Low Frequencies of Distributed Dynamic Strain Sensing enable unprecedented profiling of deep geothermal fluid production and injection

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1 Introduction

Challenge: Sustainable reservoir management depends on understanding reservoir inflow/outflow, but conventional methods can be challenging to deploy, show only snapshots, and require well intervention.

Solution: Deploy Distributed Dynamic Strain-Sensing (DDSS, also known as DAS), an fiber-optical technique that turns every fiber meter into a strain-temperature gauge.

Cable Deployment: The sensing cable (yellow, in Fig. 1) is attached to a sucker-rod and pushed into the reservoir [1].

Field campaign: Monitored restart of a 3.7 km producer (TH4, 2023) + 4.1 km injector (TH6, 2024) with DDSS; fibers reached ~1 km into the reservoir; sampled at 1 m / 2000 Hz (2m gauge length).

2 Methods

1. From Raw Strain Rate to DDSS Low-Frequency Response (LFDDSS): Fig. 2

- Cascading lowpass FIR filter for temporal decimation (2000Hz to 0.1Hz).
- Highlights ultra-slow optical phase changes with sensitivity to very small temperature variations due to thermal deformation [2,3].
- Enables visualization of DDSS data in the minute-hour range.

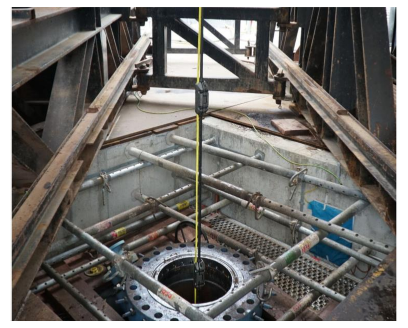

Fig 1: Fiber optic cable installation TH6.

2. From LFDDSS to flow profiling: Fig. 3

- **Velocity tracking:** Measure slopes of heightened strain-rate streaks (prod.) or strain-rate zero-crossings (inj.).
- **Flow rate conversion:** With known cross-section A and velocity v, obtain volumetric rate $Q = v \times A$.
- **Flow profile:** Distribute the picked velocities/flow rates along depth.
- **Diagnostics:** Breaks or inflections highlight active inflow/outflow zones.
- **Integration:** The velocity curve is a cumulative production profile along the well.

4 LFDDSS flow profiling along depth

Production Velocity Profile (Fig. 3a): Picked slopes of (red) plumes (Fig. 3c and Fig. 2a, Box I).

- Onset of plume indicates flow zone location and activation time; amplitude and duration show zone's heat contribution.
- Lower velocity outliers reflect the start of production ramp-up with lower flow rates and locations of significant fluid inflow (1).

Injection Velocity Profile (Fig. 3b): Picked zero-crossings (Fig. 3d and Fig. 2b, Box II).

- Overlapping zero-crossings enable multiple picks for certain depth intervals.
- Without advanced signal processing, only lower initial ramp-up velocities are discernible in the main flow zone (2).
- However, minor flow zones show higher velocities during ramp-up (3)

