Injection Induced Seismicity and Geothermal Energy:

Lessons Learned from Past Injection Projects

Induced Seismicity in Energy Technologies
June 15, 2012

Testimony of Susan Petty, AltaRock Energy, Inc.

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Injection Induced Seismicity Examples

- Rocky Mountain Arsenal - proof of theory
  - Hseih and Bredehoeft (1981) *JGR*
- Paradox V. Brine Injection – large V, high P, continuous
  - Ake *et al*. (2005) *BSSA*
- Soultz – multiple EGS demos with varied results
  - Dorbath *et al.* (2009) *GJI*
- Basel – induced seismicity caused project shutdown
  - Häring *et al.* (2008) *Geothermics*
- Newberry – EGS demonstration planned for mid 2011

Parameters affecting rate and size distribution IIS

- *In situ* stress and natural fluid pressure
- Frictional strength of faults and fractures
- Critical pressure to initiate *hydroshear*
- Tensile fracture pressures (minimum principle stress)
- G-R seismicity relation (b value)
- Characteristics of faults & fractures in the BH
- Well head pressure
- Injection rate, steps, and duration
- Total injected volume

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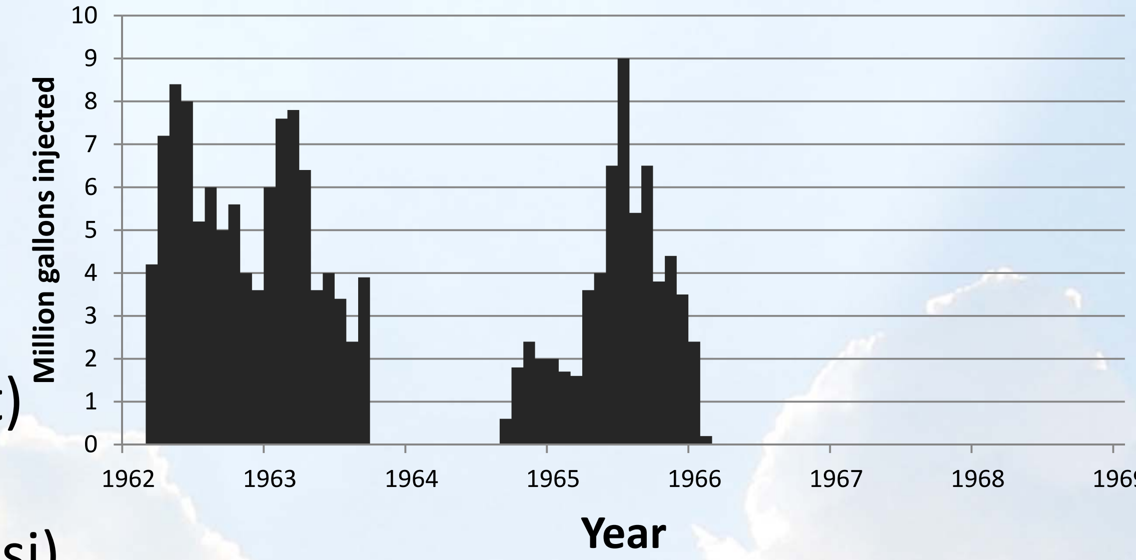
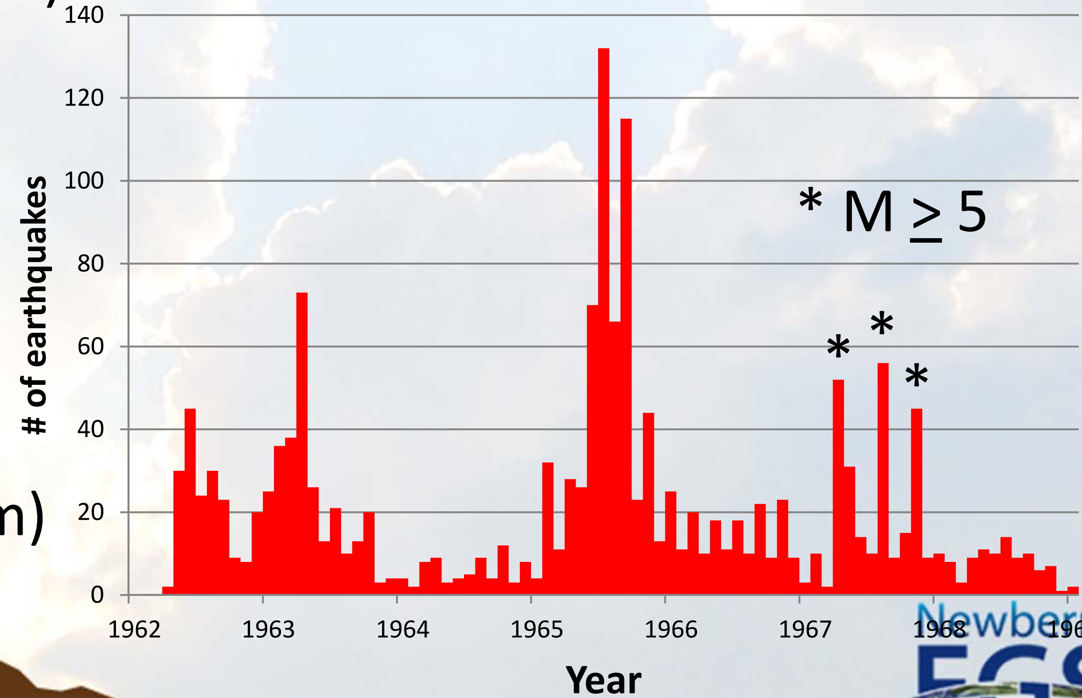
Rocky Mountain Arsenal

- Depth = 3.7 km (12000 ft)
- Fractured gneiss
- Max P = 7.2 MPa (1000 psi)
- Eventual gravity feed
- 4 years of injection





- Max R > 6.3 L/s (250 gpm)
- M_{max} = 5.3

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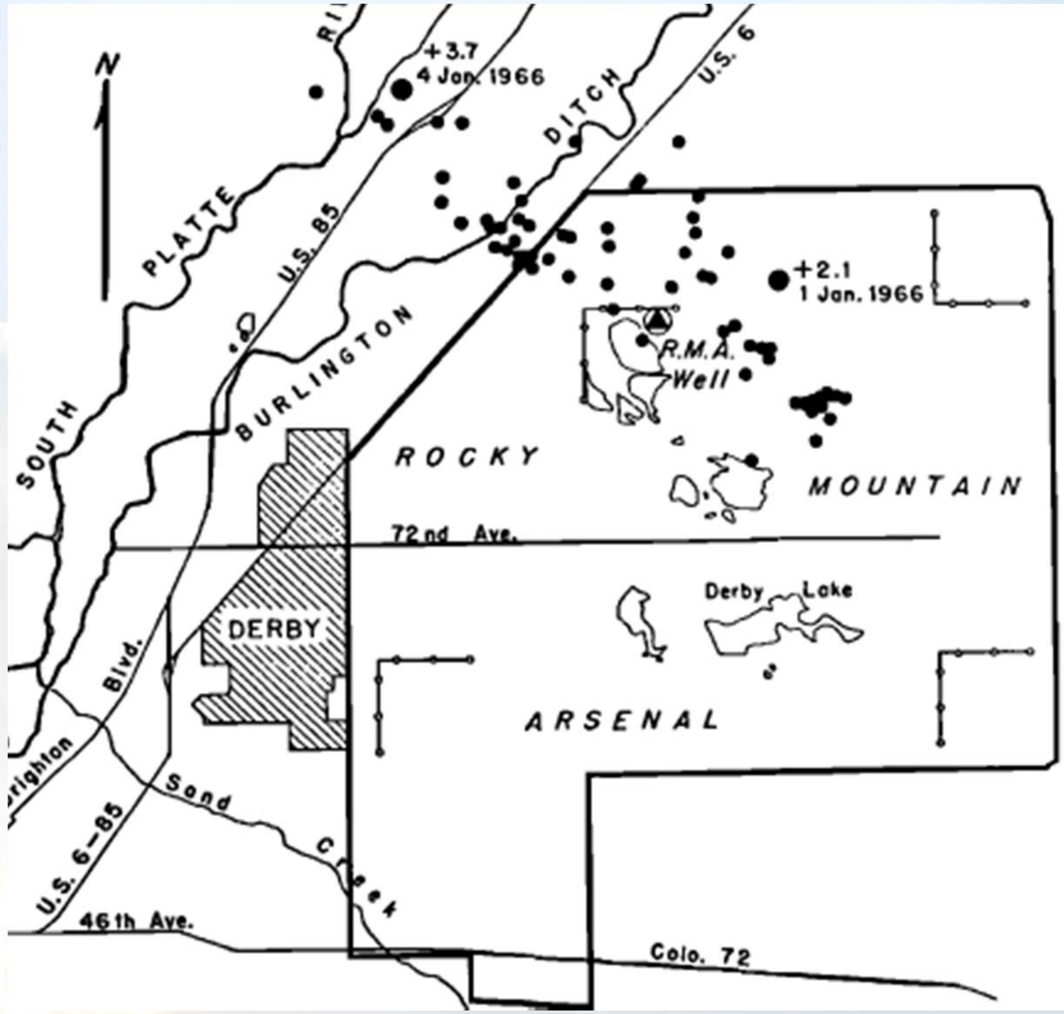
Later Observations

- Natural reservoir was under-pressured (925 m bgs)
- Seismicity didn't stop until WL dropped bgs
- ΔPc = 3.2 MPa (Δ325 m head)
- 25 newspapers reported a similar earthquake in 1882



