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In-situ characterization of fluid flow in an EGS-analog reservoir

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Motivation, Goals & Objectives

Better understanding how heterogeneity impacts fluid flow and pore pressure diffusion in geological media *in-situ* is paramount for many disciplines in earth sciences as well as for industries relying on natural resources, including deep geothermal energy (DGE) applications - as is planned as part of the **Swiss Energy Strategy 2050**.

To this end, the goals of our study are to:

- Map out the **3-D permeability structure** of a fault zone (at borehole scale);
- Determine the **connectivity structure** of permeable domains and characterize **diffusion processes** therein;
- Identify the **backbone** of the fracture network amenable to flow, solute and heat transport.

Data used in this study were collected as part of the ISC experiment completed at the Grimsel Test Site, Switzerland (see Figure 1)

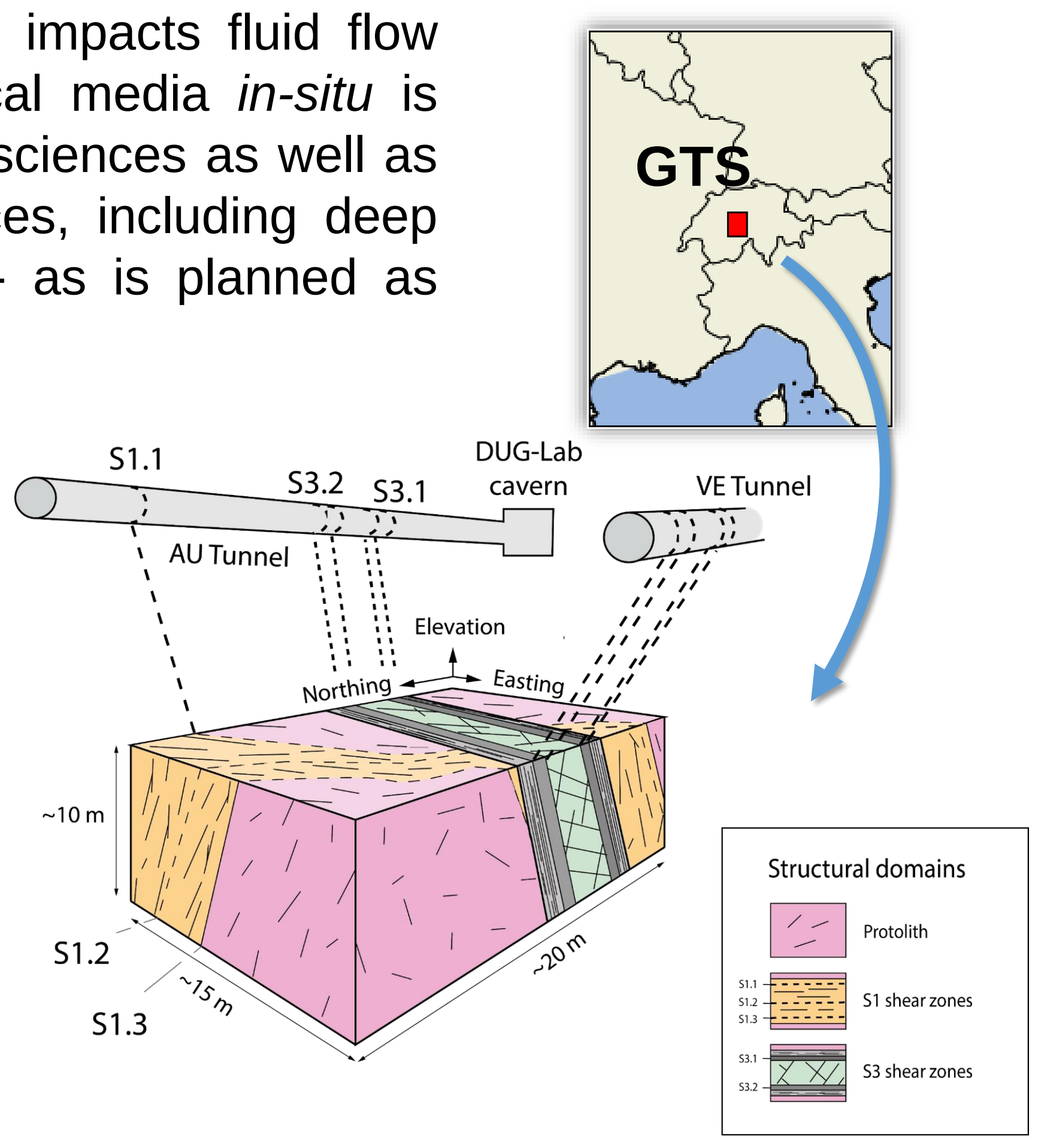

Fig. 1: Site location and geology

How «linear» is diffusion?

