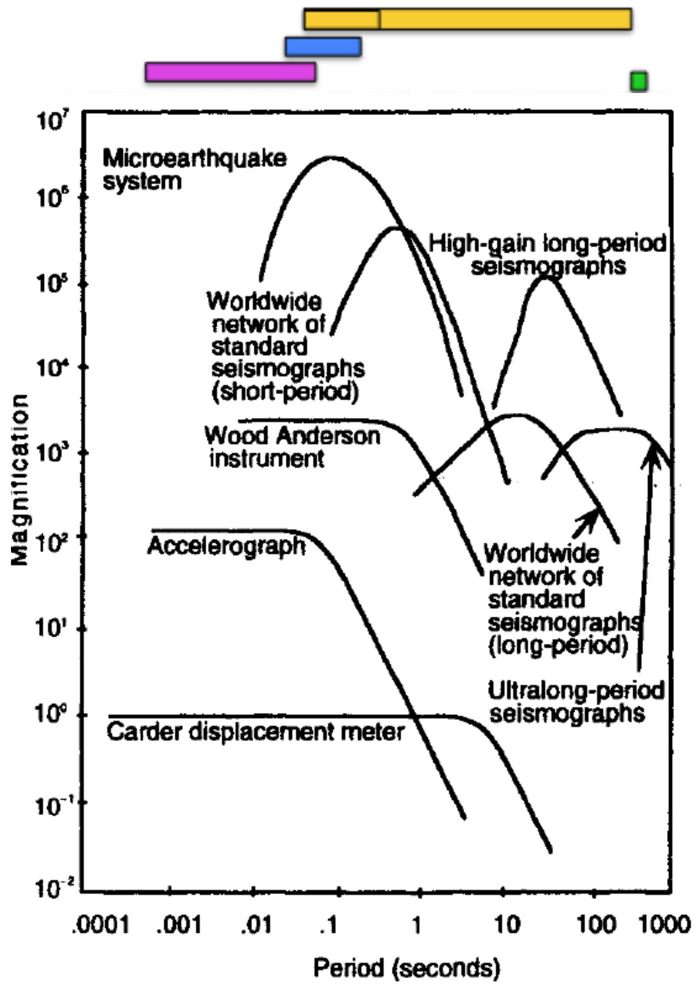
Using Low-frequency Fiber-optic DAS for Slow Deformation and Geomechanical Monitoring

Verónica Rodríguez Tribaldos

(and many collaborators)

DAS Virtual Workshop and Tutorial
August 17th, 2020

DAS: Much More than a Broadband Seismic Array

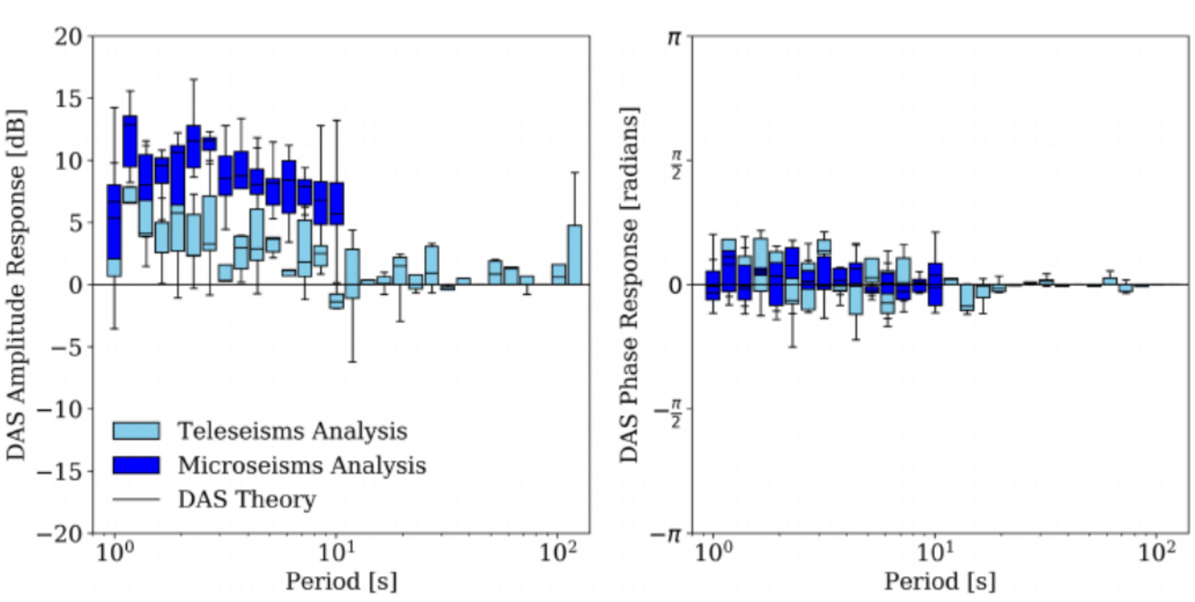


Lay and Wallace (1995)
Lindsey and Martin (2018)

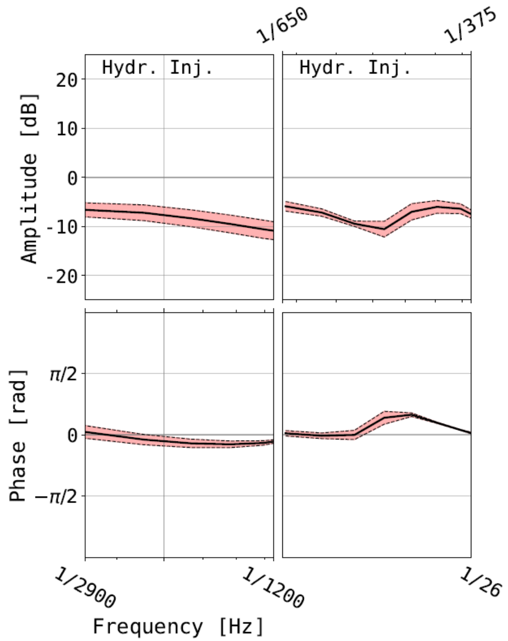
DAS is a broadband sensor commonly used for seismological applications

- Active seismic exploration (e.g. VSP) - f > 20 Hz
- Traffic noise interferometry - f ~ 5-30 Hz
- Earthquake detection - f < 1Hz
- Hydraulic tests, long-term deformation – periods > 100 s

DAS response is flat at low frequencies → we can potentially measure near-DC strain



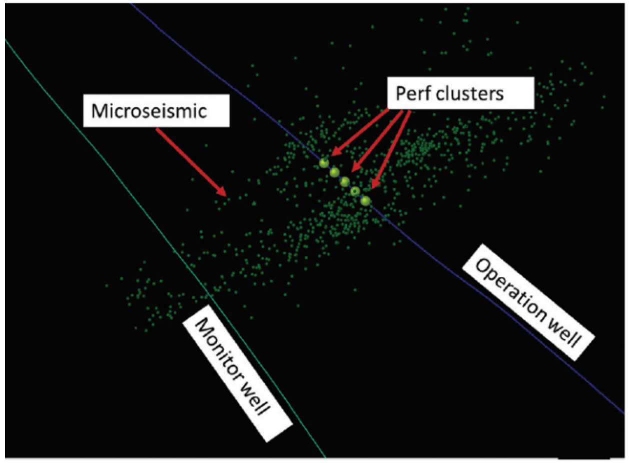
Lindsey et al. (2020)



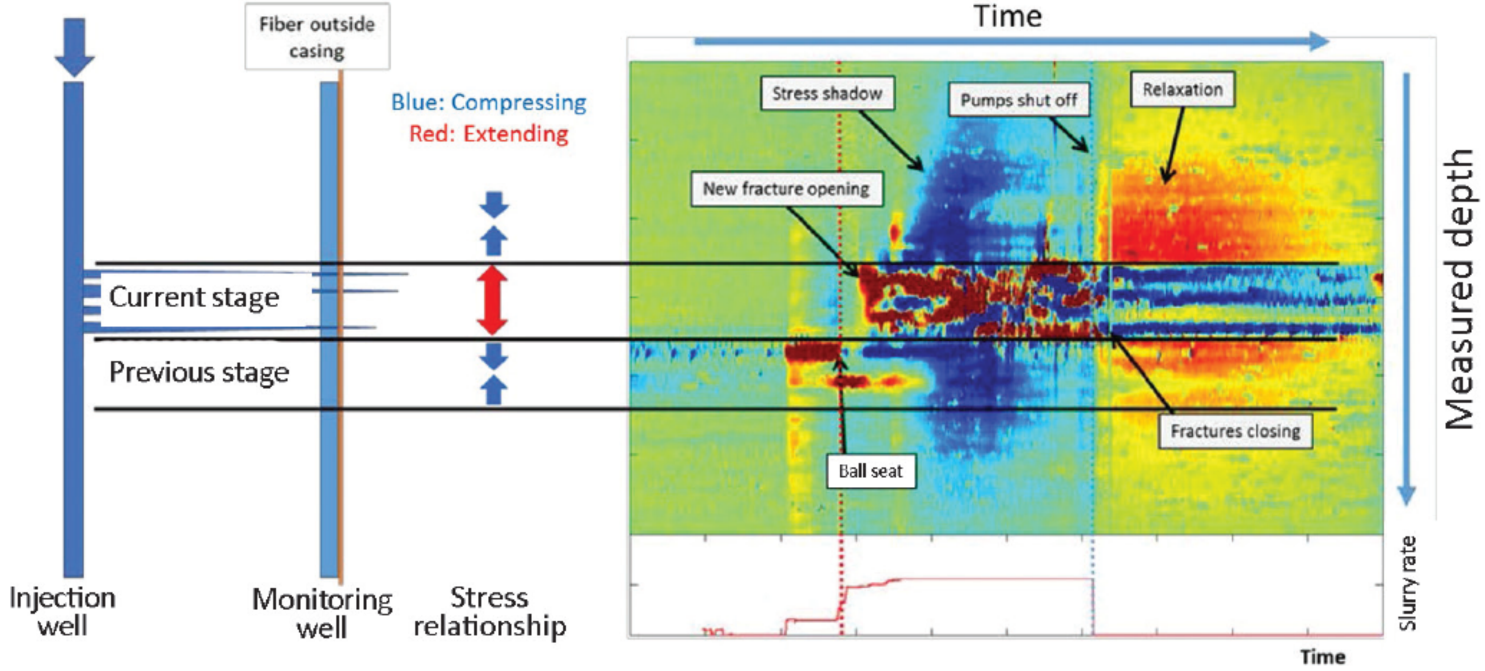
Paitz et al. (2020), *under review*

Applications of Ultra Low Frequency DAS Analysis

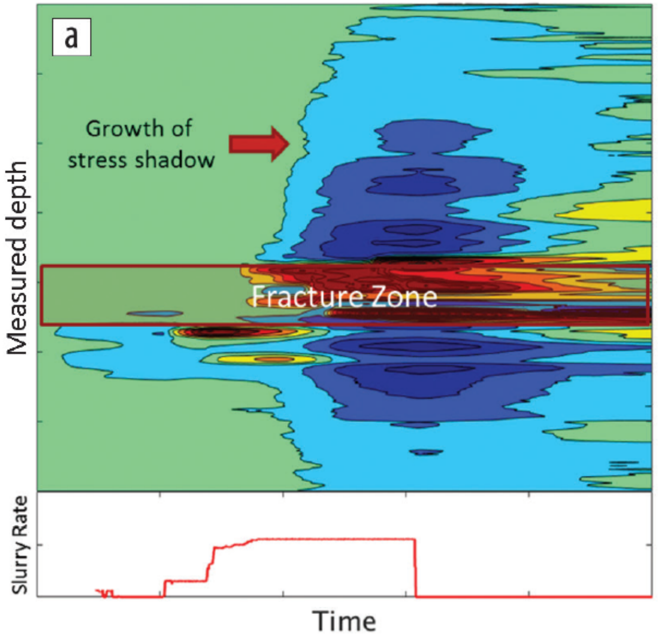
- **Hydraulic fracture geometry characterization** – *Jin and Roy (2017), The Leading Edge*
  - **Experiment:** DAS in monitoring wells during stimulation of an adjacent well
  - **Acquisition parameters:** spatial sampling of 1 m, gauge of 5 m, sampling frequency of 10 kHz
  - **Processing:** downsampling (1s) followed by median removal and low-frequency filtering (0.05 Hz)