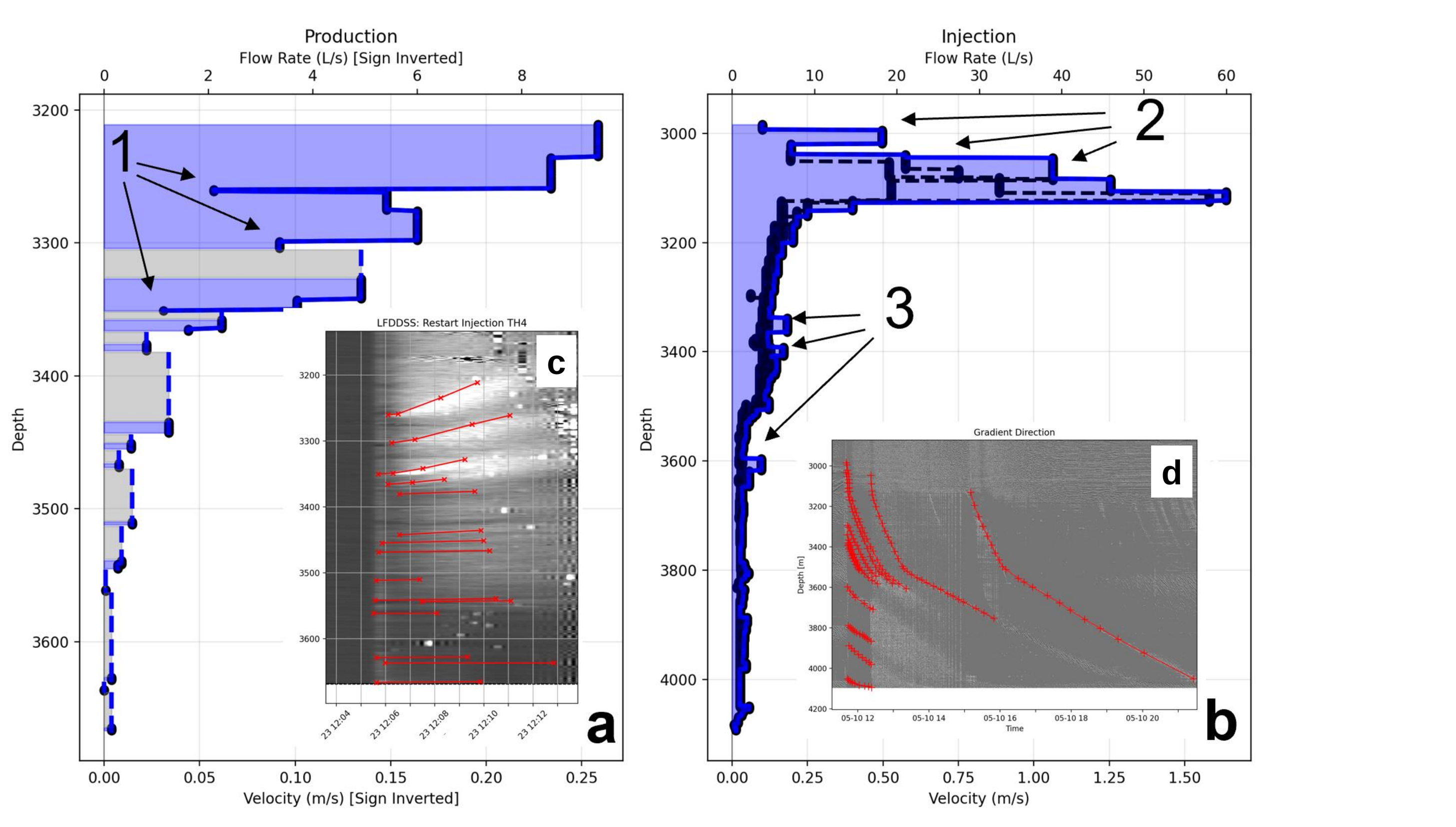

Fig. 3: Fluid velocity profiles in geothermal wells. a) Production and **b)** injection profiles with black dots marking peak fluid velocities (bottom x-axis) and flow rates (top x-axis). Solid blue lines show measured profiles; dashed lines and grey shading indicate interpolated values. **c)** and **d)** show corresponding picks (red crosses) and analyzed slopes (red lines) in the LFDDSS for production (Box I, Fig. 2a) and injection (Box II, Fig. 2b).

