High resolution soil moisture monitoring: the potential of large-N seismology

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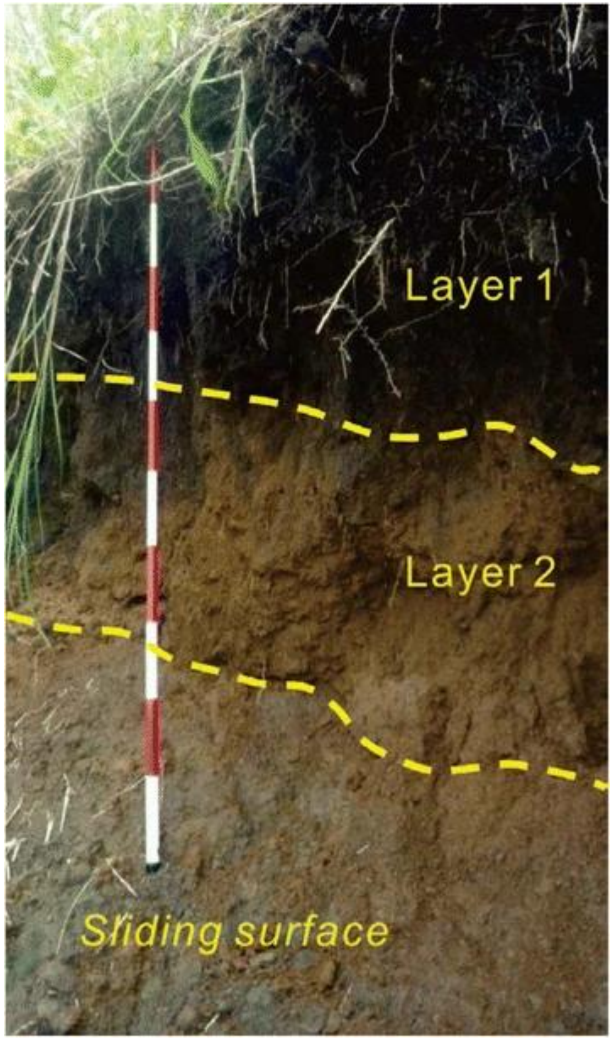
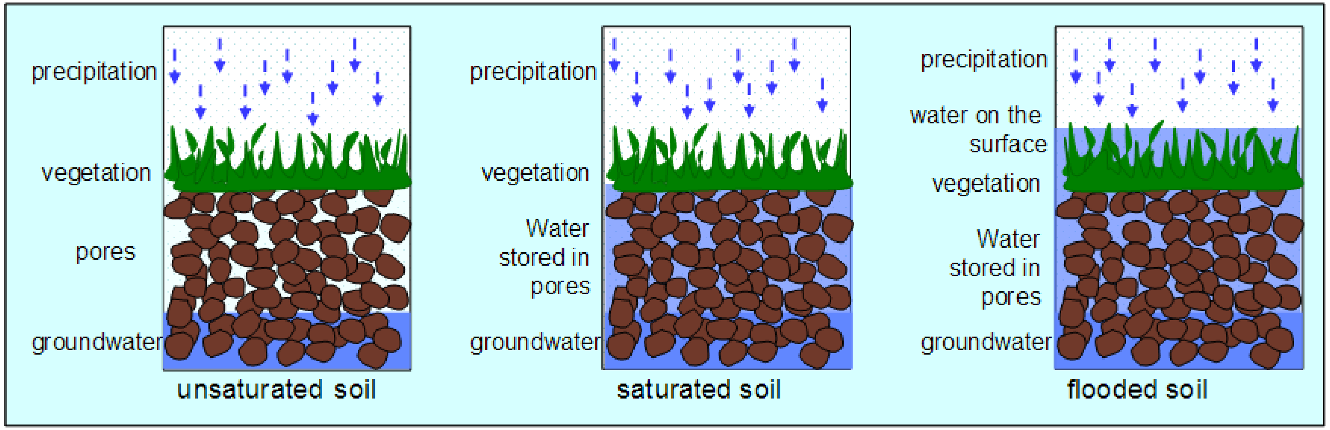
Water is key driver of soil property changes

Range of potential applications:

- Landslides
- Flooding
- **Agriculture**

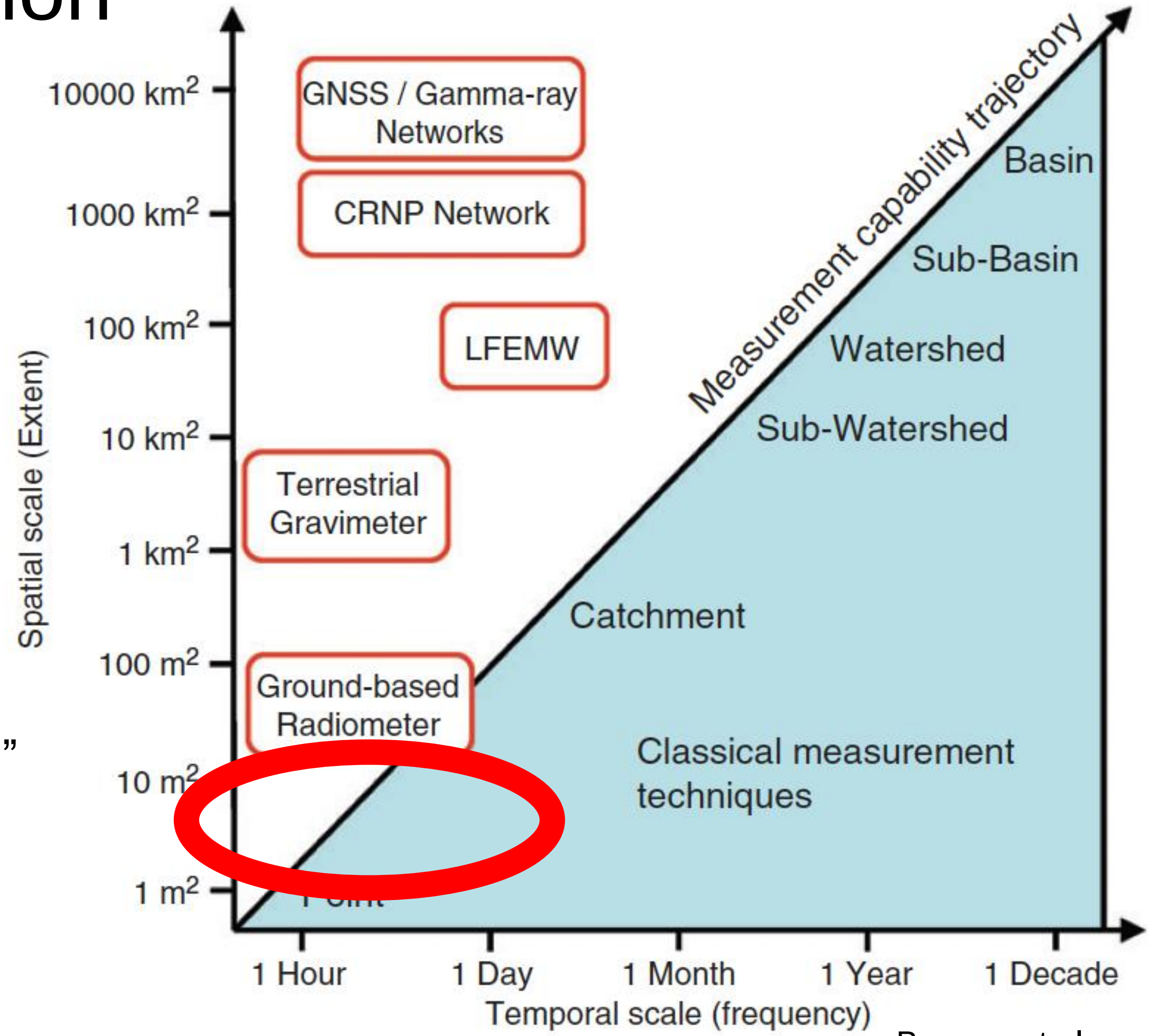




Trade-offs in resolution and cost

Method	Approx. Instrument Costs [€]
CRNP	10,000–25,000
GNSS	2000–12,000[1]
Radiometry	50,000–100,000
Gamma ray	3000–10,000[1]
Gravimetry	~250,000[4]; 50–90,000[5]
LFEMW	~3000