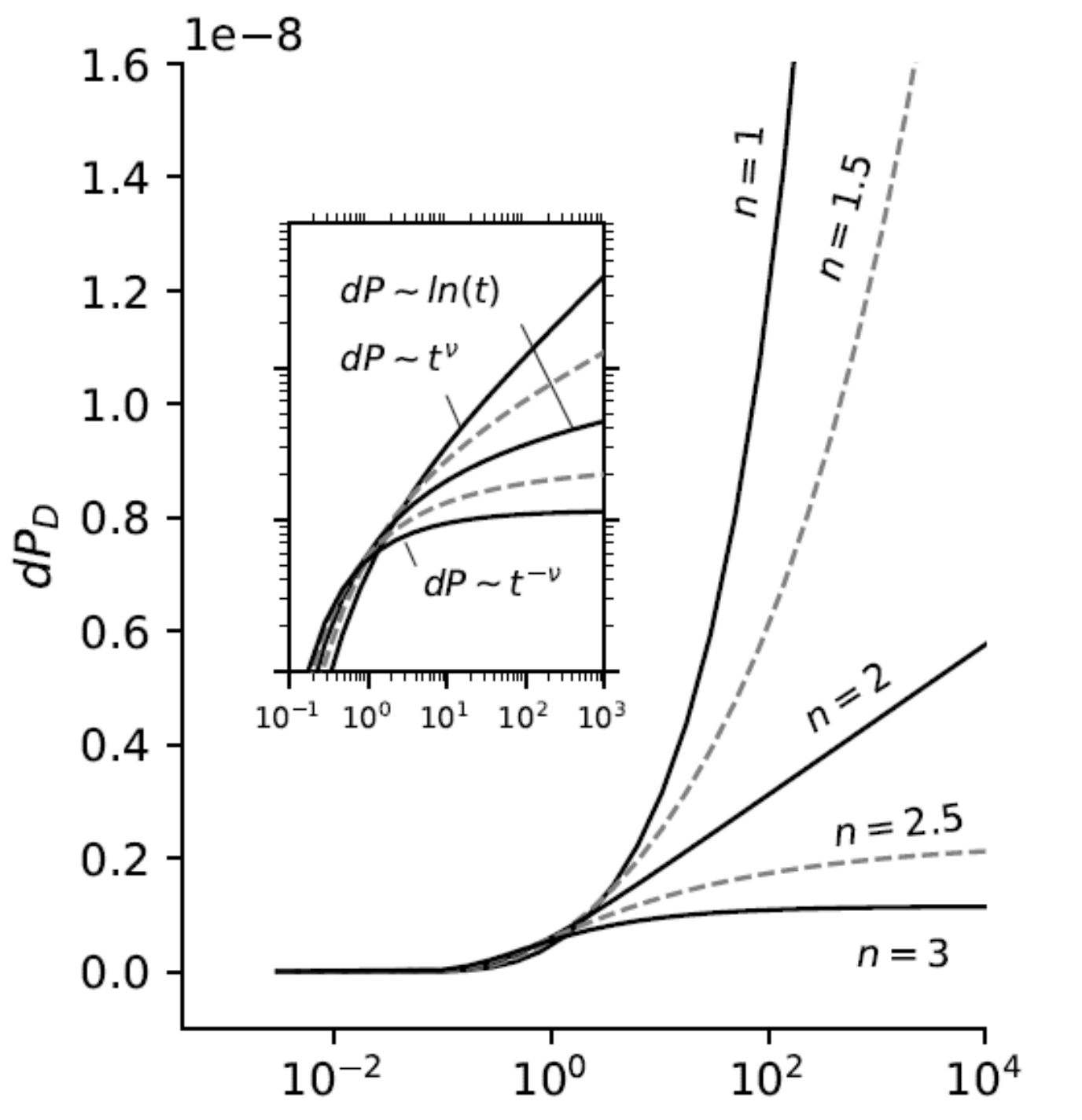

Fig. 2: Solution to Barker's model

Generalized radial flow (GRF) solution to a constant rate test, Barker [1988] :

$$dP(r,t) = \frac{Qr^{2-n}}{4\pi^{n/2}T}\Gamma\left(\frac{n}{2}-1, \frac{Sr^2}{4Tt}\right)$$

(projection of surfaces on a hypersphere)

$$\alpha_n = \frac{2\pi^{\frac{n}{2}}}{\Gamma(\frac{n}{2})}$$

Methods & Datasets

Data acquisition was carried out following standard hydrogeological field methods including single and cross-hole packer testing, the purpose of which is to induce a perturbation in the natural head field.

