DESTRESS – General Assembly in Glasgow
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Mid-Conference

Overview of the hydraulic stimulation activities at the Pohang site

Ki-Bok Min

Department of Energy Resources Engineering
Seoul National University

DESTRESS
Demonstration of soft stimulation treatments
of geothermal reservoirs

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Introduction
Pohang EGS project (2010 ~ now)

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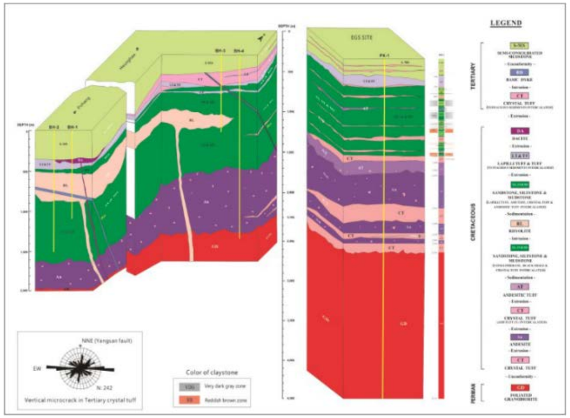
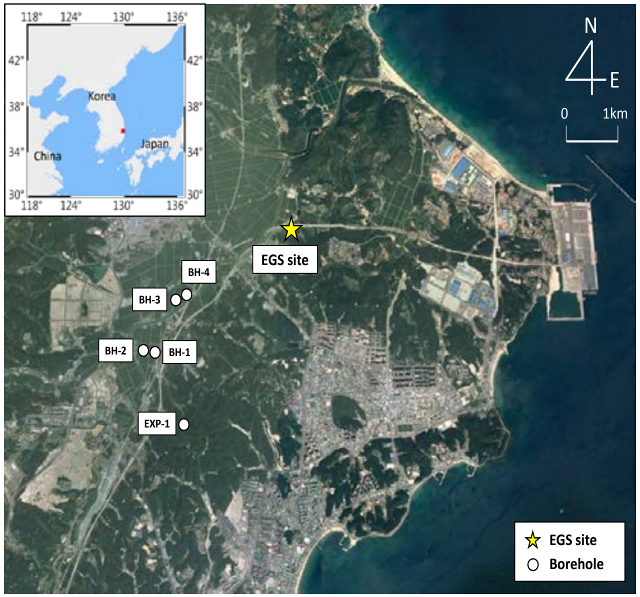
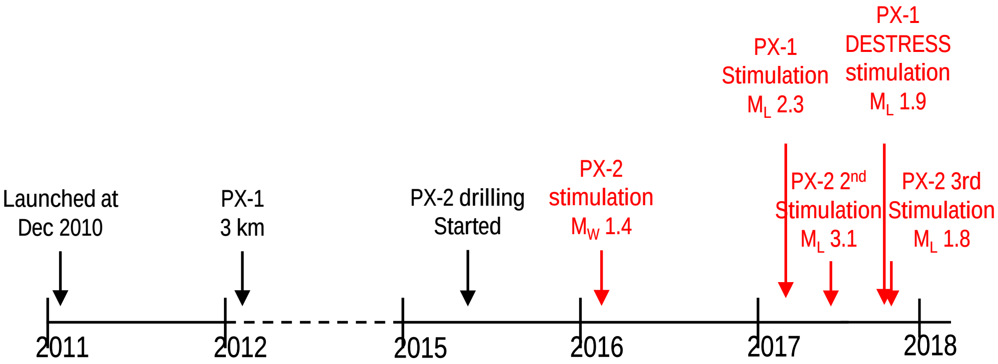
- Site location: Pohang, South Korea
- Pohang EGS consortium (Dec 2010 – 24 Nov 2017*): NexGeo (leading organization), KIGAM, SNU, KICT, POSCO, INNOGEO (+ EU Horizon 2020 DESTRESS since Mar 2016)
- Geology – ~ 2.4 km: sedimentary (semi-consolidated mudstone)
  – 2.4 km ~ : reservoir (granodiorite)
- Temperature: 140 °C @ 4.2 km (3 days after drilling)
- Boreholes: PX-1 (4,217 m), PX-2 (4,348 m)
- Nearby boreholes within 5 km:
  - BH-1 (1,100 m), BH-2 (1,504 m), BH-3 (920 m), BH-4 (2,383 m), EXP-1 (1km, ~4 km away from the site)



3D geological map of BH-1~4 and PX-1



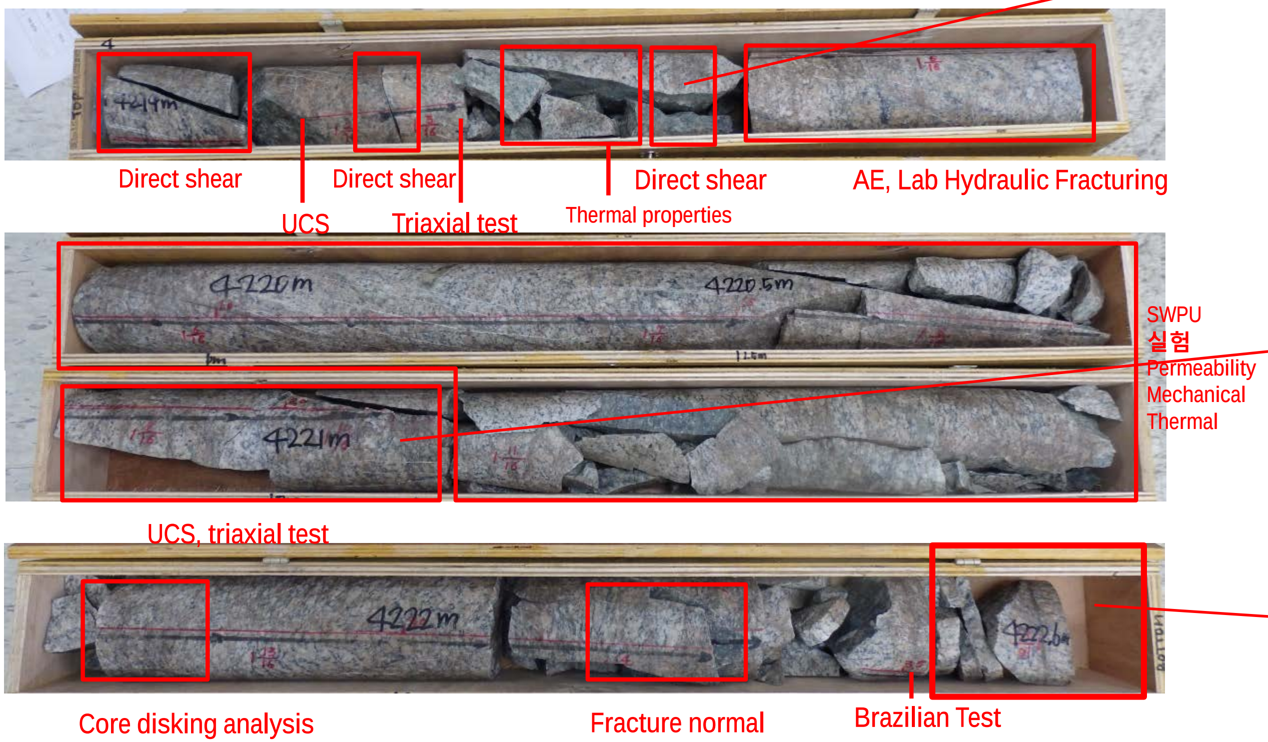


Well trajectories

* Suspended due to earthquake (ML 5.4)

Characterization from Rock Core
Core description

- Extracted core body

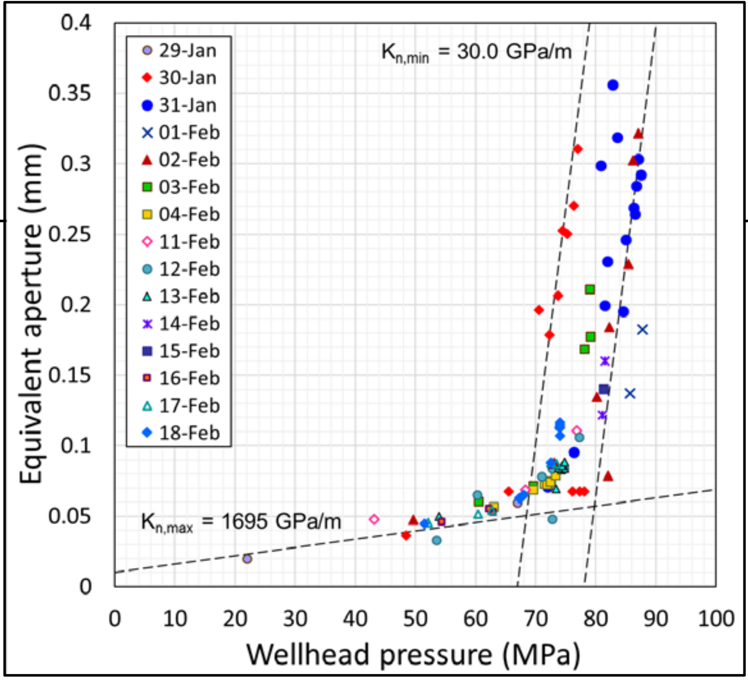


  - Extracted from depths of 4,217 m with 3.6 m length and 100 mm diameter
  - Fracture frequency of 9.7/m and RQD of 50.8% (total 35 fractures)
  - Core-disking appeared at the bottom of whole body (average thick: 12.3 mm)

