Supplementary material to:

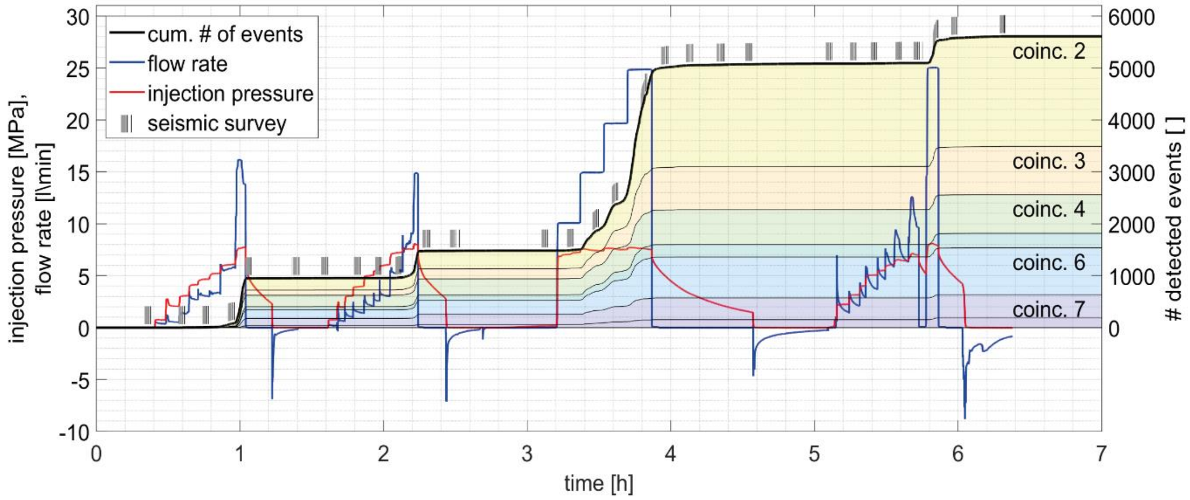
Influence of reservoir geology on seismic response during decameter scale hydraulic stimulations in crystalline rock

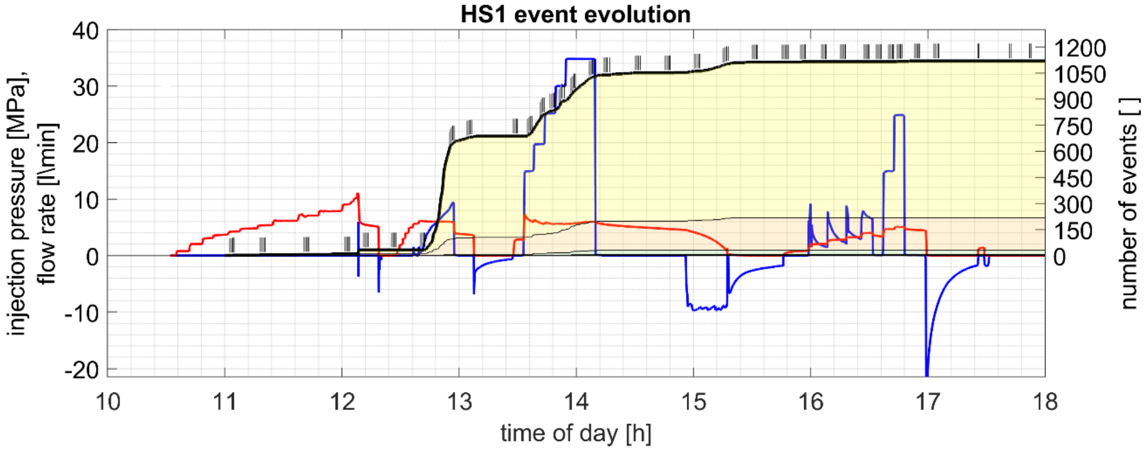
Villiger, L., Gischig, V.S., Doetsch, J., Krietsch, H., Dutler, N., Jalali, M., Valley, B., Selvaduai, P.A., Mignan, A., K. Plenkers, Giardini, D., Amann, F., Wiemer, S.

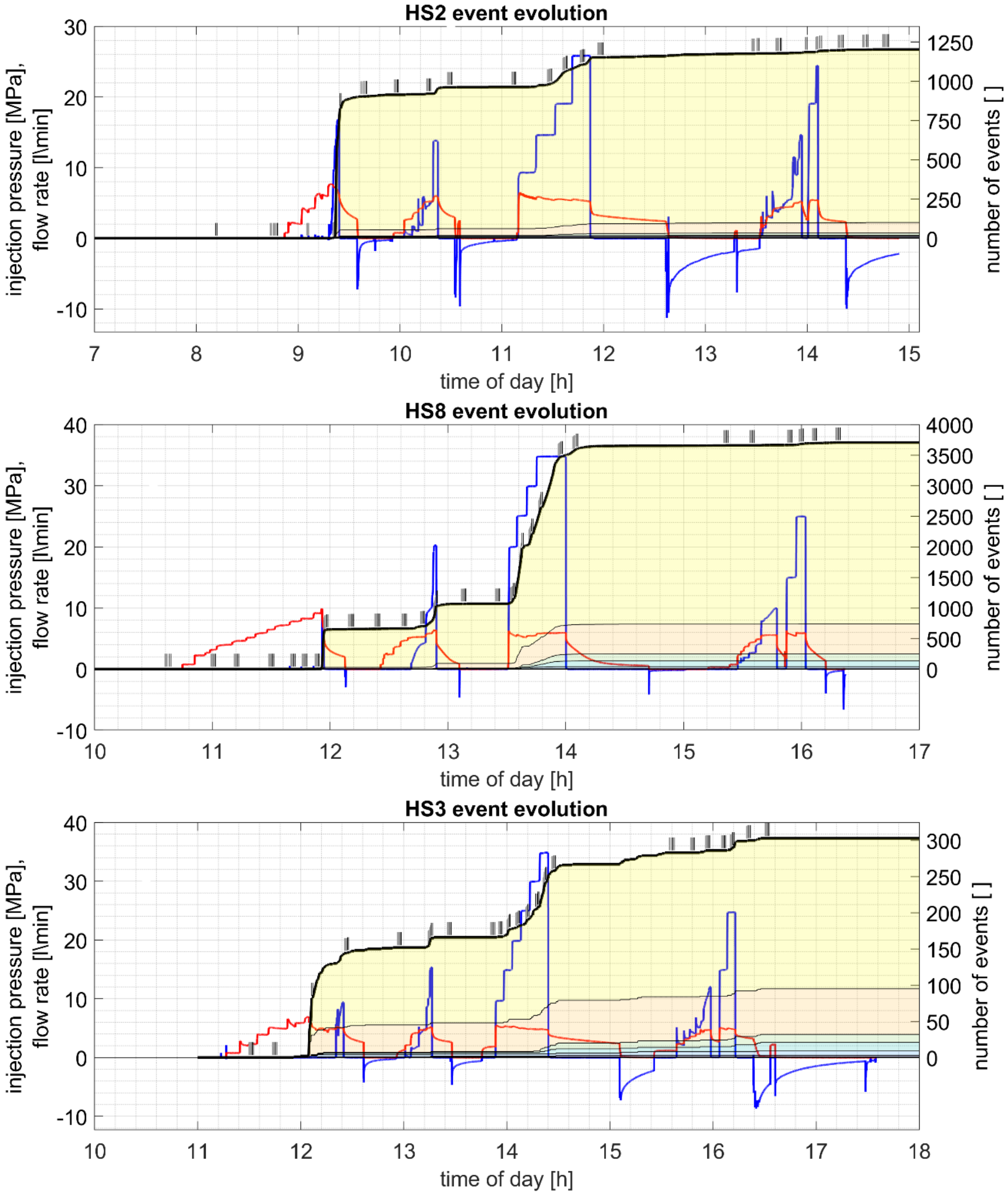
SM1: Seismic event detection
SM2: Magnitude correction
SM3: Temporal seismic event evolution
SM4: Plain fits to seismic clouds
SM5: Estimates of seismically activated areas
SM6: Estimates of seismic triggering fronts

