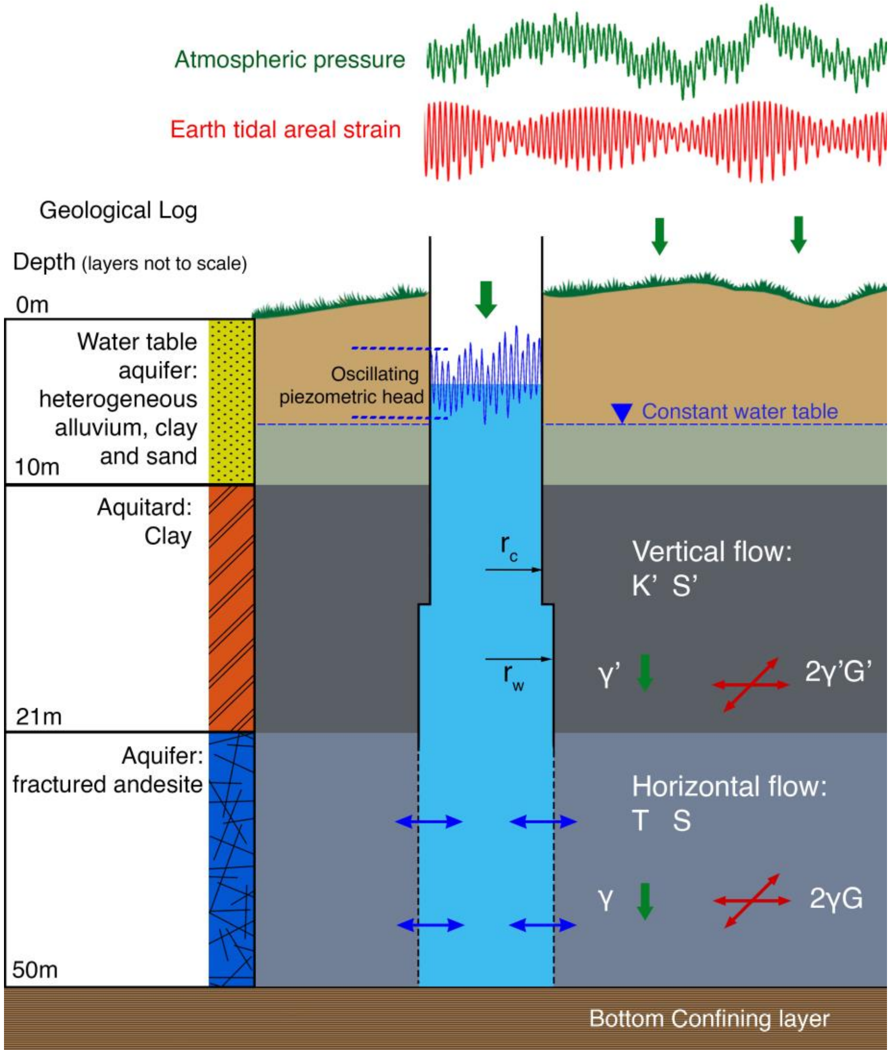

Band-pass filtering & Harmonic least square fitting to compute **phase lags** & **amplitude ratios**

