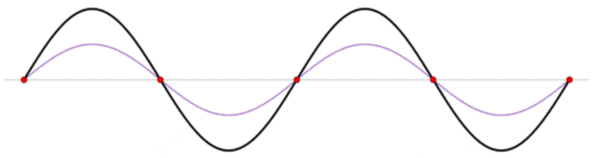
Decoding Seismic Signals with Seafloor Optical Fiber Strainmeters (SOFS)

Saiful Islam Apu [1]



[1]*Department of Geology, The University of Kansas, KS-66045, United States*

Supplementary information

Seafloor Optical Fiber Strainmeters (SOFS): A New Strain Monitoring Instrument

- Uses light-phase shifts in fiber optic cable to detect strain.
- 250m-long cable anchored to seafloor; passive & active endpoints.
- Continuous high-resolution strain data → ideal for SSE detection.
- Pioneered by Zumberge et al., 2018.

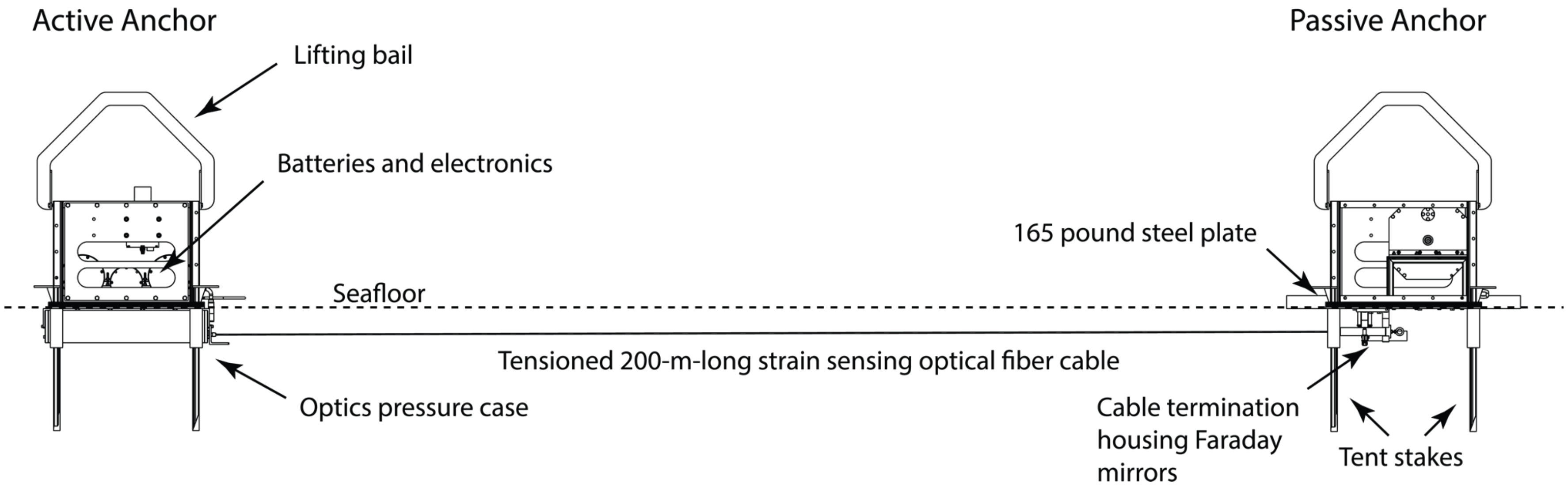


*Fig: Two anchors, one passive, the other active, marked the baseline of the optical fiber strainmeter. They were held in place both by their weight and half-meter-long "tent stakes" (**After Zubmerge et al., 2018**).*

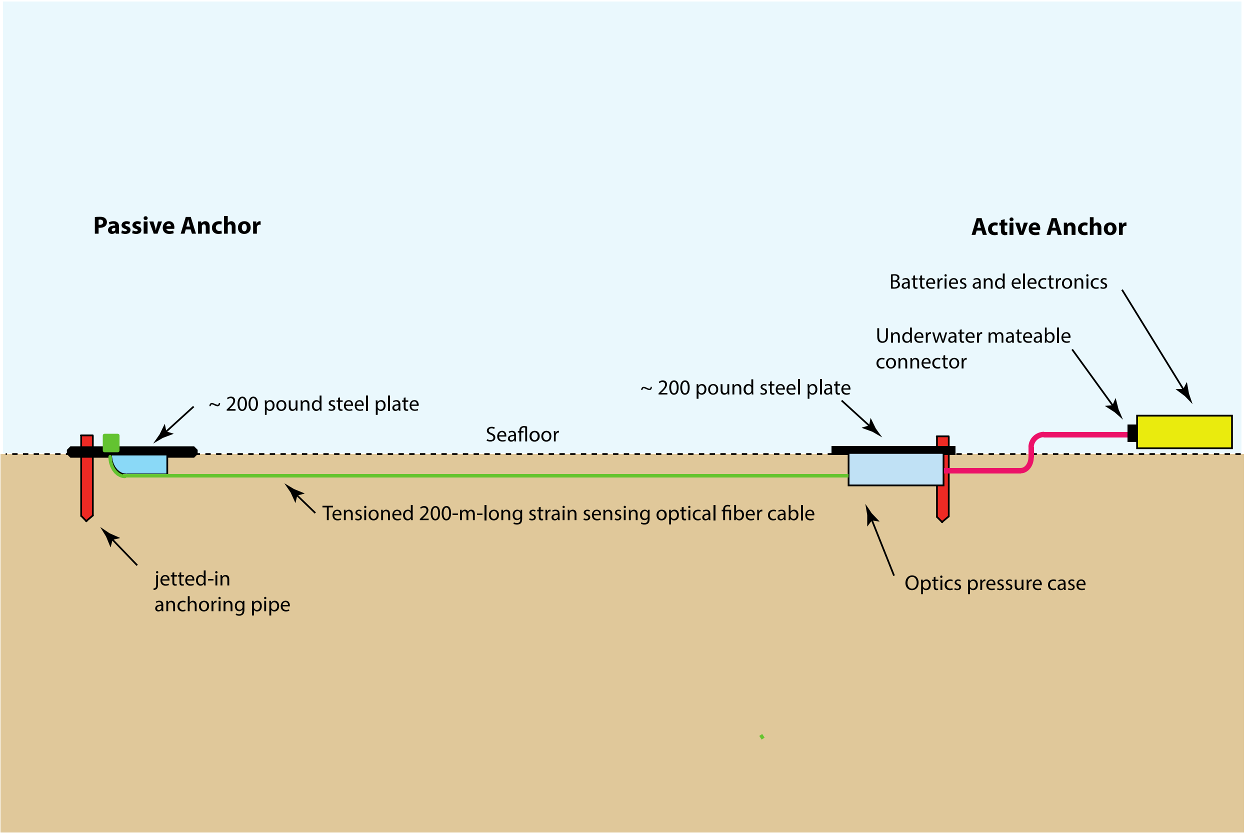


*Fig: Improved schematic cartoon of the SOFS instrument (**By Zubmerge, UCSD**).*

- **Working Principle:**
  SOFS operates on **interferometry**, splitting laser light into two beams: one travels through a seafloor-mounted optical fiber, and the other remains a reference.
- **Strain Measurement:**
  Seafloor motion stretches the fiber, changing its length (Δl). Strain (ϵ) is computed as the relative change in fiber length.
- **High Sensitivity:**
  Can detect nanostrain-level deformations, making it ideal for tracking subtle seafloor strain.
- **Conversion Formula:**

