Demonstration of soft stimulation treatments
of geothermal reservoirs

Deliverable D5.2: Demonstration of reservoir treatment (cyclic stimulation) and long-term performance of energy production

WP5 Demonstration cyclic hydraulic and multi stage treatments in granites and tight sandstones

Authors: Zimmermann G.[1], Hofmann H.[1], et al.

[1] GFZ Potsdam, Germany

Lead Beneficiary	5 – GFZ
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Dissemination level	☑ PU - Public ☐ CO - Confidential: only for members of the consortium
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Liability claim

DESTRESS is co-funded by

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Demonstration of soft stimulation treatments of geothermal reservoirs

First field application of cyclic soft stimulation at the Pohang Enhanced Geothermal System site in Korea (August 2017 stimulation in PX-1)

H Hofmann, G Zimmermann, M Farkas, E Huenges, A Zang, M Leonhardt, G Kwiatek, P Martinez-Garzon, M Bohnhoff, K-B Min, P Fokker, R Westaway, F Bethmann, P Meier, KS Yoon, JW Choi, TJ Lee, KY Kim

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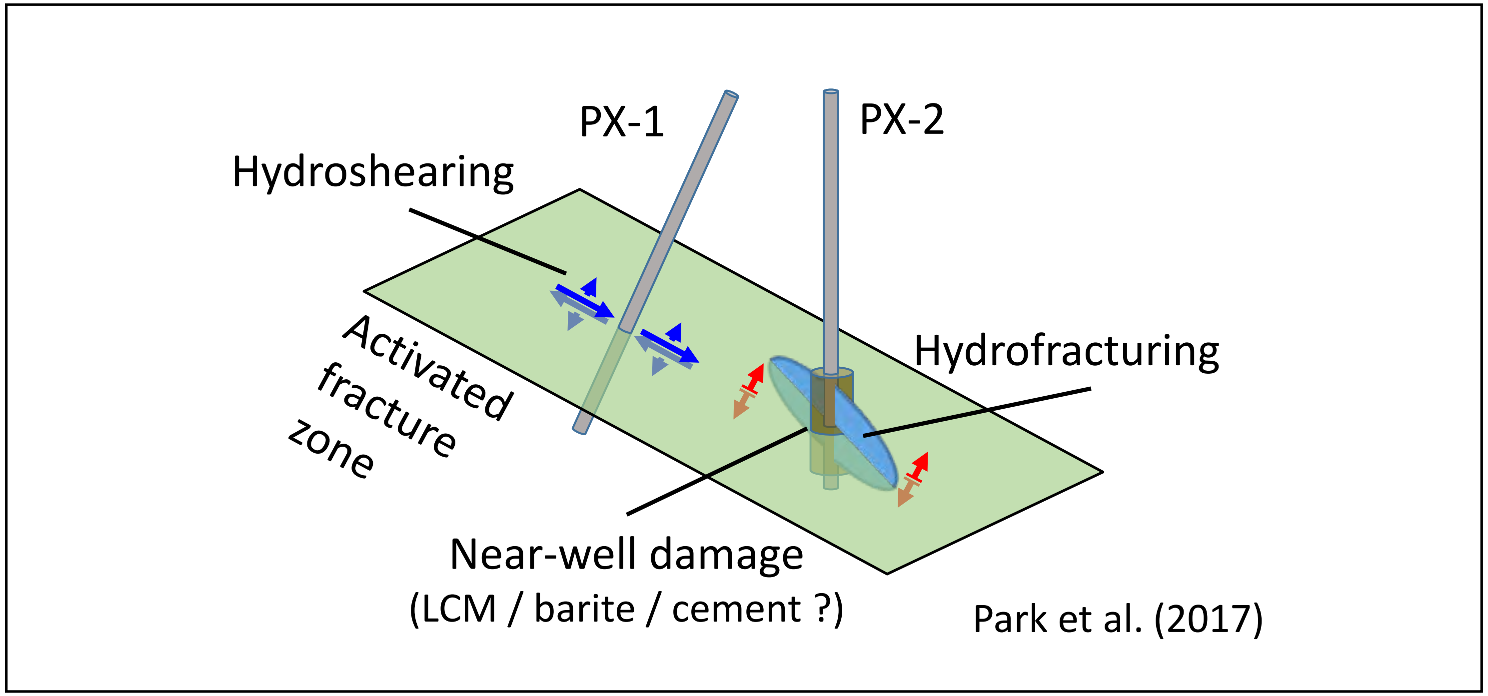
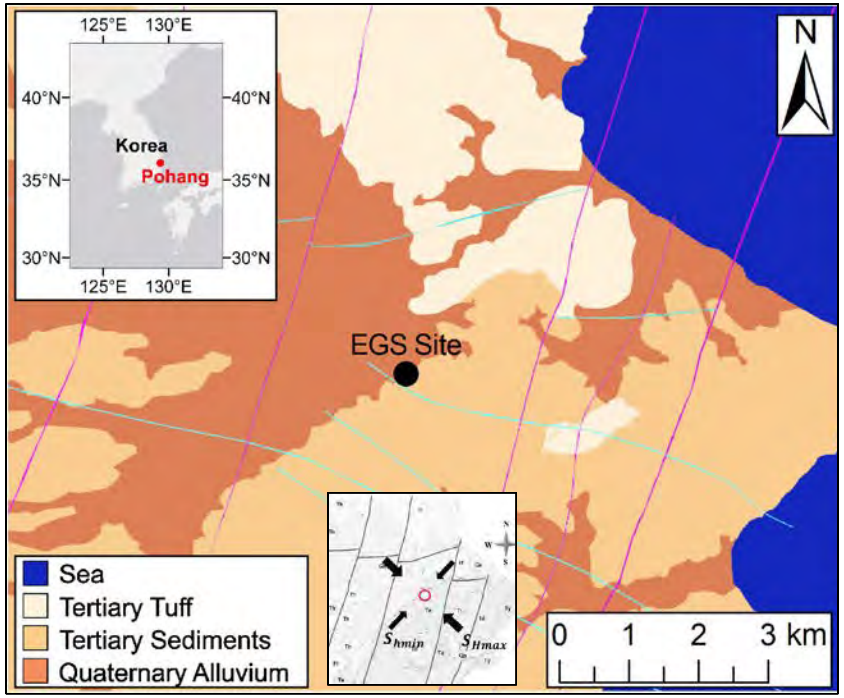
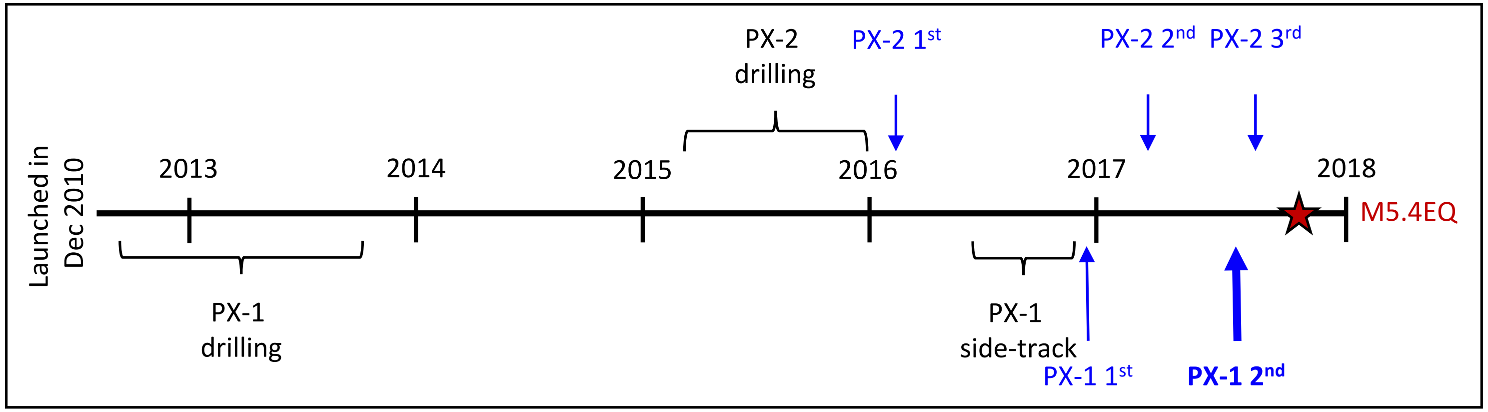
Overview Pohang EGS site







No hydraulic connection between wells

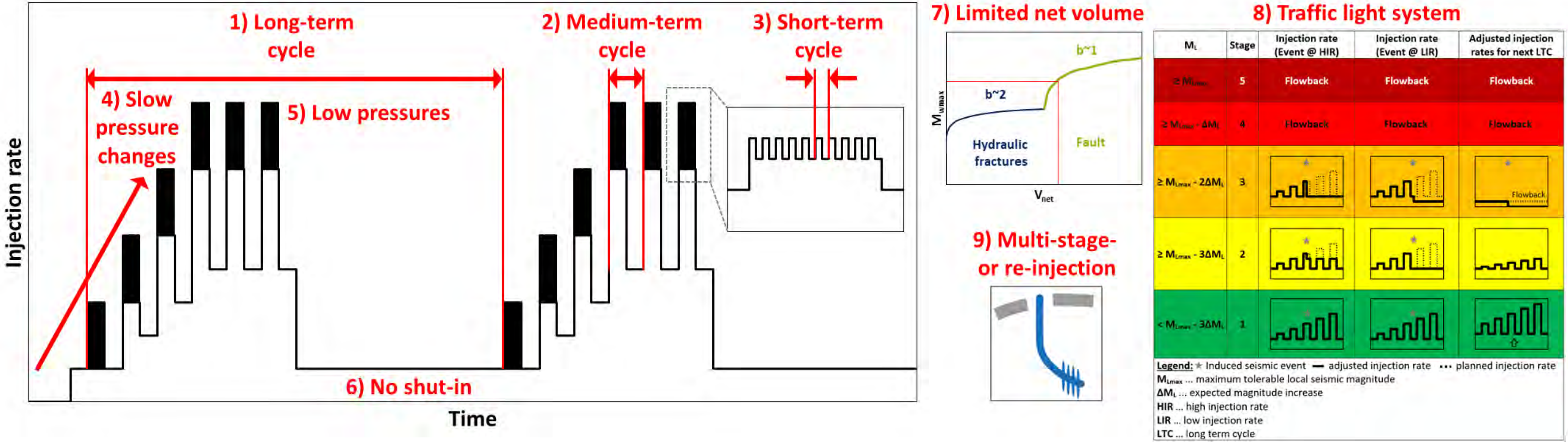
PX-1 no well damage
→ shearing+jacking at WHP=16 MPa

PX-2 near-well damage
→ fracturing+jacking at WHP=73 MPa

Motivation for „soft stimulation“ treatment in Pohang

- demonstrate the cyclic soft stimulation concept in the field as a more conservative treatment design compared to what would have been done otherwise
- inject fluid without inducing seismic events of $M_w \geq 2.0$
- map the stimulated reservoir volume as potential future drilling target
- monitor the stimulation performance in real time using harmonic pulse test analysis
- increase the hydraulic performance of the system

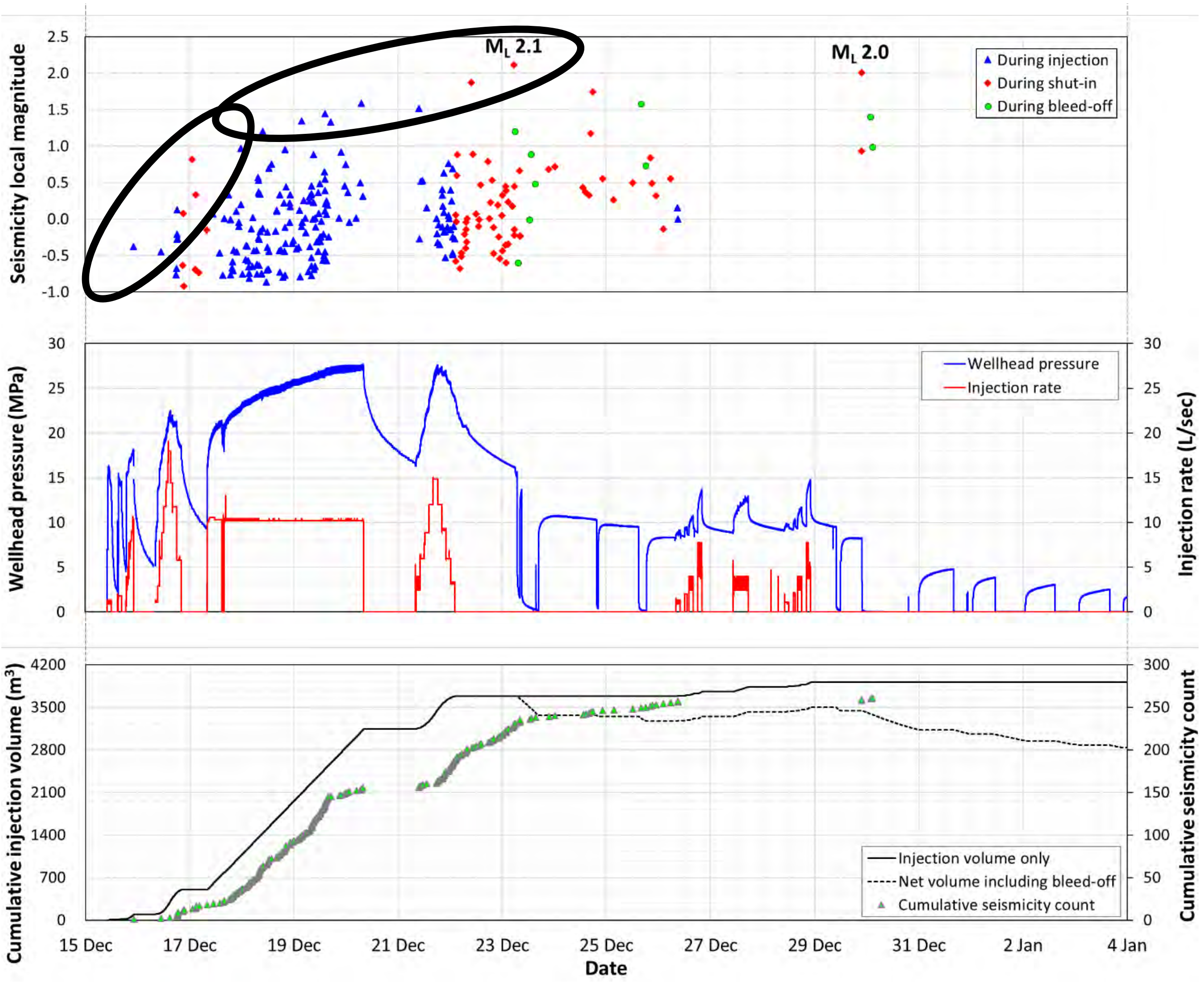
Cyclic soft stimulation concept



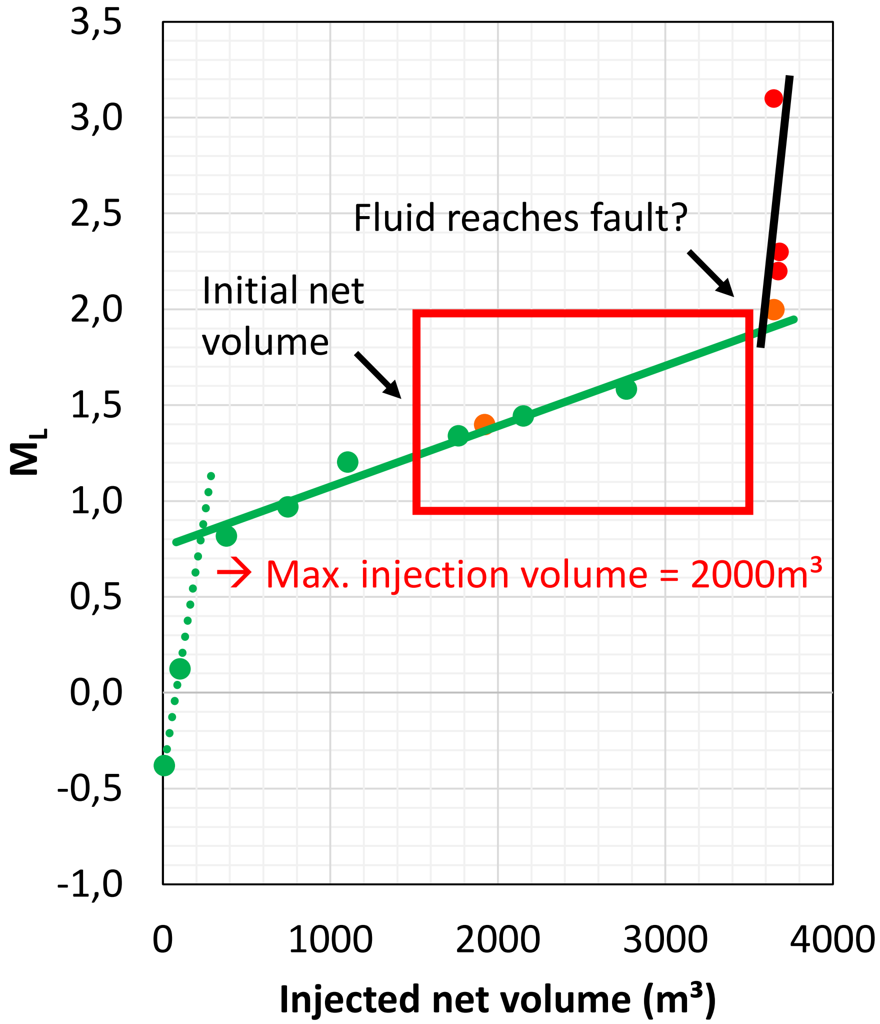
Hofmann, H., Zimmermann, G., Zang, A., Min, K. (2018): Cyclic soft stimulation (CSS): a new fluid injection protocol and traffic light system to mitigate seismic risks of hydraulic stimulation treatments. - Geothermal Energy, 6, 27. DOI: http://doi.org/10.1186/s40517-018-0114-3

