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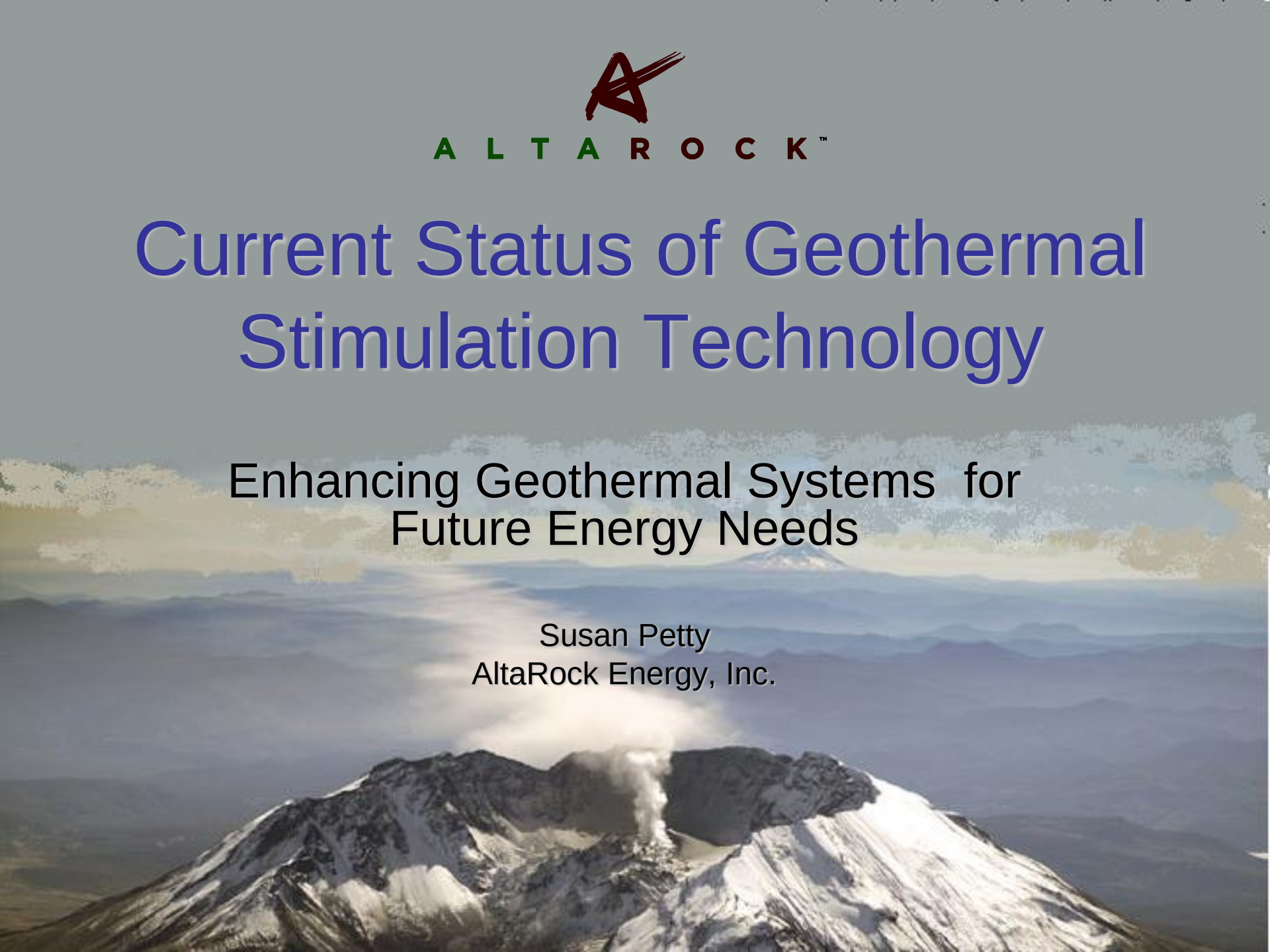
Current Status of Geothermal Stimulation Technology

Enhancing Geothermal Systems for Future Energy Needs

Susan Petty
AltaRock Energy, Inc.



Goals of Geothermal Stimulation

- Improve productivity of hot, low permeability producers
  - Really high flow rates needed: >75 kg/s (1200 gpm, 40,000 BPD)
  - Improve productivity of high temperatures zones
  - Block improvement of low temperature zones
- Improve injection wells
  - Injectivity
  - Injection conformance – improve connectivity to recharge production
  - Prevent or reduce short circuits to producers
  - Improve injectivity in high temperature zones

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Geothermal Stimulation: Comparison to Oil and Gas

Geothermal

- Very high flow rates> 1200 gpm (40,000 BPD)
- Not a commodity: Needs a power plant or end use to monetize
- Production must be sustainable over long time periods
- Generally hydrostatic or under pressured
- Open hole or perforated liner completions to get high rates
- Need fracture complexity maximum contact area with rock for good heat exchange
- Reservoirs naturally fractured so wells directionally drilled to intersect fracture direction
- High temperatures >300F (150C) preclude use of many fluid additives
- Proppants don't last in HT environment. Viscosifiers can cause formation damage

Oil and Gas

- 1000 BPD (30 gpm) is a good oil well
- Resource is in layered sedimentary rock which may or may not be naturally fractured
- Horizontal drilling used to "follow" a layer and increase access to resource
- Many stage fracturing to access tight formation
- Hydrofrac with proppant to improve near wellbore permeability
- Product is a commodity. Can be monetized immediately
- Fracture complexity needed to access very low permeability reservoir rocks
- Use of viscosifiers and other additives to improve proppant placement
- Tensile fracturing improves near wellbore permeability. Needs proppant

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Geothermal Stimulation History

- Early EGS stimulation experience
  - Fenton Hill
  - Rosemanowes
  - Hijiori
  - Ogachi
  - Soultz
- Current EGS Projects
  - Newberry
  - Desert Peak
  - Raft River
  - FORGE
- Field operator current practice

Hydrothermal Stimulation Experience

Goals of geothermal stimulation

- Geothermal production rates are really, really high compared to oil and gas
  - 10,000 BBD of 300 F water is about 750 kW.
  - Most geothermal wells produce about 5 MW or 50,000 BBD
- Stimulations are therefore trying to improve permeability when permeability may already be high
- Need to block permeable zones to improve other zones

Hydrothermal stimulation experience

- Past:
  - Philippines – Mahanadon, Malitbong -acid stimulation
  - Indonesia
  - East Mesa
  - Raft River
  - Baca – Valles Caldera
- Recent
  - Desert Peak
  - Coso
  - Raft River
  - Blue Mountain

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Early Hydrothermal Stimulation Experience

Table 1. SUMMARY OF GRWSP EXPERIMENTS

Exper. No.	Location and well	Reservoir Temp. (°F)	Stimulation Treatment	Height (ft)	Treatment Interval Fluid	Proppant	
1	Raft River,ID RRGP-4	290	Dendritic hydraulic fracture	196	7900 bbl 10 lb HP Guar/1000 gal 2 lb XC Polymer/1000 gal	Sand	50,400 lb 100-mesh 58,000 lb 20/40-mesh
2	Raft River,ID RRGP-5	290	Large hydraulic fracture	216	7600 bbl 30 lb HP Guar/1000 gal	Sand	84,000 lb 100-mesh 347,000 lb 20/40-mesh
3	East Mesa,CA 58-30	350	Hydraulic fracture	247	2800 bbl 60 lb HP Guar (Crosslinked gel)/1000 gal	Sand RCS	44,500 lb 100-mesh 59,200 lb 20/40-mesh 60,000 lb 20/40-Mesh [c]
4	East Mesa,CA 58-30	320	Dendritic hydraulic fracture	304	10,300 bbl 10 lb HP Guar/1000 gal 2 lb XC Polymer/1000 gal	Sand	44,000 lb 100-mesh
5	Baca,NM 8-23	450	Large hydraulic fracture	231	3600 bbl water prepad 4000 bbl 60 lb HP Guar (Crosslinked gel)/1000 gal	Sand RCS Bauxite	42,000 lb 100-mesh 81,5000 lb 24/40-mesh 98,500 lb 2O/40-mesh

6	The Geysers,CA OS-22	460	Acid etching	1000	476 bbl prepad 15 lb HP Guar/1000 gal 476 bbl pad 60 lb HP Guar (Crosslinked gel)/1000 gal 476 bbl 5% HCl-10% HF 445 bbl displacement 15 lb HP Guar/1000 gal	None
7	Baca, NM B-20	540	Large hydraulic fracture	240	3000 bbl water prepad 5600 bbl 60 lb HP Guar (Crosslinked gel)/1000 gal	Bauxite 119,700 lb 16/20-mesh 119,700 lb 12/20-mesh
7A	Baca, NM B-20		Acid treatment [a]	240	1045 bbl 11.9% HCl	None
8	Beowawe, NV Rossi 21-19		Acid etching [b]	1111+	Stage 1: 500 bbl 14.5% HCl 2446 bbl water displacement Stage 2: 982 bbl 12% HCl-3% HF 3019 bbl water displacement	None

Notes:

[a] To dissolve calcium carbonate fluid-loss additive

[b] To remove formation damage

[c] "RCS" is resin coated sand

Table 2. Summary of Results of Stimulation Experiments					
Experiment & Well	Formation Type	Treatment Goal	Stimulation successful?	Well Fixed?	Conclusions
1. Raft River RRGP-4	Fractured	Dendritic fracture	Yes, but long fracture	No	Flow rate too low
2. Raft River RRGP-5	Fractured	Long fracture	Partially	No	Flow rate low & fluid too cool
3. East Mesa 58-30	Sedimentary	Long fracture	Yes	Yes	Hydrofrac worked
4. East Mesa 58-30	Sedimentary	Long fracture	Yes	Yes	Hydrofrac worked
5. Baca B-23	Fractured	Fracture	Yes	No	Impermeable formation
6. Geysers OS-22	Fractured	Acidize	No	No	Fractures too short
7a. Baca B-20	Fractured	Long fracture	Yes. Fracture created.	No	Impermeable formation
7b. Baca B-20	Fractured	Acidize	Unknown	No	Permeability not increased
8. Beowawe R21-19	Fractured	Acidize	Probably	Partial	Injectivity increased 2.3 fold.

Field Operator Current Practice

- Large volume, long term, cool water injection
- Dilute large volume acidizing-acid activity increased by high temperature
- Pump from surface
- Sand back to isolate zones
- Some large volume, high pressure water stimulations in very tight wells
- No standard for zone isolation

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Field Operator Current Practice: Acidizing

Geothermal field	Chemical agents used	Number of treated wells	Variation of the injectivity index before and after chemical treatment (kg s−1 bar−1)	Ref.
Bacman (Philippines)	HCl–HF	2	0.68–3.01 0.99–1.40	Buning et al. (1995)
Leyte (Philippines)	HCl–HF	3	3.01–5.84 0.68–1.77 1.52–10.80	Malate et al. (1997); Yglopaz et al. (1998)
Tiwi (Philippines)	HCl–HF	1	2.52–11.34	Buning et al. (1995)
Mindanao (Philippines)	HCl–HF	1	Successful	Buning et al. (1997)
Salak (Indonesia)	HCl–HF	1	4.70–12.10	Pasikki and Gilmore (2006)
Berlín (El Salvador)	HCl–HF	5	1.60–7.60 1.40–8.60 0.20–1.98 0.90–3.40 1.65–4.67	Barrios et al. (2002)
Las Tres Vírgenes (Mexico)	HCl–HF	2	0.8–2.0 1.2–3.7	Jaimes-Maldonado and Sànchez-Velasco (2003)
Los Azufres (Mexico)	HCl–HF	1	3.3–9.1	Flores et al. (2006)
Beowawe (USA)	HCl–HF	1	Successful	Epperson (1983)
The Geysers (USA)	HCl–HF	1	No effect	Entingh (1999)
Coso (USA)	HCl and NTAa	30	24 wells successful	Evanoff et al. (1995); Rose et al. (2007)
Larderello (Italy)	HCl–HF	5	11–54 4–25 1.5–18 Successful 11–54	Cappetti (2006)
Fenton Hill (USA)	Na2 CO3	1	About 1000 kg of quartz were dissolved and removed from the reservoir but no impedance reduction resulted.	LANL (1977)
Fjällbacka (Sweden)	HCl–HF	1	Efficiency of acid injection in returning rock particles.	Sundquist et al. (1988); Wallroth et al. (1999)

a NTA: nitrilotriacetic acid (C6 H9 NO6).

