

Imaging the Hydrothermal Plumbing Architecture of Steamboat Geyser Using a Dense Nodal Array and Seismic Interferometry

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Steamboat (SB) eruption

The tallest geyser: height of 120 m



Cistern Spring

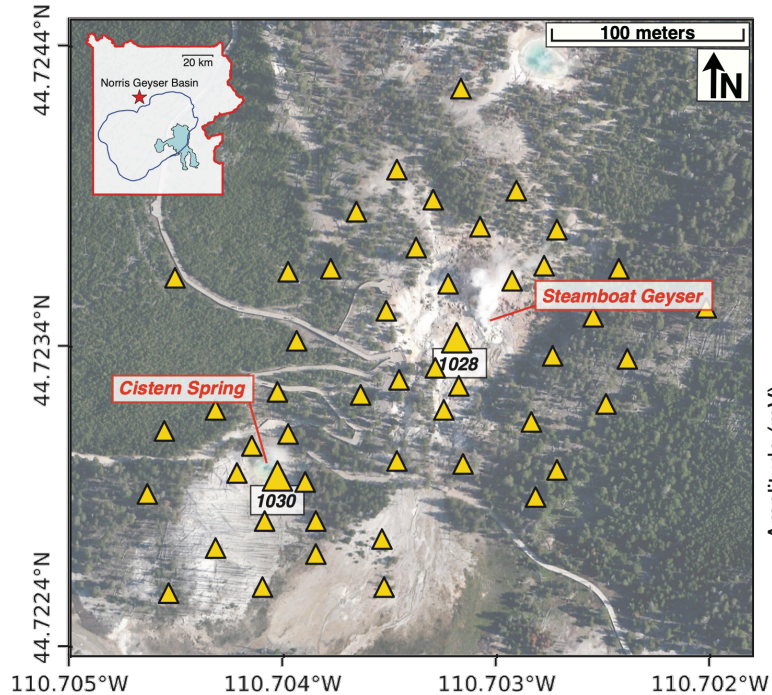
Before SB eruption

After SB eruption

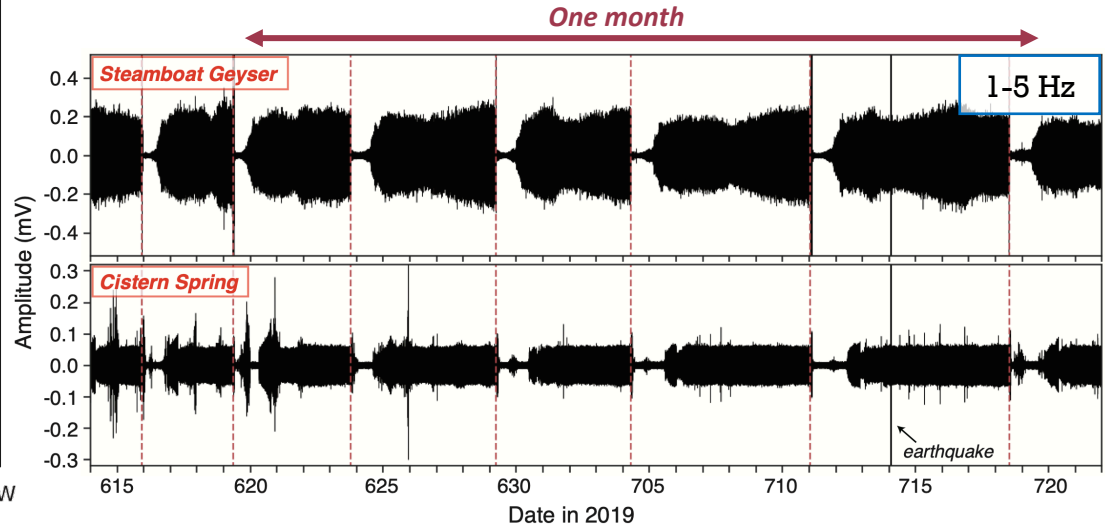


Photo credit: Michael Poland

Seismic array and hydrothermal tremor



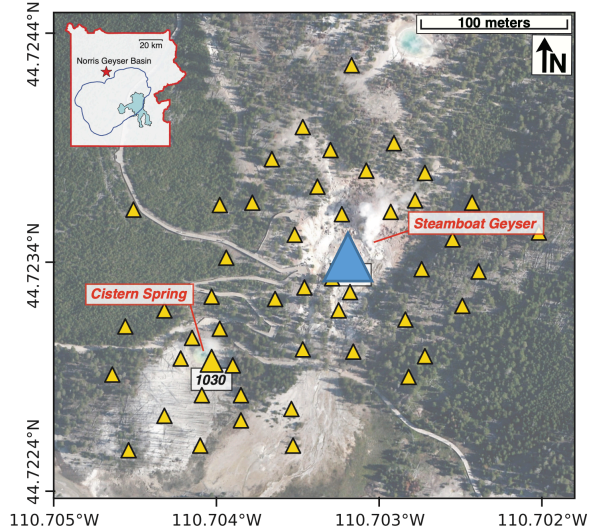
- Source mechanism: bubble collapse/nucleation
- Distinct spatiotemporal pattern between Cistern and Steamboat
→ Concurrent multiple sources within the seismic array