Observations: fracture dynamics (opening/closure), stress shadow creation and relaxation…

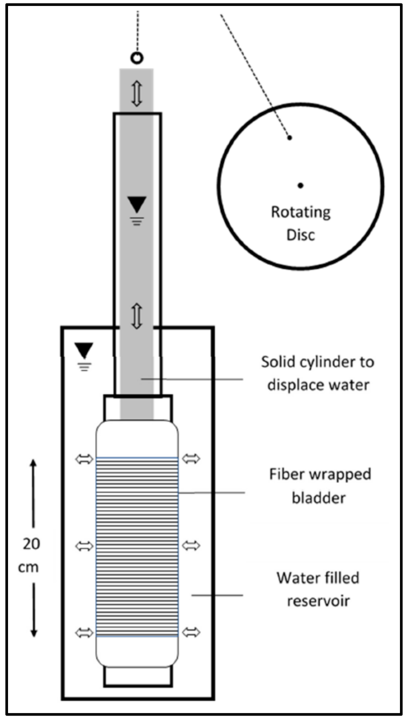


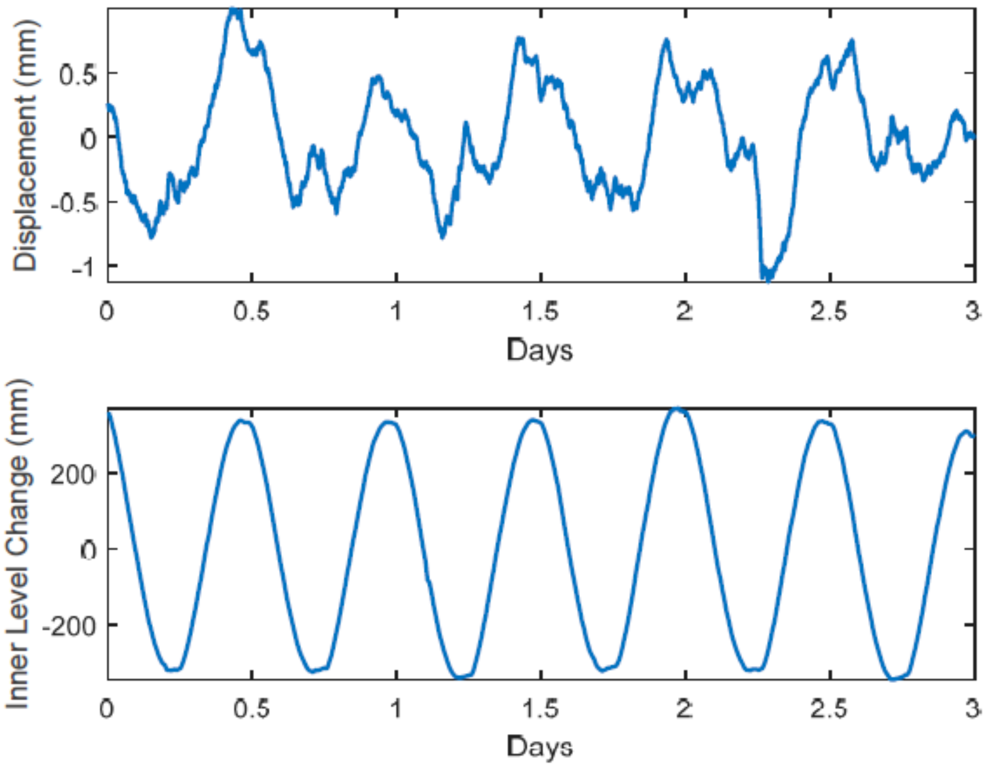
Integration to strain



Applications of Ultra Low Frequency DAS Analysis

- **Strain at Earth tides frequencies** – *Becker and Coleman (2019), Sensors*
  - **Experiment:** measuring oscillatory strain in the µHz frequency range in a laboratory setting
  - **Acquisition parameters:** spatial sampling of 0.25 m, gauge of 10 m, sampling frequency of 1 kHz
  - **Processing:** conversion to displacement rate, calculation of mean amplitude over fiber and integration





Observations:

- Oscillatory signals at frequencies corresponding to half-day lunar tidal cycles (23 µHz)
- Strain magnitude 10 times larger (165,000 nε) than tidal-induced strains (23 nε)
- Question remains: can we use DAS to measure tidal strains in boreholes?

Case Studies

1) Monitoring Long-term Subsidence in an Induced Permafrost Warming Experiment

2) Tracking Hydraulic Fracturing at an Enhanced Geothermal System Experiment

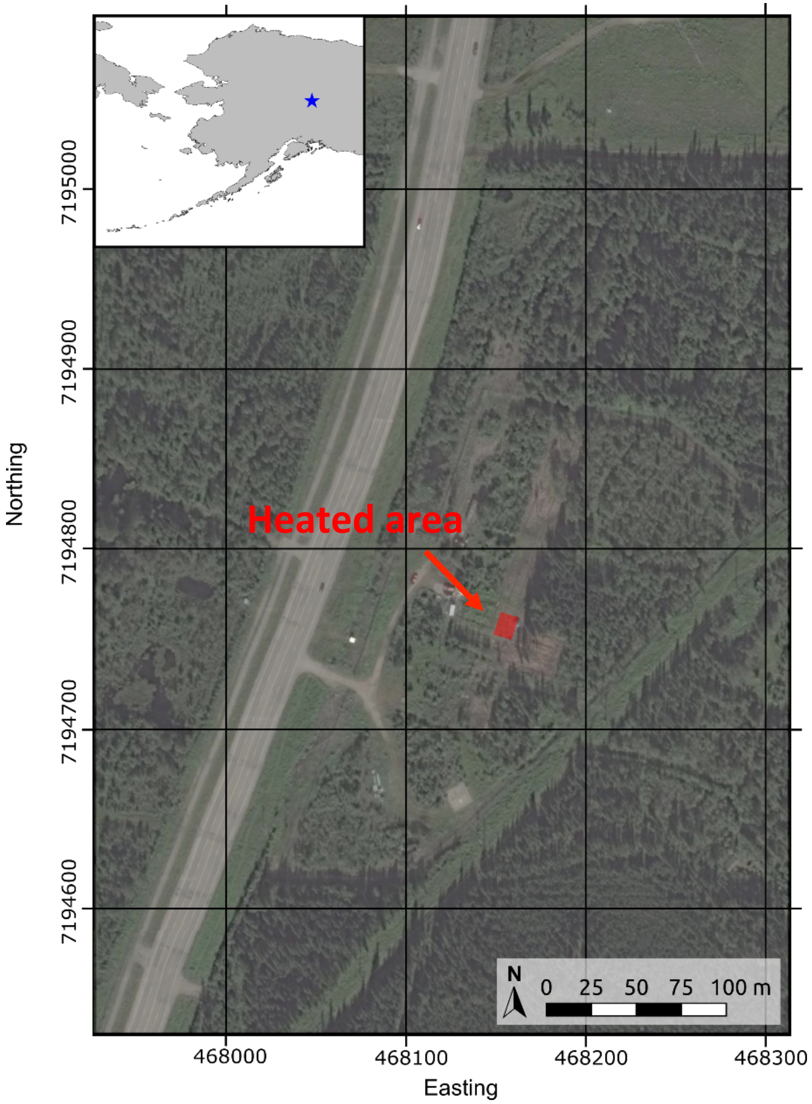
Processing Scheme to Extract Low-frequency Signals (in these two studies)

Raw strain-rate records (100’s Hz to kHz sampling) ➡ 1. Decimation to 1 Hz and concatenation; 2. Despike and median removal (to remove outliers and instrumental noise) ➡ Long-term strain-rate ➡ Temporal integration and detrending ➡ Strain since start of measurement

Case Study 1: Monitoring Long-term Subsidence in an Induced Permafrost Warming Experiment

Verónica Rodríguez Tribaldos, Nate Lindsey, Aleksei Titov, Anna Wagner, Arthur Gelvin, Ian Ekblaw, Craig Ulrich, Barry Freifeld, Jonathan Ajo-Franklin

Monitoring Permafrost Degradation During a Controlled Warming Experiment



- **Controlled permafrost thawing** experiment at the US Army Corps of Engineer's Permafrost experiment Station in **Fairbanks, Alaska**
- 121 electrical heaters placed over **an area of 10.5 m x 12.7 m**
- Heating lasted **from August 5th through to November 11th 2016**

Wagner et al. (2018)

Monitoring Permafrost Degradation During a Controlled Warming Experiment

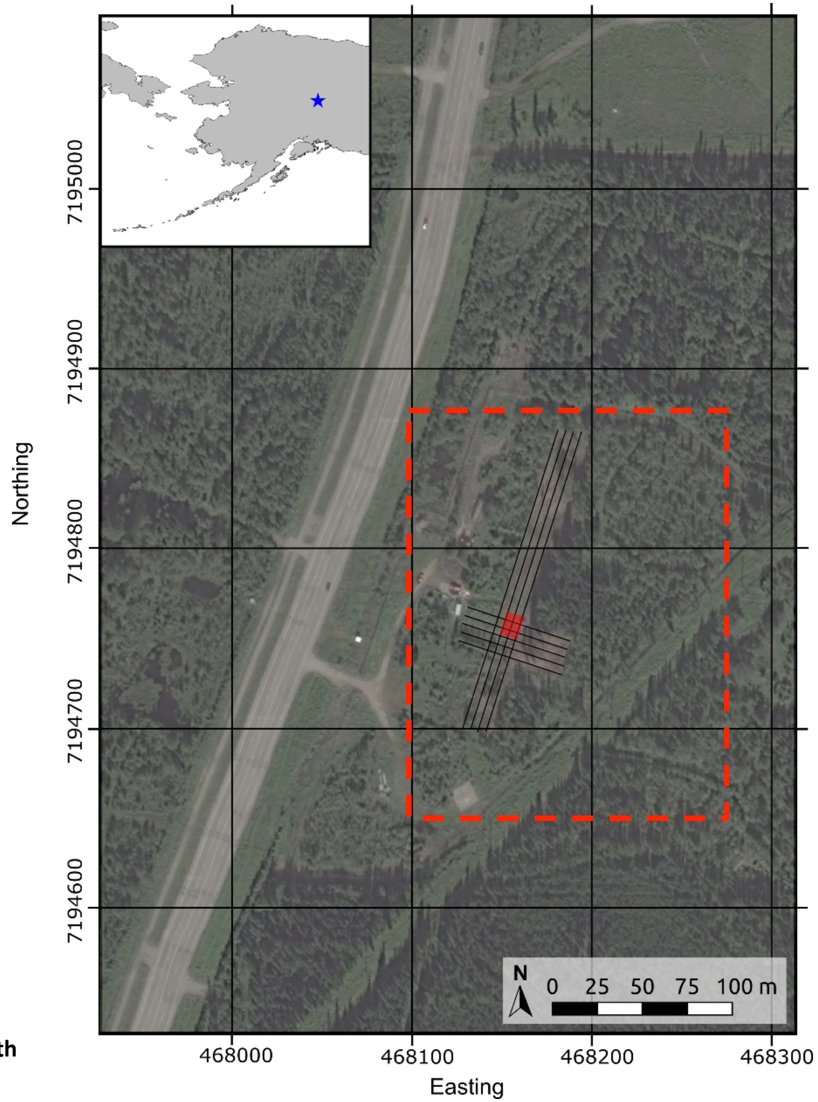
Monitoring instrumentation:

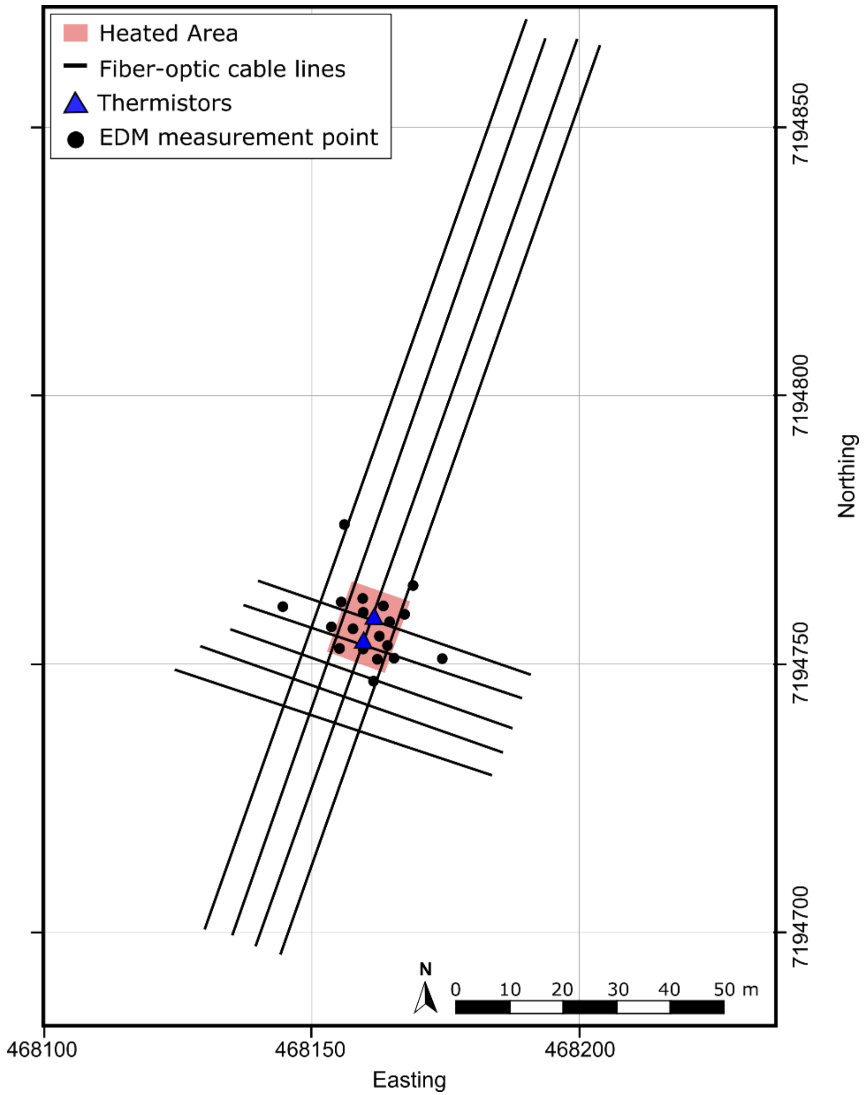
- **4000 m-long 2D array fiber-optic cable** for **DAS, DSS and DTS**

  Channel spacing = 1 m
  Gauge length = 10 m

- **Thermistor arrays**
- **Electronic Distance Measuring (EDM)**
- **LiDAR**
- 10 DTS wells
- 1 Geophone array
- 2 Broadband seismometers
- 2 ERT lines
- 2 NMR wells
- Moisture content probes

DAS acquired between August 5th and October 4th

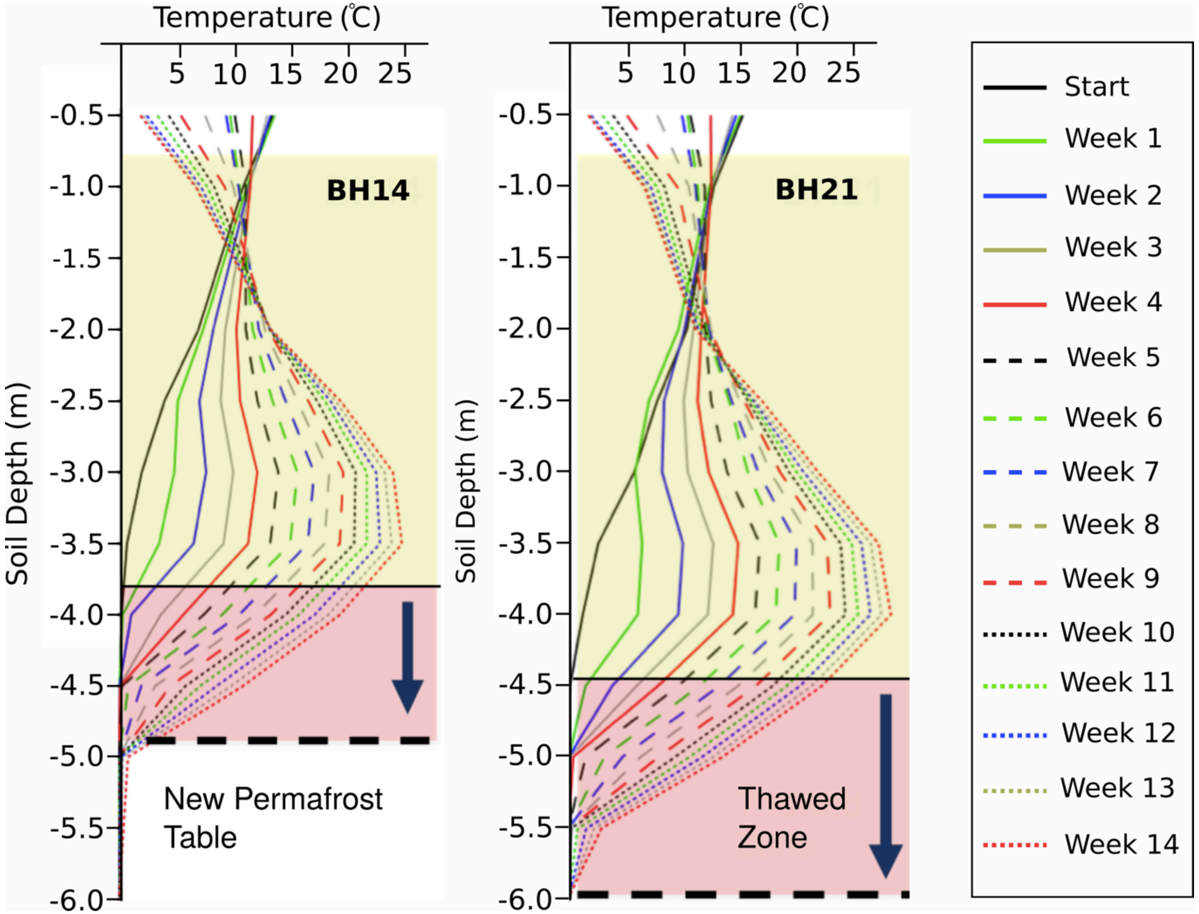


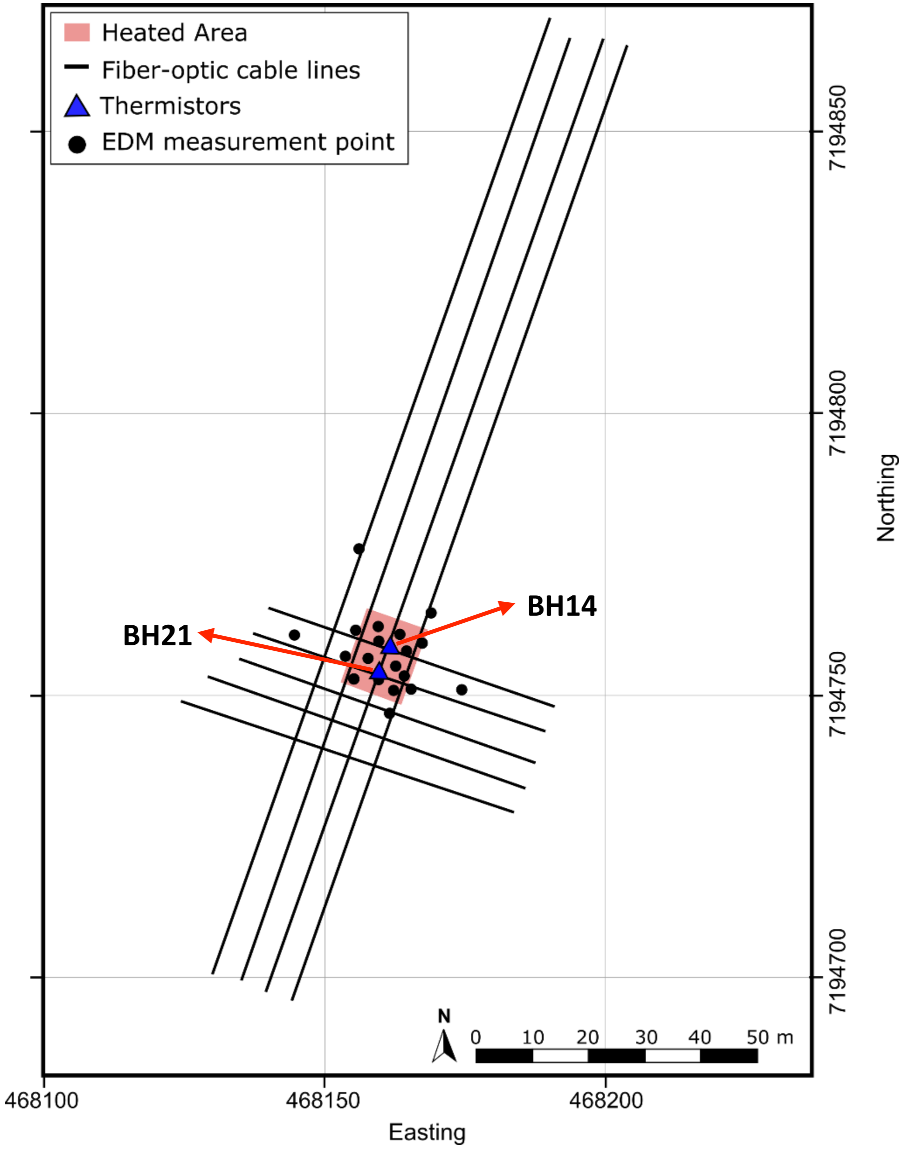


Wagner et al. (2018)

Monitoring Permafrost Degradation During a Controlled Warming Experiment

- Temperatures were increased **from slightly below 0°C to 25 °C**
- The **permafrost table** was **lowered by 1.25 m to 1.5 m**





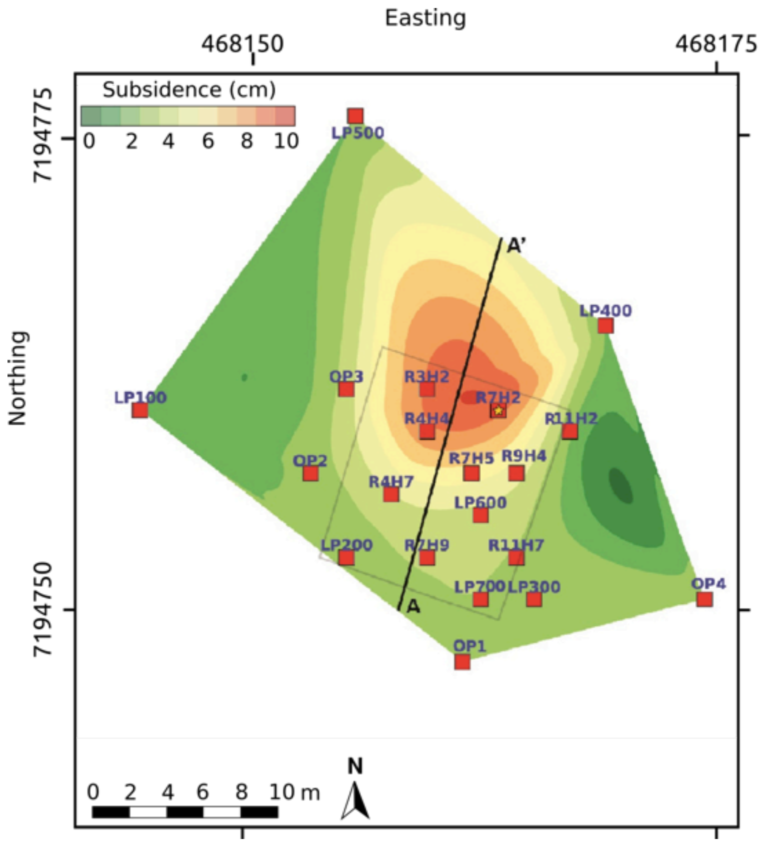
Wagner et al. (2018)

