Induced Seismicity Mitigation in Enhanced Geothermal Systems

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Conventional Geothermal Resources:

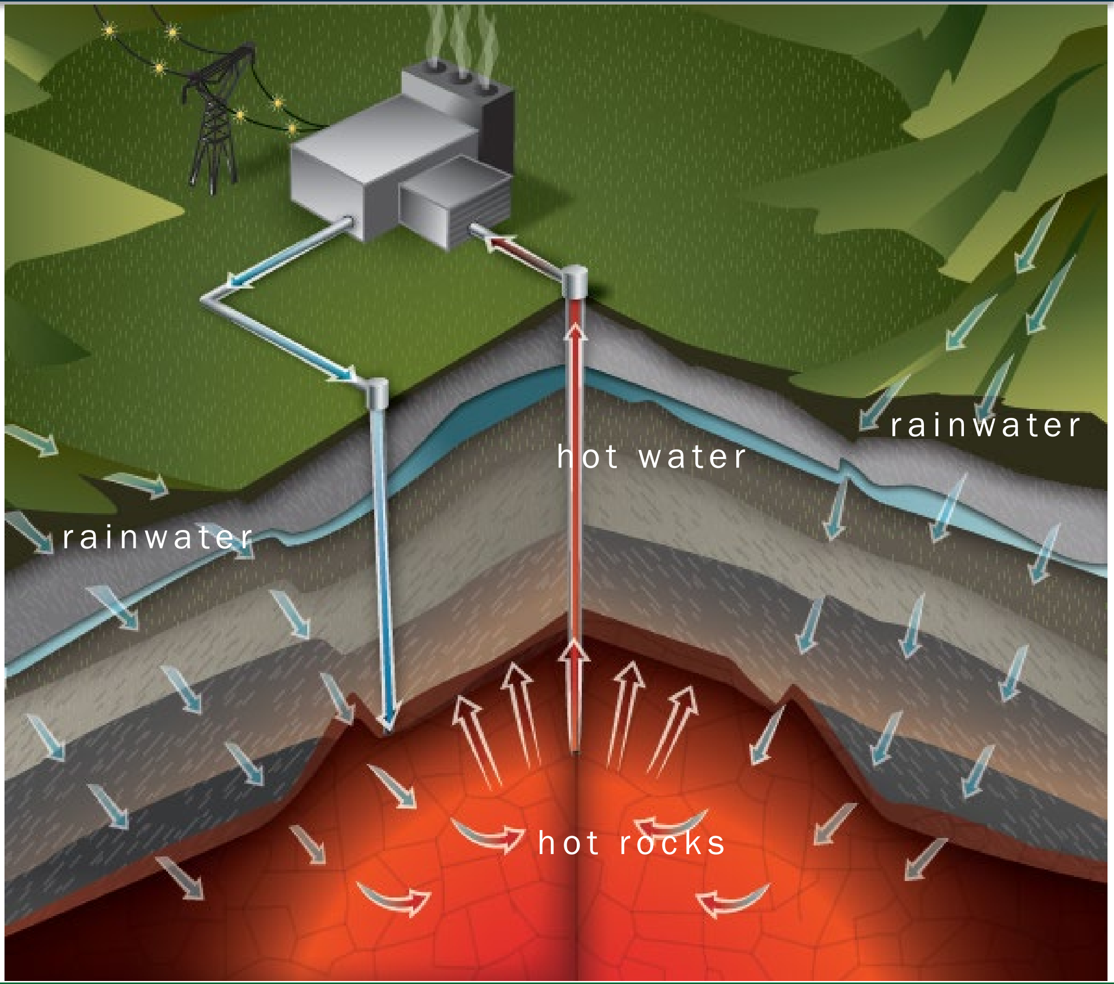
How do they work?

A geothermal resource requires **fluid**, **heat**, and **permeability** to generate electricity. Conventional hydrothermal resources contain all three components naturally.

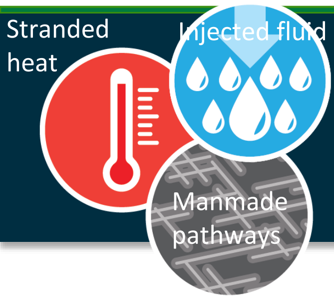
Elevated temperatures may exist in the subsurface, but insufficient fluid and/or flow pathways “strand” this heat resource.

