

# Micro-seismic monitoring during hydraulic-shearing experiments at the Grimsel Test Site

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## Introduction

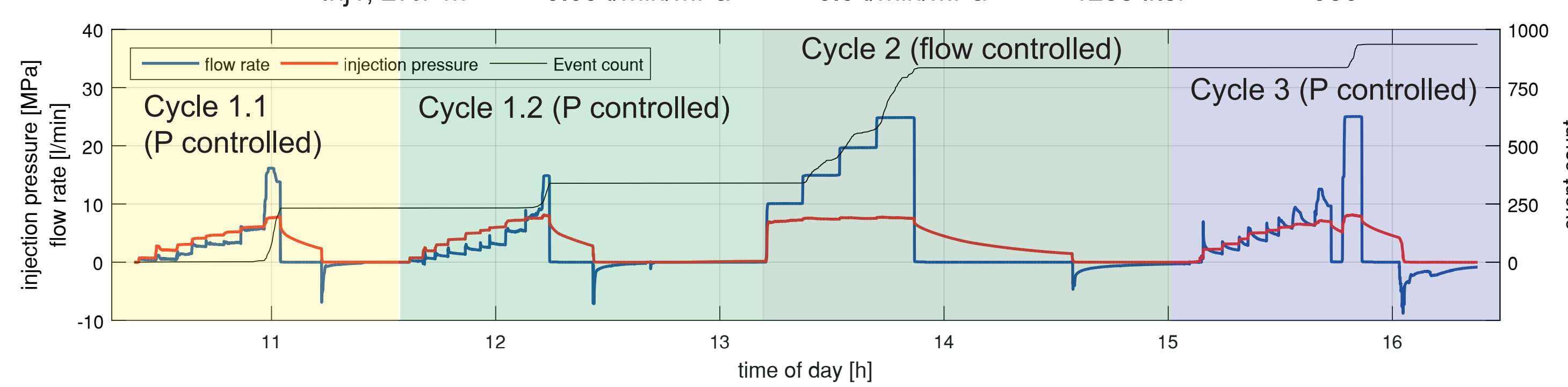
The In-situ Stimulation and Circulation (ISC) experiment at the Grimsel Test Site (GTS) is an ongoing interdisciplinary project to study the pressure, temperature and stress changes in the rock mass due to hydraulic stimulation. In early 2017, the project entered the second phase, which included the main stimulation experiment. It involved the high-pressure fluid injections into a fault zone along which slip was induced (i.e. hydraulic-shearing). The experiment series was established to support research related to deep geothermal energy which should play a significant role in the Swiss energy mix by 2050 (Swiss Energy Strategy 2050). Six sections (HS02, 04, 05, 03, 08, 01) of 1 to 2 m length distributed over the two injection boreholes were stimulated. During the experiments a multi-sensor monitoring system was in place.

Hydraulic monitoring	Deformation monitoring	Seismic monitoring
<ul style="list-style-type: none"> <li>injection pressure, flow rate</li> <li>pressure monitoring boreholes</li> </ul>	<ul style="list-style-type: none"> <li>fiber-optics (FBG's, distributed) in deformation monitoring boreholes</li> <li>3 tilt meters in tunnel</li> </ul>	<ul style="list-style-type: none"> <li>continuous and triggered acquisition</li> <li>26 Acoustic emission sensors in tunnels and seismic monitoring boreholes</li> <li>5 accelerometer in tunnels</li> <li>2 seismic sources in boreholes, 8 hammers in tunnels</li> </ul>