- Pressure pulse tests were used to compute discrete (i.e. local) Transmissivity (T) estimates, using Neuzil's method (Neuzil, 1982). These estimates were then used as a proxy for the permeability (k) structure.
- Constant rate injection tests were conducted over durations of 20 minutes to 2.5 days. Pressure responses were analysed using standard approaches (Cooper and Jacob, 1946) as well as fractional models (Barker, 1988) – see inset on the left.
- Thermal tracer tests were conducted through the injection of hot water and the propagation of thermal anomalies using two loops of distributed fibre-optics temperature sensing systems (FO-DTS).

Key Results – Pulse Tests

- The distribution of single-hole Transmissivity estimates appears to be binomial and range as:
  - $10^{-10}<T_{SZ}<10^{-6}$ m²/s
  - $10^{-14}<T_{PL}<10^{-8}$ m²/s

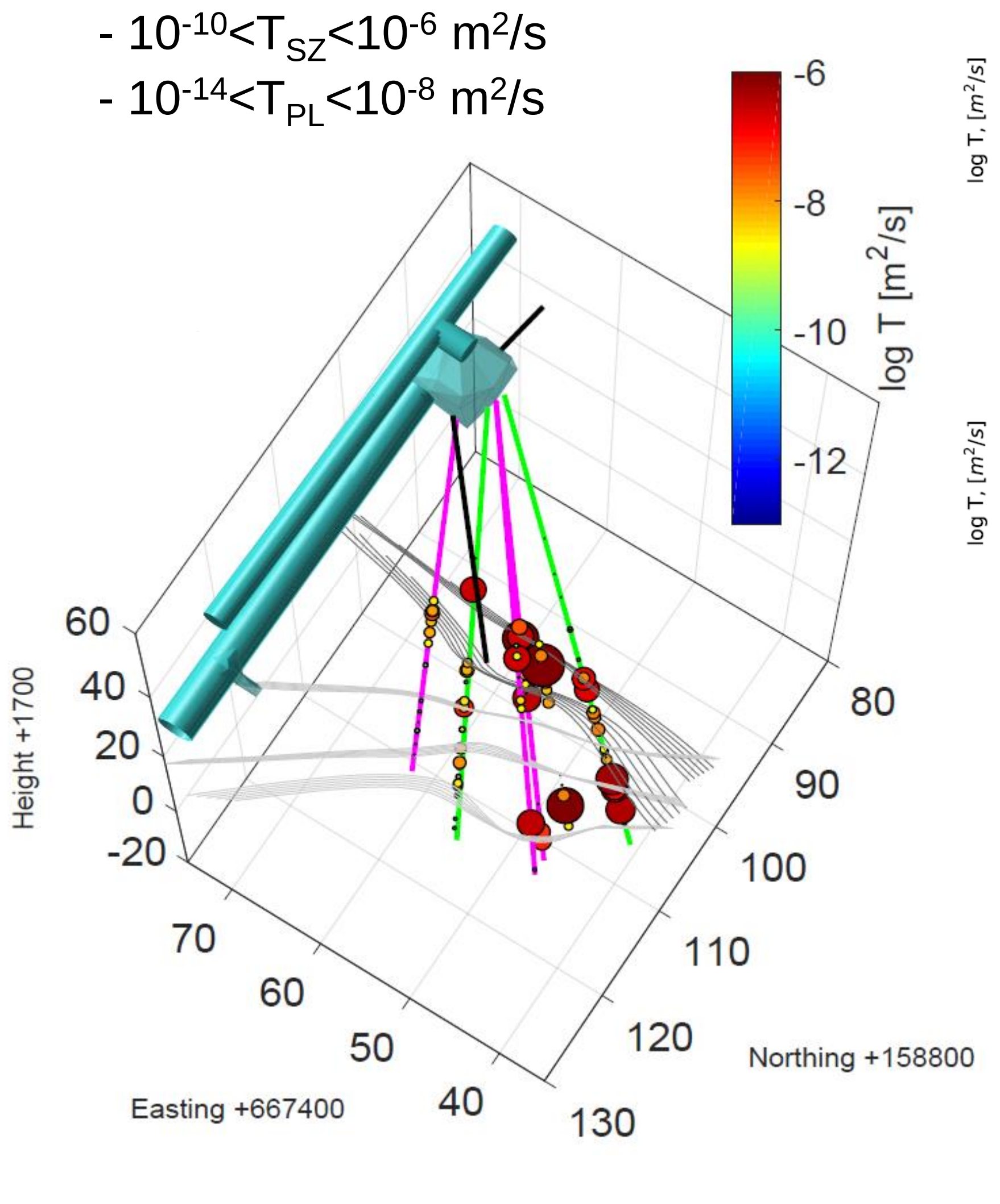

Fig. 4: 3D bubble plot showing single-hole Transmissivity values

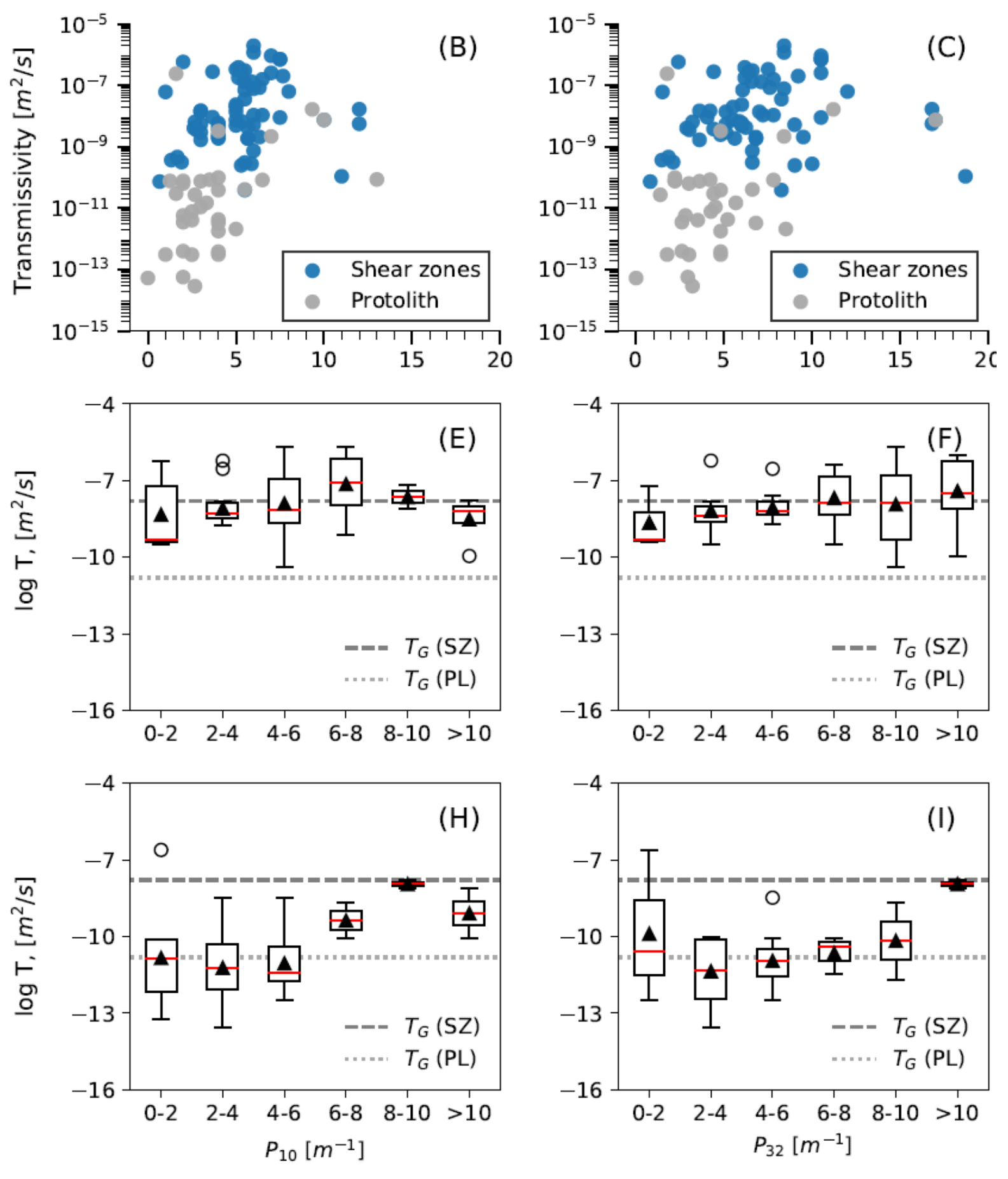

Fig. 3: Scaling of Transmissivity and fracture intensity

- Spatial correlation between high-T clusters and deformation zones (Fig. 4)
- Complex scaling with fracture intensity metrics (Fig. 3)

Key Results – Cross-hole Tests

- Normalized cross-hole pressure responses are distributed into two clusters, generally consistent with known structural domains
- Responses in the S3 shear zone (grey curves) show a strong power-law behaviour (unlike most breakthrough in S1), with a mean fractional dimension of 1.3 – see Fig 5.