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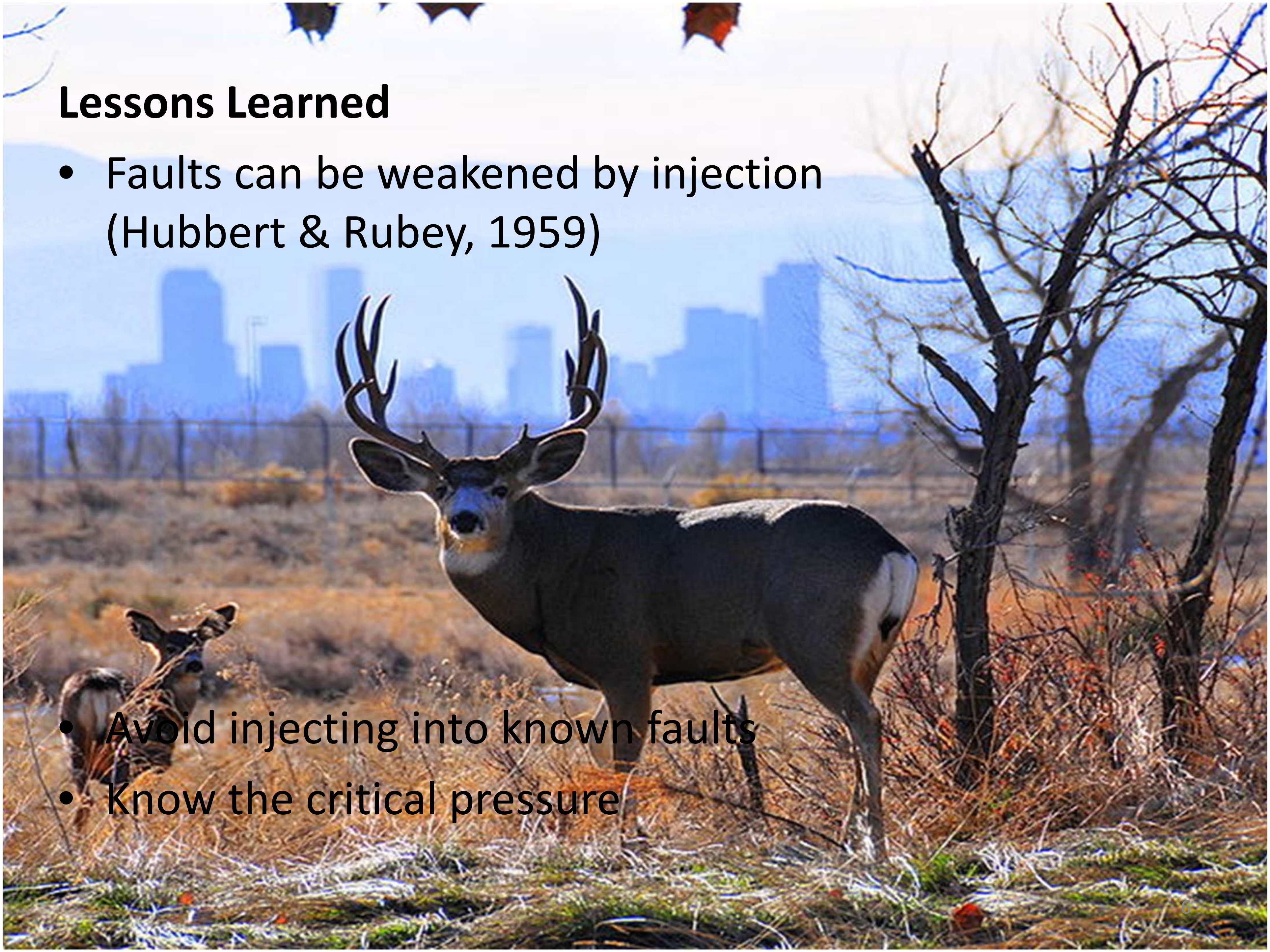
Lessons Learned

- Faults can be weakened by injection (Hubbert & Rubey, 1959)

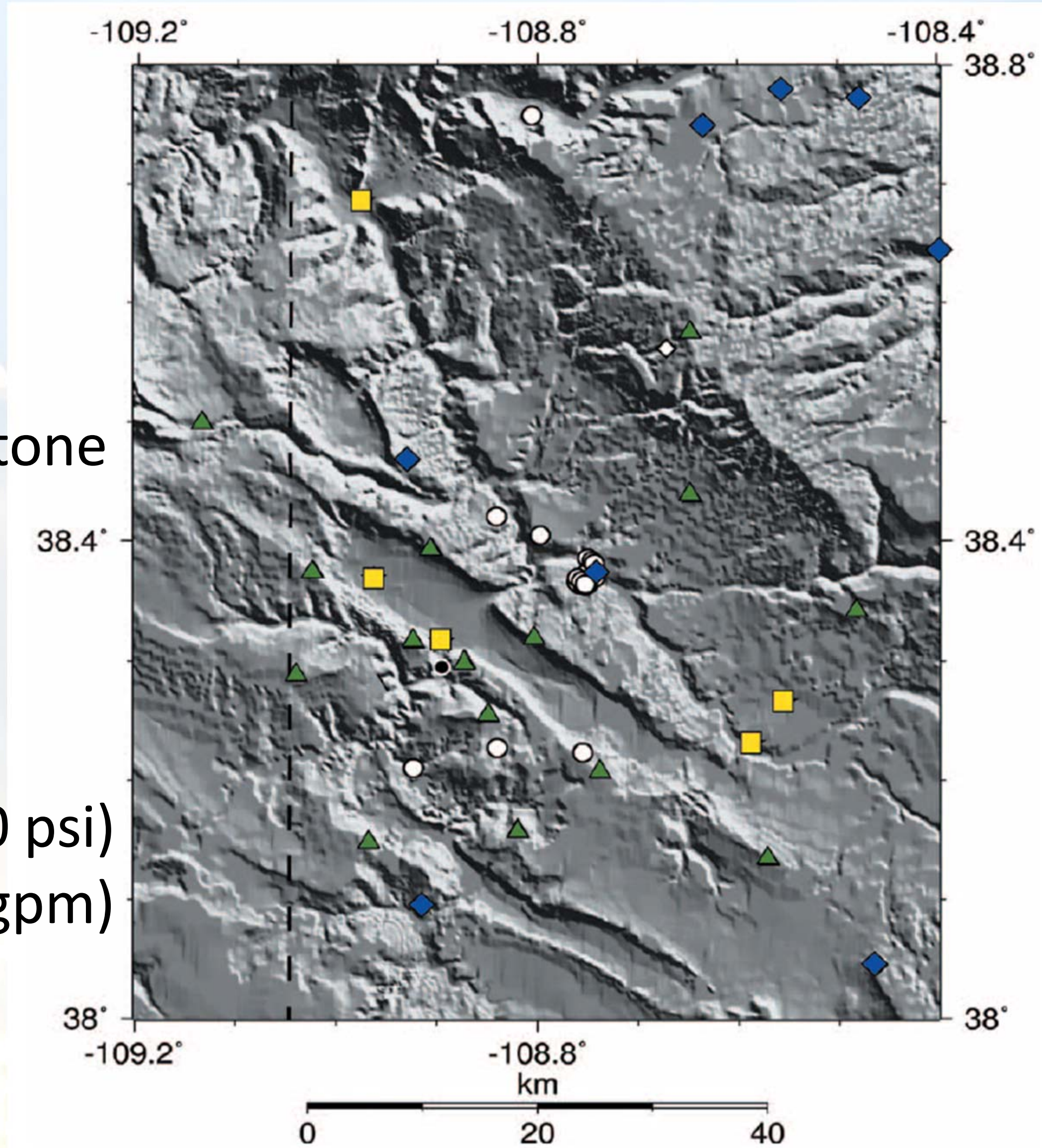
- Avoid injecting into known faults
- Know the critical pressure



Paradox Valley Brine Injection

- Depth = 4.5 km (14750')
- Fractured dolomitic limestone
- Continuous since 1996

- ΔPc = 17 MPa (2465 psi)
- Max P_{wh} = 34.2 MPa (4960 psi)
- Max Rate = 21.5 L/s (340 gpm)



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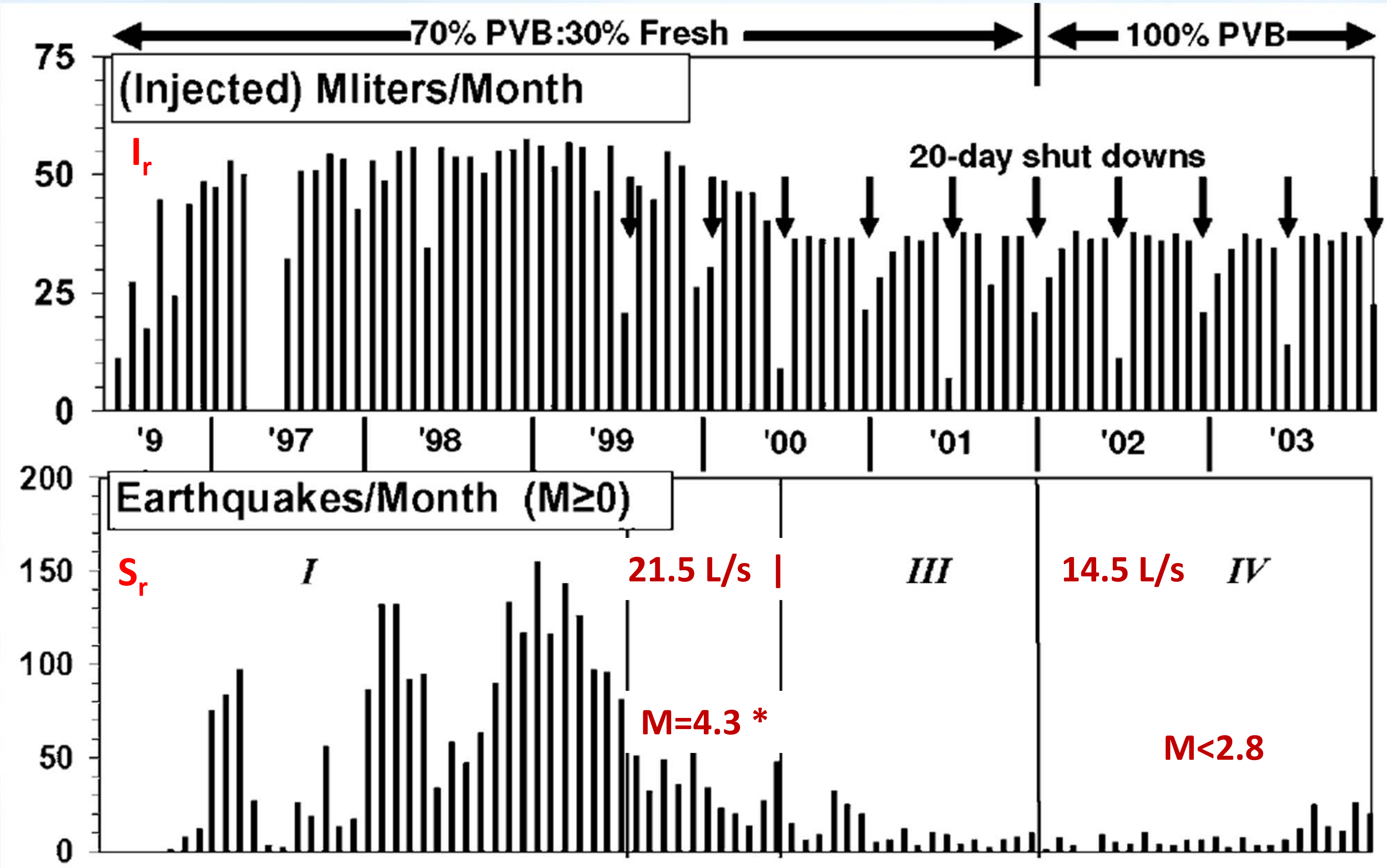