3 DDSS Low-Frequency Response.

1. Slope indicates velocity: Strain-rate slope changes indicate fluid speed; slope breaks mark casing transitions.

2. Amplitude spikes: High amplitudes in the 9 ⅝" liner reveal fast turbulent flow noise in the main inflow zone.

3. Vertical stripes: Instantaneous, uniform signals are likely sucker-rod motion artifacts [4].

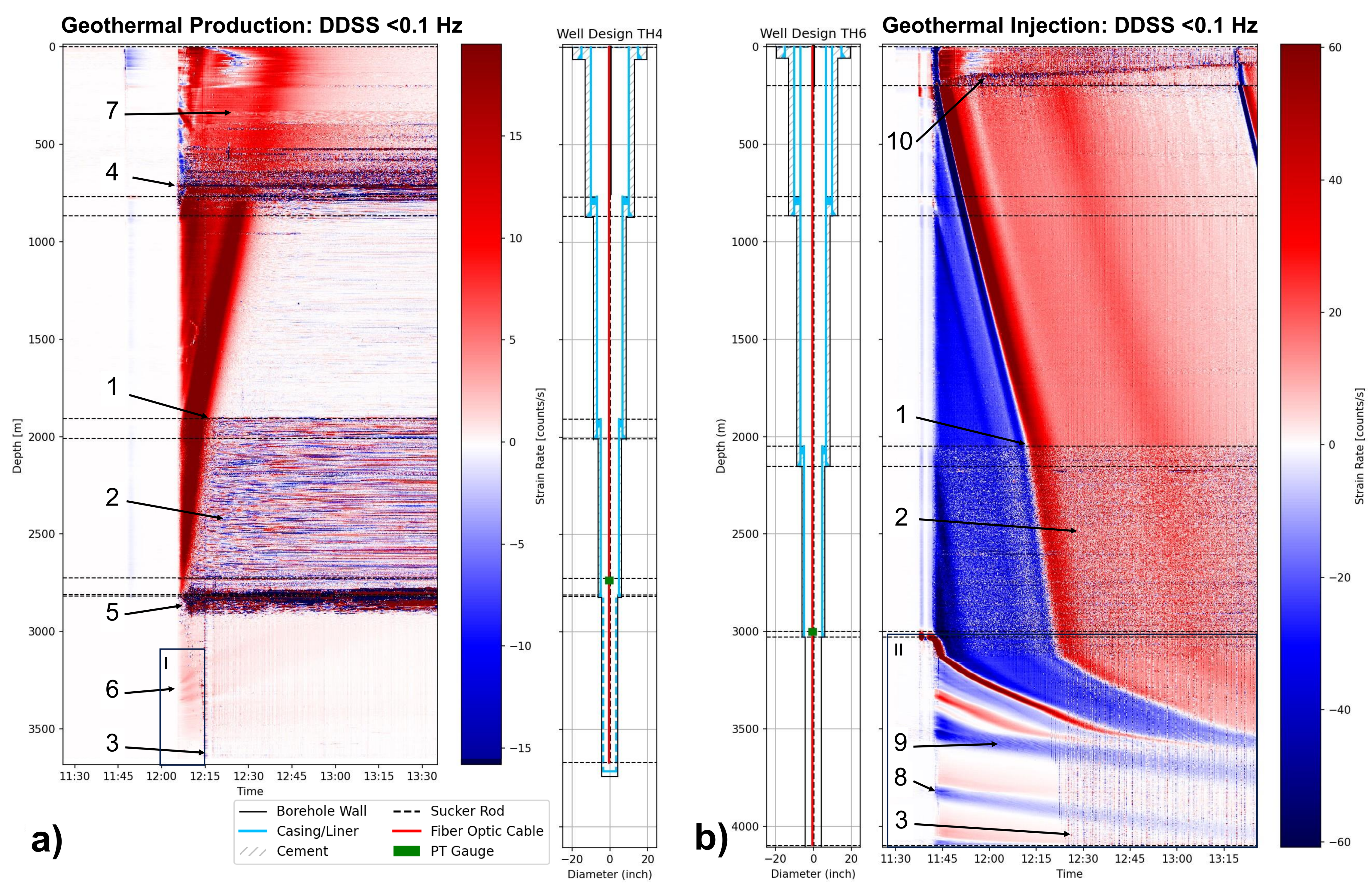

Fig 2: LFDDSS (<0.1 Hz) response during geothermal system restart. a) Production and **b)** injection phases. Blue indicates fiber compression and red indicates extension, driven by fluid flow induced temperature changes. Key features (1–10) are described above and below. Box I (a) and Box II (b) mark the sections analyzed for production and injection fluid velocity profiling, respectively.

Low-Frequency Response: Production (Fig. 2, a)

4. Pump: High amplitudes around the pump due to turbulence.

5. Slotted liner: Entry through slots may amplify turbulence in the main feed zone.

6. Minor inflows: Red plumes mark minor inflow zones.

7. Water table: Strain signals here show two water table signatures likely due to an oil phase on the water column.

Low-Frequency Response: Injection (Fig. 2, b):

8. Cooled zones: Blue/red streaks from water column displacement and prior injection cooling (shut-in temp., Fig. 4a)

9. Natural Convection? Steeper minor slopes suggest fluid redistribution downward.

10. Water table: Sharp amplitude jump marks and tracks the water level.

5 Natural Convection? when temperature gradients cause buoyant fluid movement.

- **Shut-in:** Intervals with minor flow patterns (0.04–0.06 m/s) interrupt the calm reservoir where temperature rises (Fig. 4a).
- **12 h into Injection:** Minor flow pattern broadens vertically with the temperature gradient change (Fig. 4b).
- **Temperature link:** Faster temperature rise (obtained from parallel DTS) ⇒ larger-amplitude/higher-slope streaks.
- **Interpretation:** Observed pattern of interchanging slopes suggests buoyancy-driven thermal slugs/convection cell (Fig. 4c).
- **Geometry effect:** In a 66°-deviated well, the sensing fiber lies on the low side of the borehole, where cooler fluid may sink; whether warmer up-flow travels back along the top or is partly displaced into the formation, remains unclear (Fig. 4d).
- **Impact on Flow Profiling:** Due to chaotic mixing, the area of the flow path and, hence, the flow rate remain unclear.