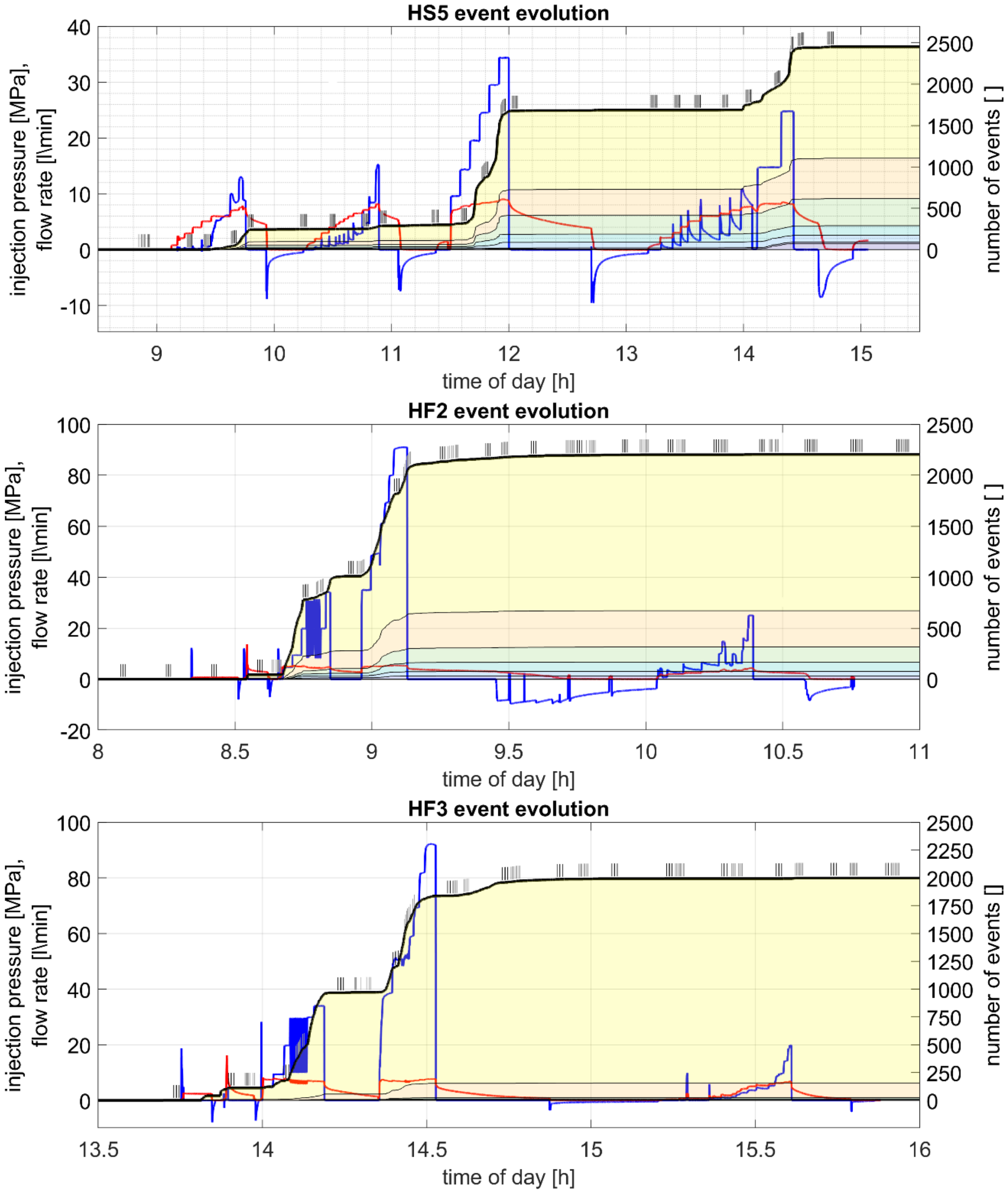
SM1: Seismic event detection

The following figures show evolution of event detection of all experiments, additionally to flow rate and injection pressure. The color-coded area represents the contribution of events according to their detection within the borehole sensor array (i.e., events recorded on all eight borehole sensors correspond to a coincidence level of eight). The strips on top of the “cumulative number of events” line indicate performed seismic surveys during which passive event detection was on hold.

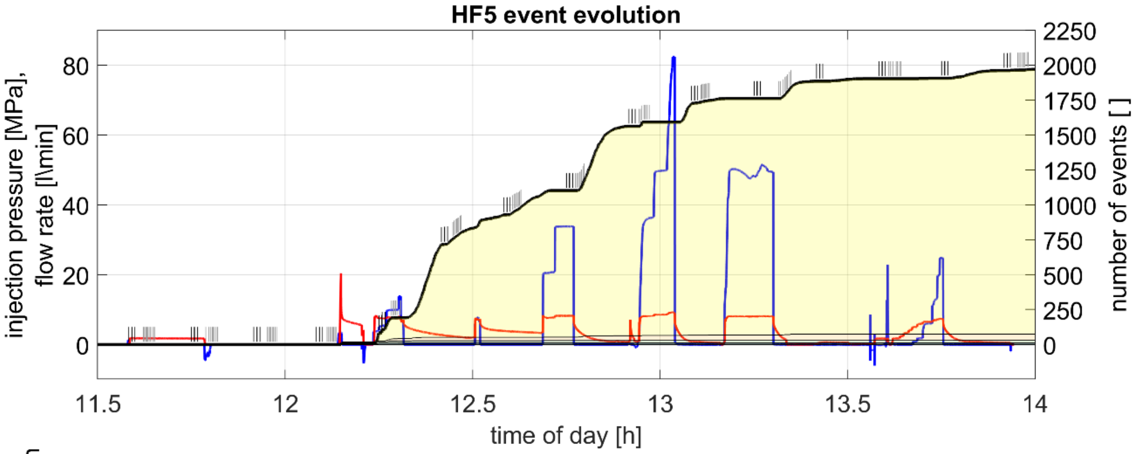


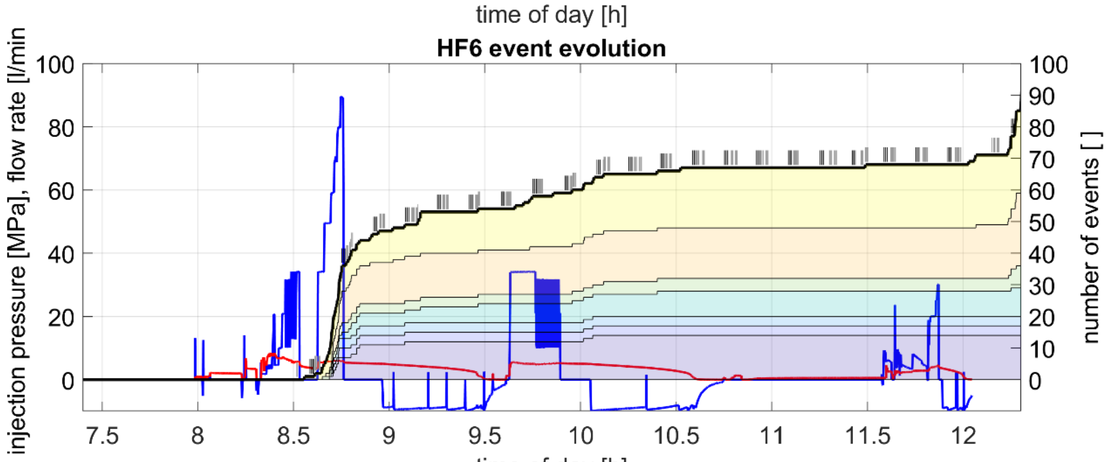


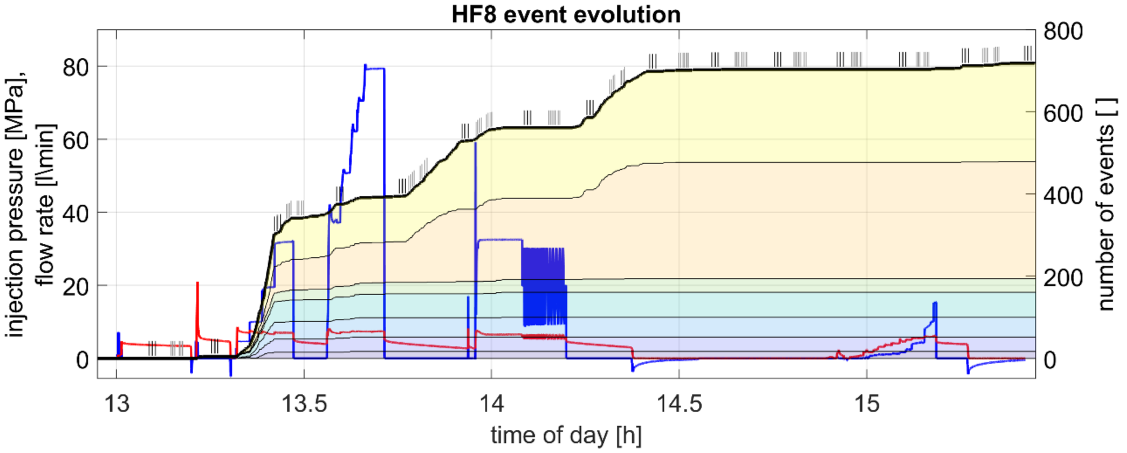

HS2 event evolution
injection pressure [MPa],
flow rate [l\min]
number of events [ ]
time of day [h]
HS8 event evolution
injection pressure [MPa],
flow rate [l\min]
number of events [ ]
time of day [h]
HS3 event evolution
injection pressure [MPa],
flow rate [l\min]
number of events [ ]
time of day [h]



HS5 event evolution
injection pressure [MPa], flow rate [l\min]
number of events [ ]
time of day [h]
HF2 event evolution
injection pressure [MPa], flow rate [l\min]
number of events [ ]
time of day [h]
HF3 event evolution
injection pressure [MPa], flow rate [l\min]
number of events []
time of day [h]