Stranded Heat:

An Opportunity



Enhanced Geothermal Systems:

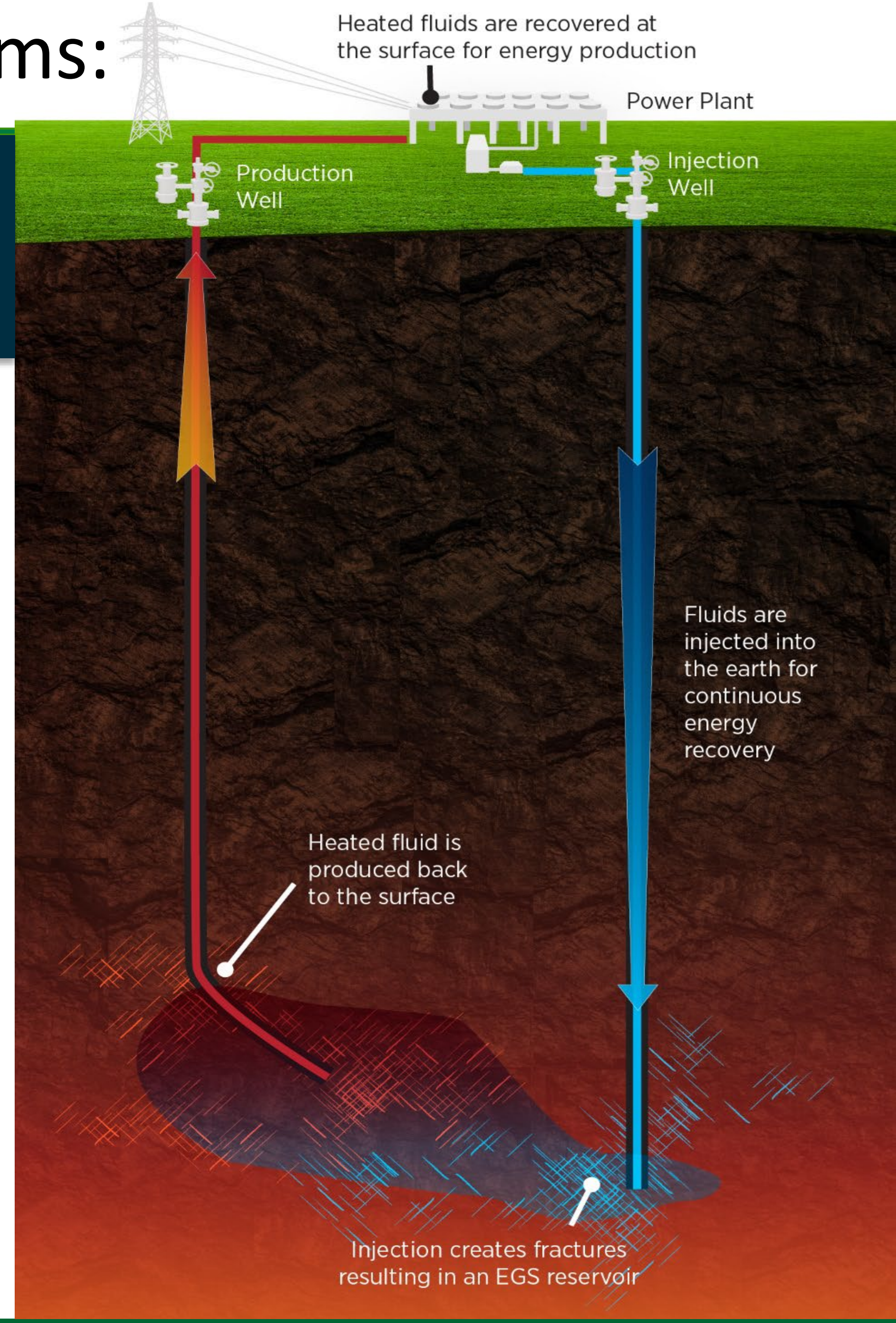


EGS: Manmade geothermal systems harnessing Stranded Heat

- EGS offer the opportunity to access 100-5000 GWe (USGS, NREL) of EGS resource by engineering fracture networks in accessible hot rock.