# Transfer functions




1 data point:
30 days - window of data analysis

# Conceptual model



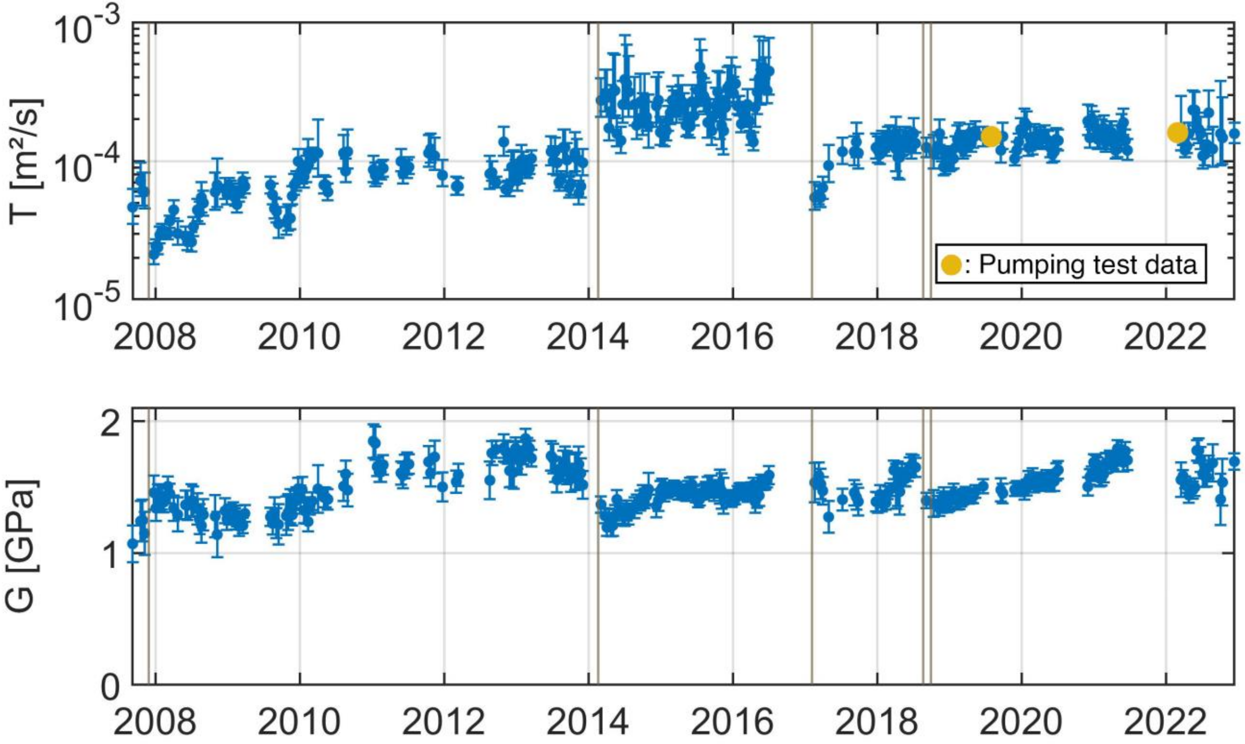

3 layers

4 « free » parameters
4 calibrated parameters (Pumping test & Seismic survey)

$T$ Transmissivity
$K'$ Hydraulic conductivity
$S, S'$ Storativities
$\gamma, \gamma'$ Loading efficiencies
$G, G'$ Shear moduli

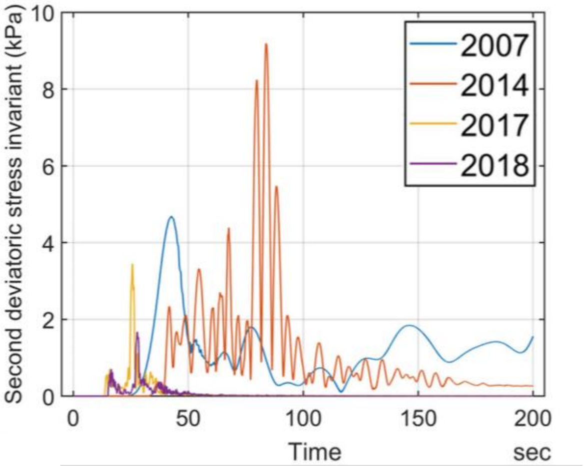
# Model inversion and validation

Aquifer Transmissivity and **Shear modulus**




Shear modulus range validated with the seismic survey (G < 2GPa!)

# Co-seismic changes




Numerical simulation of the seimic dynamic stresses at the borehole

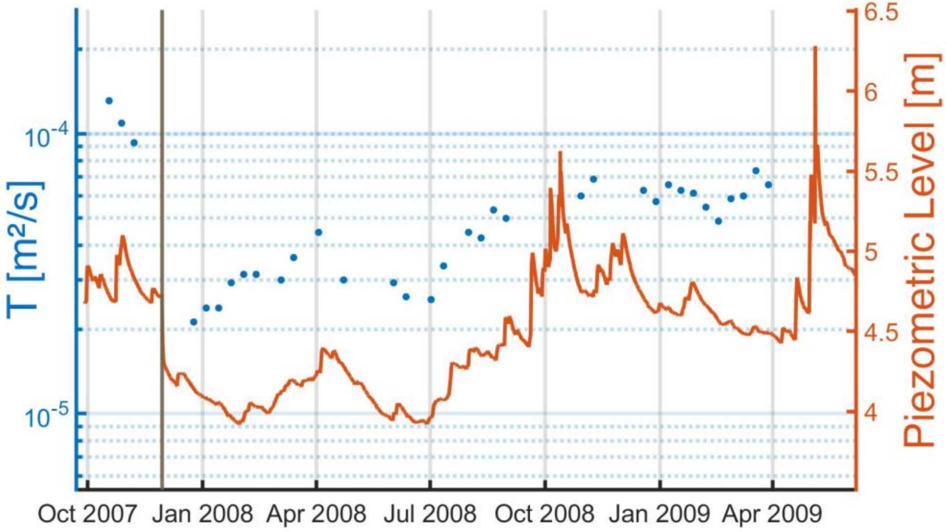
- Peak **shear stress** amplitude are the best predictors of transmissivity and shear modulus variations