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Field Operator Current Practice: Example

- Steamboat 13-5
  - Pumped 50,000 bbls water, to build wellhead pressure to breakover
  - Injected HCl 7%, HF 5%, HCl 7% then 50,000 bbl water
  - Allowed well to heat
  - Flowed back and tested
- Steamboat 13-5
  - Raised flowing WHP from ~50 psi to 120psig
  - Increased temperature ~35°F
  - Flow decreased, but more than doubled production from high temperature zone
  - Production increased from ~2.5 MW at sub-commercial WHP to 7 MW at 120 psig

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Recent Stimulations

- Raft River
  - Long term cold water pumping
  - Over a year of injection connected to main reservoir
- Desert Peak
  - Well recompleted with scab liners for zone isolation
  - Long term high volume, high pressure pumping connected injector to main reservoir
- Calpine
  - Cold water injection at high rate to extend stimulation to deep HT zone
  - Very high rates needed to obtain deeper stimulation
- Blue Mountain
  - Long term pumping into low permeability injectors to improve connection to reservoir, increase injectivity
  - Improvement of injection profile to block fast paths to producers
- Other Basin and Range projects

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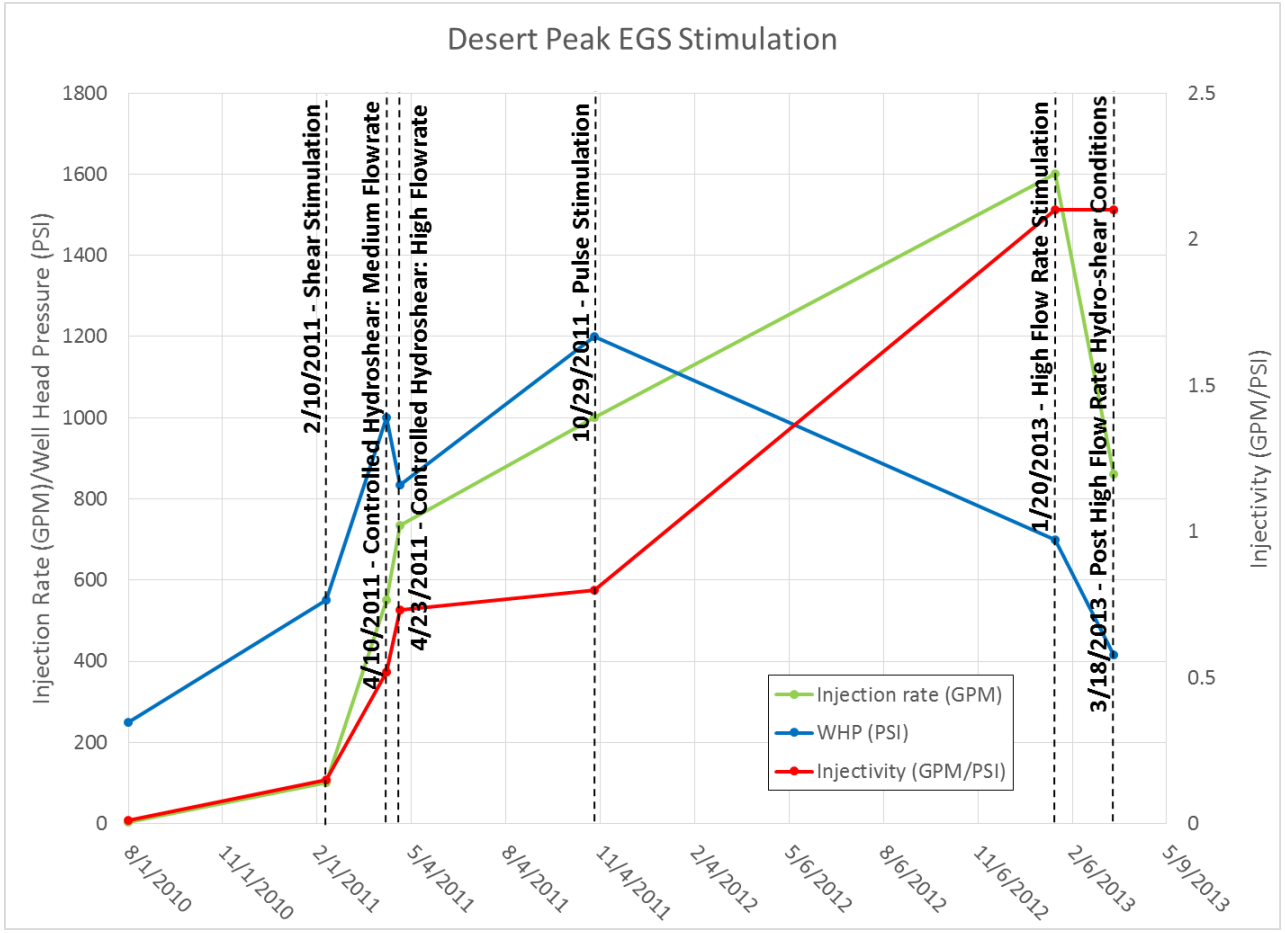
Desert Peak Stimulation Of Injector

Multistage stimulation following well recompletion

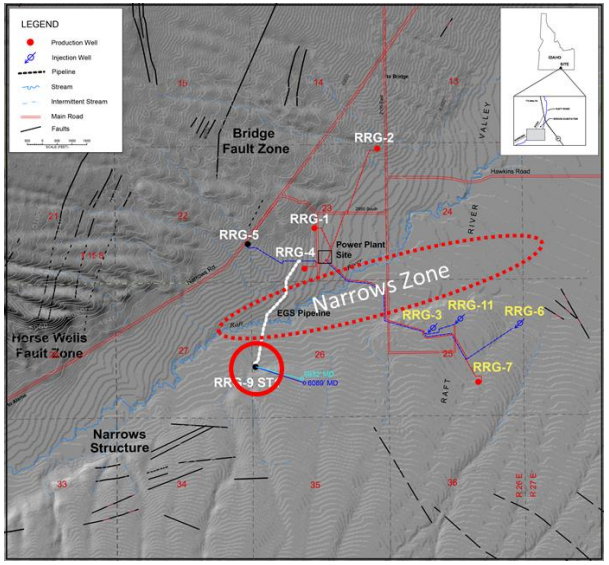
Desert Peak

- Series of single hydroshear zone stimulations using different methods
- High flow rate, low pressure stimulation finally increased injectivity significantly
- Injection continued at low pressure, moderate rate while injectivity held constant
- Well was later recompleted to allow multizone stimulation with packers



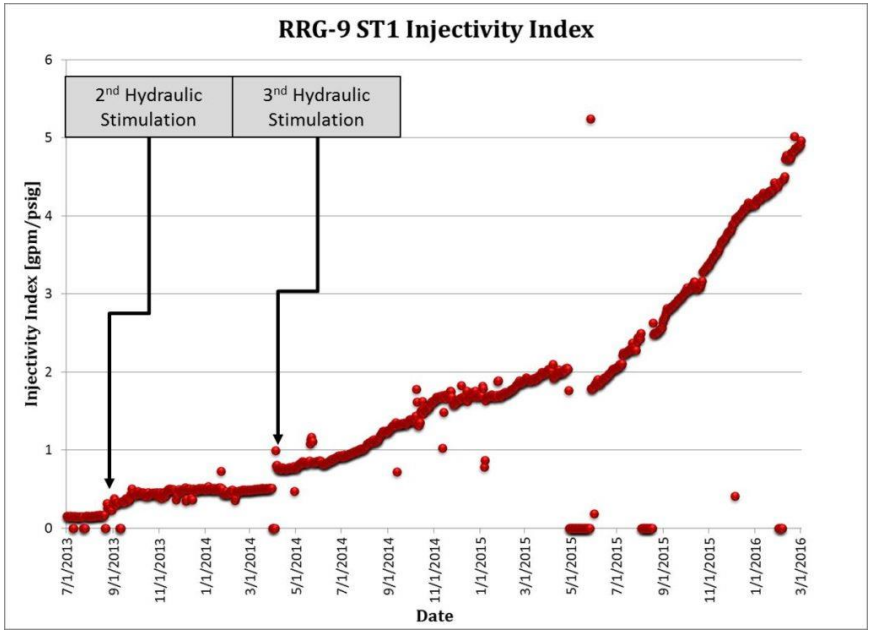
Raft River Stimulation Of Injector

Cold water injection over time



RRG-9

- RRG-9 ST1 was hydraulically stimulated in February 2012
- Injection flow rates increased 11 gpm to 760 gpm - wellhead pressure of 1150 psi
- Injection cool fluid from the plant - June 2013 at an injection rate of 20 gpm
- 2013 2nd hydraulic stimulation improved flow rates from 50 gpm to 120 gpm
- Injection through March 2014 with little improvement in the injectivity.
- 3rd hydraulic stimulation April 2014 using pump trucks to pump fluid up to injection rates of 1,260 gpm at a wellhead pressure of 980 psi. Following the third hydraulic stimulation, injection through the 10-inch resumed with injection maintained on a nearly continuous basis. Unlike the

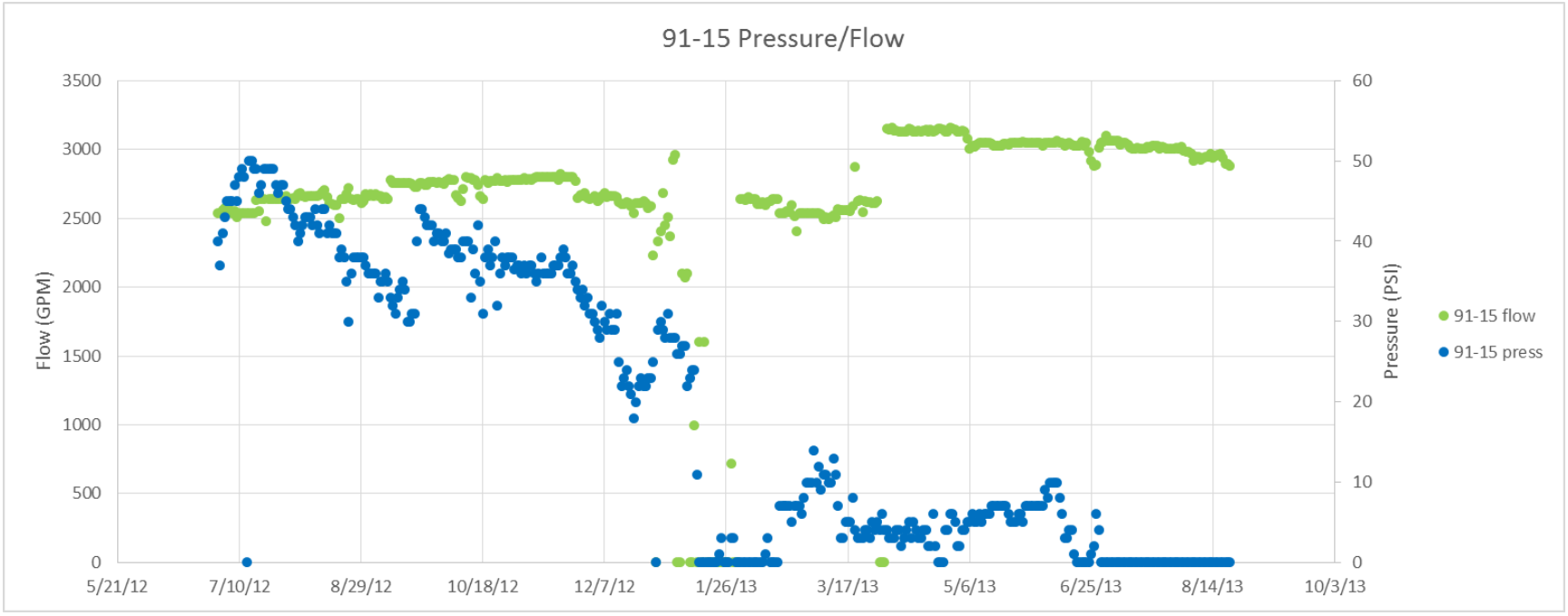


Blue Mountain Stimulation

Cold water injection with time

Blue Mountain injection wells

- 91-15 drilled as an injector, but had poor injectivity
- Single zone stimulated with cold water injection initially Feb 2012
- Initial injectivity 500 gpm at about 17 psi wellhead pressure
- Continuous injection at > 2500 gpm since July 2012 with decreasing wellhead pressure