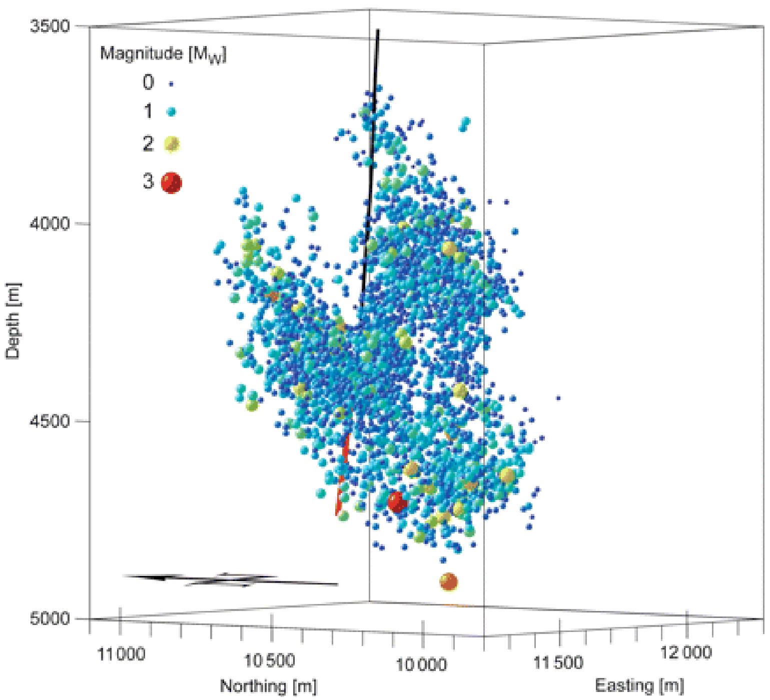
- Water is injected at pressure, to enhance permeability, and circulated to harness energy in the form of heat.

- Heated water is pumped to the surface to generate electricity.



Induced Seismicity in Geothermal Development

- Recognized and studied for more than 100 years
- Fundamental causes are well understood:
  - Changes in pore pressure (effective stress changes)
  - Thermal stress
  - Volume change – total balance of fluid
  - Chemical alteration of slip surfaces



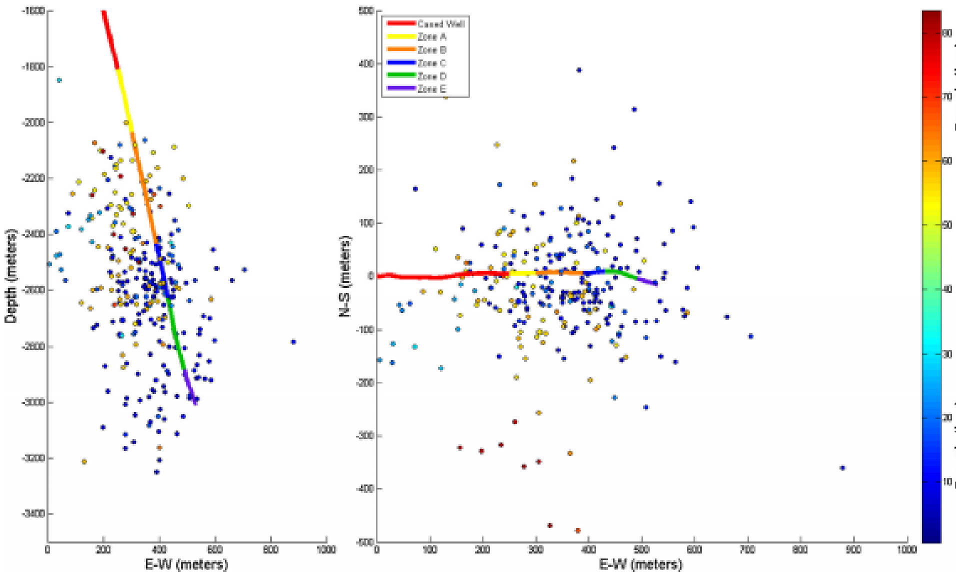
3D view of micro-seismic events during the main stimulation at Soultz*

Dyer, B.C, T. Spillman, U. Schen, F. Ladner, and M. O. Haring. 2008. Microseismic imaging of a geothermal reservoir stimulation. The Leading Edge. V. 27, no. 7, p. 856-869

- Can be controlled and managed by:
  - understanding the mechanisms
  - diligent monitoring of operations, seismicity and ground shaking
  - establishing a plan in advance to ramp-down or stop activities

Majer et. al, (2012). Protocol for Addressing Induced Seismicity Associated with EGS