$S_r = 0.27\, I_r - 3.1$ R=96%

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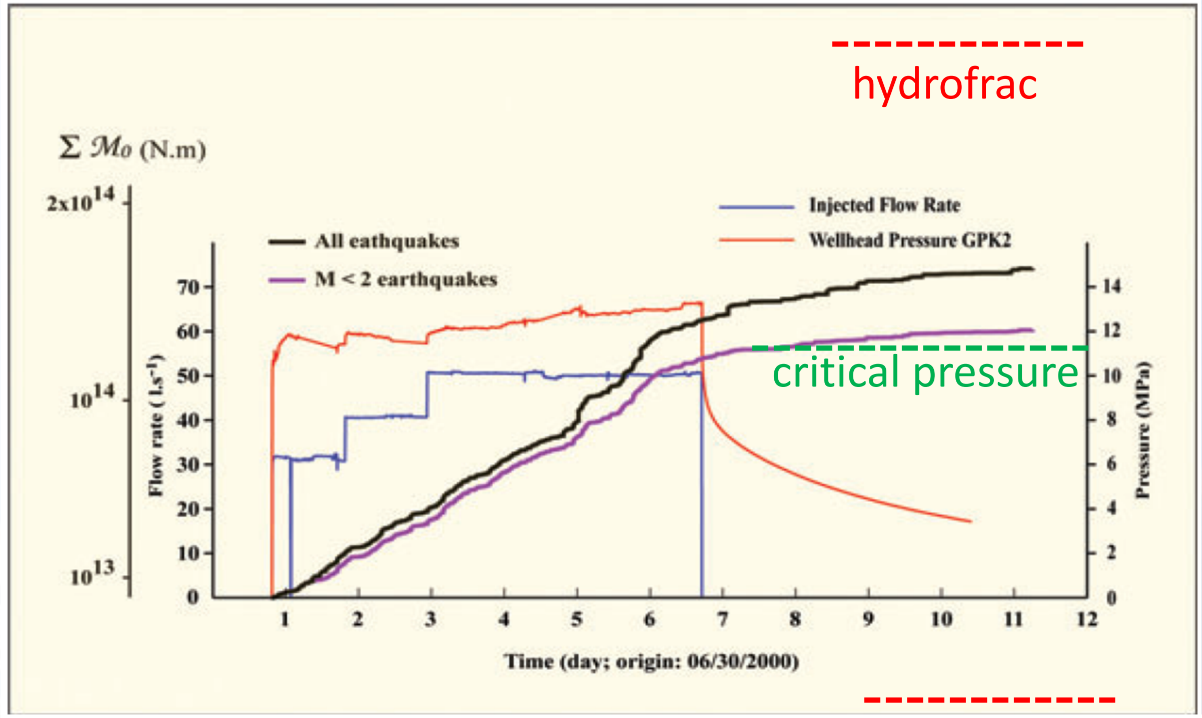
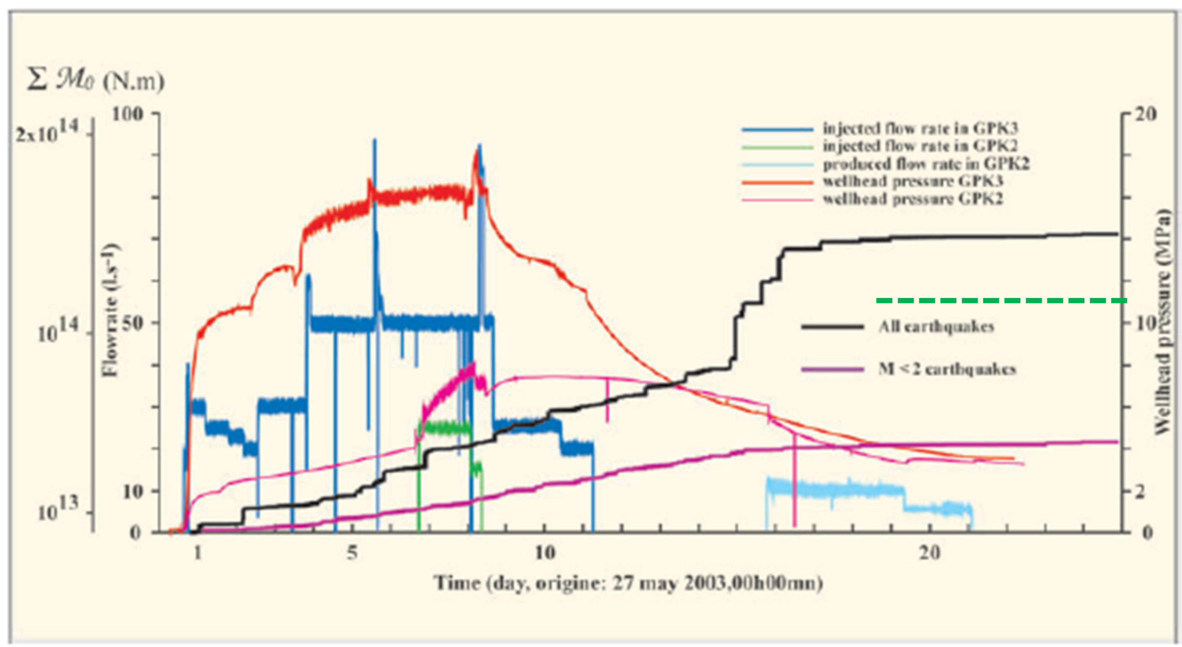
Soultz

- 3 deep stimulations
- Depth = 5.0 km
- Granite

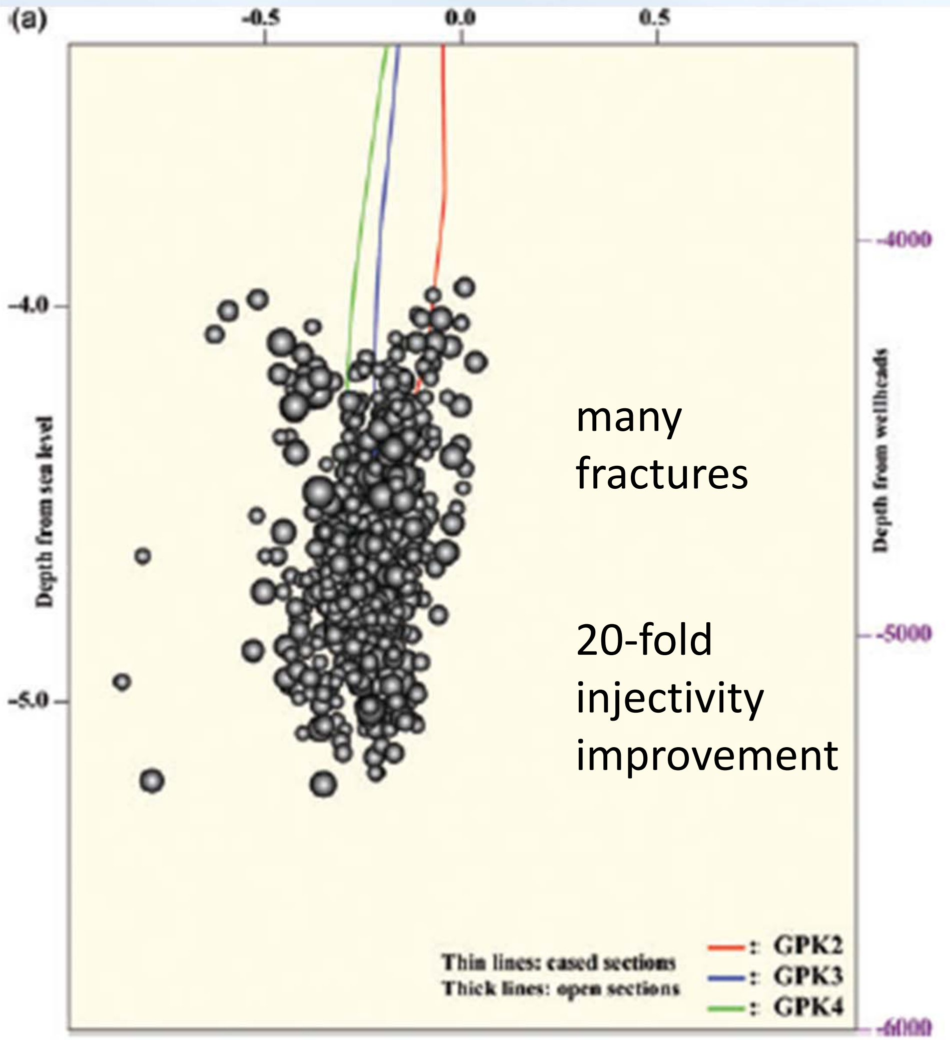
- $\Delta P_c \approx 12$ Mpa
- Max $P_{wp} \approx$ 14-16 MPa
- Max rate = 50 l/s
- 7-11 days of injection