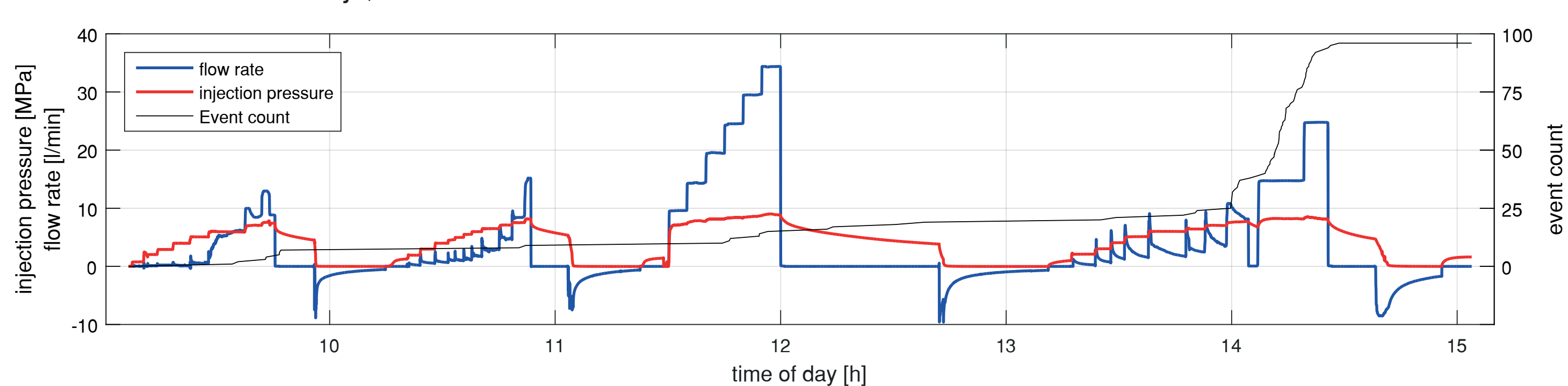
## Overview of experiments

In the following section, flow rate, injection pressure and counted seismic events (recorded by the triggered DAQ) of experiment HS04 and HS05 are shown. Additionally, injectivity increase of all experiments estimated from the slope of injection pressure vs. flow rate at low pressure during step-pressure tests are stated.

**Experiment HS04:** Injection in Inj1, 27.7 m Initial injectiv. 0.09 l/min/MPa Final injectiv. 0.9 l/min/MPa Inj. Volume 1253 liter Total events 936