EGS needs microseismicity



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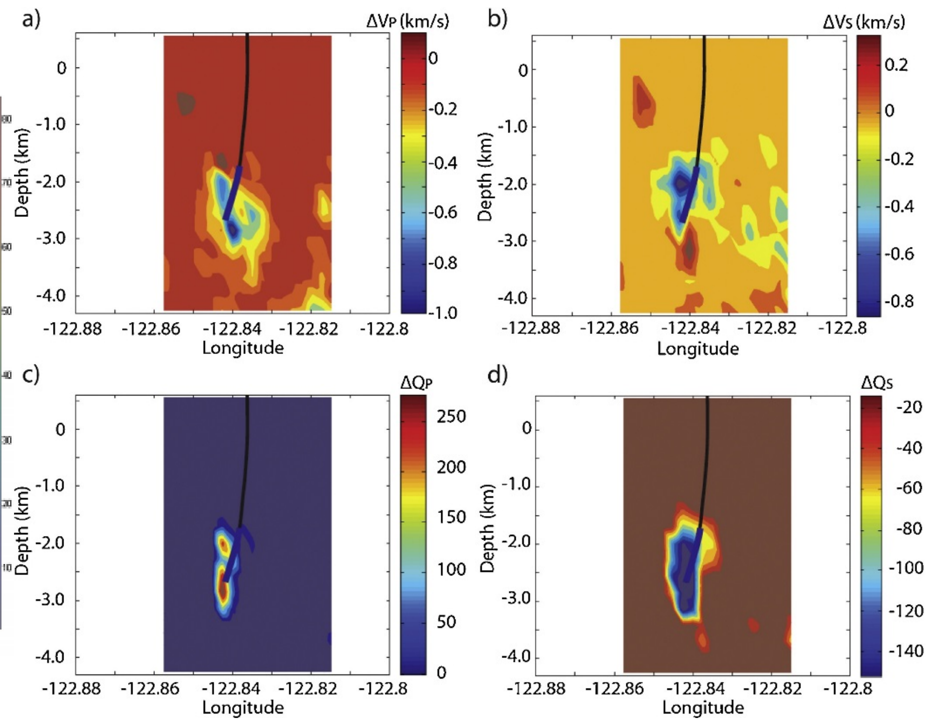


Rutqvist, et al., 2016. The Northwest Geysers EGS Demonstration Project, California – Part 2: Modeling and interpretation. Geothermics, V 63. 201-138.

Induced Seismicity and Geothermal Development

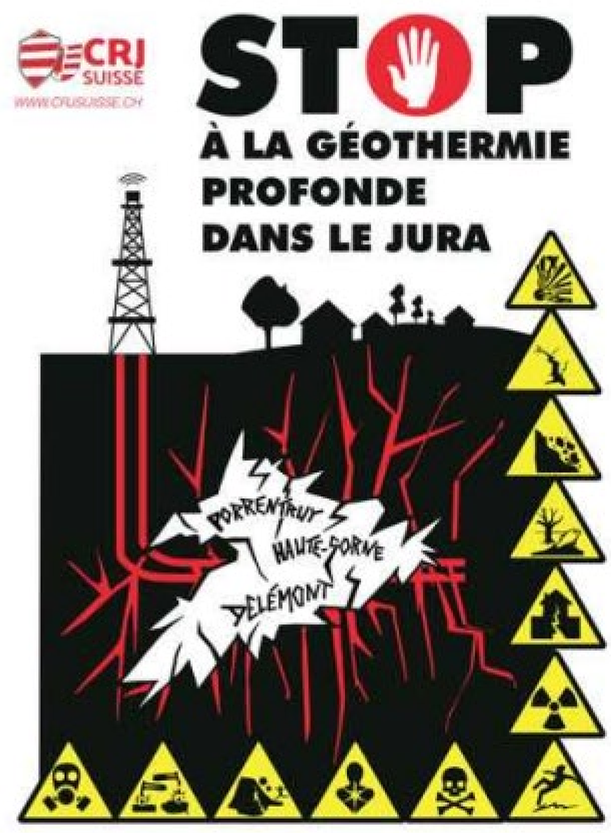
- The success of EGS technologies will depend on the ability to successfully inject/withdraw fluids in high volumes

- **Communications challenges**:

  Public, economic and regulatory concerns can delay and possibly cancel projects

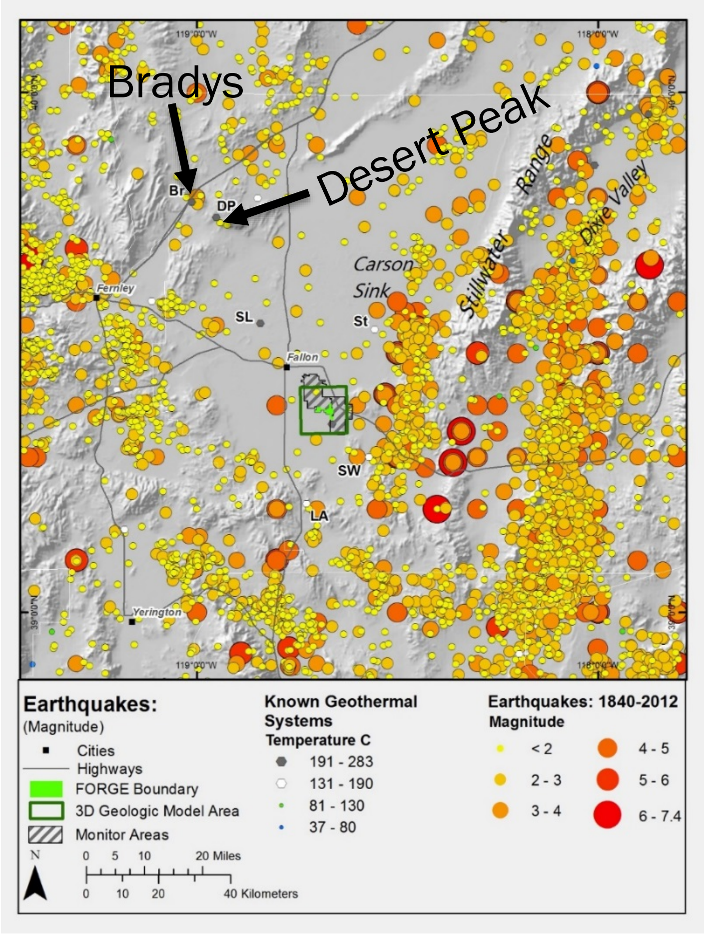
  - High-profile press coverage

  - Risk must be assessed properly and technically:
    - Public assurance and trust
    - Industry confidence
    - Facilitates further development



U.S. EGS Geothermal Projects

- Desert Peak
  - 2 years of seismic monitoring before EGS injection
  - Largest event in 2 years = M 1.7
  - **Largest EGS injection-induced event = M 1.0**
- Bradys Hot Springs
  - 3 years of seismic monitoring before EGS injection
  - Largest event in 3 years = M 2.0
  - **No detectable events during EGS injection**

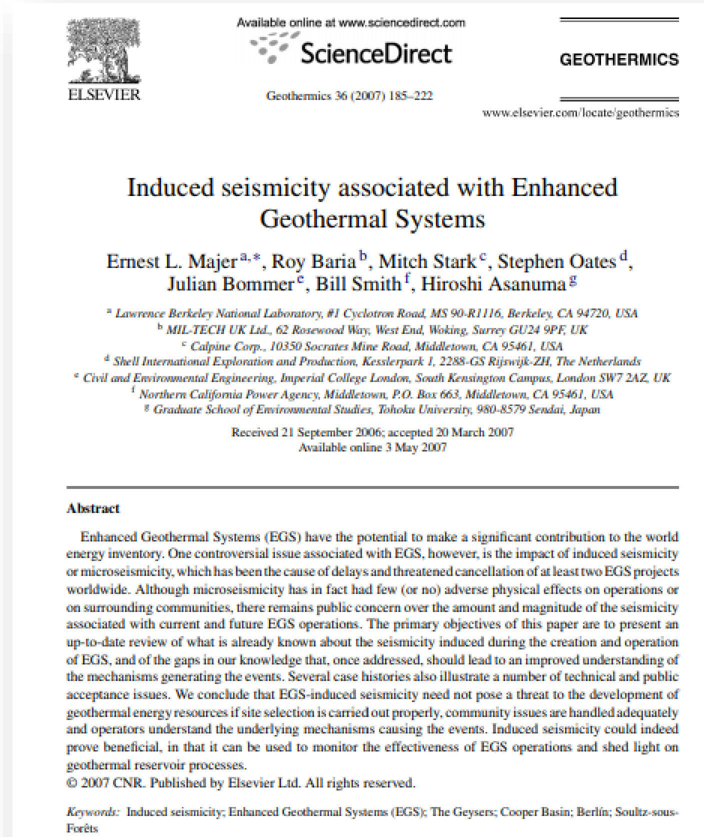


Main Challenges

- How to regulate/manage/mitigate a process that:
  - Is often (always?) site specific
  - Often has unknown or “fuzzy” boundary conditions
  - Frequent lack of subsurface data
  - Has a variety of stakeholders (some hostile)
  - Upsetting but not necessarily high risk
  - May occur in areas of no measured historical seismicity
  - Is rate/pressure dependent (non stationary)
  - Still under study by the research community