Zang, A., Zimmermann, G., Hofmann, H., Stephansson, O., Min, K., Kim, K. Y. (2019): How to Reduce Fluid-Injection-Induced Seismicity. - Rock Mechanics and Rock Engineering, 52, 2, pp. 475-493. DOI: http://doi.org/10.1007/s00603-018-1467-4

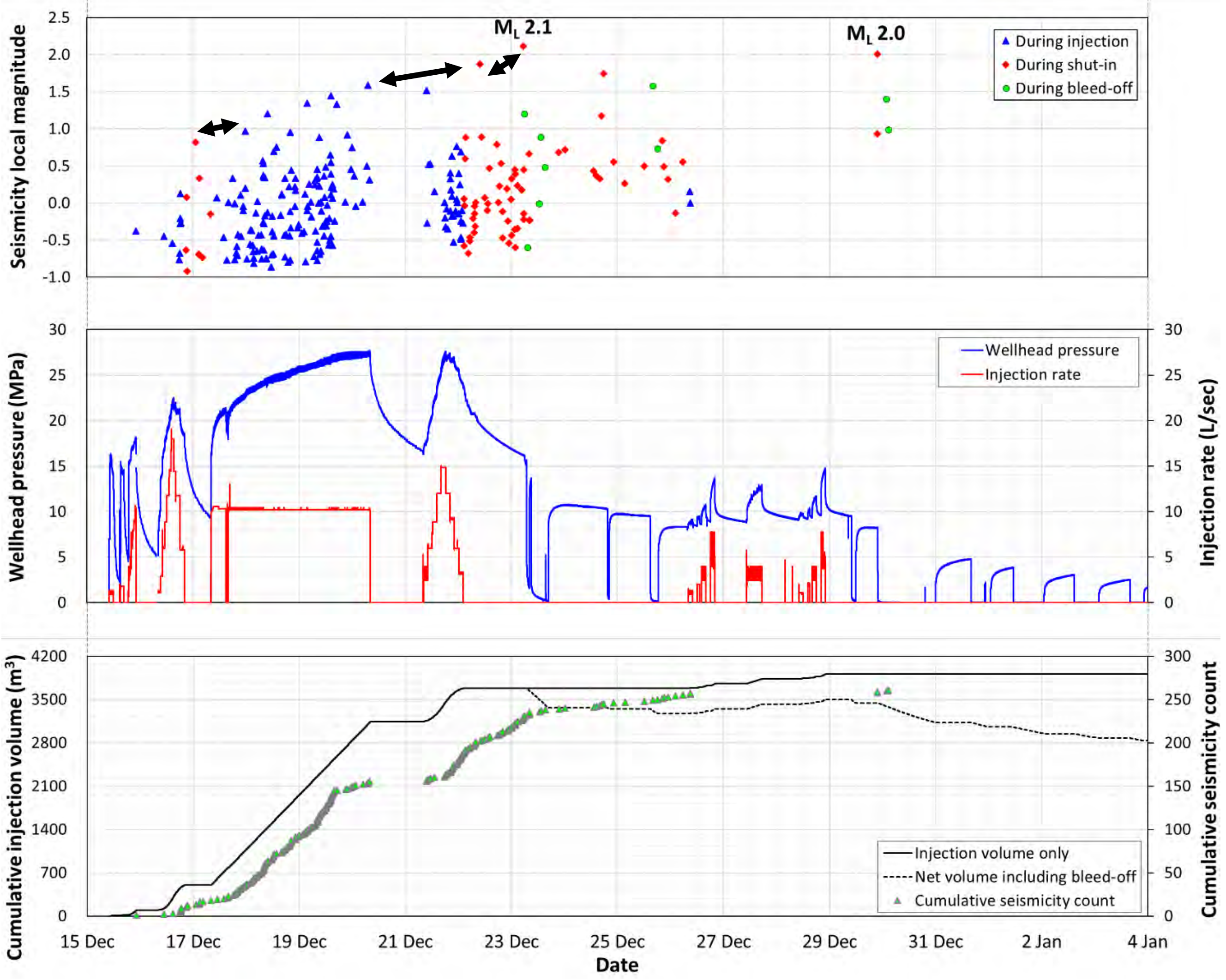
For example: maximum fluid volume



Park et al. (in preparation)



For example: Identification of magnitude increase for traffic light system



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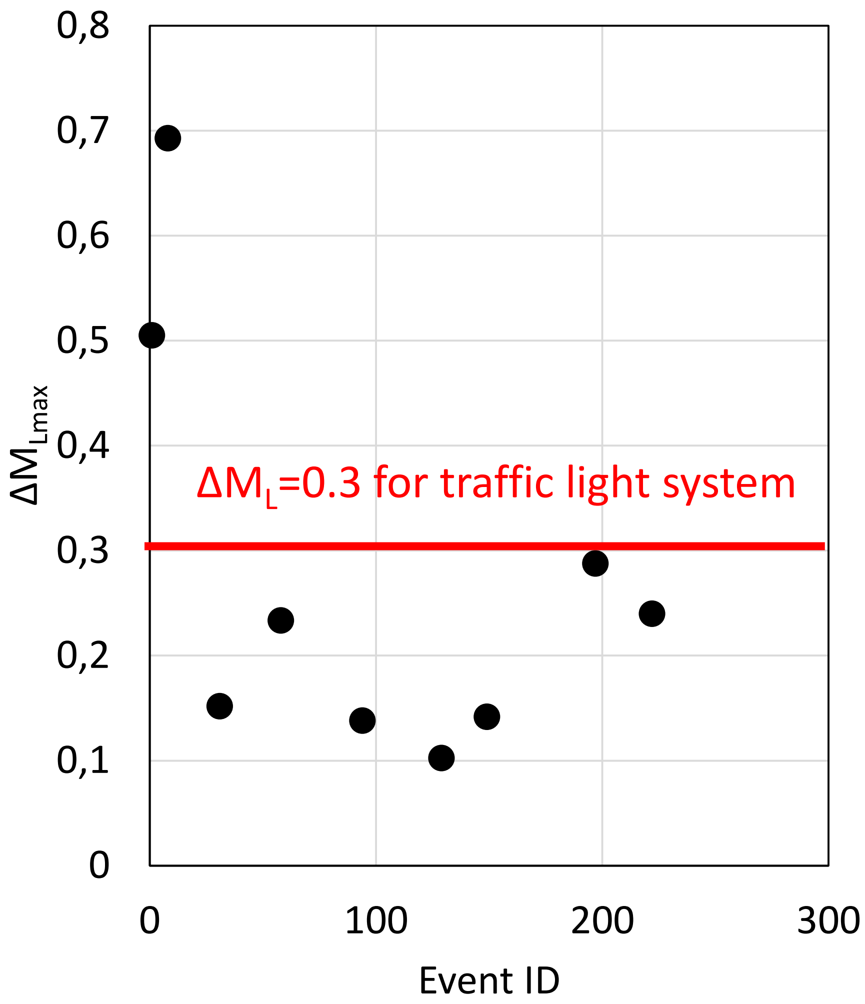
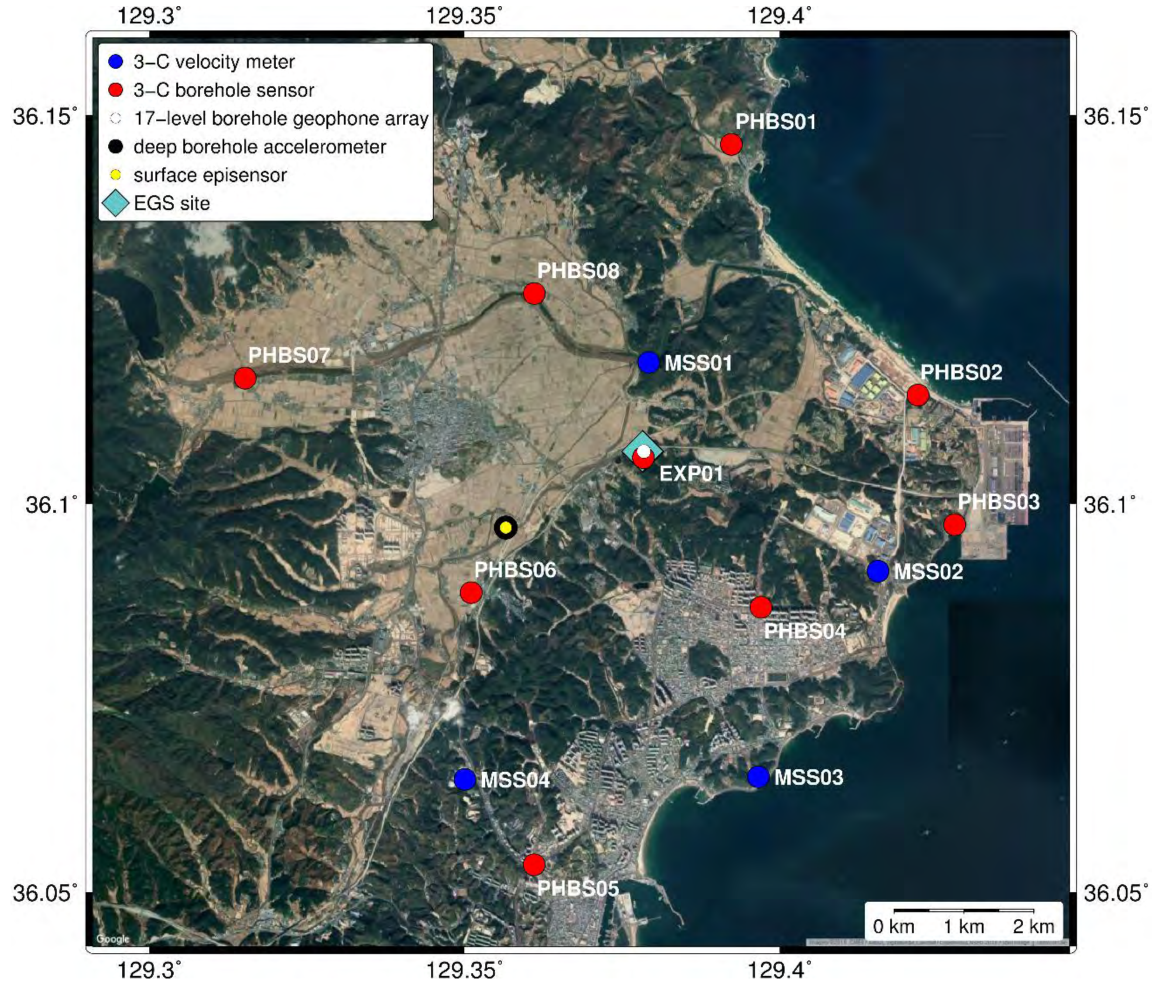
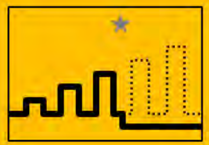
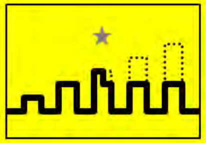
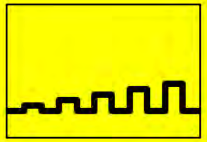
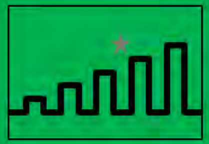
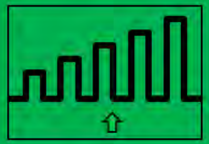


Real-time seismic monitoring and traffic-light system

1) Automatic real-time triggering of TLS based on PGV@MSS01 (automatic alert via email)
2) Manual revision (real alert?, confirmation of magnitude, preliminary location)



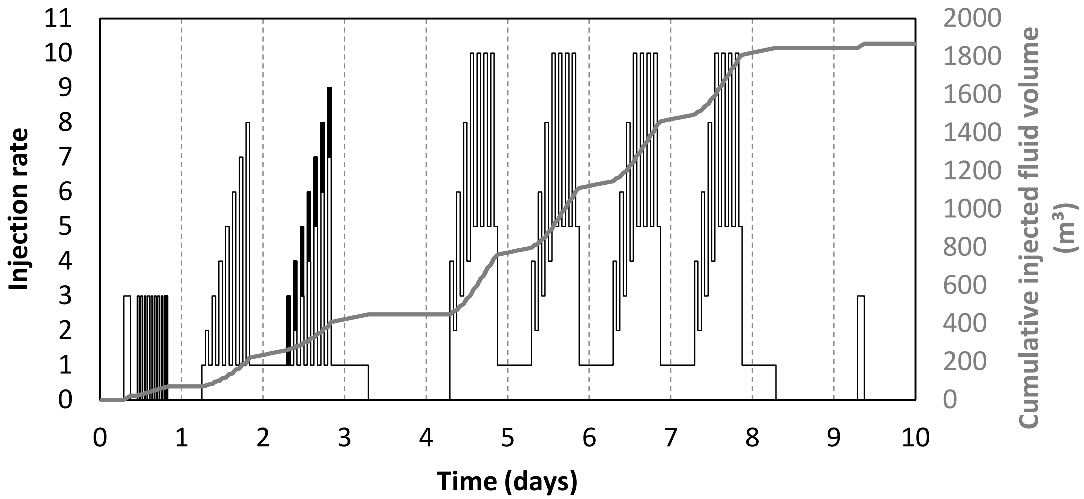
PGV (µm/s) @ MSS01	M_L	Stage	Injection rate (Event @ high rate)	Injection rate (Event @ low rate)	Adjusted injection rates for next cycle
> 100	> 2.0	5	Flow back	Flow back	Flow back
52 – 100	1.7 – 2.0	4	Flow back	Flow back	Flow back
27 – 52	1.4 – 1.7	3			 Flowback
10 – 27	1.0 – 1.4	2			
< 10	< 1.0	1			

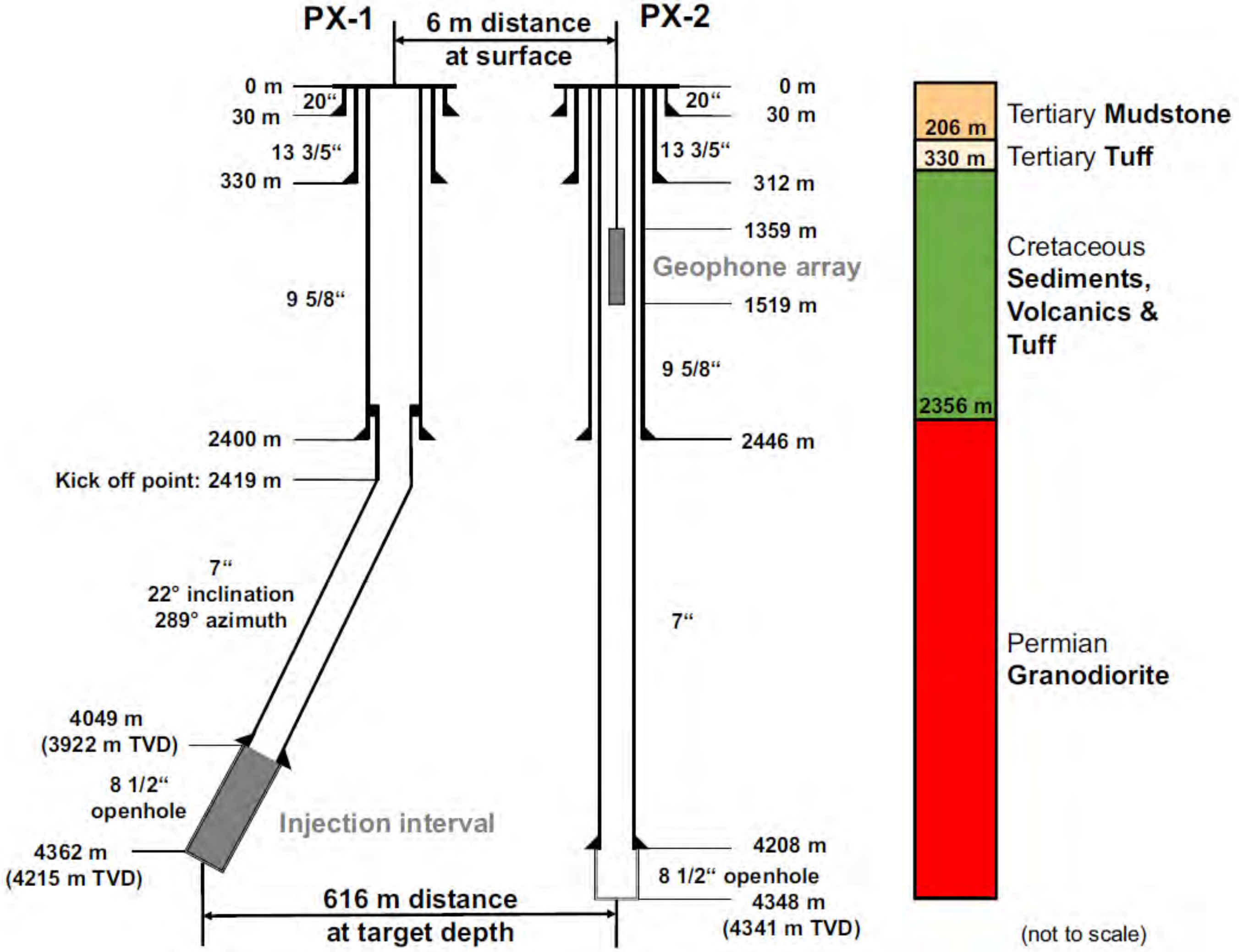
Legend: ★ Induced seismic event ▬ adjusted injection rate ▪▪▪ planned injection rate