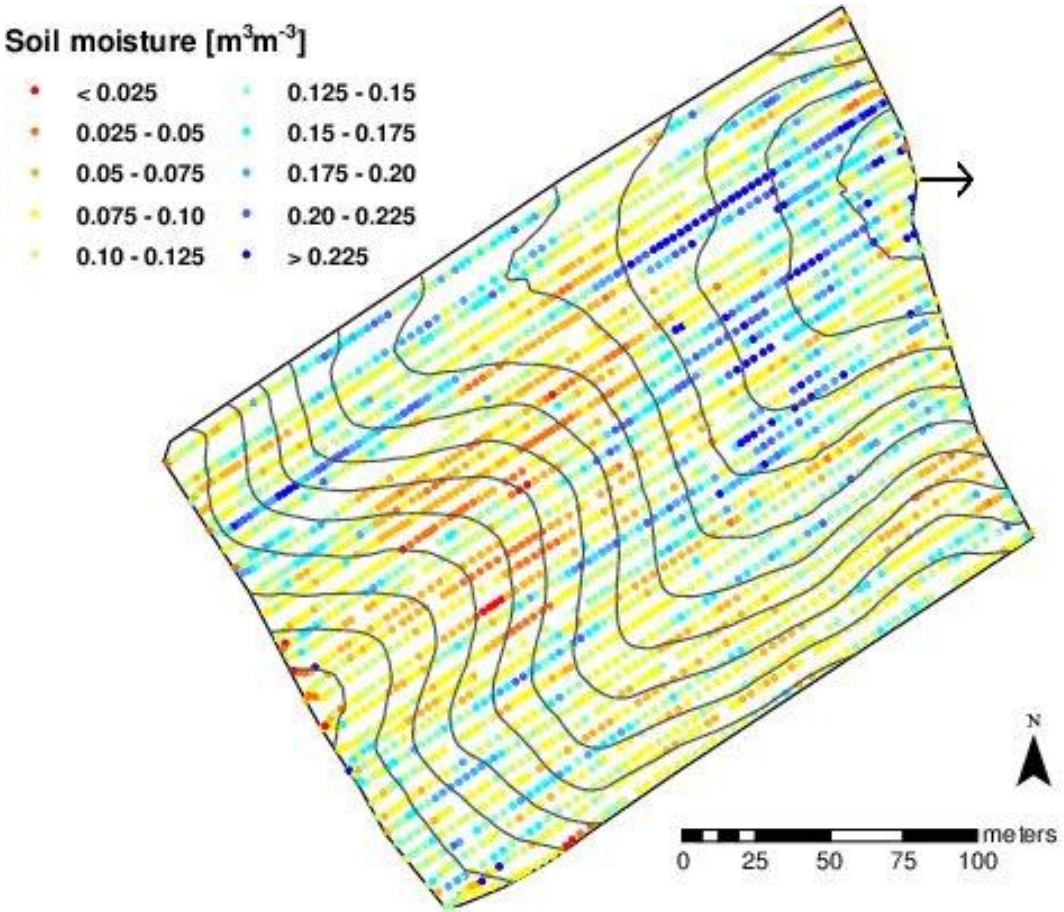
- There is a gap in coverage at “field” scales – 10s -100s of meters



Bogena et al.

Geophysical methods

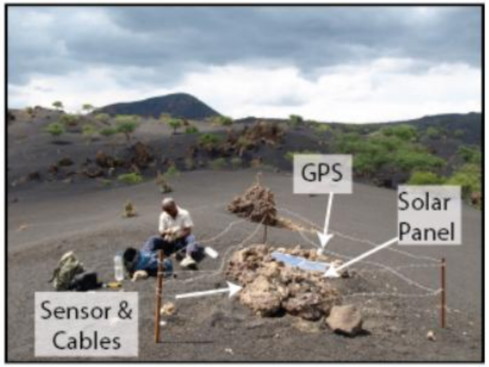
- Geophysical methods such as Ground Penetrating Radar or Electrical Resistivity Tomography can occupy this spatial gap
- However, conventional methods provide a “snapshot” image of a point in time
- We want to **monitor** changes over time at a high temporal resolution
- This requires a **continuous** signal – omnipresent **seismic ambient noise** provides this

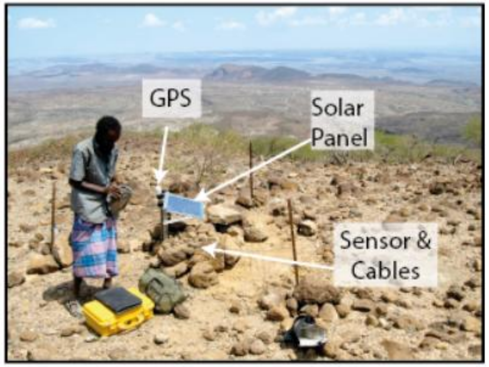


Minet et al., 2011

Instrumentation – Stryde nodal seismometers

- Broadband seismometers are expensive, cumbersome and target lower bandwidths





We need a lot of closely-spaced sensors to monitor shallow depths to account for the **attenuation** at high frequencies

- For large-N studies we use a cheap **node** sensor

Advantages of nodes for agriculture

- Self-contained and battery powered, no need for external cabling or solar panels
- No specialist knowledge required to deploy or retrieve, can be scheduled around harvesting
- Non-intrusive – no excavation
- Redundancy through large numbers, important where sensors may be damaged or lost

Case Study – Crichton Royal Farm, Dumfries

- Located in south-west Scotland, our study site hosts a UK-CEH environmental monitoring station recording soil moisture and temperature profiles along with meteorological data