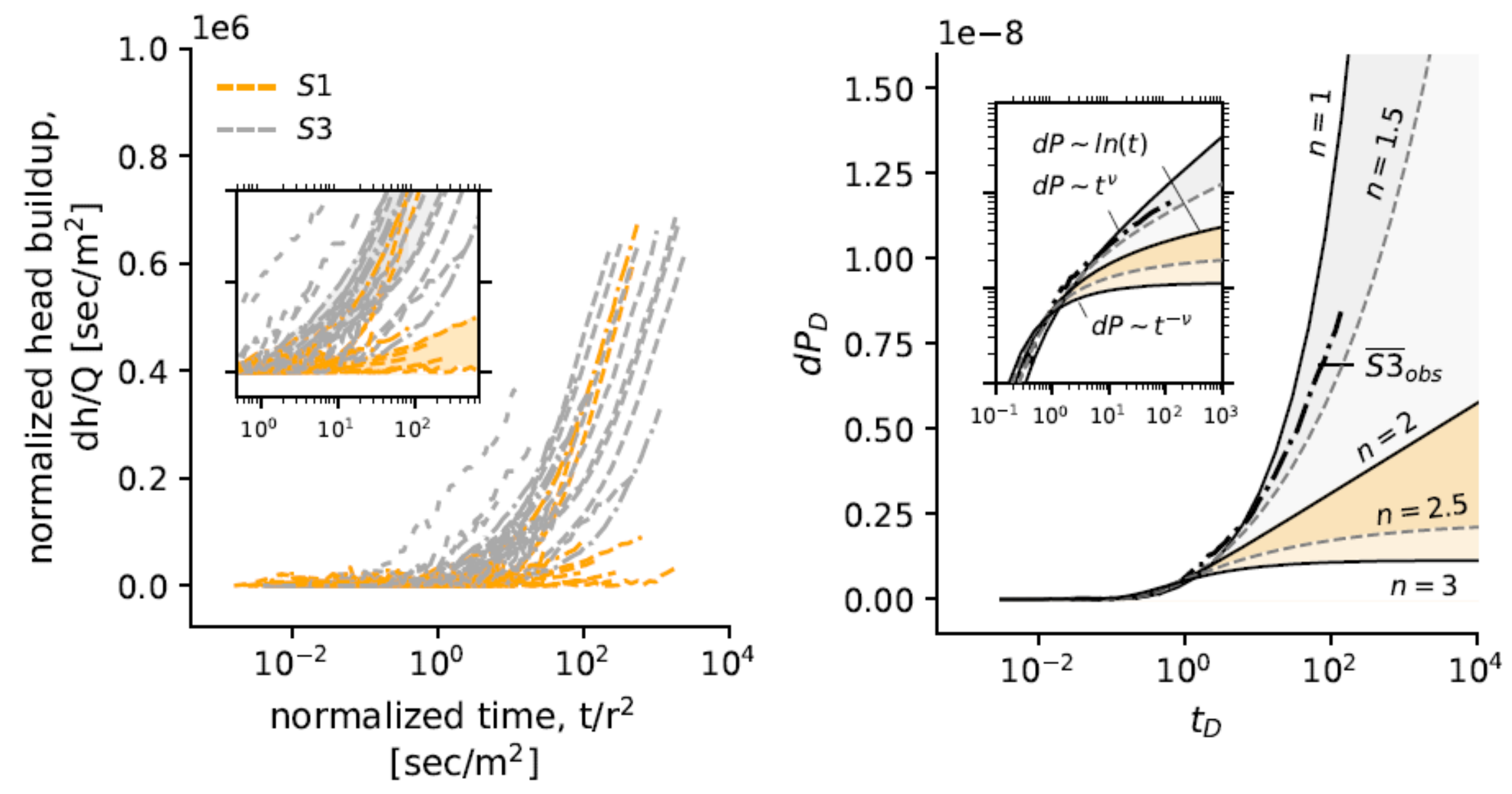

Fig. 5: Cross-hole responses (left) and mean fractional flow model (right) for our study site

- Converging pressure derivatives indicate that the flow dimension increases from n=1 to 1.5 as pressure fronts diffuse into the S1 shear zone. We interpret this as the result of the spatial integration of new forms of heterogeneities (Fig. 6).