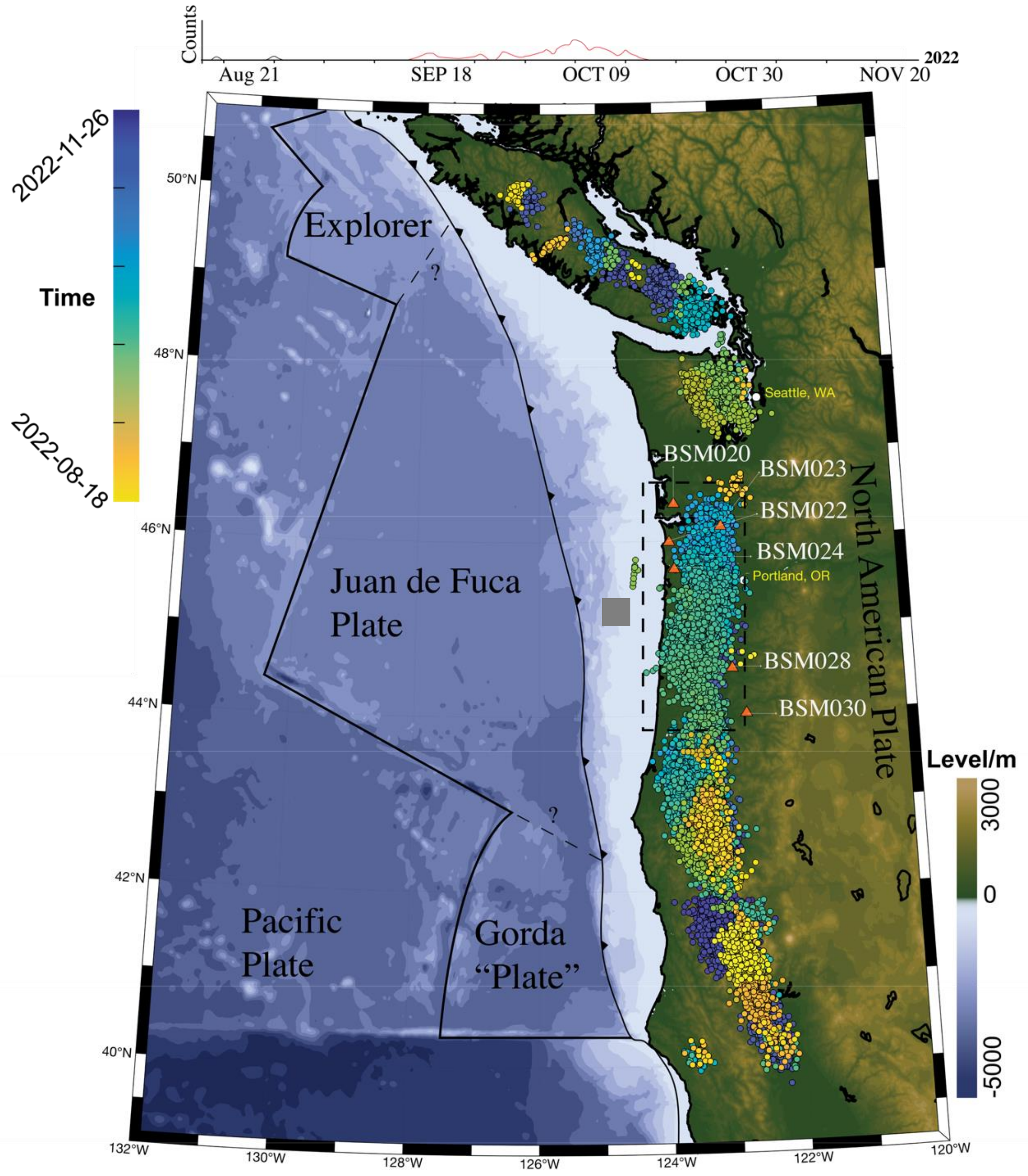
$$\epsilon = \frac{\Delta l}{l} = \frac{\lambda}{1.17 \cdot 4\pi \cdot l} \cdot \Delta\phi$$

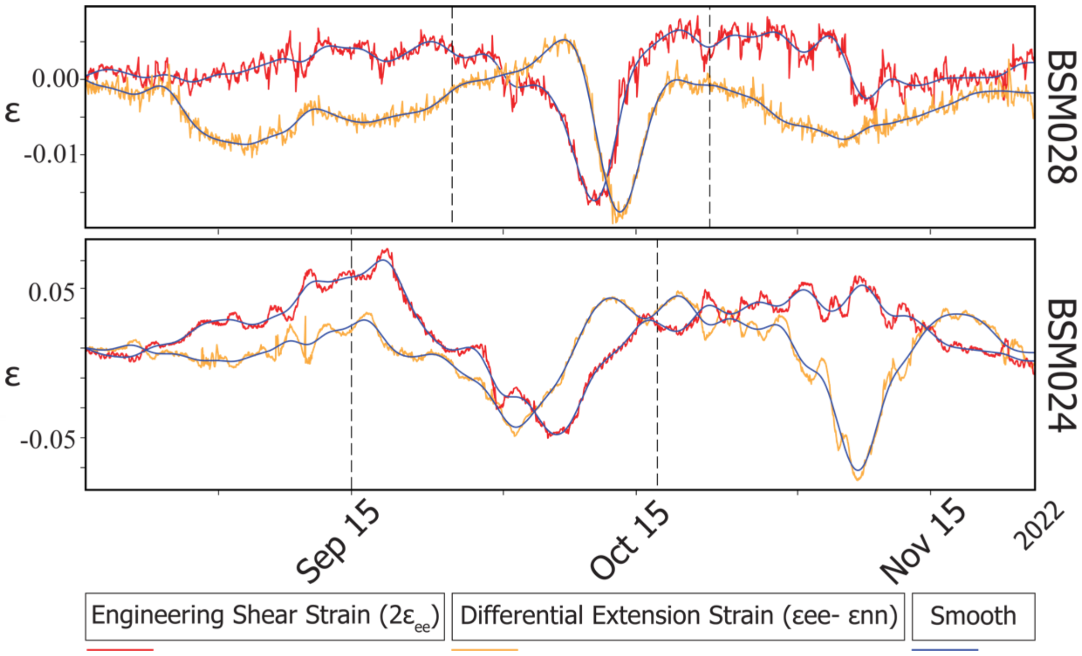
where:

- λ = laser wavelength (1310 mm)
- l = fiber length (250.0 m)
- $\Delta\phi$ = optical phase change in radians

- **Sampling Rate:**
  Optical phase values are recorded at high resolution and sampled to 8 Hz, then stored on flash memory.

SSE Events 2022





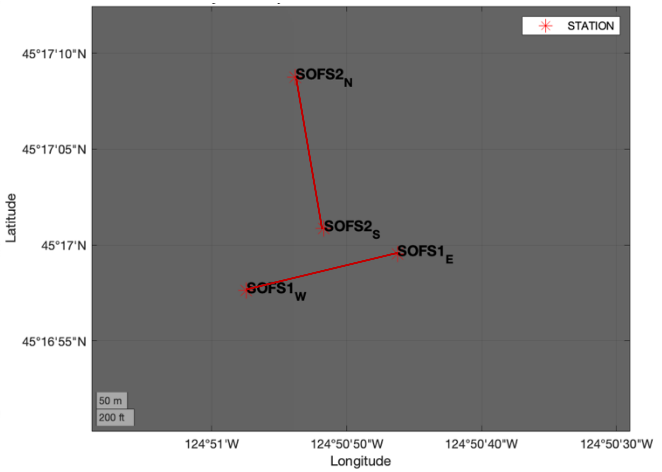
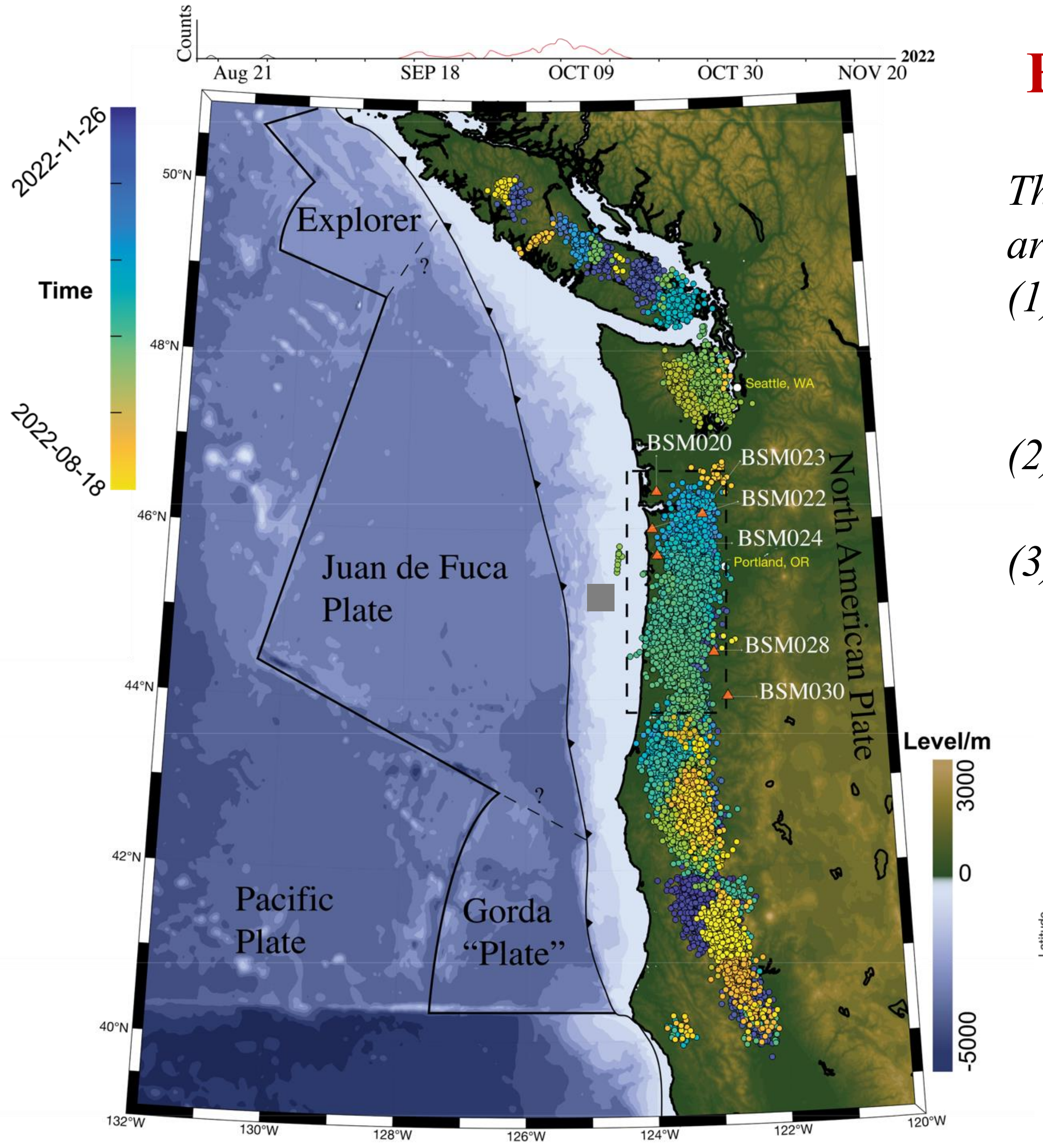


Fig: Location of the SOFS instruments which was already been deployed within the timeframe of the SSE event in 2022.