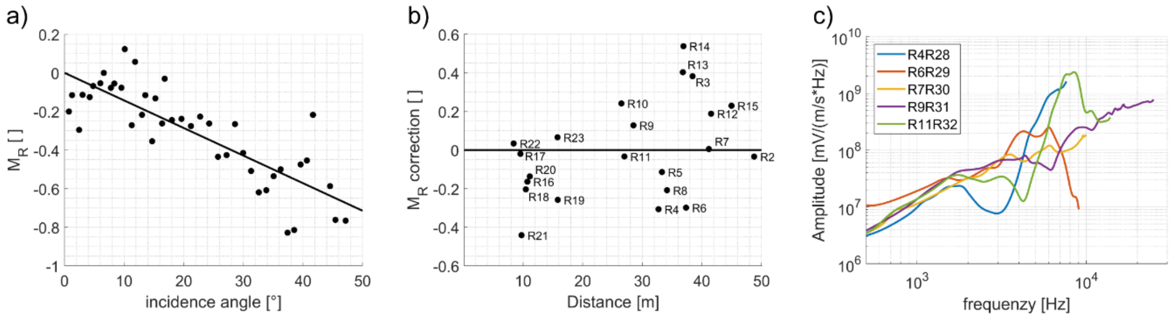

HF5 event evolution
injection pressure [MPa], flow rate [l\min]
number of events [ ]
time of day [h]
0
20
40
60
80
0
250
500
750
1000
1250
1500
1750
2000
2250
11.5
12
12.5
13
13.5
14


HF6 event evolution
injection pressure [MPa], flow rate [l/min
number of events [ ]
time of day [h]
0
20
40
60
80
100
0
10
20
30
40
50
60
70
80
90
100
7.5
8
8.5
9
9.5
10
10.5
11
11.5
12

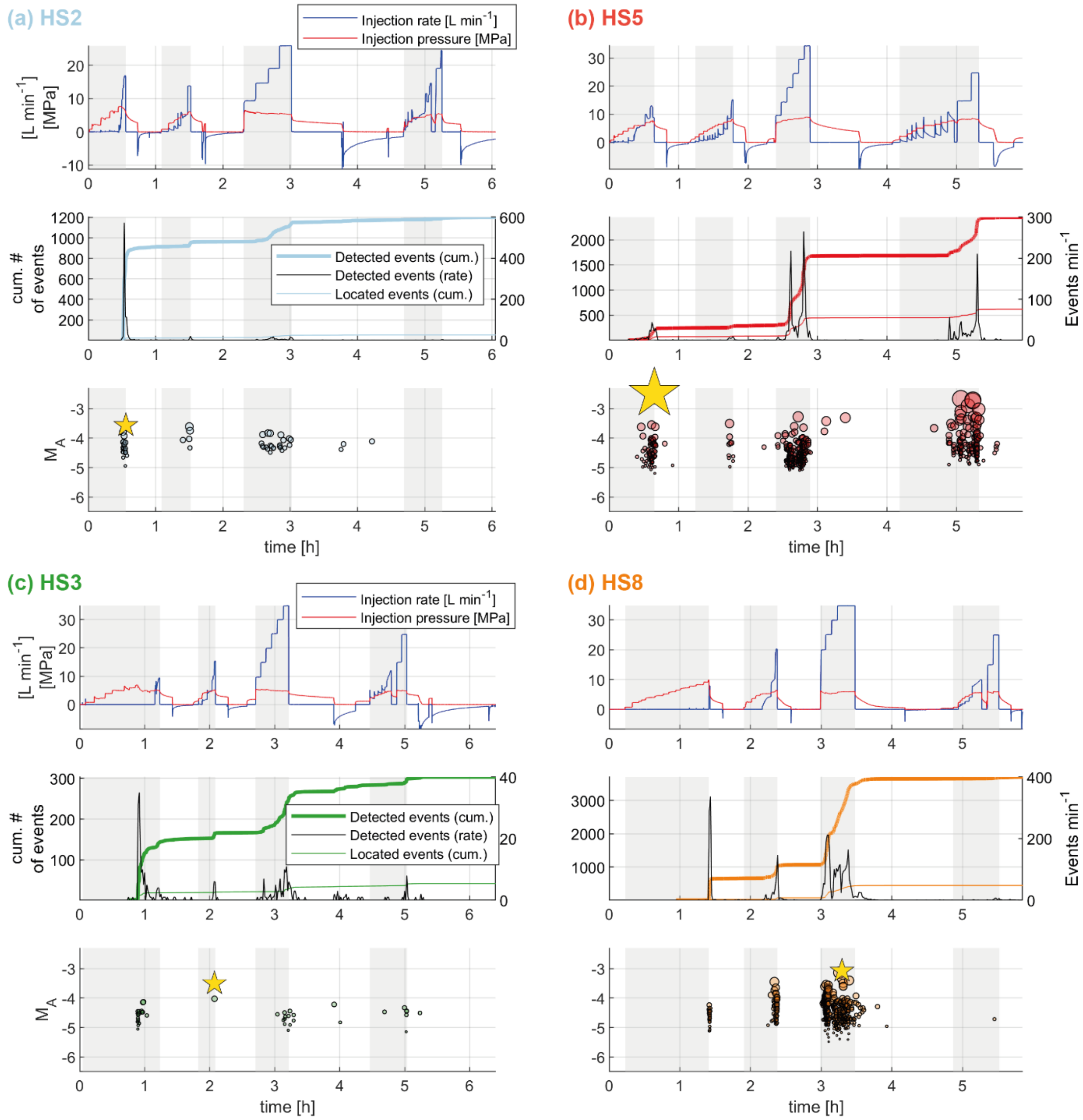

HF8 event evolution
injection pressure [MPa], flow rate [l\min]
number of events [ ]
time of day [h]
0
20
40
60
80
0
200
400
600
800
13
13.5
14
14.5
15

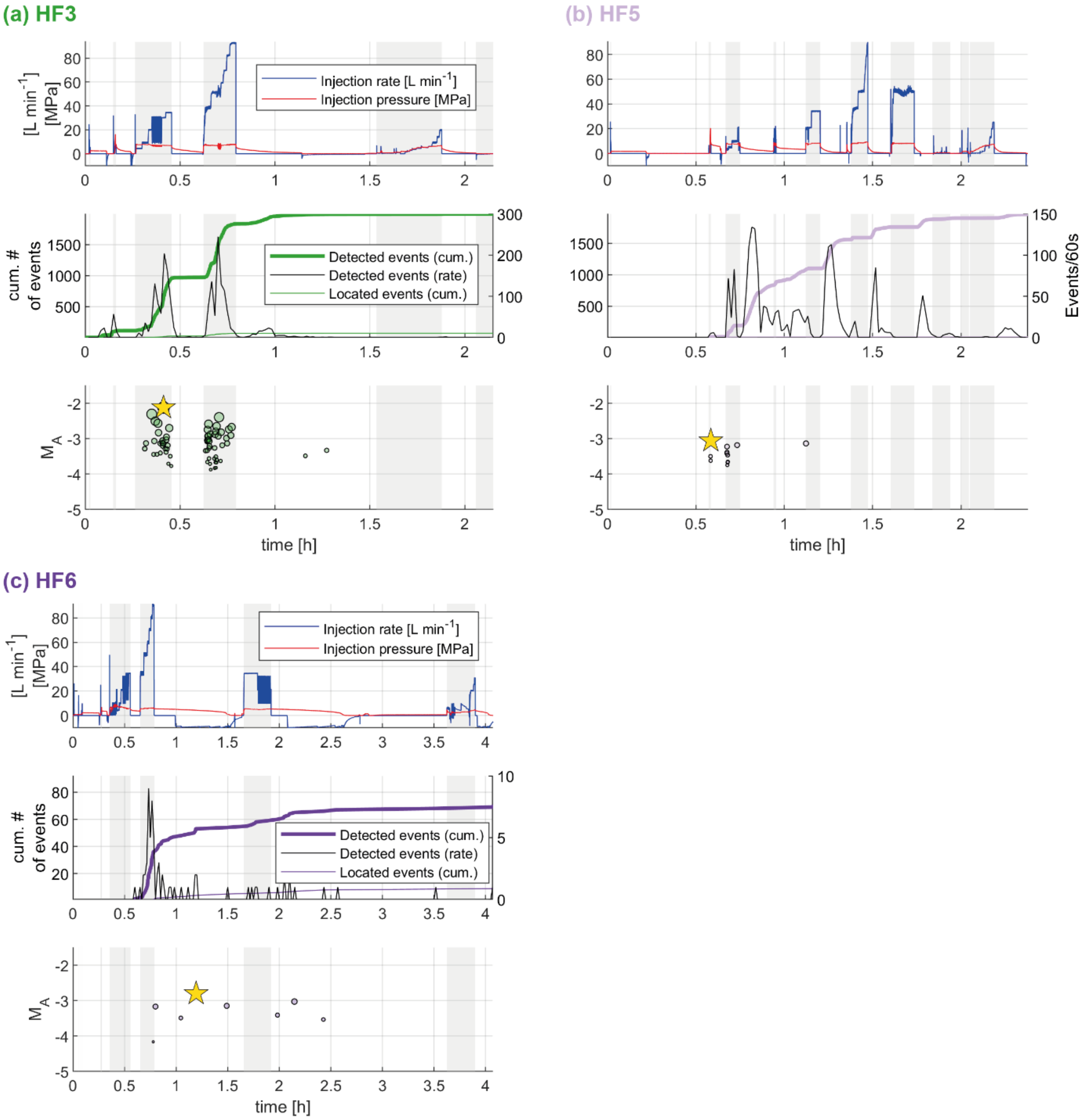
SM2: Magnitude correction

The following figure shows a) the estimate of angle dependency on M_R, (b) the estimate of M_R correction due to variations in the coupling quality, (c) instrument responses referenced to velocity for the five piezosensors which are paired with an accelerometer.