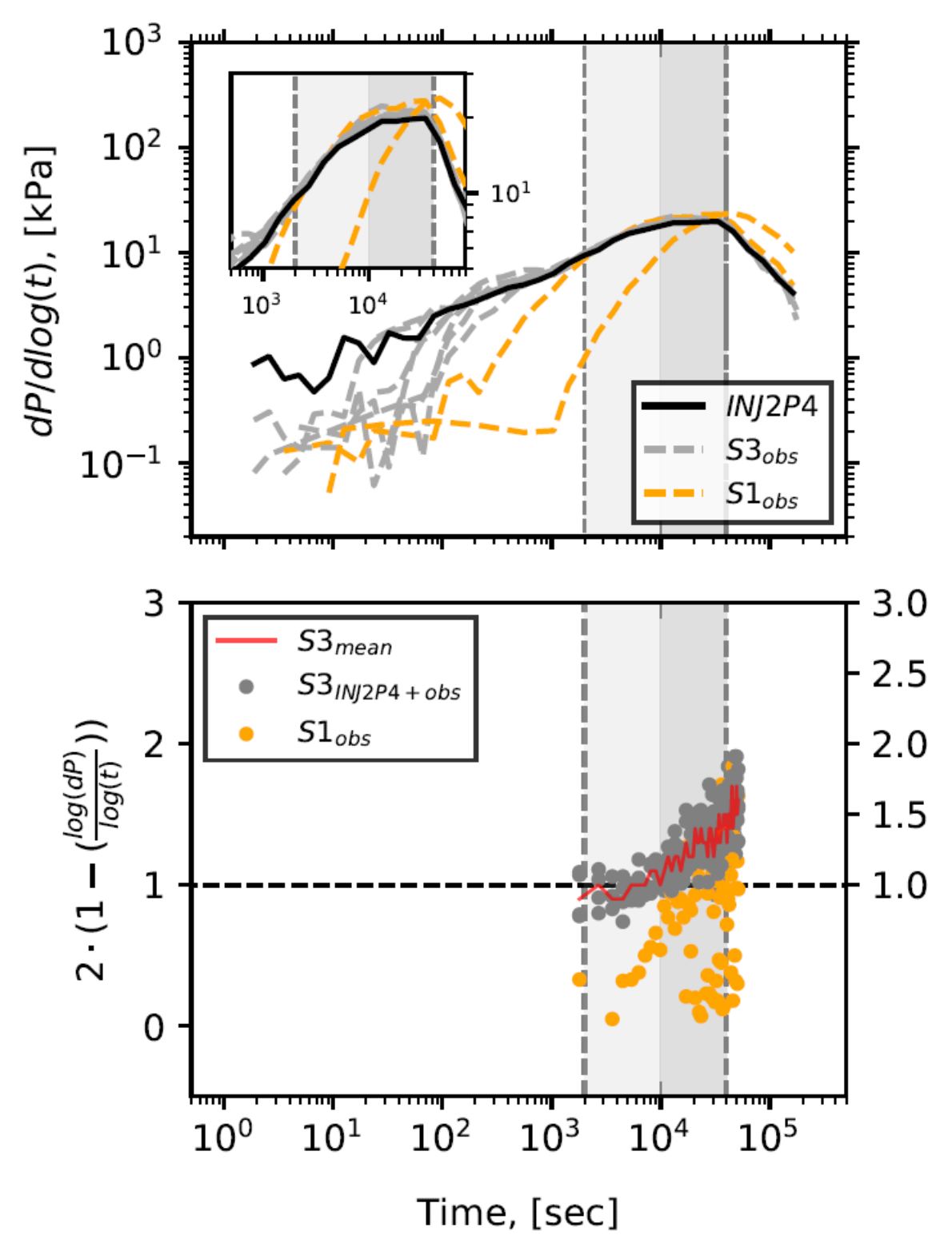

Fig. 6: Temporal evolution of the apparent flow dimension

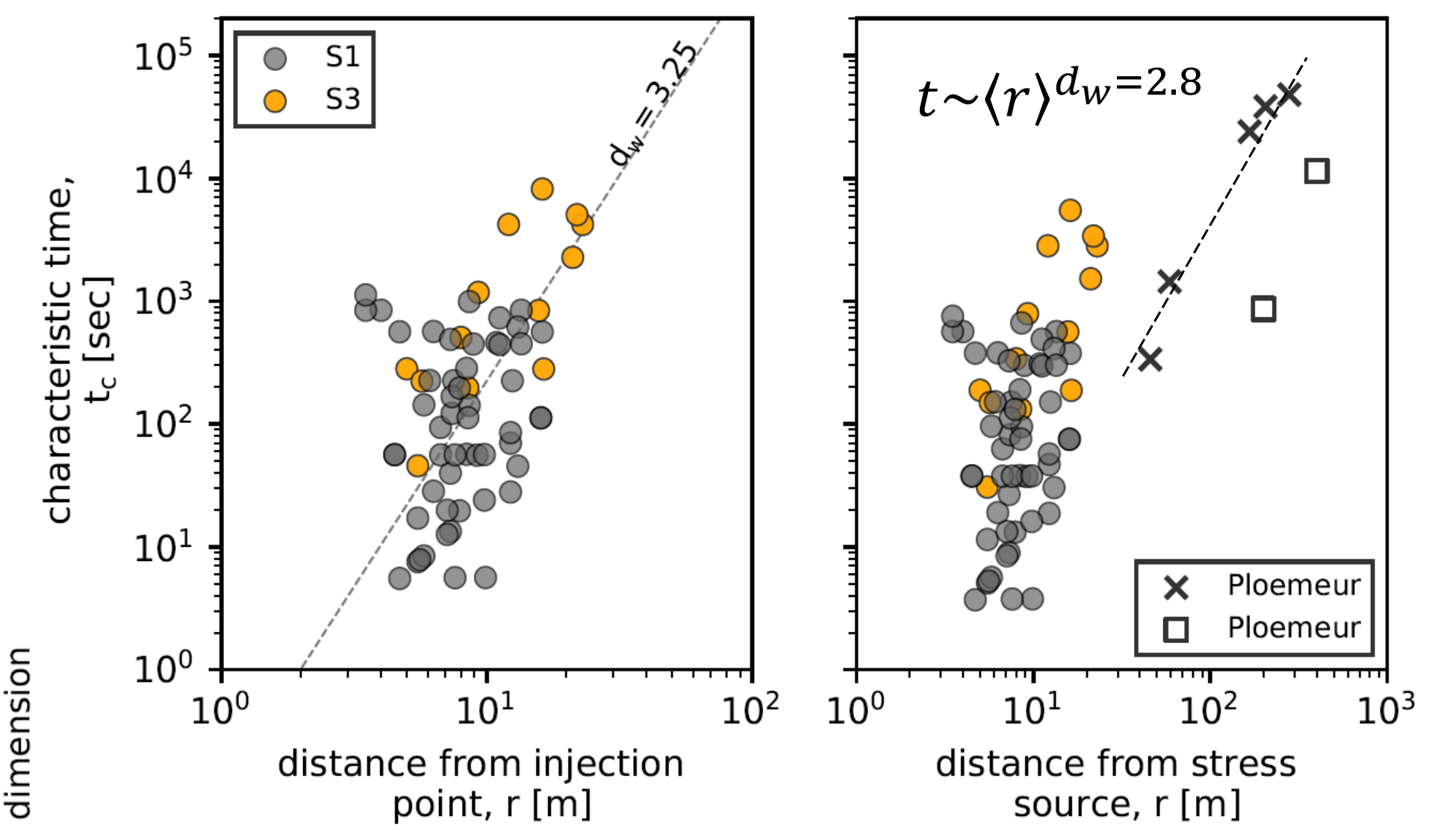

Fig. 7: Evolution of the characteristic time t_c in space (including a comparison with data obtained from a pumping test in a crystalline aquifer in Ploemeur, Brittany, carried out by other researchers (Le Borgne et al., 2004)

- Scaling exponents between the characteristic time and the Euclidean radial distance from injection are in the order of 3.2 to 3.4, i.e well above the theoretical value of 2 for normal diffusion, indicating that diffusion is anomalously slow (Fig. 7)