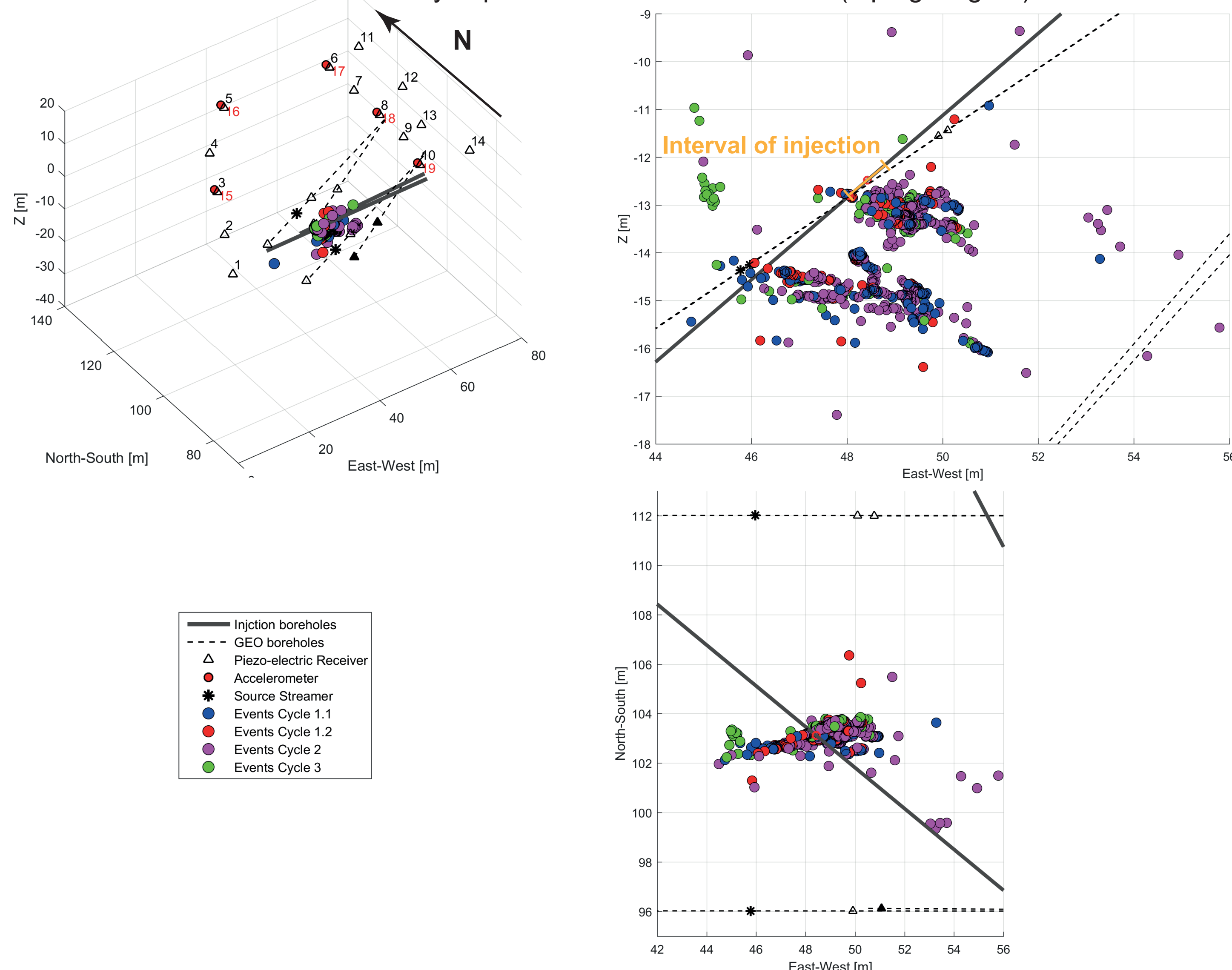
**Experiment HS05:** Injection in Inj1, 32 m Initial injectiv. 0.086 l/min/MPa Final injectiv. 0.4 l/min/MPa Inj. Volume 1211 liter Total events 96