Cyclic soft stimulation design for PX-1

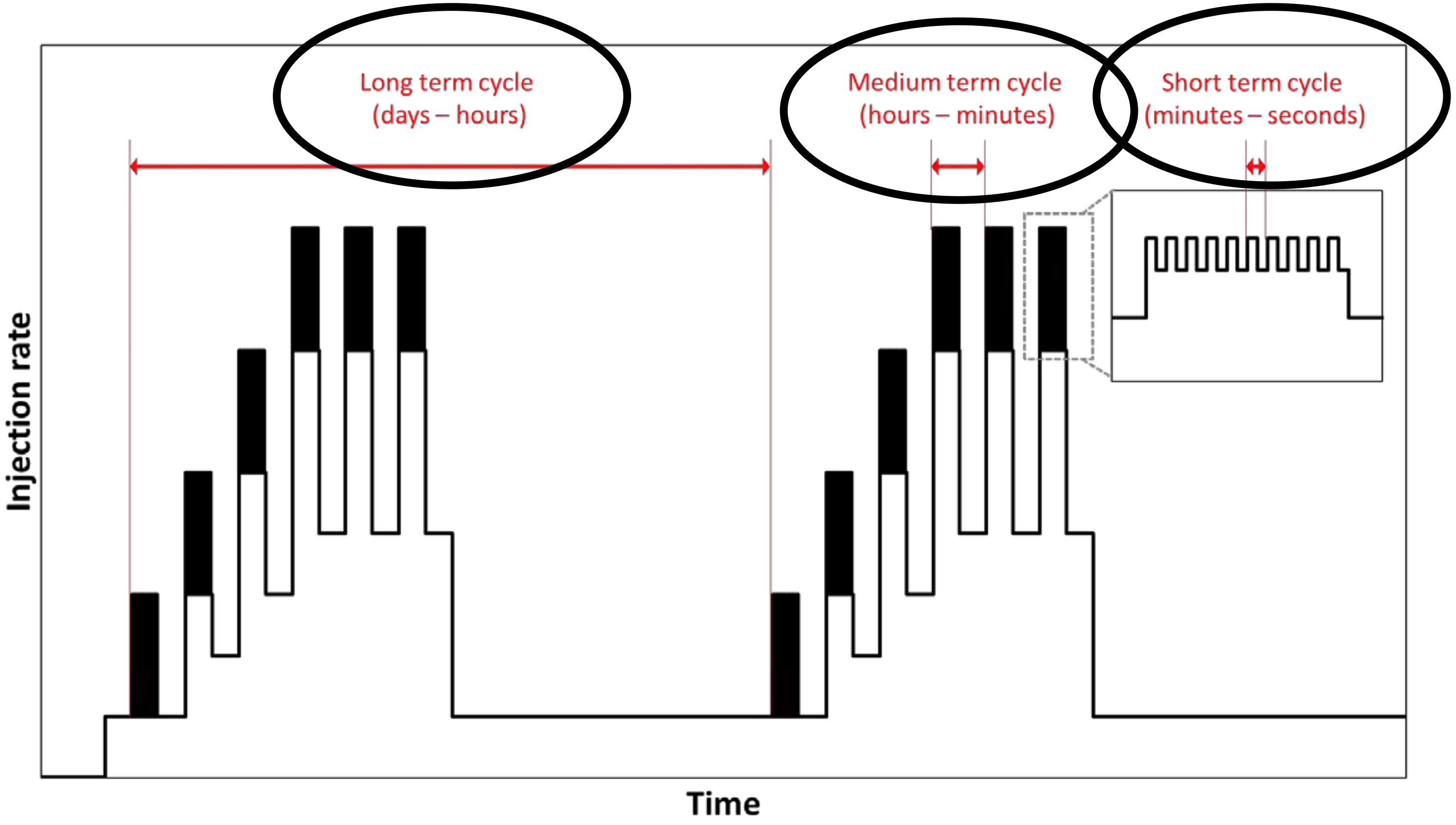
- Volume < 2000 m³
- WHP < 25 MPa
- Flow rate < 10 l/s
- Duration < 10 days
- Mw < 2.0

- Cyclic injection
- High rate injection during daytime
- No shut-in
- Sufficient storage for continuous flowback





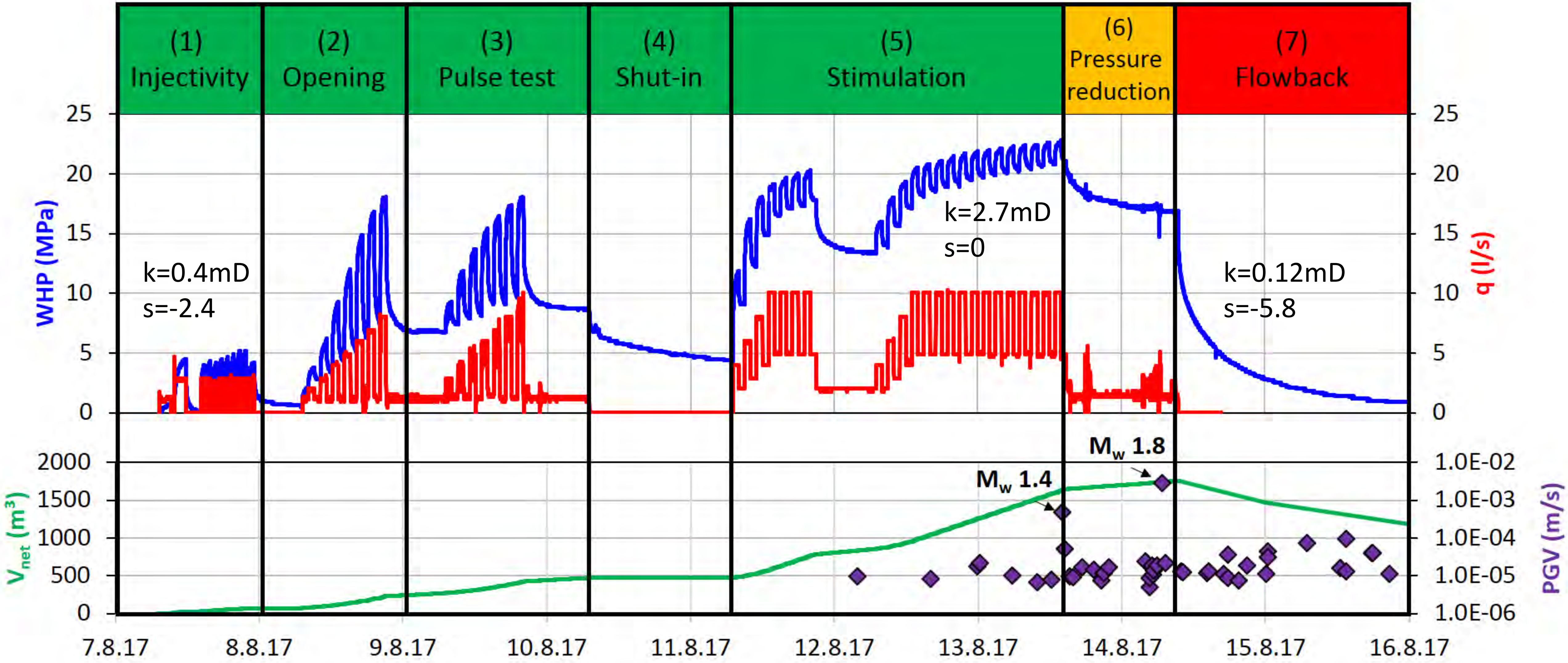
Hydraulic fatiguing and partitioning of energy



Cyclic injection leads to:

- Hydraulic fatiguing (additional microcracks form that extent the heat exchanger area and lower the breakdown pressure)
- The partitioning of the injected hydraulic energy leads to a partitioning of the released seismic energy and a stepwise stimulation

Hydraulic stimulation results 7.-14. August 2017 in PX-1



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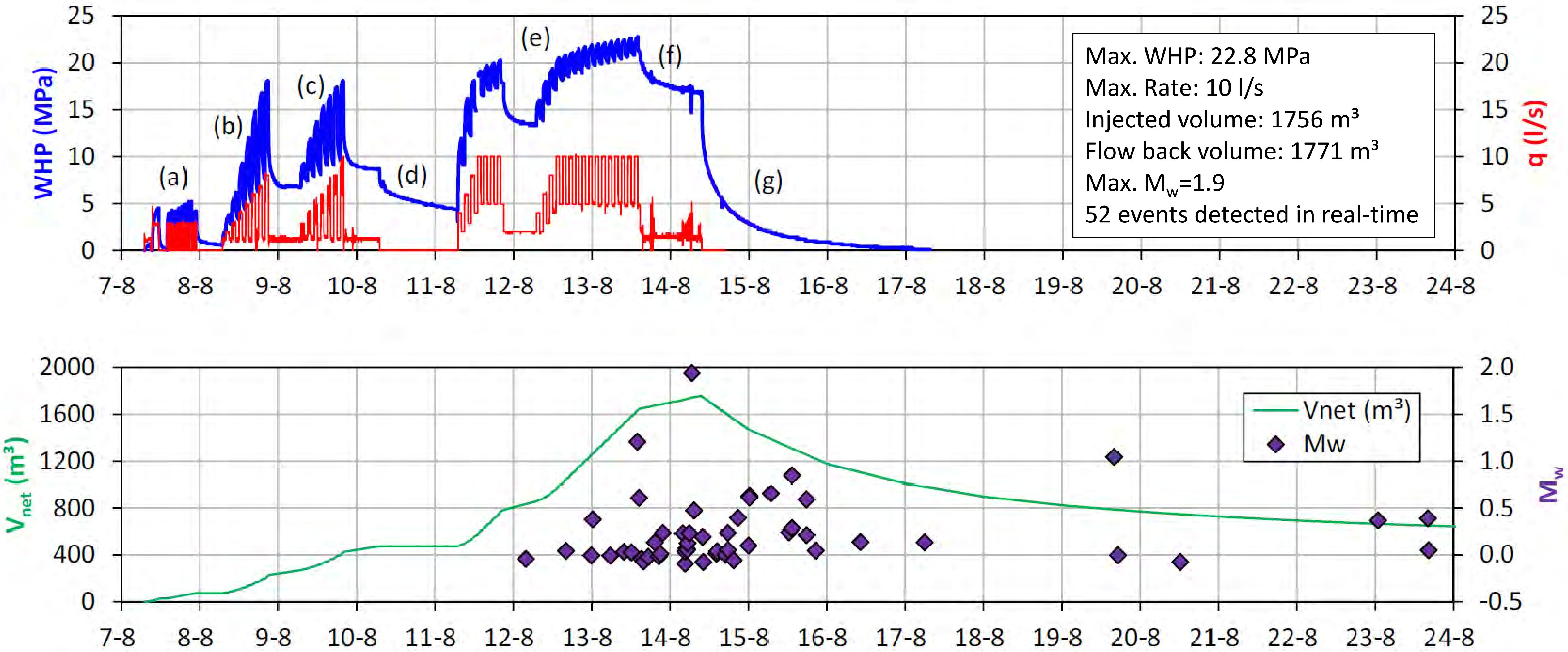
Flowback limited maximum magnitude during stimulation



Hofmann, H., et al. (2019): First field application of cyclic soft stimulation at the Pohang Enhanced Geothermal System site in Korea . - Geophysical Journal International, 217, 2, pp. 926-949.
DOI: http://doi.org/10.1093/gji/ggz058

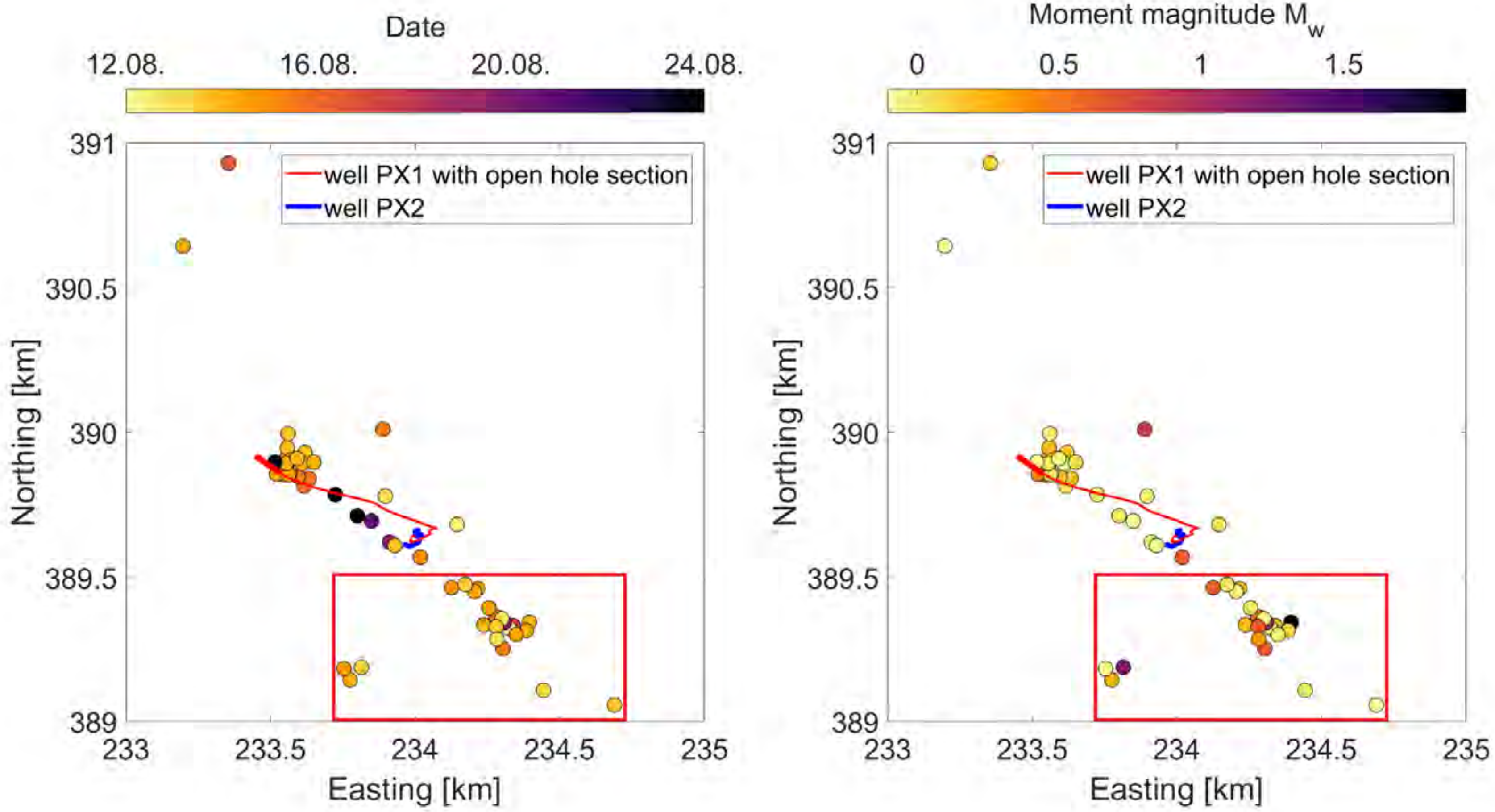
Summary of hydraulic analysis

Table 1. Results of hydraulic analysis.

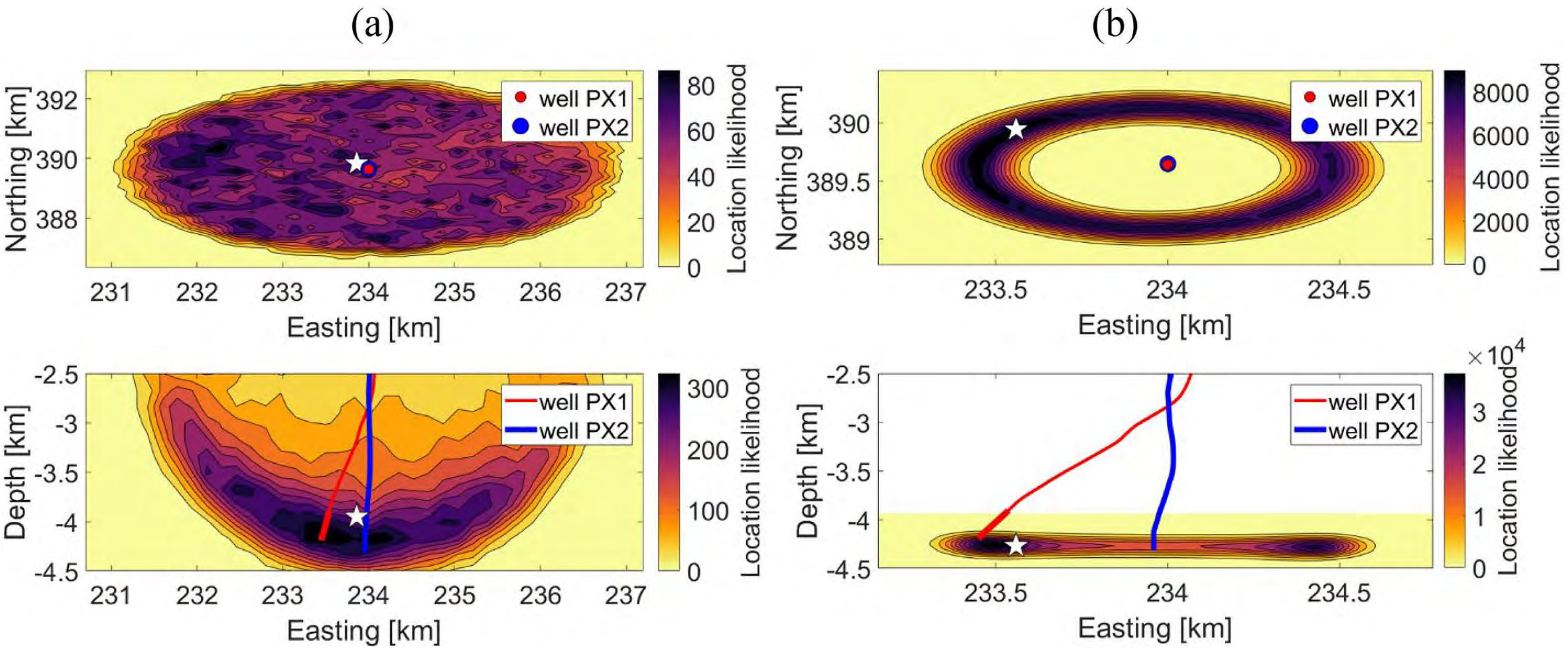
	Fall off #1 Day 1	Fall off #2 Day 1	Pulse test Day 1–3	Fall off Day 4	Pulse test Day 5	Pulse test Day 6–7	Flowback Day 8
Cumulative net volume V_{net} (m^3)	28	47	28–473	473	571–785	955–1647	1756–897
Initial pressure p_0 (MPa)	-0.36	0.21	-	3.34	-	-	3.30
Transmissivity kh (10^{-13} m^3)	1.15	0.93	1.97	0.52	5.92	7.90	0.34
Permeability k (10^{-15} m^2)	0.40	0.32	0.68	0.18	2.03	2.71	0.12
Skin s (-)	-2.40	-3.08	0.00	-3.99	0.00	0.00	-5.76
PI (l/s/MPa) pseudo steady-state R = 600 m	0.44	0.41	0.52	0.28	1.57	2.10	0.34
PI (l/s/MPa) well doublet d = 600 m	0.39	0.35	0.48	0.24	1.44	1.92	0.25
Distance to no-flow boundary L (m)	-	-	-	-	-	-	90.7
Storage coefficient C (m^3 Pa^{-1})	4.12E-08	1.71E-08	5.60E-09	2.59E-09	7.47E-09	7.47E-09	2.50E-09

Results are shown for three fall-off periods and one flowback using conventional well test analysis (after injection) and three periods of pulse injection interpreted by harmonic pulse testing analysis (during injection).