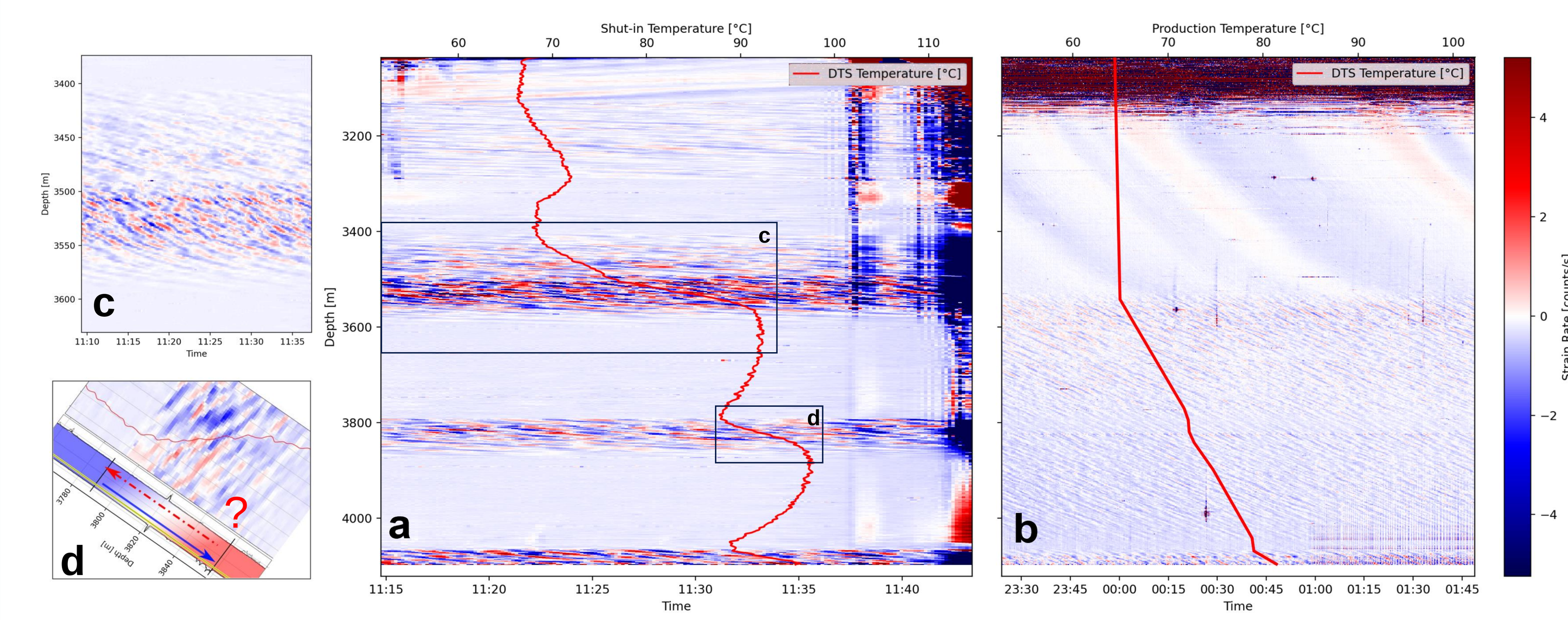

Fig 4: Correlation of minor flow patterns with the temperature gradient. a) LFDDSS under shut-in conditions and **b)** during injection, shown alongside the corresponding temperature gradient (top x-axis, DTS) across the reservoir. **c)** Close-up of a potential convection cell; **d)** detail of a second convection cell, with a schematic showing the flow principle and actual borehole deviation. Blue arrows indicate sinking colder/denser fluid; dashed red arrows indicate potential path of displaced warmer/lighter fluid.

6 Conclusion

- Applying a cascading Lowpass FIR filter to DDSS data can isolate low-frequency signals (LFDDSS) linked to thermal deformation by fluid movement.
- Strain-rate slopes in LFDDSS indicate fluid displacement and reveal flow velocity profiles along the borehole, including location, activation time, and heat contribution of individual flow zones.
- Stacking during flow rate ramp-up reduces the accuracy of a profile. (The Next step is profiles for discrete time intervals.)
- At full flow rate, the thermal signature of the main flow zones is masked by noisy turbulent flow, and the lower part of the reservoir by minor flow patterns (advanced signal processing may enhance the trackability).
- Indication for convection-dominated intervals, where the minor flow pattern reflects likely local slug motion, not full-column flow, making total flow quantification complex.
- Unprecedented insights into very low flow velocities along the reservoir and the characteristics of minor flow zones make this approach ideal for challenging wells where conventional tools fail.

Abstract:

References:

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