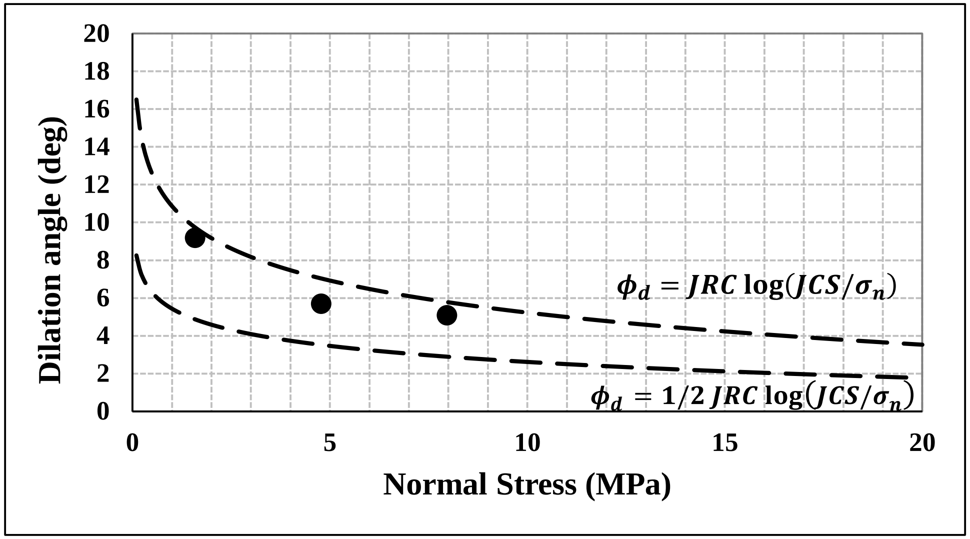
Characterization from Rock Core
Direct shear tests

- Stress dependency of properties
  - Normal stiffness
    - 7.9 GPa/m (σ_n~ 1.6-4.8 MPa)
    - 14.0 GPa/m (σ_n~ 4.8-8.0 MPa)
    - 23.4 GPa/m (σ_n~ 6.5-13.0 MPa)
  - Dilation angle
    - 5~9 º
    - Barton and Choubey (1977) suggested an empirical equation

$$\phi_d = \frac{1}{\mathrm{M}} JRC \log(JCS/\sigma_n)$$



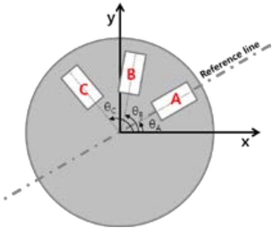
Normal stiffness from hydraulic jacking from well (Park et al., 2018)

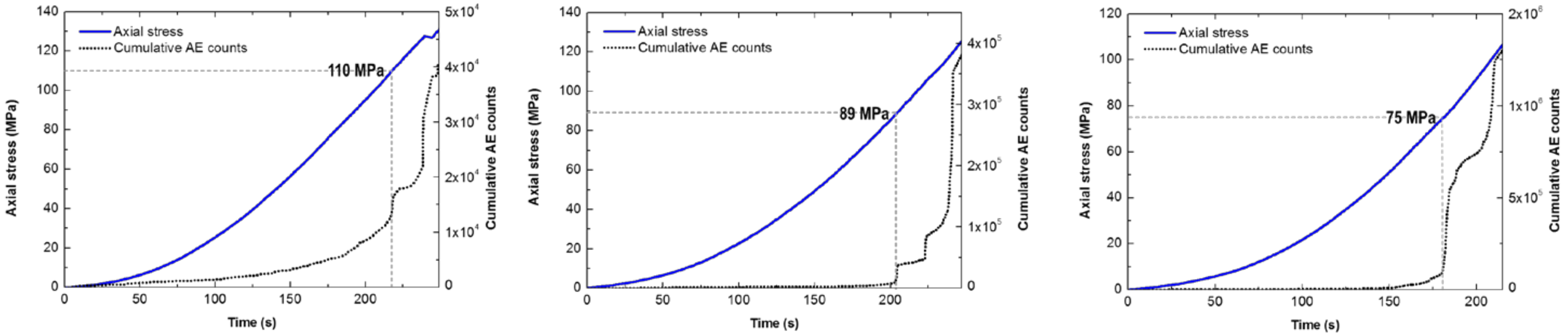


Trend line of dilation angle by normal stress

Characterization from Rock Core
Direct shear tests

- Stress estimation at PX-2
  - Acoustic emission test using Kaiser effect
    - No information about orientation
    - Uniaxial AE test using 3 sub-cores with 30° on same horizontal plane
    - 3 maximum previous stresses (Kaiser stresses) from 3 sub-cores
    - Using stress transformation: S_{Hmax}= 117 MPa, S_{hmin} = 74 MPa



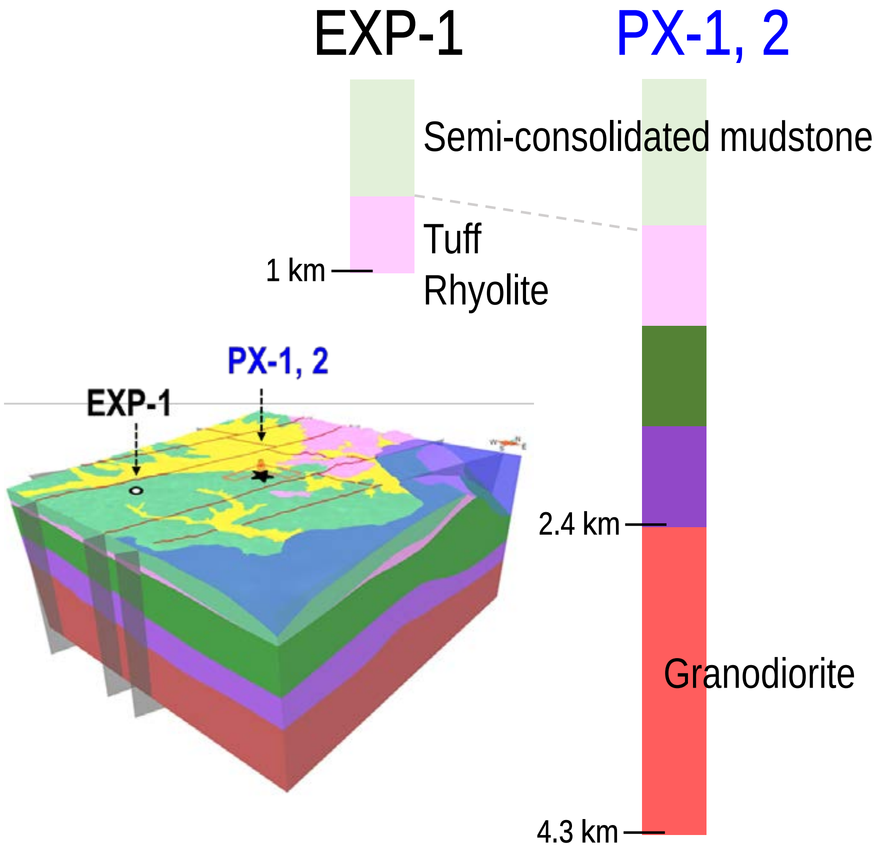


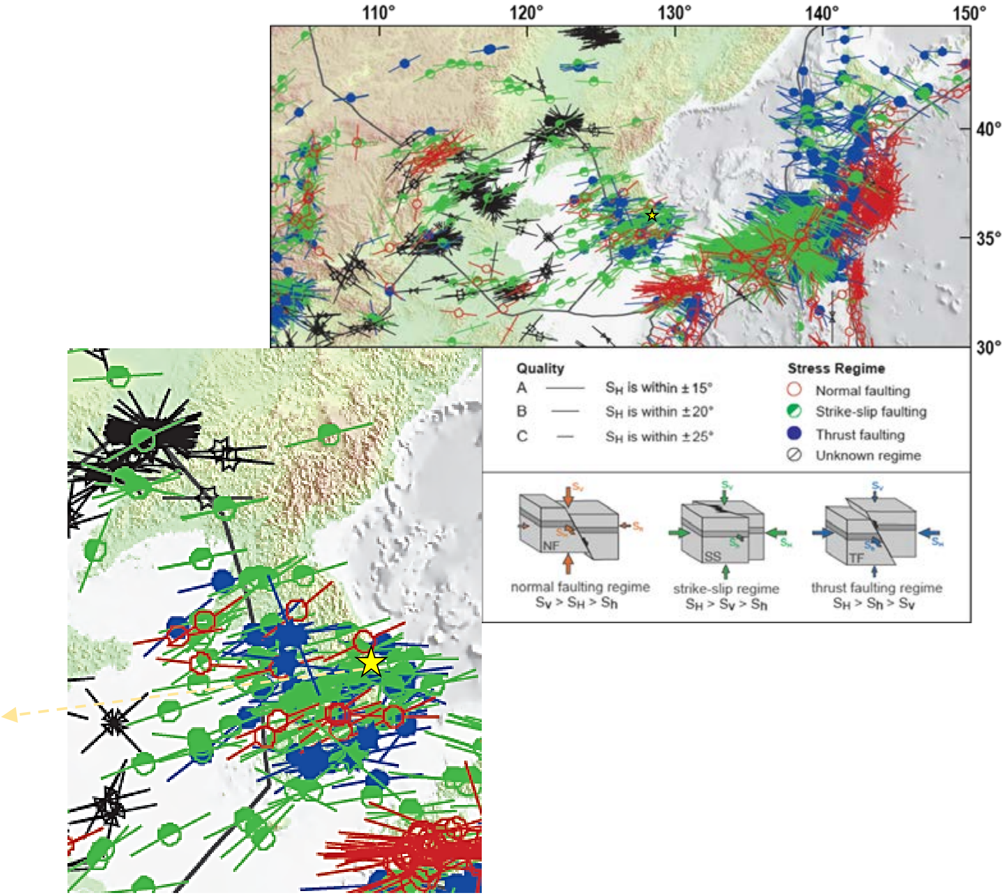
AE test results of sample A, B, C

Kim, 2017, Integrated Estimation of In-situ Rock Stress at Pohang Geothermal Reservoir in Korea, PhD thesis, Seoul National University