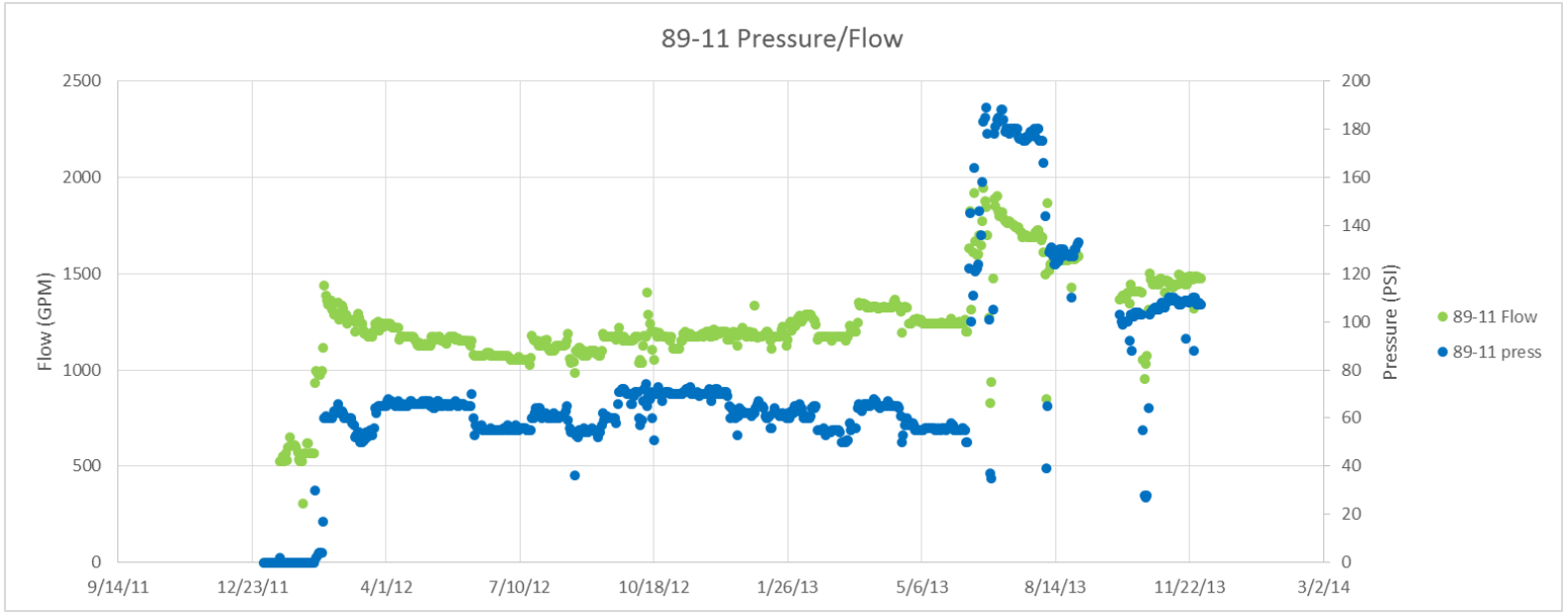


Blue Mountain Stimulation

Cold water injection with time

Blue Mountain injection wells

- 89-11 drilled as injector, but would not take fluid initially except at very high pressure
- Single zone stimulated with cold water injection in 2011
- Initial injectivity 500 gpm with no wellhead pressure after stimulation
- Continuous injection at > 1100 gpm since December 2011 with slowly decreasing wellhead pressure
- Injection pressure increased in July 2013 caused decrease in injectivity
- Injectivity now improving over time



Multizone Diverter Stimulation

Improvement of Production Well

- **Goals of production well stimulation:** Increase well production particularly from deeper reservoir

➢ Achieved - **TZIM stimulation** created 2 new zones, stimulated 3 existing zones for estimated **400 kW increased** plant production.

➢ Achieved - **Two new production zones** in deeper, zones of well

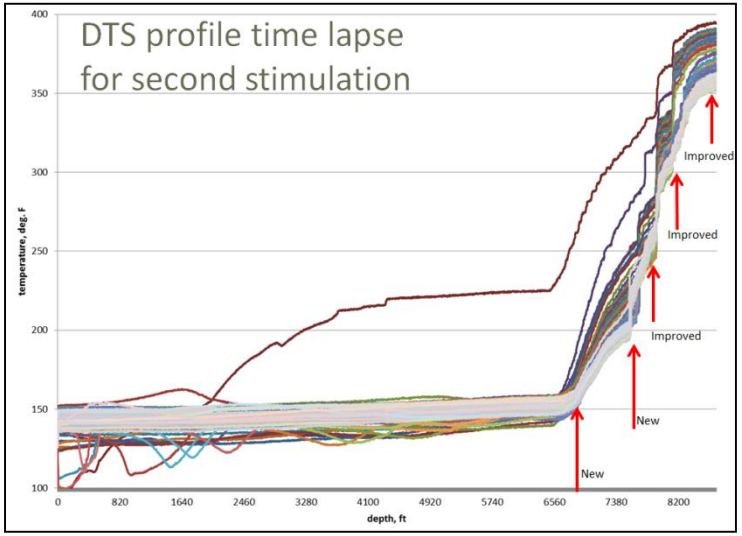
➢ Achieved - **Existing high temperature permeable zones improved** through TZIM stimulation.

➢ Achieved - Multiple zones stimulated produce 200 gpm more flow at 30°F higher temp

➢ Achieved - Overall increase in enthalpy flow rate of over 134%

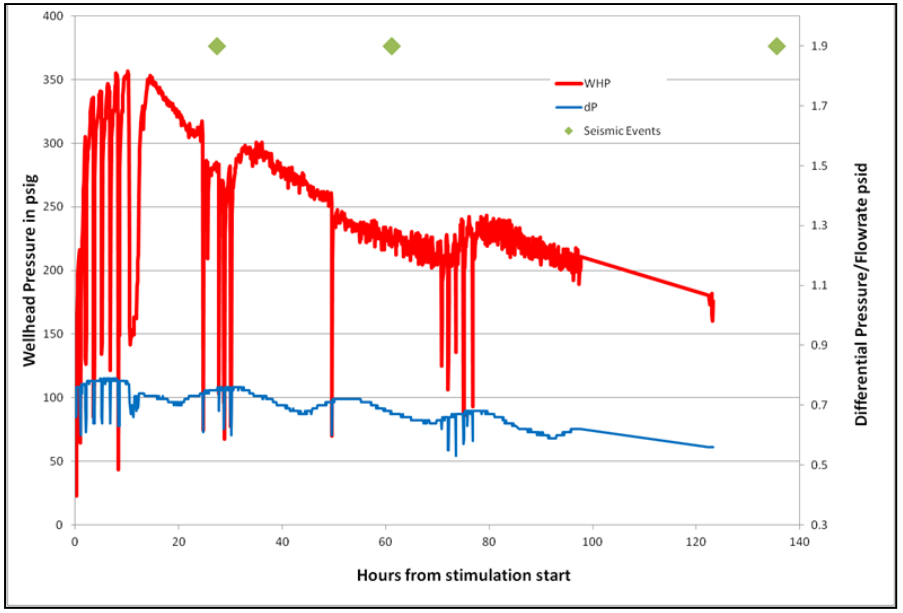
Injection Optimization

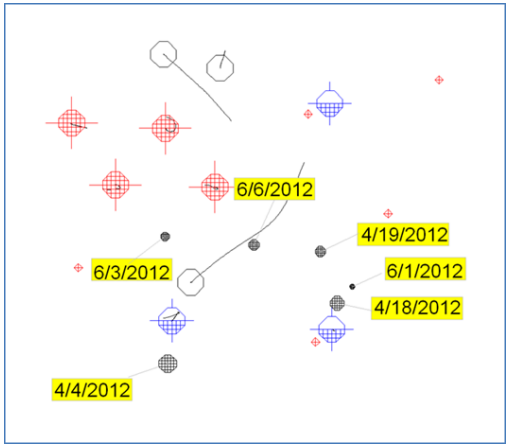
- **Improved injection capacity** in deeper, hotter reservoir through multizone stimulation
- **Increase injection** to deeper hotter zones in field
- **Improved overall plant output** by removing injection limitation
- **Supply pressure support** to production wells through improved injection connection to production without cool water breakthrough