Evidence of Subsidence From Mechanical Deformation Measurements

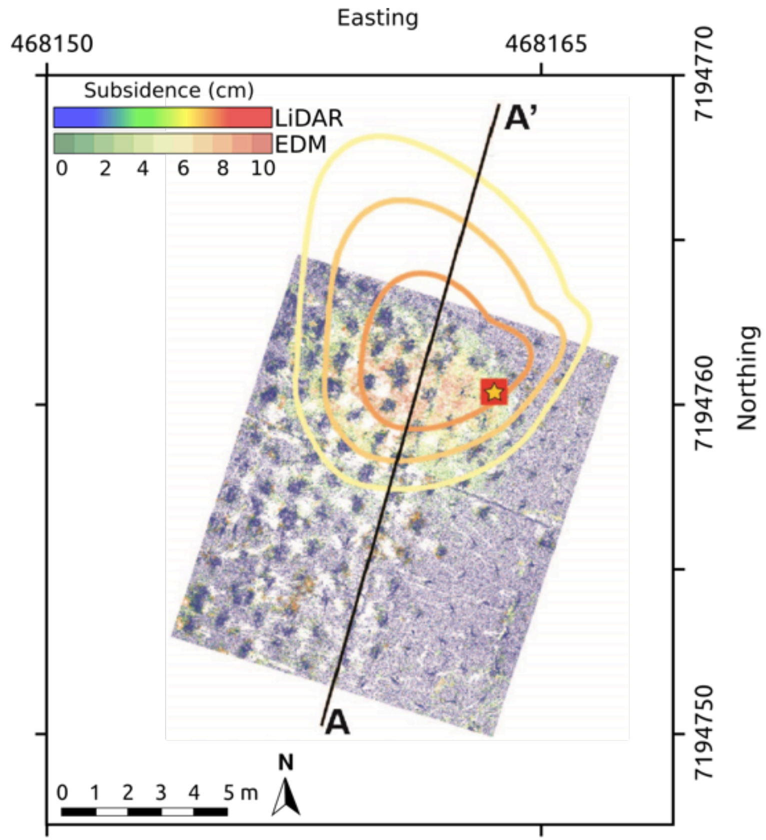
- EDM and LiDAR measure surface subsidence of **up to 10 cm** over 4 months of heating
- Surface deformation observable **starting ~ August 22nd**

Can we use DAS to record long-term strain related to ground subsidence?

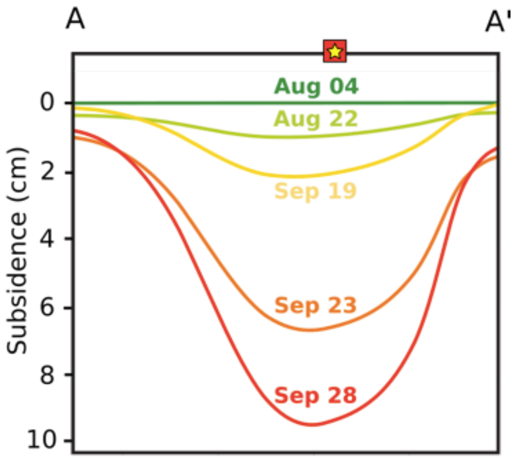
Electronic Distance Measuring (EDM) at end of experiment



Differential LiDAR (EDM contours superimposed) at end of experiment

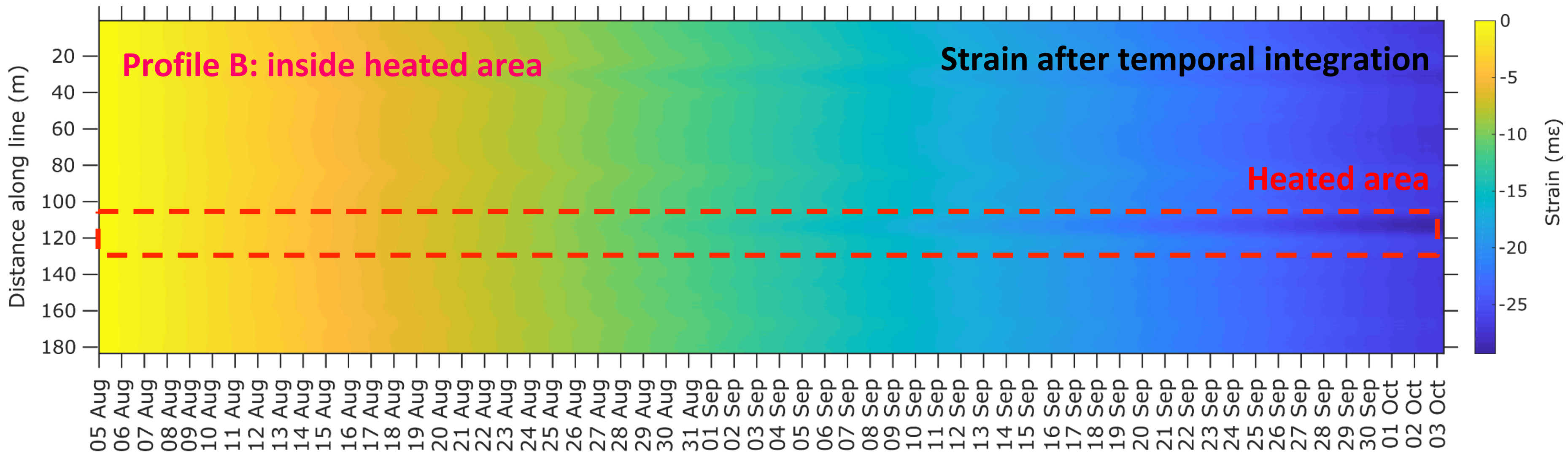


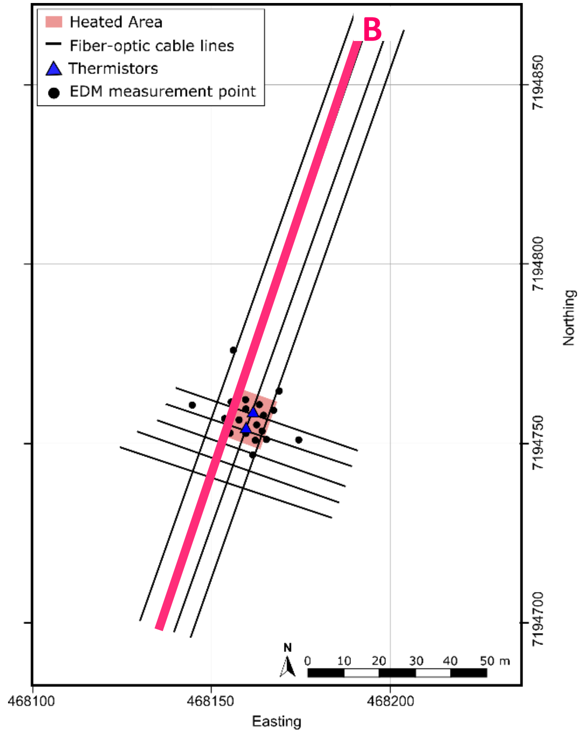
Cross-section of elevation change across heated area along profile A-A'



Wagner et al. (2018)

Extracting Low-Frequency Signals in DAS records





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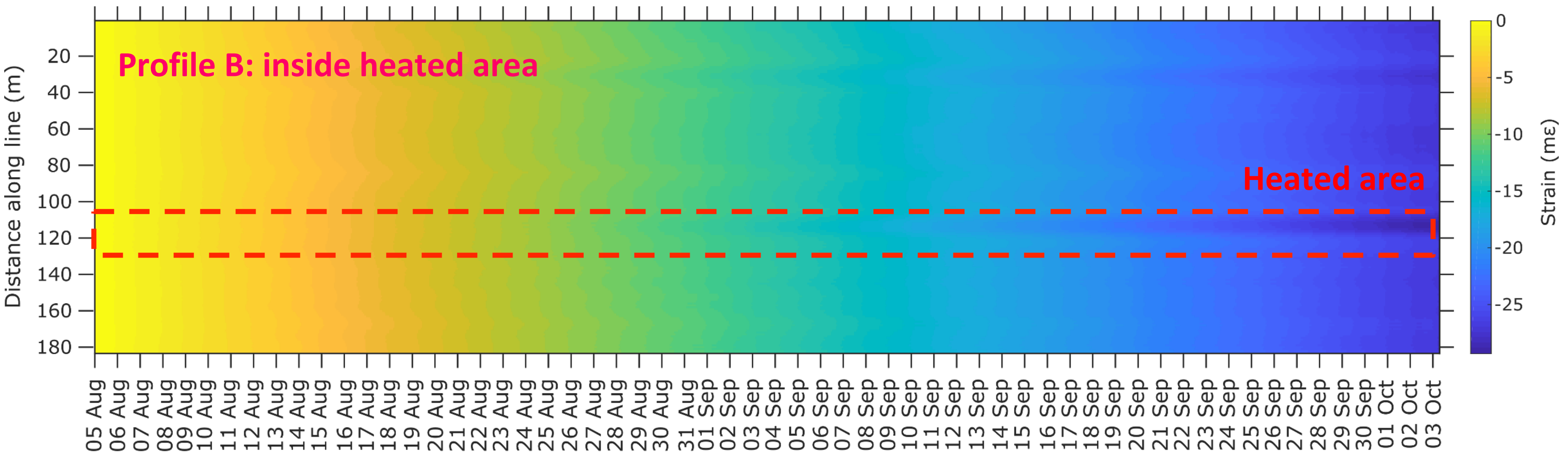