Sensor deployment

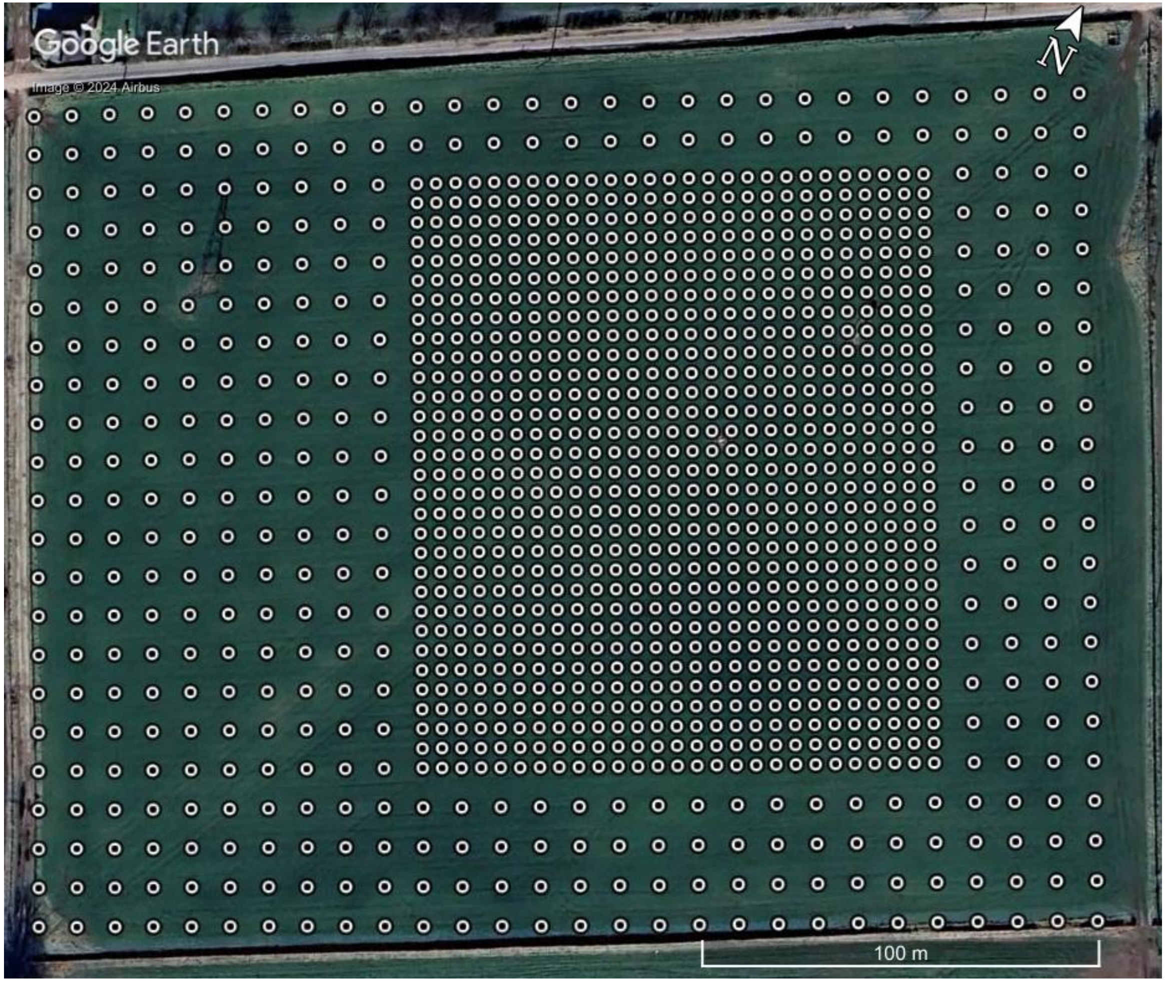
- Nodes with 5m – 10m spacing

- 1230 vertical component nodes in array in total

- ~4 days to deploy, 2 to retrieve

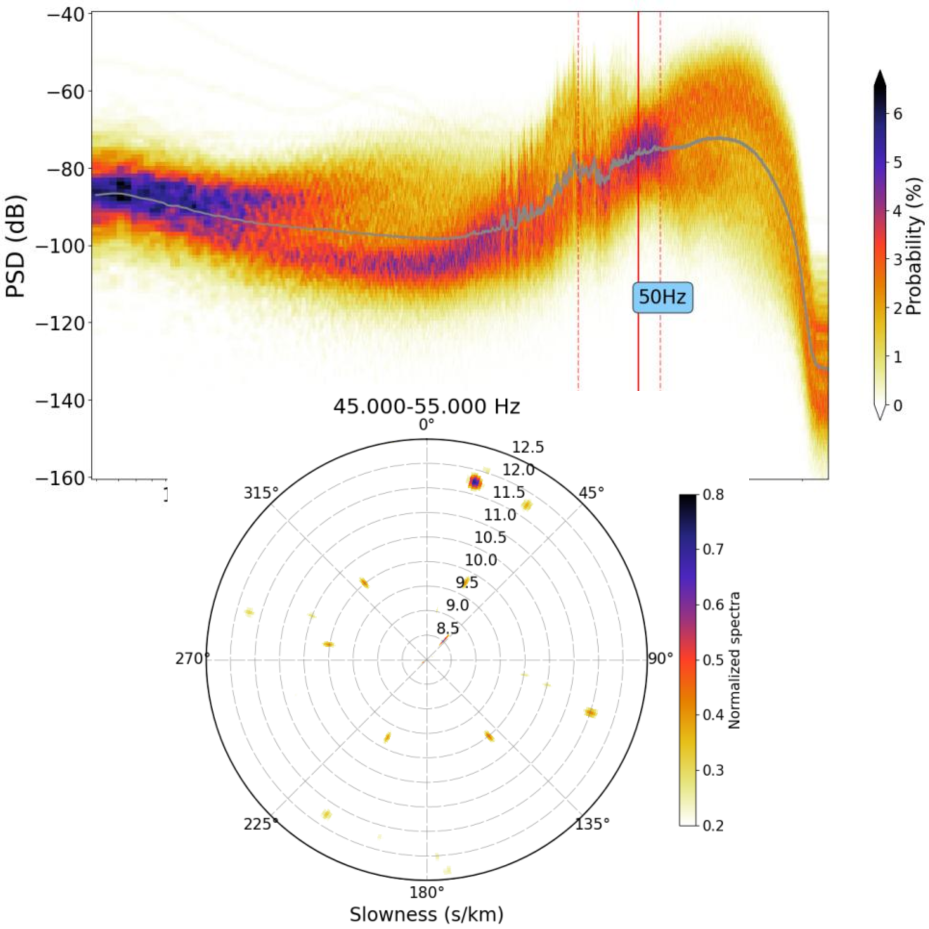
- 28 days recording time

- 6TB of data



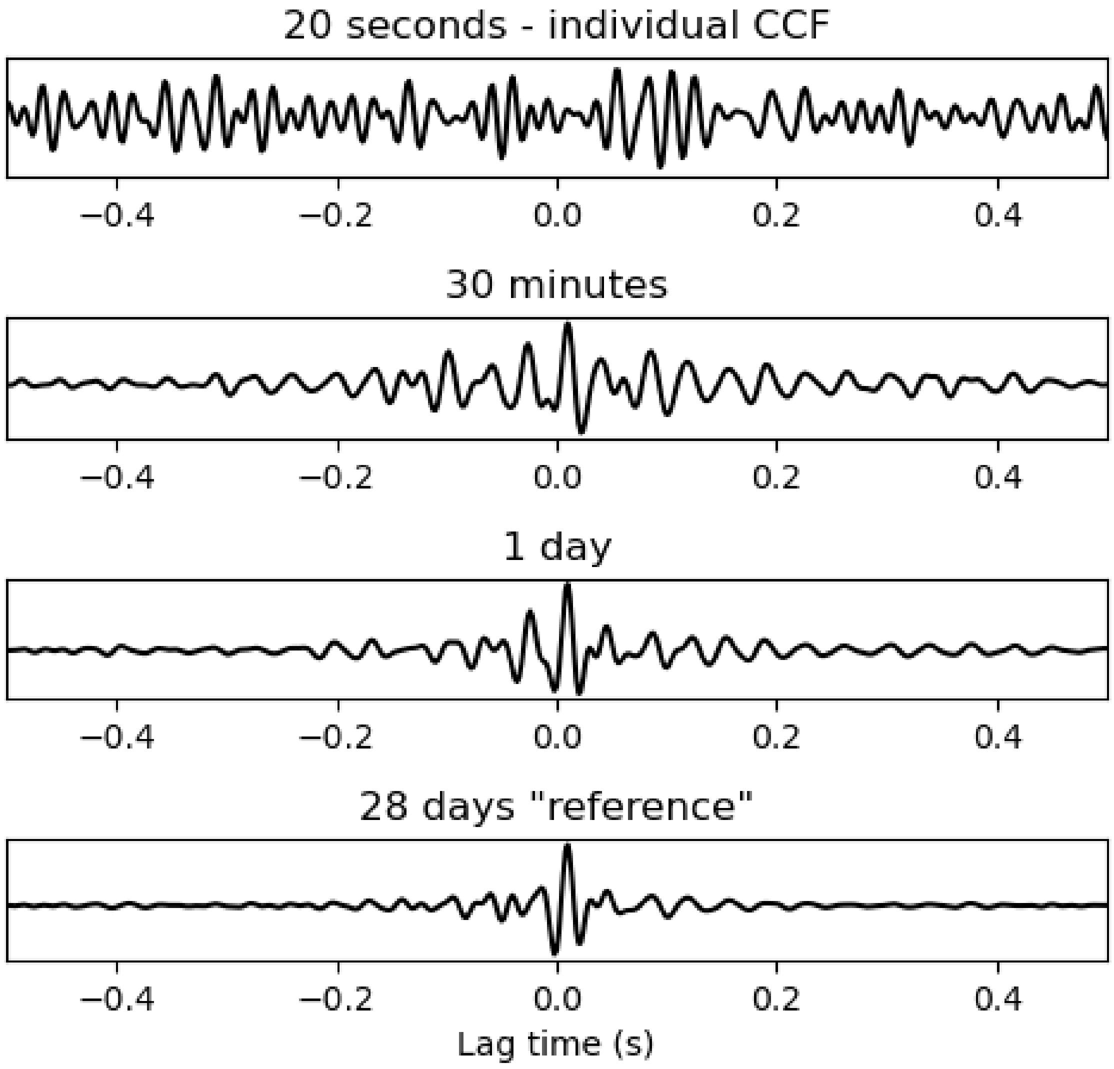
What noise sources do we see?

- Strong continuous noise signal ~50Hz



Stacking for the Green's Function

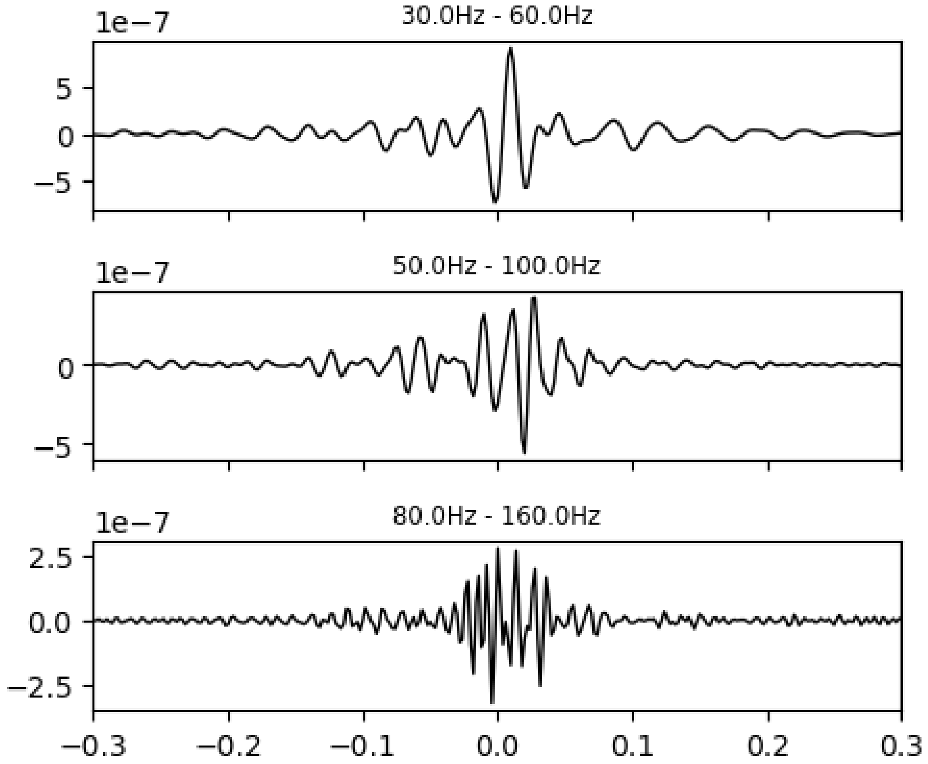
- Stacking the cross-correlations allows us to improve signal-to-noise ratio and produce the Green's Function
- Equivalent to the signal recorded if a source was at one station and the receiver at the other
- For our study, a 30 minute stack provides good signal-to-noise.
- We compare a short-term CCF to the long-term reference to detect variations in velocity