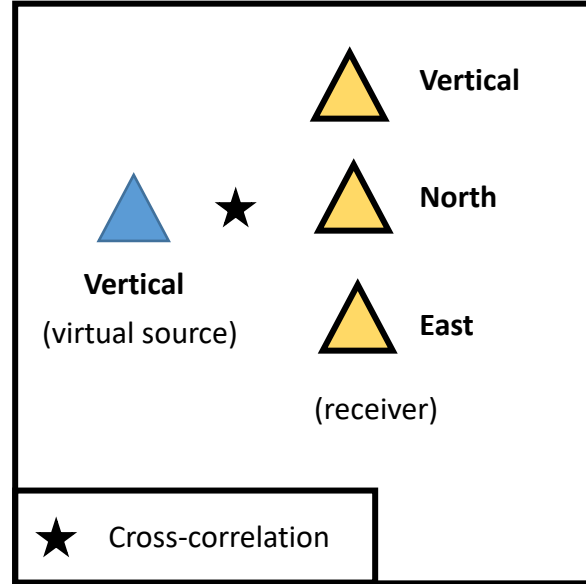
Number of stations: 50 Spacing: 15–35 m Aperture: ~250 m

June–July 2019 Seven eruption cycles

Seismic interferometry



Non-diffusive source environment



Cross-correlation helps us:

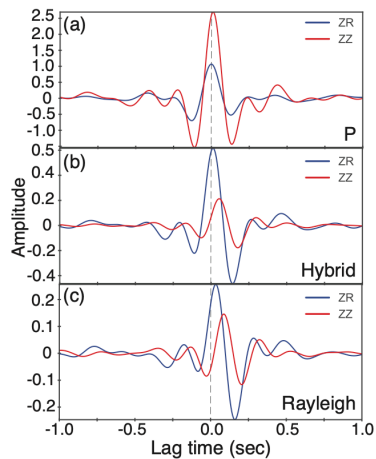
- Amplify coherent signal
- Filter out incoherent signal
- Isolate the signal of interest