- The main hypothesis found in the literature to explain *Transmissivity* variations (clogging & unclogging of fractures) is not sufficient to explain *Shear modulus* variations

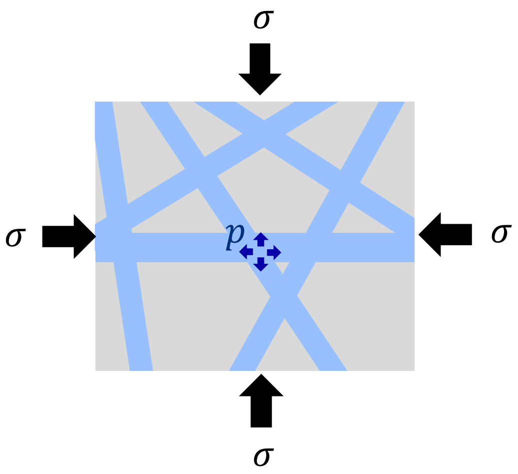
- Micromechanical models suggests that there was a crack density variation (re-opening of closed fracture) up to 60% in 2014

# Reversible changes controlled by hydraulic head

At the Galion borehole




These reversible changes seem to be controlled by piezometric level




The effective stress $\boldsymbol{\sigma}^* = \sigma - \alpha p$ controls the opening of fractures

$$h \propto p \rightarrow \sigma^* \rightarrow w \rightarrow T$$

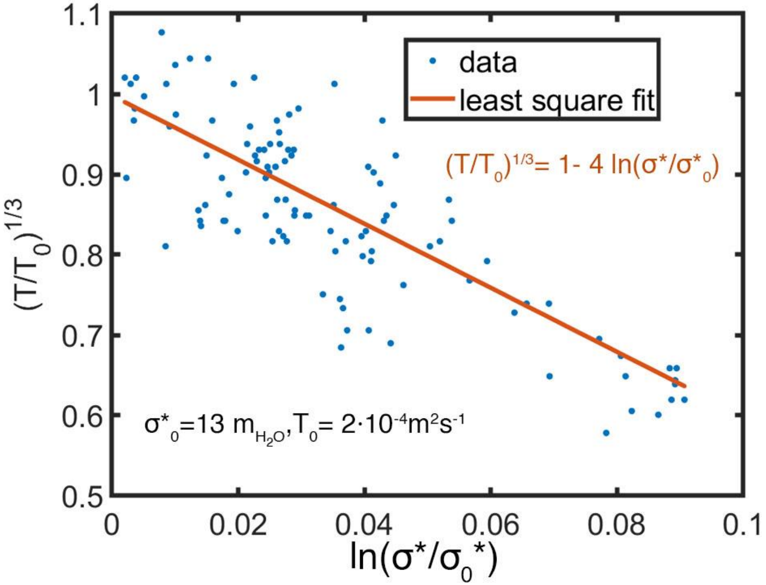
# Reversible changes controlled by hydraulic head

$$\sigma^* = \sigma - \alpha p$$

Walsh (1987) for a single fracture:

$$\left(\frac{T}{T_0}\right)^{\frac{1}{3}} = 1 - \frac{\sqrt{2}h}{a_0}\ln\left(\frac{\sigma^*}{\sigma_0^*}\right)$$

Transmissivity vs effective stress:

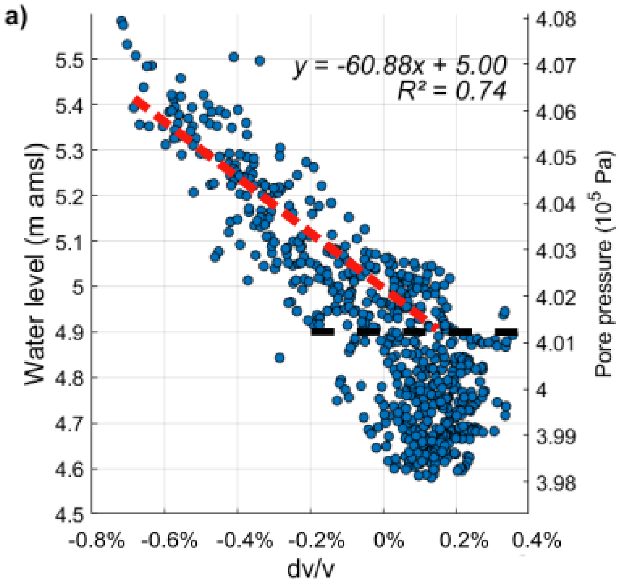


# Reversible changes controlled by effective pressure

Same site, different method

Relative seismic velocity $\frac{\delta v}{v} \propto \frac{\delta G}{G}$

Good correlation between water level and seismic velocity until a threshold is reached (crack closure?)