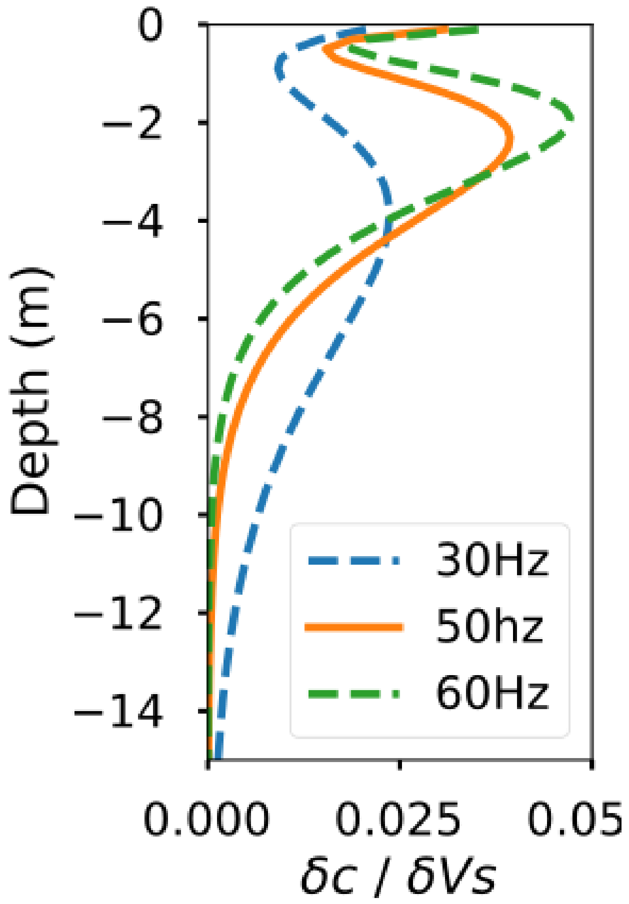


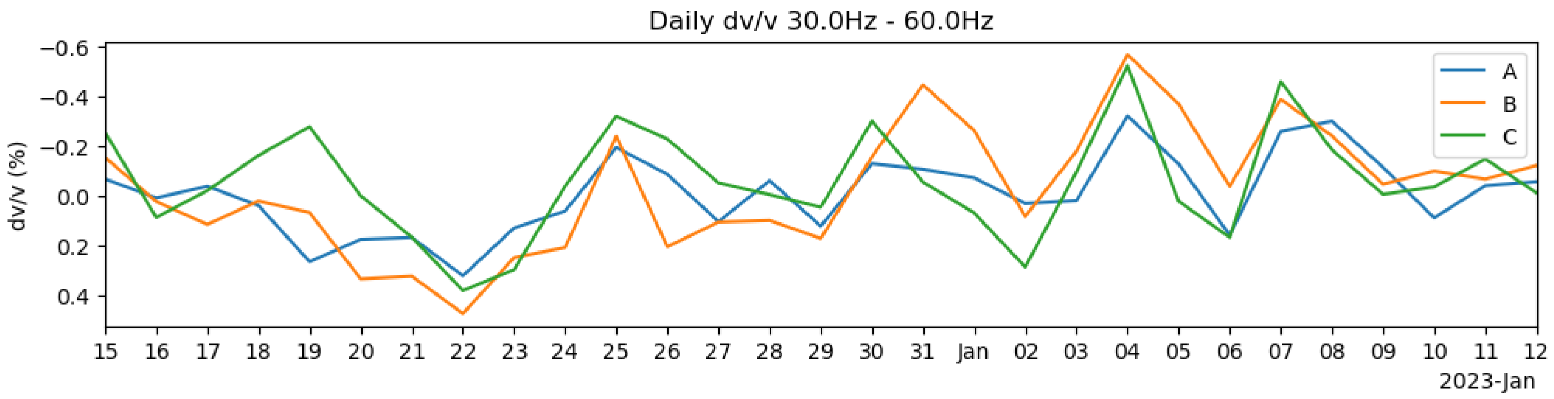
Depth depends on frequency

- We can view different frequencies to investigate different depths

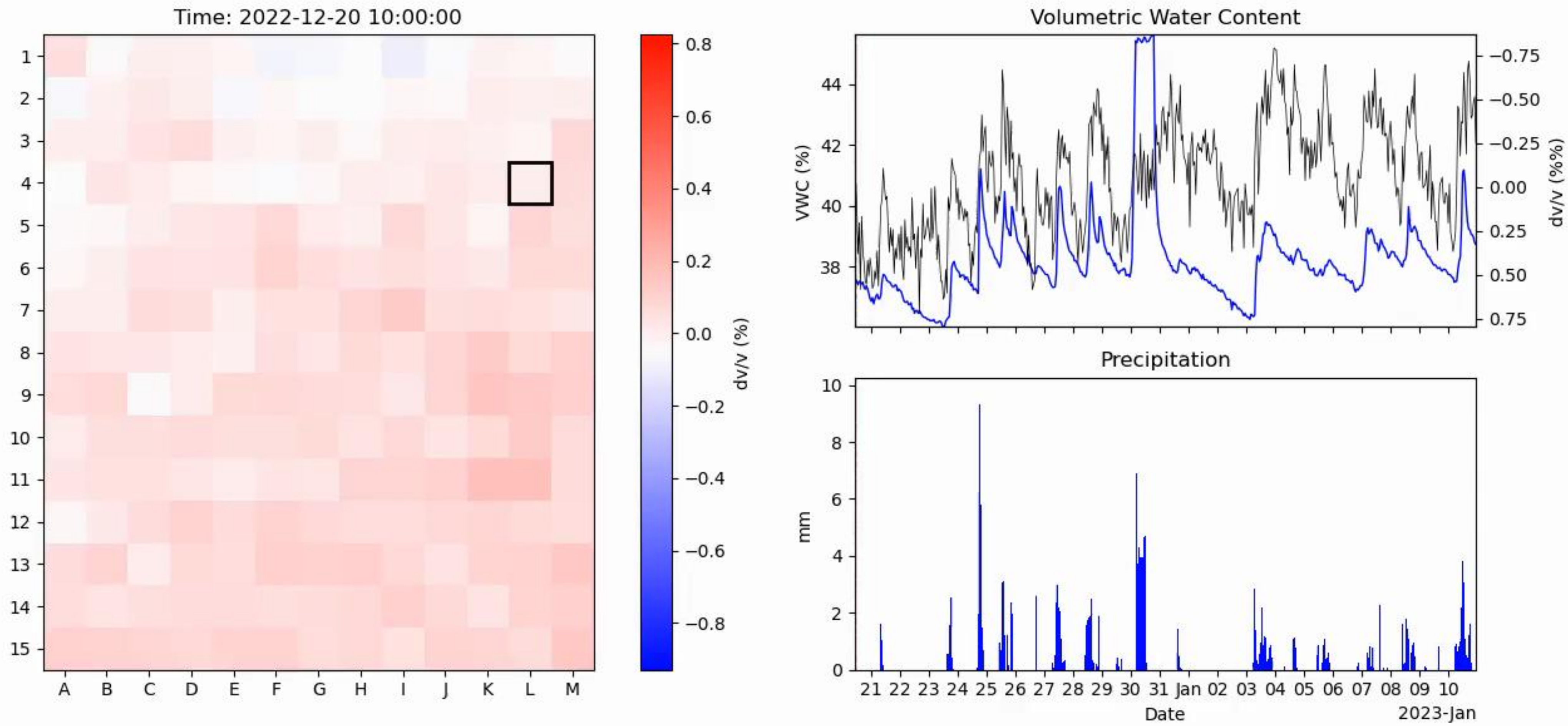
- Our data have resolution in the top few metres