By preserving the relative amplitude, we can study its

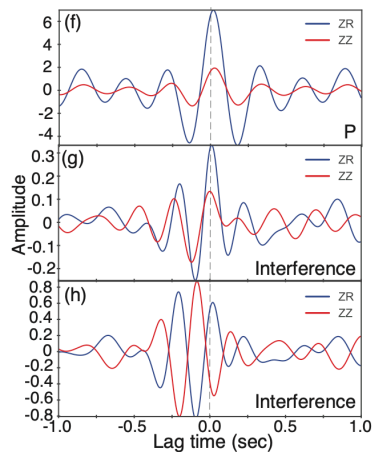
- Particle motion
- Polarization

CCFs

Source station
near Steamboat



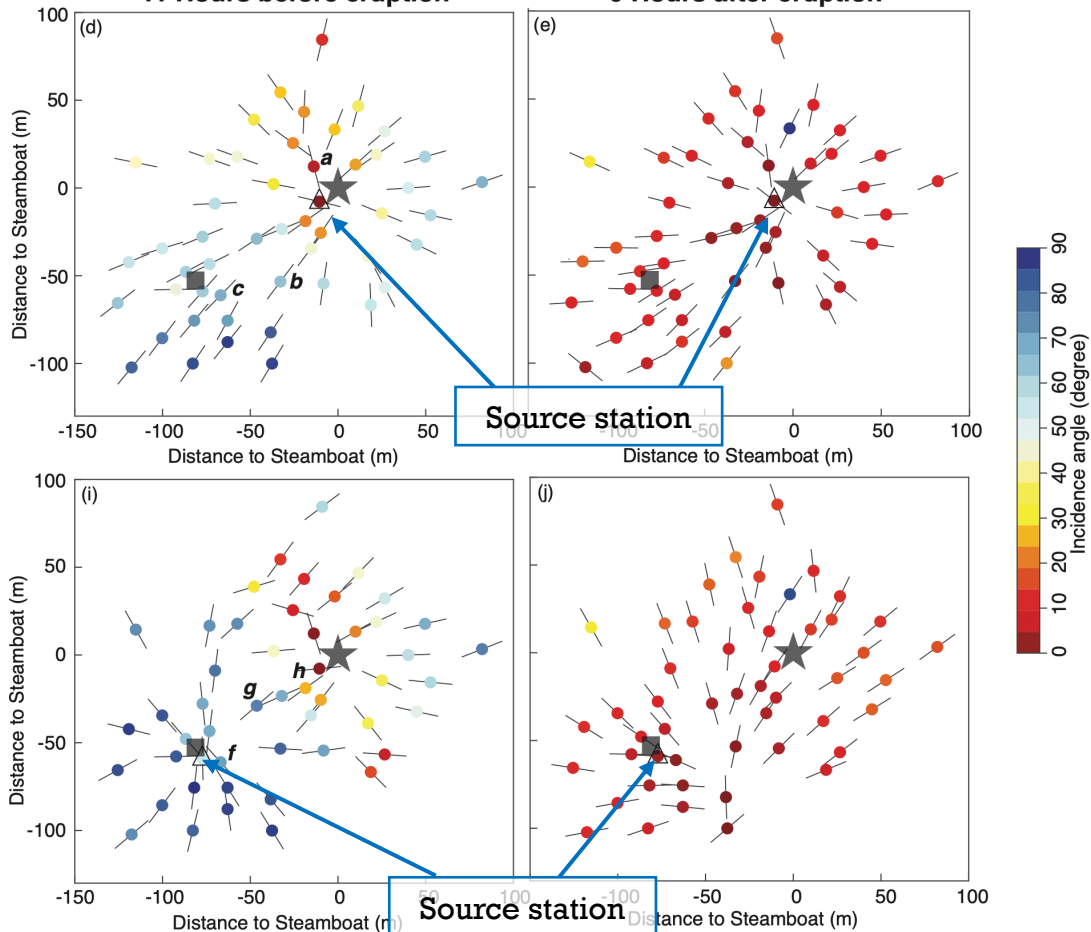
Source station
near Cistern



Polarization

11 Hours before eruption

9 Hours after eruption



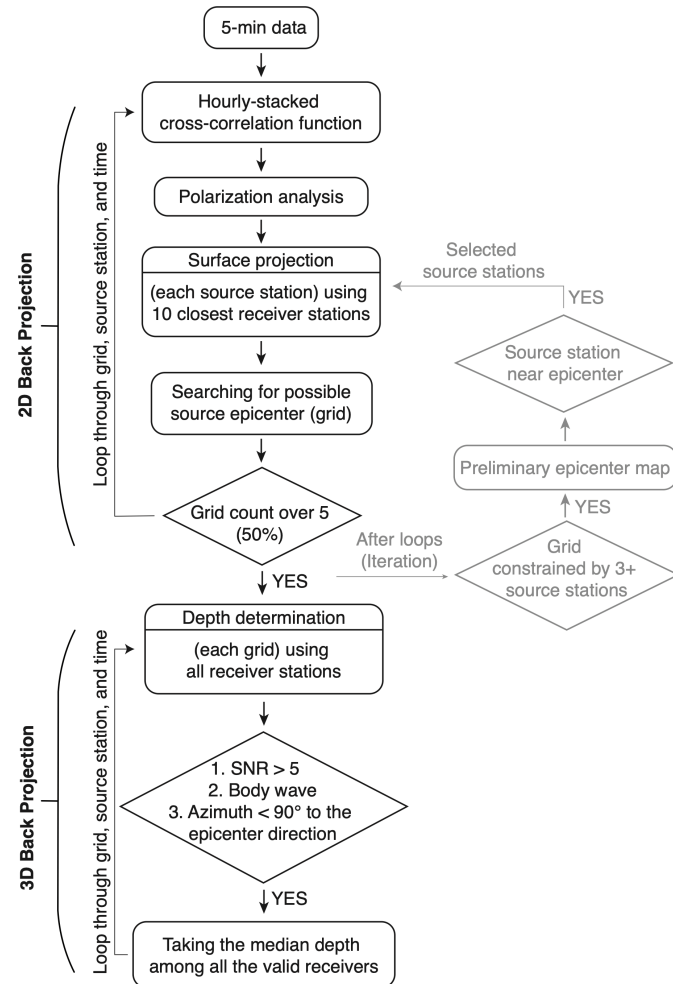
Workflow

(2D)