In Situ Stress Estimation

- EXP-1 and PX-1, 2 boreholes



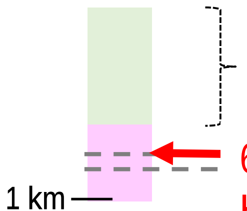


In-situ stress in Korea from the World Stress Map

In Situ Stress Estimation

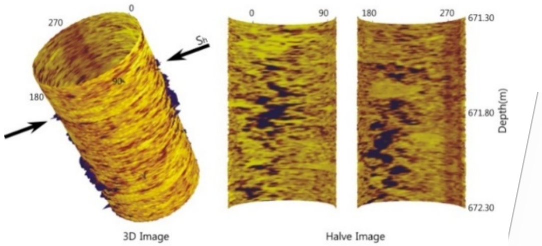
- Stress estimation at EXP-1

EXP-1



~ 650 m Casing

658 m,685 m, 715m
Hydraulic fracturing



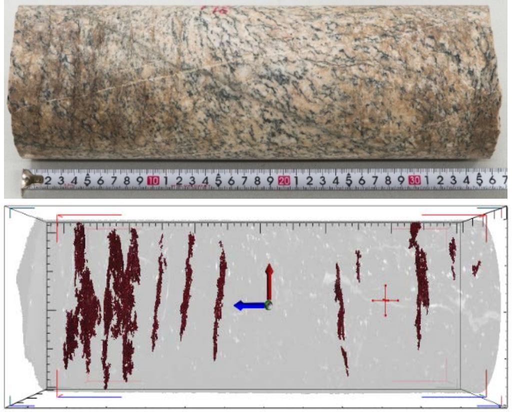
670 ~ 700 m Borehole Breakouts
770 ~ 810 m Drilling Induced Fractures (DIFS)

Hydraulic Fracturing Test + Borehole Breakout Analysis + DIFS Analysis + BEM Numerical Analysis

Stress estimation
@ EXP-1

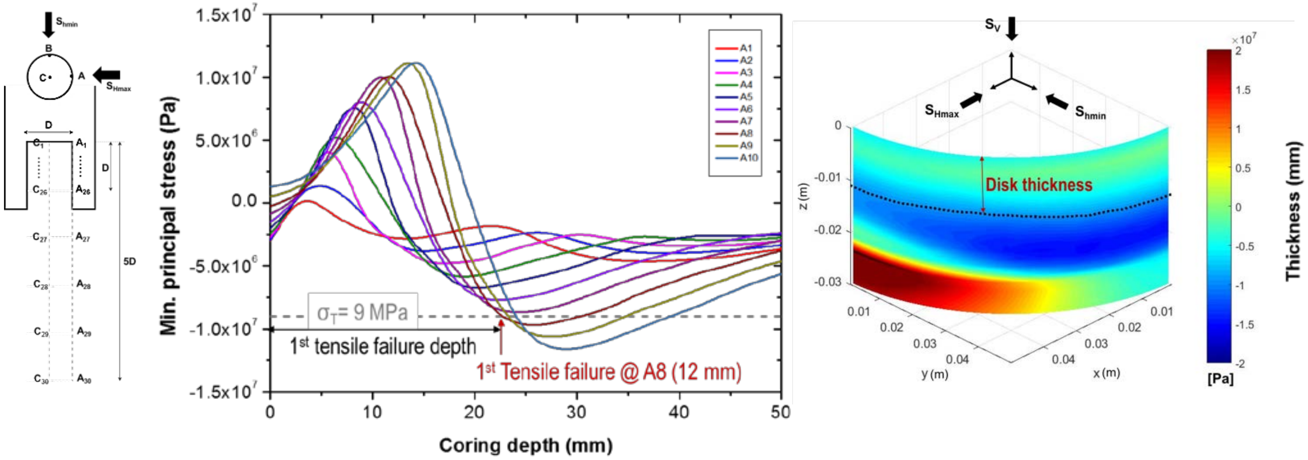
In Situ Stress Estimation

- Stress estimation at PX-2
  - Core disking analysis
    - Fracture information from CT scanning (KICT)
    - BEM modeling with FLAC3D
    - $S_{Hmax}/S_V/S_{hmin}$ = (1.05-1.2)/1.0/(0.7-0.8)

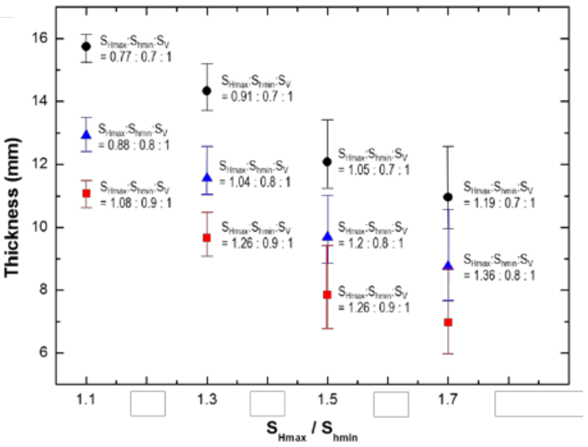


Avg. thickness = 12.3 mm

Disked core & scanned image (KICT)



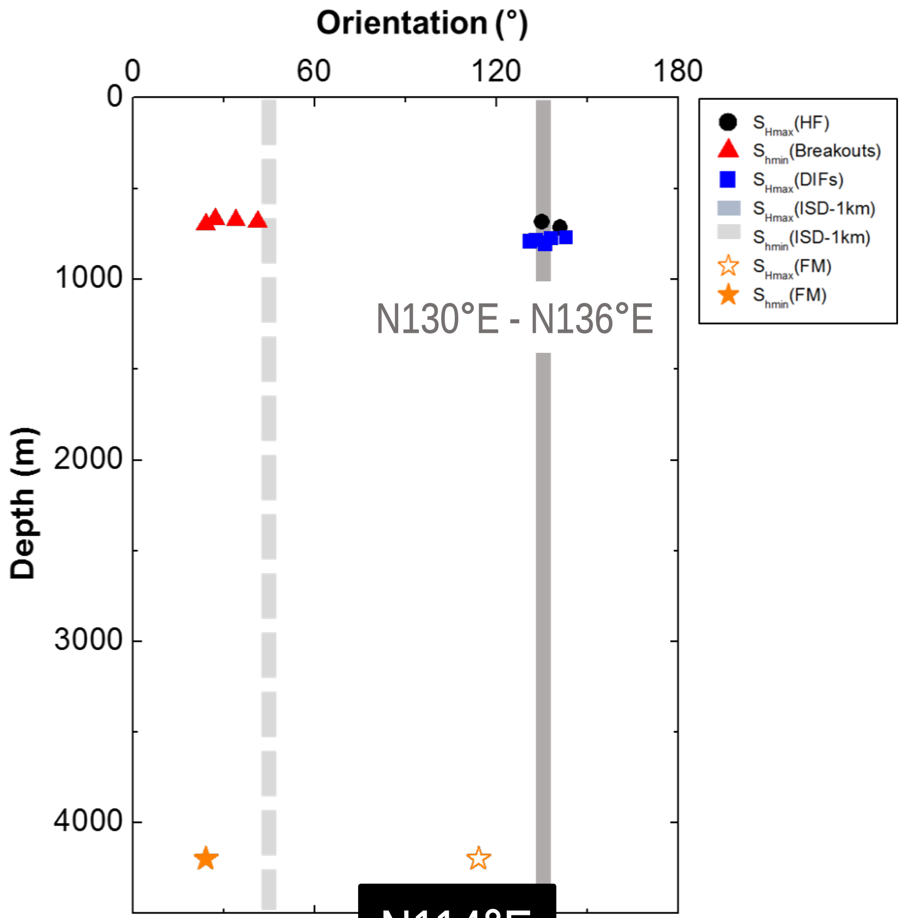
First tensile failure depth & distribution of min. principal stress around core ($S_{Hmax}/S_V/S_{hmin}$ = 1.05/1.0/0.7)