SM3: Temporal seismic event evolution





(a) HF3
[L min-1]
[MPa]
Injection rate [L min-1]
Injection pressure [MPa]
cum. # of events
Detected events (cum.)
Detected events (rate)
Located events (cum.)
MA
time [h]
(b) HF5
Events/60s
time [h]
(c) HF6
[L min-1]
[MPa]
Injection rate [L min-1]
Injection pressure [MPa]
cum. # of events
Detected events (cum.)
Detected events (rate)
Located events (cum.)
MA
time [h]

SM4: Plane fits to seismic clouds

Table 1: Orientation of plane fits through seismic clouds (azimuth, dip) along with the standard deviation of positive and negative orthogonal distances to the fitted planes

Injection	**Azimuth [°]**	**Dip [°]**	**σ_{dist} [m]**	**Injection**	**Azimuth [°]**	**Dip [°]**	**σ_{dist} [m]**
HS1	322	89	-1.4 / 1.4	**HF2 – C1**	29	83	-0.3 / 0.5
HS2	175	90	-1.1 / 0.7	**HF2 – C2**	175	76	-0.3 / 0.3
HS3	164	70	-0.4 / 0.1	**HF3**	-	-	-
HS4 – C1	169	76	-0.1 / 0.1	**HF5**	17	73	-0.3 / 0.2
HS4 – C2	6	82	-0.1 / 0.2	**HF6**	-	-	-
HS4 – C3	30	45	-0.2 / 0.2	**HF8**	178	70	-0.4 / 0.5
HS5	172	81	-0.9 / 1.2				
HS8	181	79	-0.6 / 0.9				

SM5: Estimate of seismically activated area

The planes fitted through the seismicity cloud allow an estimate of the an upper (convex hull) and lower bound (concave hull) of seismically activated area (Table 2) and its temporal evolution. In general, for all the HS injection experiments, the seismically active area during the actual stimulation cycle (C3), where about 50% of the total volume per injection was pumped, is the largest. Injection experiments HS1, HS2 and HS3 performed on S1 shear zones reveal overlapping seismically-activated areas, which is interpreted as repeated rupturing on seismically active patches. Injection HS2 shows ongoing seismicity around the injection interval, and in injection HS3 the seismicity cloud changes from an upward migration (cycle 1) towards a migration direction facing downwards (cycle 3, 4). In injection HS1, seismicity clouds migrate upwards in a consecutive fashion. Injection experiments HS5, HS4 and HS8 performed on S3 structures are the experiments where the seismically activated area was highest (among the HS injection experiments). In experiment HS5 and HS8, injection borehole INJ1 was hydraulically connected to injection borehole INJ2. In experiment HS5 the seismic events induced during cycles 1, 2 formed around the injection interval in INJ1 in an upward facing direction. In cycle 3 seismicity migrated further upwards, towards the East. In cycle 4, the seismicity cloud changed its migration direction downwards, arriving at the injection borehole INJ2 (more information on injection experiment HS5 can be found in Krietsch et al. (in preparation)).

Injection experiment HS8 was performed in an interval that includes an S1 structure south of the S3 shear zones. During injection cycle 1, only the area around injection borehole INJ1 was seismically activated. In cycle 2, seismicity further migrated towards the East in the direction of the injection borehole INJ2. During injection cycle 3, injection boreholes INJ1 and INJ2 were definitely hydraulically connected. In addition, seismicity occurs in the lower regions of shear zone S3.1.

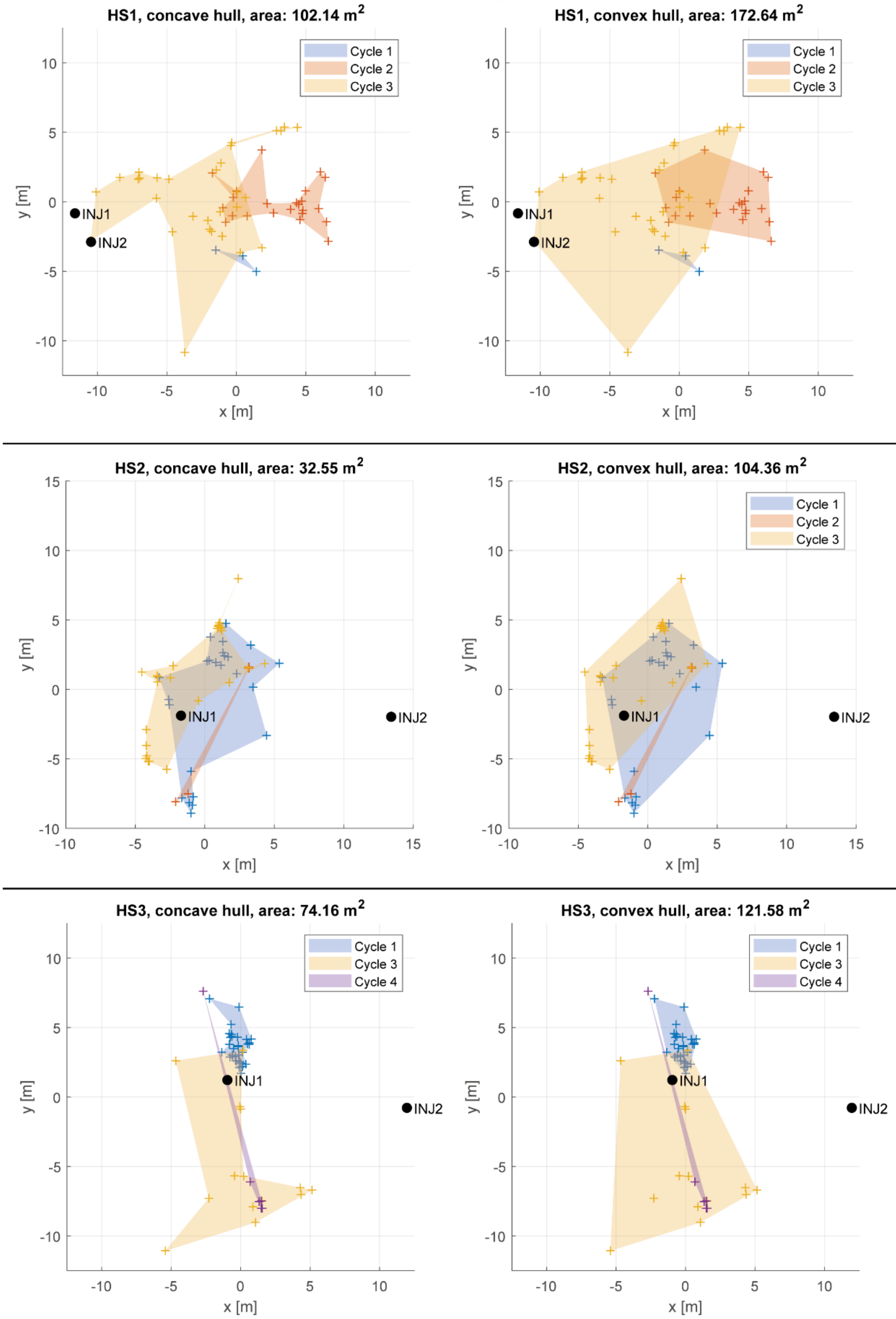
Injection experiment HS4, with over 50% of located seismic events from all injection experiments, is contained in a comparatively small volume. The seismicity clouds induced during injection experiment HS4 formed in the metabasic dykes (cluster 1) and the pre-existing fractures (cluster 2) and show a very high density of seismicity around the injection interval over all injection cycles, providing evidence of repeated rupturing on seismically active patches. A new seismicity cloud induced in cycle 3 formed perpendicular to the minimum principal stress of the perturbed stress state in an Easterly direction over a time period of 12 minutes and reopened in injection cycle 4.