Source detection and epicenter

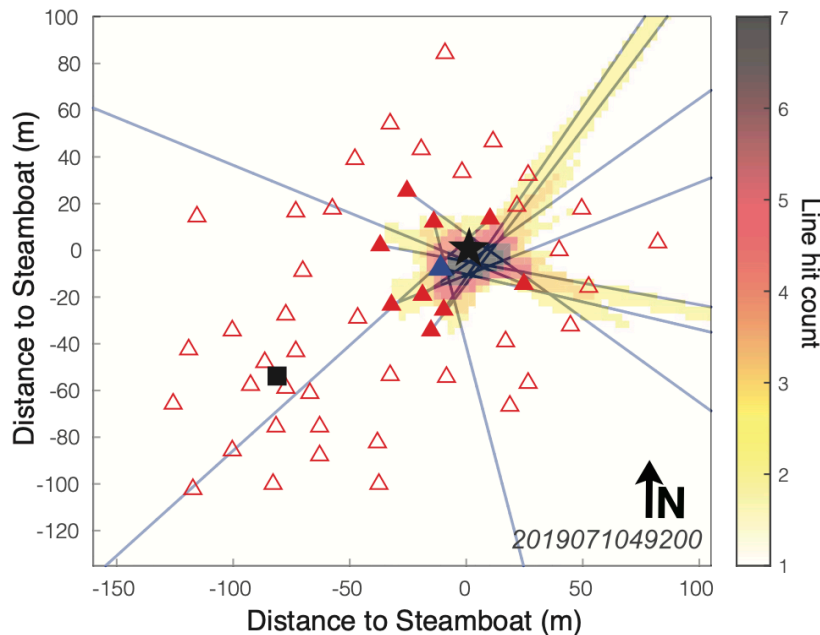
(3D)

Source depth and hypocenter



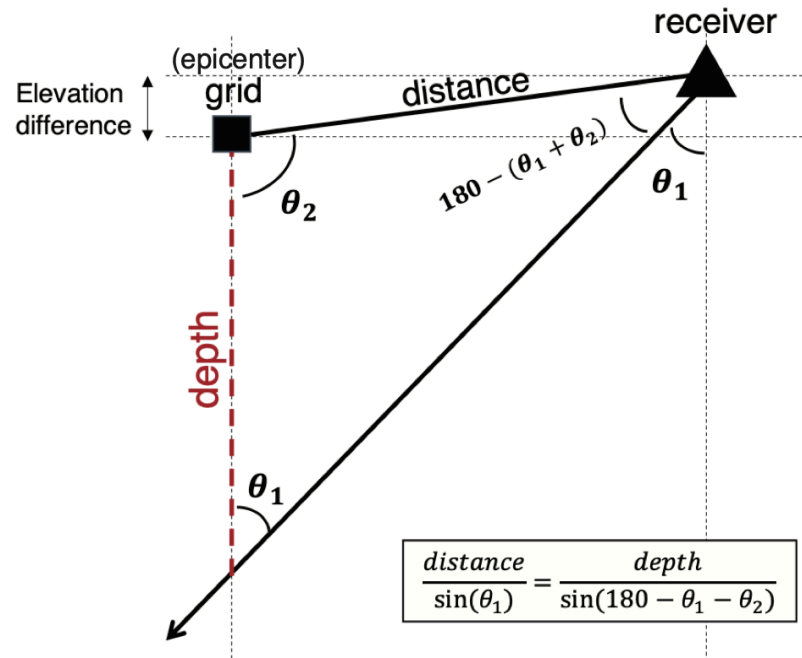
Back projection

Surface back projection (2D)