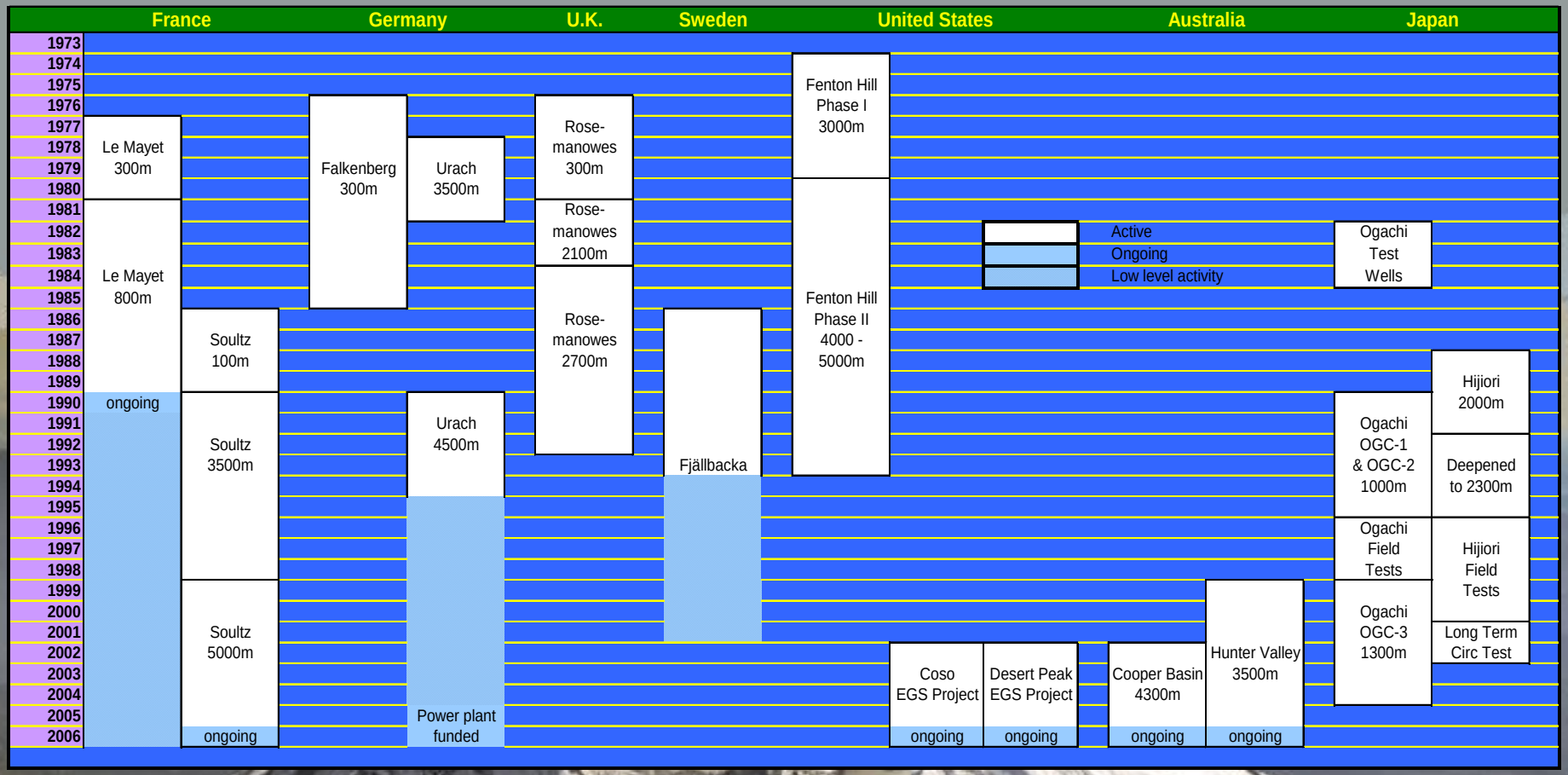
Microseismic Monitoring

- 6 total events mapped during monitoring
- 2 microseismic events occurred during the stimulation
  - Events appear to be the result of stimulation
  - No clear temporal relation to WHP changes
    - Possibly due to a lag in pressure response in low transmissivity fracture connections between the well and the event epicenters
- 3 events within 2 days after the production or injection pumps were turned off
- 1 event mapped prior to stimulation





EGS Projects



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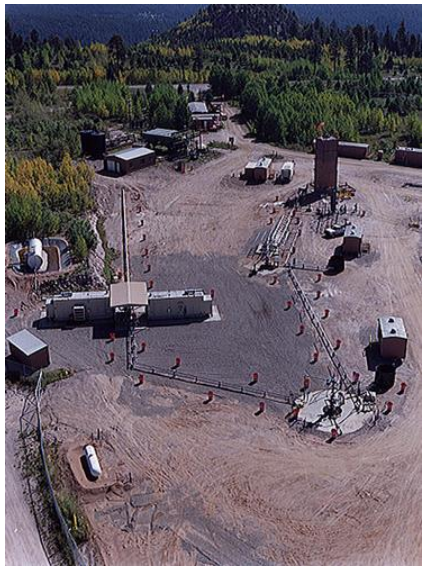
EGS Test Sites

First test of engineered geothermal at Fenton Hill, New Mexico

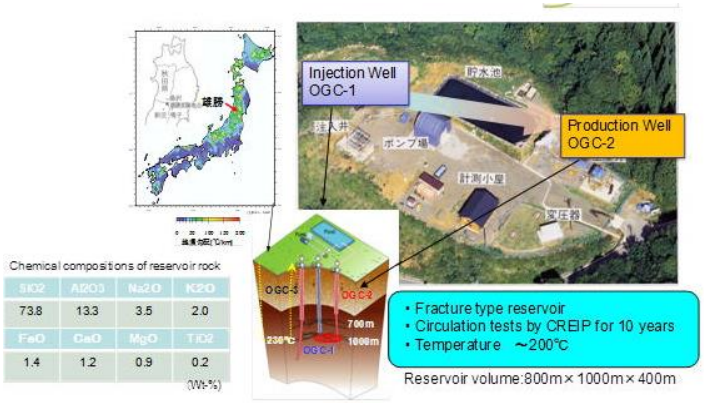


Rosemanowes Quarry, UK, logging tower on wheels

Binary power plant at Hijiori EGS site, Japan

Testing at Soultz EGS test site, France

Deep Heat Mining project in Basel, Switzerland-Suspended due to induced seismicity



Ogachi HDR test site in Japan

EGS Development Worldwide

Commercializing the EGS resource

Test of EGS well, Cooper Basin, Australia. 30 MW test project planned with expansion to 450 MW

Binary power plant at Landau, Germany, now on line.

EGS power plant at Unterhaching, Germany

New Turboden power plant goes on line at Soultz, France

EGS combined heat and power project at Rittenhoffen

Recent EGS Stimulation Experience

- Europe
  - Large number of deep geothermal projects using acidizing to improve productivity of geothermal wells
  - Stimulation of injector combined with natural fractures
    - Landau
    - Rittenhoffen
    - Unterhaching
- US
  - Newberry EGS Demonstration

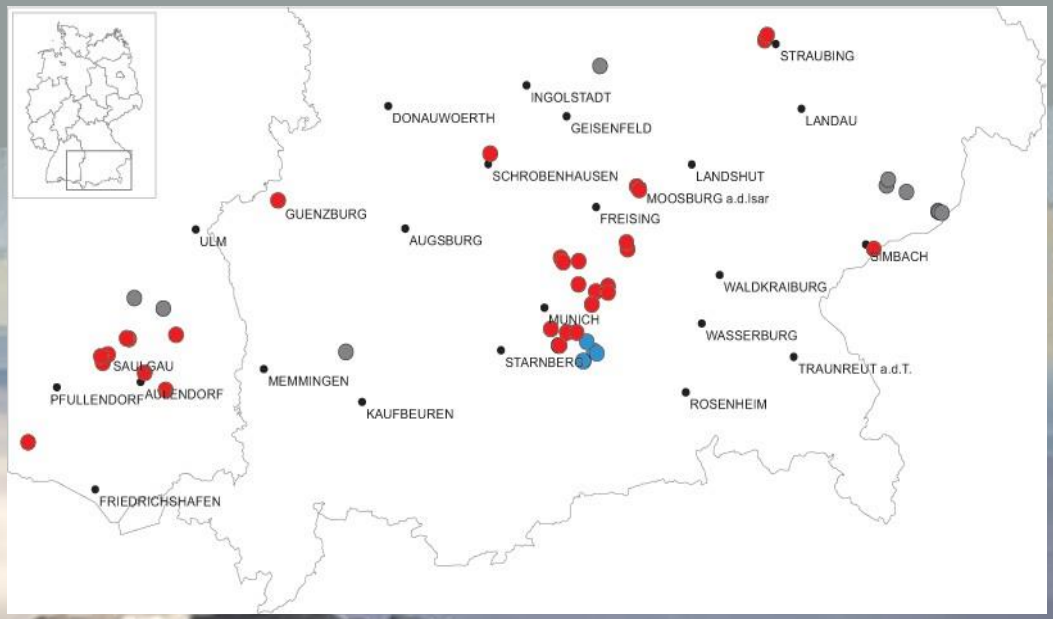


Figure 1. A map of southern Germany and geothermal installations within the Malm aquifer. Main uses are district heating (red dots), power generation (blue dots), and spas (gray dots).

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EGS Stimulation Current Practice

- Drill and stimulate injector first
- Monitor and map fractures with microseismicity
- Large volume injection with possible chemical/acid stimulation
- Inject at pressures below tensile failure
- Pump from surface
- Induced seismicity mitigation plan in place

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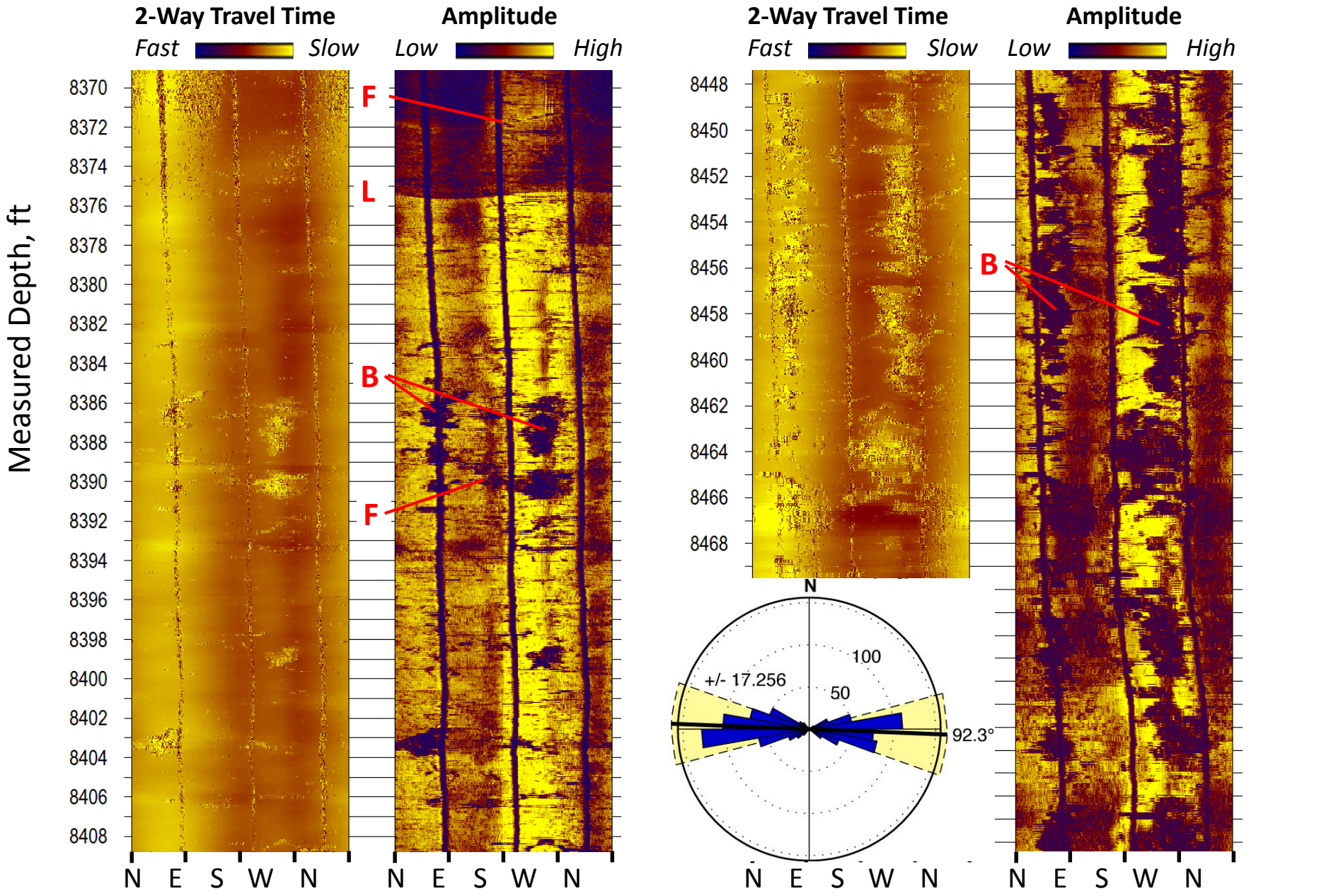
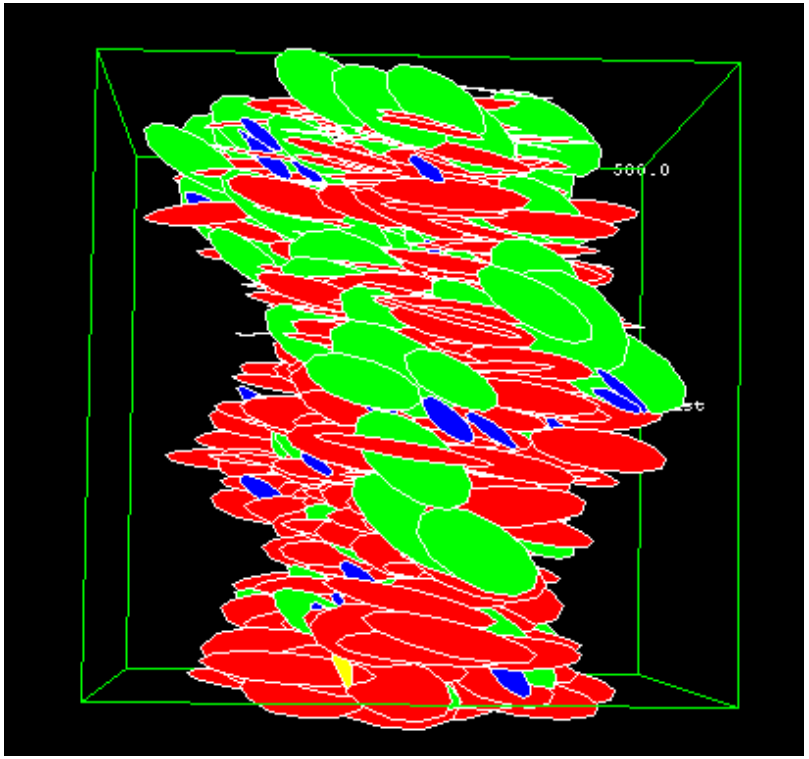
NWG 55-29 Borehole Televiewer Image Log