Structure of GPK2 vs. GPK3

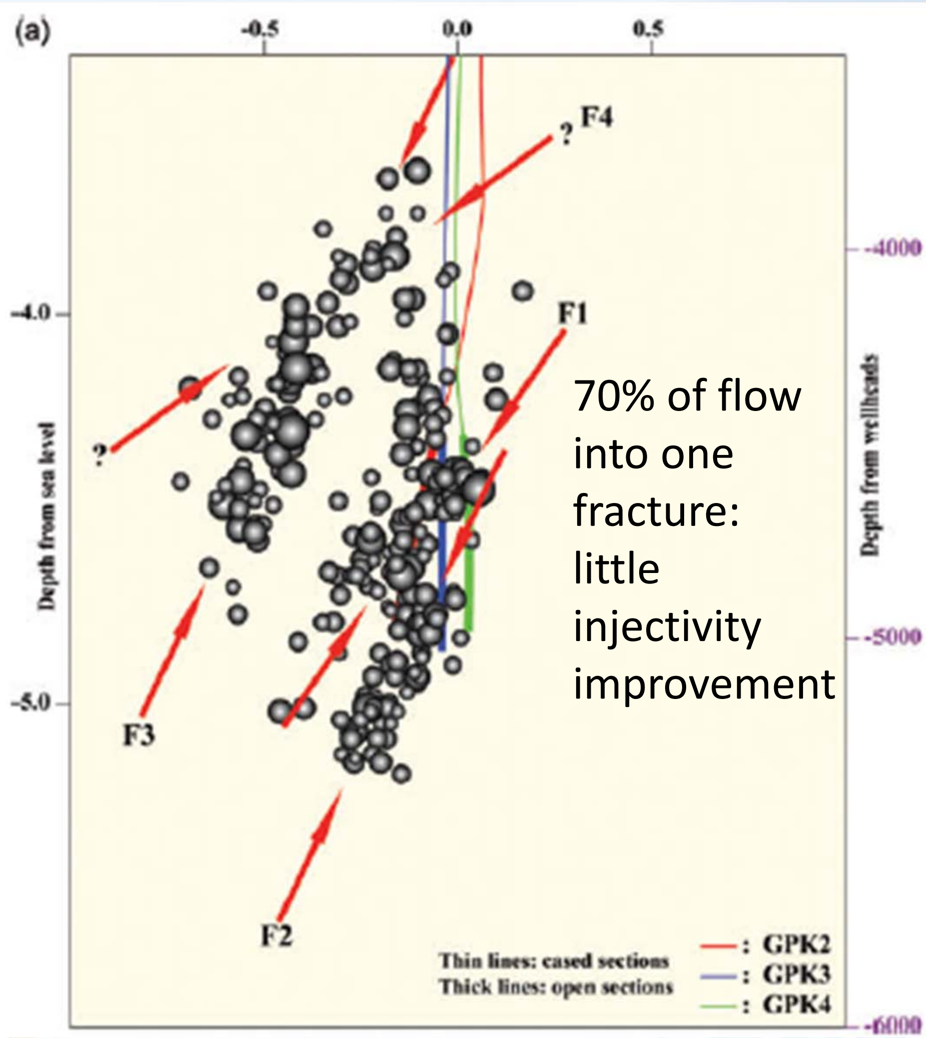
Side view of GPK2 stim



many fractures

20-fold injectivity improvement

Side view of GPK3 stim



70% of flow into one fracture: little injectivity improvement

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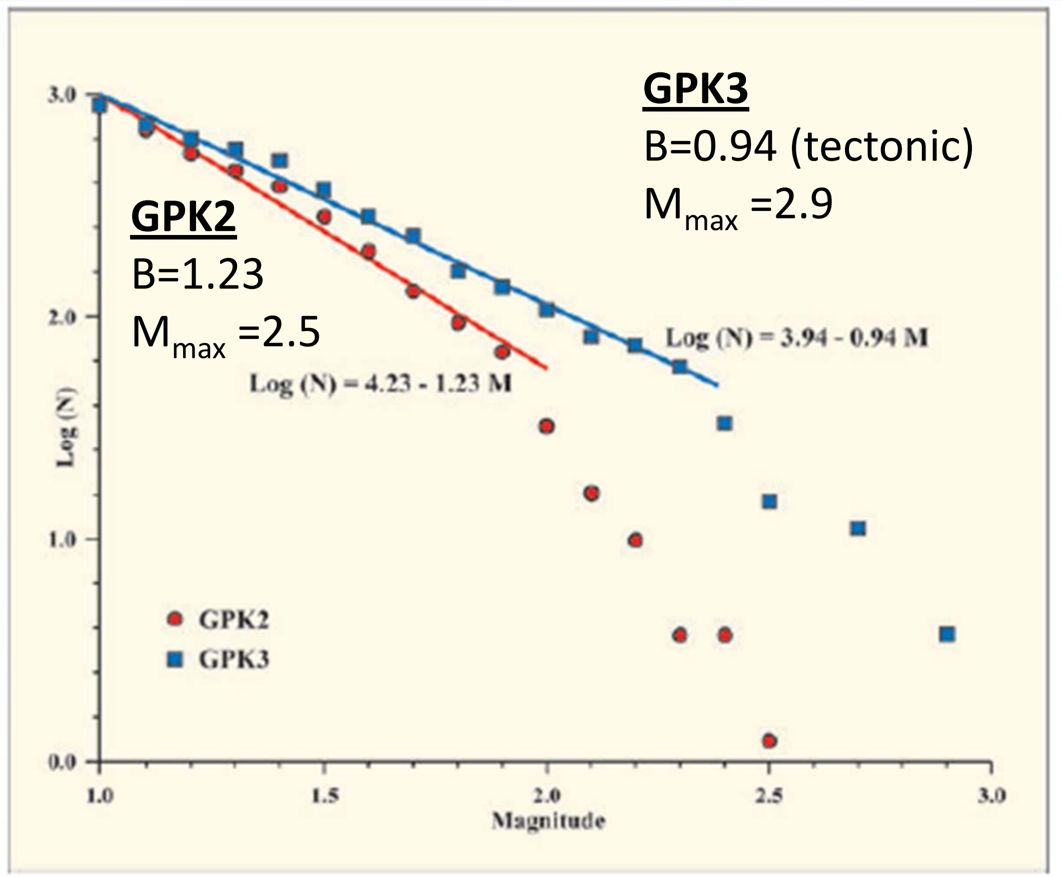

Lessons Learned

- Avoid injecting into fracture zones with already high transmissivity (GPK3)
- Higher b-value results in lower maximum event size and better fracture network for EGS

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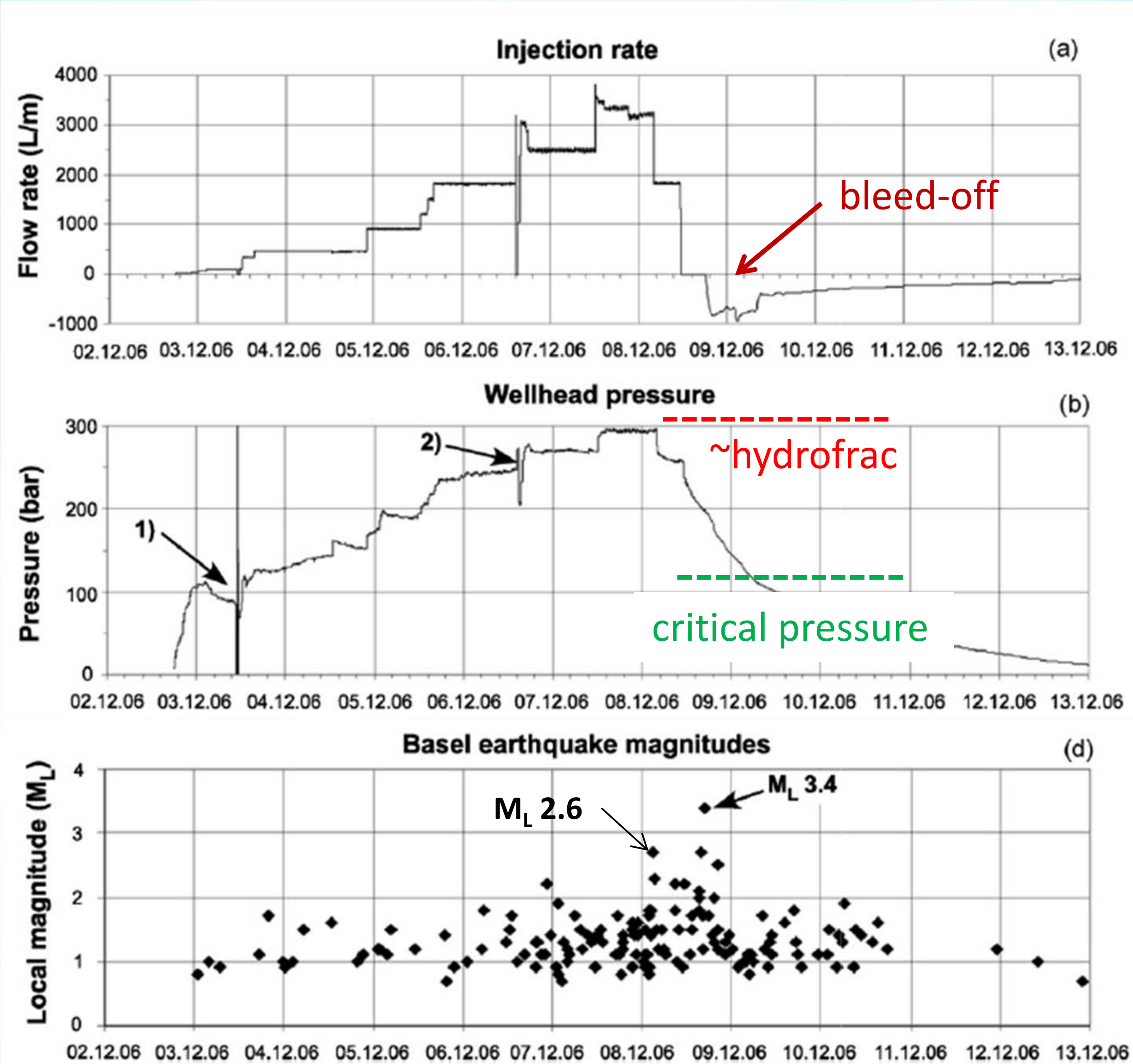
Basel DHM

- Depth = 5 km
- Granite

- $\Delta Pc \approx 11$ Mpa
- Max P_{wh} = 29.6
- Max Rate = 55 L/s
- M_{max} = 3.4