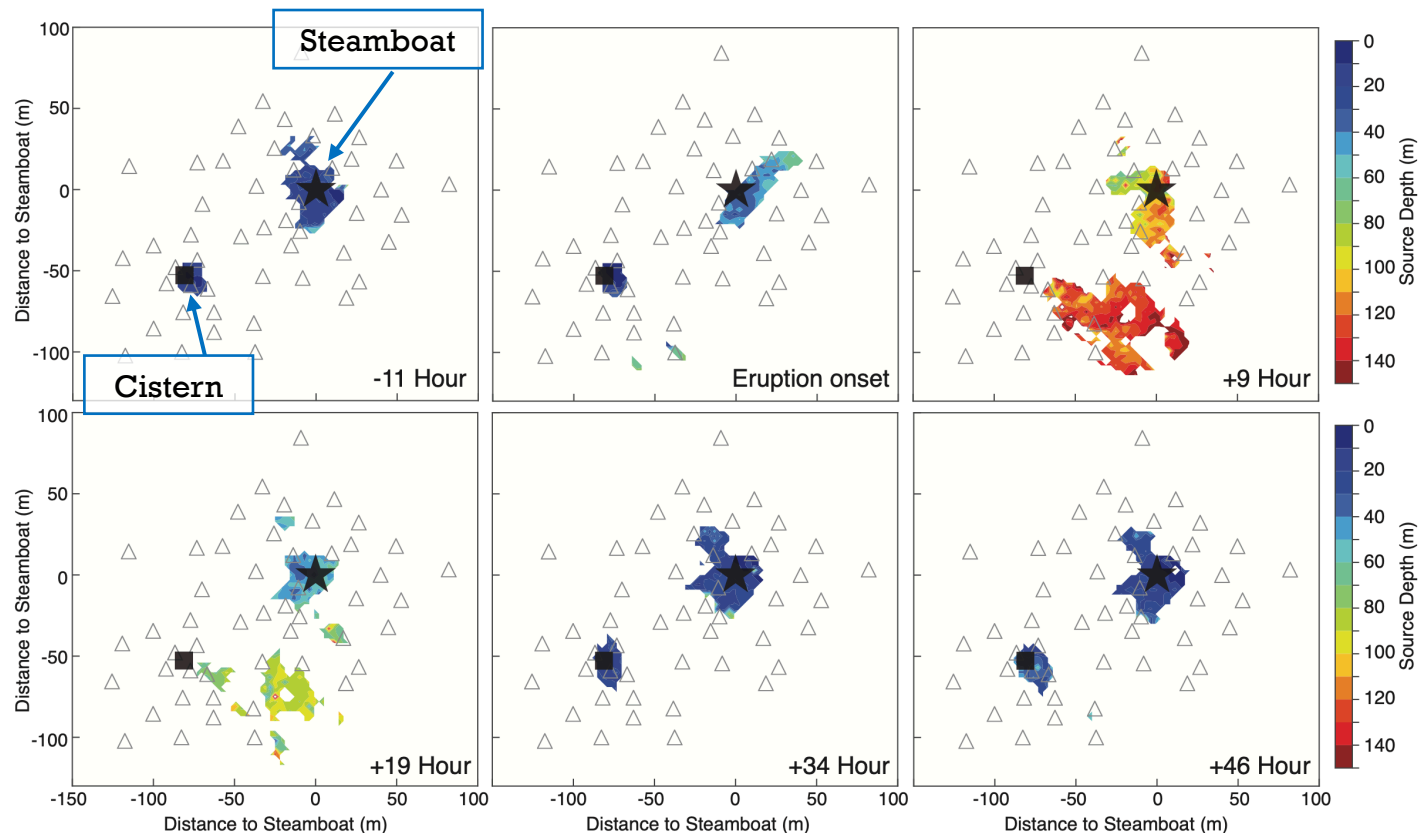
- To account for different source strength, we use a subset of nearby receivers (10) to detect the possible source epicenter.

Depth back projection (3D)



- We utilize the linearity of the observed P wave to back project the source depth assuming a 1D half space model.