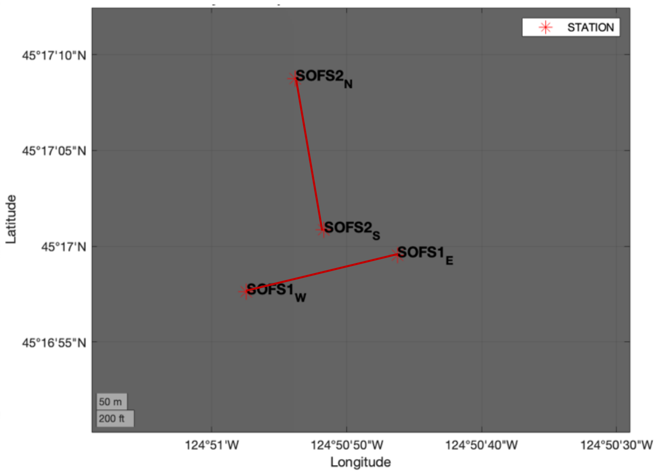
Broader Scientific Goals

The expected outcomes include but are not limited to—

(1) Improved detection and characterization of offshore SSEs using seafloor strain data;

(2) refined geodetic inversions for offshore slip processes;

(3) enhanced modeling of fluid-fault interactions in SSEs



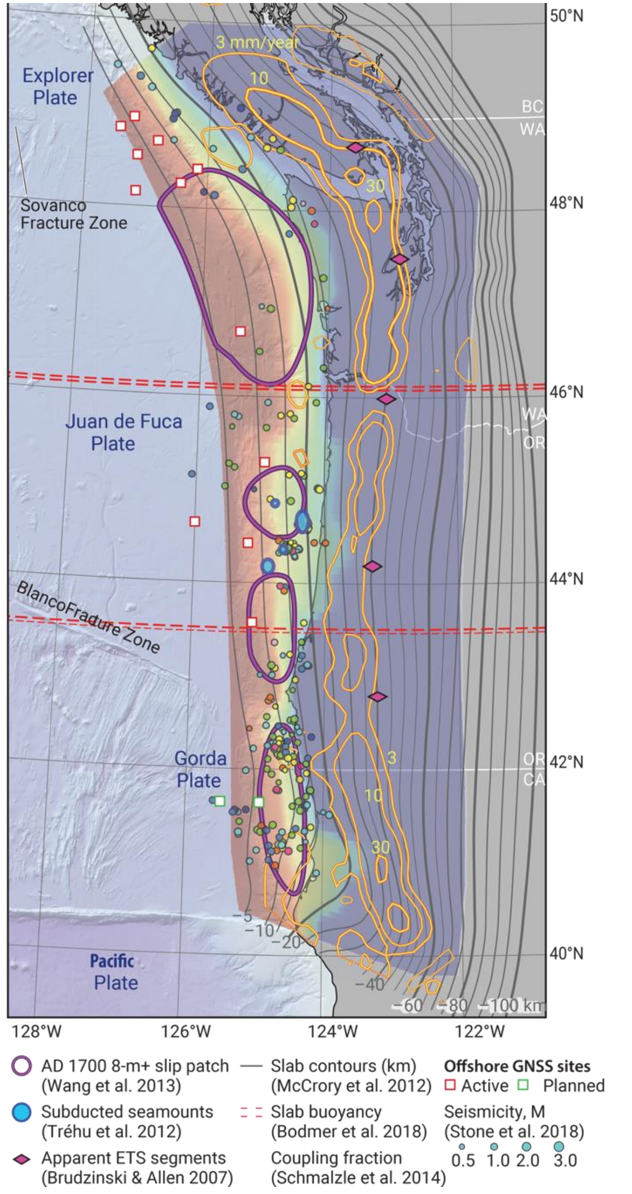


*Fig: Maps of geophysical data sets used to infer along-strike heterogeneities along the CSZ. (**Modified from Walton et al., 2021**)*

Time-series analysis of Seafloor Optical Fiber Strainmeters (SOFS) Data

- **Goal:** Improve detection of offshore tremors and low-frequency earthquakes (LFE/VLFE) where geodetic coverage is sparse or absent.
- Develop **correction procedures**, filtering strategies, and time-series detection algorithms.

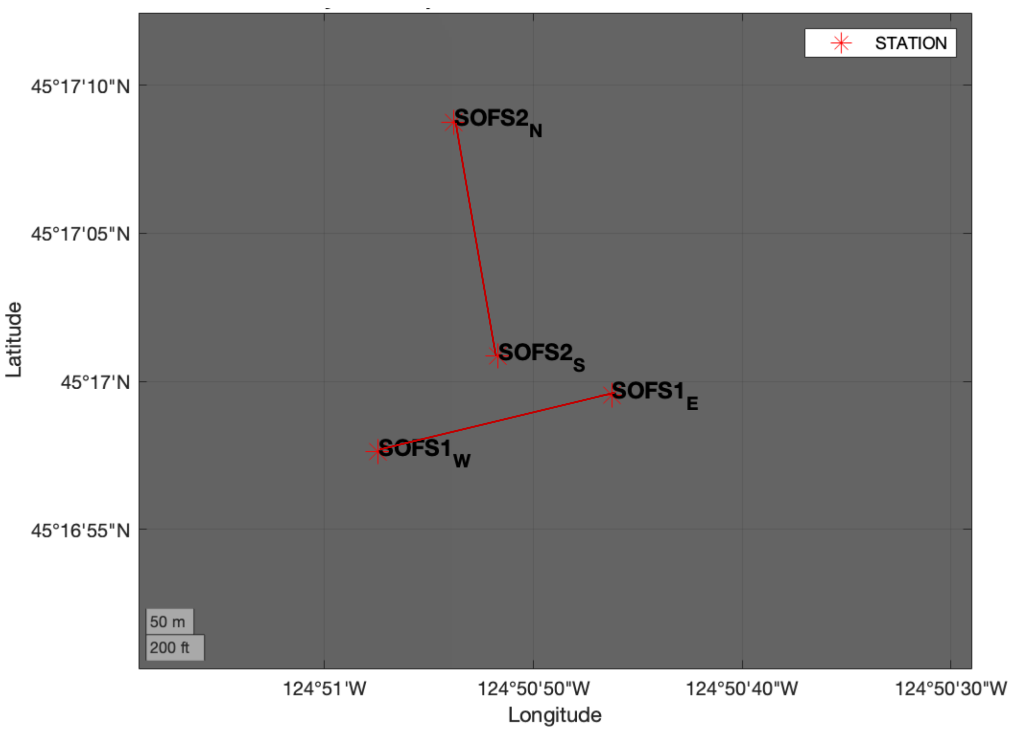
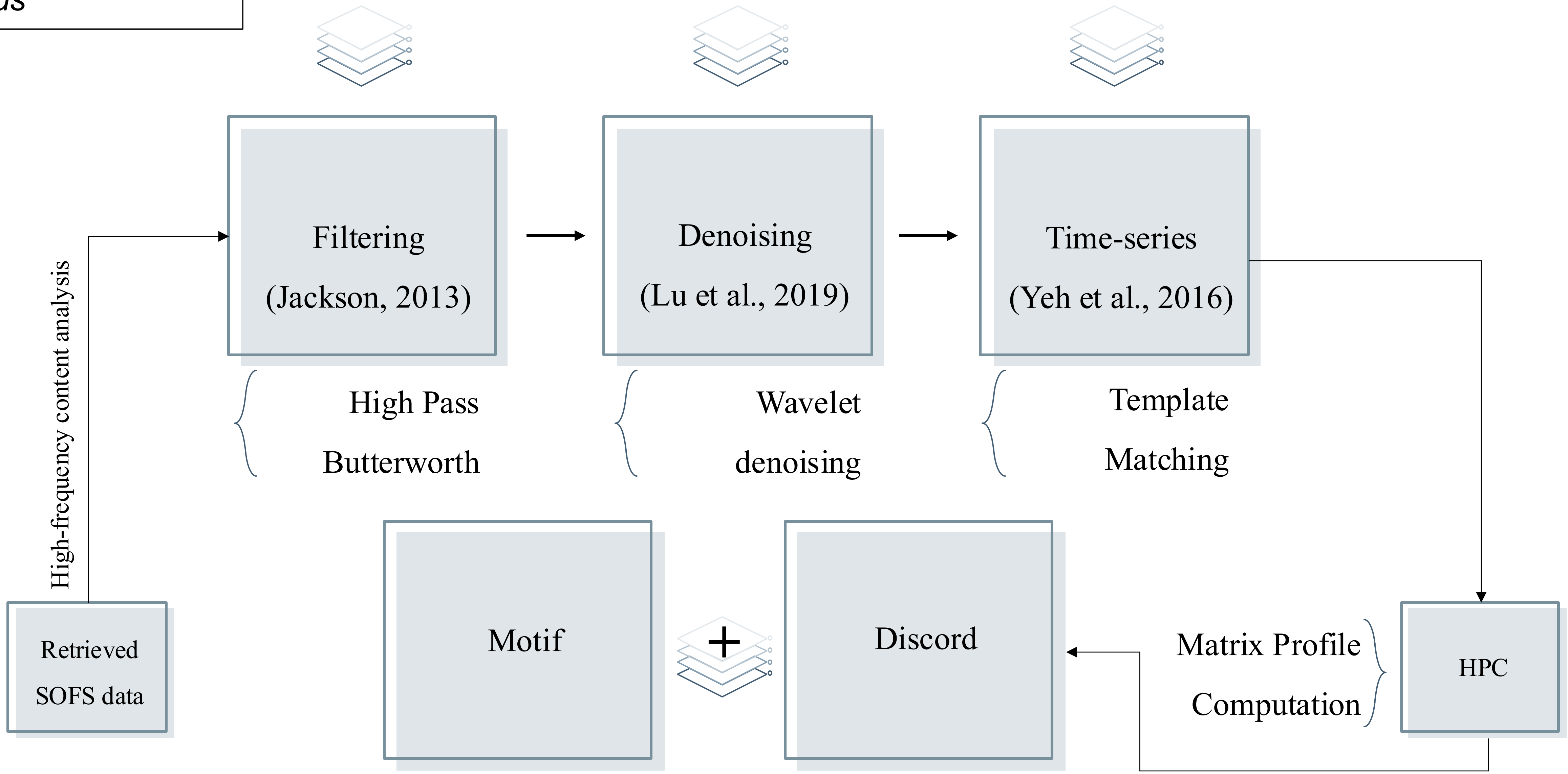