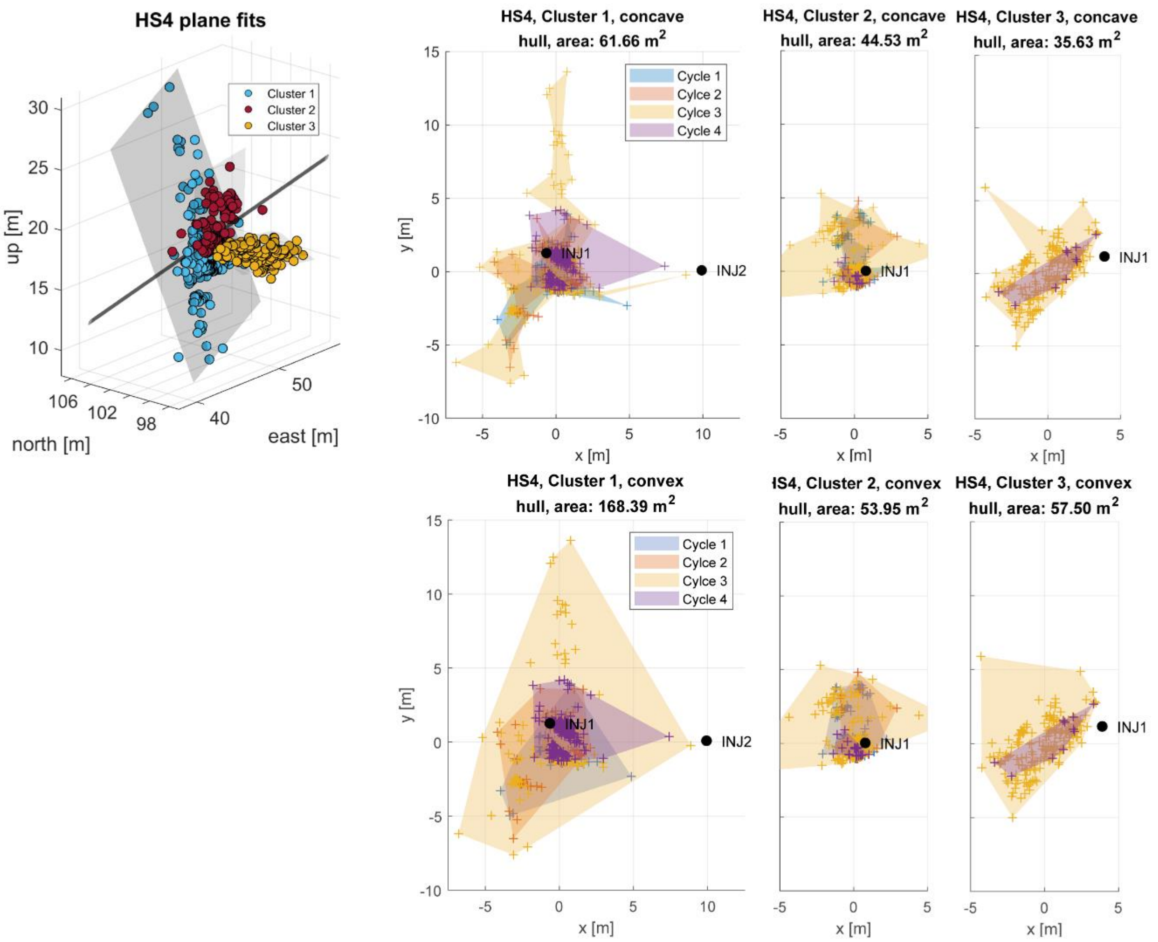
Table 2: Upper and lower bound of the seismically activated area from all injection experiments, where a plane fit seemed adequate. Note: The area estimates stem from induced seismic events from all cycles. Repeated seismicity on seismically active patches do not add to the seismically activated area estimate.

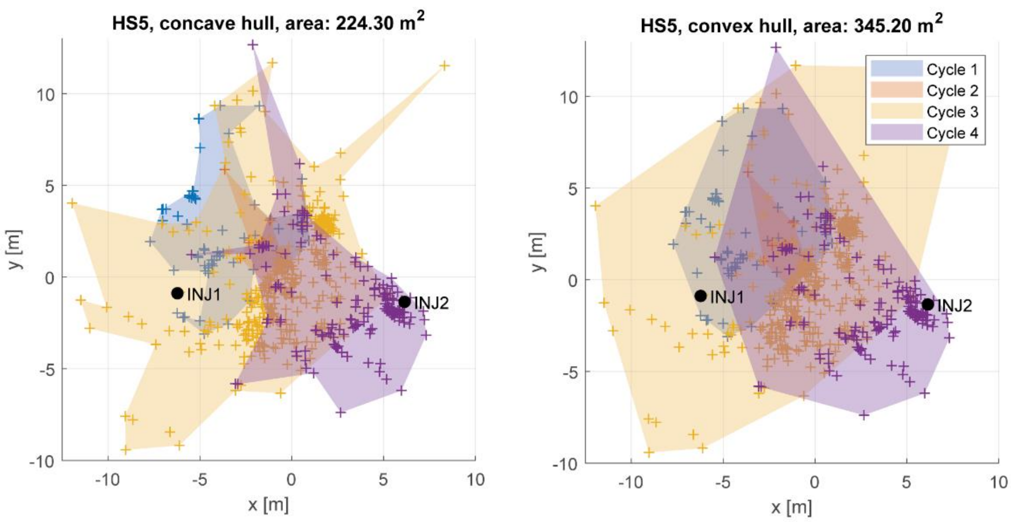
Injection	Lower bound (concave hull) [m^2]	Upper bound (convex hull) [m^2]	Injection	Lower bound (concave hull) [m^2]	Upper bound (convex hull) [m^2]
HS1	102.1	172.6	**HF2**	66.0	123.1
HS2	33.6	104.4	**HF3**	-	-
HS3	74.2	121.6	**HF5**	6.8	9.1
HS4	141.8	279.8	**HF6**	-	-
HS5	224.3	345.2	**HF8**	160.5	310.8
HS8	120.6	183.0			

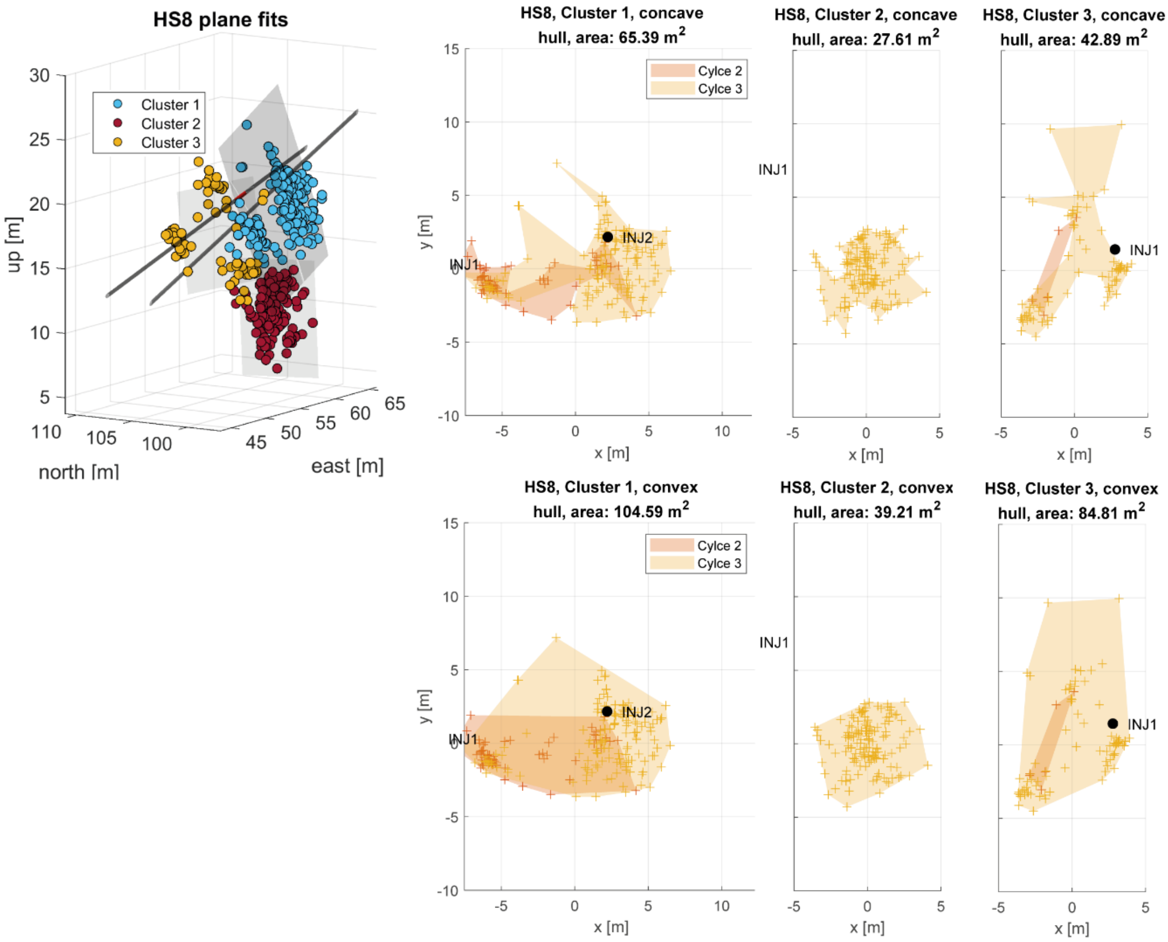
Hydraulic fracturing experiments HF5 and HF8, both performed south of shear zones S3 in close proximity to each other, could not be more different in terms of seismically activated areas. Injection HF5 activated a comparably small area, with activated areas over cycles overlapping. Experiment HF8, on the other hand, activated a larger area; seismicity begins to light up in the formation breakdown cycle in close proximity to the injection interval, followed by a significant area gain during the first refrac cycle surrounding the injection interval. The seismicity clouds of the subsequent two refrac cycles overlap, suggesting repeated rupturing on seismically active fault patches. The propagation direction of the two refrac cycles is downwards with respect to the injection interval. During injection experiment HF2, the first seismic events are located at the beginning of refrac 2 in close proximity to the injection interval in borehole INJ1 (start of cluster 1). The initiated seismic events orient themselves in parallel to the injection interval axis, in a direction perpendicular to the minimum principal stress of the perturbed stress state. During the subsequent flow controlled refrac cycle 3, the seismically activated area of cluster 1 increases, and a new seismicity cloud forms in an East-West orientation (cluster 2). In cluster 1, during refrac cycles 4 and 5, seismicity clouds overlay the seismicity induced during cycle 2 and 3. During cycle 4, cluster 2 is enlarged in the planar East-West direction. The seismicity cloud induced during cycle 5 overlays seismicity of the previous cycles in cluster 2.