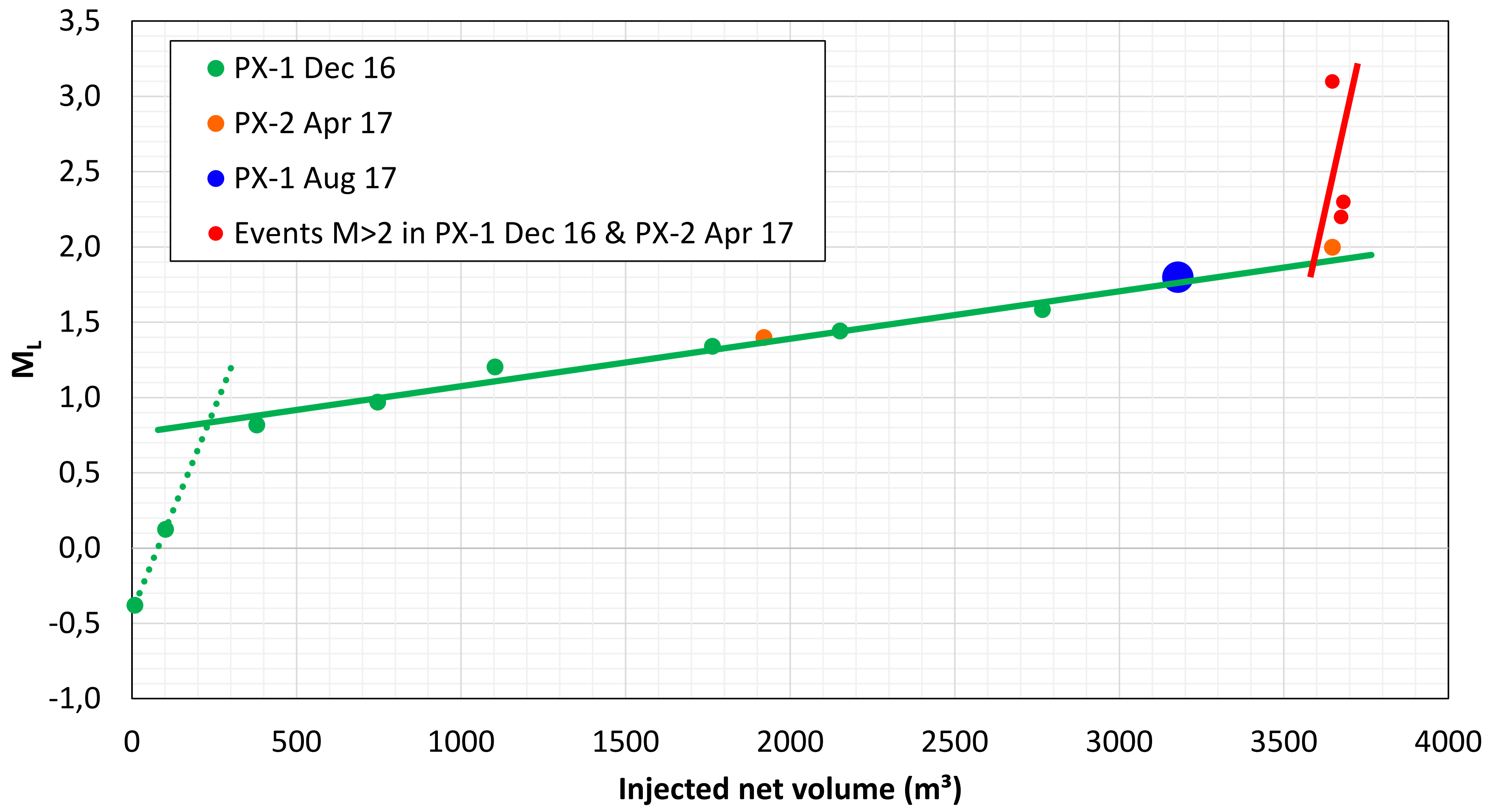
Induced seismicity locations (to be improved)



Hypocentre location likelihood



Largest magnitude event predicted through site-specific net volume magnitude relation



Summary

First field application of cyclic soft stimulation (CSS) with adjusted fluid injection design to limit seismic magnitudes

Seismicity

- Cyclic injection + traffic light system + flowback → $M_w < 2.0$ during injection and flowback
- No increase in seismic magnitude during flowback
- Largest event predicted with magnitude – net volume relation
- Largest event occurred during pump malfunction
- Locations + magnitudes + source mechanisms still under investigation

Hydraulics

- Pressure dependent injectivity
- No hydraulic connection between PX-1 and PX-2

outlook

- Further analysis of the DESTRESS stimulation seismicity dataset from August 2017 is under way and will supersede the previous analyses

Key publications

Borello, E. S., Fokker, P. A., Viberti, D., Verga, F., Hofmann, H., Meier, P., Min, K., Yoon, K., Zimmermann, G. (2019): Harmonic Pulse Testing for Well Monitoring: application to a fractured geothermal reservoir. - Water Resources Research, 55, 6, 4727-4744.

Burnside, N. M., Westaway, R., Banks, D., Zimmermann, G., Hofmann, H., Boyce, A. J. (2019): Rapid water-rock interactions evidenced by hydrochemical evolution of flowback fluid during hydraulic stimulation of a deep geothermal borehole in granodiorite: Pohang, Korea. - Applied Geochemistry, 111.

Hofmann, H., Zimmermann, G., Farkas, M. P., Huenges, E., Zang, A., Leonhardt, M., Kwiatek, G., Martinez Garzon, P., Bohnhoff, M., Min, K.-B., Fokker, P., Westaway, R., Bethmann, F., Meier, P., Yoon, K. S., Choi, J. W., Lee, T. J., Kim, K. Y. (2019): First field application of cyclic soft stimulation at the Pohang Enhanced Geothermal System site in Korea. - Geophysical Journal International, 217, 2, 926-949.

Hofmann, H., Zimmermann, G., Zang, A., Min, K.-B. (2018): Cyclic soft stimulation (CSS): a new fluid injection protocol and traffic light system to mitigate seismic risks of hydraulic stimulation treatments. - Geothermal Energy, 6.

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Zhuang, L., Kim, K. Y., Jung, S. G., Diaz, M., Min, K.-B., Zang, A., Stephansson, O., Zimmermann, G., Yoon, J.-S., Hofmann, H. (2019): Cyclic hydraulic fracturing of pocheon granite cores and its impact on breakdown pressure, acoustic emission amplitudes and injectivity. - International Journal of Rock Mechanics and Mining Sciences, 122

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Swiss State Secretariat for Education, Research and Innovation (SERI)

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Demonstration of soft stimulation treatments of geothermal reservoirs

Demonstration of cyclic soft stimulation on Geldinganes

H. Hofmann & the DESTRESS-Team

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 691728

Selected partners & contractors

Hannes Hofmann, Günter Zimmermann, Ernst Huenges, Simona Regenspurg (GFZ Section 4.8 Geoenergy)

Claus Milkereit, Sebastian Heimann, Simone Cesca, Stefan Mikulla, Torsten Dahm (GFZ Section 2.1 Physics of Earthquakes and Volcanoes)

Santiago Aldaz, Jochem Kück, Marco Groh, Martin Töpfer (GFZ Section 4.2 Geomechanics and Scientific Drilling)

Arno Zang (GFZ Section 2.6 Seismic Hazard and Risk Dynamics)

Arnaud Mignan, Marco Broccardo, Antonio Rinaldi, Luca Scarabello, Dimitrios Karvounis, Francesco Grigoli, Stefan Wiemer (ETH Zürich)

Vala Hjörleifsdóttir, Bjarni Reyr Kristjánsson, Sandra Osk Snæbjörnsdóttir, Edda Sif Aradóttir (Reykjavik Energy)

Ragnheidur St. Ásgeirsdóttir, Kristján Ágústsson, Rögnvaldur Magnússon, Olafur Flovenz (ISOR)

Sveinbjörn Hólmgeirsson (GeoEnergy Consulting)

Benedikt Jakobsson, Oddgeir Gudnason, Jón Árni Jónsson, Tobías Brynleifsson, Helga Vala Jónsdóttir (Iceland Drilling)

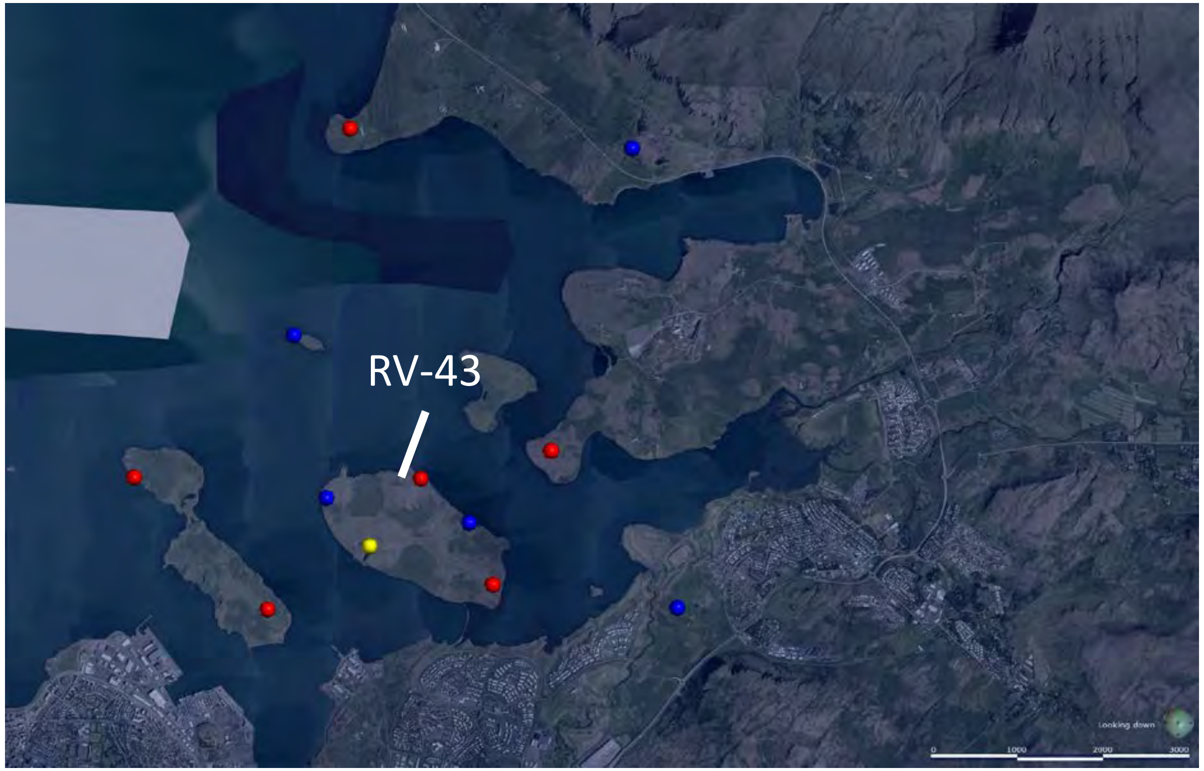
Ivan Kosorok, Francis Ford (Inflatable Packers International)

Thibault Candela, Brecht Wassing, Peter Fokker (TNO)