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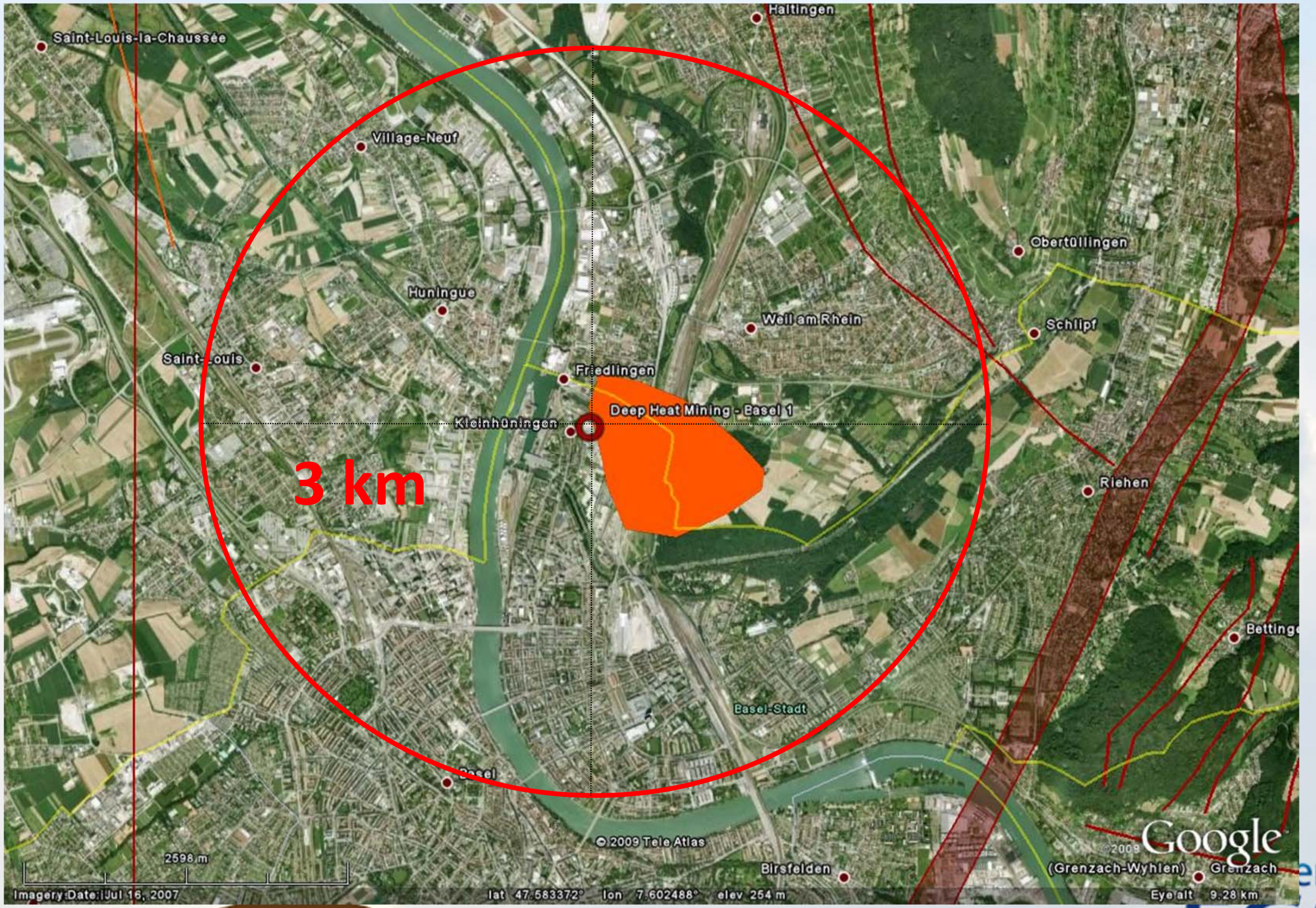
Basel Deep Heat Mining Project



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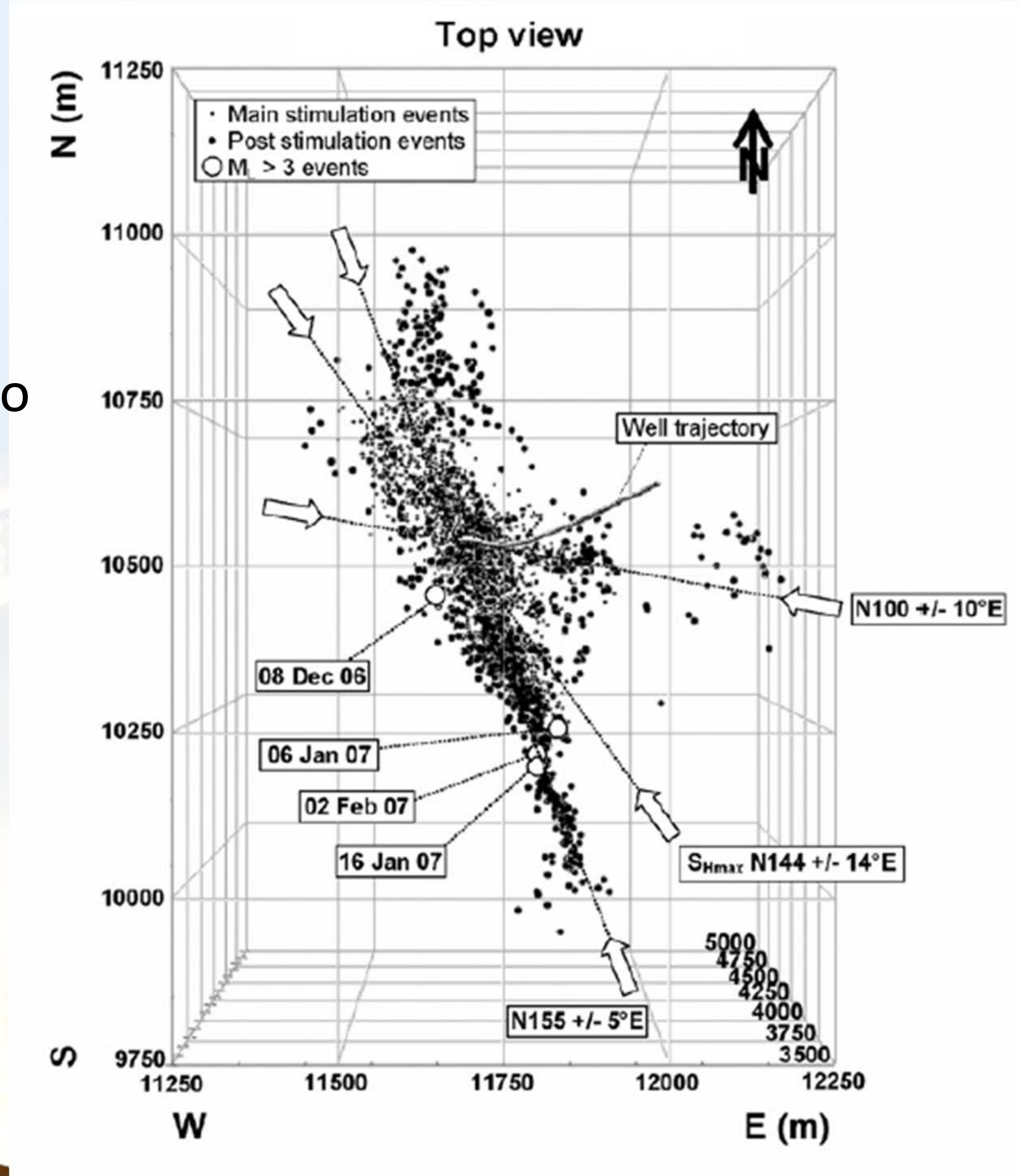
Lessons Learned

- Avoid injecting into faults
- If pressure builds, wait to increase rate
- Bleed off works to slow felt IIS



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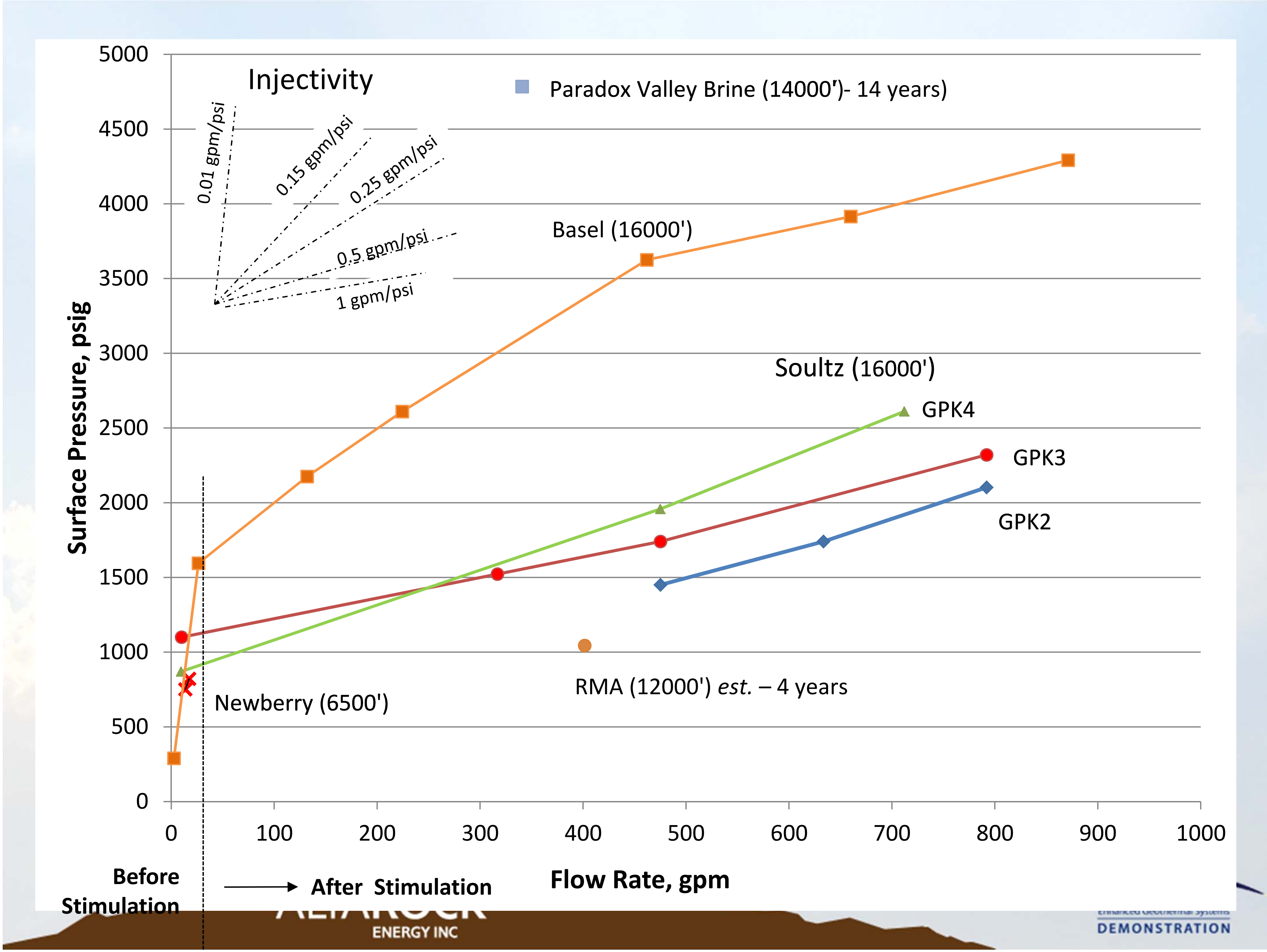