Relationship between ratio of horizontal stresses & estimated thickness of disk

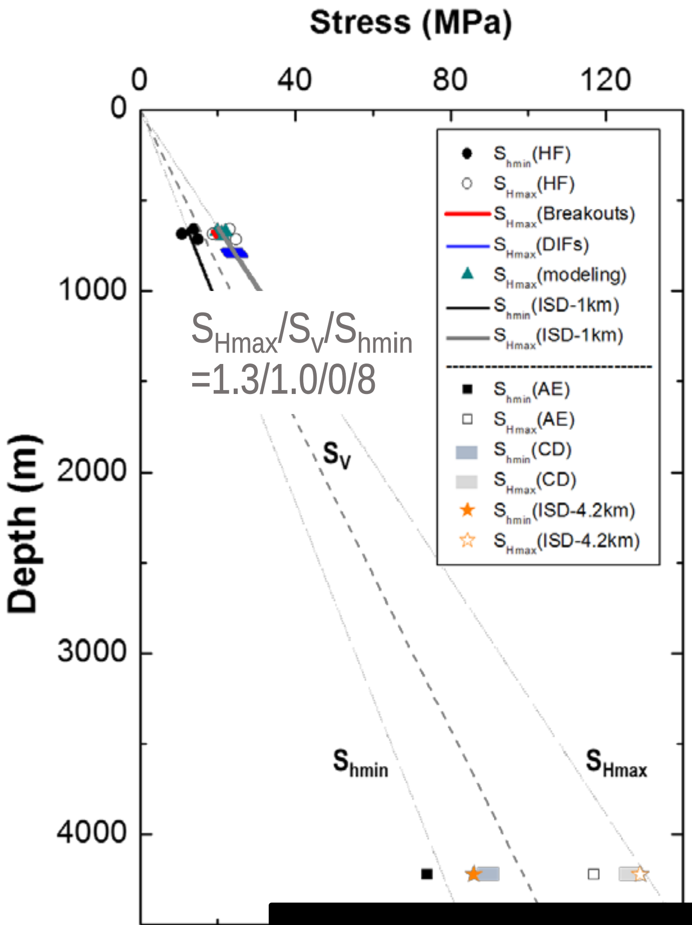
In Situ Stress Estimation

- Integrated stress estimation at PX-1, 2



N130°E - N136°E

N114°E

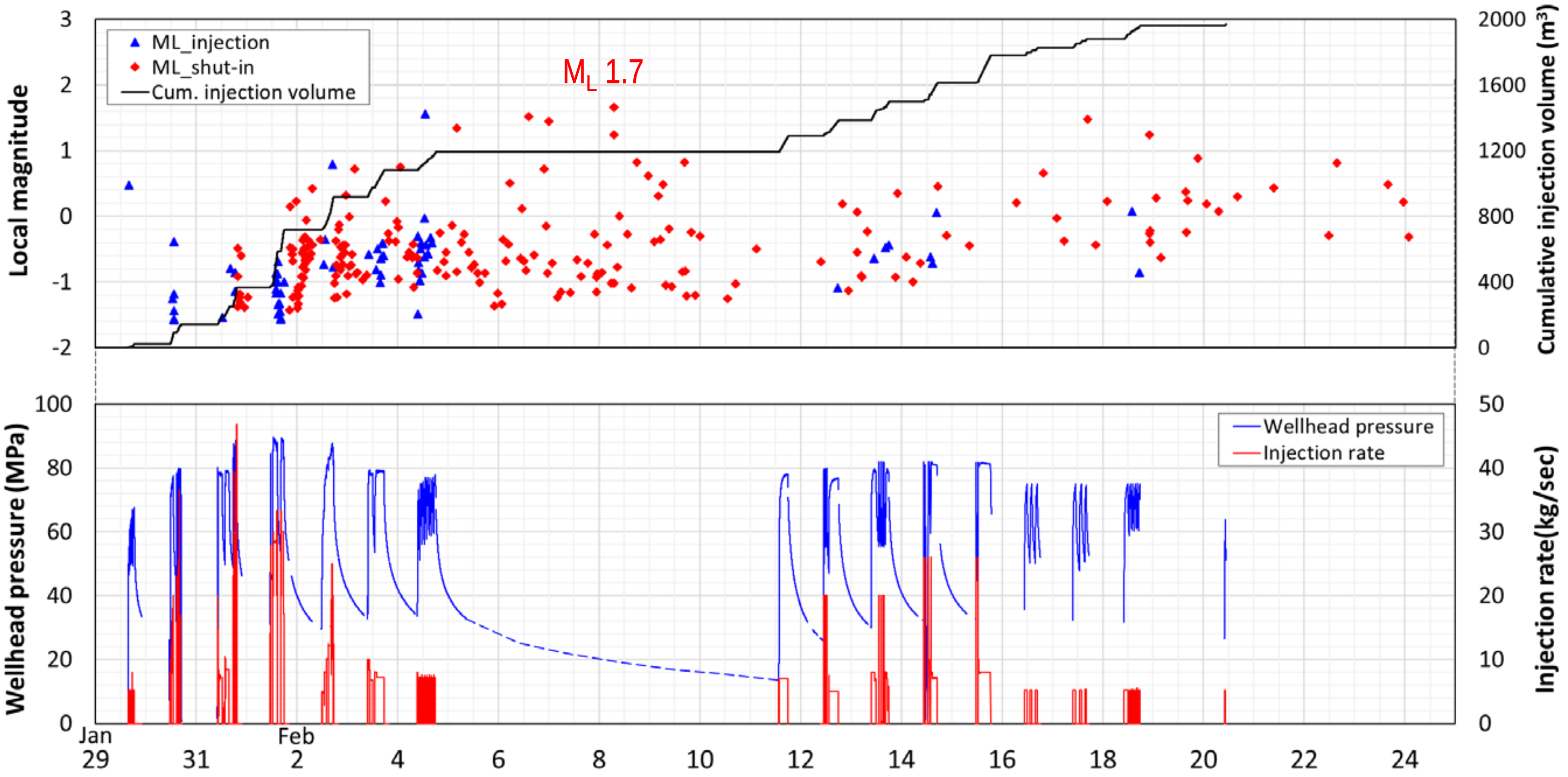


$S_{Hmax}/S_V/S_{hmin}$ =1.3/1.0/0/8

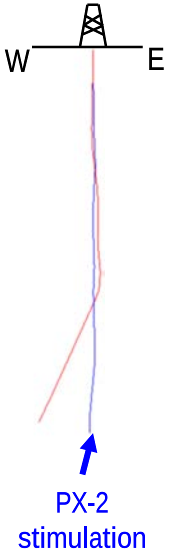
$S_{Hmax}/S_V/S_{hmin}$=1.2/1.0/0.8

Hydraulic Stimulation

1st stimulation (PX-2 1st Jan 29 - Feb 20, 2016)

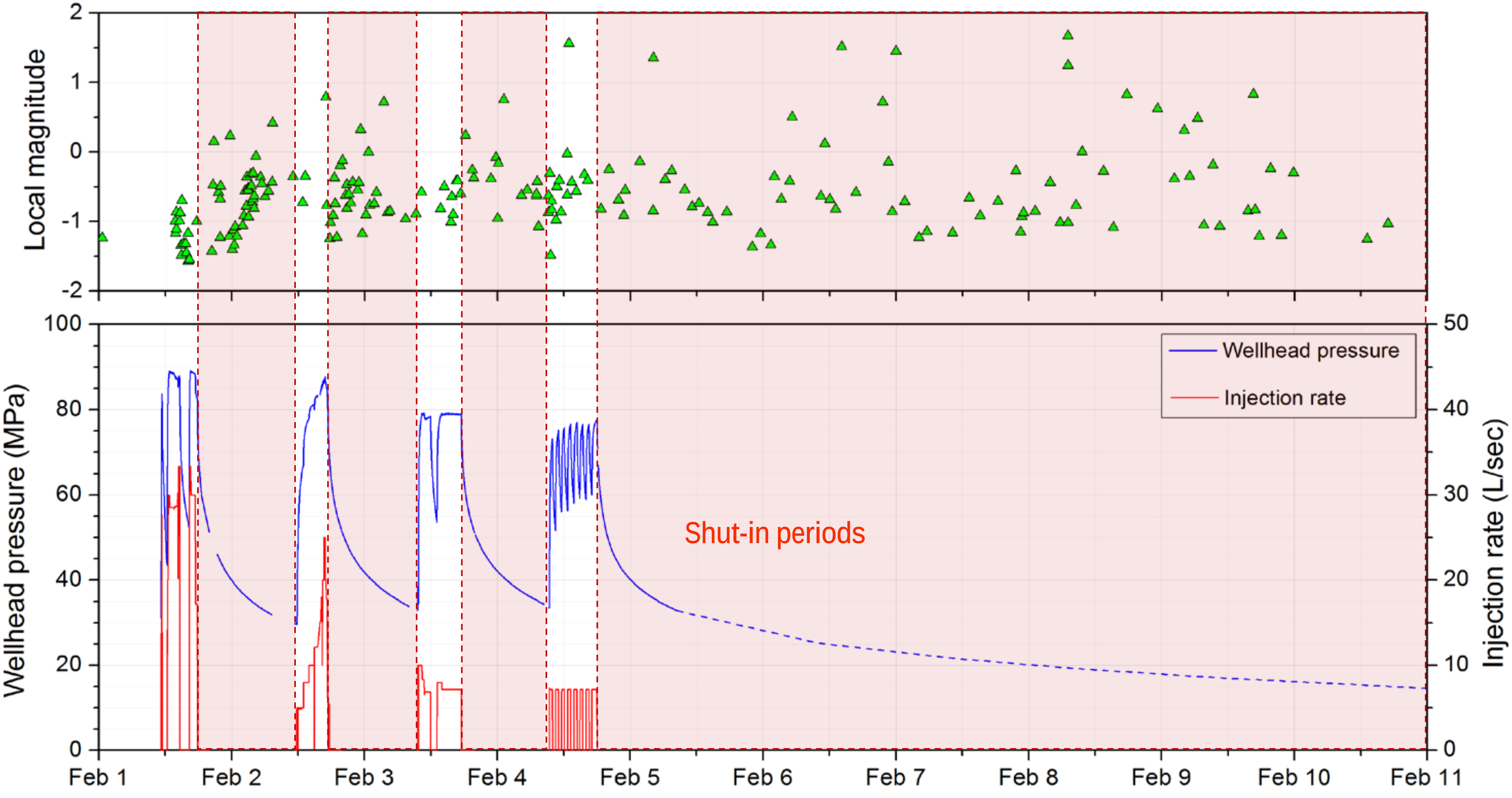


- Max. wellhead pressure: 89.2 MPa (= bottomhole pressure 131.8MPa)
- Max. injection rate: 46.8 L/sec
- Injected water volume: 1,970 m^3
- Max. seismicity magnitude: M_L 1.7
- # seismic events: 271 (Jan 29 – Feb 24, 2016)