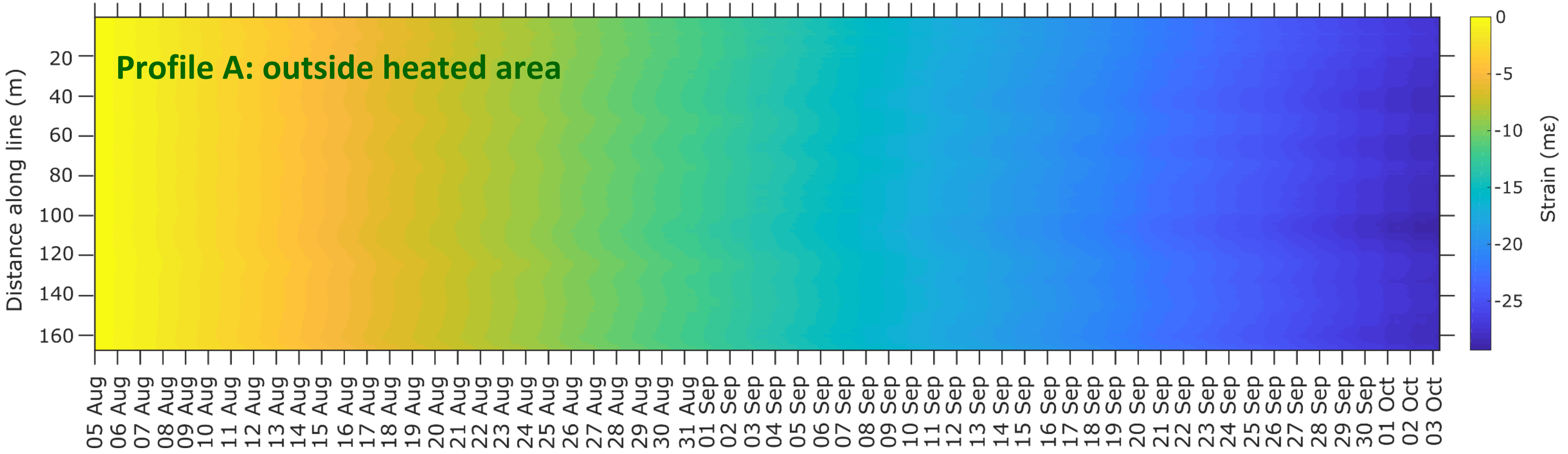

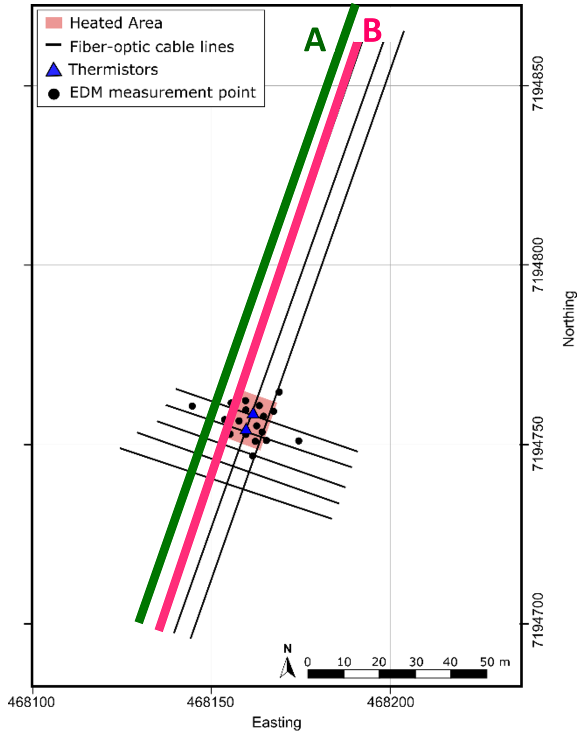

In both profiles, **long-term strain dominated by negative trend**

Combination of **instrument drift and temperature**

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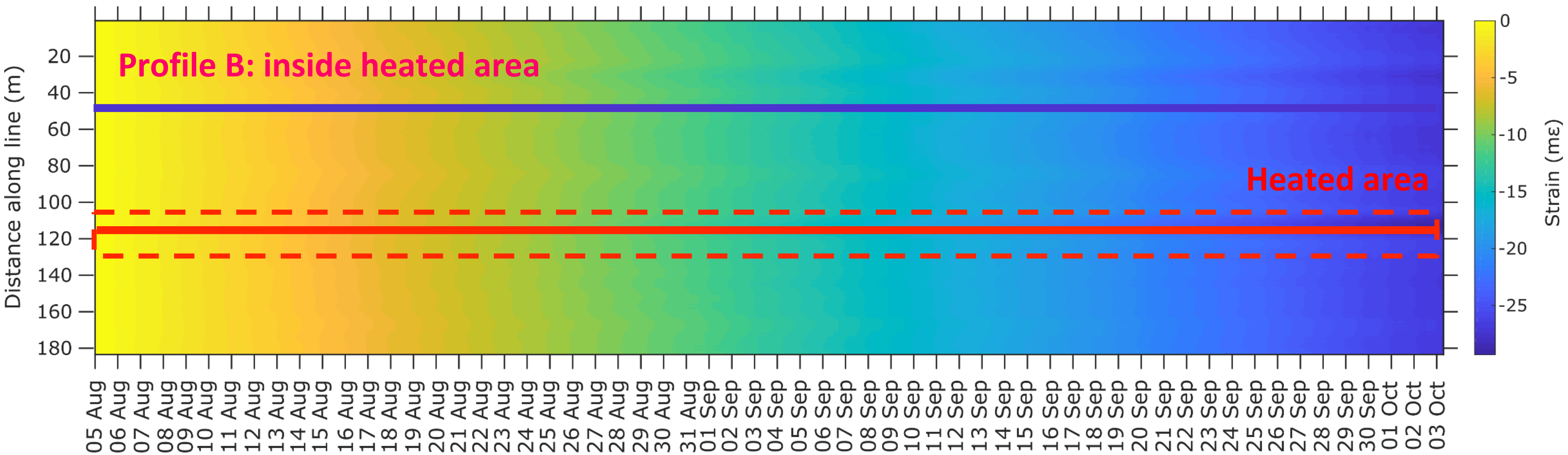

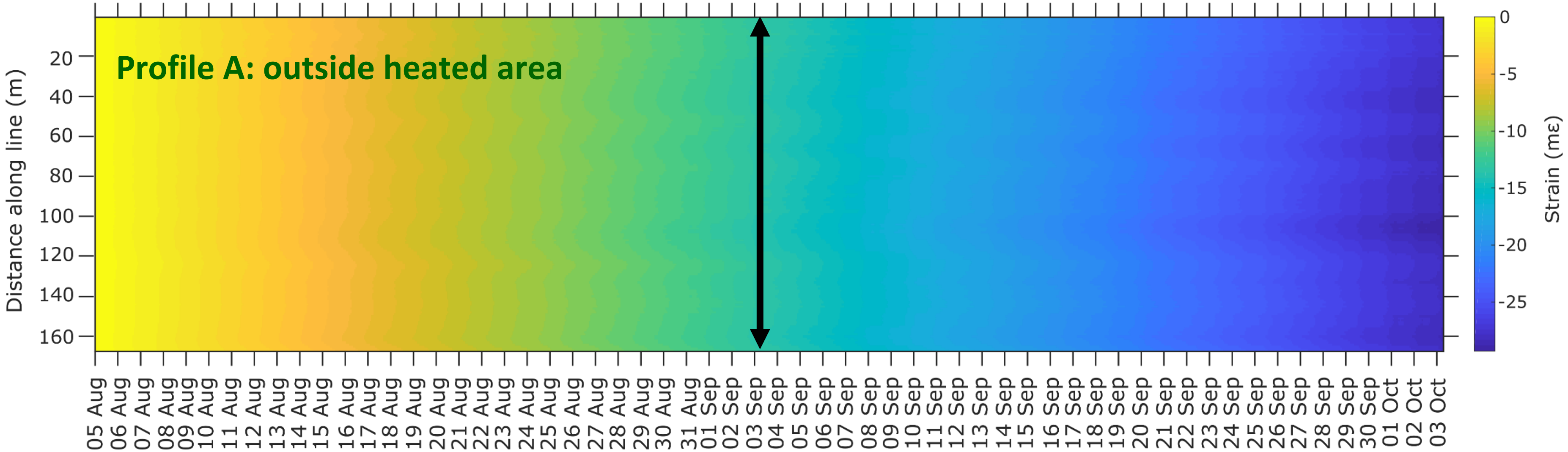

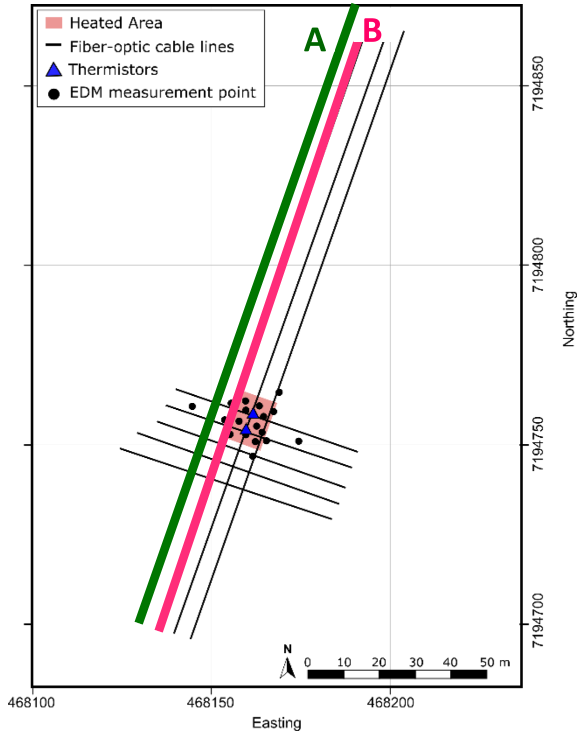

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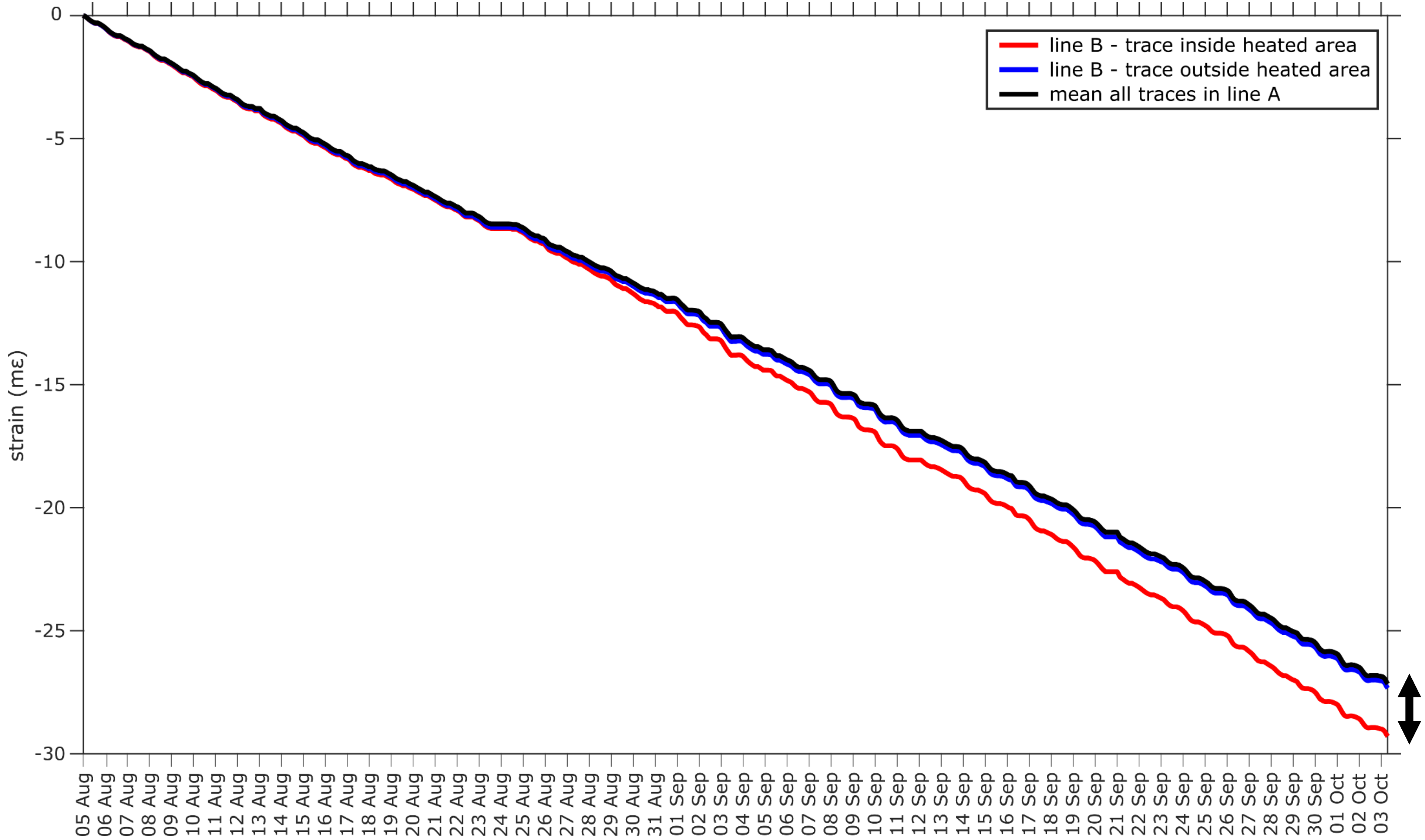
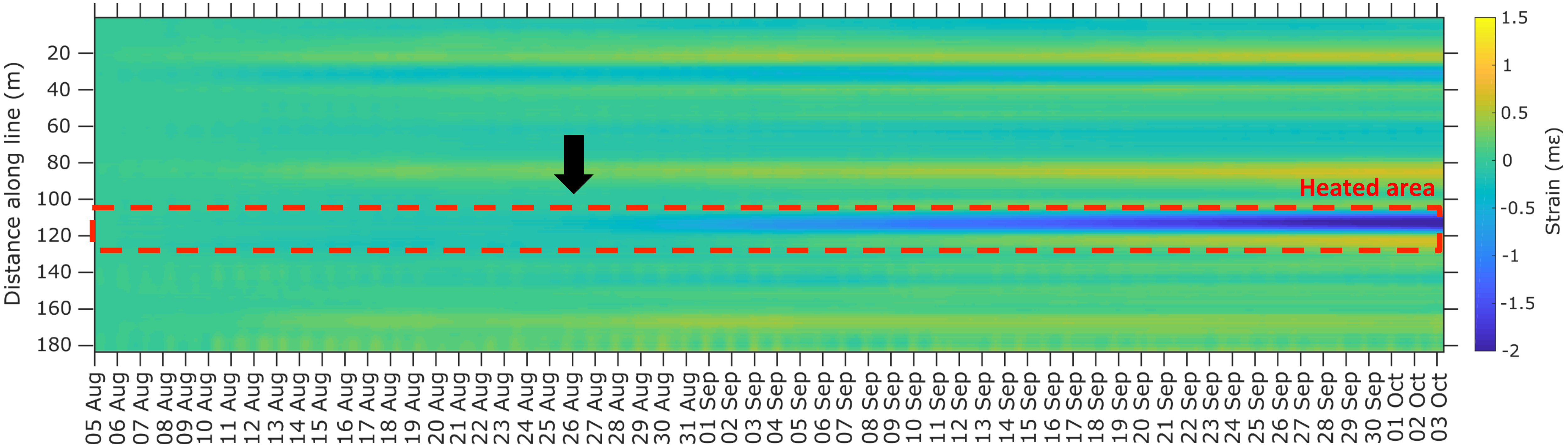