Injectivity
0.01 gpm/psi
0.15 gpm/psi
0.25 gpm/psi
0.5 gpm/psi
1 gpm/psi
Paradox Valley Brine (14000')- 14 years)
Basel (16000')
Soultz (16000')
GPK4
GPK3
GPK2
RMA (12000') est. – 4 years
Newberry (6500')
Surface Pressure, psig
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
100
200
300
400
500
600
700
800
900
1000
Flow Rate, gpm
Before Stimulation
After Stimulation
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Theoretical Model (Shapiro et al. 2010)

$$\log N_M(t) = \log Q_c(t) - bM + \{a - \log (CS/N)\}$$

where Σ

- $N_M(t)$ *is number of events greater than M*
- $Q_c(t)$ *is cumulative injected volume*
- *b and a are constants in Gutenburg-Richter relation*
- *Σ , the seismogenic index, is independent of the injection*
- *Σ characterizes the rock mass (seismicity rate, critical pressure, fracture density, and poroelastic coefficient)*
- *Σ can be determined from ongoing stimulation results*

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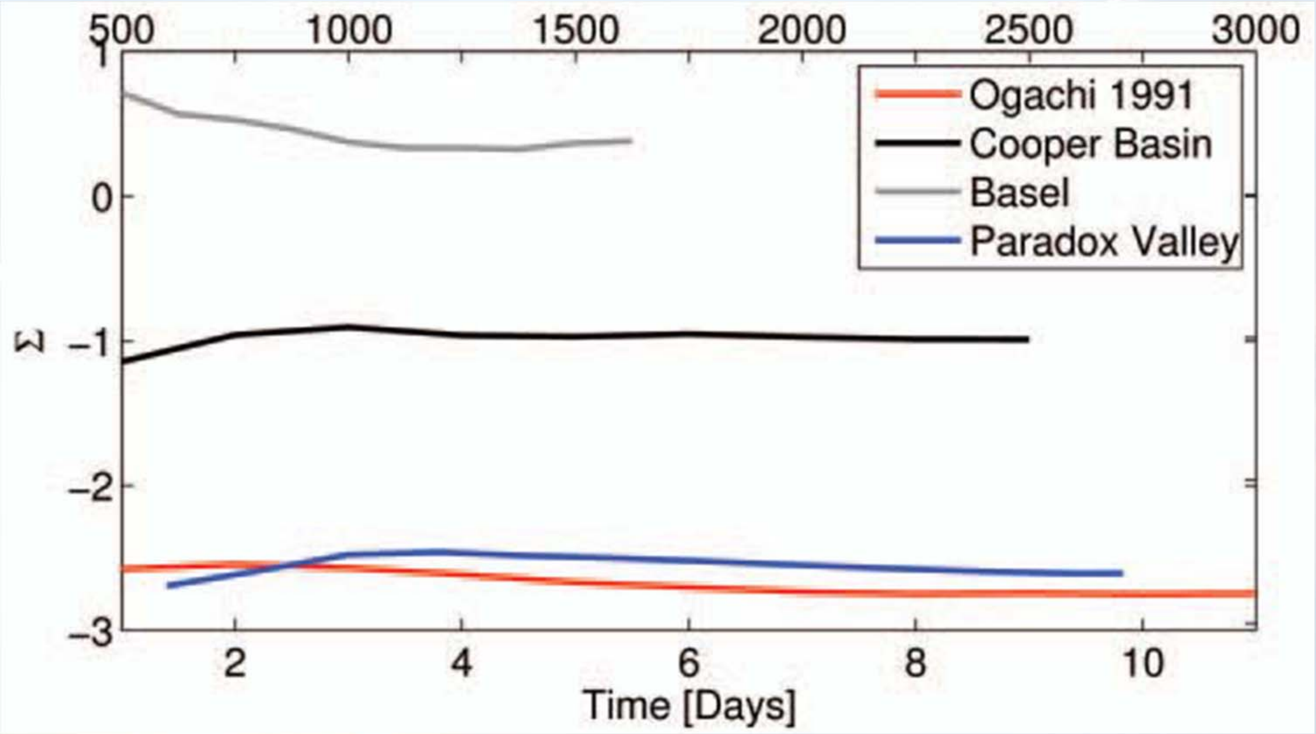
Seismogenic Index for injection projects

the seismicity induced by the same quantity of injected volume will depend upon the inherited local geomechanical setting



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Newberry EGS Demonstration Project Experience: Strategy for Mitigation of Induced Seismicity

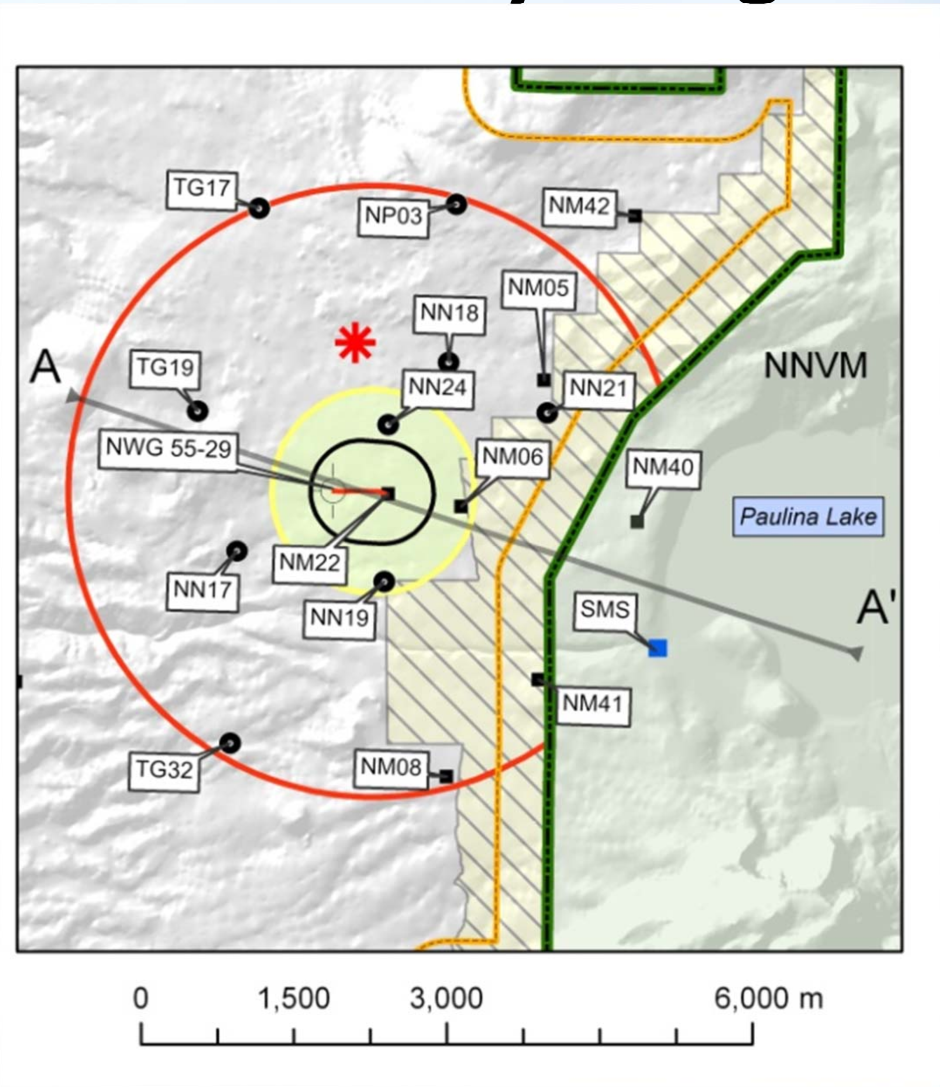
- EGS Demonstration Project with DOE 50% funding
- NEPA permitting process through BLM, Forest Service and DOE
- State and local permitting through BLM as lead agency
- Environmental Assessment includes Induced Seismicity Mitigation Plan

Newberry EGS Demonstration – Pre-stimulation

- Baseline injection tests
- Surface shot calibration survey - USGS
- Monitor background seismicity
- LiDAR collection for neotectonic data
- Examine mud-logs & cuttings for evidence of faults
- Borehole televiewer survey
- Model expected seismicity with AltaStim
- Induced Seismicity Mitigation Plan
- Install permanent borehole MSA
- Monitor background data

Permanent Microseismic Array Design

- **Phase II array – stimulation**
  - 15-station array of borehole and surface sensors
  - Nine borehole sensors at 700-900 feet, with hole-lock
  - Six surface sensors
  - Real-time telemetry
- **Strong motion sensor (SMS) at Paulina Lake Visitor Center**
- **BH drilling and installation: March-June 2012**



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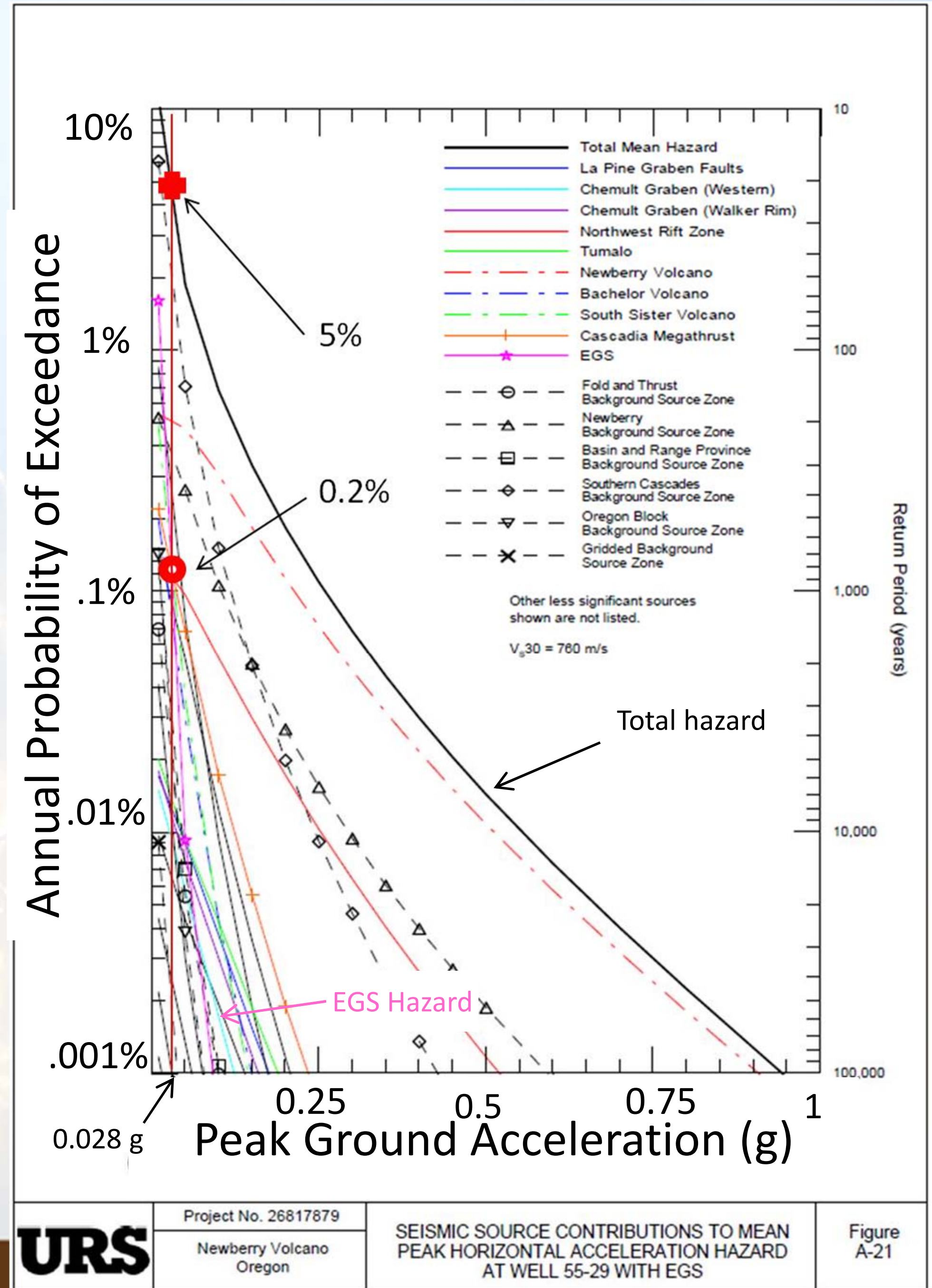
Probablistic Seismic Hazard Assessment