Davatzes & Hickman, 2011

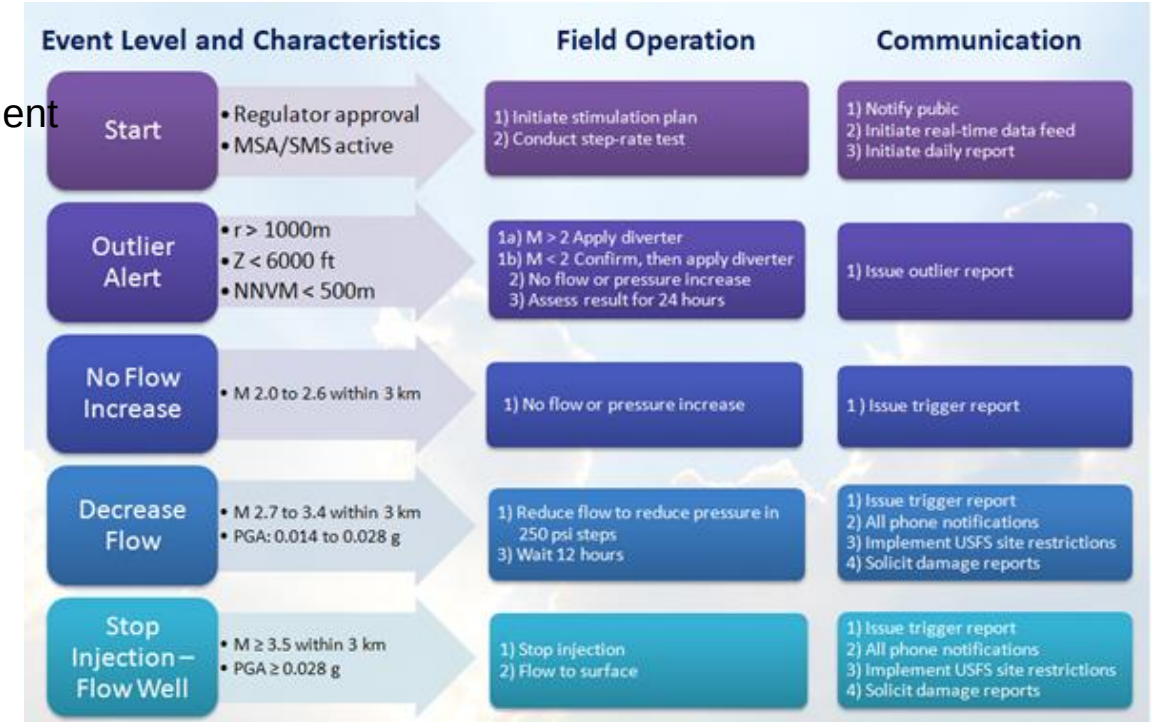
AltaStim
AltaRock's EGS simulation software

- Stochastic and Deterministic Fracture Model
  - Generate Fracture Population
  - Apply Stress Model
- Stimulation Modeling
  - Hydroshearing – increased fluid pressure induces shear-slip which increases apertures and permeability
  - Increased permeability allows connected fracture network to grow
- Generate microseismicity maps
- Calculate reasonable volumes and pressures
- See Cladouhos et al. 2011, GRC meeting



Environmental, Safety and Health

- Comprehensive ES&H Plan
- Induced Seismicity Mitigation Plan
- Environmental Monitoring
  - Groundwater protection
  - Invasive weed management



Mapping Newberry EGS with Microseismic Array

15-station seismic array (installed 2012)

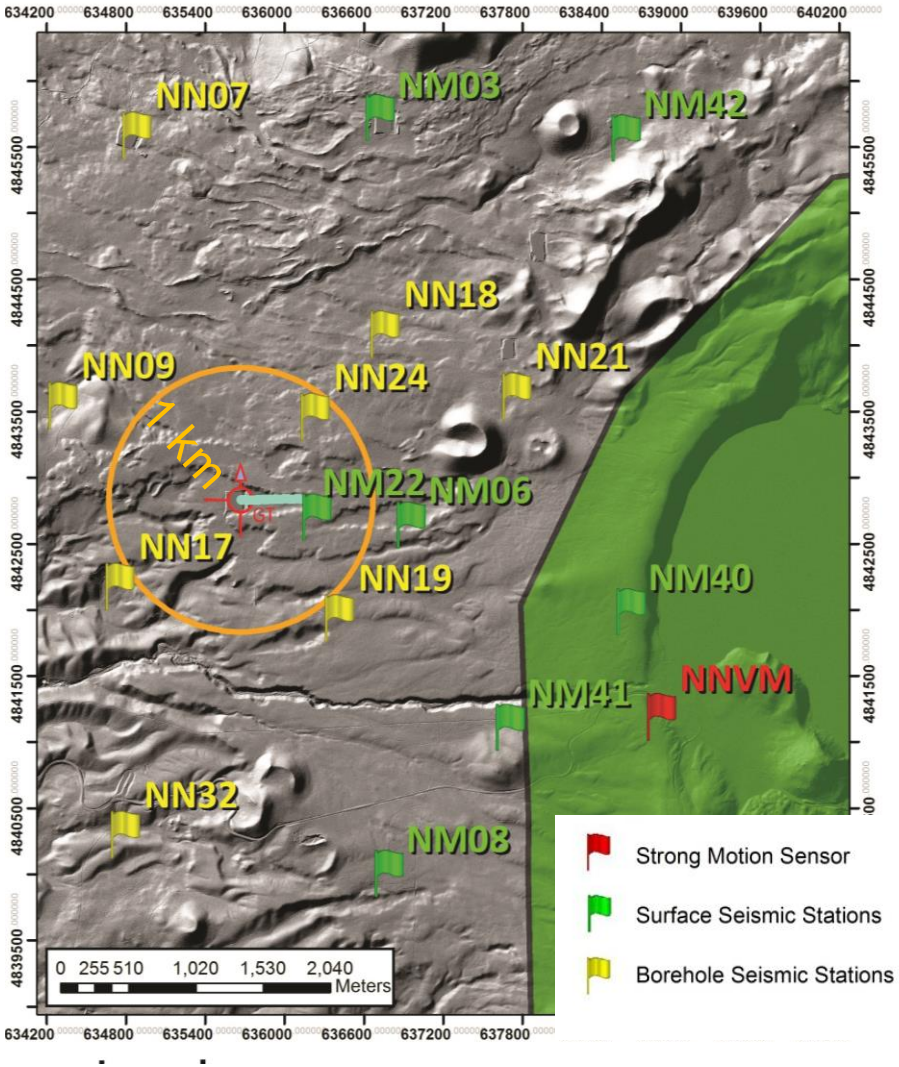
8 borehole (250 m deep) geophones

7 surface geophones

Real-time telemetry

Strong motion [illegible] t building

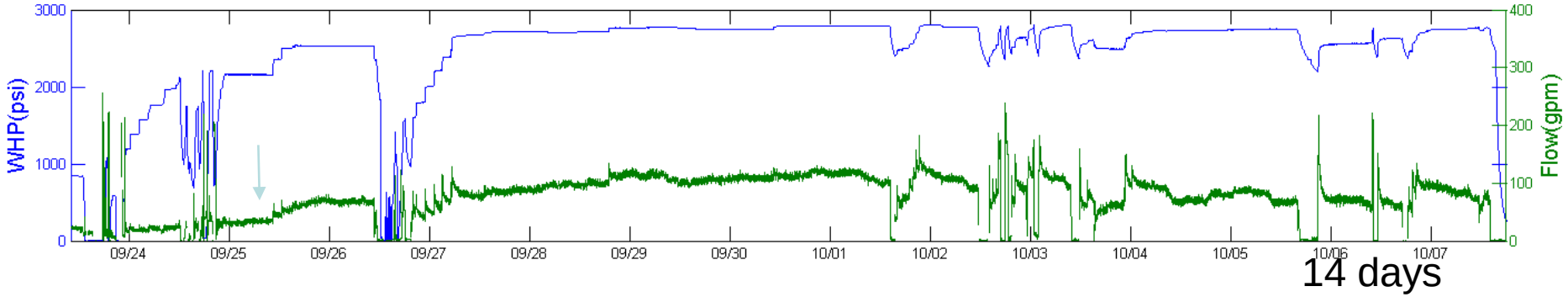
2 Hz, 3 component geophones



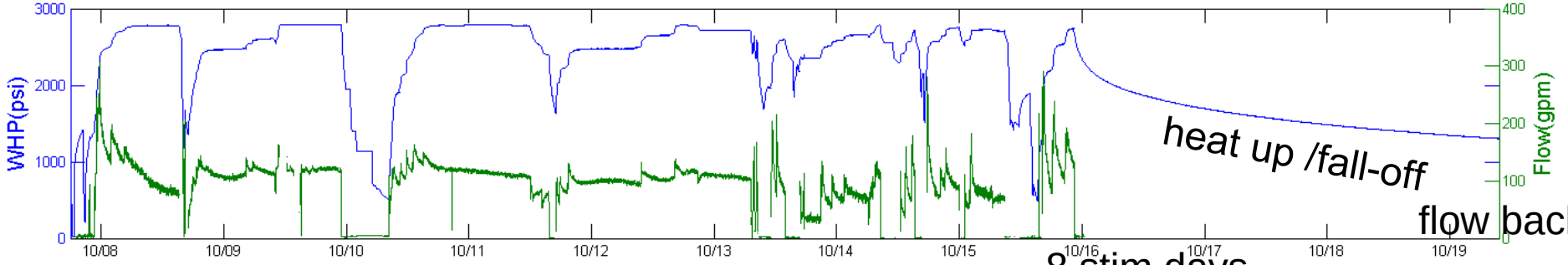
Electric Centrifugal Stimulation Pumps

Wellhead pressure and flow rate during stimulation

Round 1 (Sept 23- Oct 15)