- The **mean of all channels in profile A** and a **channel outside of the heated plot for profile B** show the same strain
- **Channel inside heated area** for profile B shows **“residual” negative strain**
- Assumption that **line A and line B outside heated plot are affected by the same processes**, which we want to remove

Monitoring Subsidence using Low-frequency DAS

Calculate the **mean of all channels in profile A** and **subtract it from profile B** to obtain "residual" subsidence signal



Negative strain associated with compression of the cable in the subsiding area starting ~ August 26th

Monitoring Subsidence using Low-frequency DAS

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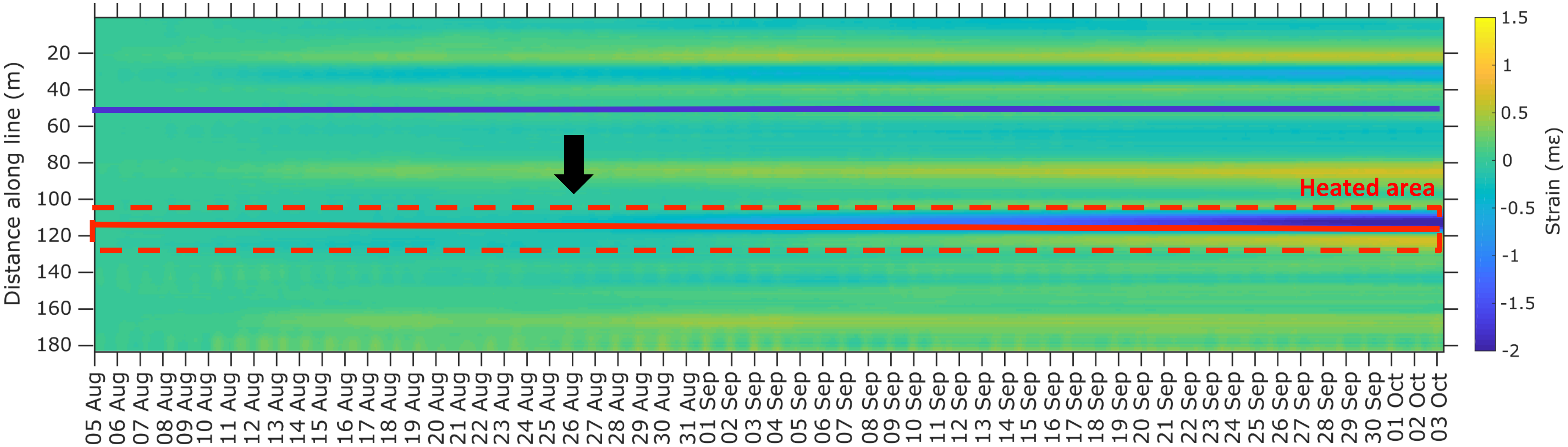

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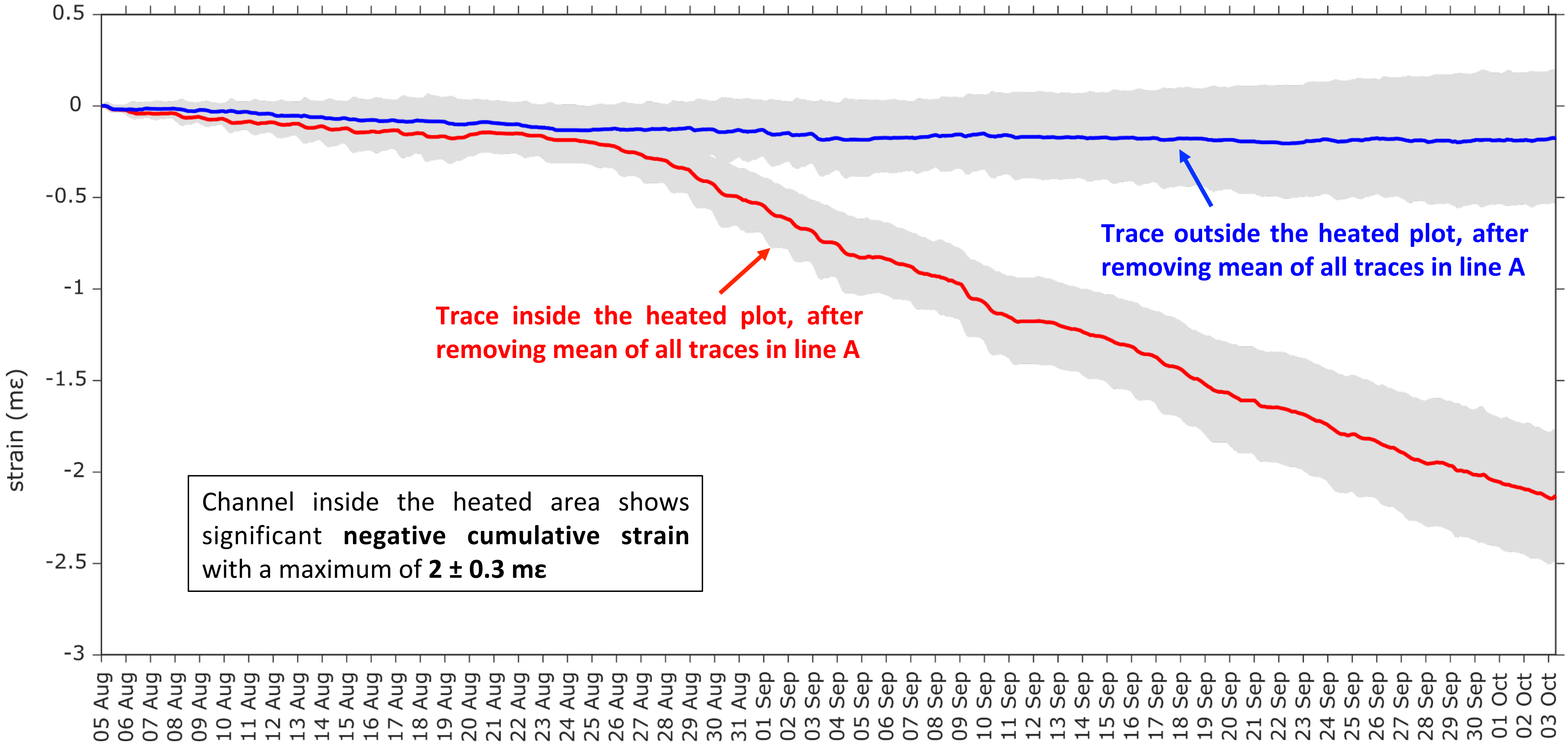
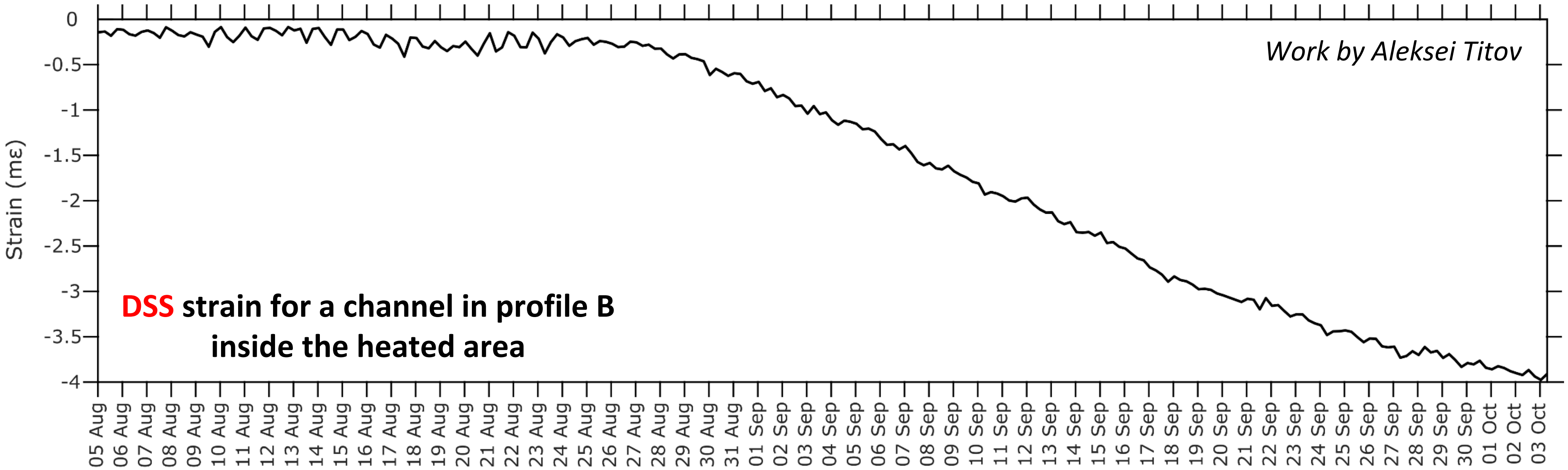
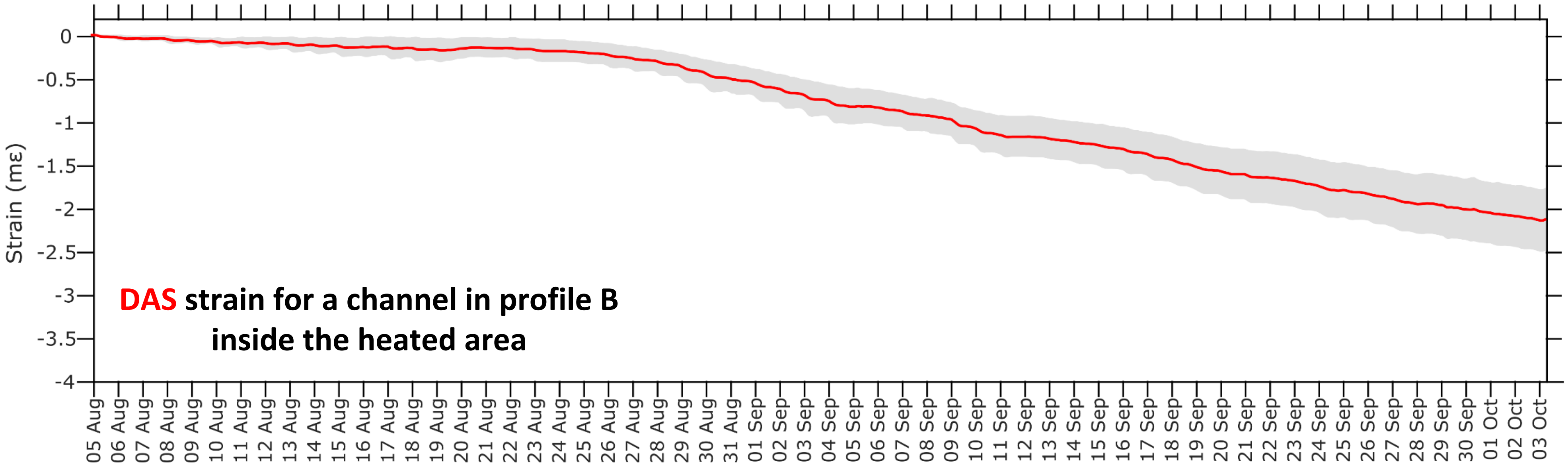
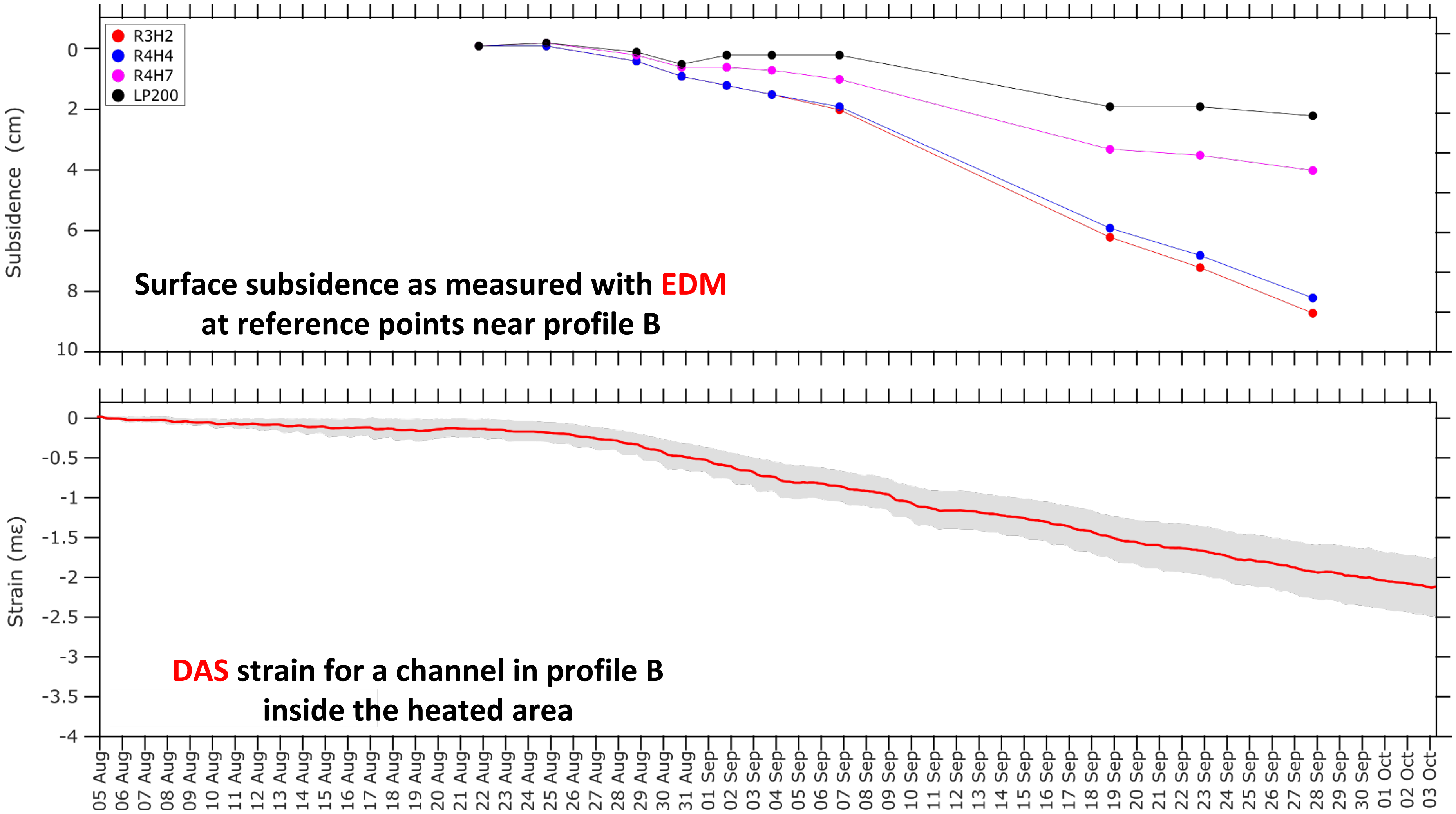