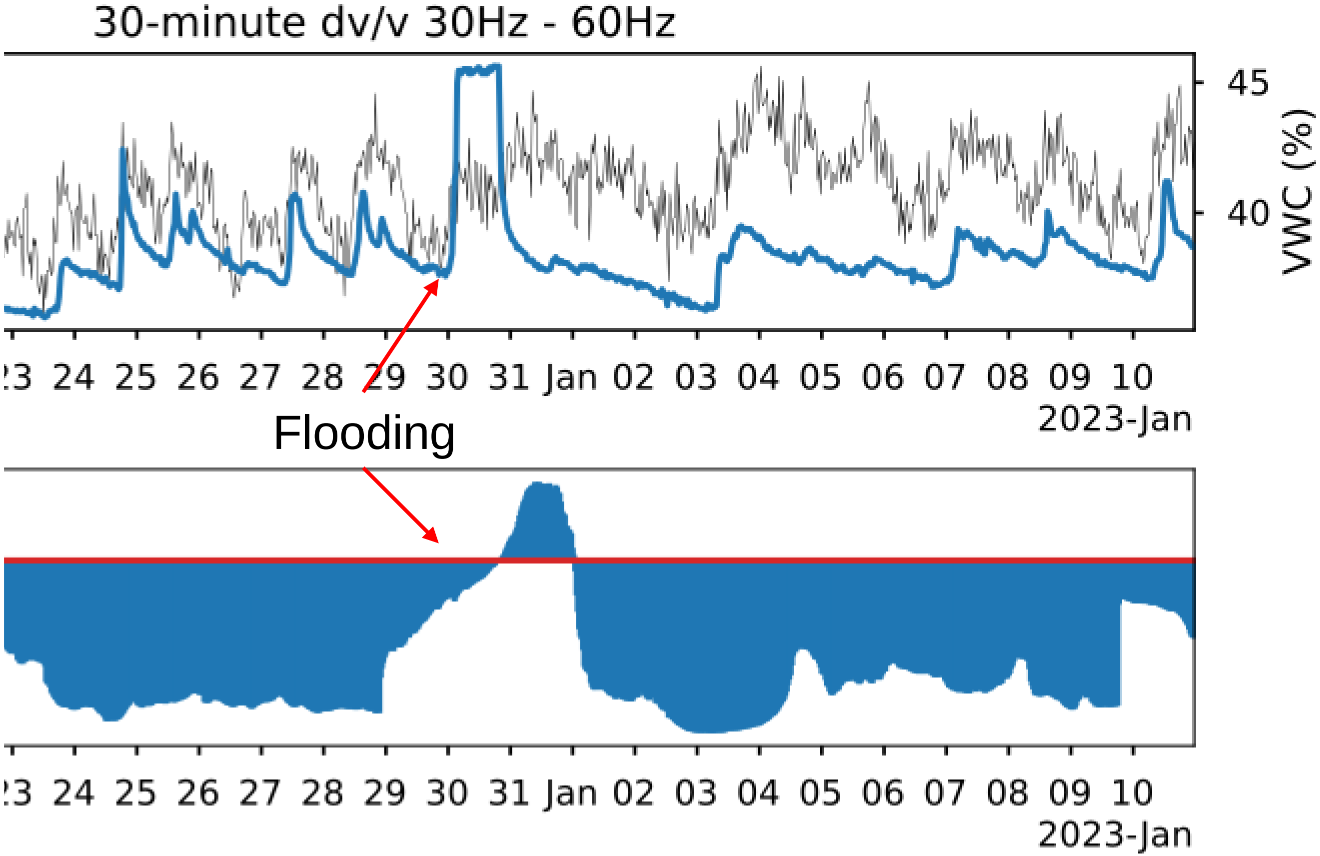




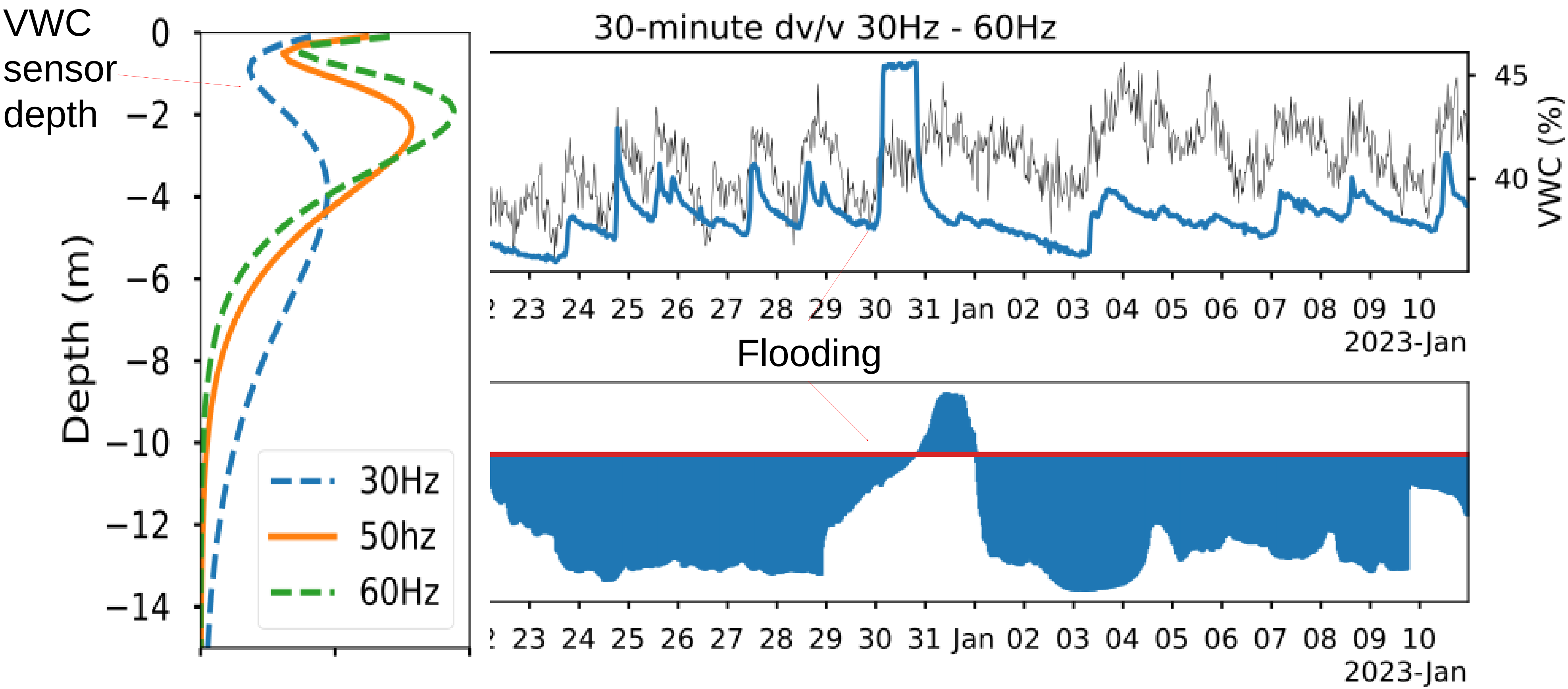
- We stack data across 9-station sub-arrays
- Daily stacks show consistent velocity changes across the field



Time: 2022-12-20 10:00:00
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
A B C D E F G H I J K L M
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
dv/v (%)
Volumetric Water Content
VWC (%)
44
42
40
38
−0.75
−0.50
−0.25
0.00
0.25
0.50
0.75
dv/v (%%)
Precipitation
mm
10
8
6
4
2
0
21 22 23 24 25 26 27 28 29 30 31 Jan 02 03 04 05 06 07 08 09 10
Date
2023-Jan