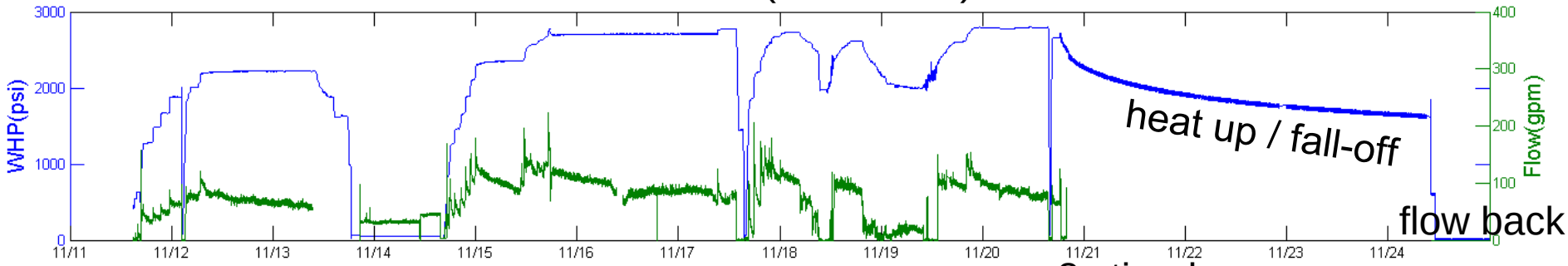


14 days



8 stim days

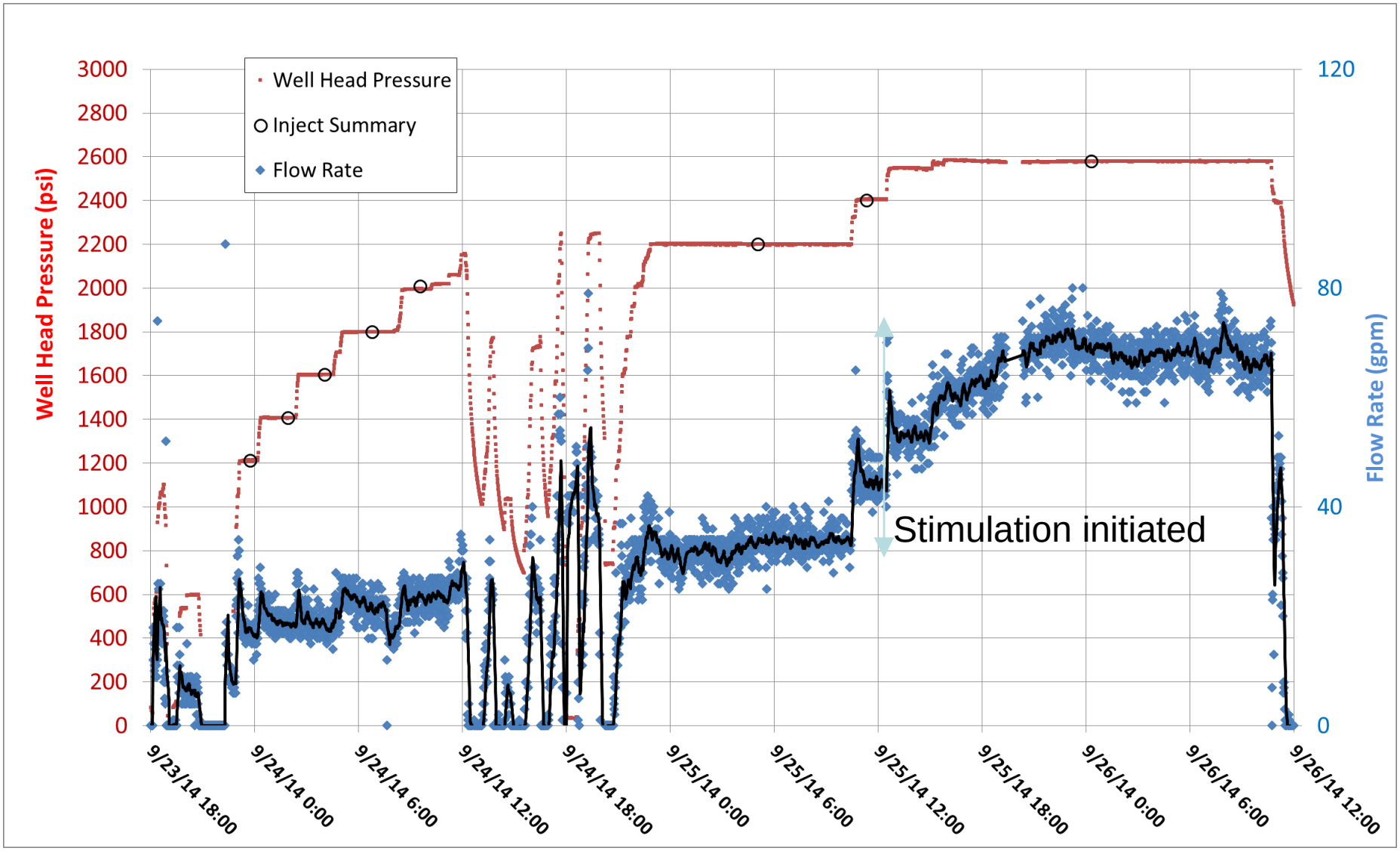
Round 2 (Nov 11-20)