a. Seismically activated area estimates HS experiments

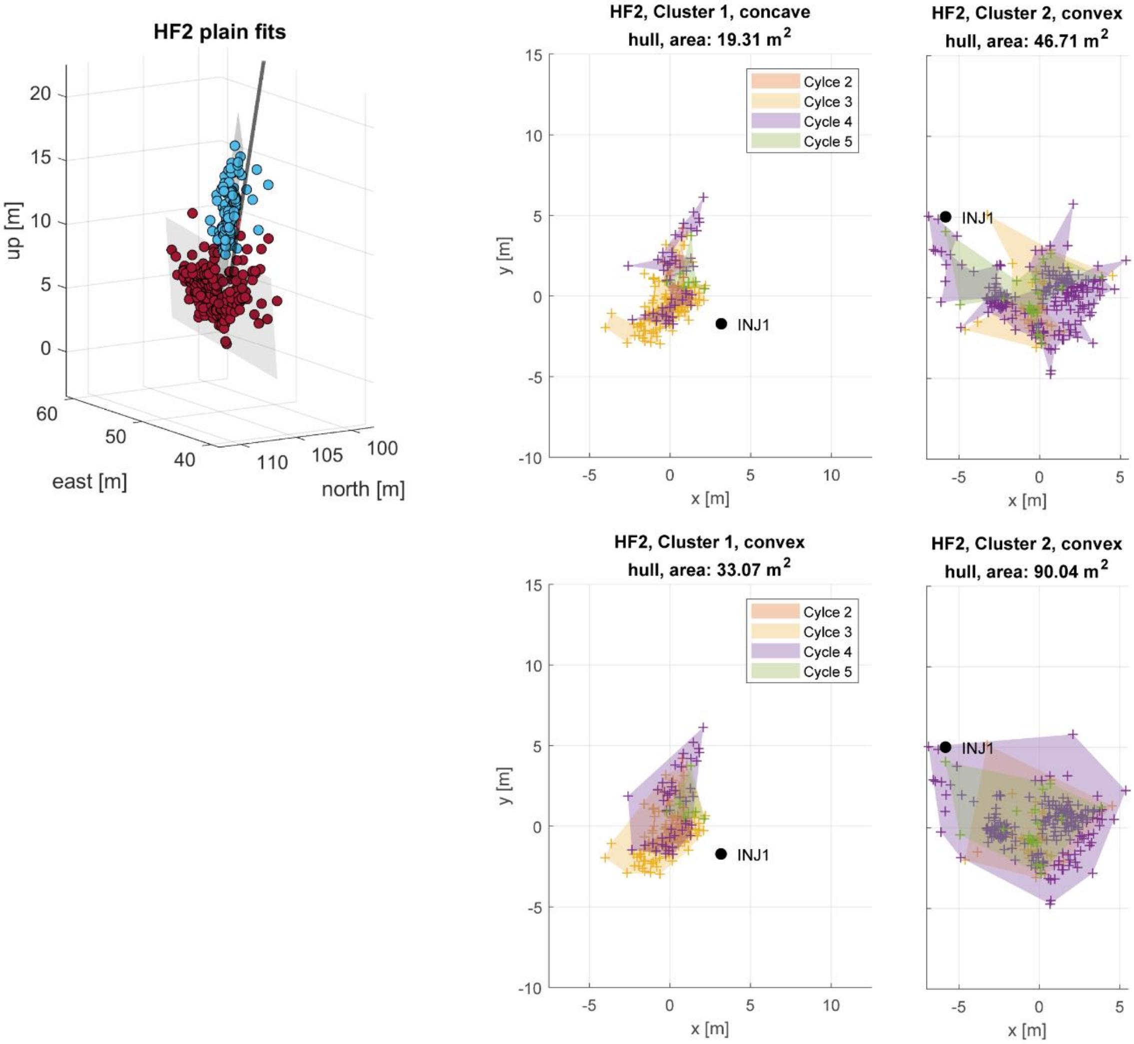


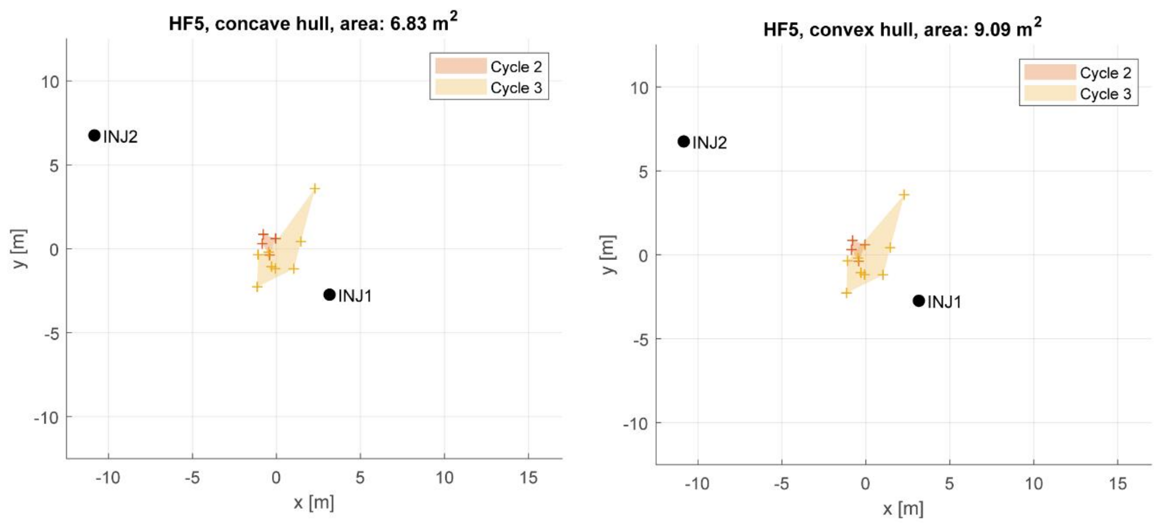

HS4 plane fits
Cluster 1
Cluster 2
Cluster 3
up [m]
north [m]
east [m]
HS4, Cluster 1, concave hull, area: 61.66 m2
HS4, Cluster 2, concave hull, area: 44.53 m2
HS4, Cluster 3, concave hull, area: 35.63 m2
HS4, Cluster 1, convex hull, area: 168.39 m2
HS4, Cluster 2, convex hull, area: 53.95 m2
HS4, Cluster 3, convex hull, area: 57.50 m2
Cycle 1
Cylce 2
Cylce 3
Cycle 4
INJ1
INJ2
x [m]
y [m]

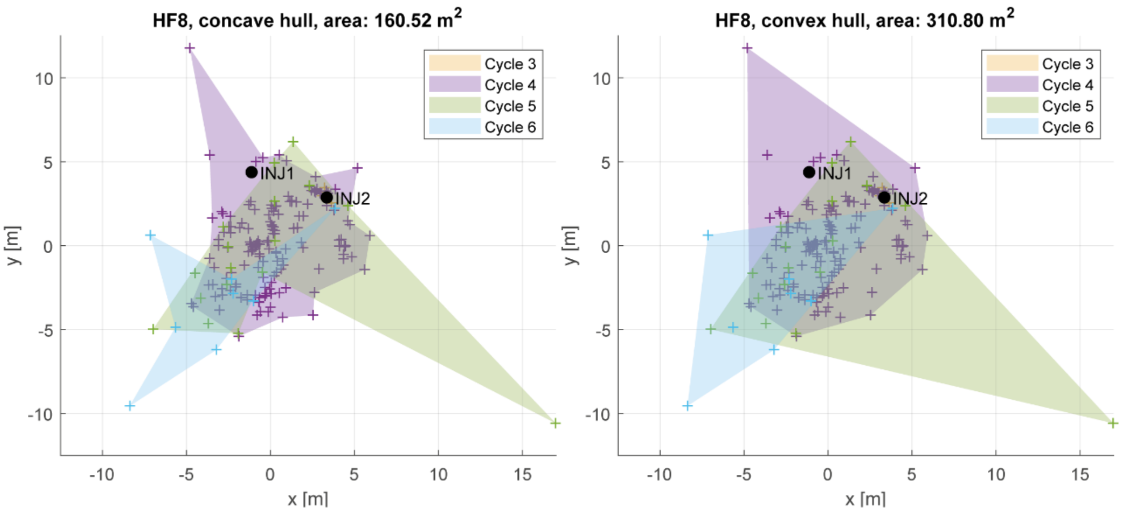

HS5, concave hull, area: 224.30 m2
HS5, convex hull, area: 345.20 m2
Cycle 1
Cycle 2
Cycle 3
Cycle 4
INJ1
INJ2
x [m]
y [m]