Developing an EGS Protocol

- Continuation of 2004-2006 process
  - Draft LBNL internal whitepaper (2004)
  - Three international workshops (2005-2006)
- Form technical basis for understanding induced seismicity and a strategy for developing a protocol
- International group of experts gathered to identify critical issues (technical and non technical) associated with EGS induced seismicity
- Peer reviewed white paper (IEA Report, Majer et al., 2007)
- Protocol for the development of geothermal sites and a Best Practice guide (IEA Report, Majer et al, 2009)



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Induced seismicity associated with Enhanced Geothermal Systems

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Abstract

Enhanced Geothermal Systems (EGS) have the potential to make a significant contribution to the world energy inventory. One controversial issue associated with EGS, however, is the impact of induced seismicity or microseismicity, which has been the cause of delays and threatened cancellation of at least two EGS projects worldwide. Although microseismicity has in fact had few (or no) adverse physical effects on operations or on surrounding communities, there remains public concern over the amount and magnitude of the seismicity associated with current and future EGS operations. The primary objectives of this paper are to present an up-to-date review of what is already known about the seismicity induced during the creation and operation of EGS, and of the gaps in our knowledge that, once addressed, should lead to an improved understanding of the mechanisms generating the events. Several case histories also illustrate a number of technical and public acceptance issues. We conclude that EGS-induced seismicity need not pose a threat to the development of geothermal energy resources if site selection is carried out properly, community issues are handled adequately and operators understand the underlying mechanisms causing the events. Induced seismicity could indeed prove beneficial, in that it can be used to monitor the effectiveness of EGS operations and shed light on geothermal reservoir processes.

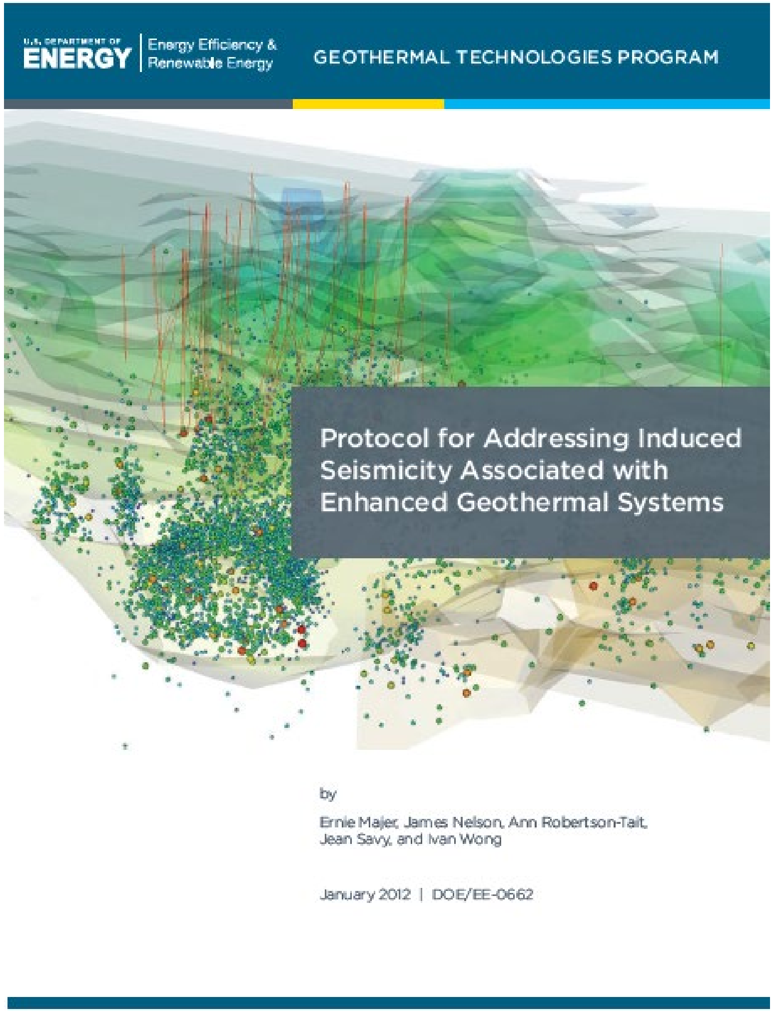
Keywords: Induced seismicity; Enhanced Geothermal Systems (EGS); The Geysers; Cooper Basin; Berlín; Soultz-sous-Forêts