- Methodology: C.A. Cornell (1968)
- Software: HAZ38 (PG&E)
- Analysis: I. Wong, URS
- Seismic Sources
  - Natural and EGS
  - Source geometry
  - Earthquake recurrence
- PGA>0.028 g has cosmetic damage potential, probability of exceeding threshold is
  - 5% per year for natural events
  - 0.2% per year for EGS events



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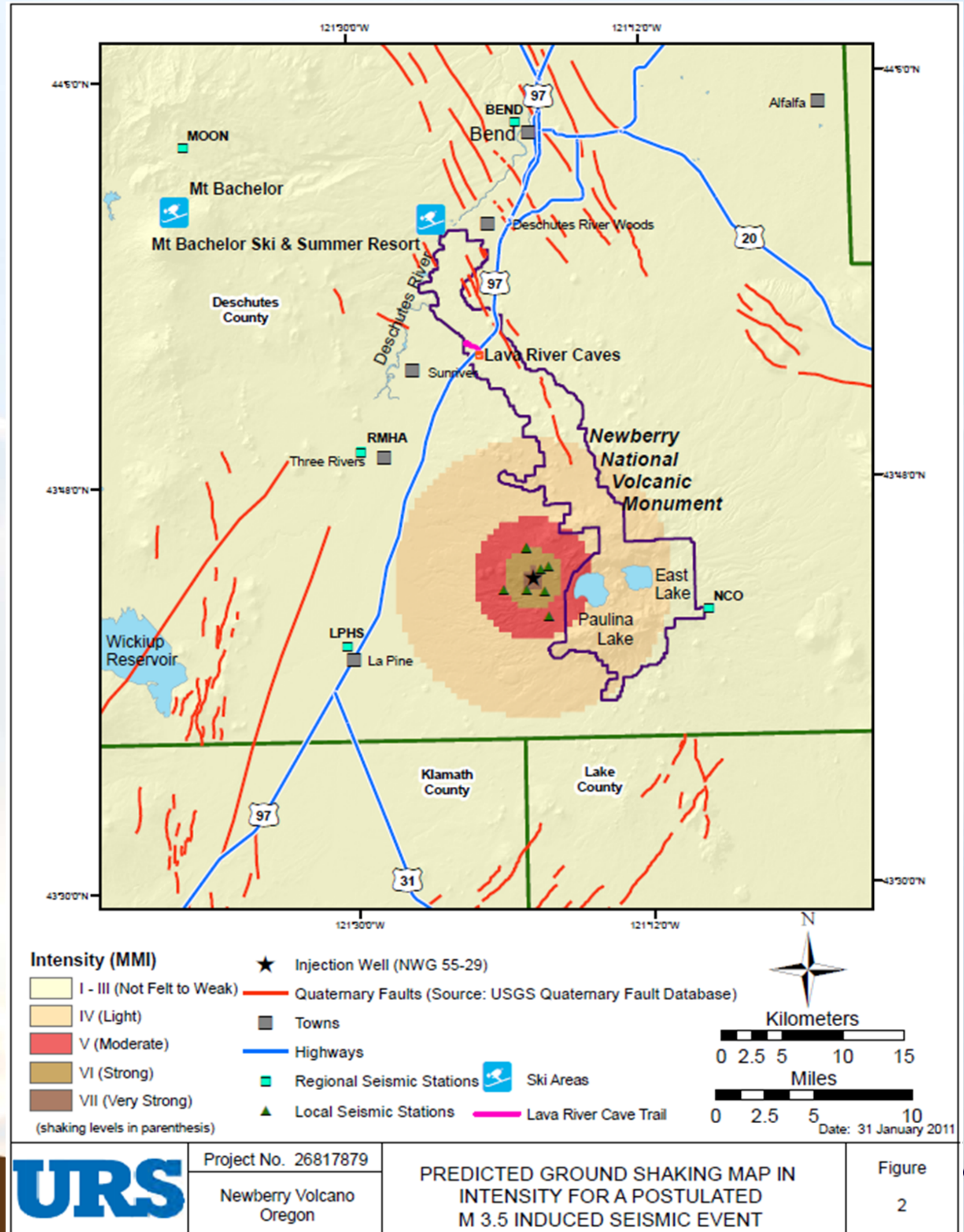
Risk from induced event

- Historical / theoretical maximum magnitude = 3.5-4.0
- M_w 3.5 probability < 0.3% within 30 day stimulation period
- Shake Map shows predicted shaking from M 3.5 at well
- Nearest structures, cabins in NNVM: MMI V (felt, light damage potential)
- Nearest town MMI<III (barely felt, no damage potential)



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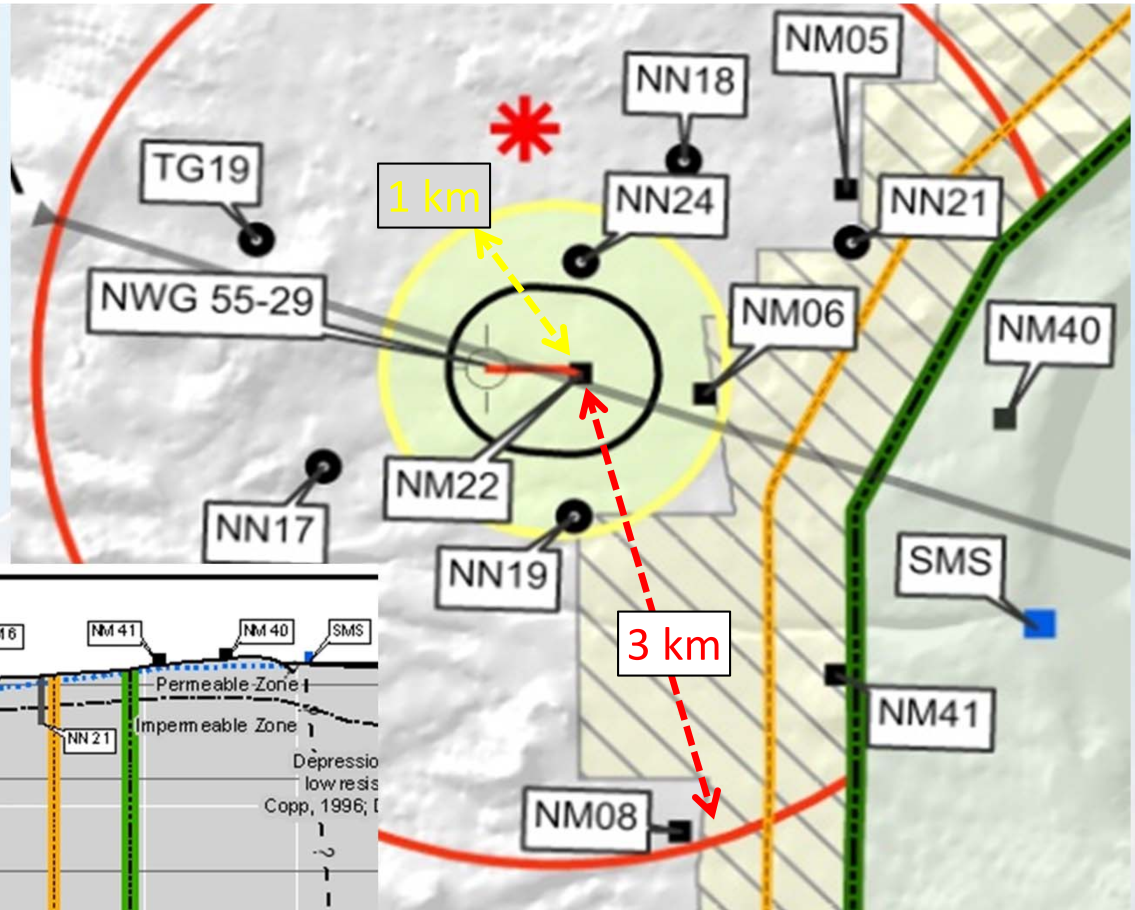
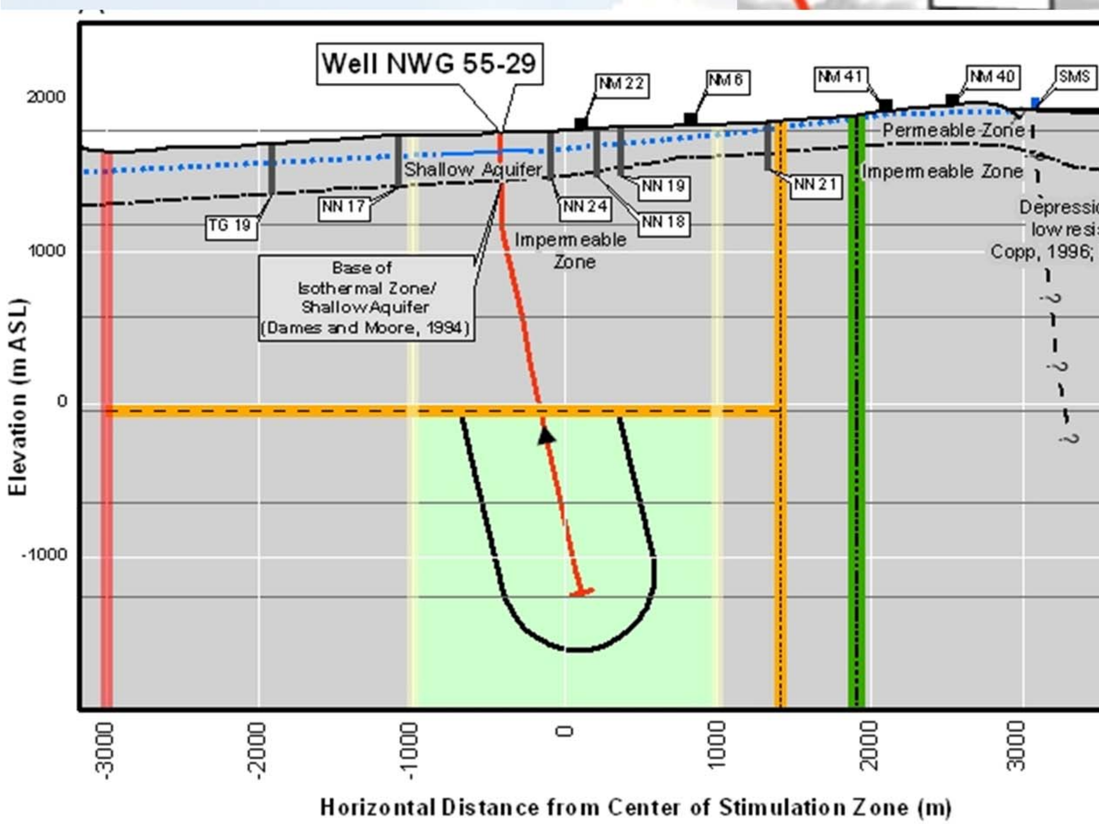
Seismic Triggers