HS8 plane fits
Cluster 1
Cluster 2
Cluster 3
up [m]
north [m]
east [m]
HS8, Cluster 1, concave hull, area: 65.39 m2
HS8, Cluster 2, concave hull, area: 27.61 m2
HS8, Cluster 3, concave hull, area: 42.89 m2
HS8, Cluster 1, convex hull, area: 104.59 m2
HS8, Cluster 2, convex hull, area: 39.21 m2
HS8, Cluster 3, convex hull, area: 84.81 m2
Cylce 2
Cylce 3
INJ1
INJ2
x [m]
y [m]

b. Seismically activated area estimates HF experiments






HF8, concave hull, area: 160.52 m2
HF8, convex hull, area: 310.80 m2
Cycle 3
Cycle 4
Cycle 5
Cycle 6
INJ1
INJ2
y [m]
x [m]

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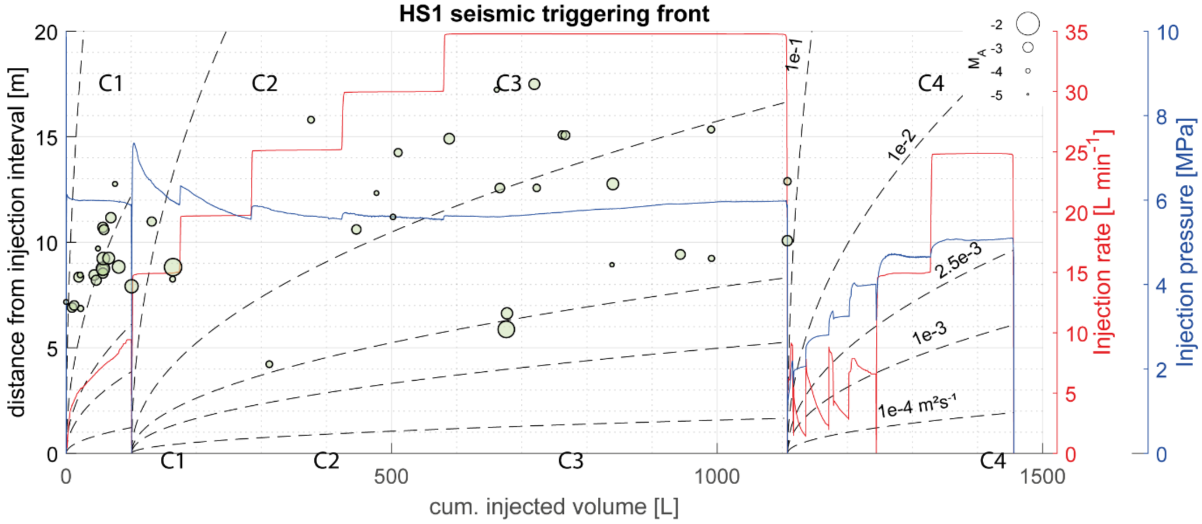
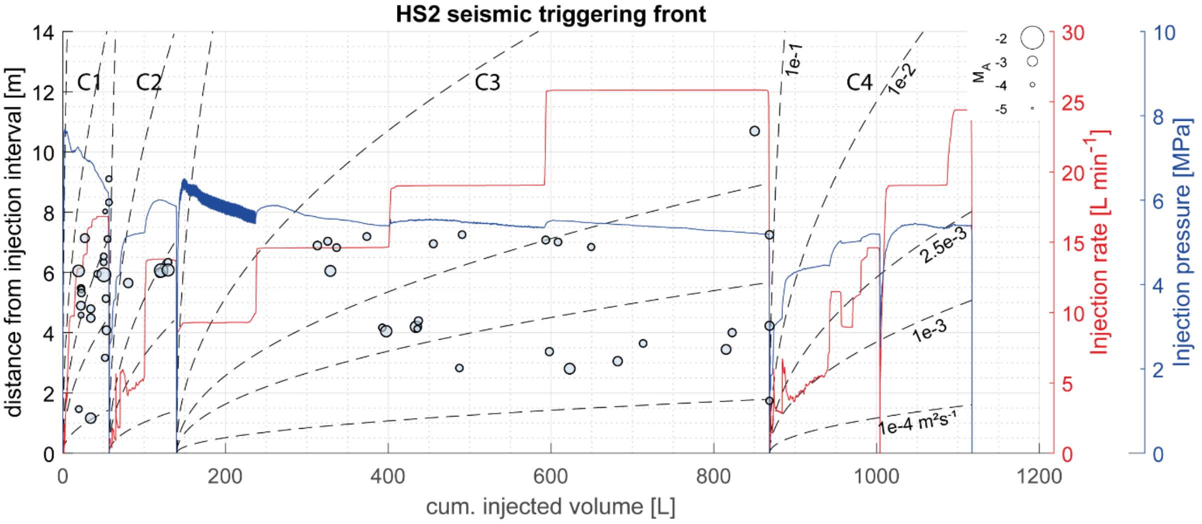
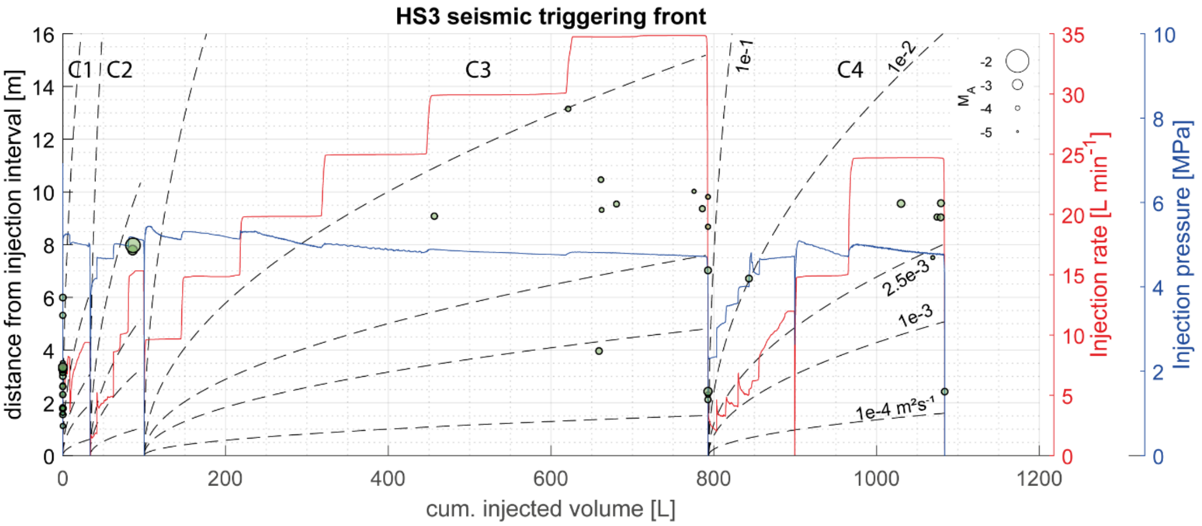
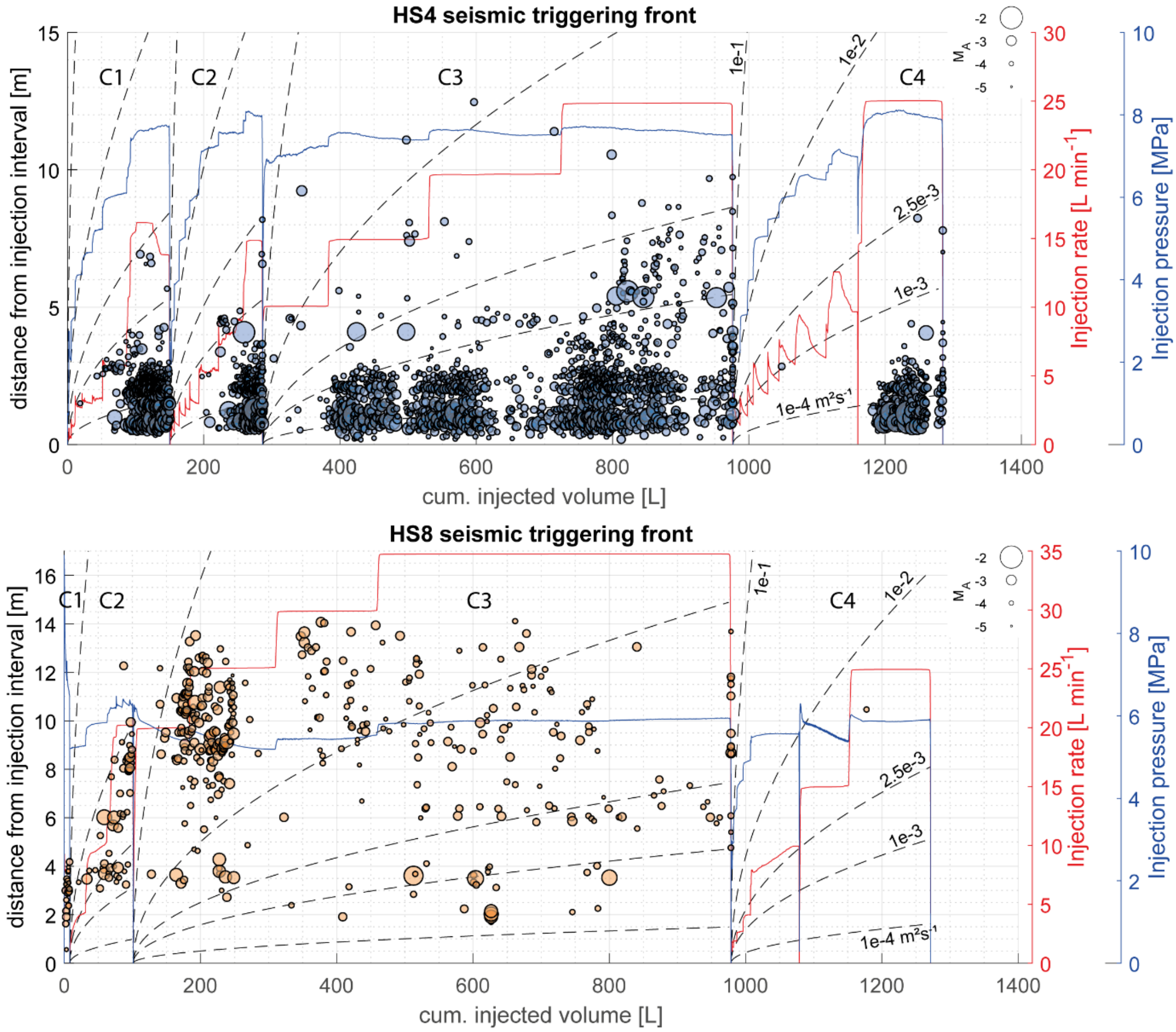
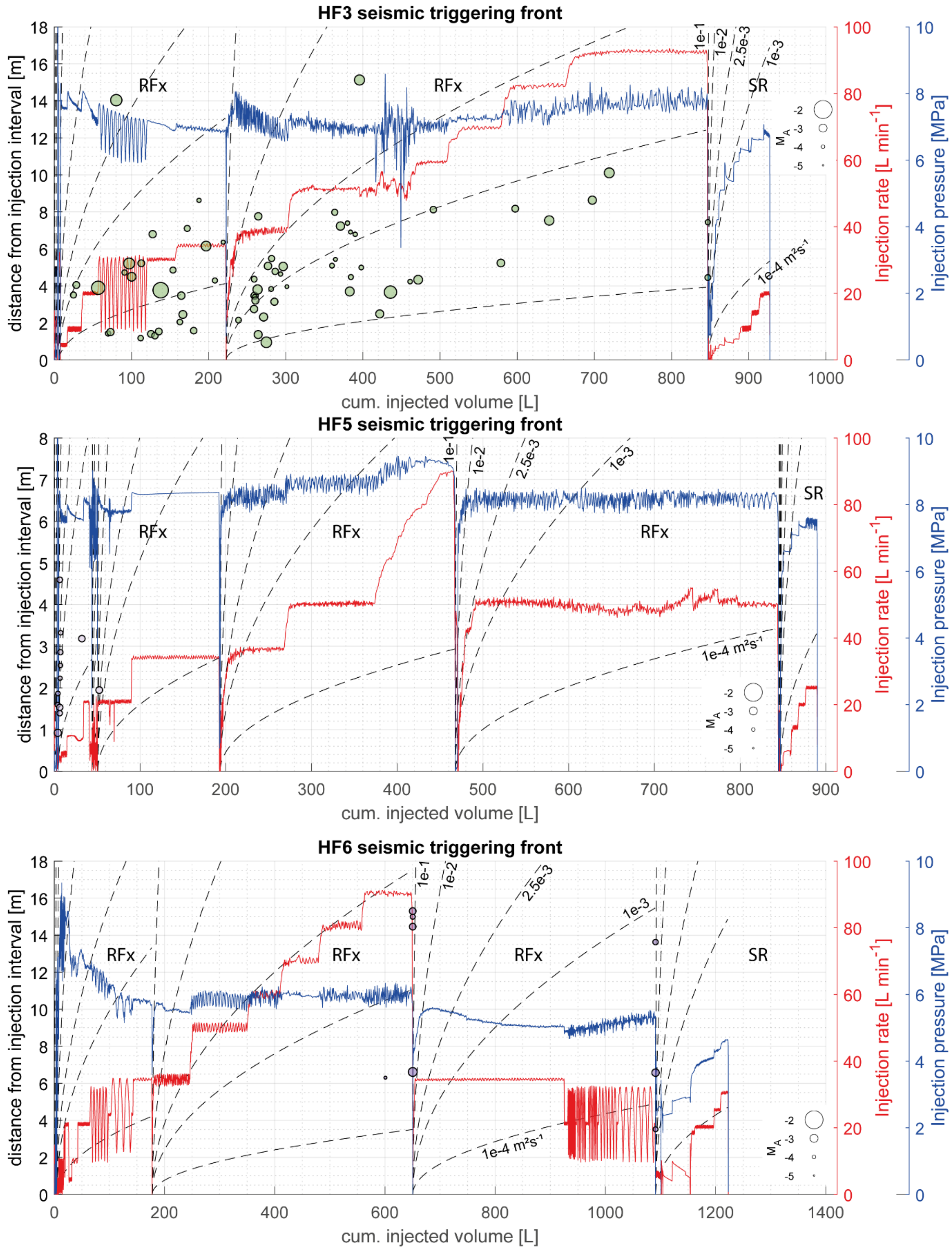
SM6: Estimates of seismic triggering fronts