Majer, E.L, Baria , R., Stark, M., Oates, S., Bommer, J., Smith, B., and Asanuma, H., 2007, Induced seismicity associated with Enhanced Geothermal Systems, Geothermics 36, 185-227. LBNL- 61681

Majer, E., Baria, R. and Stark, M., 2009. Protocol for induced seismicity associated with enhanced geothermal systems. Report produced in Task D Annex I (2008), International Energy Agency-Geothermal Implementing Agreement (incorporating comments by: C. Bromley, W. Cumming, A. Jelacic and L. Rybach).

Developing an EGS Protocol, 2012

- Funded by US Department of Energy
- Used by domestic and international businesses to guide their approach to induced seismicity associated with EGS projects
- Required for all Federally funded EGS projects
- Cited as the only existing IS protocol , which could "serve as a template for other technologies" by NRC, 2012 "Induced Seismicity Potential in Energy Technologies" Report
- Adopted by 17 countries
- Accepted by Oil and Gas industry for induced seismicity control
- Adopted for deep underground CO_2 sequestration



Protocol: http://esd1.lbl.gov/files/research/projects/induced_seismicity/egs/EGS-IS-Protocol-Final-Draft-20120124.PDF
Best Practices: https://escholarship.org/uc/item/3446g9cf

Developing a U.S. Protocol

Two main elements:

- Technical
  - Identify and understand factors controlling microseismicity
  - Effect of microseismicity on community and operations
- Legal – Community interaction
  - Propose guidelines for a geothermal developer to deal with the issue of induced seismicity.
  - Inform and interact with the community to understand their concerns and partner with them to achieve a win-win situation

"One size" does not fit all – not a regulatory document

Ground Motion as an Indicator

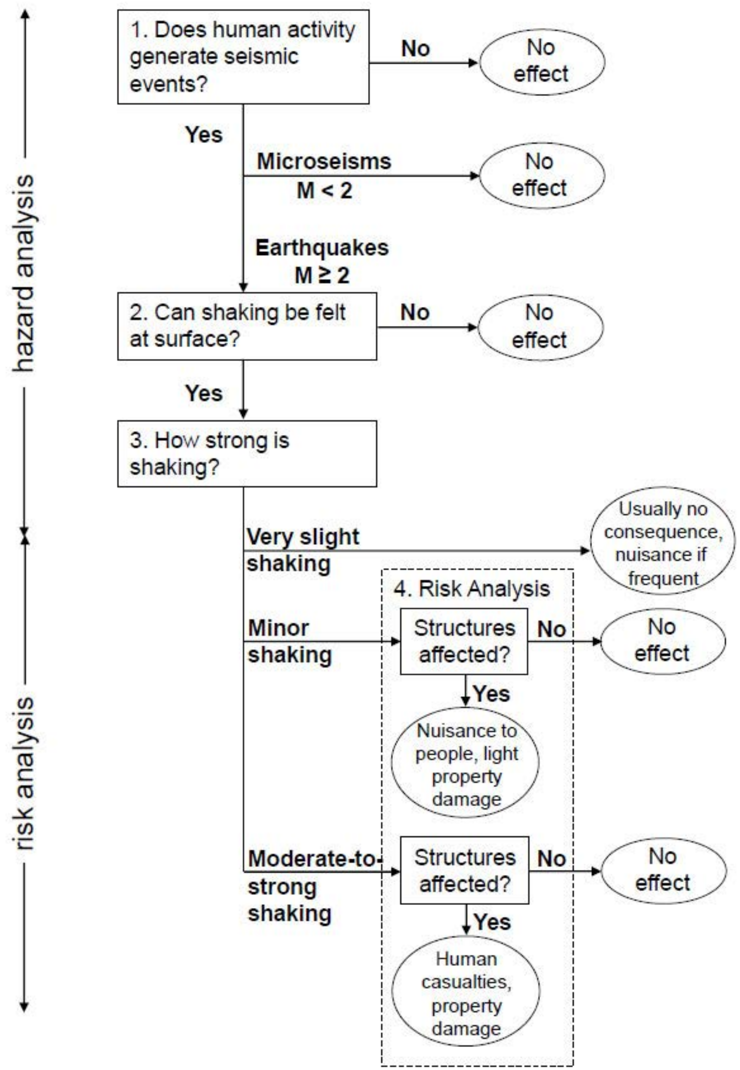
Impact	Maximum Velocity	Acceleration	Section
Bridges, Reinforced concrete structures	125 mm/sec PGV	0.2 g PGA	3.3, 3.4
Building Damage	12.5 mm/sec PGV	0.02 g PGA	3.2
Human Disturbance	0.1 mm/sec RMS (1-sec) 0.4 mm/sec PGV	0.00036 g RMS (1-sec)	3.6
Hospital laboratories, wet chemistry laboratories	0.05 mm/sec RMS (1-sec)	0.00018 g RMS (1-sec)	3.7
MRIs, scanning electron micro-scopes	0.0063 mm/sec RMS (1-sec)	0.0005 g PGA	3.7
Semiconductor manufacturing, research laboratories, scanning transmission electron microscopes	32 mm/sec RMS (1-sec)	10 micro-g RMS (1-sec)	3.7