Hydraulic Stimulation

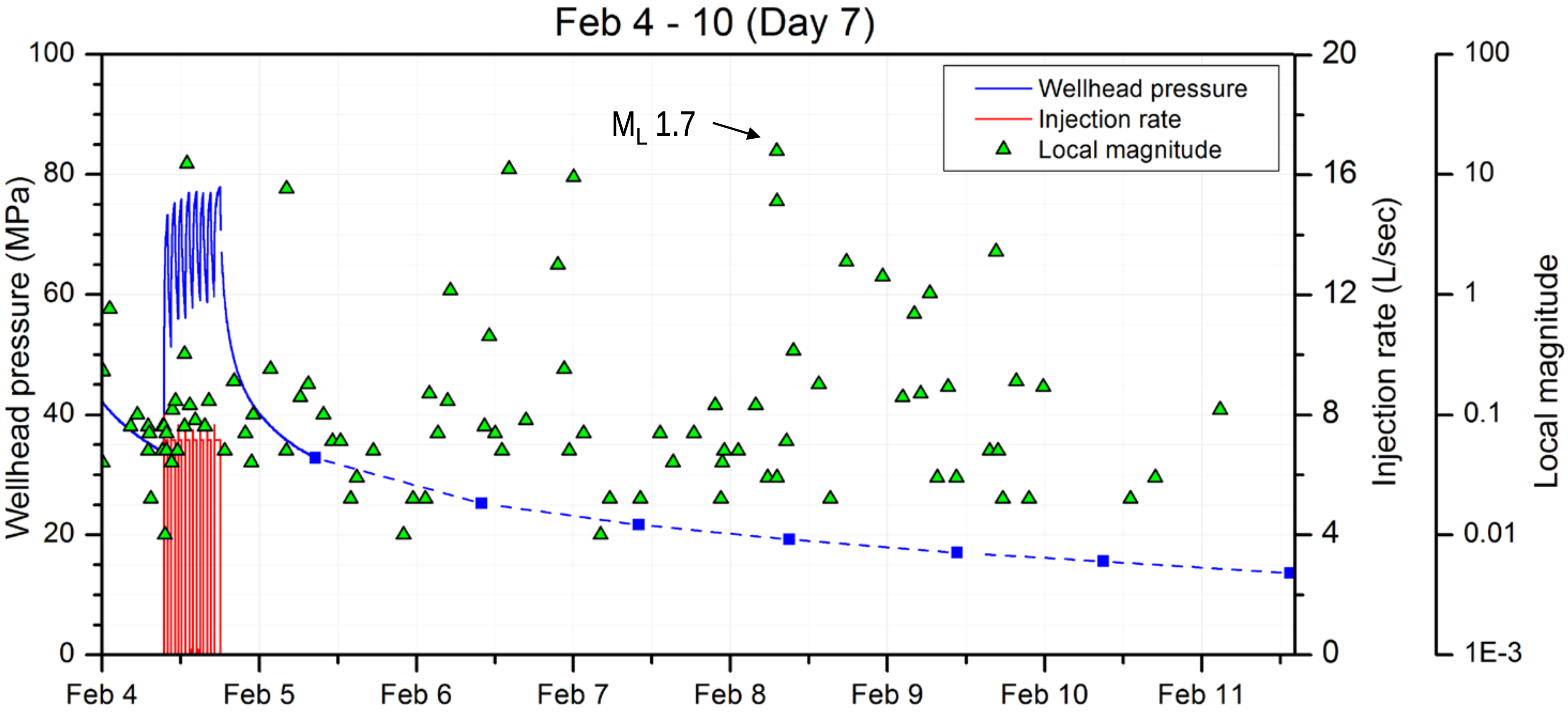
1st stimulation (PX-2 1st Jan 29 - Feb 20, 2016)



- Bigger & more events during shut-in than injection periods

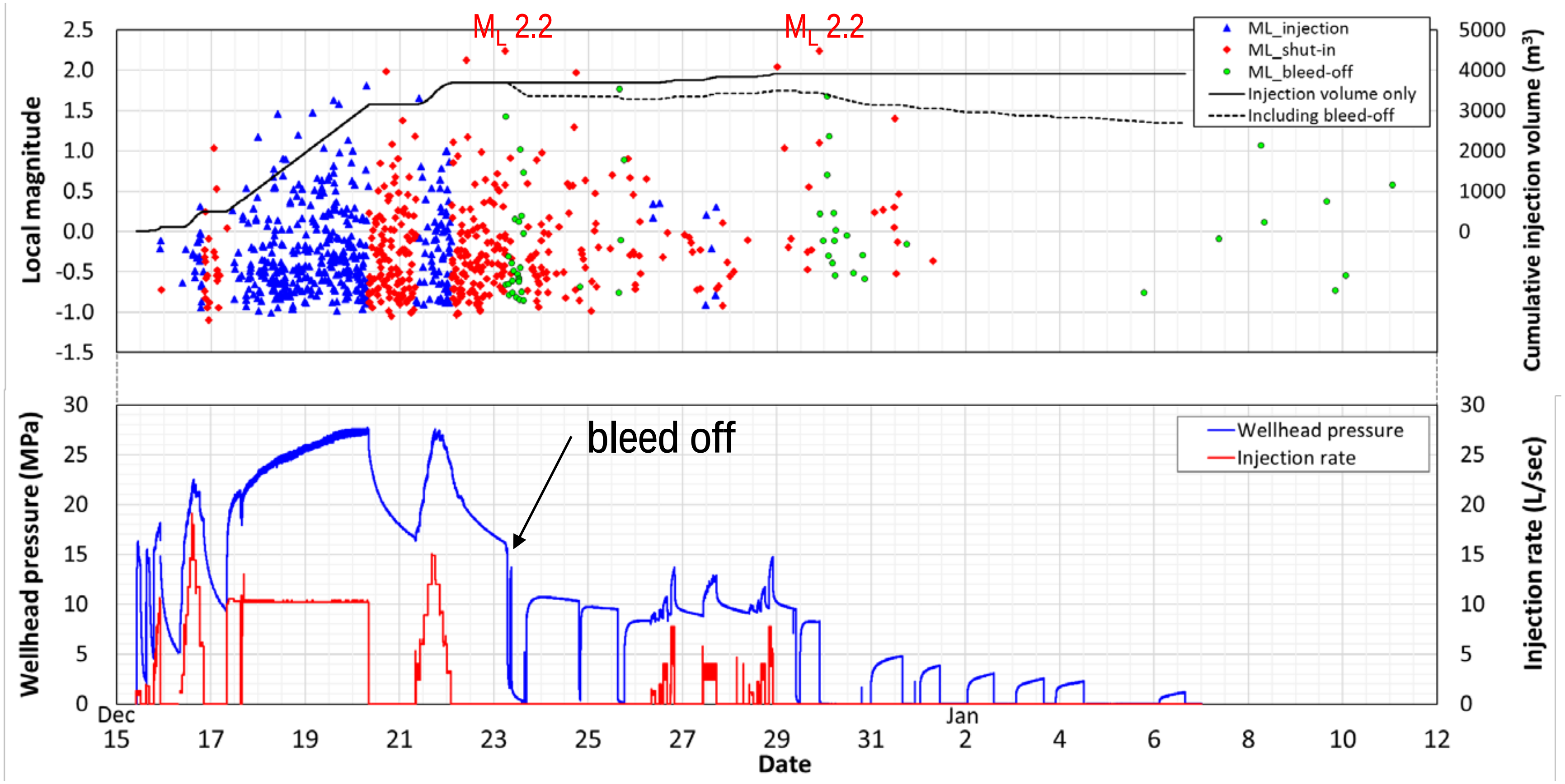
Hydraulic Stimulation

1st stimulation (PX-2 1st Jan 29 - Feb 20, 2016)