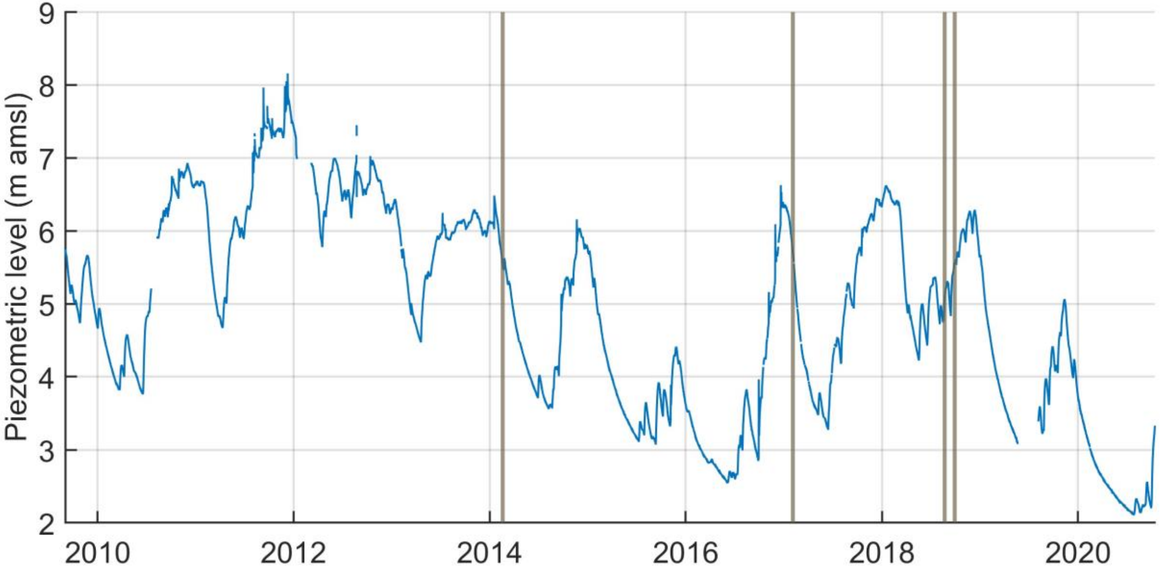



**B. Vittecoq, A. Burtin, and J. Fortin**

# Reversible changes controlled by effective pressure

Another site in Martinique: Grande Anse

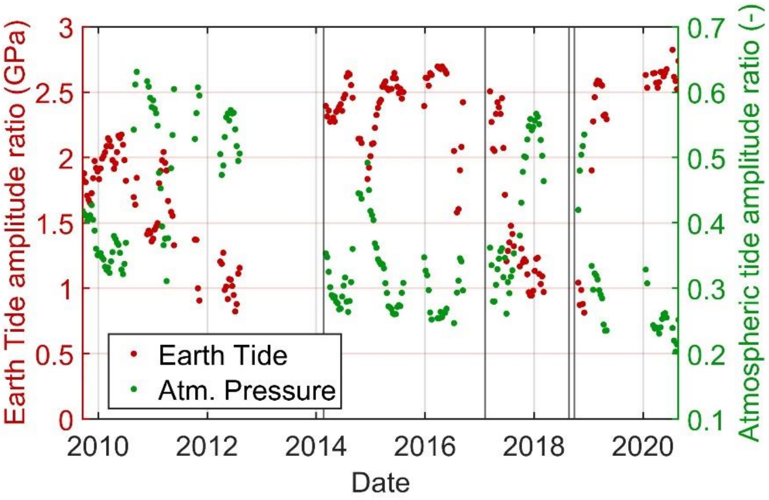
Large piezometric variations



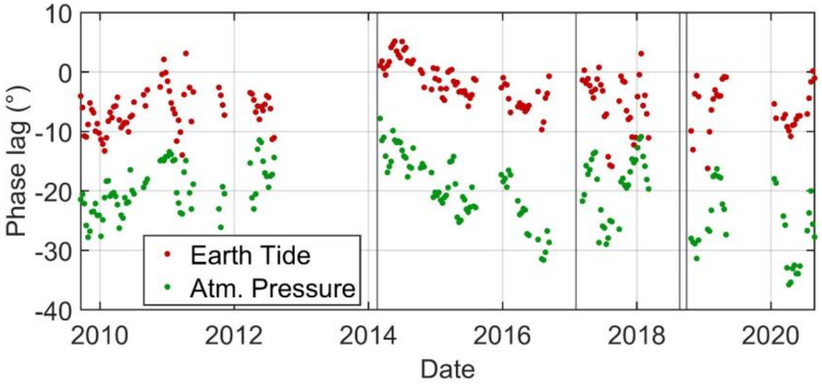
# Reversible changes controlled by effective pressure

Another site in Martinique: Grande Anse

Same workflow



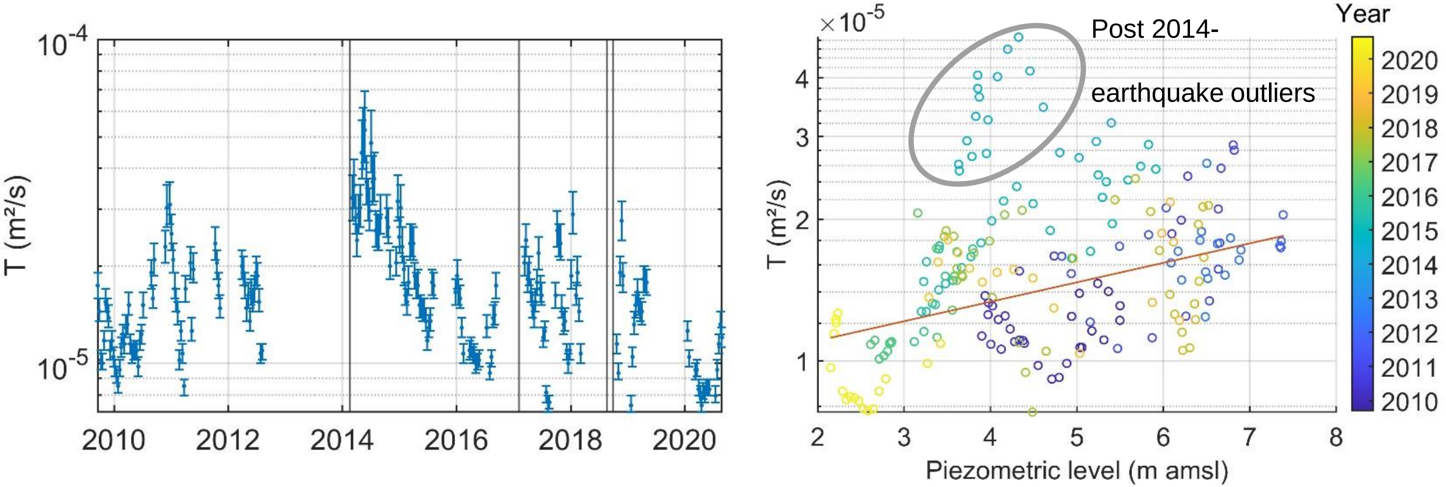

***Amplitude ratios between earth tidal strain (red) or atmospheric pressure (green) and piezometric level at the bi-diurnal frequencies.***




***Phase lags earth tidal strain (red) or atmospheric pressure (green) and piezometric level at the bi-diurnal frequencies. No clear correlation with piezometric level is noticeable.***