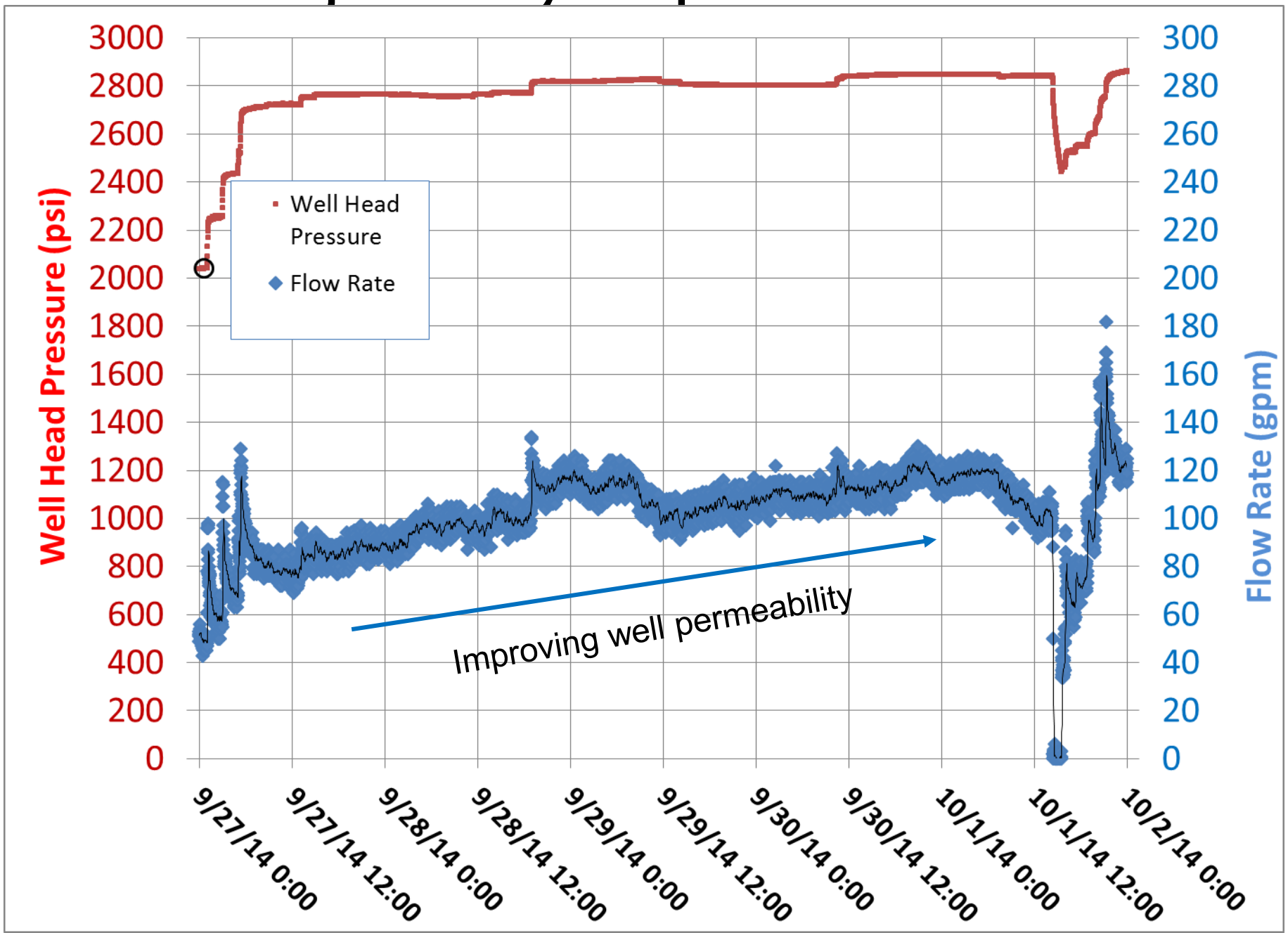
8 stim days

srt = step-rate test

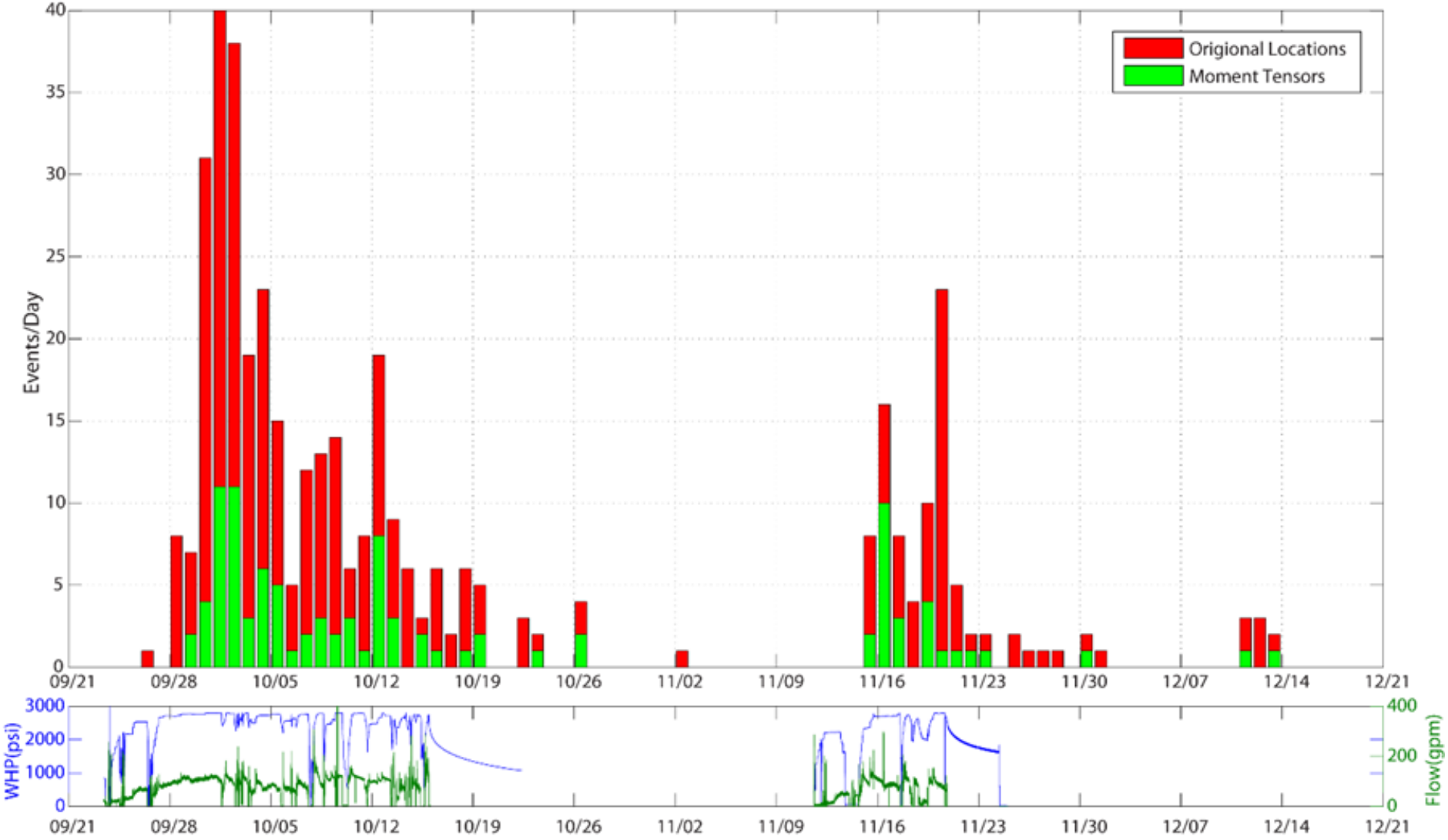
Stimulation Start



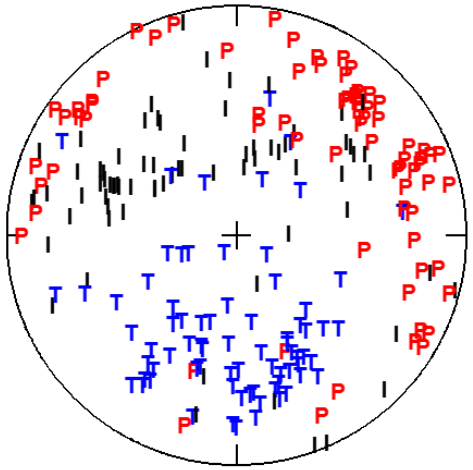
Injectivity Improvement



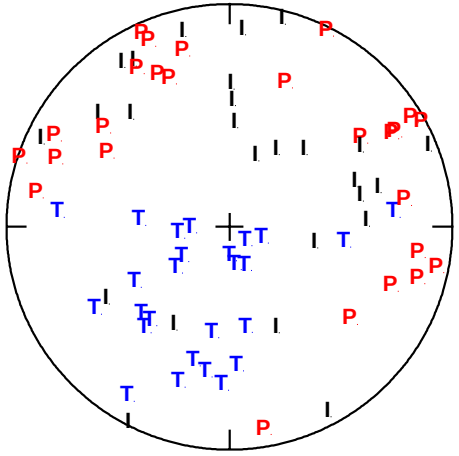
Seismicity Rate



Moment Tensor: P&T axis analysis



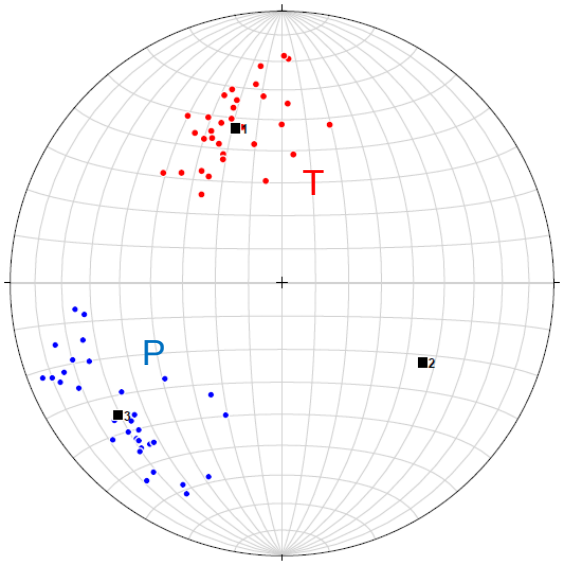
All MTs, 1st Round
N=75

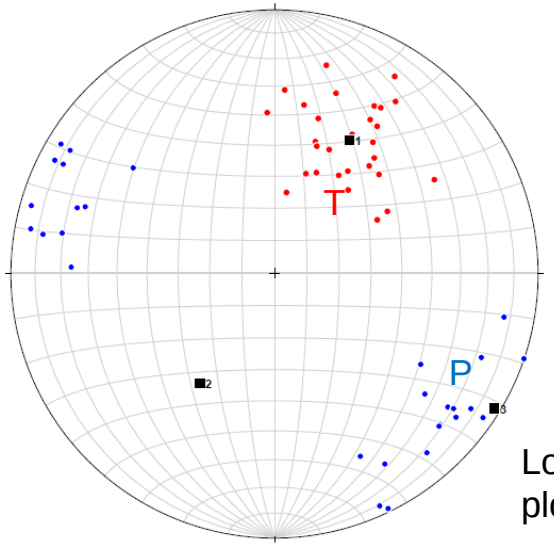


All MTs, 2nd Round
N=25

Upper hemispheres plots

P&T axis sets

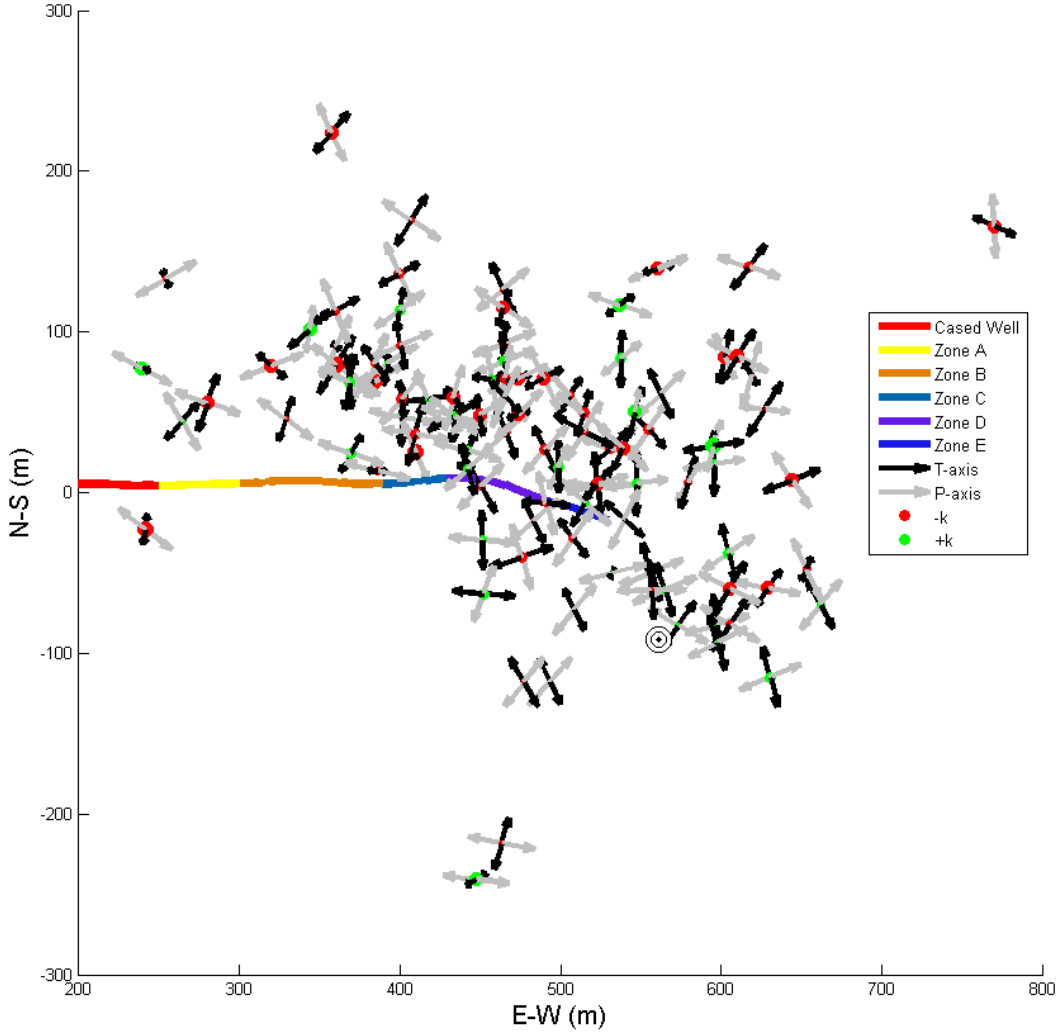


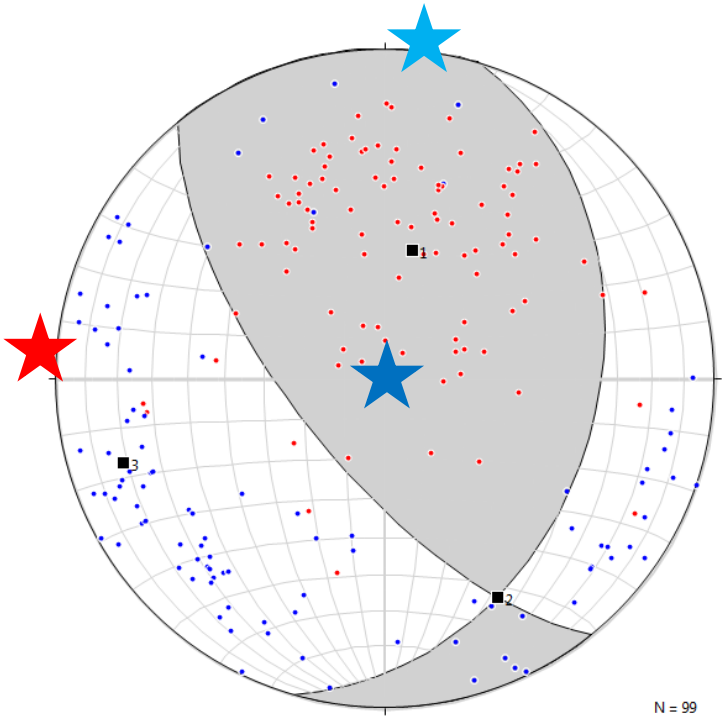


Lower hemispheres plots

	Set 1	Set 2
N (R1+R2) = tot	32 + 0 =32	18 + 10 = 28
Abs(k)<0.15	22 double couples	10 double couples
k < -0.15	5 implosive	16 implosive
k > 0.15	5 explosive	1 explosive
Relative to 10/4 am Mw 1.6, 1.6, 2.1	50% before - Includes first Mw 1.6	80% after 10/4 –Includes Mw 1.6, 2.4