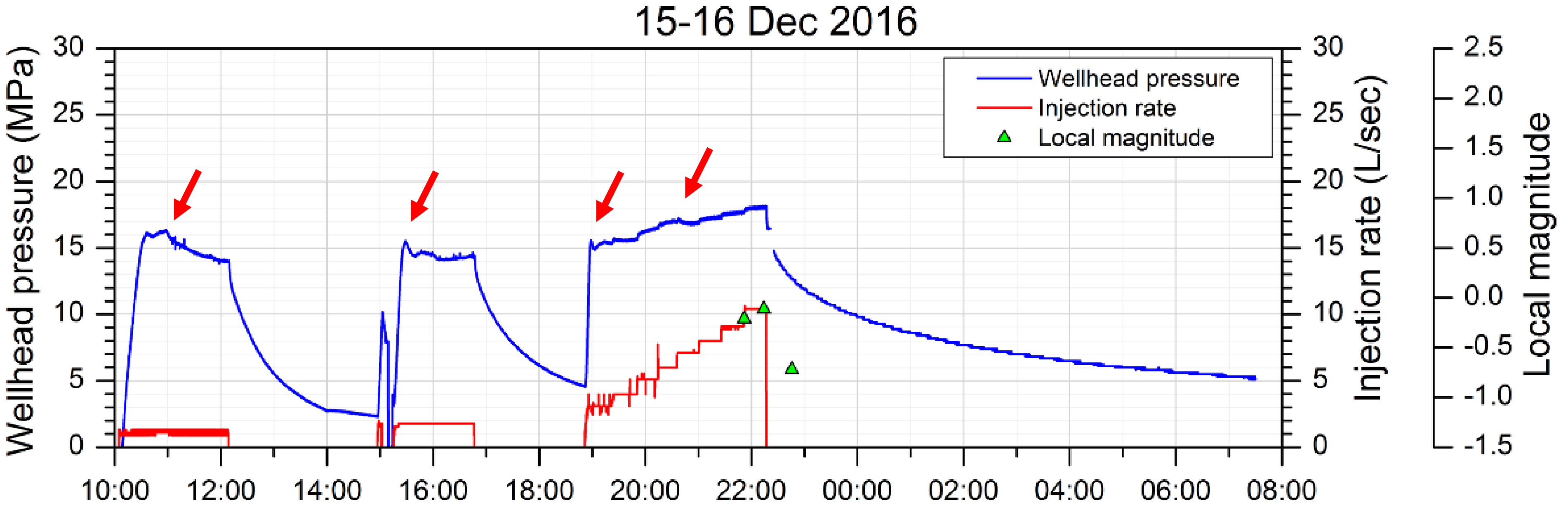
- Max. magnitude of M_L 1.7 during the shut-in (~ 4 days after shut-in)

Hydraulic Stimulation
2nd stimulation (PX-1, Dec 15 - Dec 28, 2016)

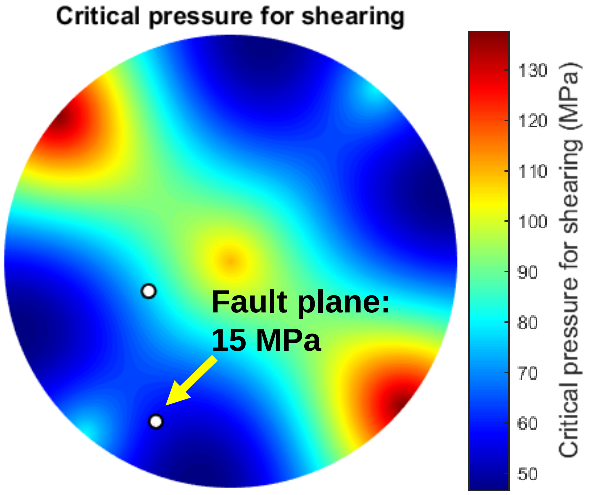


- Max. pressure: 27.7 MPa / Max. Injection rate: up to 18.0 L/sec in Dec 16
- Net injection: 2,689 m^3 at Jan 6 15:44 (total injection: 3,907 m^3, bleed-off: 1,218 m^3)
- Biggest events: M_L 2.2 (Dec 23) @ WHP 16.2 MPa, M_L 2.2 (Dec 29) @ WHP 8.2 MPa
- # of seismic event: 837 (~ Jan 11 1:30)

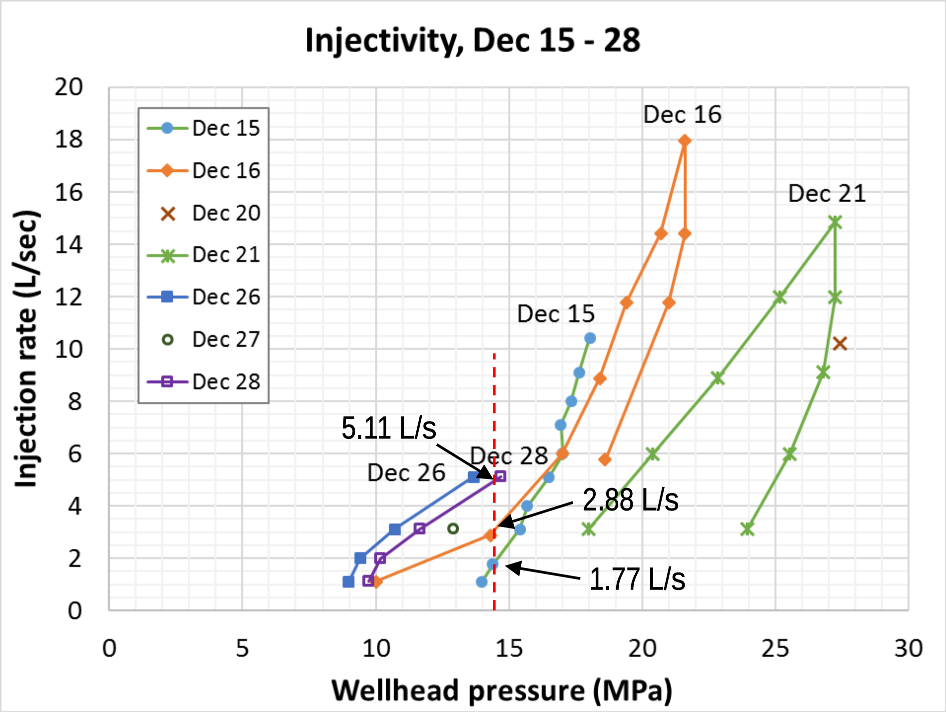
Hydraulic Stimulation
2nd stimulation (PX-1, Dec 15 - Dec 28, 2016)

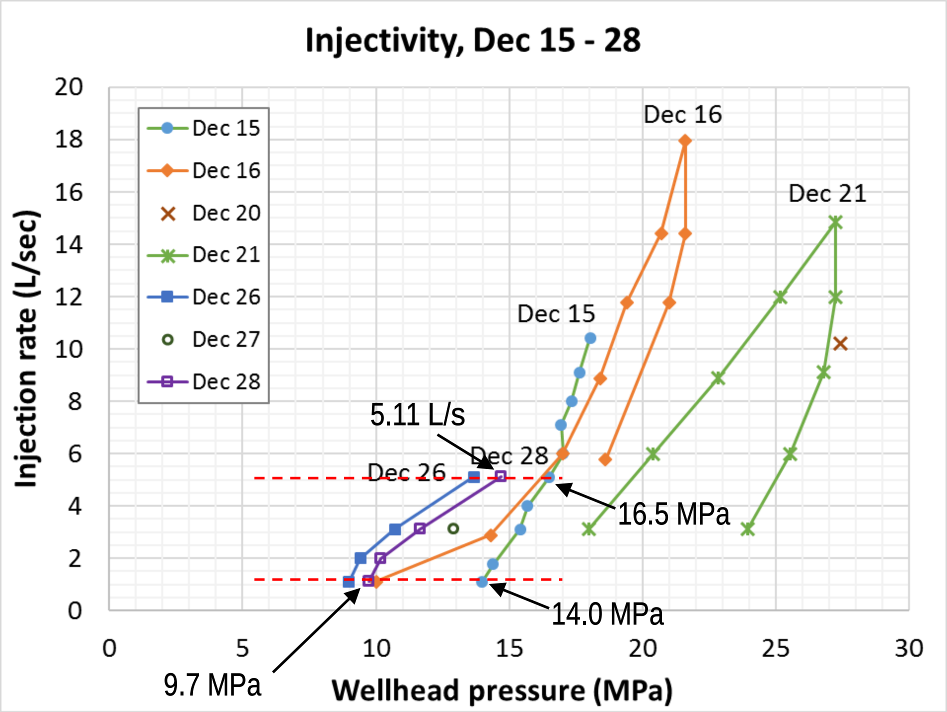


- Pressure peaks at 15~ 17 MPa in Dec 15 2016, during the stimulation in PX-1



Hydraulic Stimulation
2nd stimulation (PX-1, Dec 15 - Dec 28, 2016)