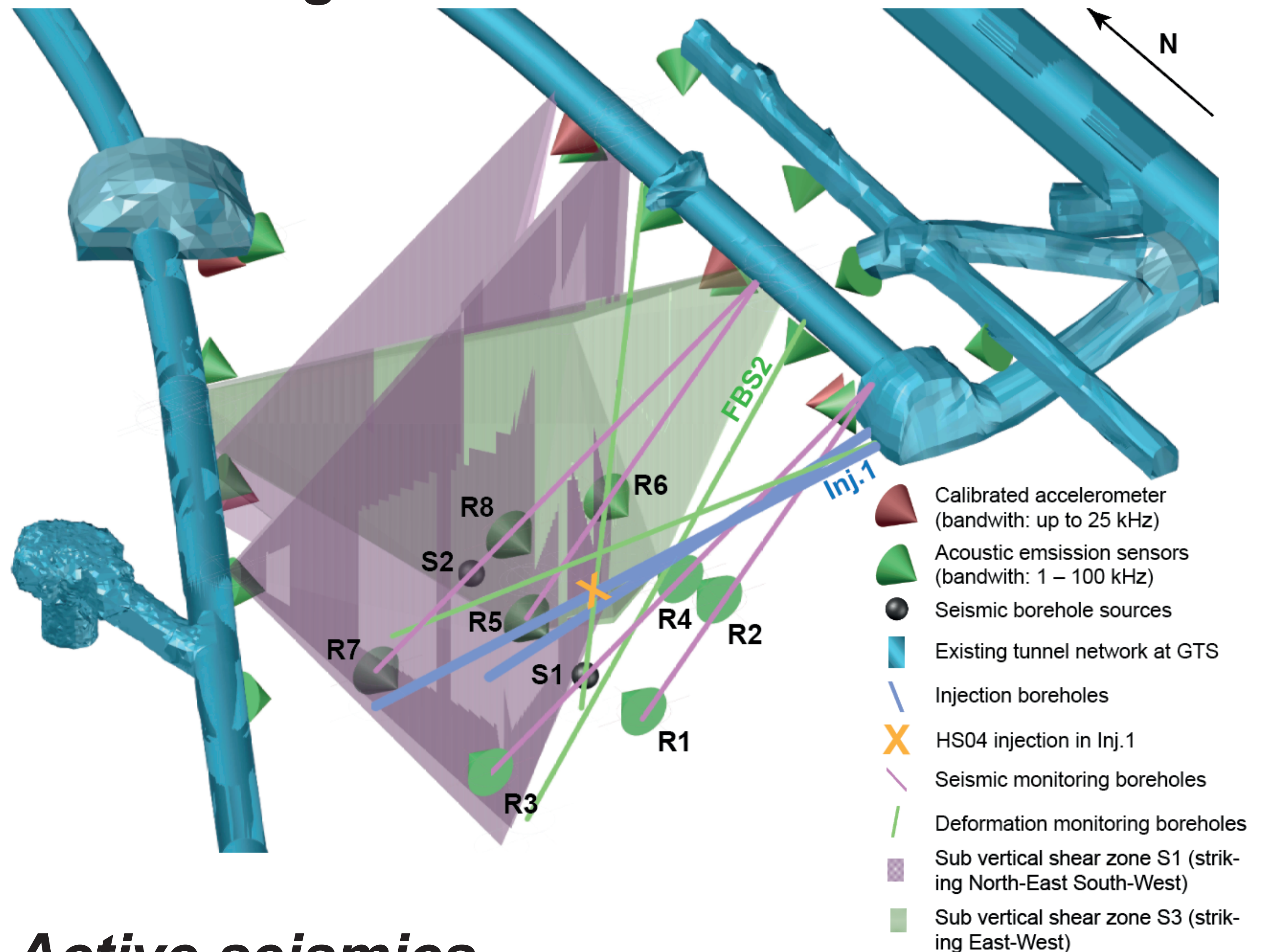
Experiment	Injection in	Initial injectiv.	Final injectiv.	Inj. Volume	Total events
Experiment HS02	Inj1, 39 m	0.018 l/min/MPa	1.6 l/min/MPa	797 l	14
Experiment HS03	Inj1, 34.8 m	0.0035 l/min/MPa	1.7 l/min/MPa	831 liter	19
Experiment HS08	Inj1, 22.5 m	0.002 l/min/MPa	0.54 l/min/MPa	1258 liter	39
Experiment HS01	Inj2, 20.3 m	0.0006 l/min/MPa	1.11 l/min/MPa	982 liter	6

## Location of triggered events

This section shows the location of the 936 triggered events recorded during experiment HS04. For location an automated STA/LTA picker was used for P-wave onset picking in combination with a homogeneous and isotropic velocity model (P-wave velocity: 5150 m/s). The seismicity cloud extends in East-West direction (figure at bottom) and is mostly below the injection point (top right). Most events concentrate in two clusters that are vertically separated and trend East-West (top right figure).