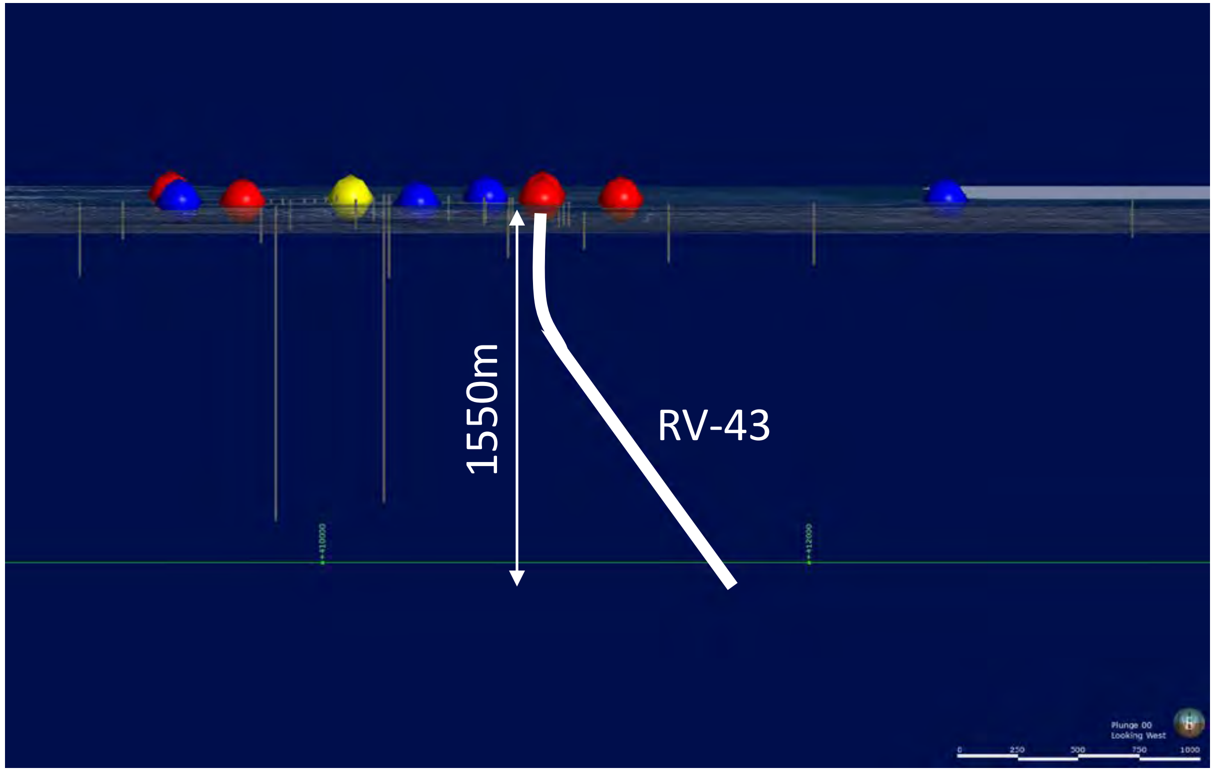
Geldinganes:
Heat for Reykjavik

Well RV-43

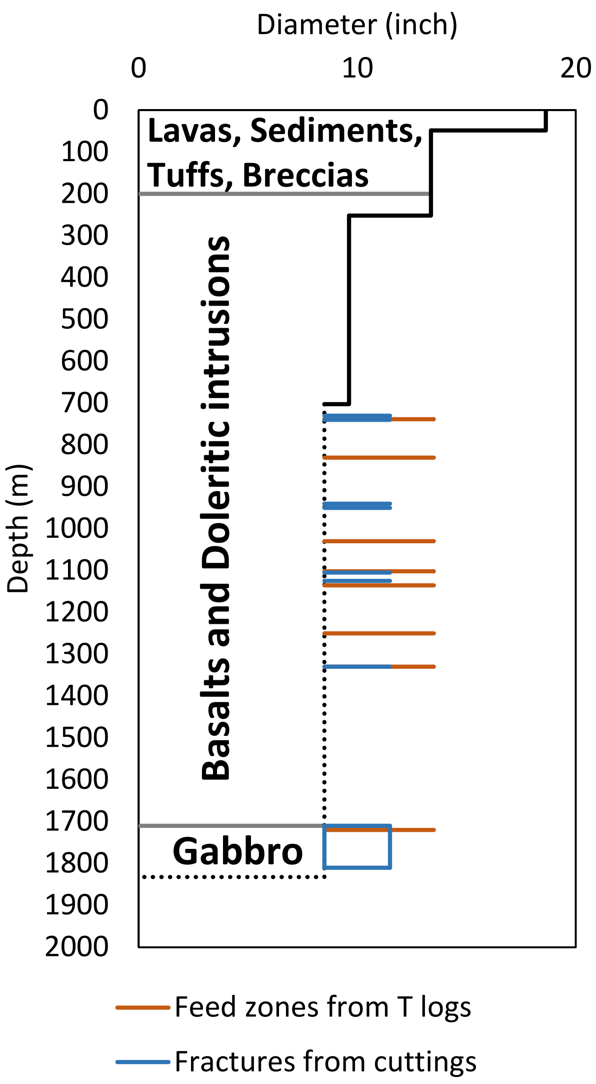
Top view

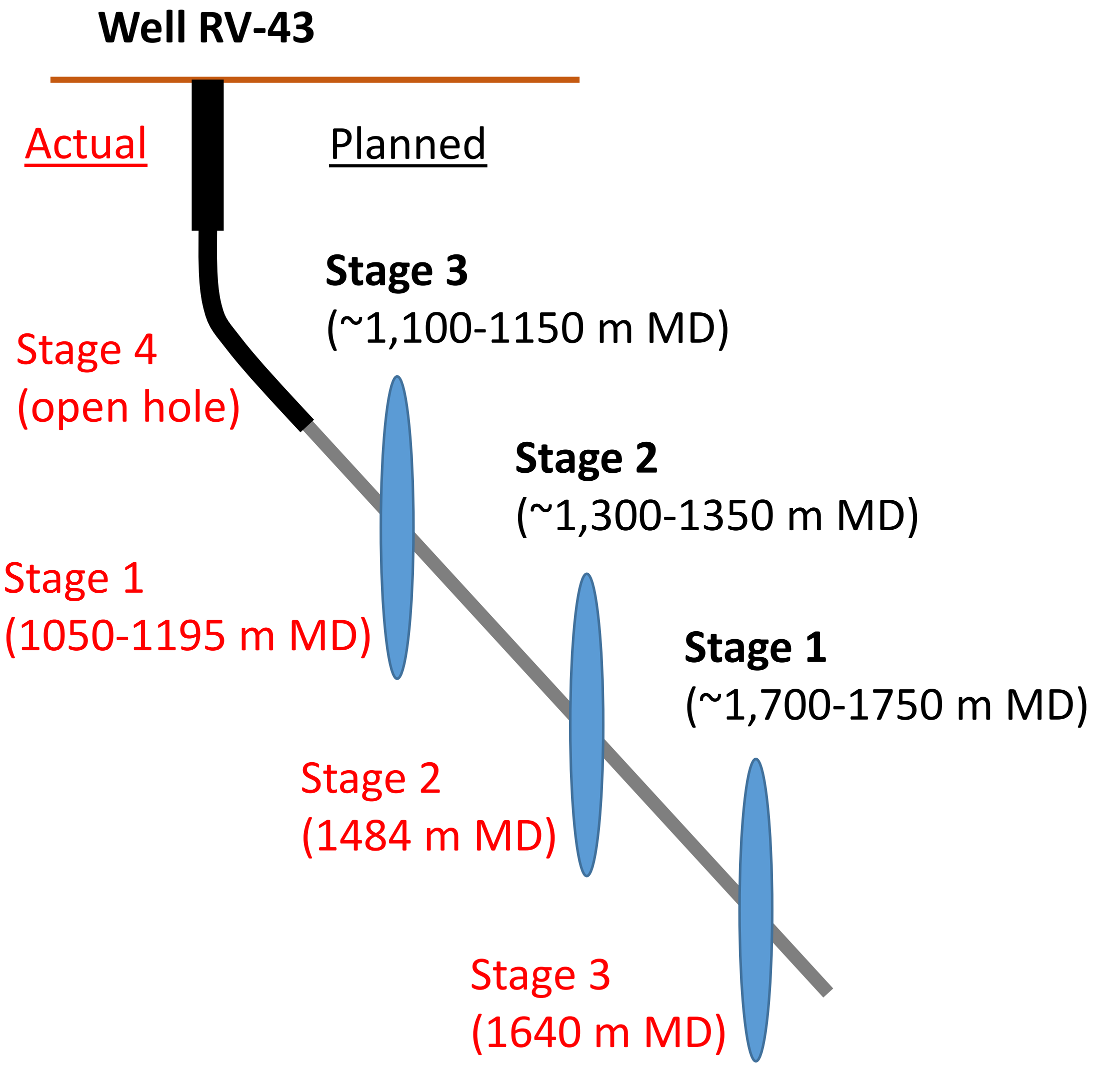


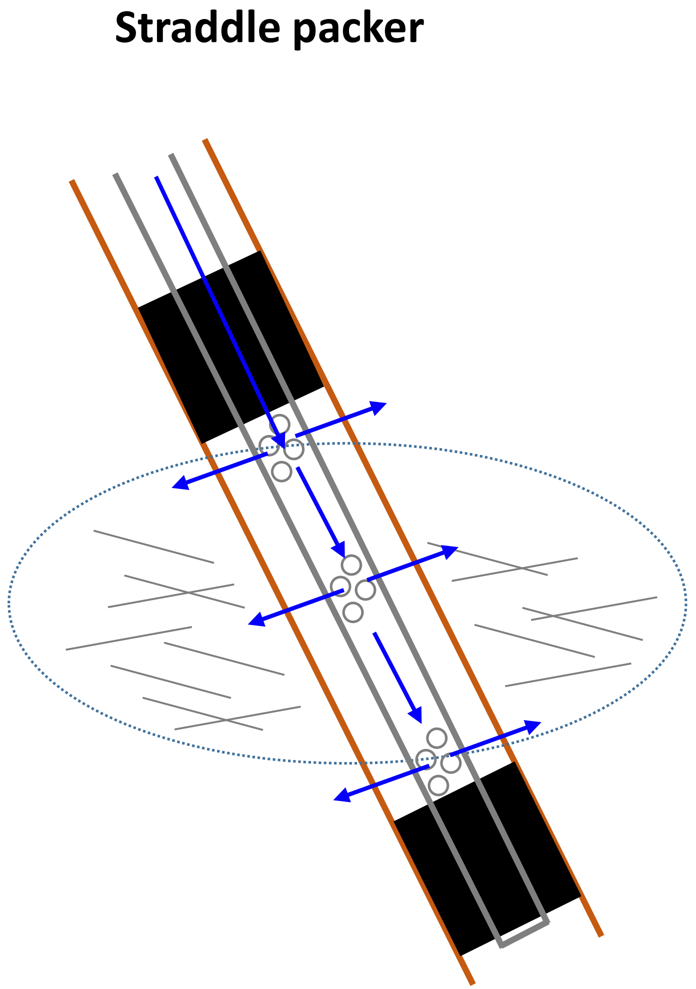
Looking west



Hydraulic stimulation stages







Field operations (timeline)

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Field operations from 11 October – 1 November 2019

<table>
<tr><th colspan="2">Mo, 07.10.</th><th colspan="2">Tue, 08.10.</th><th colspan="2">Wed, 09.10.</th><th colspan="2">Thur, 10.10.</th><th colspan="2">Fr, 11.10.</th><th colspan="2">Sa, 12.10.</th><th colspan="2">Sun, 13.10.</th></tr>
<tr><td colspan="8">Rig up</td><td colspan="4">Reaming</td><td colspan="2">Logging/Liner</td></tr>
<tr><th colspan="2">Mo, 14.10.</th><th colspan="2">Tue, 15.10.</th><th colspan="2">Wed, 16.10.</th><th colspan="2">Thur, 17.10.</th><th colspan="2">Fr, 18.10.</th><th colspan="2">Sa, 19.10.</th><th colspan="2">Sun, 20.10.</th></tr>
<tr><td colspan="2"></td><td colspan="2">Prep. Stage 1</td><td colspan="10">Stage 1 stimulation</td></tr>
<tr><th colspan="2">Mo, 21.10.</th><th colspan="2">Tue, 22.10.</th><th colspan="2">Wed, 23.10.</th><th colspan="2">Thur, 24.10.</th><th colspan="2">Fr, 25.10.</th><th colspan="2">Sa, 26.10.</th><th colspan="2">Sun, 27.10.</th></tr>
<tr><td></td><td>POOH</td><td colspan="2">Prep. Stage 2</td><td colspan="3">Reaming</td><td colspan="2">Logging/DP</td><td>Stage 2</td><td>POOH</td><td>Prep. Stage 3</td><td colspan="2">Stage 3</td></tr>
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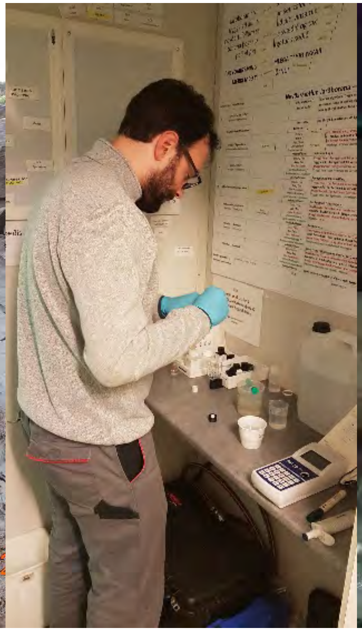
</table>

Monitoring

Monitoring

- Hydraulic monitoring (WHP, pressure below, between, above packers, annulus pressure, injection rate, return rate, water level of neighboring wells)
- Real-time seismic monitoring
- Continuous chemical monitoring + sampling of flowback water



Logging

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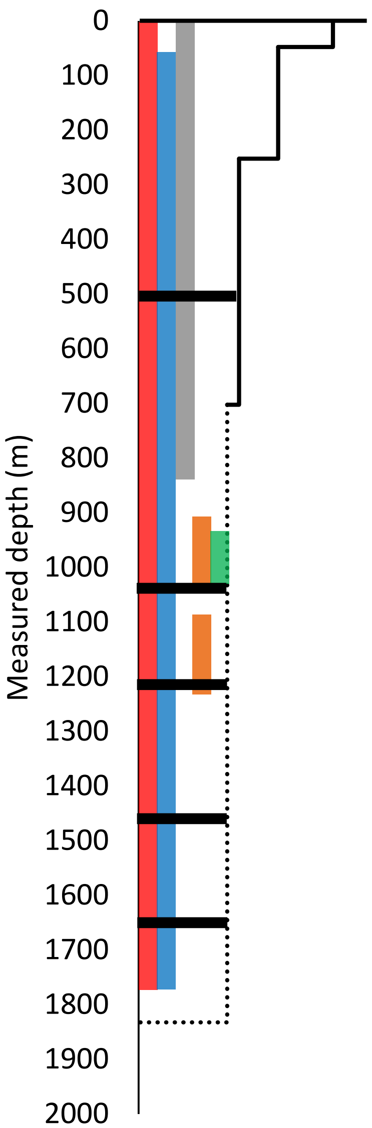
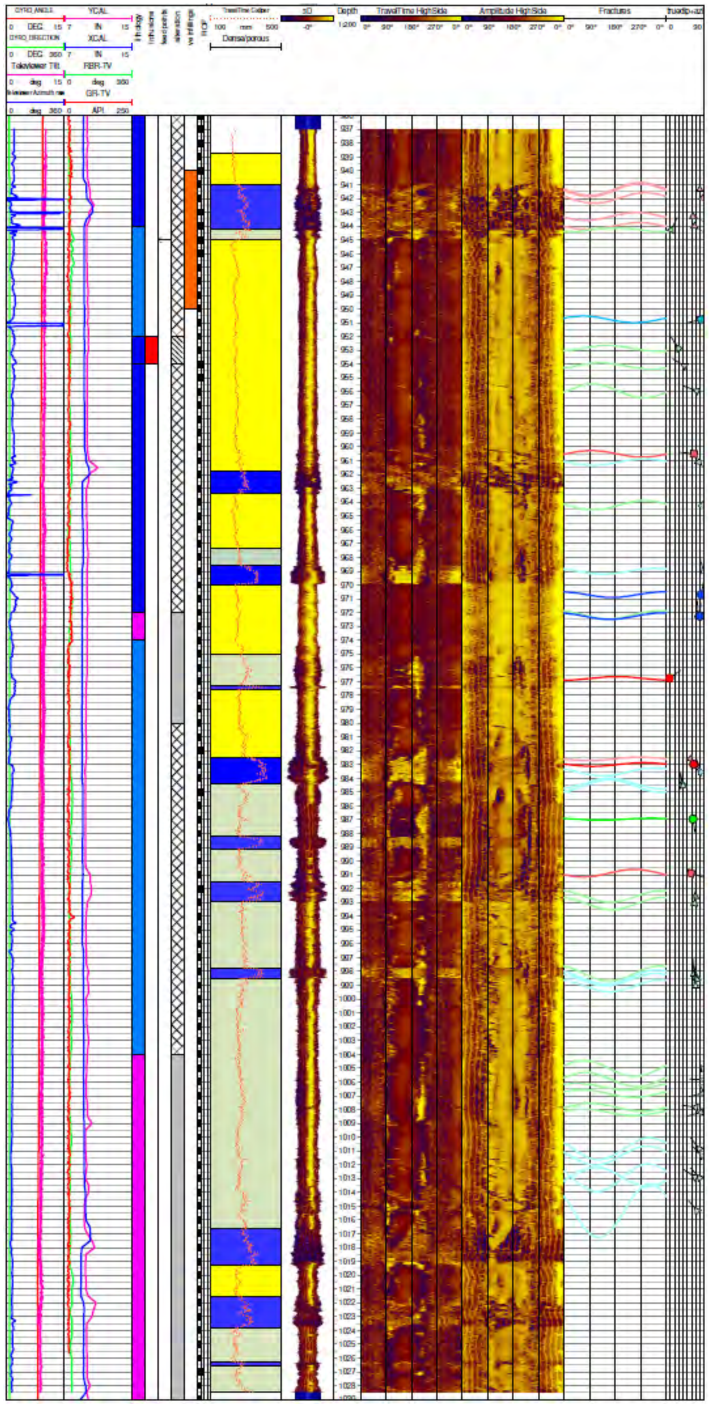
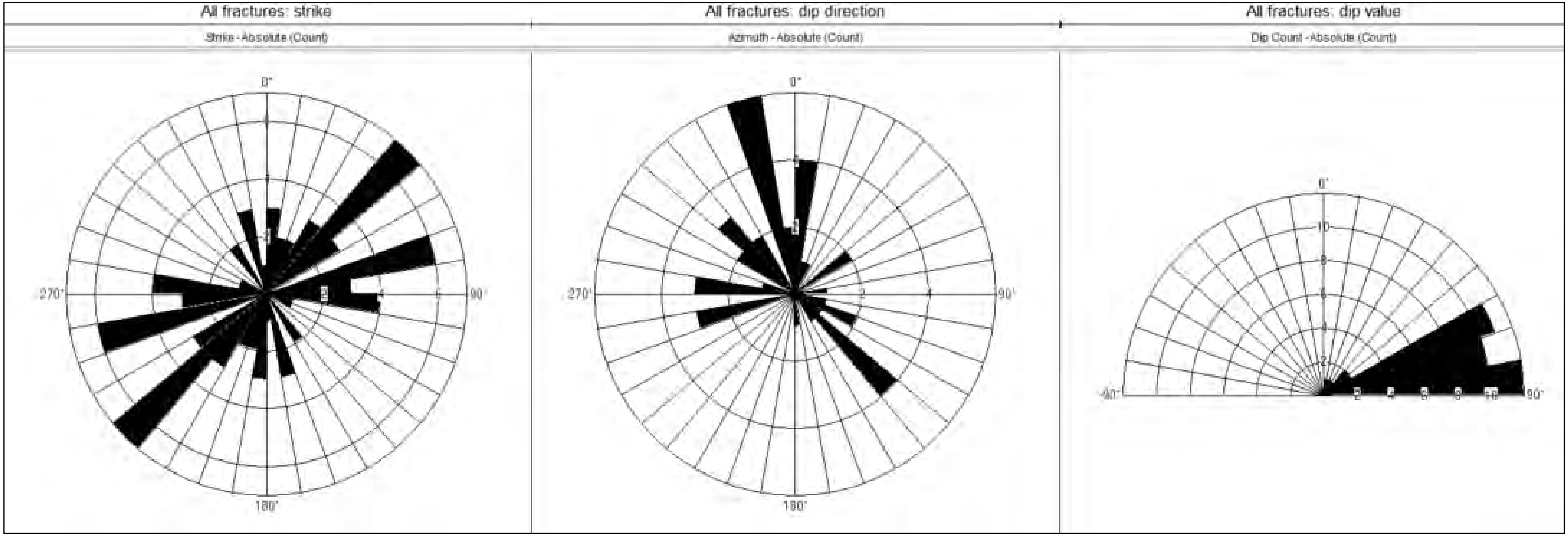
Well logs to determine packer locations



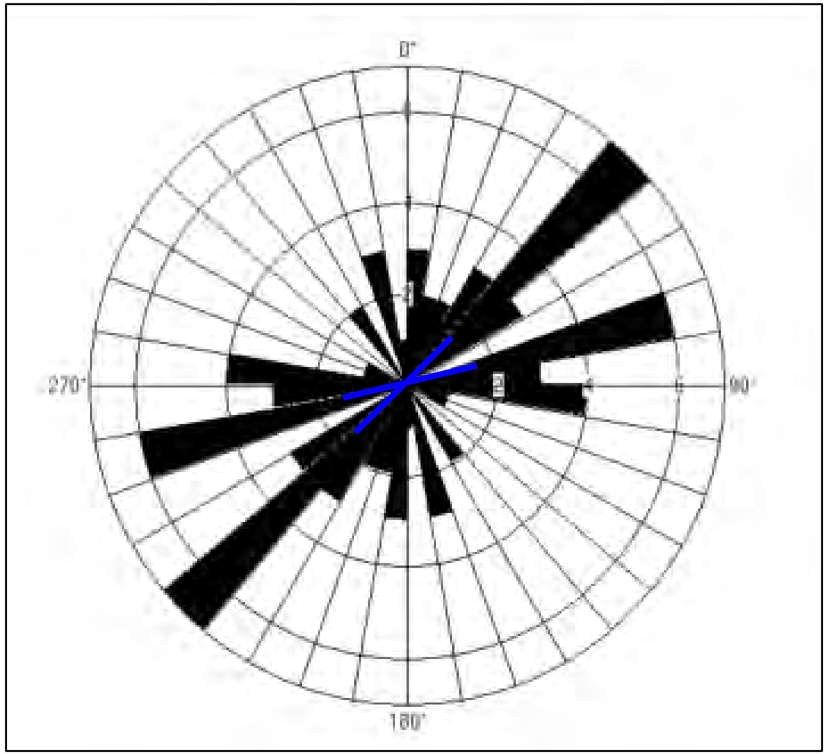
Date	Log	Interval	Comment
17.05.2019	Camera	0 – 830 m	No liner
13.10.2019	Temperature	0 – 850 m	No liner
13.10.2019	Temperature	0 – 1225 m	Temporary liner
13.10.2019	Caliper	913 – 1054 m	Temporary liner
13.10.2019	Televiewer	938 – 1029 m	Temporary liner
14.10.2019	Caliper	1089 – 1228 m	Temporary liner
25.10.2019	Temperature	0 – 1770 m	Through drillstring
25.10.2019	Neutron	50 – 1770 m	Through drillstring
08.11.2019	Temperature	0 – 1769 m	Permanent liner