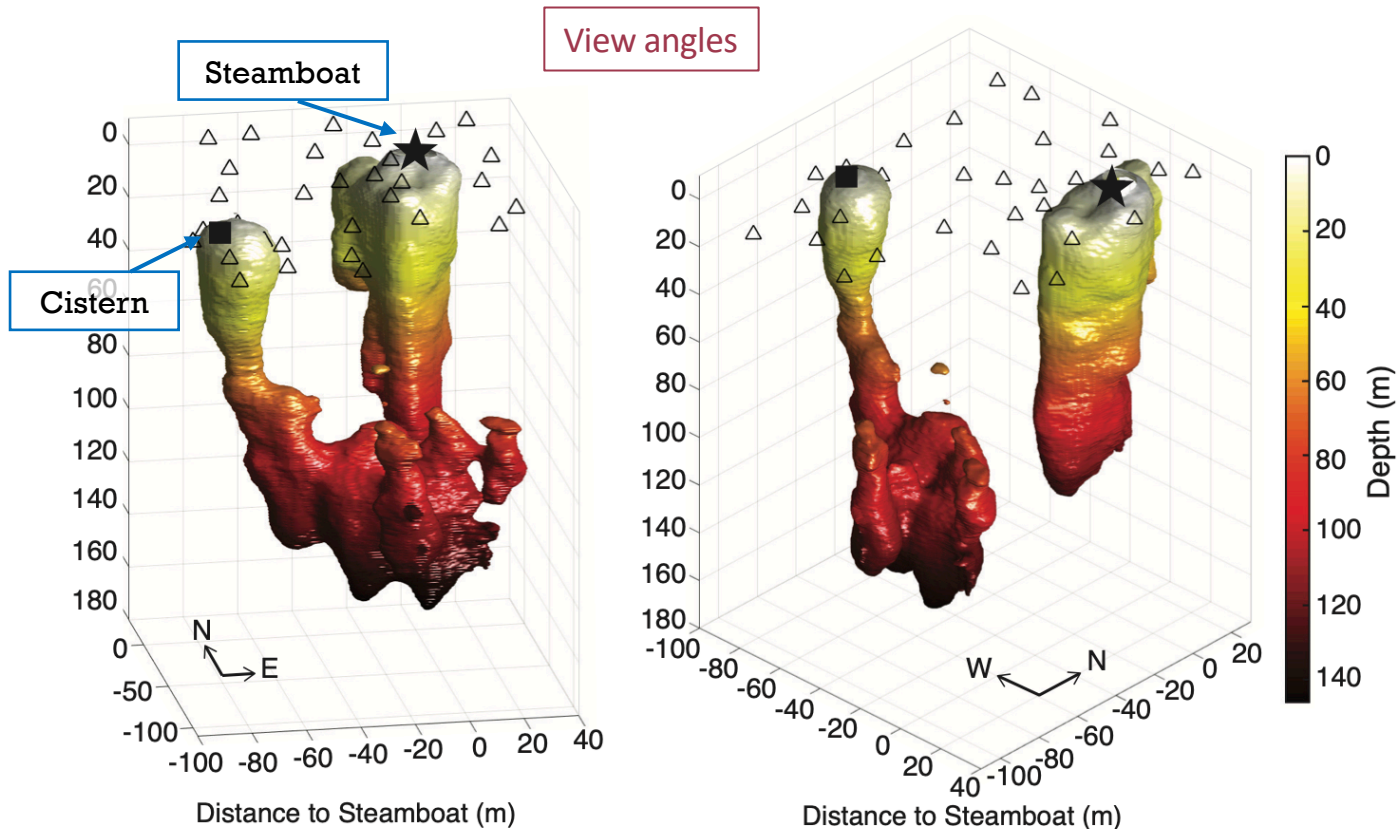
Tremor source distribution



- The tremor distribution is presented as the possible source area (2D) with the corresponding depth (3D).
- Before eruption, both tremors are right beneath both features.
- Steamboat tremor immediately drops at the onset of eruption while Cistern tremor has a delayed response.
- Cistern tremor reveals a deep and offset source area likely representing a hydrothermal reservoir.

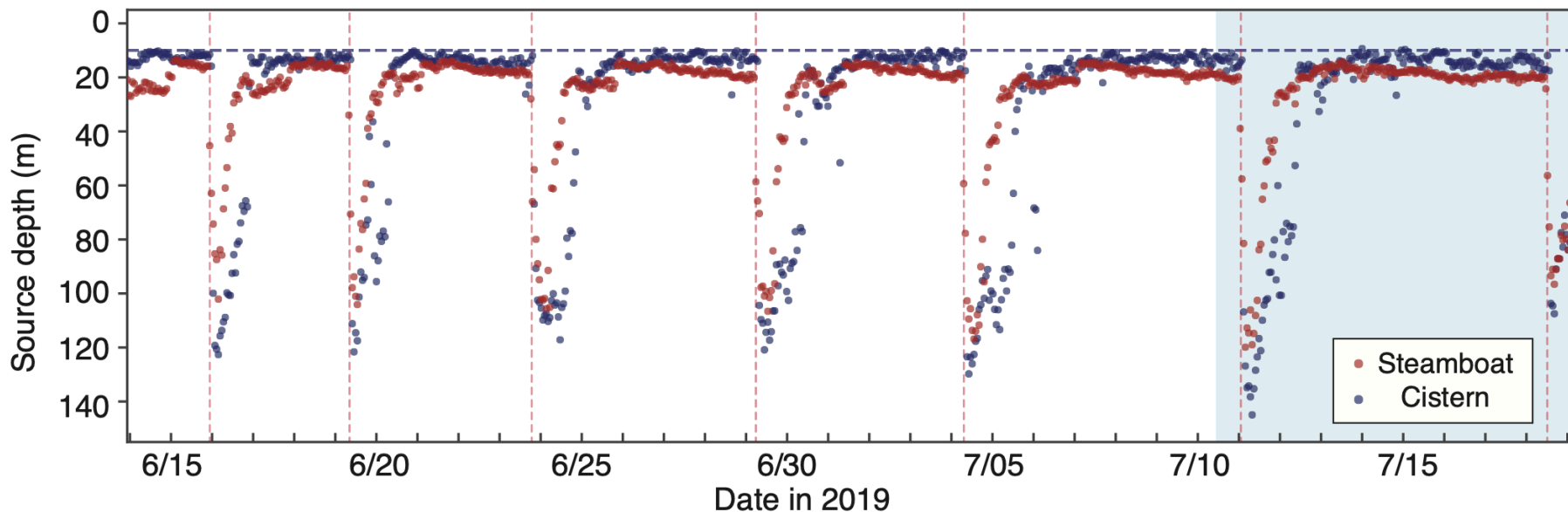
Plumbing outline

- Isosurface of the tremor distribution
- The plumbing extends to 140 m depth
- No clear connection between Steamboat and Cistern