# Reversible changes controlled by effective pressure

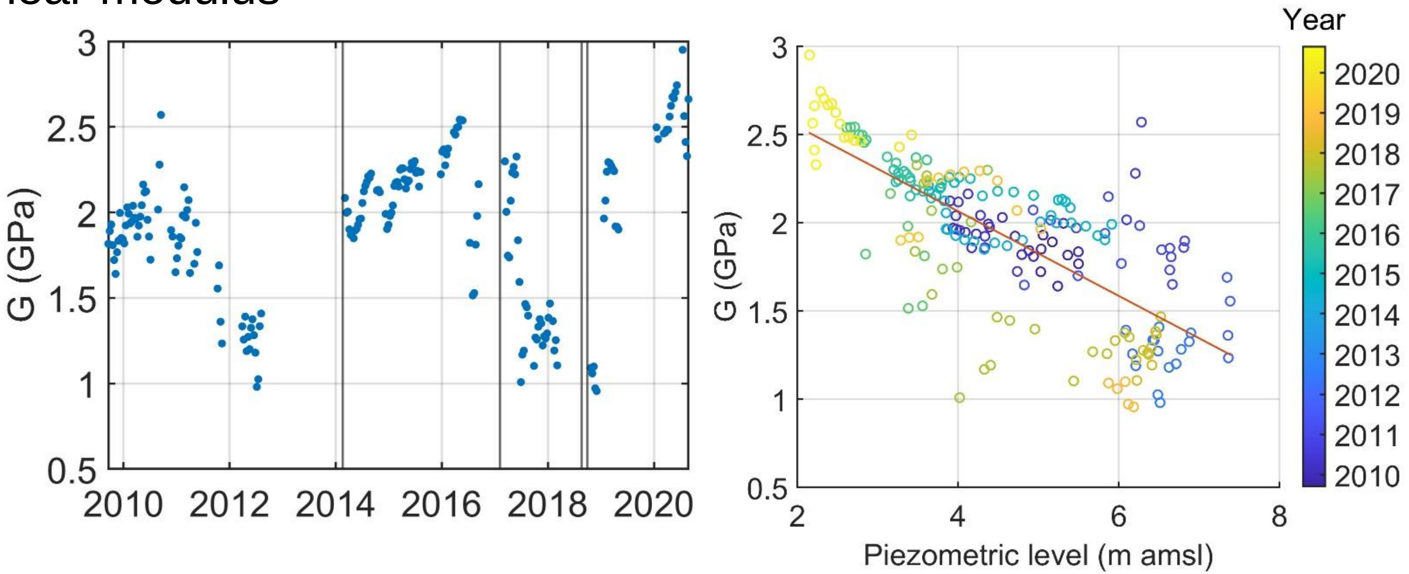
## Transmissivity




***Results of model inversion in terms of aquifer transmissivity T, as a function of time* (left) *or piezometric level* (right)*. Error bars correspond to the propagation of a 1° error on phase lag. Dot colors refer to the time of measurement.***

# Reversible changes controlled by effective pressure

Shear modulus



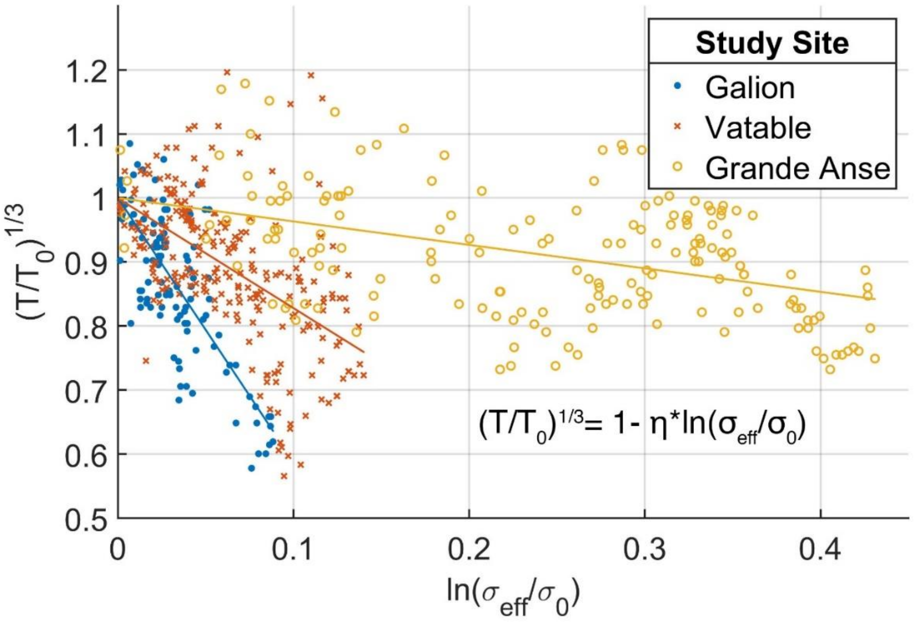

*Results of model inversion of Grande Anse aquifer shear modulus as a function of time* **(left)** *or piezometric level* **(right)**. *Dot colors refer to the time of measurement.*