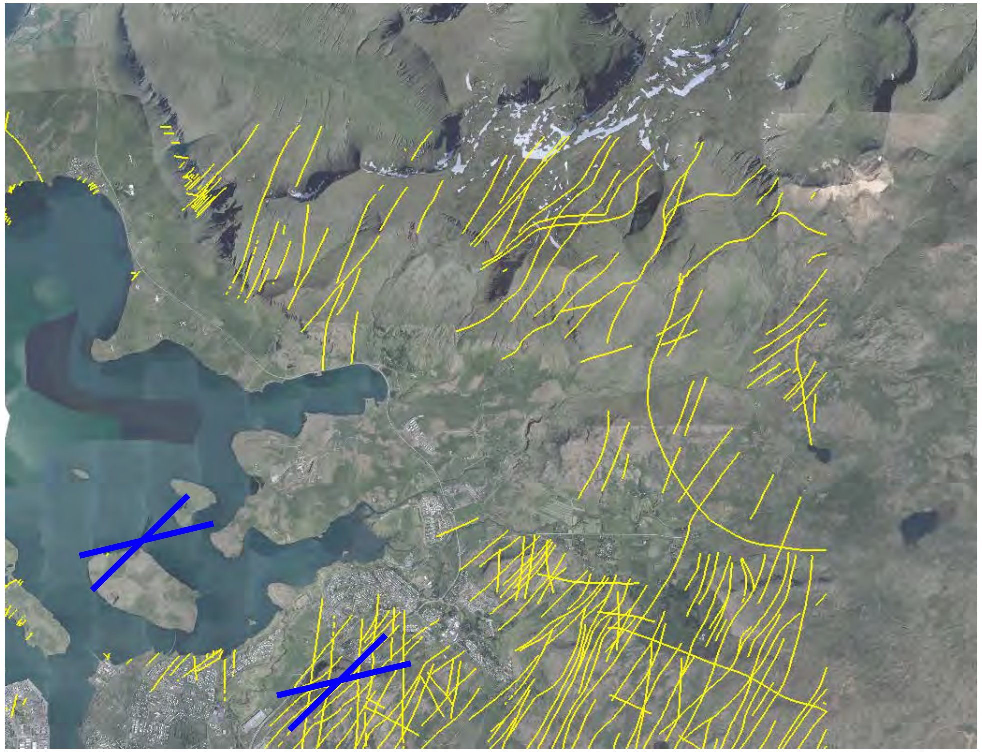


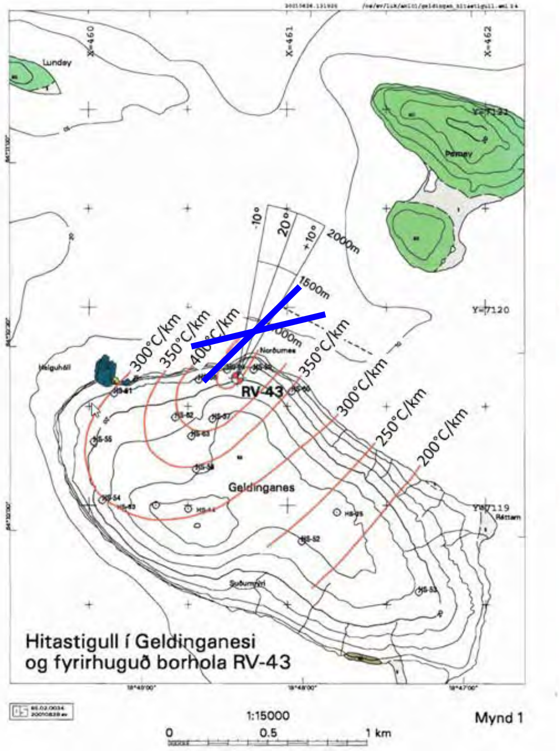
Televiewer results: Fractures strike NE-SW



Televiewer results: In agreement with surface geology

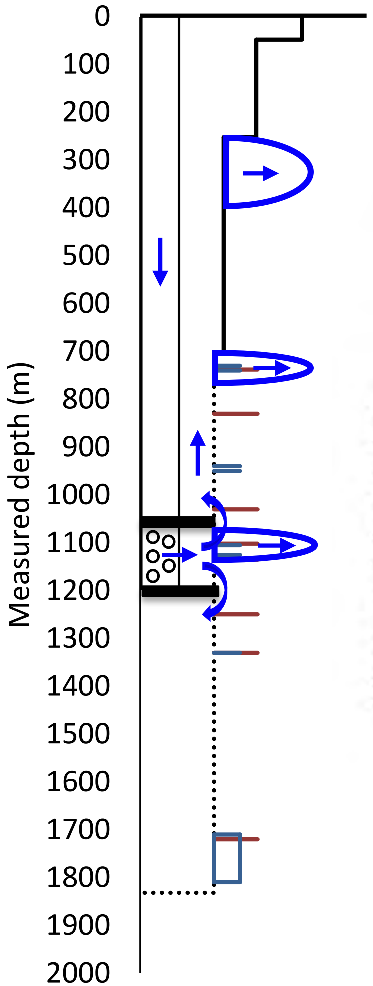


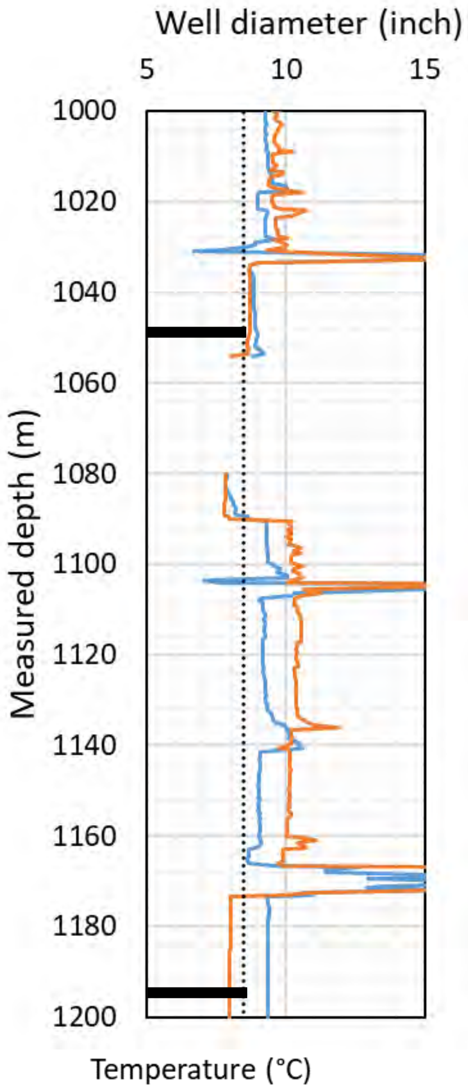




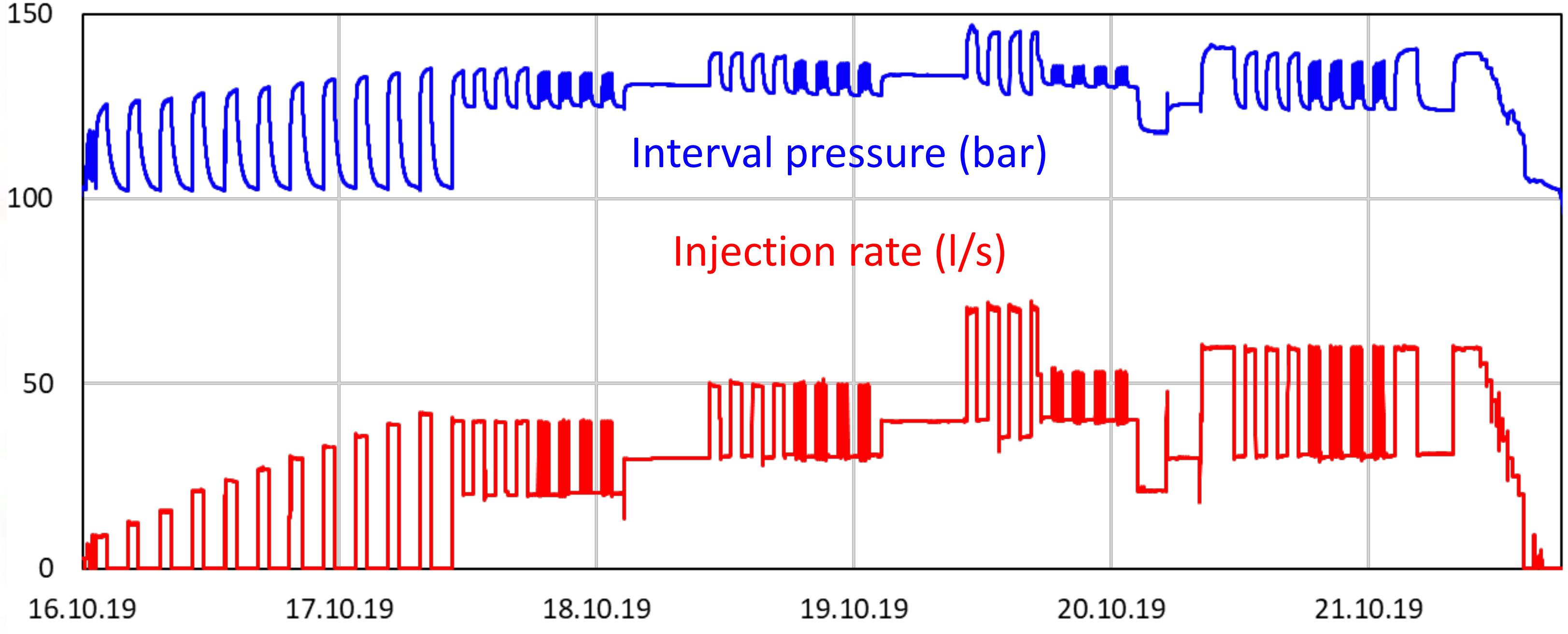
Results: Stage 1 (1050 – 1195 m)

Stage 1 - Overview

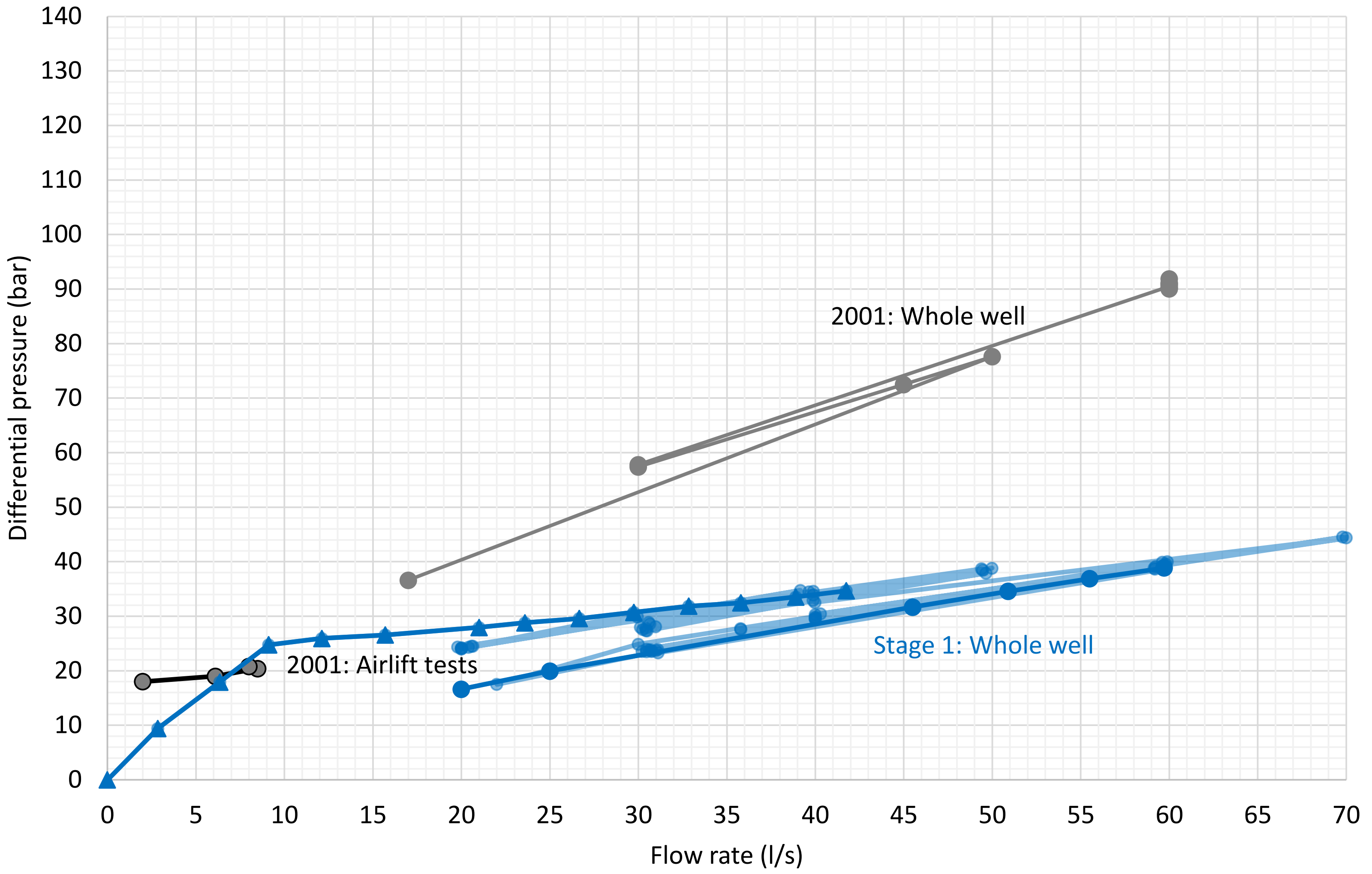




- 14.873 m³ water injected in 5.5 days with only 4 m³ flowback
- Comparison of injection schemes (seismicity/hydraulics)
- Injectivity increase by a factor of ~3 (from 8 l/s to 25 l/s @ 20 bar)
- No seismicity
- Crossflow around packers
- Damaged casing



Stage 1 - Hydraulic performance



Results: Stage 2 (below 1484 m)

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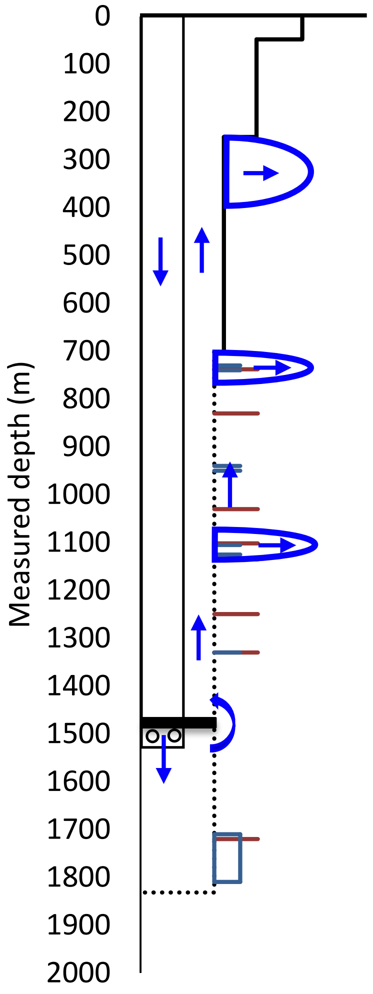
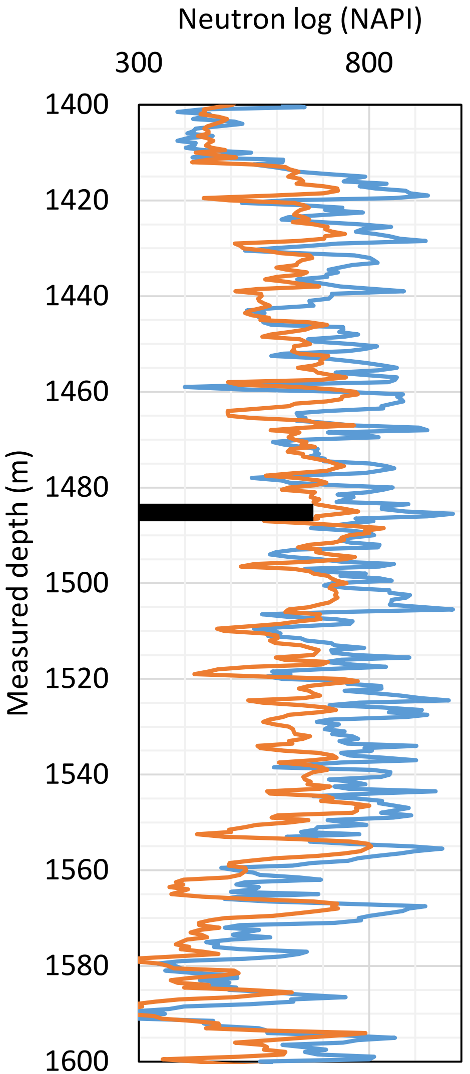
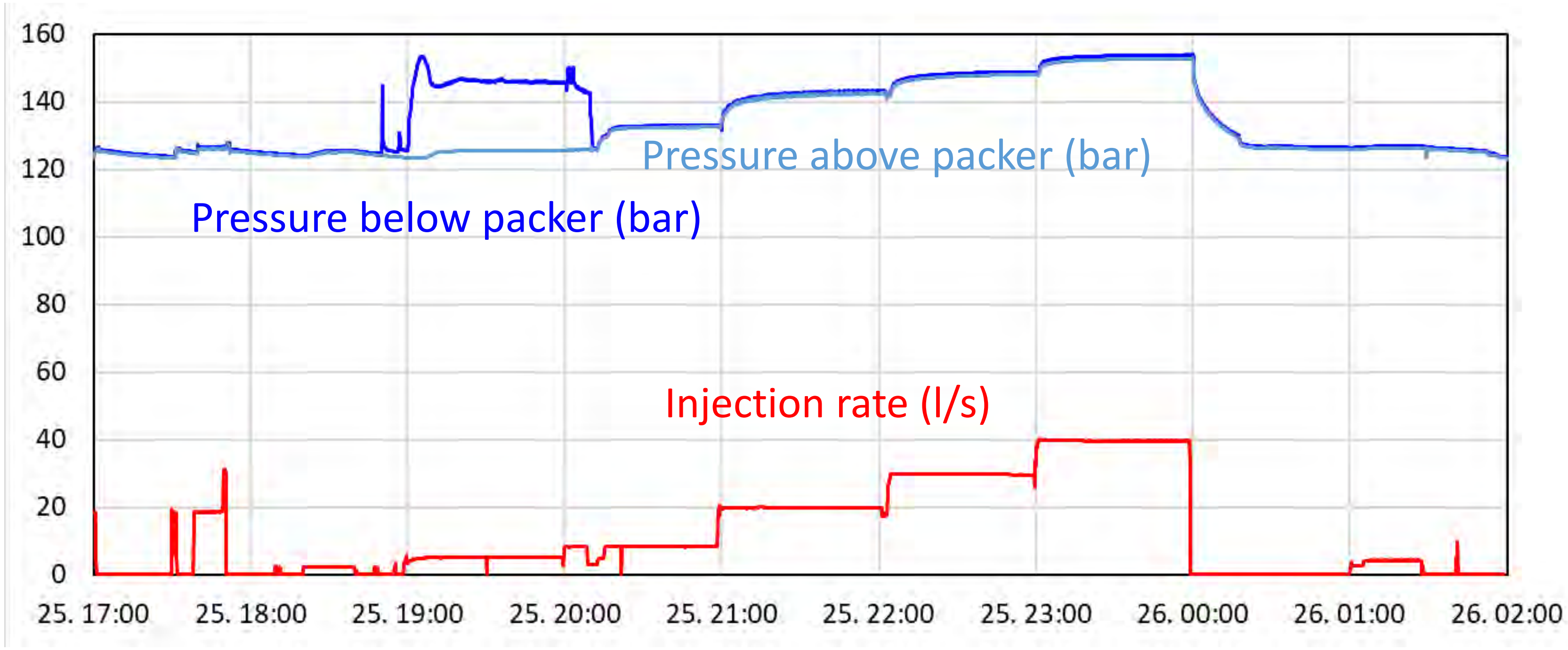
Stage 2 - Overview