Fig: Location of the SOFS instruments in Pacific NW.

Methods


Filtering
(Jackson, 2013)
Denoising
(Lu et al., 2019)
Time-series
(Yeh et al., 2016)
High Pass
Butterworth
Wavelet
denoising
Template
Matching
High-frequency content analysis
Retrieved
SOFS data
Motif
Discord
Matrix Profile
Computation
HPC

Time-series

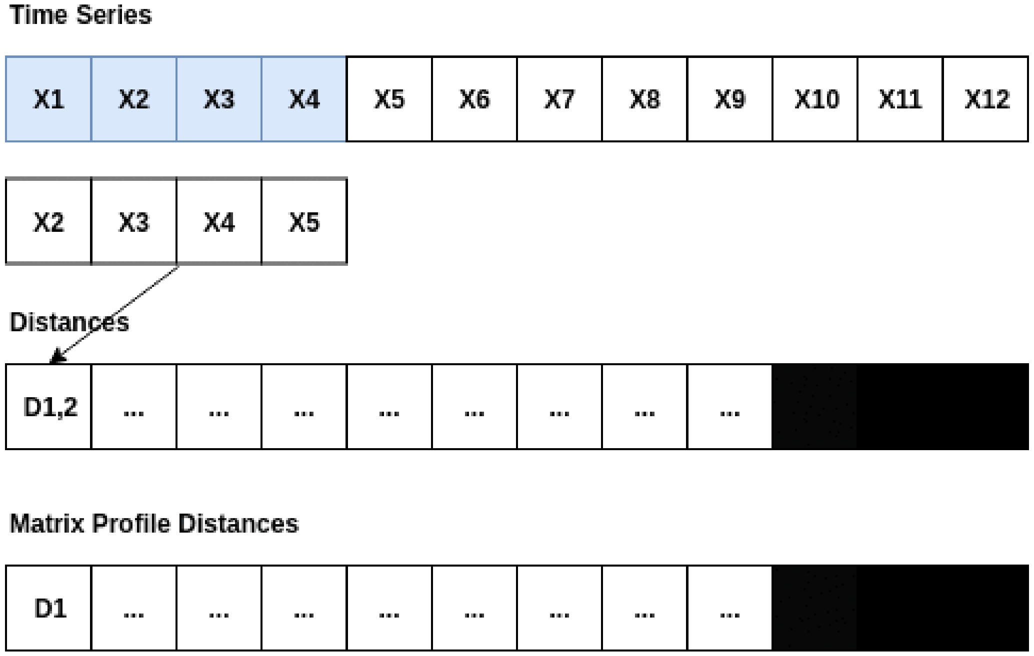
(Yeh et al., 2016)

(Yeh et al., 2016, 2017, 2018; Zhong & Mueen, 2024)

Matrix Profile

$$\mathbf{MP}[i] = \min\left(\mathrm{dist}(\mathbf{T}[i : i+m], \mathbf{T}[j : j+m])\right)$$

*Here, **MP**[i] is the Matrix Profile value at index i; **T**[i : i+m] and **T**[j : j+m] are subsequences of length m from the time series **T**; dist represents the z-normalized Euclidean distance.*



*Fig/GIF: Computation procedure of Matrix profile without any prior templates (**Source: Marrs, 2019 at TDS Archive**)*

Time-series

(Yeh et al., 2016)

(Yeh et al., 2016, 2017, 2018; Zhong & Mueen, 2024)

Matrix Profile

$$\text{Motif} = \arg\min_{i,j} \mathbf{MP}[i], \quad i \neq j$$

Finds repeated patterns (i.e., LFEs, tremor bursts):

Motif

$$\mathbf{MP}[i] = \min\left(\mathrm{dist}(\mathbf{T}[i : i+m], \mathbf{T}[j : j+m])\right)$$

Finds unusual patterns (i.e, instrument noise bursts, marine activities):

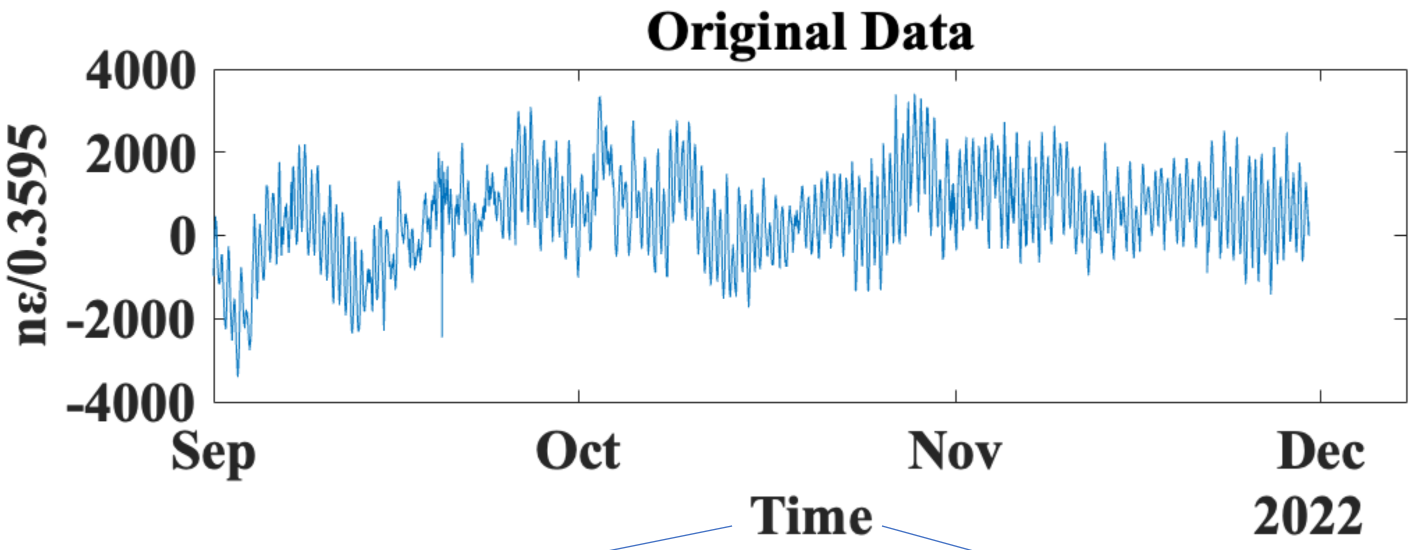
Discord

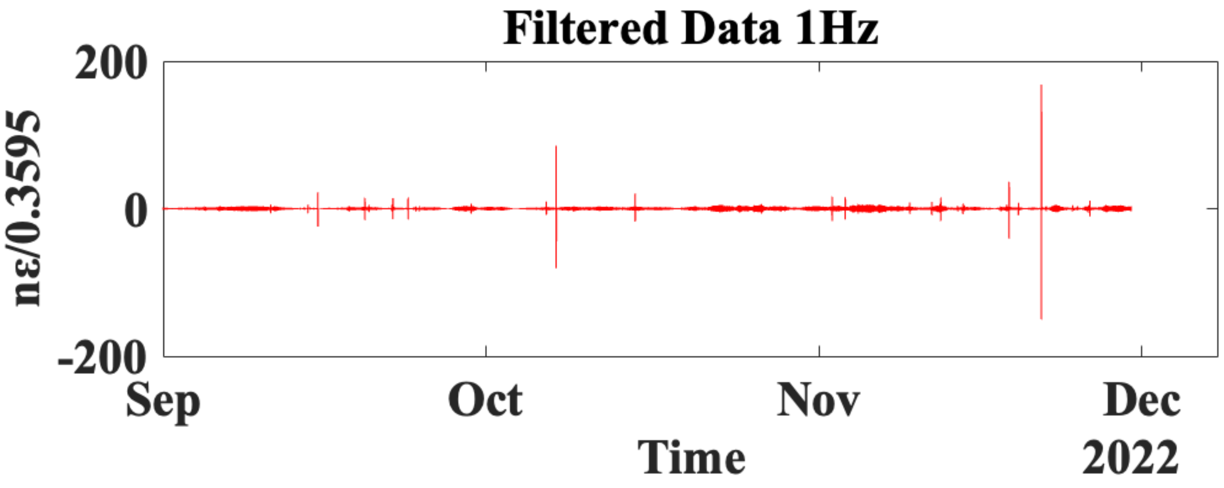
$$\text{Discord} = \arg\max_{i} \mathbf{MP}[i]$$