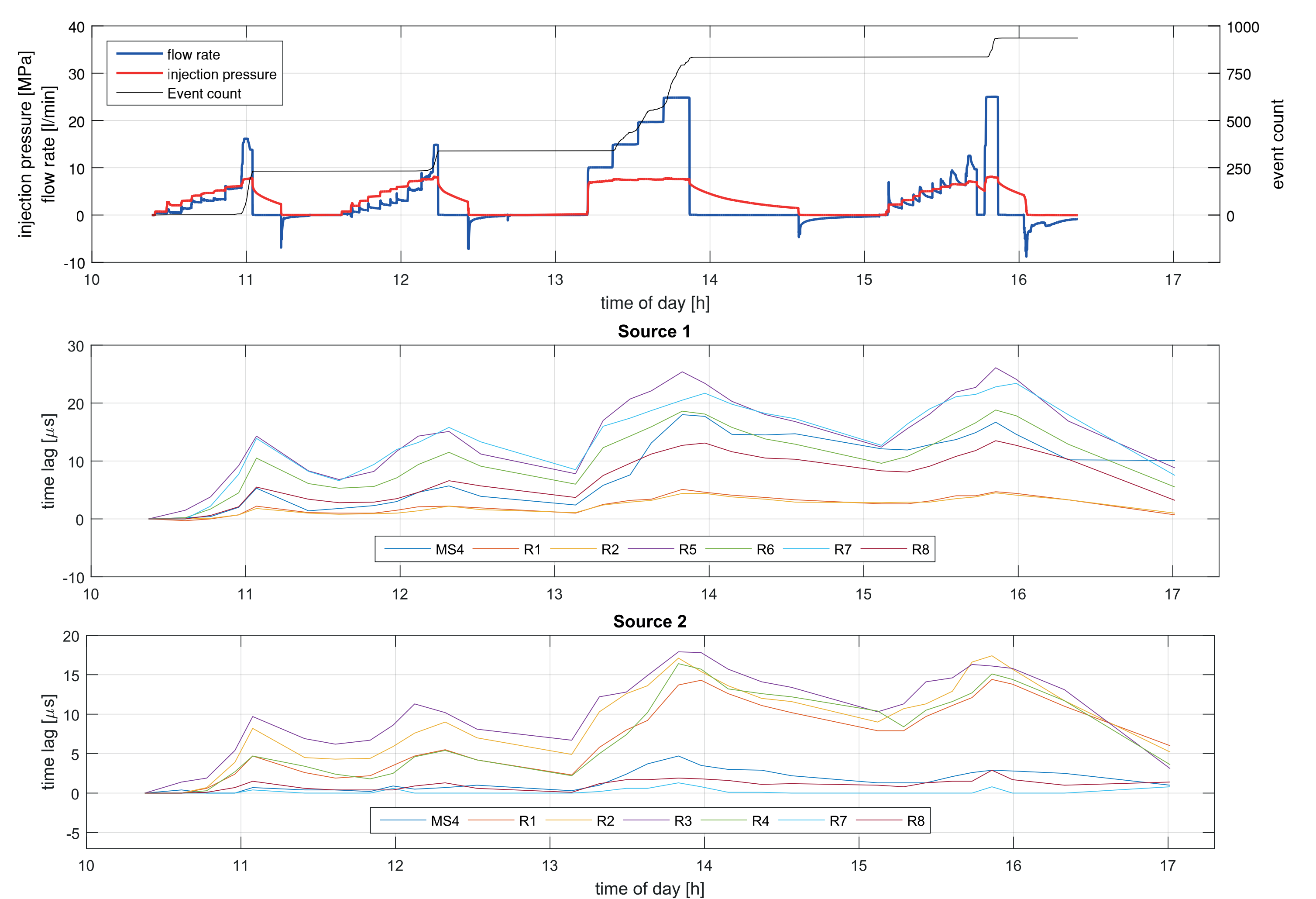


## Monitoring networks at GTS



## Active seismics

Two seismic borehole sources in addition to eight hammers distributed in the tunnels allowed for seismic surveys. At each pressure or flow-rate step of the stimulation, a full seismic survey (seismic borehole sources and hammers) was performed as soon as steady state was reached but at least every 15 minutes. The figures below show time lag of P-wave arrivals recorded at the sensors placed in the seismic monitoring boreholes as well as sensor MS3 installed at tunnel level. The seismic pulse was transmitted by the two borehole sources installed in the seismic monitoring boreholes. The time lag is referenced to P-wave arrivals recorded before injection started.



## Deformation

To monitor deformation two fiber-optic monitoring systems were in place. The figure below shows deformation measured by the Fiber Bragg grating (FBG) monitoring system installed in deformation monitoring borehole FBS 2 which was drilled parallel to shear zone S3. Micro-strain is measured over 1 m intervals. The location of the centerpoint of an interval in the borehole is stated on the left hand side of the figure. A rising micro-strain value represents extension whereas a decreasing value represents contraction of the fiber.