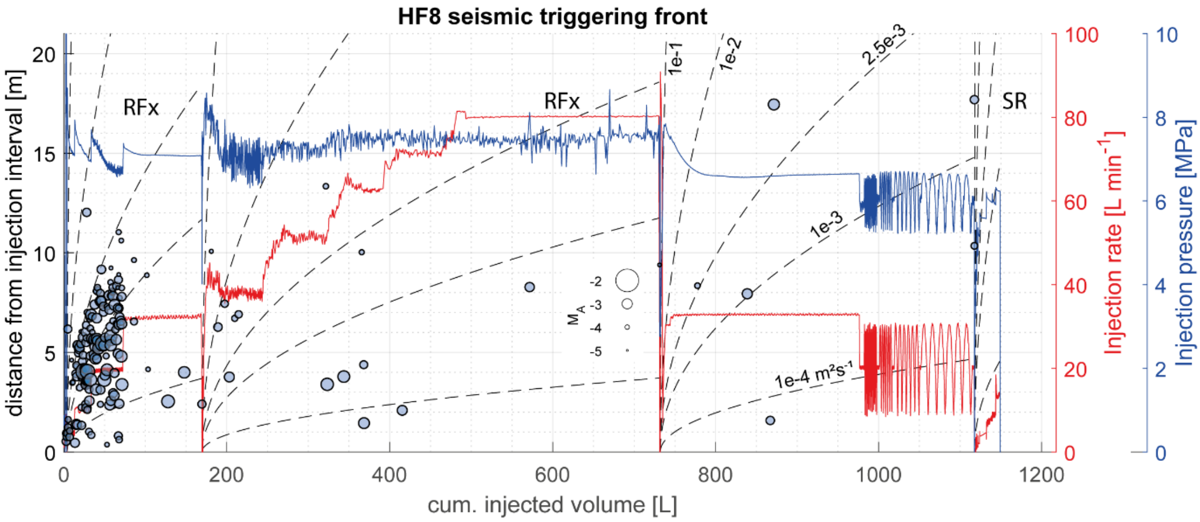







HS4 seismic triggering front
distance from injection interval [m]
cum. injected volume [L]
Injection rate [L min-1]
Injection pressure [MPa]
C1
C2
C3
C4
1e-1
1e-2
2.5e-3
1e-3
1e-4 m²s-1
HS8 seismic triggering front
distance from injection interval [m]
cum. injected volume [L]
Injection rate [L min-1]
Injection pressure [MPa]
C1
C2
C3
C4
1e-1
1e-2
2.5e-3
1e-3
1e-4 m²s-1


HF3 seismic triggering front
distance from injection interval [m]
cum. injected volume [L]
Injection rate [L min-1]
Injection pressure [MPa]
RFx
RFx
SR
1e-1
1e-2
2.5e-3
1e-3
1e-4 m²s-1
MA
-2
-3
-4
-5
HF5 seismic triggering front
distance from injection interval [m]
cum. injected volume [L]
Injection rate [L min-1]
Injection pressure [MPa]
RFx
RFx
RFx
SR
1e-1
1e-2
2.5e-3
1e-3
1e-4 m²s-1
MA
-2
-3
-4
-5
HF6 seismic triggering front
distance from injection interval [m]
cum. injected volume [L]
Injection rate [L min-1]
Injection pressure [MPa]
RFx
RFx
RFx
SR
1e-1
1e-2
2.5e-3
1e-3
1e-4 m²s-1
MA
-2
-3
-4
-5



115 # Referneces

Krietsch, H., Villiger, L., Doetsch, J., Gischig, V., Evans, K., Brixel, B., Jalali, M., Loew, S., and Amann, F.: Interplay between Hydraulic Shearing and Hydraulic Fracturing observed during an In-Situ Hydraulic Stimulation Expriement, in preparation.