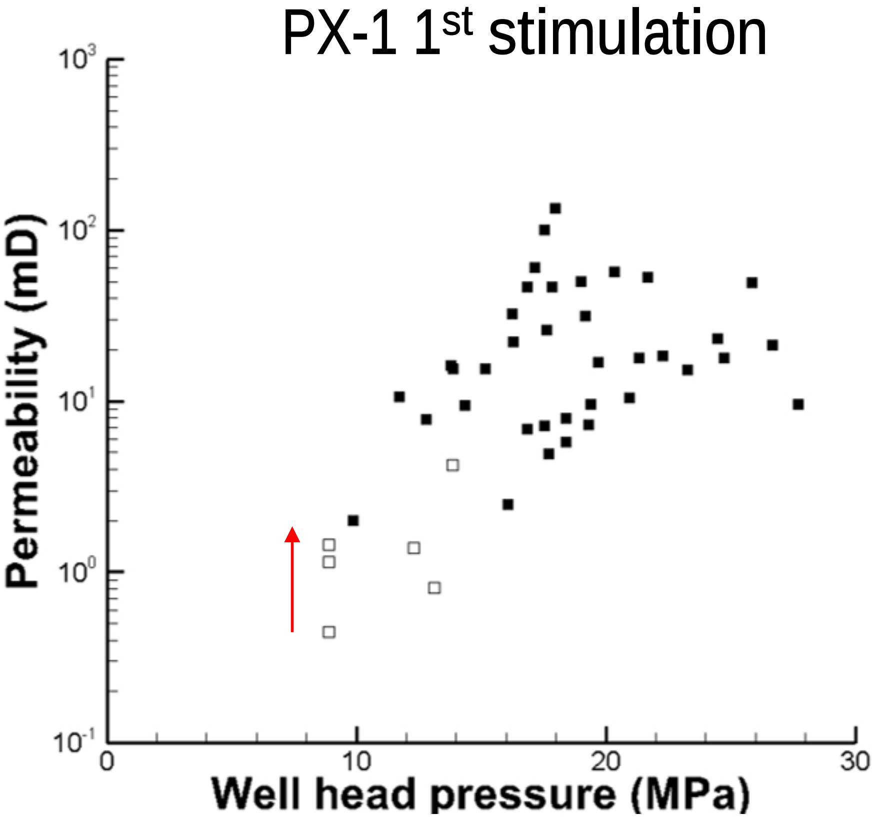
- Injection rate at ~14.5 MPa: 1.77 L/s (Dec 15) → 2.88 L/s (Dec 16) → 5.11 L/s (Dec 28)
- Injectivity at ~14.5 MPa: 0.08 L/s/MPa (Dec 15) → 0.20 L/s/MPa (Dec 16) → 0.35 L/s/MPa (Dec 28)

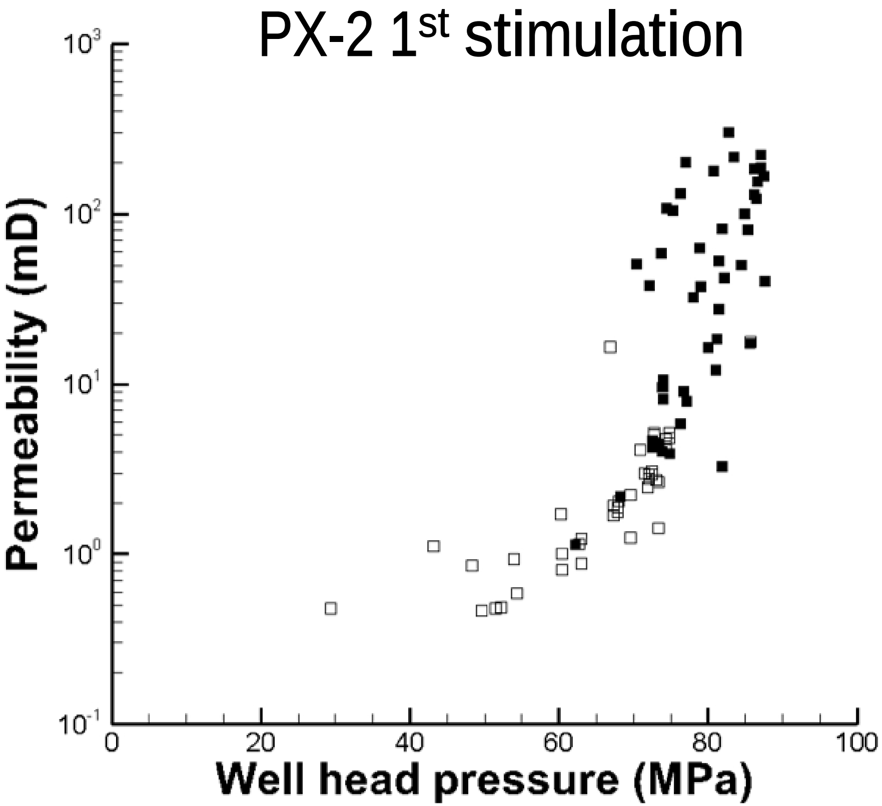
- Wellhead pressure at 1.11 L/s: 14.0 MPa at Dec 15 → 9.7 MPa at Dec 28
- Wellhead pressure at 5.11 L/s: 16.5 MPa at Dec 15 → 14.71 MPa at Dec 28

Hydraulic Stimulation

PX-1 and PX-2

- Permeability change during hydraulic stimulation

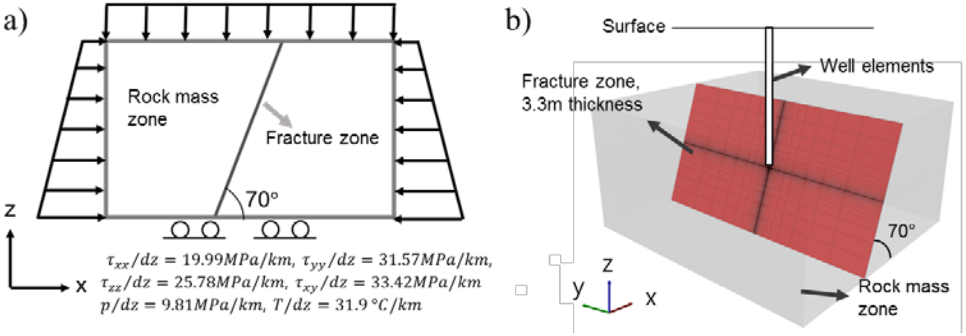


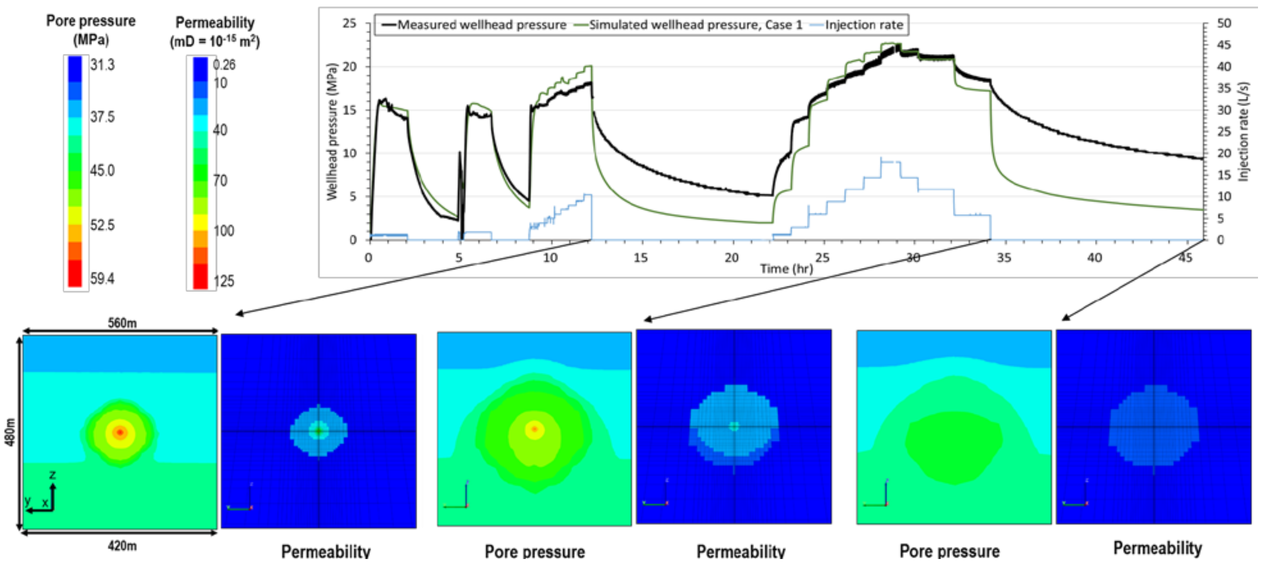


- Permanent k increase by ~ 3 times (PX-1)
- Non-linear jacking (reversible k change, PX-2)