*Here, **MP**[i] is the Matrix Profile value at index i; **T**[i : i+m] and **T**[j : j+m] are subsequences of length m from the time series **T**; dist represents the z-normalized Euclidean distance.*

Preliminary Results

Fig: Original data and filtered data with 1hz and 2hz cut off frequency





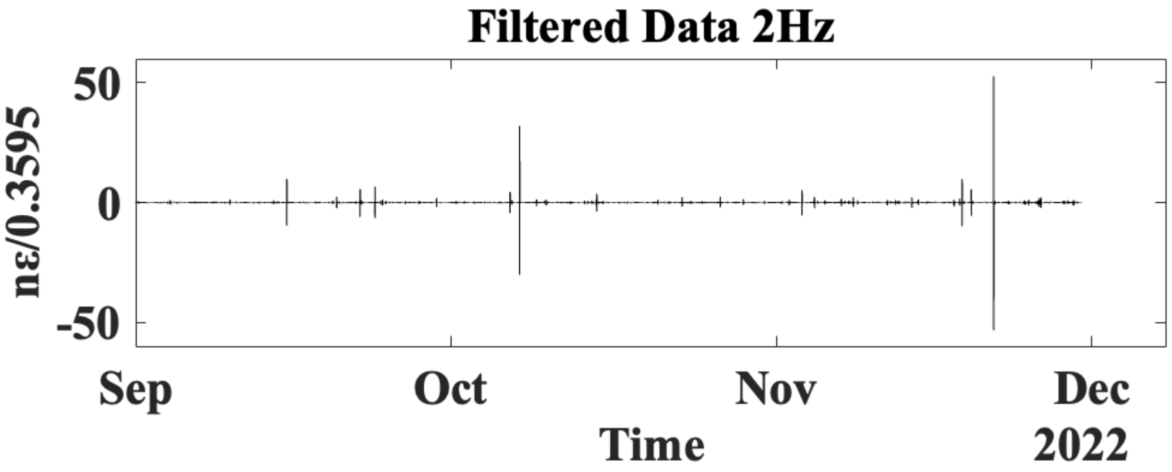
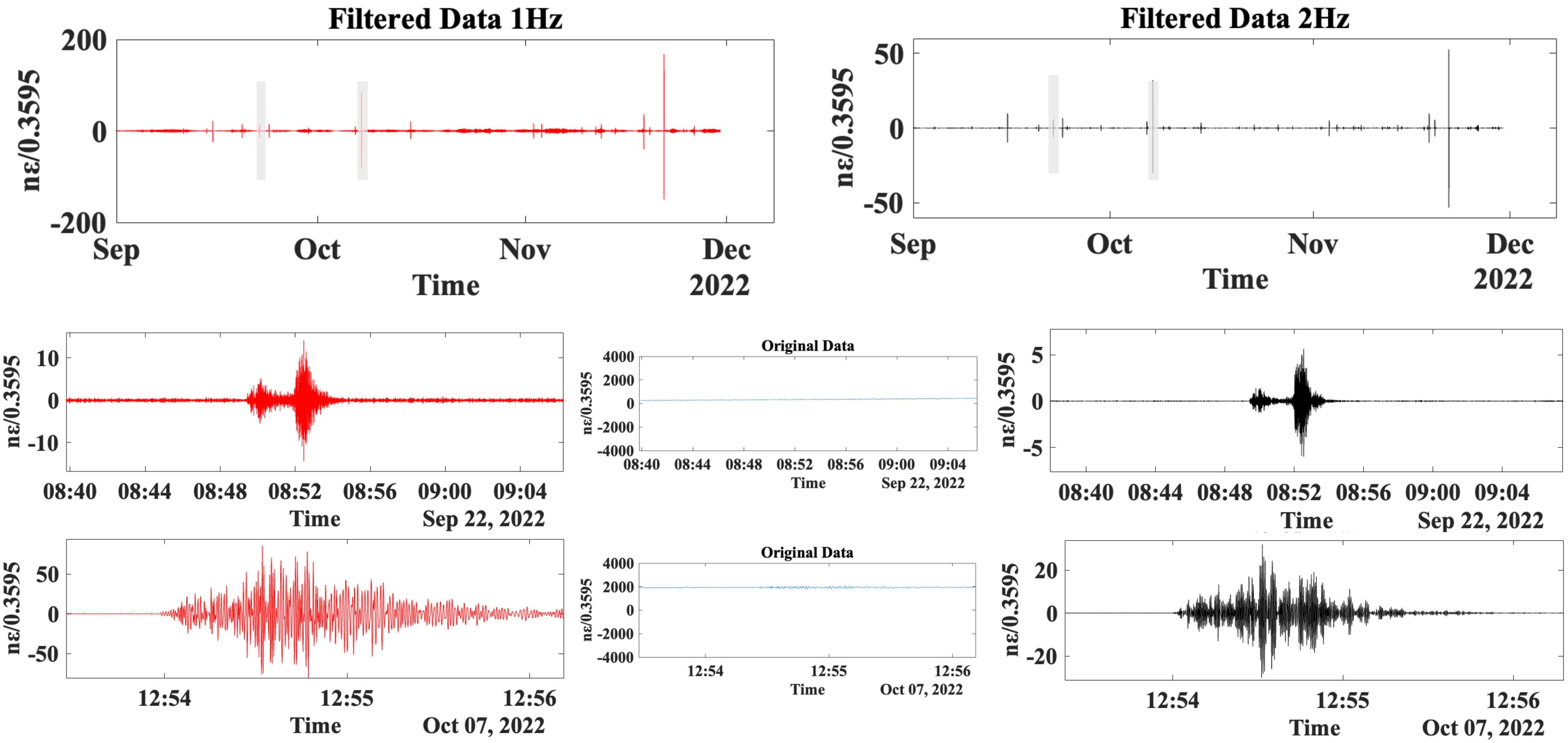


Fig (Cont.)


Filtered Data 1Hz
200
0
-200
nε/0.3595
Sep
Oct
Nov
Dec
2022
Time
Filtered Data 2Hz
50
0
-50
nε/0.3595
Sep
Oct
Nov
Dec
2022
Time
nε/0.3595
10
0
-10
08:40 08:44 08:48 08:52 08:56 09:00 09:04
Time
Sep 22, 2022
Original Data
4000
2000
0
-2000
-4000
nε/0.3595
08:40 08:44 08:48 08:52 08:56 09:00 09:04
Time
Sep 22, 2022
nε/0.3595
5
0
-5
08:40 08:44 08:48 08:52 08:56 09:00 09:04
Time
Sep 22, 2022
nε/0.3595
50
0
-50
12:54 12:55 12:56
Time
Oct 07, 2022
Original Data
4000
2000
0
-2000
-4000
nε/0.3595
12:54 12:55 12:56
Time
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nε/0.3595
20
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Time
Oct 07, 2022

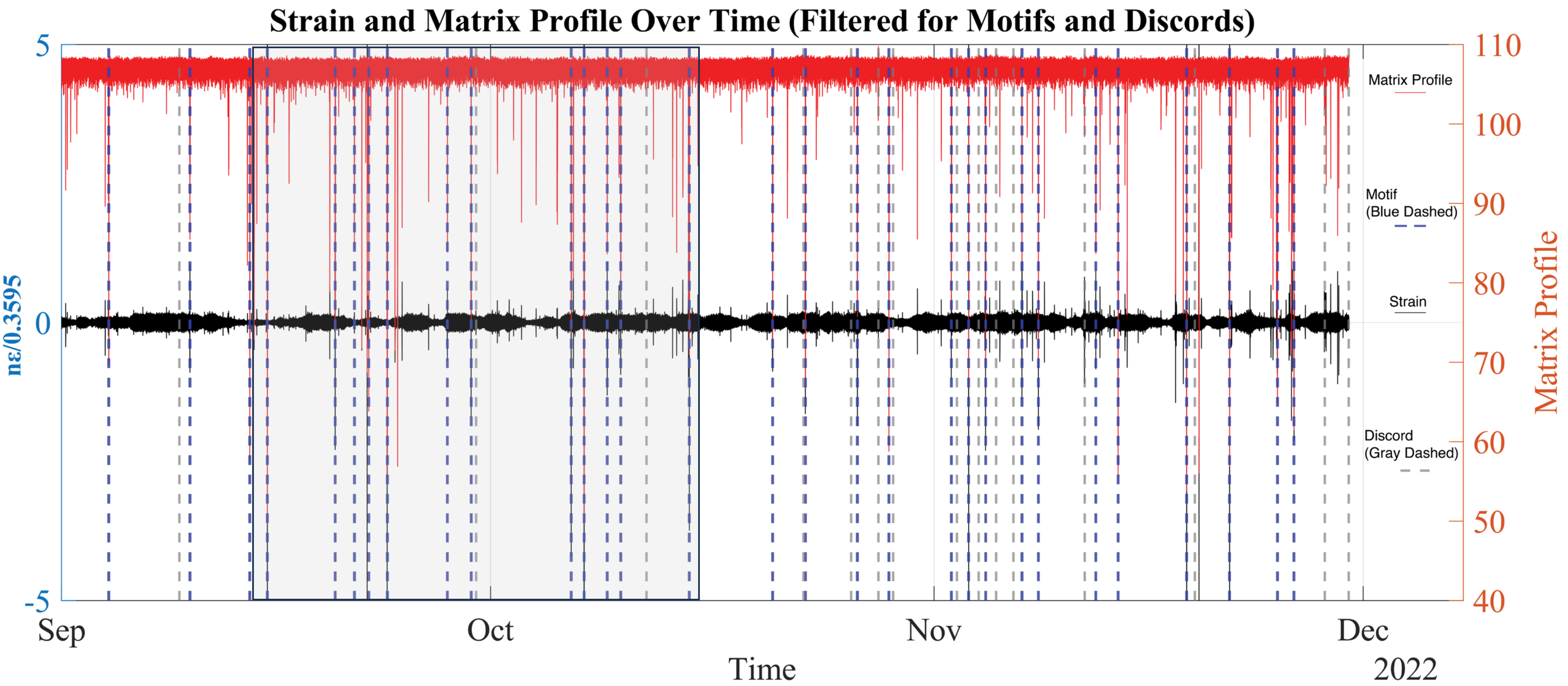


Fig: 15-minute matrix profile with motif and discord discovery for full 8hz strain data (EW) for 90 days including the SSE events.