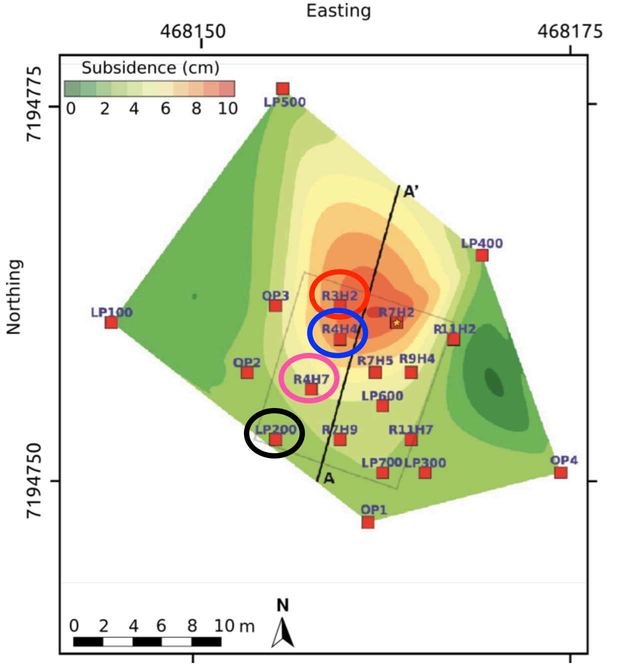
Comparison with Distributed Strain Sensing (DSS) signals



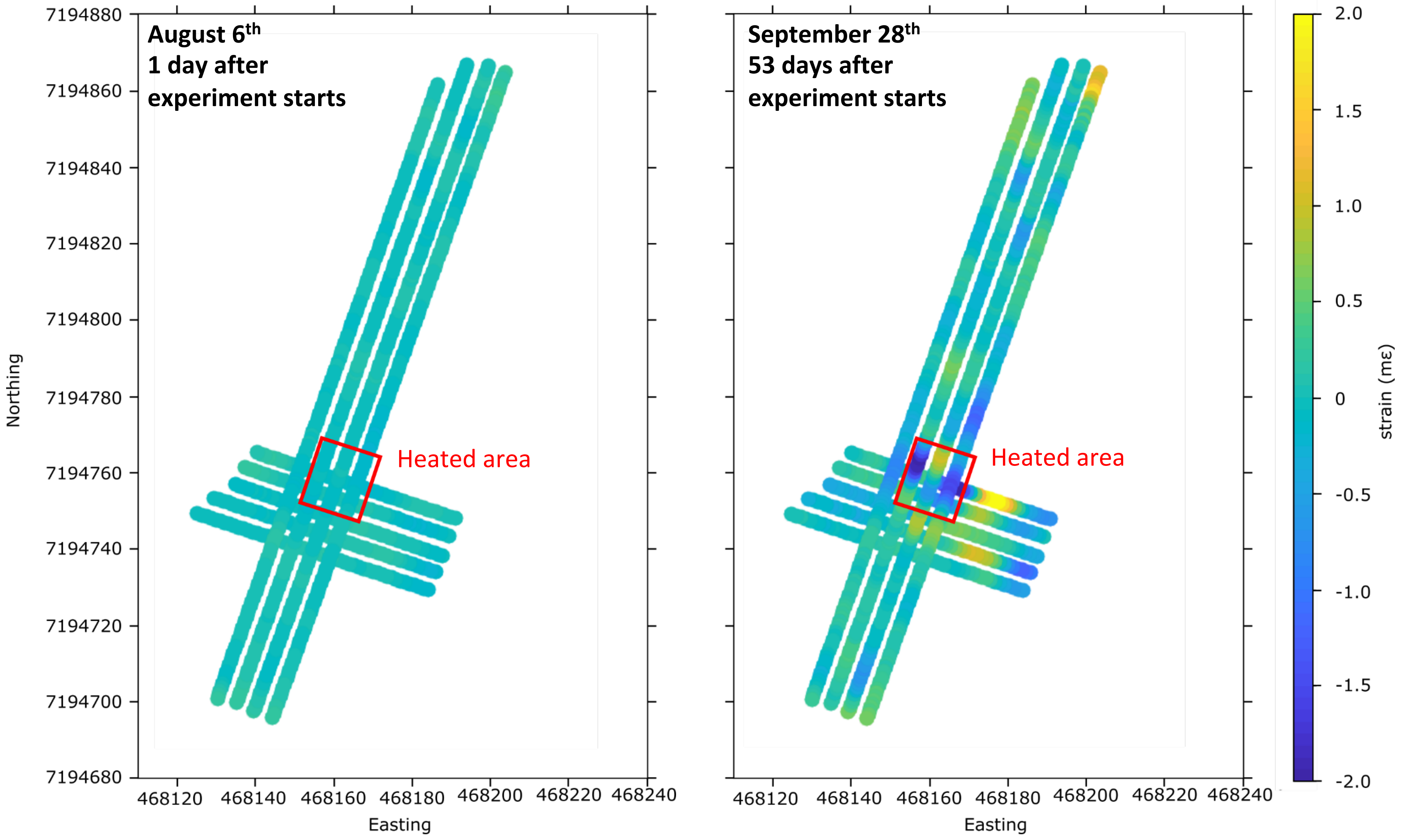


Comparison with Electronic Distance Measuring (EDM)





Spatial Distribution of Strain

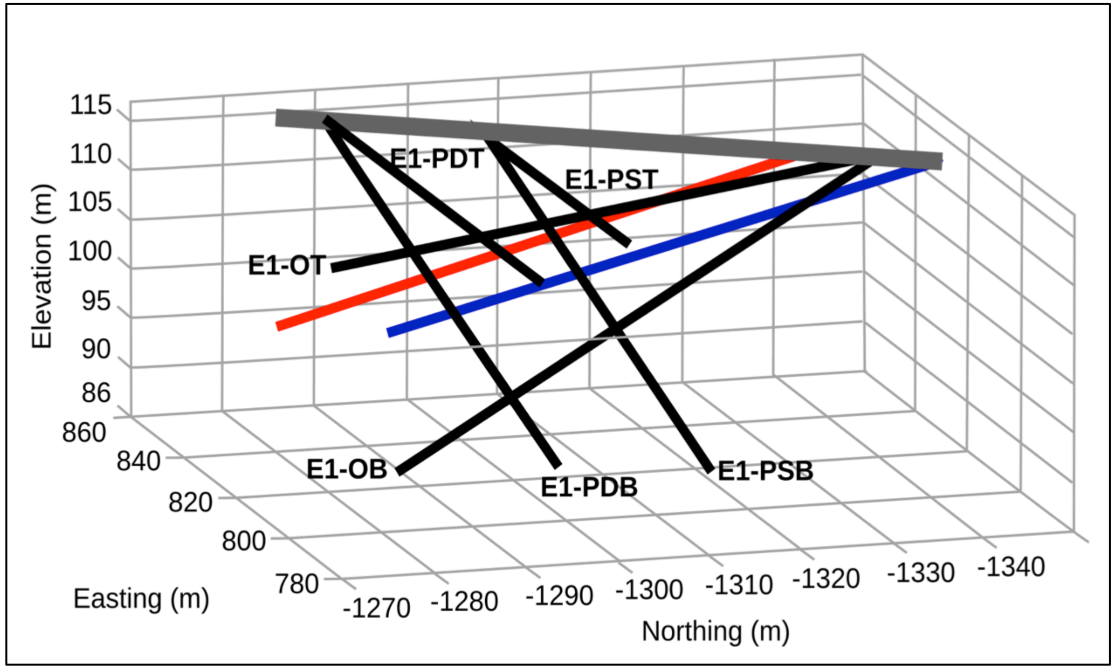


Case Study 2: Tracking Hydraulic Fracturing at an Enhanced Geothermal System Experiment