# Conclusions

- Thanks to an **adapted theoretical framework & analytical models** we demonstrated and validated tidal analysis potential to yield **transmissivity** and **shear modulus** time series

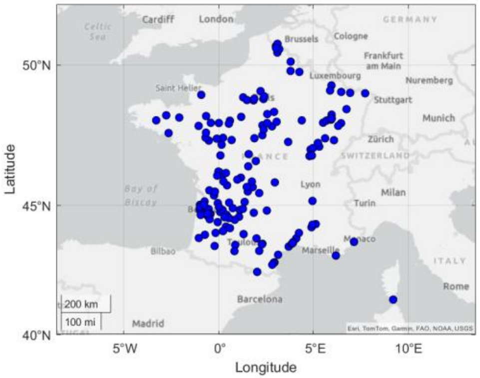
- **Significant variations** of hydrodynamic parameters were identified and **validated with pumping tests**

- The variations highlight **the high sensitivity of shallow fractured aquifer to stresses** (poromechanical or seismogenic), which vary depending on sites, probably beacause of different degrees of fracturation



# Perspectives:

- Despite regular assertions of the potential of tidal analysis in the literature & the extensive availability of tidally influenced piezometric data, it has never been systematized to larger databases




Map of the localization of the piezometers influenced by tidal signals at the 4 main frequencies in metropolitan France

All types of lithology & contexts (limestone/ granite/sand; confined/unconfined; coastal/ continental/mountain catchments)

- Depending on the wells, tidal analysis can yield **aquifer transmissivity**, **elastic moduli**, information about **aquifer vulnerability**, constrains on **pumping tests inversions**,…

# Read more:

JGR Solid Earth

RESEARCH ARTICLE

10.1029/2024JB028847

**Key Points:**

- The 15-years' time series of permeability and shear modulus of the aquifer is deduced from the analysis of solid earth and barometric tides
- Co-seismic irreversible changes of fractured aquifer permeability are induced by earthquakes dynamic shear stresses
- Interseismic permeability variations of the aquifer are controlled by pore pressure, that is, the hydraulic head

## Hydro-Mechanical Characterization of a Fractured Aquifer Using Groundwater Level Tidal Analysis: Effect of Pore Pressure and Seismic Dynamic Shear Stresses on Permeability Variations

**A. Thomas**[1,2], **J. Fortin**[1], **B. Vittecoq**[3], **H. Aochi**[1,4], **S. Violette**[1,5], **J. Maury**[4], **F. Lacquement**[4], and **A. Bitri**[4]