Hydraulic Stimulation
Numerical modeling

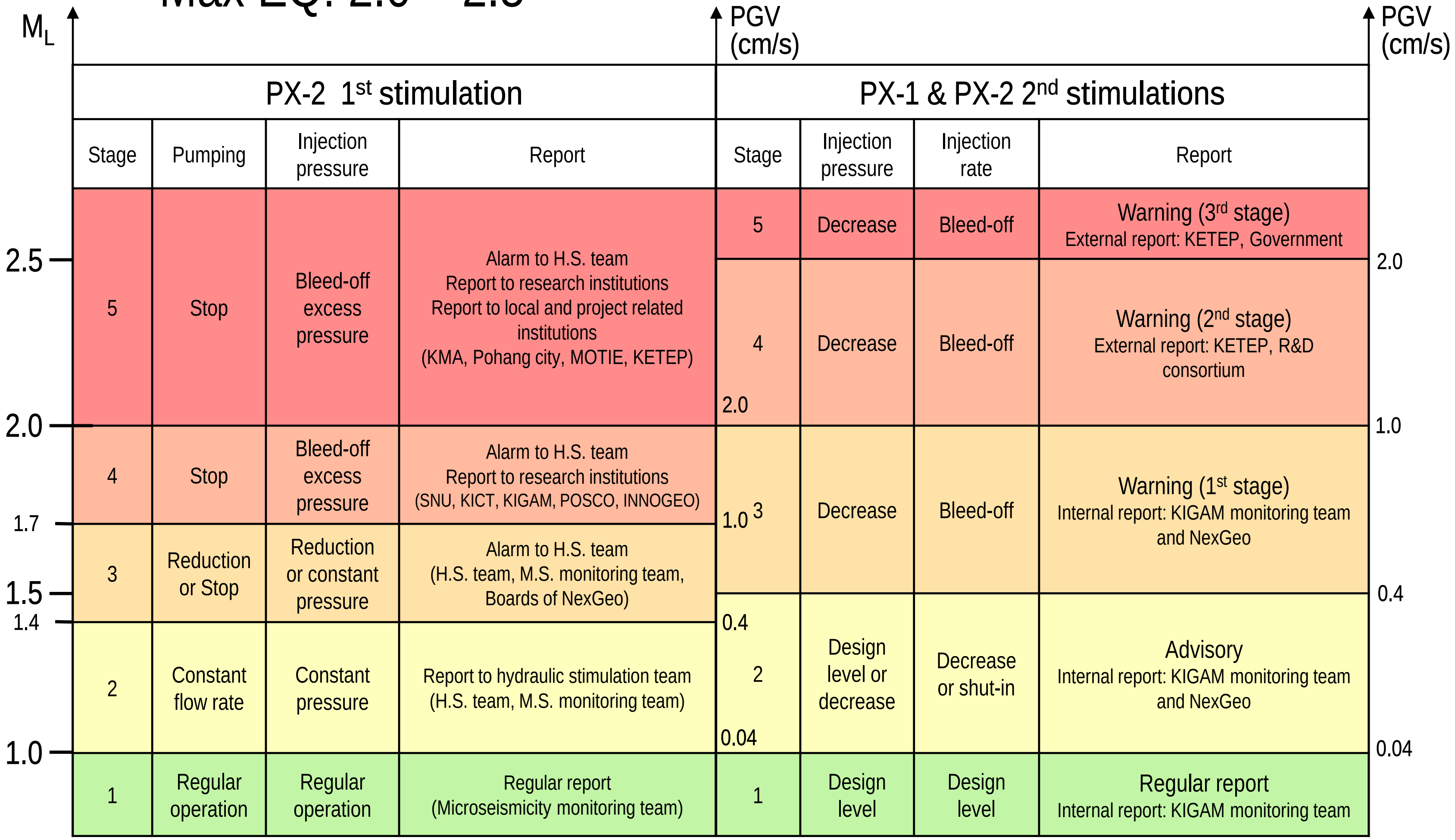
- Pressure-flowrates were reproduced by coupled hydromechanical numerical model (TOUGH-FLAC)





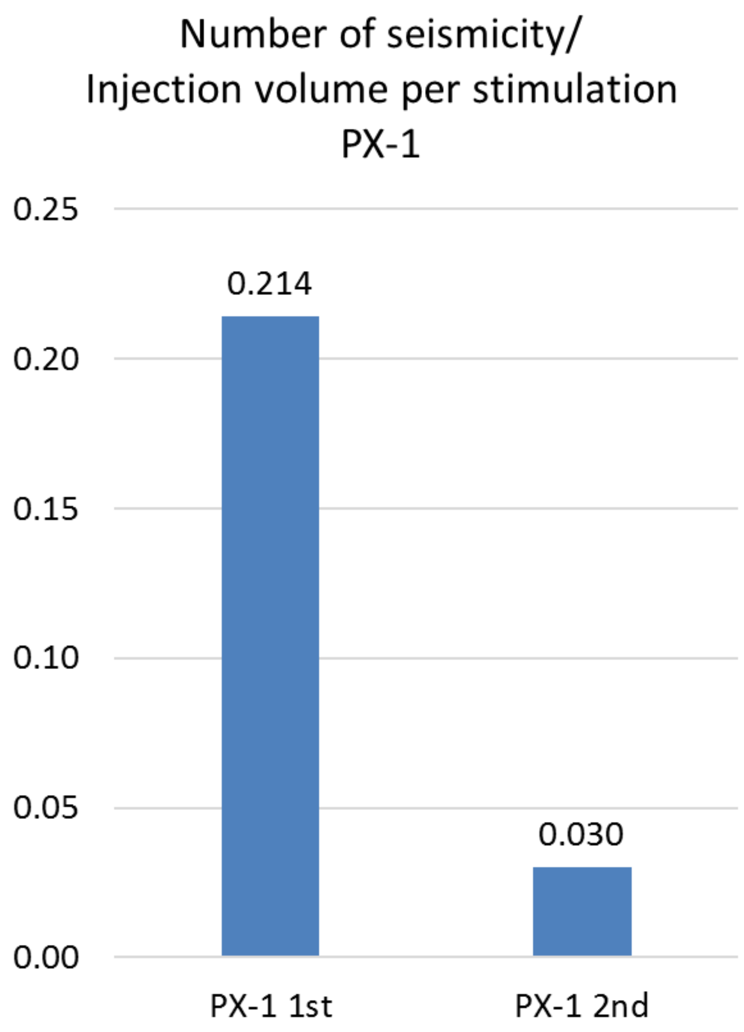
Hydraulic Stimulation
Management of Induced Seismicity

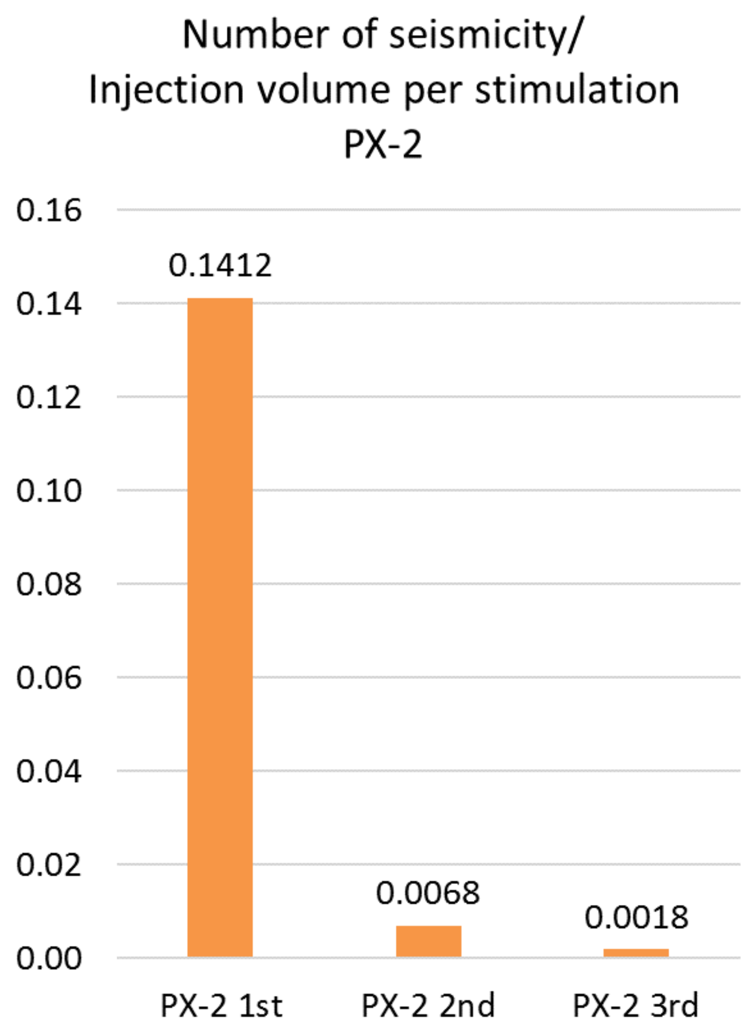
- Traffic light system was used to manage induced seismicity
  - Max EQ: 2.0 – 2.5



PX-2 1st stimulation				PX-1 & PX-2 2nd stimulations			
Stage	Pumping	Injection pressure	Report	Stage	Injection pressure	Injection rate	Report
5	Stop	Bleed-off excess pressure	Alarm to H.S. team Report to research institutions Report to local and project related institutions (KMA, Pohang city, MOTIE, KETEP)	5	Decrease	Bleed-off	Warning (3rd stage) External report: KETEP, Government
4	Stop	Bleed-off excess pressure	Alarm to H.S. team Report to research institutions (SNU, KICT, KIGAM, POSCO, INNOGEO)	4	Decrease	Bleed-off	Warning (2nd stage) External report: KETEP, R&D consortium
3	Reduction or Stop	Reduction or constant pressure	Alarm to H.S. team (H.S. team, M.S. monitoring team, Boards of NexGeo)	3	Decrease	Bleed-off	Warning (1st stage) Internal report: KIGAM monitoring team and NexGeo
2	Constant flow rate	Constant pressure	Report to hydraulic stimulation team (H.S. team, M.S. monitoring team)	2	Design level or decrease	Decrease or shut-in	Advisory Internal report: KIGAM monitoring team and NexGeo
1	Regular operation	Regular operation	Regular report (Microseismicity monitoring team)	1	Design level	Design level	Regular report Internal report: KIGAM monitoring team

Hydraulic Stimulation
Induced seismicity (Kaiser Effect)





- Reservoir becomes aseismic due to repeated stimulation

Conclusions

- Pronounced hydraulic shearing was observed.
  - Permanent Δk (permeability increase) ~ factor of 3
- Significant non-linear jacking occurred without significant permanent Δk
- Significantly different behavior between two boreholes shows that the proper drilling operation is very important
- Hydromechanical numerical reproduction of hydraulic shearing or jacking is possible
- More and greater seismic events during shut-in
- Seismic events show significant Kaiser memory effect.
- Investigation on the linkage between hydraulic stimulation in Pohang (<10,000m3) and EQ 5.4 (Nov 15 2017) is ongoing.
  - Great lessons for EGS community