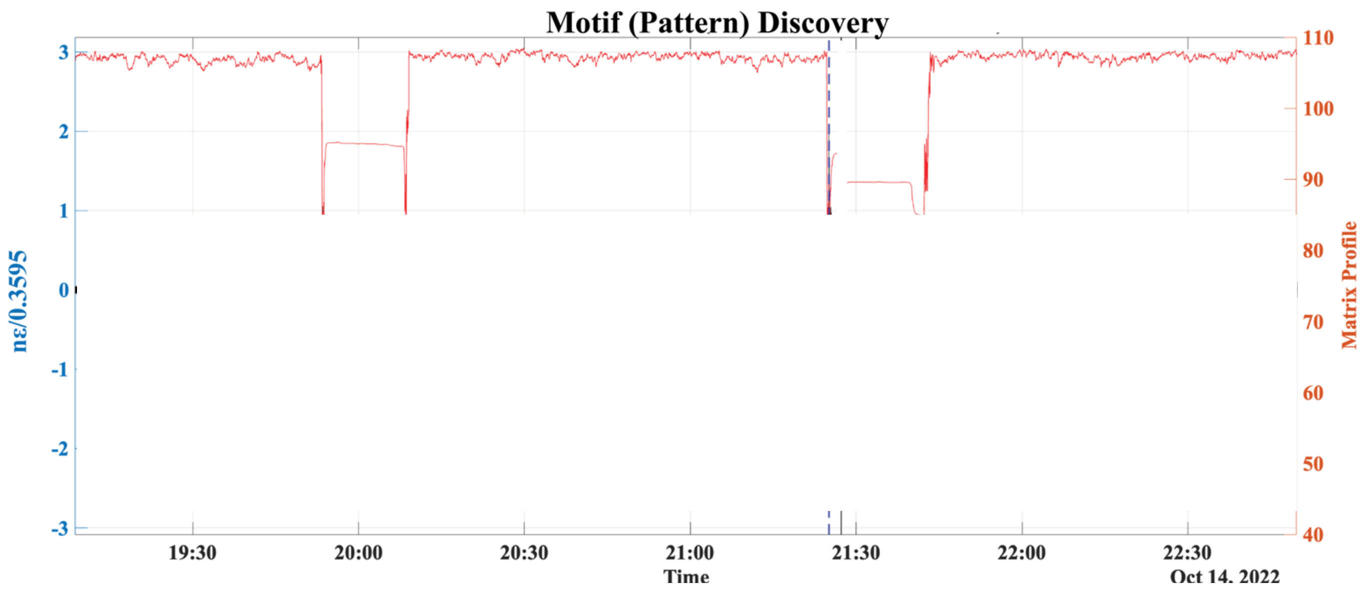
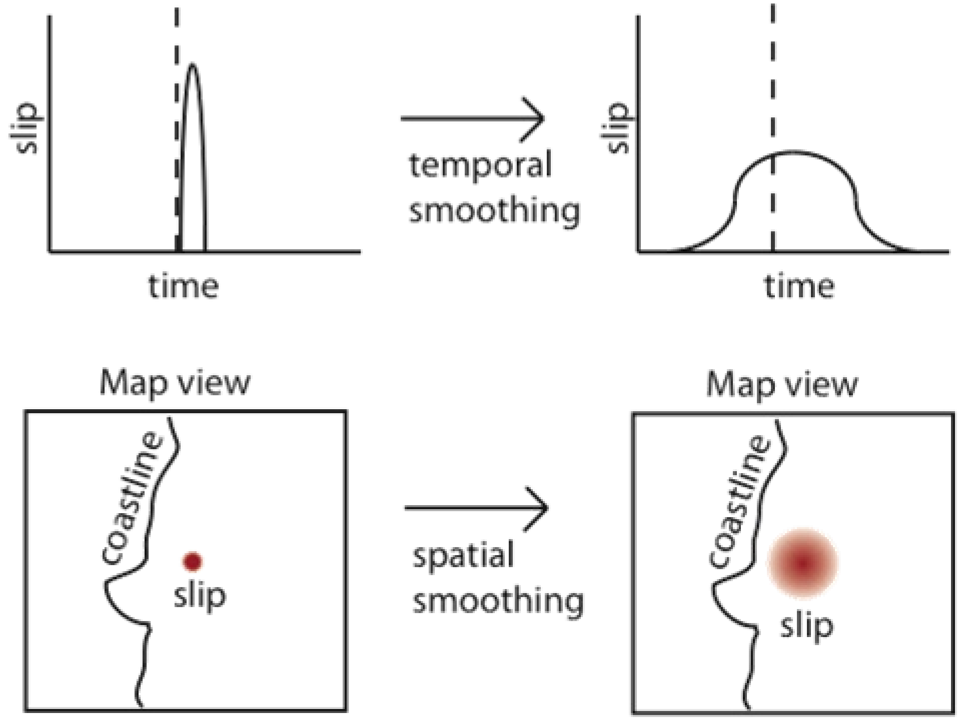


Fig: Motif discovery of a small cataloged event, where seismic events have been perfectly captured (Top Panel). In the bottom panel, there are discord showing the anomaly and uncatalogued events time. Denoising was performed prior to the matrix profile computation in the high-performance computer cluster.

Joint Inversion of Strain Signals

- **Goal:** Integrate offshore SOFS strainmeter data with existing onshore geodetic and strain measurements.
- Build a time-dependent inversion model to identify offshore slow slip patches and improve the spatial and temporal resolution of slip distributions.



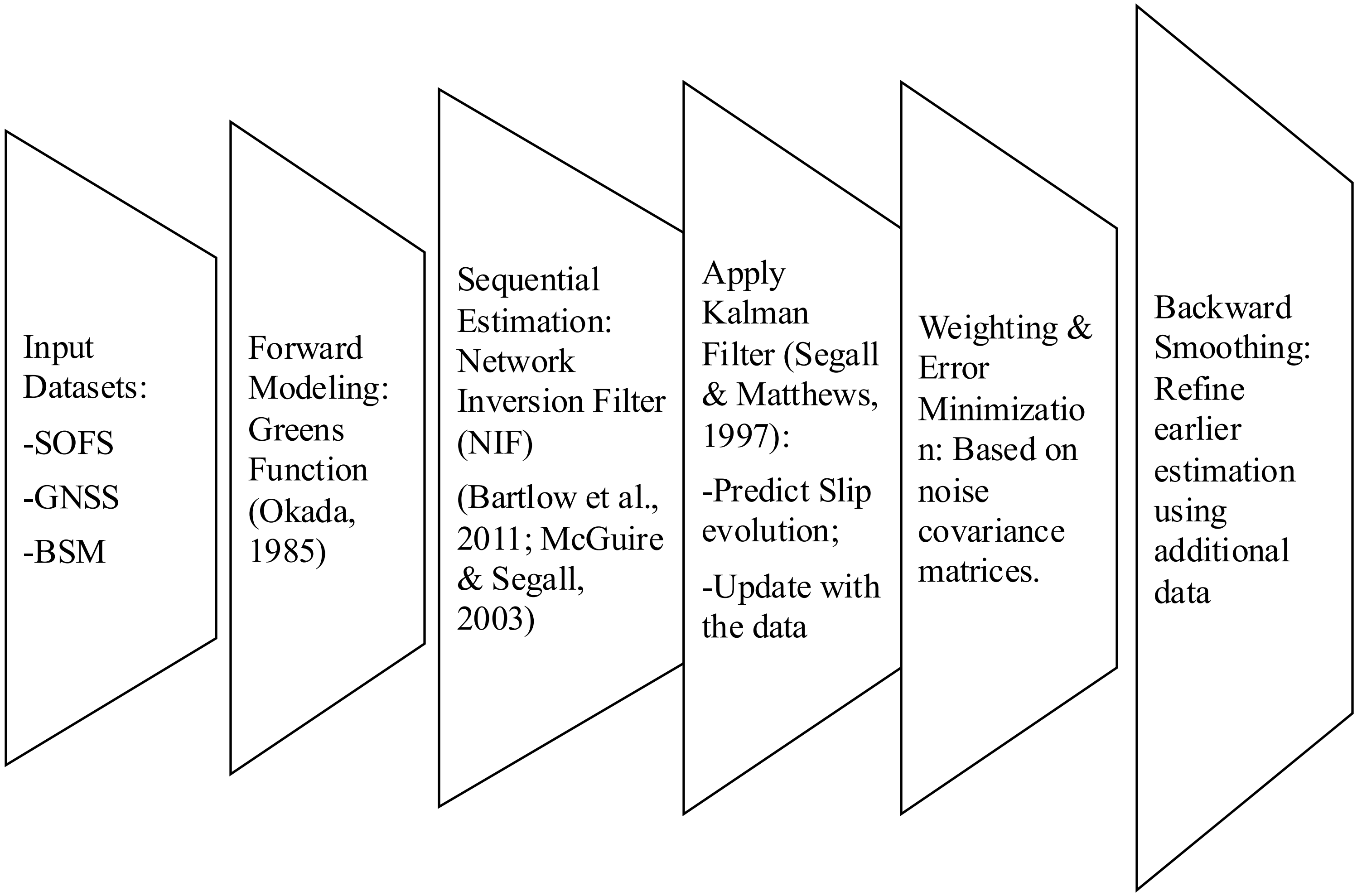
Proposed Methods

Integrated Data Approach:

- Combines offshore SOFS strain data, onshore GNSS displacement, and BSM shear strain to resolve offshore slip.
- Enhances spatial coverage, especially in poorly instrumented offshore regions.

Network Inversion Filter (NIF)

- The inversion starts with a prior slip model based on existing observations or a uniform distribution.
- The model evolves by assimilating new geodetic data using a Kalman filter:
    - Prediction step: Based on prior slip evolution.
    - Update step: Incorporates new observations to adjust predictions.



Expected Results

Reproduced attempt based on Bartlow et al., 2011 for Time-dependent onshore GPS/GNSS inversion

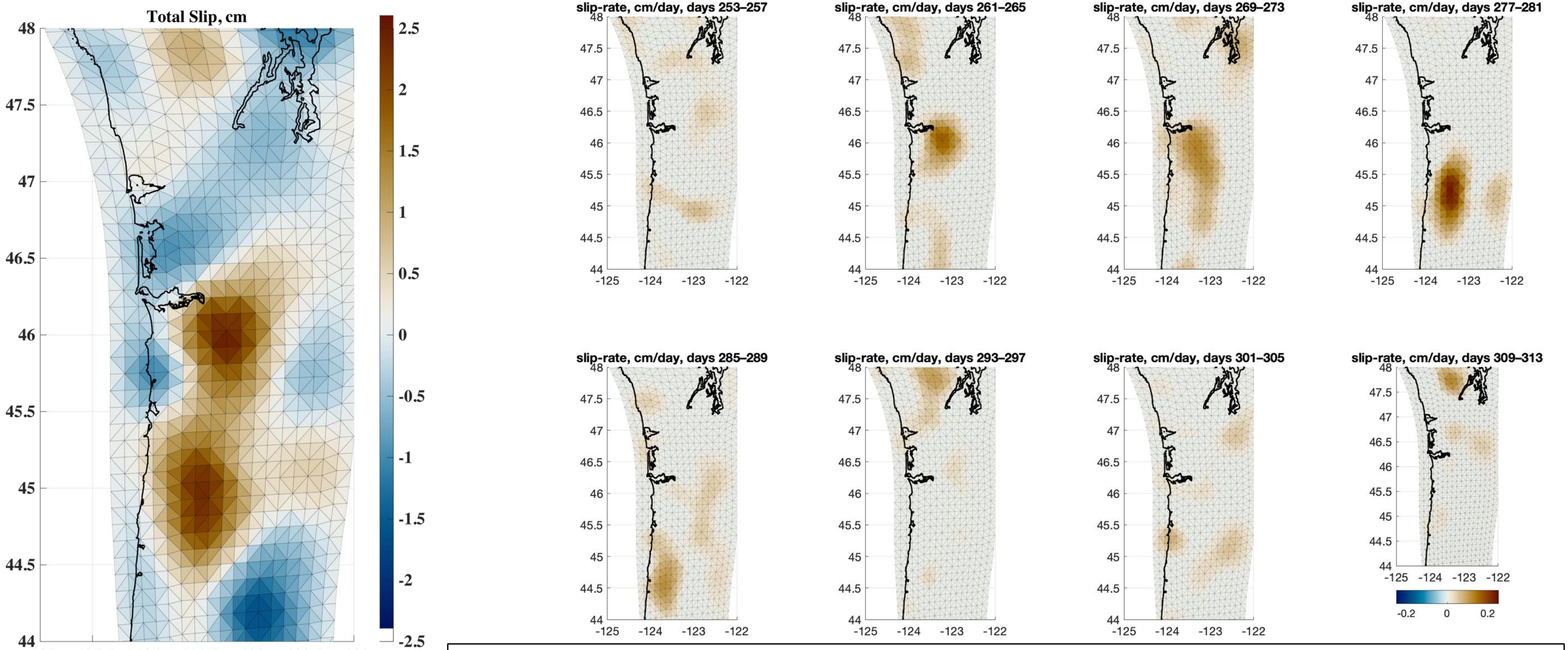
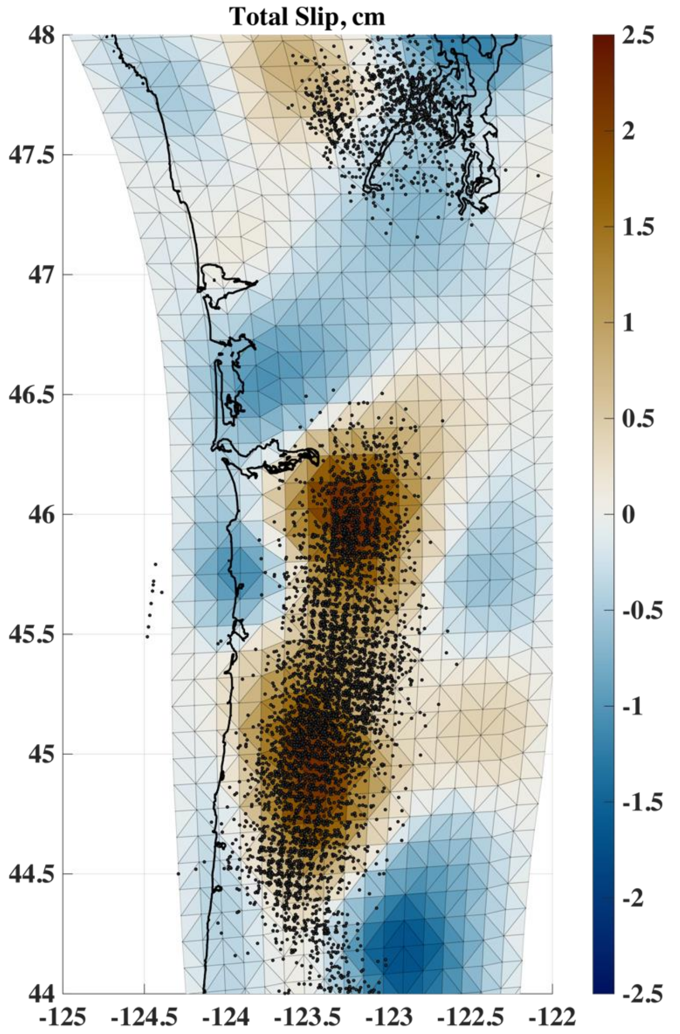


Fig: Estimated cumulative slip on the plate interface for the 2022 ETS event (Left). Snapshots from the slip-rate history (Right).

Expected Results

Reproduced attempt based on Bartlow et al., 2011 for Time-dependent onshore GPS/GNSS inversion