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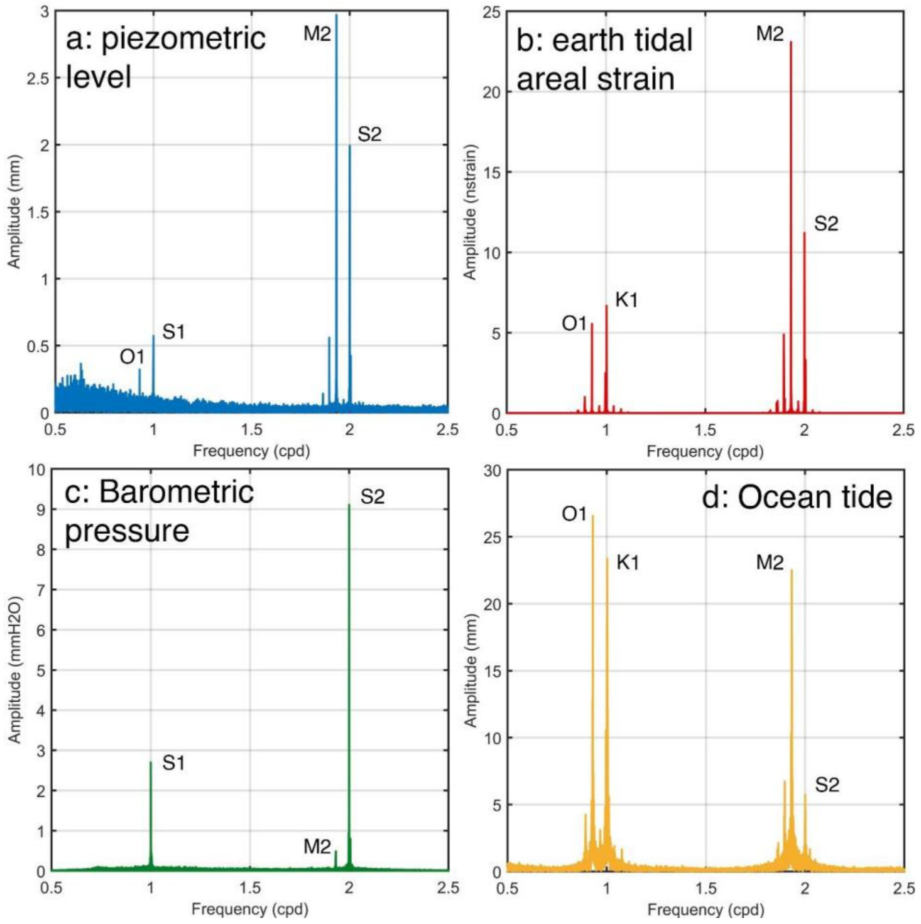
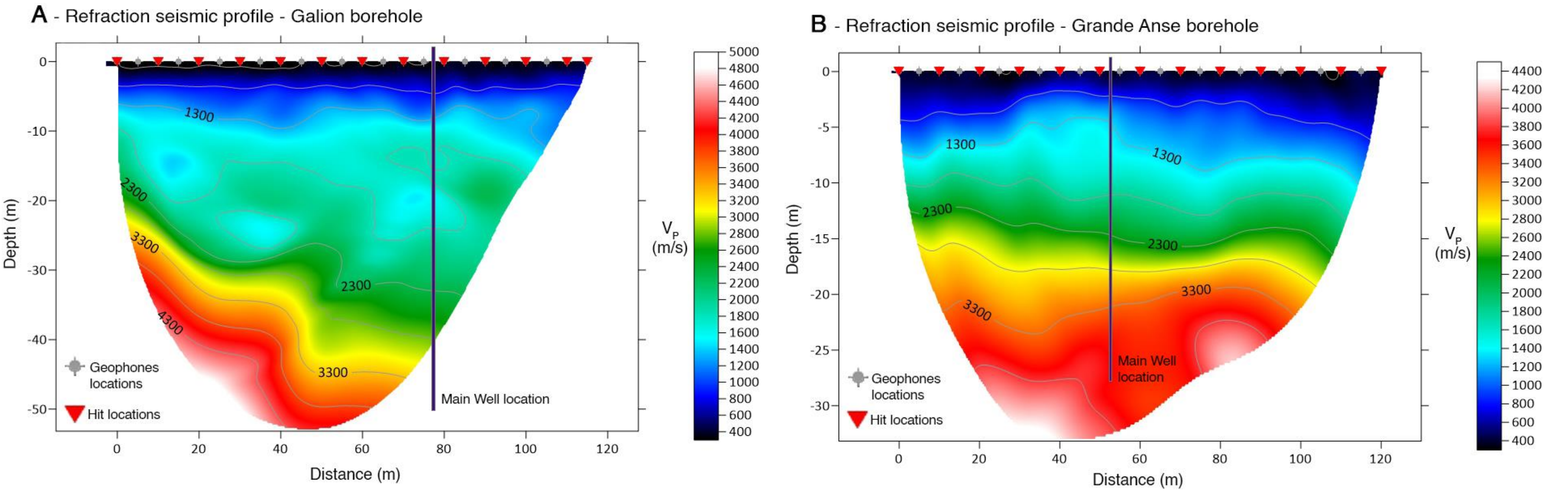
# Appendix

# Ocean tide?



a: piezometric level
M2
S2
S1
O1
Amplitude (mm)
Frequency (cpd)
b: earth tidal areal strain
M2
S2
K1
O1
Amplitude (nstrain)
Frequency (cpd)
c: Barometric pressure
S2
S1
M2
Amplitude (mmH2O)
Frequency (cpd)
d: Ocean tide
O1
K1
M2
S2
Amplitude (mm)
Frequency (cpd)

# Seismic refraction profiles




***Refraction seismic profiles ($V_p$) around: A the Galion borehole, B the Grande Anse borehole. Well location and depth are represented by thin dark blue rectangles. The studied aquifers are located: between -20 and -50m at the Galion and -14 and -25.5m at Grande Anse.***

***2300m/s -> 12GPa***

***3000m/s -> 20 GPa***