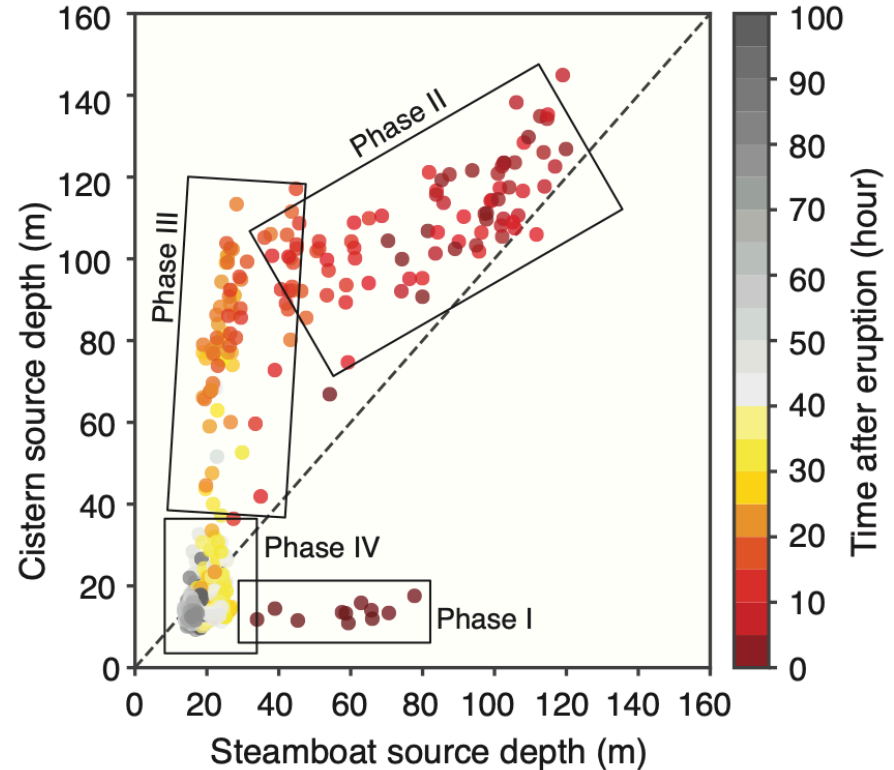
Recharge evolution

- The tremor depth is found the deepest compared to other geyser systems worldwide.
- The upward migration follows the warming of the conduit until the next eruption.
- The distinct migration rate indicates the connection between is likely porous media.