Key Results – Thermal Tracers

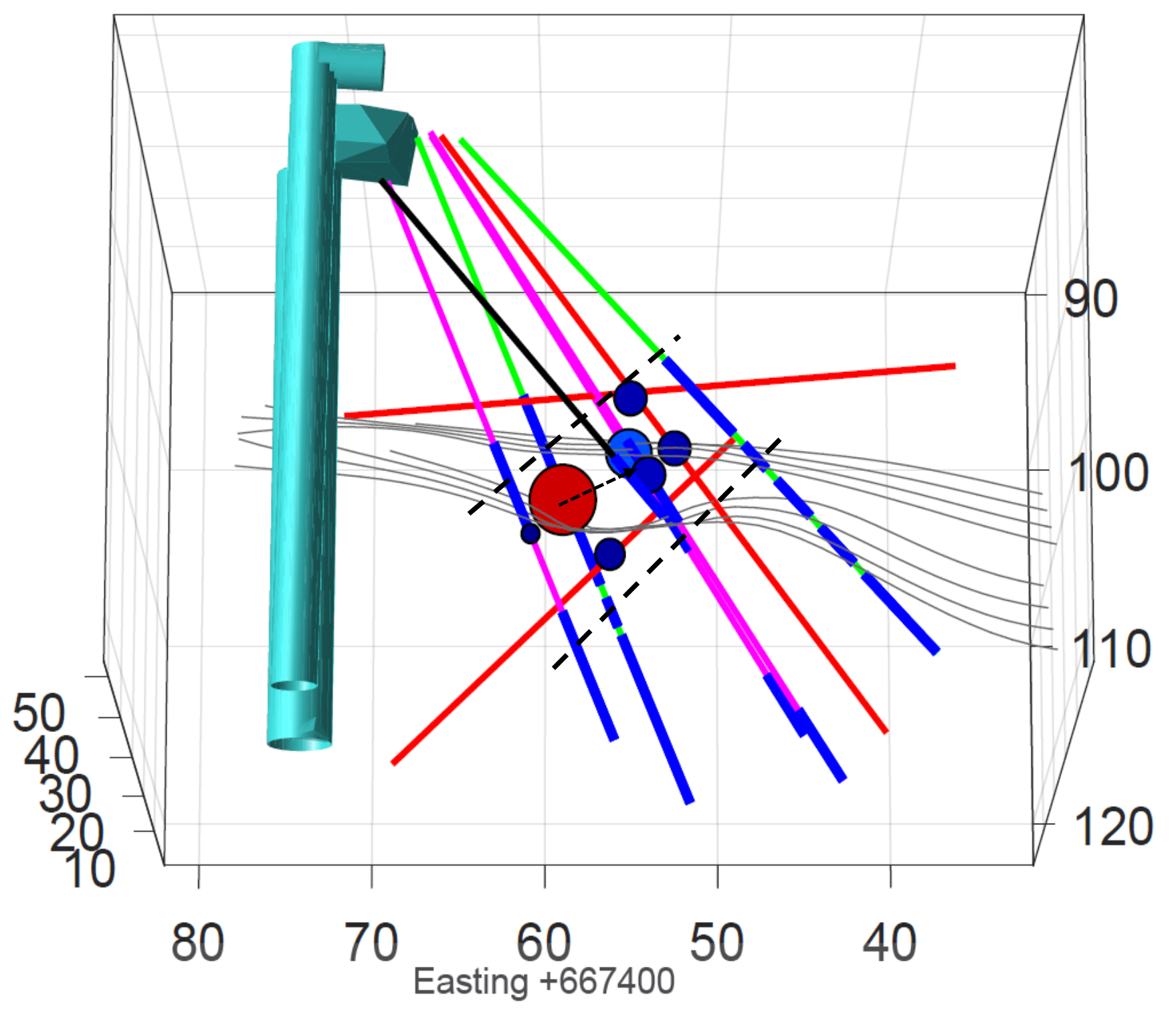

Fig. 8: 3D bubble plot showing the location of thermal breakthroughs

- Based on a 40-day thermal tracer test at 50° C, discrete thermal breakthroughs were observed along every borehole equipped with a FO-DTS system. Thermal anomalies ranged from >1°C to a maximum of 10°C about 4m from the injection point (shown in red on Fig. 8). These field results allow refining the delineation of the backbone of the fracture network and provide insights into the heat carrying capacity of fractures in granite.

Conclusions & Outlook

This study yields significant insights into the hydraulic behaviour of crystalline rocks that have similar properties to the deep reservoirs targeted for the extraction of geothermal energy in Switzerland. Here, we show that

- The permeability structure of crystalline reservoir cross-cut by shear zones is bimodal, with high-Transmissivity zones limited to shear zones
- Steady linear flow regimes develop rapidly in shear zones, even though diffusion appears to be anomalously slow (i.e. slower than expected under normal conditions where $t \sim \langle r^2 \rangle$; Using a model that accounts for anomalous diffusion yields fractal dimensions for the Grimsel Test Site and Ploemeur of 2.11 and 2.24 respectively (Acuna and Yortsos, 1995)
- Thermal tracer tests allowed refining the delineation of the principal flow paths and will be used in future studies for the parameterization of DFN models.

References

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