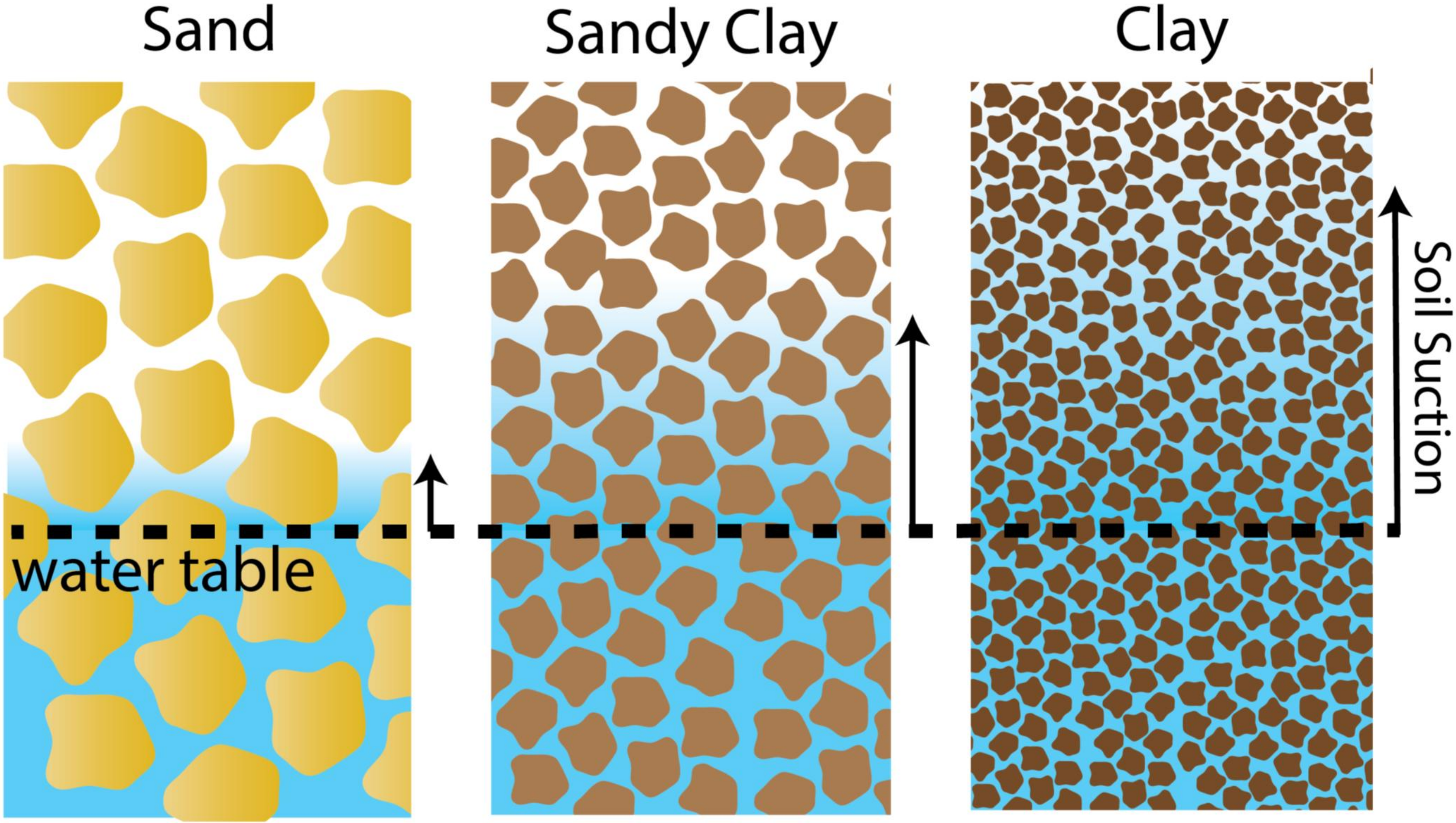


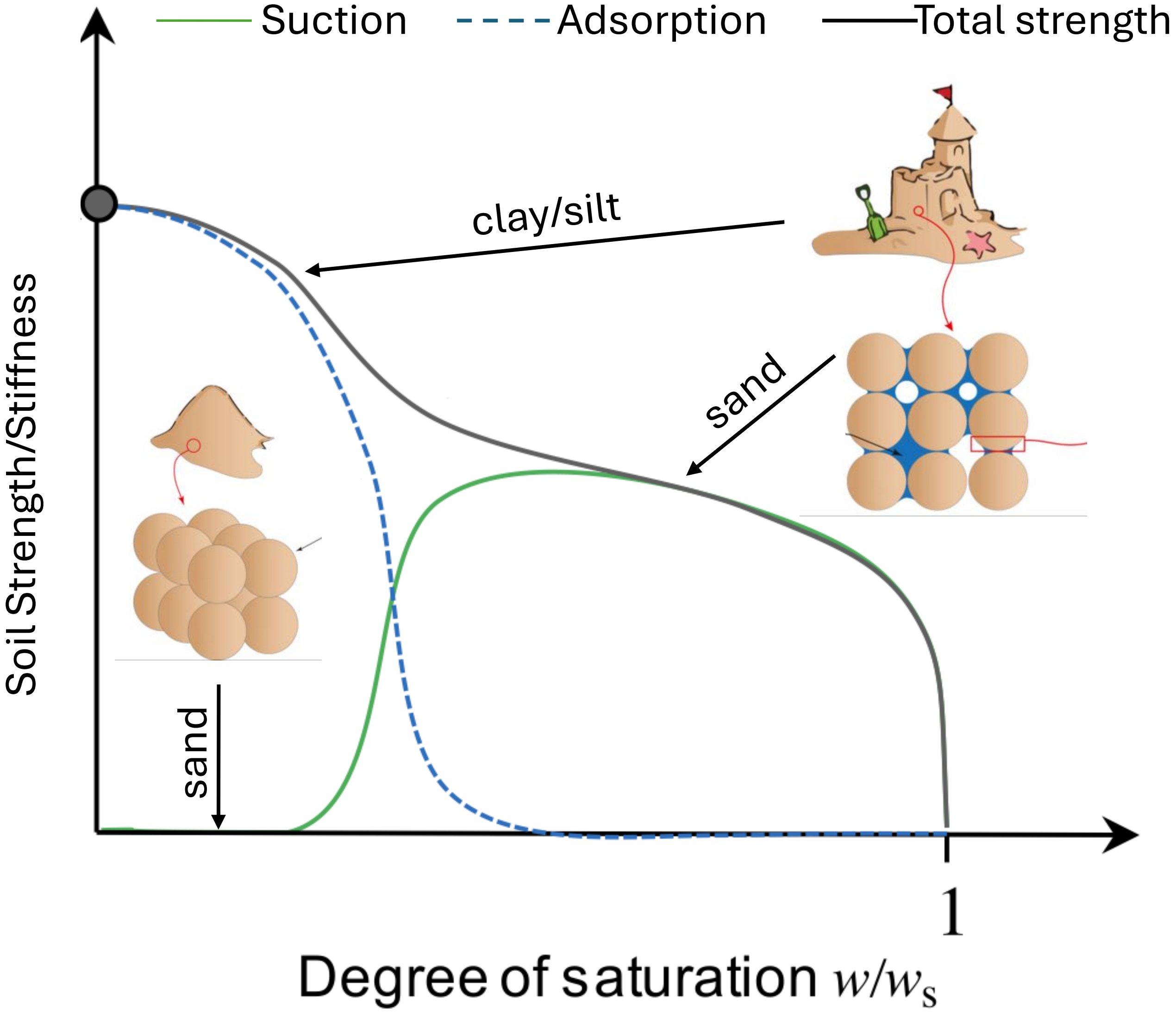
- Volumetric Water Content generally correlates with relative seismic velocity
- r ~ -0.75

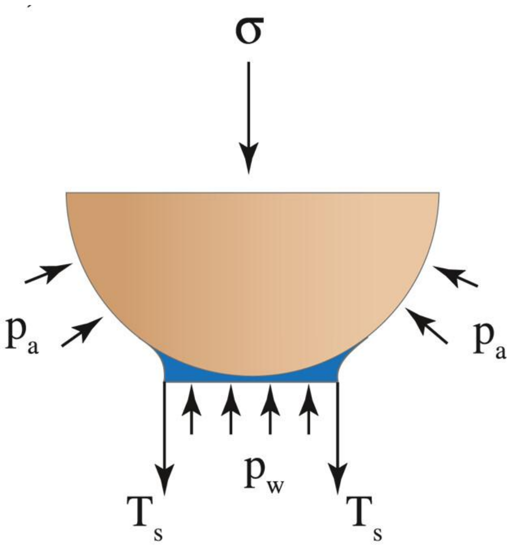


- **Hypothesis:** that the deeper soil reaches *saturation* ~ 1 day early

A possible flood precursor?


Sand
Sandy Clay
Clay
water table
Soil Suction

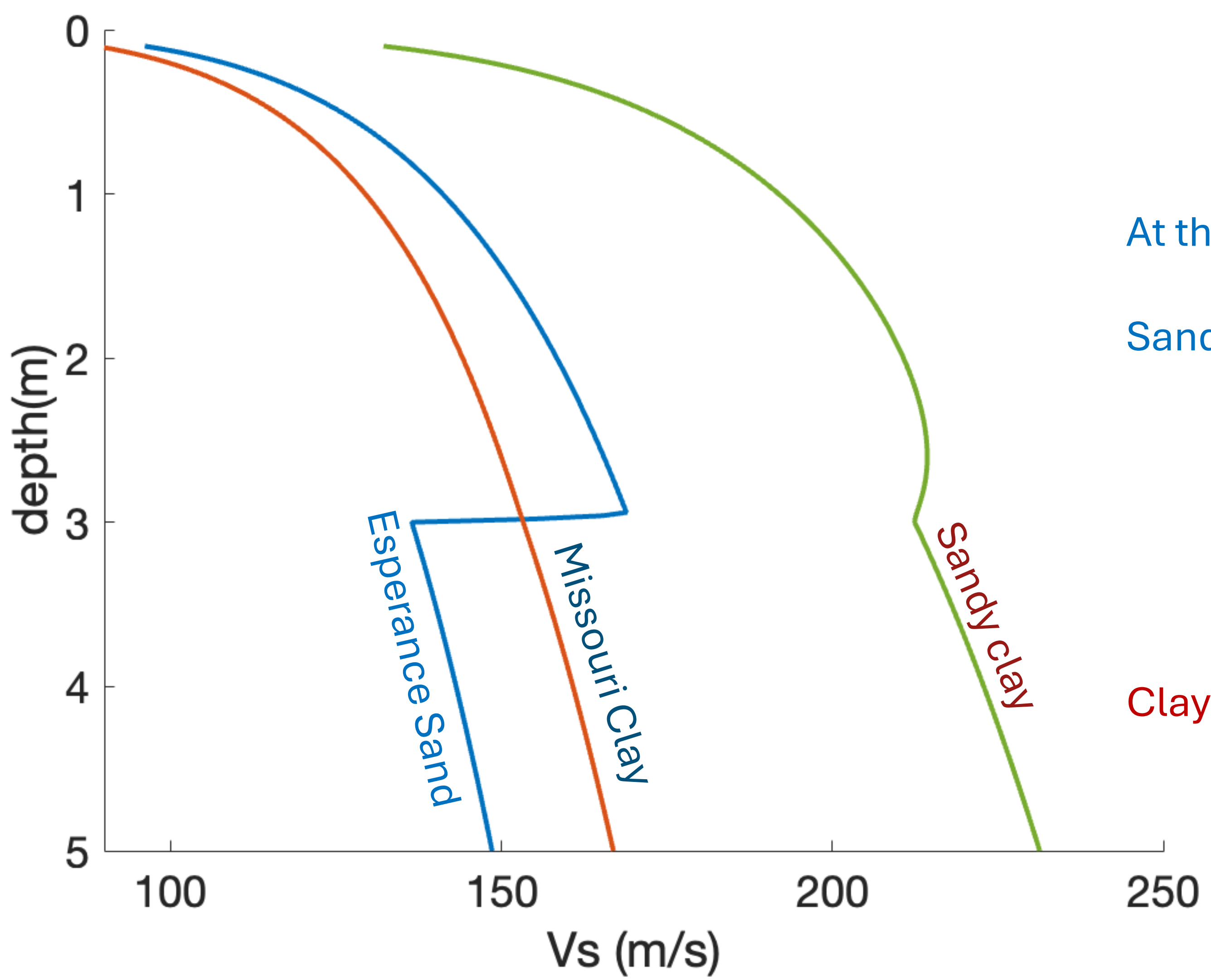




- = Overburden stress
- P_w/P_a = Water/air pressure
- T_s = Capillary tension

Zhang & Lu, 2020

Solazzi et al., 2021



$$V_S = \sqrt{\left(\frac{\mu}{\rho}\right)}$$

At the water table:

Sand: Density ↑

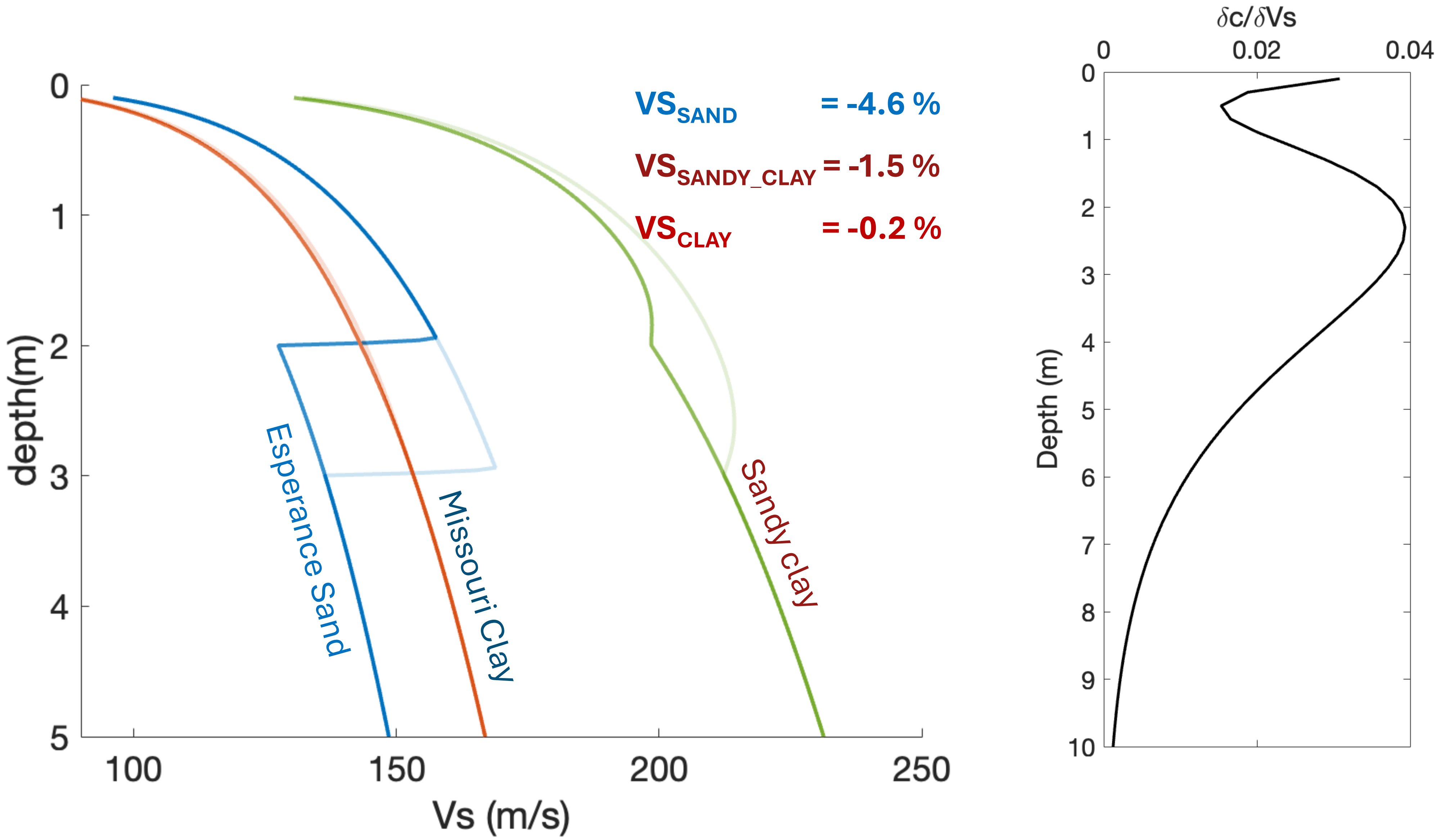
Shear modulus ↓

Velocity decreases ↓

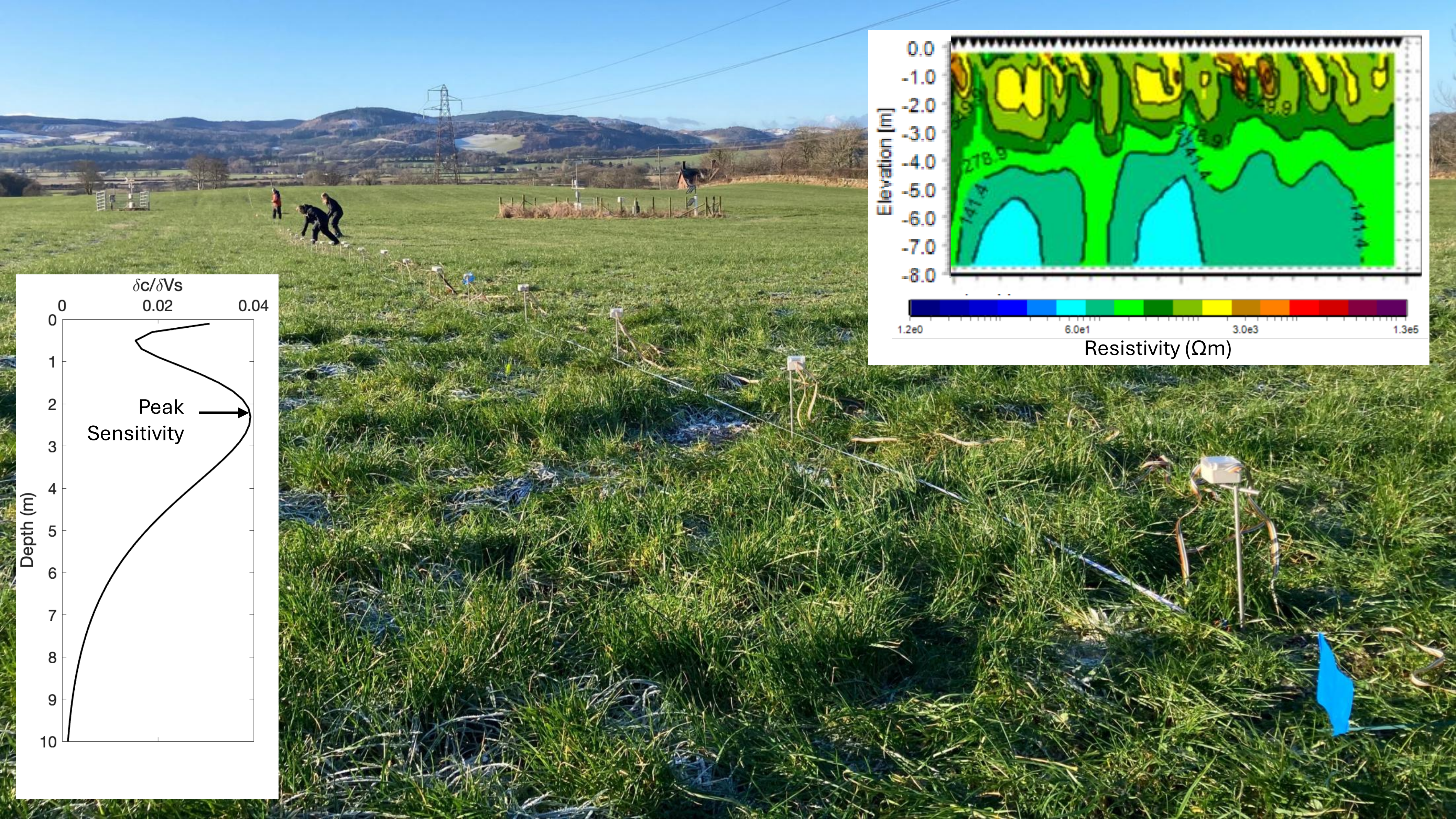
Clay: Density →

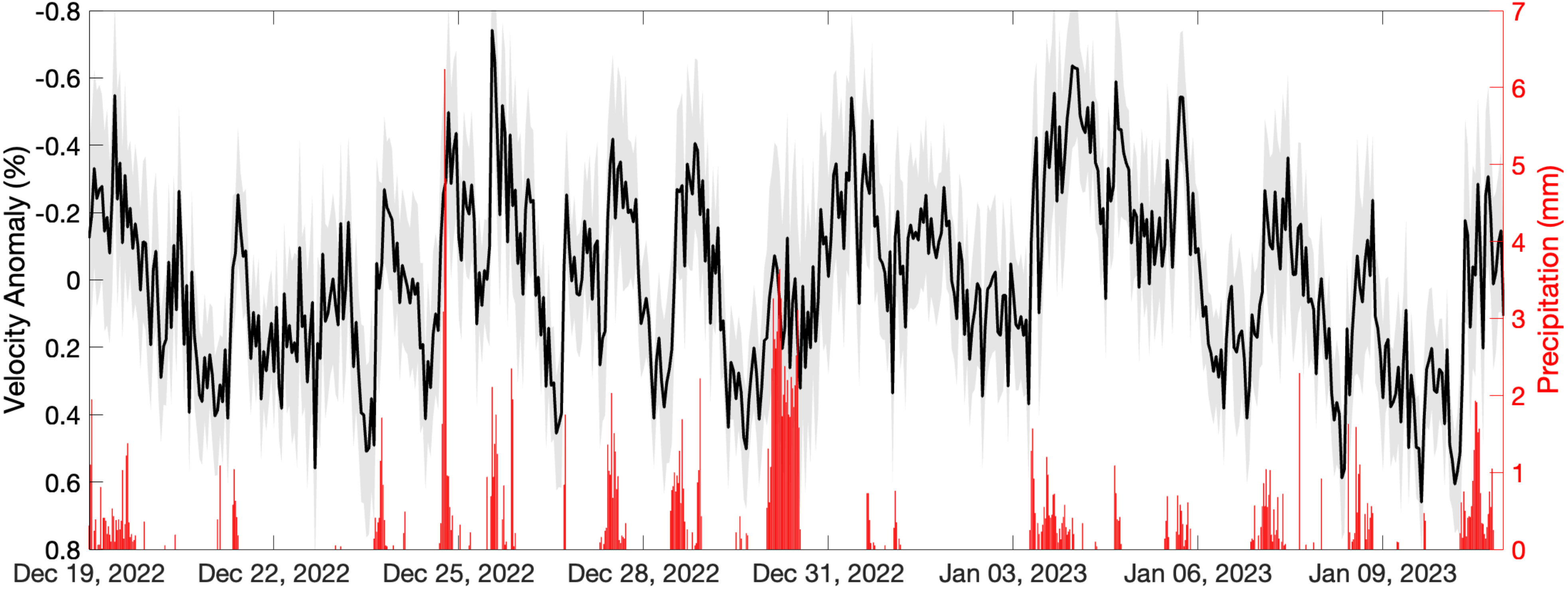
Shear modulus →

No change in velocity →



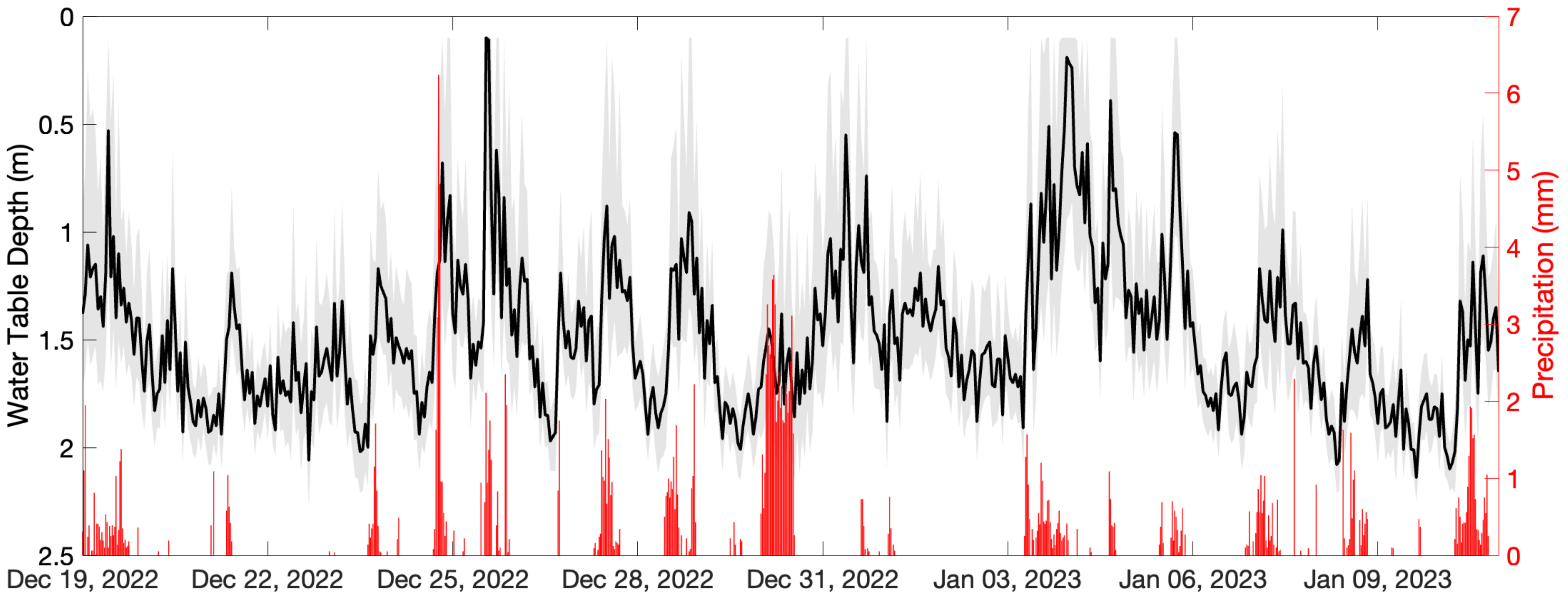
0
1
2
3
4
5
depth(m)
100
150
200
250
Vs (m/s)
VS_{SAND} = -4.6 %
VS_{SANDY_CLAY} = -1.5 %
VS_{CLAY} = -0.2 %
Esperance Sand
Missouri Clay
Sandy clay
$\delta c/\delta Vs$
0
0.02
0.04
Depth (m)
0
1
2
3
4
5
6
7
8
9
10


δc/δVs
0
0.02
0.04
Depth (m)
0
1
2
3
4
5
6
7
8
9
10
Peak Sensitivity
Elevation [m]
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
-7.0
-8.0
278.9
141.4
1.2e0
6.0e1
3.0e3
1.3e5
Resistivity (Ωm)



Assumptions

- Sandy Clay soil type
- Not a bad assumption, but real soil composition unconstrained.
- 0 % velocity anomaly = 1.8 m water table depth
- This is plausible, but unconstrained