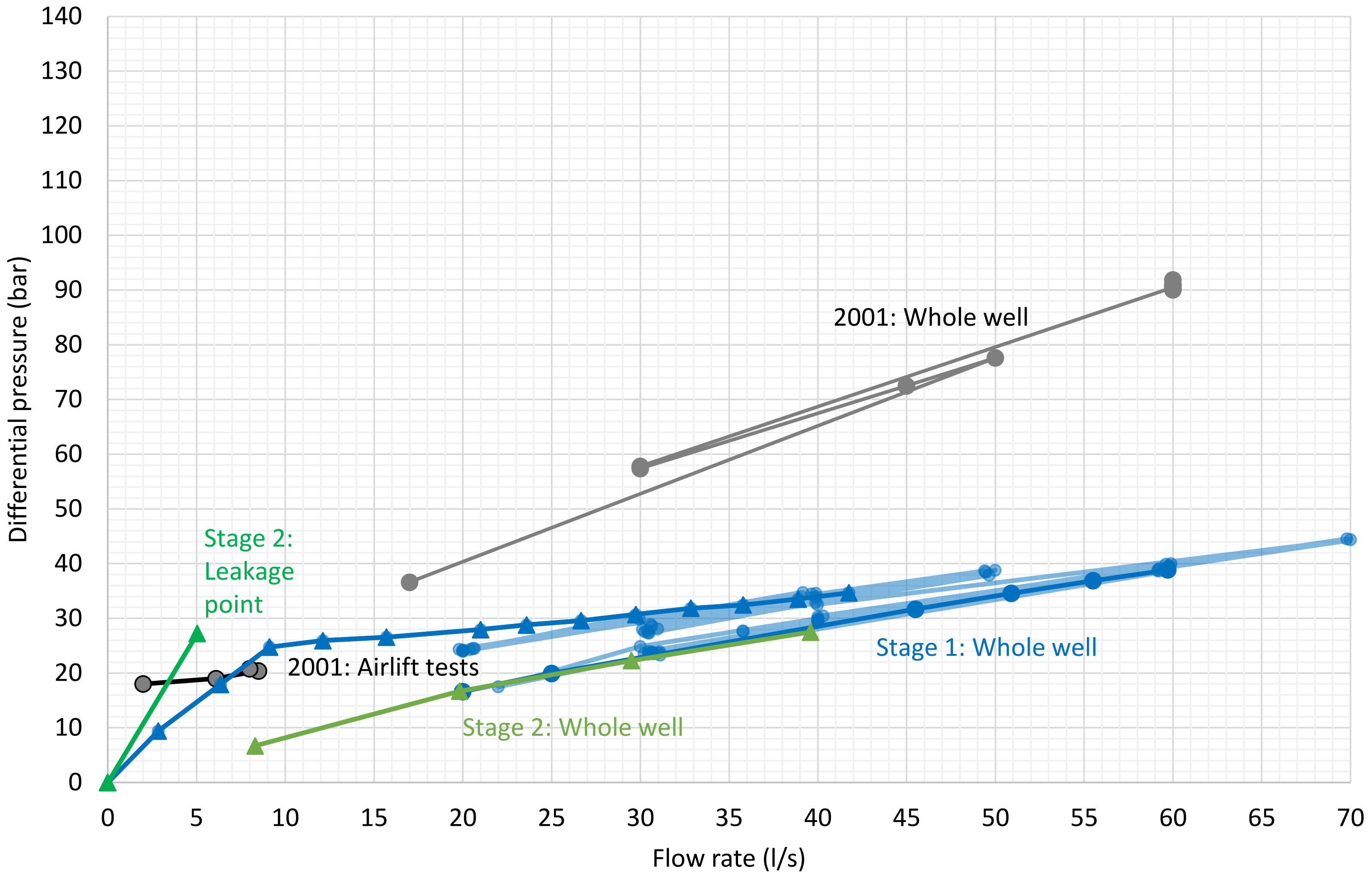




- After stage 1 reaming was necessary to reach target depth
- Packer location based on resistivity, neutron, temperature logs & cuttings
- After few minutes crossflow around packer



Stage 2 - Hydraulic performance



Results: Stage 3 (below 1640 m)

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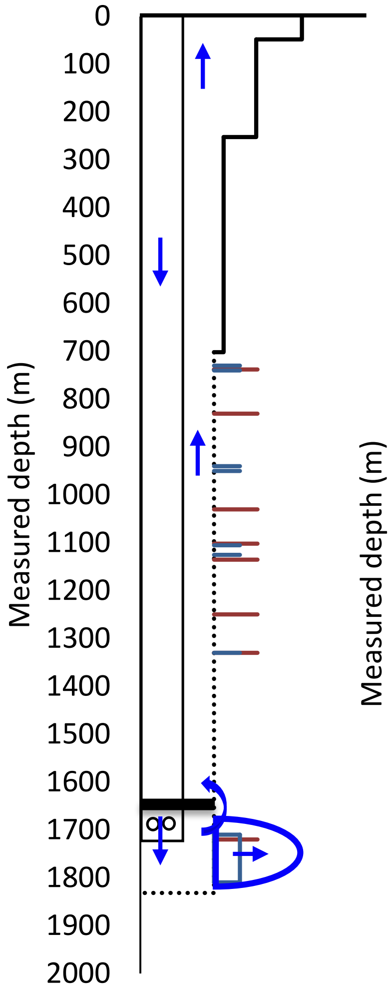
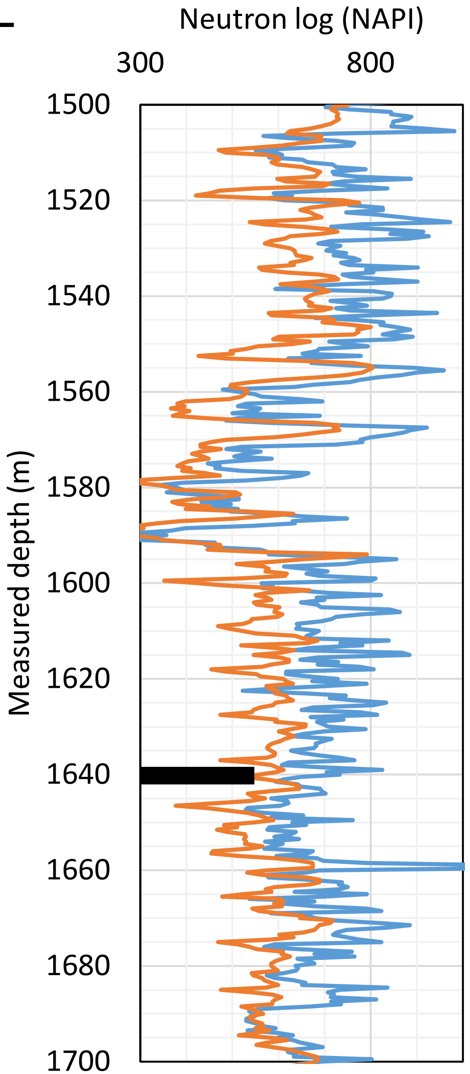
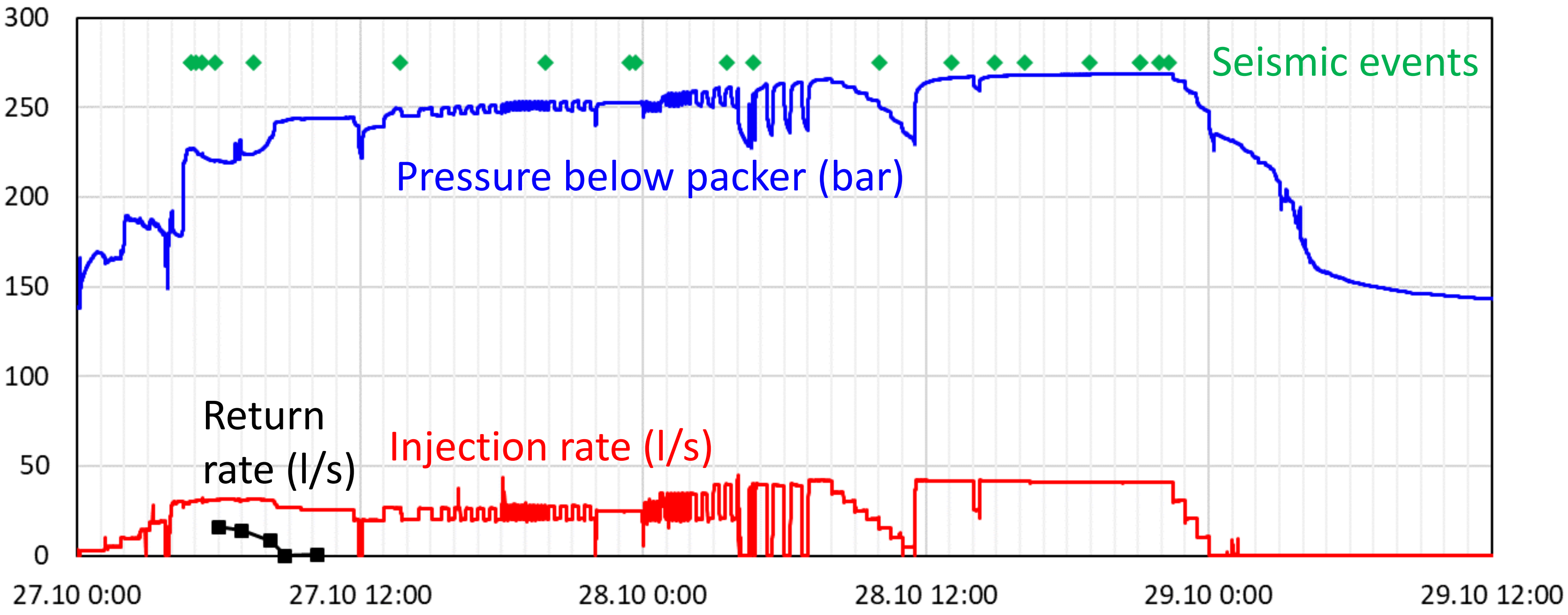
Stage 3 - Overview

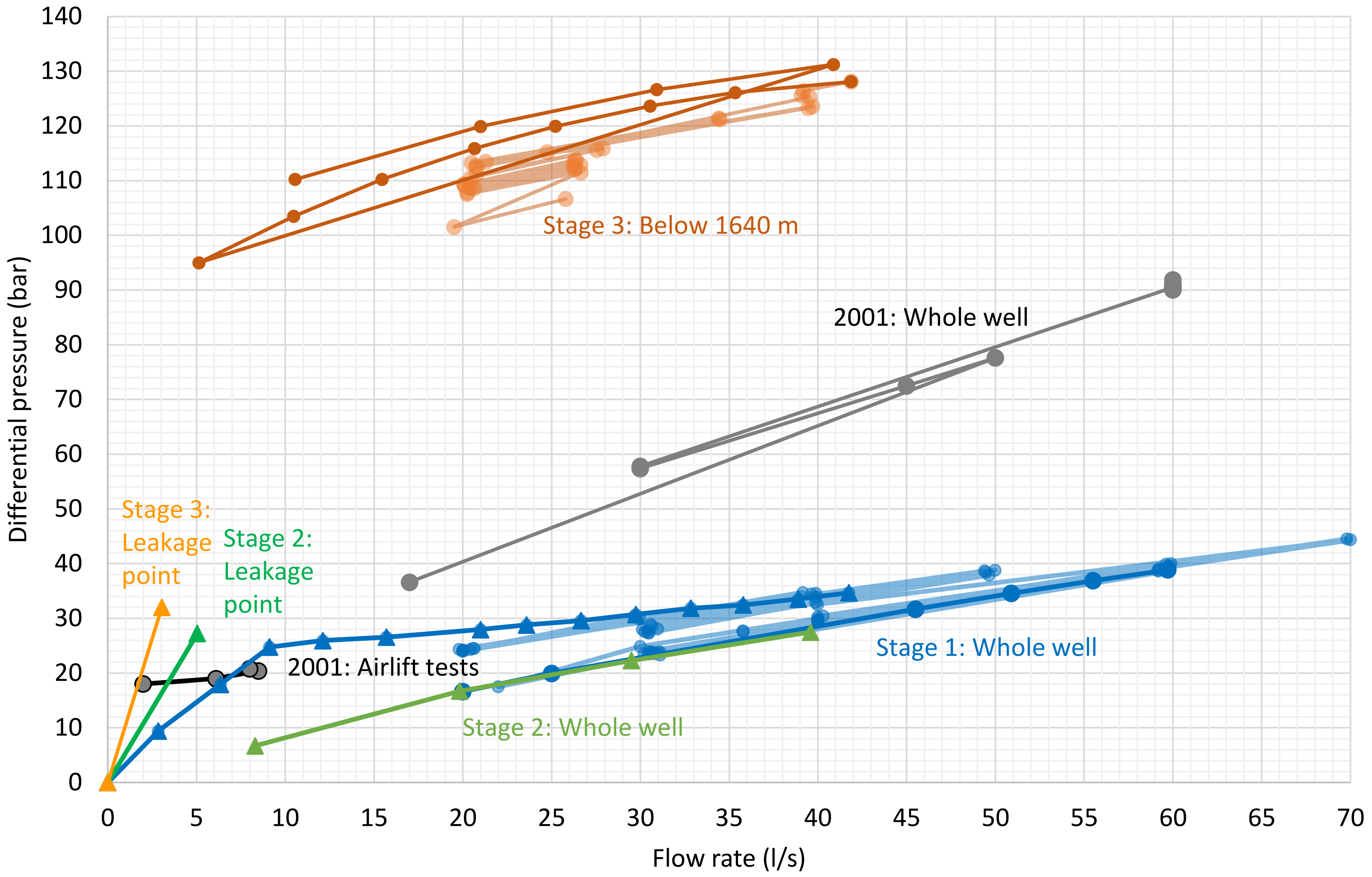




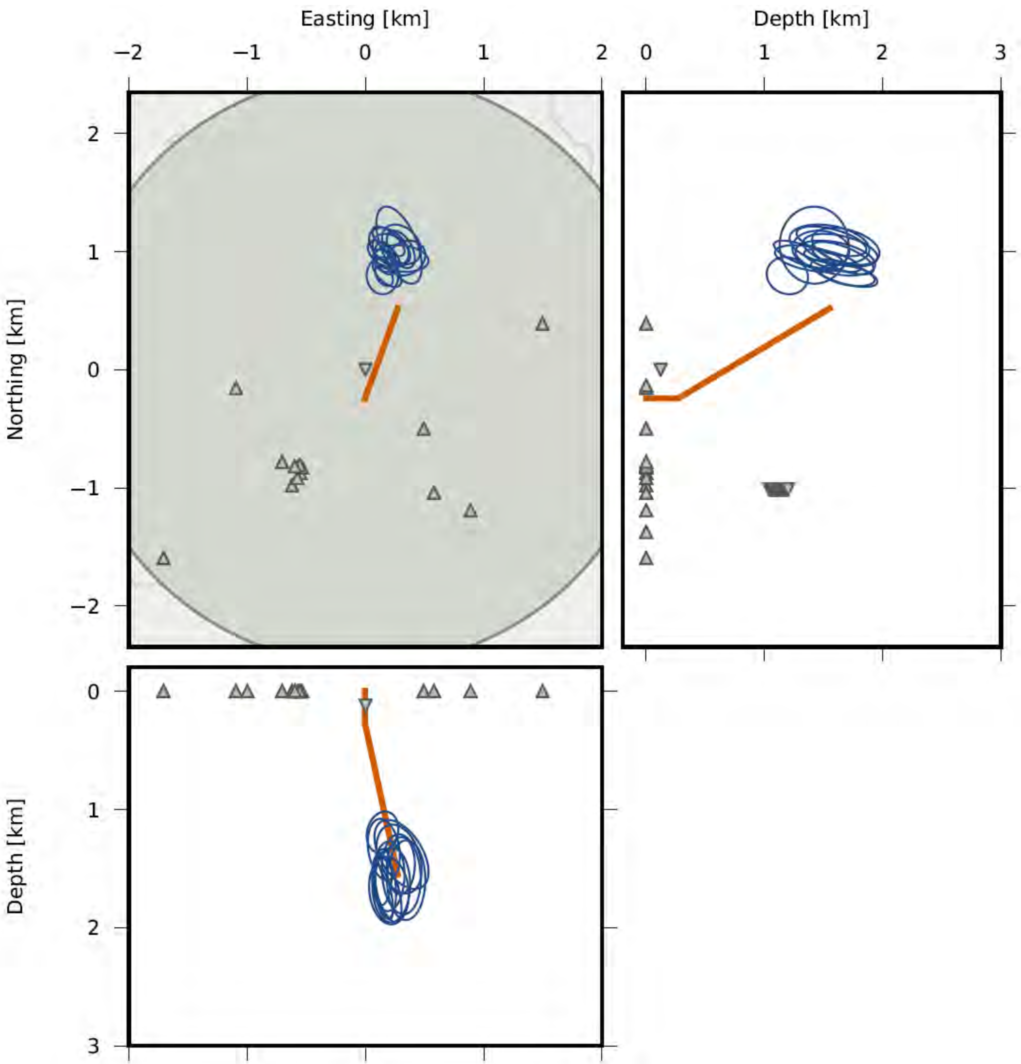
- 4807 m³ water injected in 2 days with >534 m³ flowback
- After initial crossflow zonal isolation was achieved
- Seismicity occurred after packer was sealing
- No significant differences in seismicity for different injection schemes
- Flowback showed massive pressure spikes