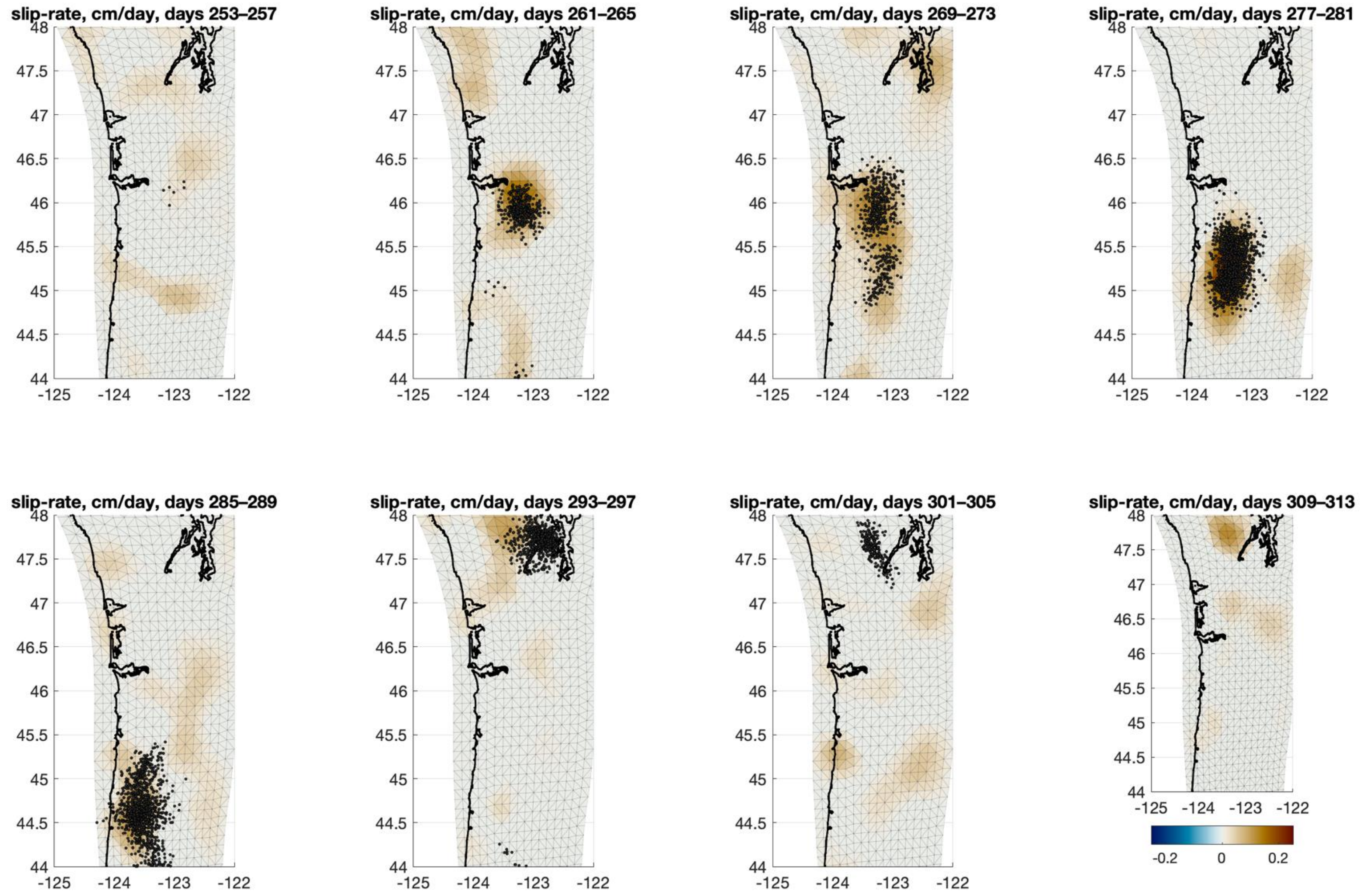


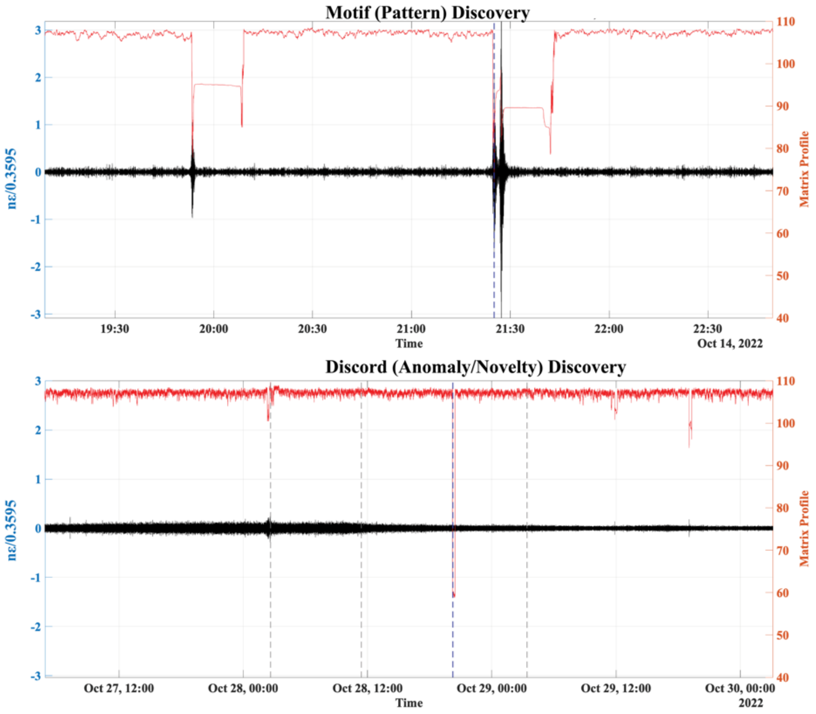
Fig: Estimated cumulative slip (Left) & Snapshots from the slip-rate history (Right) with the PNSN tremor cataloged overlay.

- **Advancing detection**
  Demonstrated the potential of SOFS strainmeter data to detect offshore tremors where traditional geodetic tools fall short.
- **Algorithmic innovation**
  Matrix Profile enables event discovery without templates, revealing subtle, repeating, and deformation signals in strain data.
- **Scientific implication**
  This opens new pathways for studying offshore and retrospective tremor analysis in otherwise data-poor environments.

Current & Future Directions

- **Integration of data to enhance resolution**
  By integrating offshore (SOFS) and onshore (GNSS, BSM) data in a Network Inversion Filter (NIF) framework, the offshore slip field is better resolved.
- **Time-dependent modeling**
  Sequential Kalman filtering + backward smoothing captures evolving slip distributions across the megathrust.
- **Implication for hazard modeling**
  This offers refined estimates of strain accumulation and release offshore—critical for assessing megathrust rupture potential.

- **Physics-informed ML tackles complexity**
  PINNs simulate the co-evolution of slip, pore pressure, porosity, and permeability—offering an alternative to traditional FEM approaches.
- **Coupled fluid-fault dynamics**
  Results highlight how feedback between evolving porosity and fluid pressure can influence SSE triggering, especially near the fault core.
- **Scalable framework**
  Integrates GNSS constraints to produce physically plausible and data-consistent spatiotemporal slip models.



→ **Detection** (Project 1)

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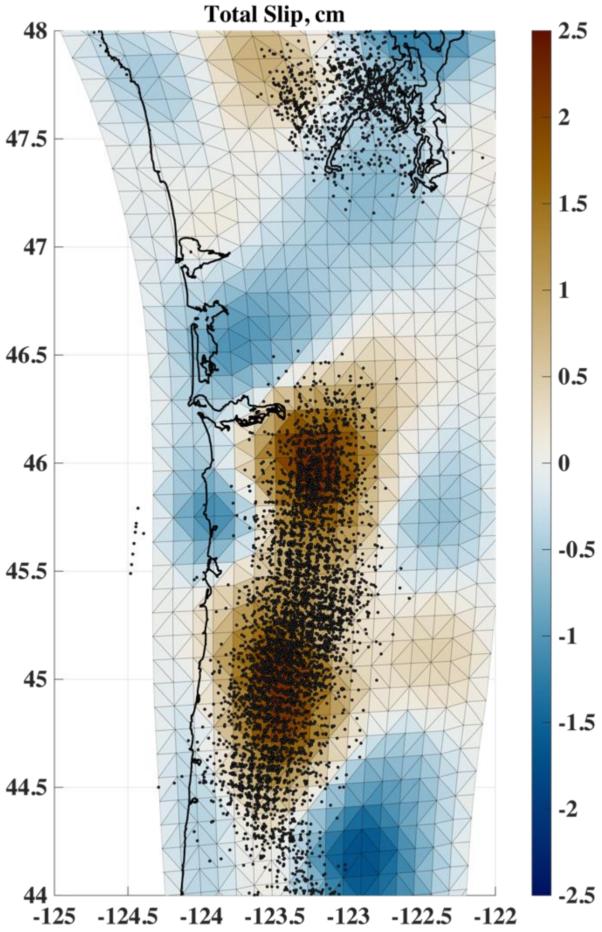

→ **Modeling slip distribution** (Project 2)

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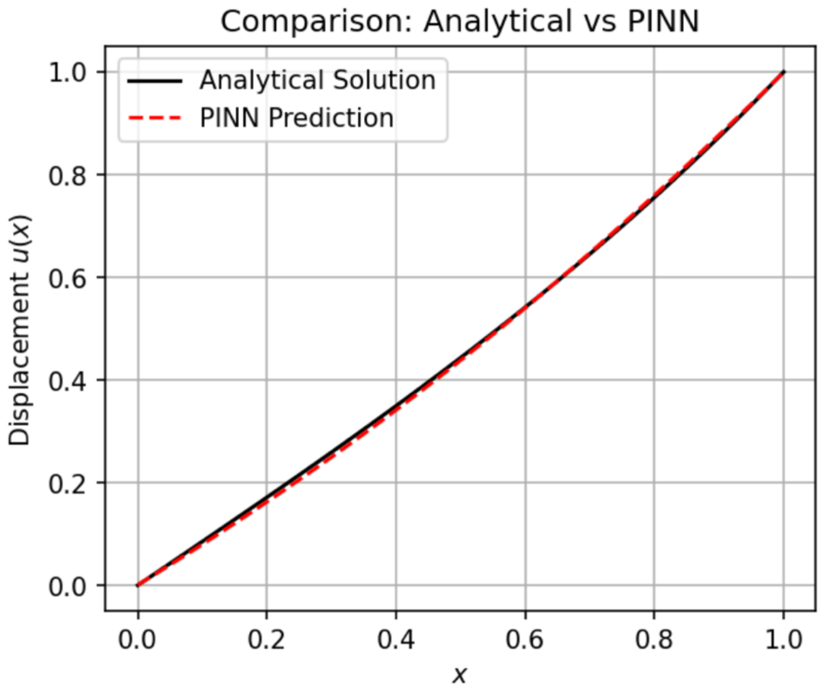

→ **Understanding mechanisms** (Project 3)

Thank You