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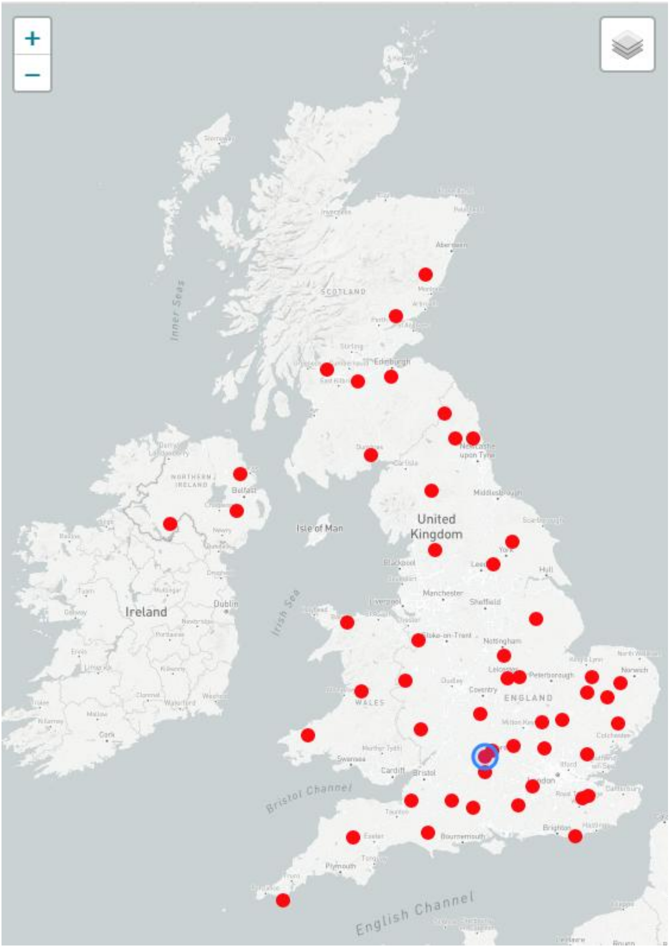
Future work

Our pilot study has shown the approach is valid and fills a gap in current soil monitoring methods

We would like to repeat the study at other sites across the UK (and beyond?)

To do:

- Calibration of velocity variation with water content
- Lab constraints on soil properties
- Test sensitivity at different frequencies (depths)



Conclusions and Acknowledgements

- Non-intrusive monitoring of subsurface changes in the CZ is possible with ambient noise and nodal seismometers
- Dense nodal arrays are quick to deploy at scale
- In a pilot study, we show a correlation between seismic velocity and changes in soil moisture with 30-minute temporal and 10 metre spatial resolutions
- This offers new possibilities for high-resolution studies at local scales – important for understanding agriculture, flooding, landslides...
- Scaling up becomes a “big data” challenge!