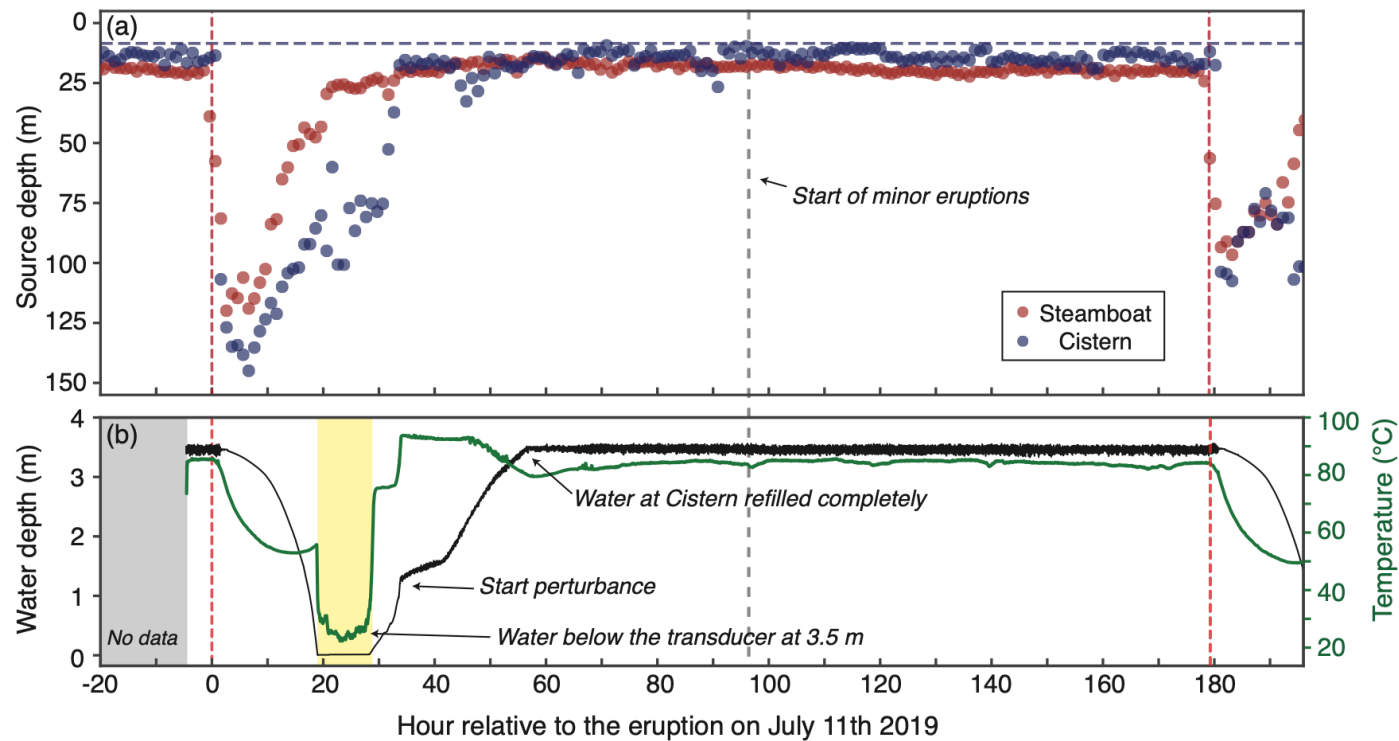
Distinct migration rates

- This is showing the distinct depth and migration rate of the tremors (the black-dashed line marks the equal depth).
- Phase I represents the delayed response of Cistern to the Steamboat eruption.
- Phase II represents Cistern has a slower migration in which the outlined large reservoir.
- Phase III represents a sudden fast migration along the depth at Cistern, which corresponds to the narrow conduit.
- Phase IV represents both tremors return to shallow until the next eruption. Note that the elevation at Cistern is ~10 m lower than Steamboat, suggesting Cistern's tremor is closer to the surface.



In situ data

- This plot serves as a ground truth validation (in the shallow depth) with the tremor location comparing the in situ pressure and temperature data recoded within Cistern's pool.
- The fact that Cistern's physical status is not responding to Steamboat's minor eruption also suggests the two features might not connected via open channels.



Conclusions

- Seismic interferometry permits extraction of signal of interest, which enables the studies on weak seismic sources and/or within noisy environments.
- We developed a method that combines multicomponent cross-correlation, polarization analysis, and 2D then 3D progressive back projections to constrain spatiotemporal locations of the 1–5 Hz hydrothermal tremor.
- The 3D tremor source locations outlines Steamboat and Cistern's plumbing structure down to 140-meter depth.
- Tracking the depth horizon of the tremor migration, we reveal the recharge evolution and interaction of Steamboat and Cistern throughout the eruption cycles with hourly resolution.
- We infer that Steamboat and Cistern are likely connected through a porous medium instead of open channels.

Thank you for your attention!

This work has recently published at JGR (Wu et al., 2021).

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JGR Solid Earth

RESEARCH ARTICLE

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Key Points:

- We develop an interferometric-based polarization analysis to investigate high-resolution spatiotemporal pattern of hydrothermal tremor
- We construct the first image of the plumbing architecture for the Steamboat-Cistern system to a depth of 140 m
- We illuminate the recharge evolution of Steamboat Geyser and Cistern Spring and the dynamic subsurface interaction between the two features

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Imaging the Subsurface Plumbing Complex of Steamboat Geyser and Cistern Spring With Hydrothermal Tremor Migration Using Seismic Interferometry

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Abstract Steamboat Geyser in Yellowstone National Park is the tallest active geyser on Earth and is believed to have hydrologic connection to Cistern Spring, a hydrothermal pool ~100 m southwest from the geyser vent. Despite broad scientific interest, rare episodic Steamboat eruptions have made it difficult to study its eruption dynamics and underground plumbing architecture. In response to the recent reactivation of Steamboat, which has produced more than 130 eruptions since March 2018, we deployed a dense seismic nodal array surrounding the enigmatic geyser in the summer of 2019. The array