All P&T Axes





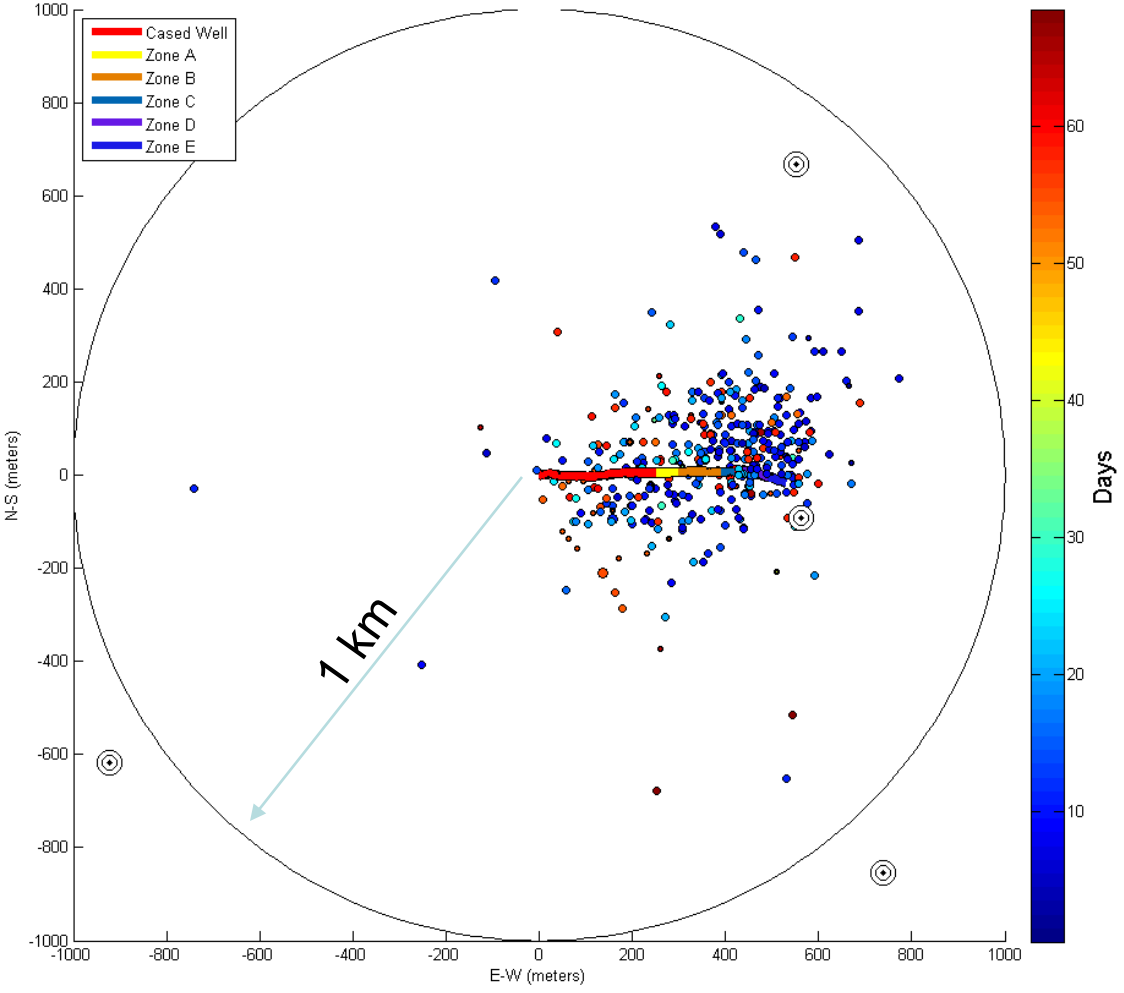
Axis	Trend	Plunge
1. σ_3	012.2	57.4
2. σ_2	152.8	26.3
3. σ_1	252.0	17.9

T-axes from BHTV breakouts

P-axis if strike-slip regime

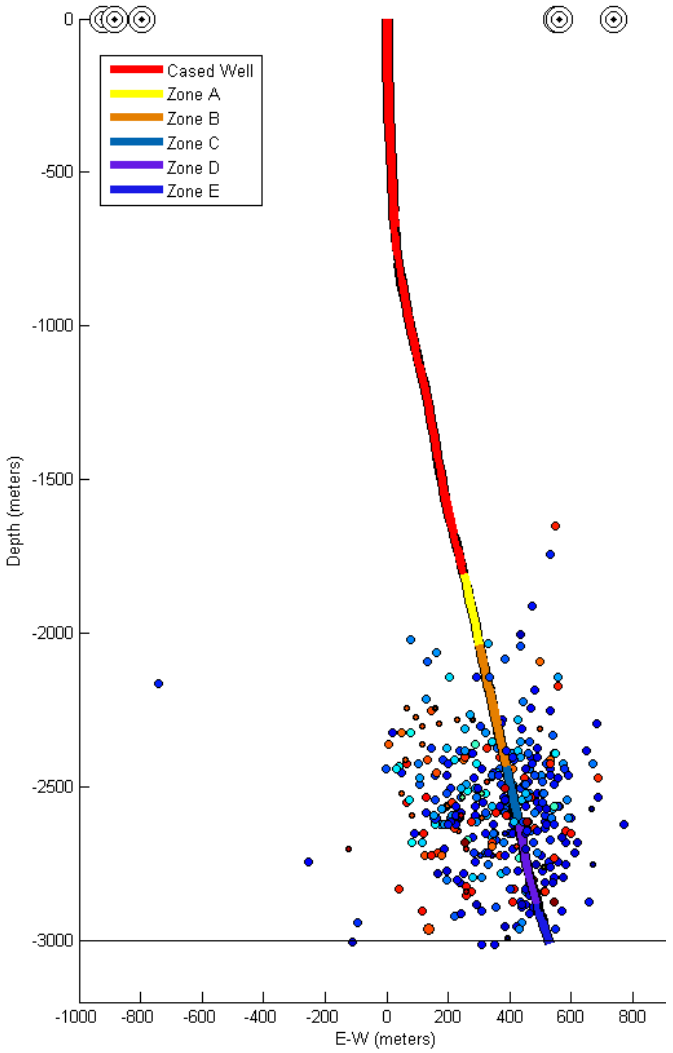
P-axis if normal regime

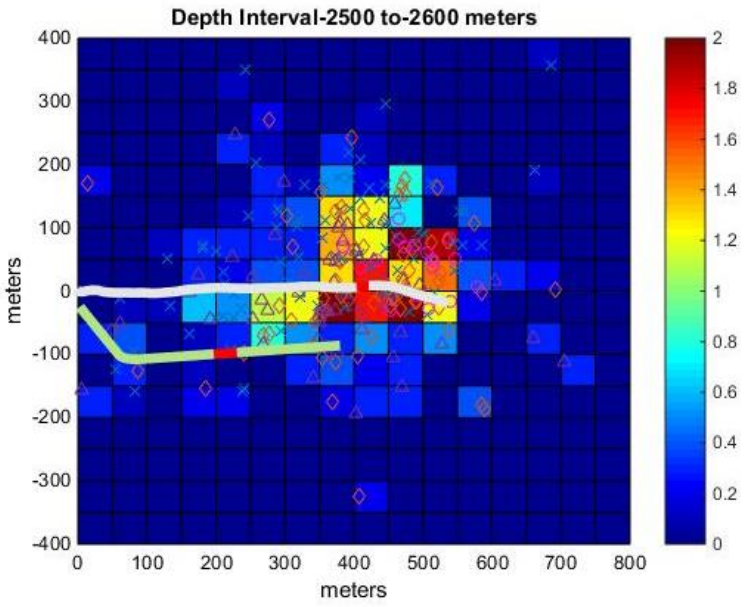
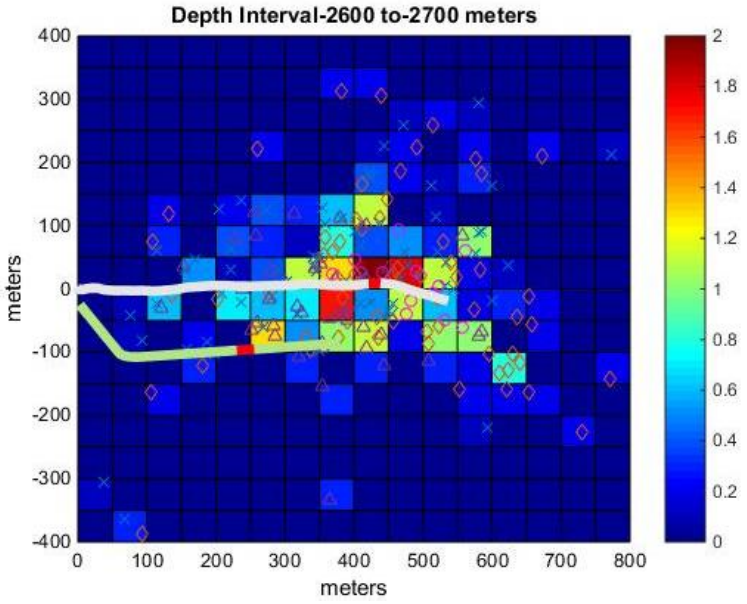
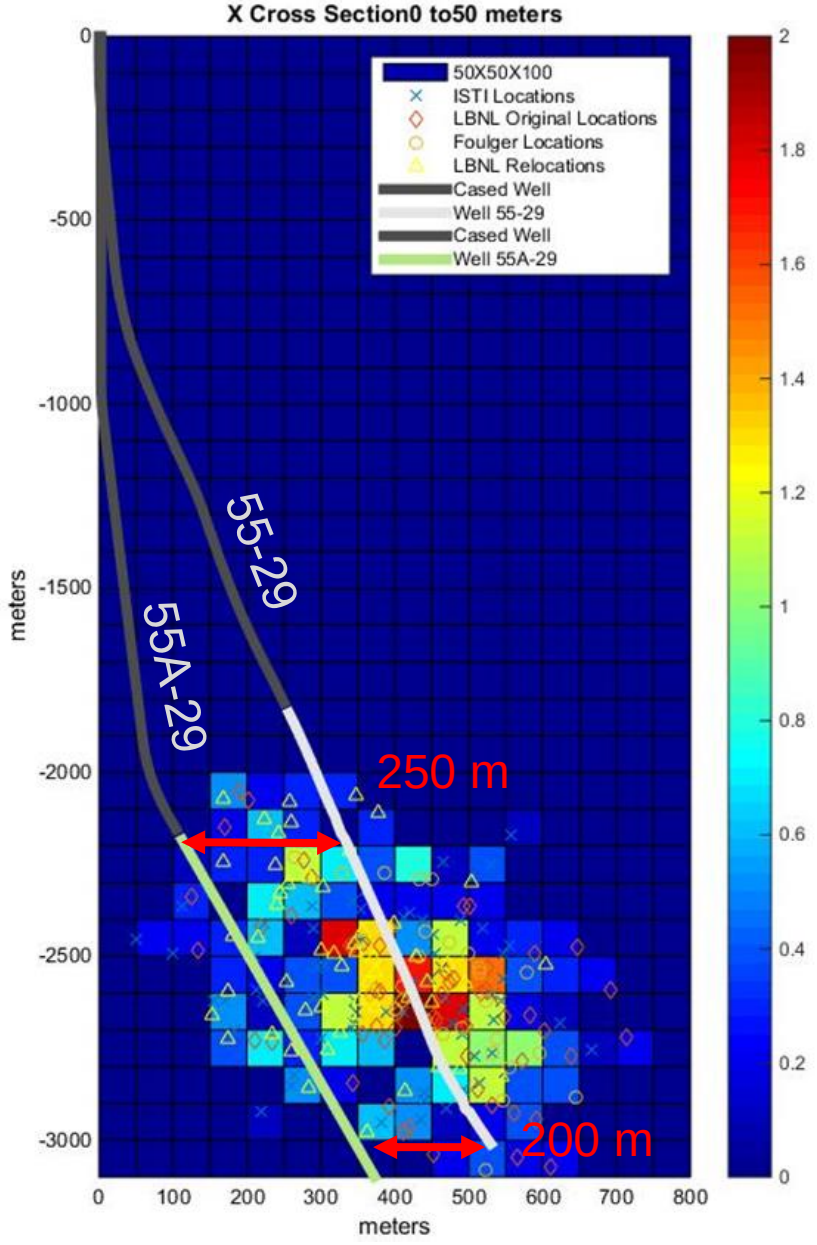
400 Microseismic Event Locations (hand-picked)



Map View

ISTI



North View

Production Well Course and Target