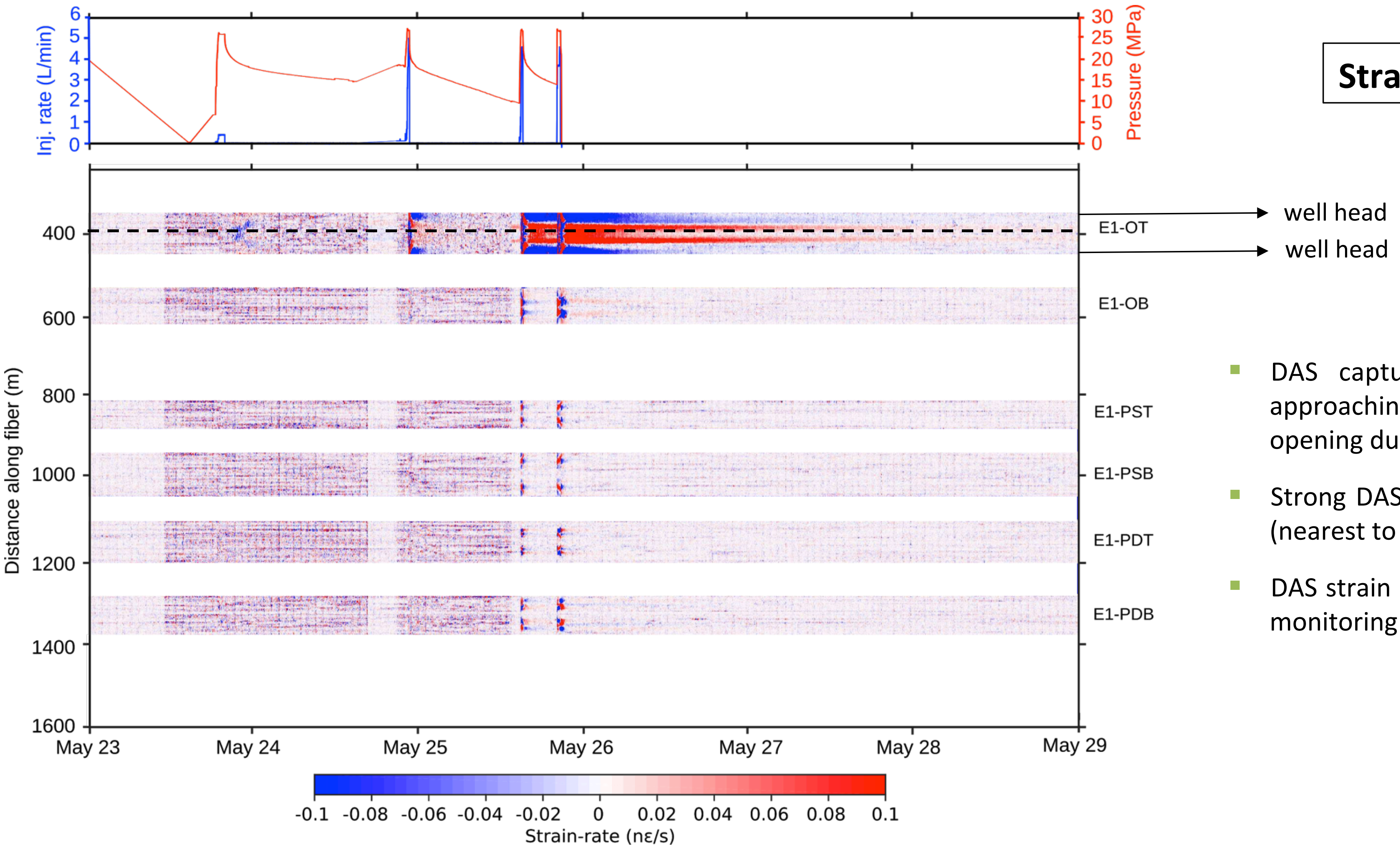
Verónica Rodríguez Tribaldos, Martin Schoenball, Chet Hopp, Yves Guglielmi, Jonathan Ajo-Franklin
and the EGS Collab team

Strain Monitoring with DAS at the EGS Collab Experiment

- EGS Collab project: continuing sequence of meso-scale experiments aiming at improving understanding of hydraulic stimulations in crystalline rock for EGS
- Continuous monitoring of hydraulic fracture creation and stimulation using DAS (amongst many other techniques)
- Continuous ~2000 m long fiber-optic cable looping at bottom hole and going to the next borehole
- Grouted in 6 monitoring boreholes, free-hanging in coils in the drift
- Sampling rate 1 kHz or 10 KHz, 1 m channel spacing, 10 m gauge length
- Hydraulic fracture hits well E1-OT



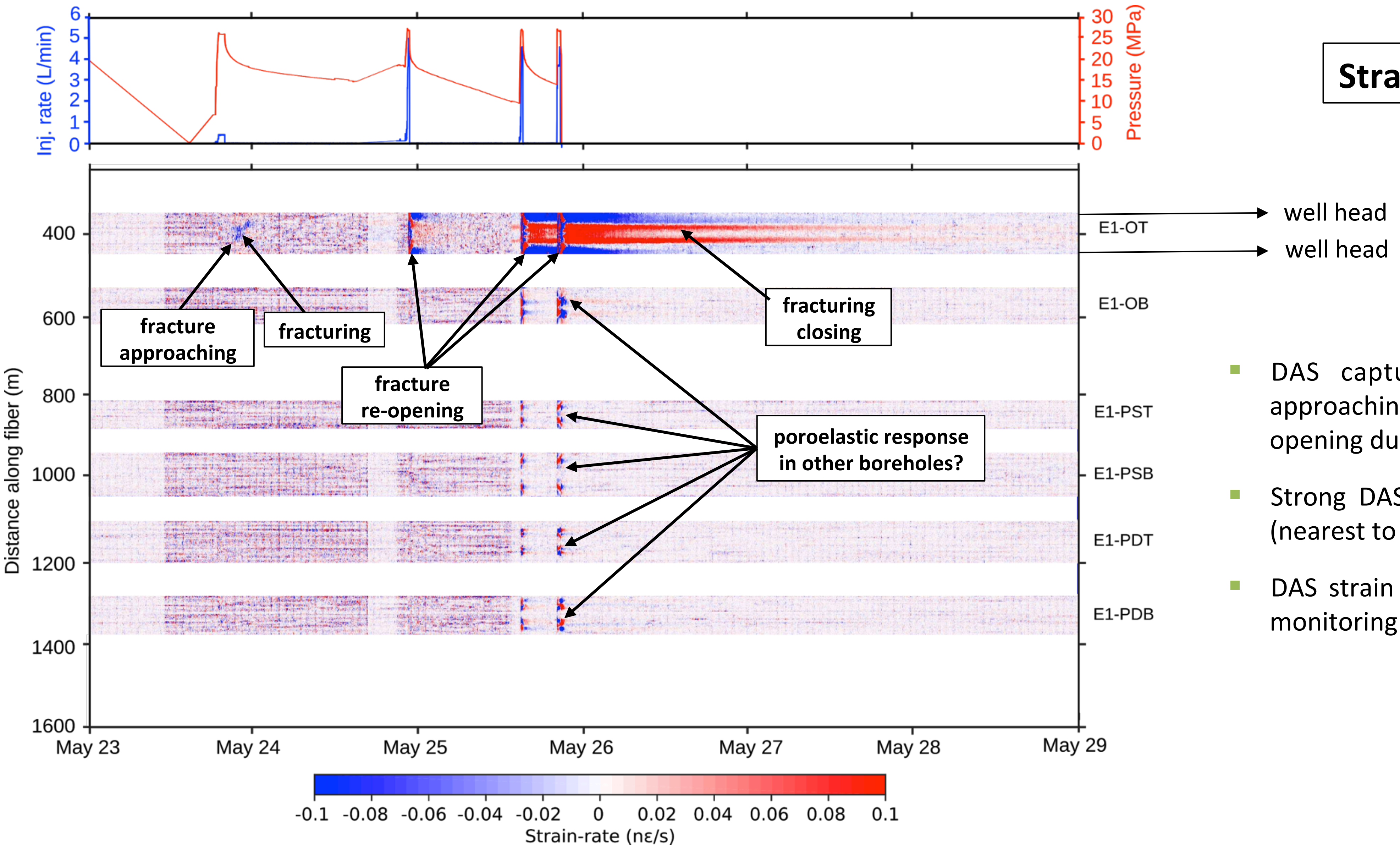
Ultra-low Frequency DAS during Hydraulic Fracture Stimulation



Strain-rate

- DAS captures hydraulic fracture approaching, hit the well and re-opening during later stimulations
- Strong DAS response in well E1-OT (nearest to injection borehole)
- DAS strain response observed in all monitoring boreholes

Ultra-low Frequency DAS during Hydraulic Fracture Stimulation



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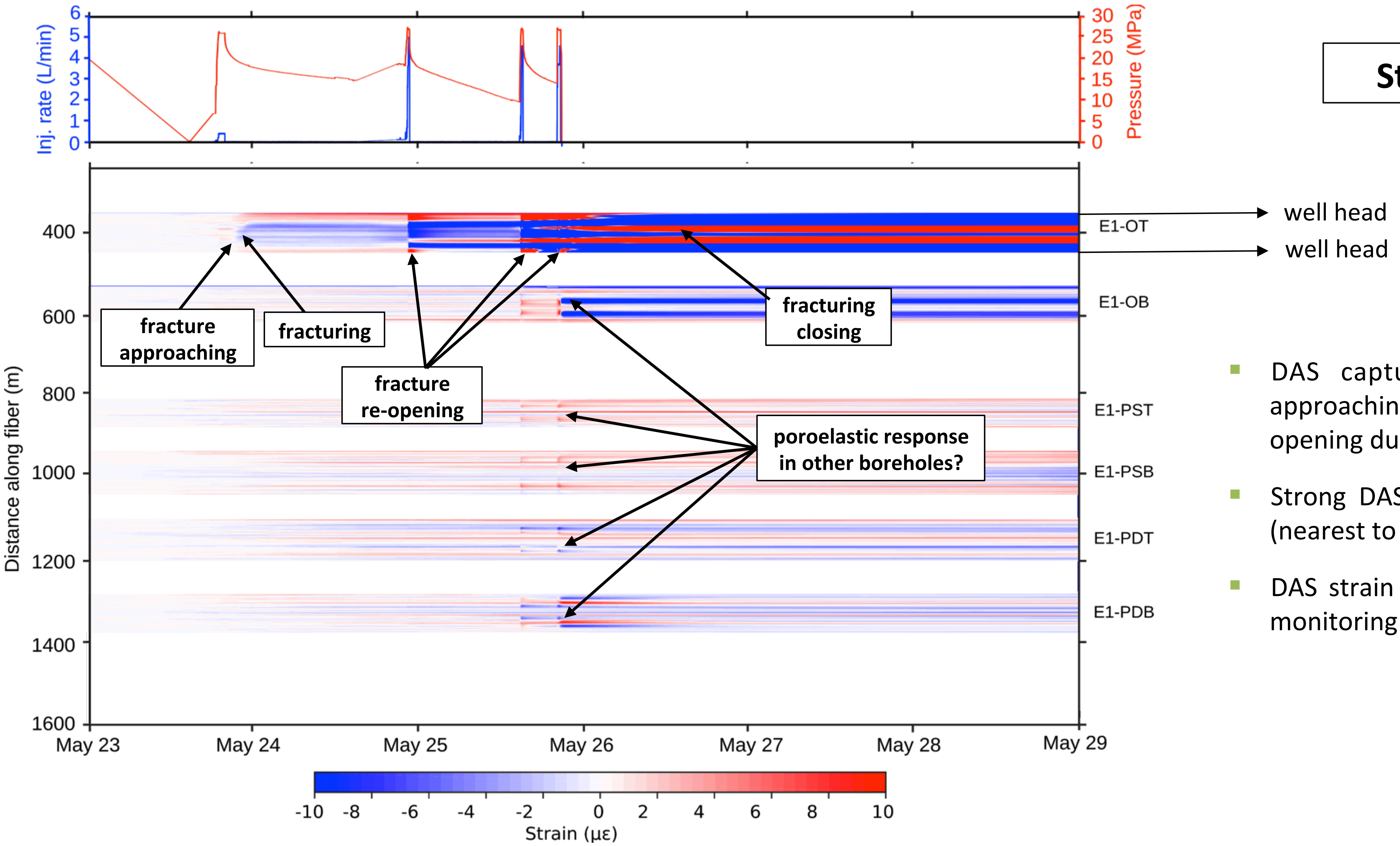

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Summary

- DAS is an extremely broadband sensor (mHz to KHz) that can be used for **dynamic strain measurement (seismology), but also for geodetic/geomechanics-type observations**
- **Extraction of low-frequency component** is relatively simple, little processing is required
- **Quantification of strain amplitudes remains a challenge**: effects such as **instrumental drift** and **thermal strain** affecting the cable need to be understood
- Best practices include **instrument calibration, temperature monitoring and record at "reference/quiet sections" when possible**
- **More experimentation** in varying fields of application, different instruments, different cables… is necessary!

Thanks for listening!
Questions?

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