- Outliers
  - horizontal
  - Vertical
  - NNVM





- Magnitude
- PGA on SMS

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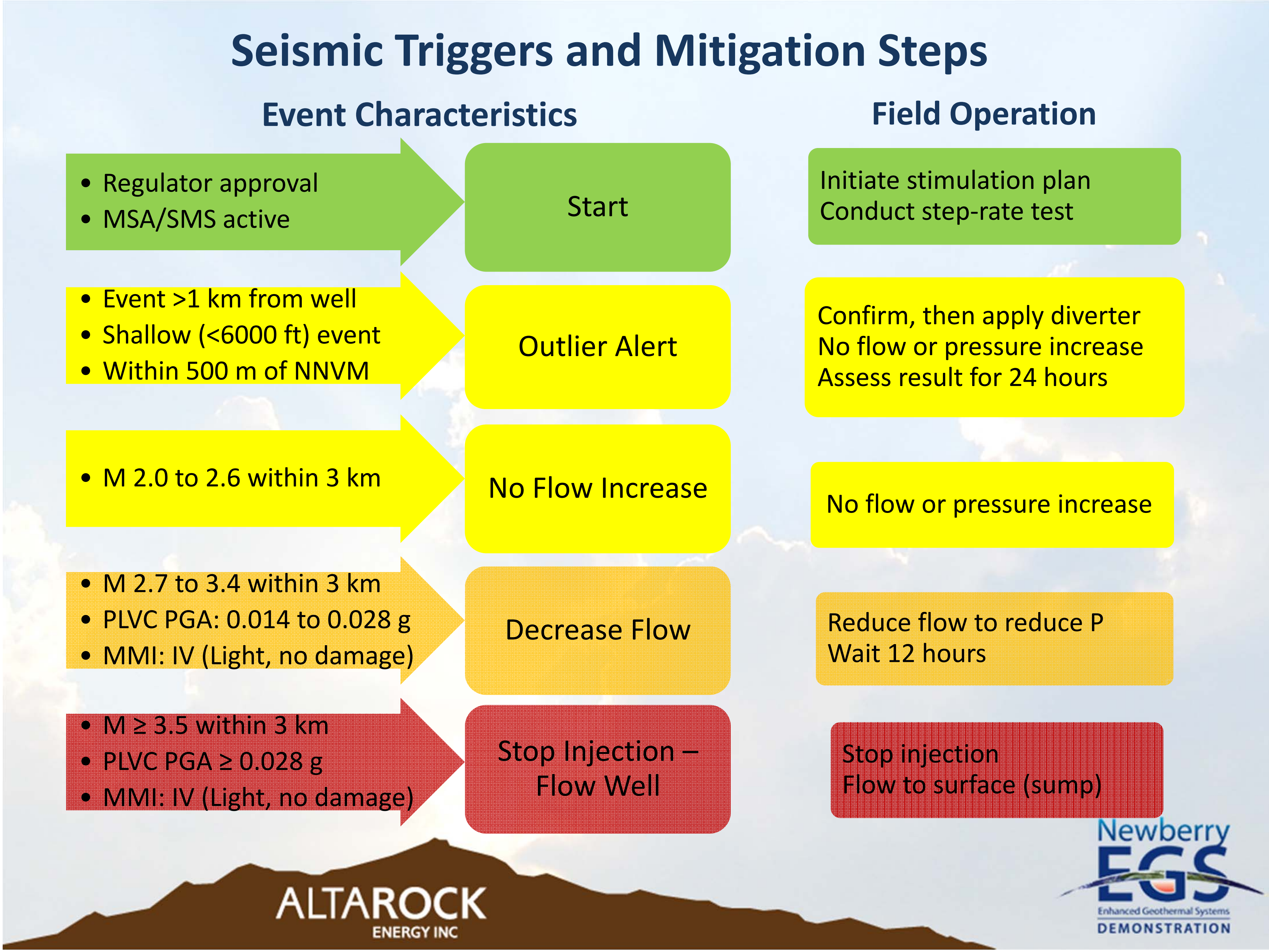
Seismic Triggers and Mitigation Steps
Event Characteristics
Field Operation
• Regulator approval
• MSA/SMS active
Start
Initiate stimulation plan
Conduct step-rate test
• Event >1 km from well
• Shallow (<6000 ft) event
• Within 500 m of NNVM
Outlier Alert
Confirm, then apply diverter
No flow or pressure increase
Assess result for 24 hours
• M 2.0 to 2.6 within 3 km
No Flow Increase
No flow or pressure increase
• M 2.7 to 3.4 within 3 km
• PLVC PGA: 0.014 to 0.028 g
• MMI: IV (Light, no damage)
Decrease Flow
Reduce flow to reduce P
Wait 12 hours
• M ≥ 3.5 within 3 km
• PLVC PGA ≥ 0.028 g
• MMI: IV (Light, no damage)
Stop Injection – Flow Well
Stop injection
Flow to surface (sump)
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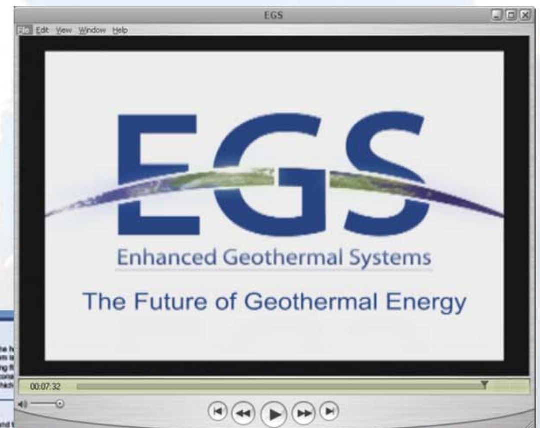
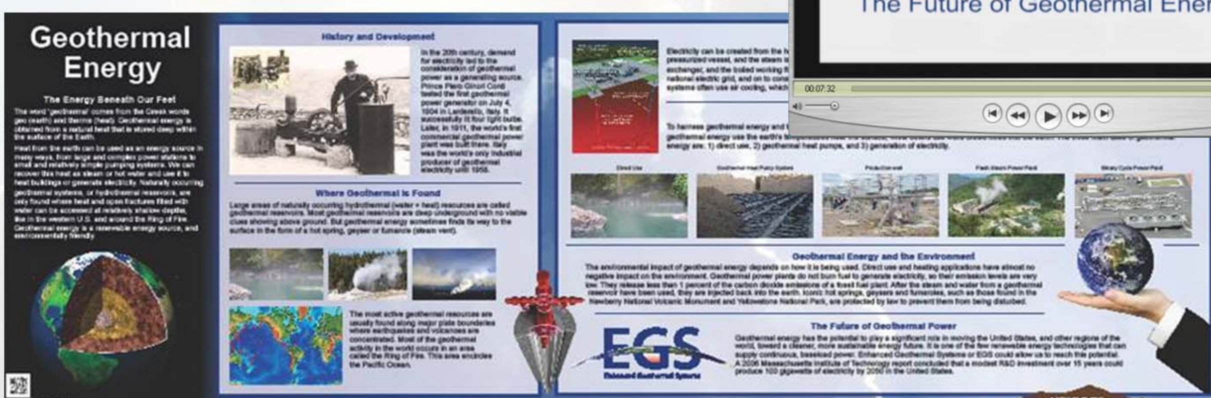
Permitting and Review Process

- Induced Seismicity Mitigation Plan (DOE reviewed. Included in EA)
- Phase I Report and Phase II Plan (Submitted August 2012)
- Stage-Gate Review (DOE approved Nov. 2012)
- Environmental Assessment (BLM published December 22, 2011)
  - Public comment (completed January 25, 2012)
  - Decision record (*February,* 2012)
  - Phase IIa (MSA install and stimulation) may begin
- Phase IIb (production drilling) requires additional DOE stage gate review
- Construction and long-term operations will require more permitting (requires data collected during demonstration)

Public Outreach

- Community meetings
- Print and radio interviews
- TV segments
  - Oregon Field Guide (Feb. 16)
  - Seattle news stations
- Documents posted online
- 855-USA4EGS
- Animated project video
- NNVM displays
- Facebook.com/NewberryEGS





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Acknowledgments

Funded by AltaRock Energy and *Development of a Geological and Geomechanical Framework for the Analysis of MEQ*, DOE/Recovery Act grant to A. Ghassemi, Texas A&M and N. Davatzes, Temple University.

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