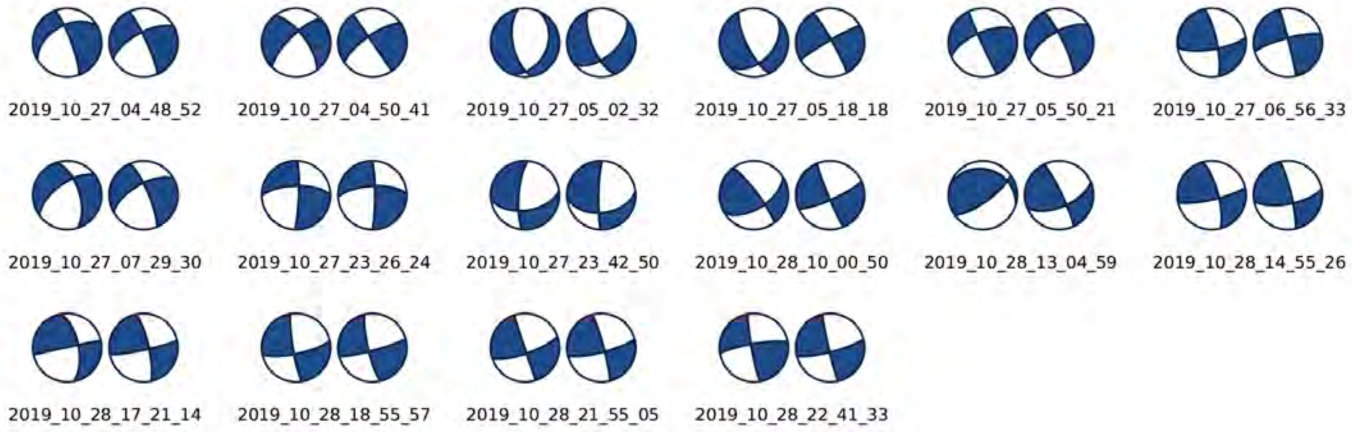


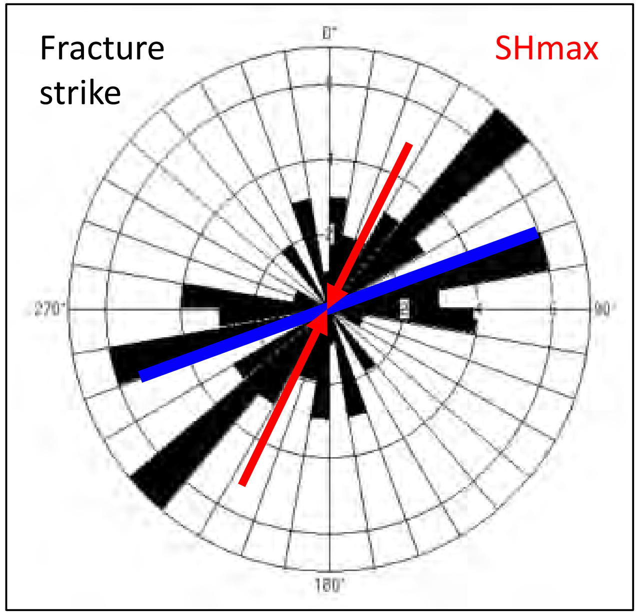
Stage 3 - Hydraulic performance



Stage 3 – Induced seismicity (M_{Lmin}=-1.1, M_{Lmax}=-0.1)







Results: Stage 4
(casing integrity and open hole test)

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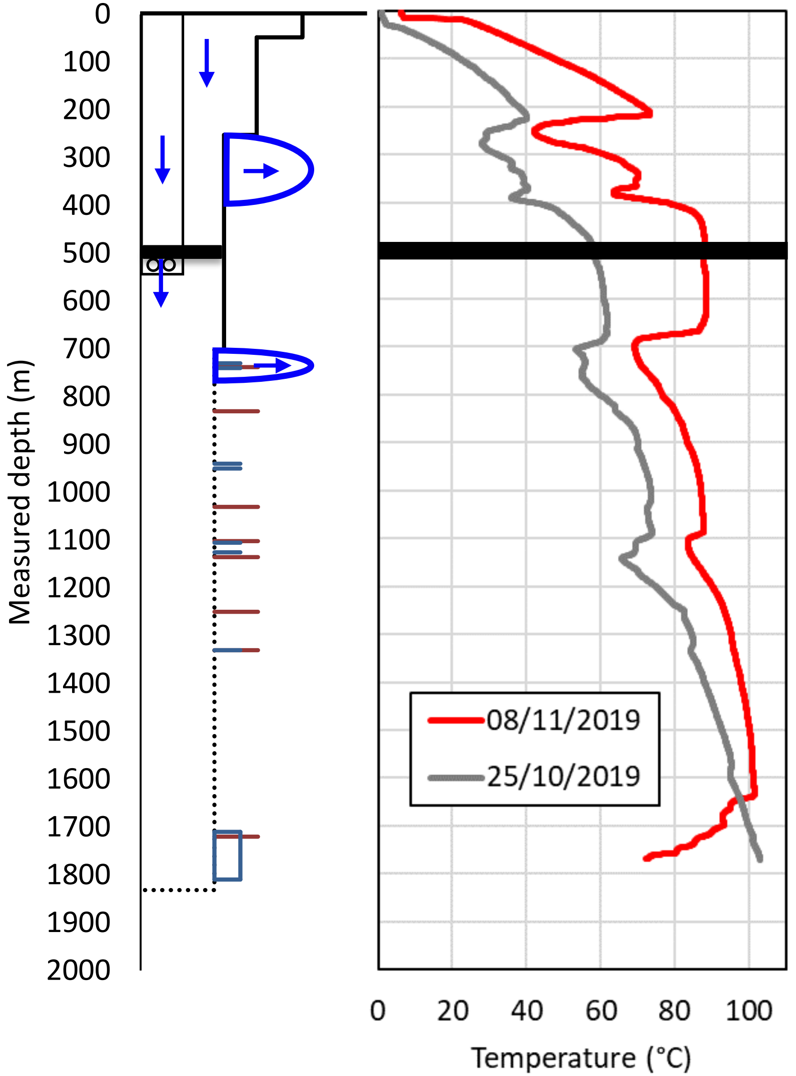
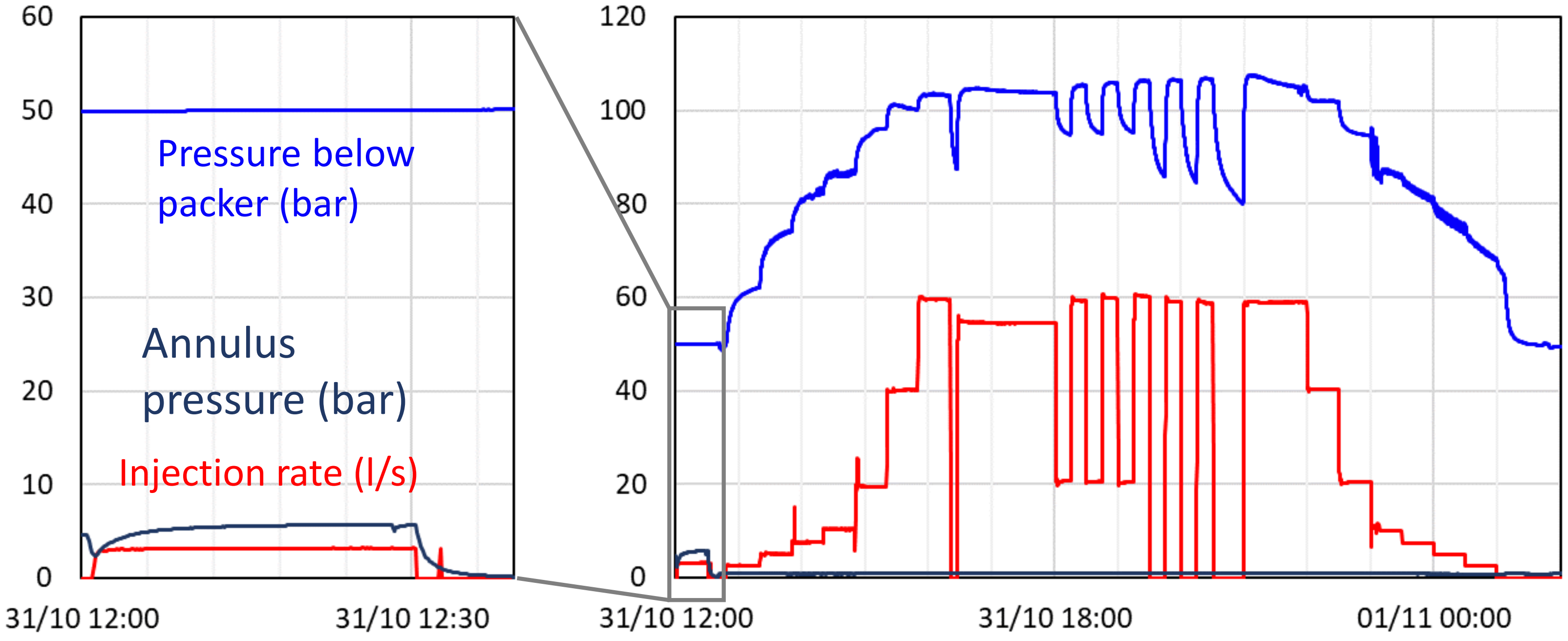
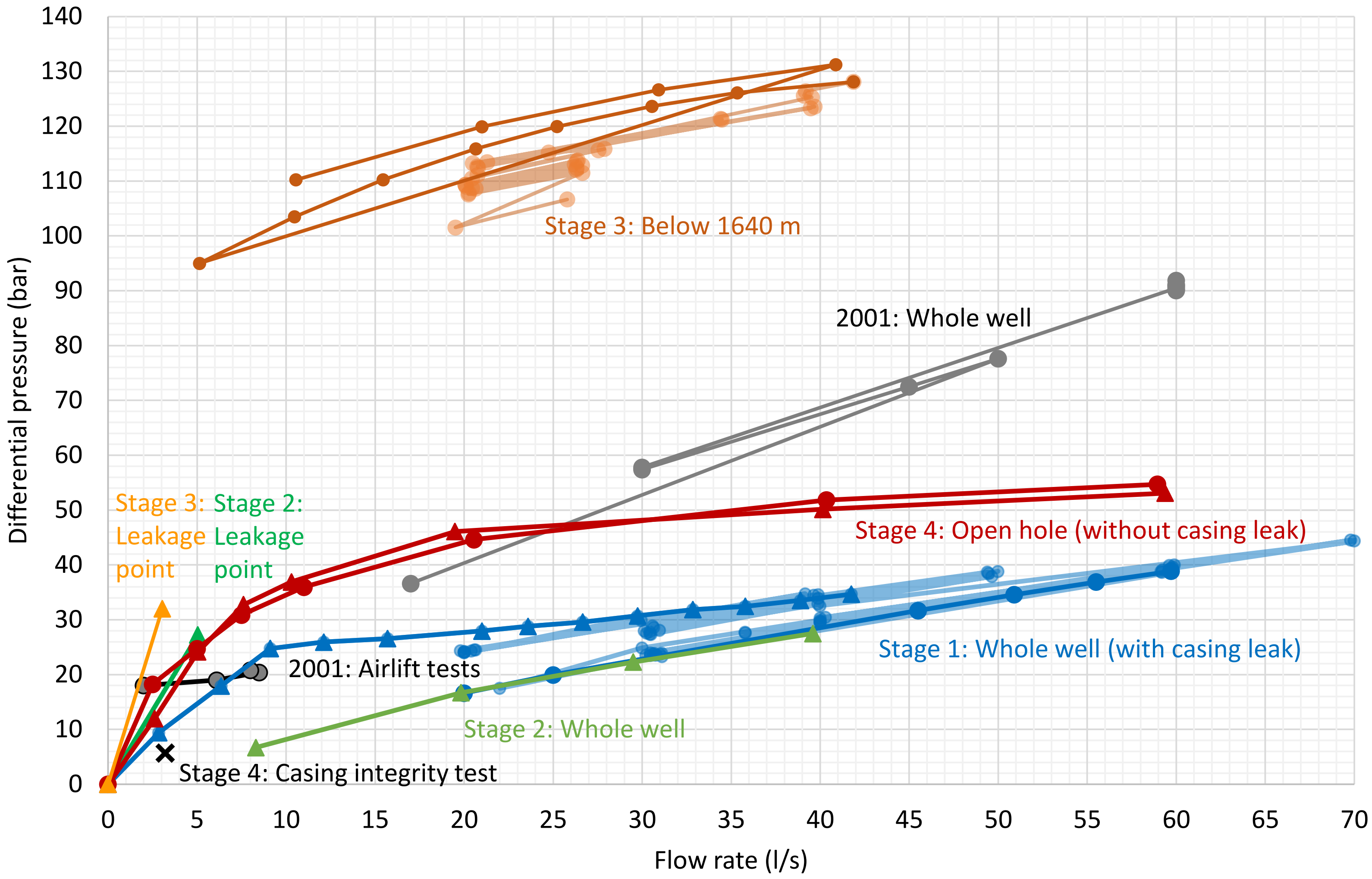
Stage 4 - Overview

- Casing integrity test confirmed leak in casing
- Open hole injection showed injectivity increase
- 1261 m³ injected in ~1/2 day





Stage 4 - Hydraulic performance



Conclusions & Outlook

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Conclusions

- **Zonal isolation challenging**
  - Minimum requirement: temperature, caliper, and televiewer log
  - Better: wells designed for stimulation
- **Cyclic injection improved hydraulic performance of well RV-43**
  - More efficient if casing was not damaged and logging/zonal isolation was more successful
  - High flow rates have biggest impact
- **Induced seismicity very low**
  - Knowledge about seismic risk of future projects in the area increased
- **Knowledge of local geological conditions improved**
  - E.g. stress field and fractures

→ **Hydraulic stimulation is feasable for low temperature wells in Reykjavik**

Outlook

- **Detailed interpretation of all acquired data is ongoing**
  - Hydraulic, thermal, seismic, chemical, operational, well logs
- **Lessons learned for future stimulation projects in Reykjavik and beyond**
  - Risk assessment, risk mitigation, logging, monitoring, zonal isolation, injection design, field operations, ...

Publications

Broccardo, M., Mignan, A., Grigoli, F., Karvounis, D., Rinaldi, R. P., Danciu, L., Hofmann, H., Milkereit, C., Dahm, T., Zimmermann, G., Hjörleifsdóttir, V., & Wiemer, S. (2019). Induced seismicity risk analysis of the hydraulic stimulation of a geothermal well on Geldinganes, Iceland. Natural Hazards and Earth System Sciences Discussions. doi:10.5194/nhess-2019-331.

Hannes Hofmann, Günter Zimmermann, Arno Zang, Santiago Aldaz, Simone Cesca, Sebastian Heimann, Stefan Mikulla, Claus Milkereit, Torsten Dahm, Ernst Huenges, Vala Hjörleifsdóttir, Sandra Osk Snæbjörnsdóttir, Edda Sif Aradóttir, Ragnheidur St. Ásgeirsdóttir, Kristján Ágústsson, Rögnvaldur Magnússon, Stefán Auðunn Stefánsson, Ólafur Flovenz, Arnaud Mignan, Marco Broccardo, Antonio Pio Rinaldi, Luca Scarabello, Dimitrios Karvounis, Francesco Grigoli, Stefan Wiemer, Sveinbjörn Hólmgeirsson (2020). Hydraulic Stimulation Design for Well RV-43 on Geldinganes, Iceland. Proceedings World Geothermal Congress 2020. Reykjavik, Iceland, April 26 – May 2, 2020.

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Demonstration of soft stimulation treatments of geothermal reservoirs

Imprint

Project Lead	GFZ German Research Centre for Geosciences Telegrafenberg 14473 Potsdam (Germany) www.gfz-potsdam.de/en/home/
Project Coordinator	Prof. Ernst Huenges huenges@gfz-potsdam.de +49 (0)331/288-1440
Project Manager	Dr. Justyna Ellis ellis@gfz-potsdam.de +49 (0)331/288-1526
Project Website	www.destress-H2020.eu
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