- The amount of perceived shaking depends on
  - The size of the earthquake (Richter magnitude)
  - Distance from the earthquake

Majer et. al, (2013). Best Practices for Addressing Induced Seismicity Associated with Enhanced Geothermal Systems (EGS)

Determining Acceptable Seismic Risk from a Geothermal Injection?

- Depends Upon:
  - What the maximum as well as cumulative “shaking” will be.
  - Will this shaking be acceptable to the public?
  - Will this shaking be below the “damage” threshold for structures with interest?



National Research Council. (2013). Induced seismicity potential in energy technologies. 10.17226/13355.

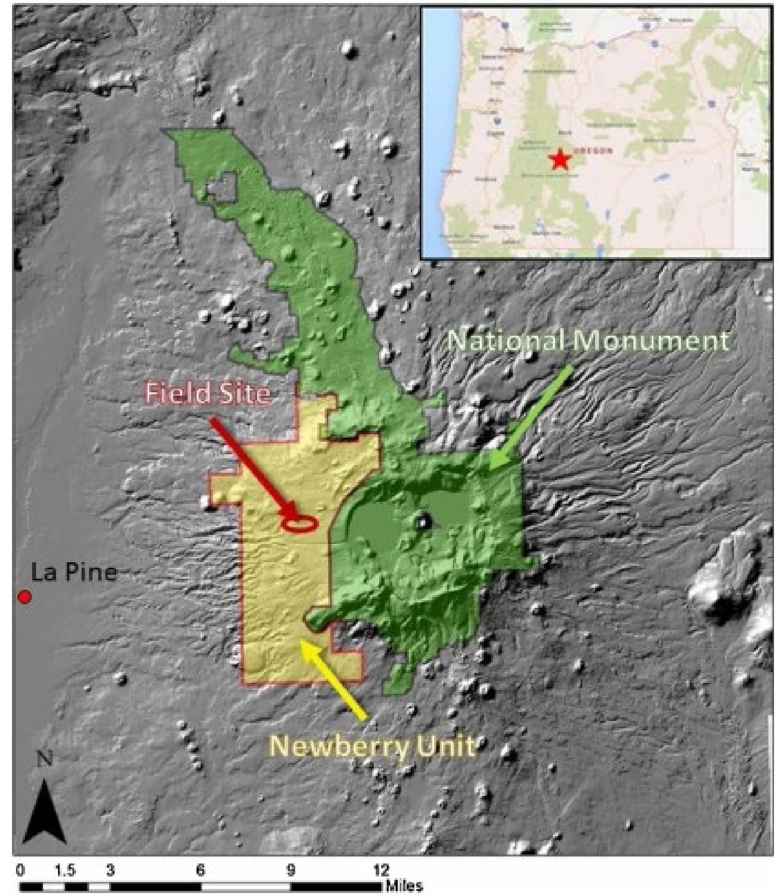
U.S. Induced Seismicity Protocol for EGS: 7 Steps

1. Perform a preliminary screening evaluation
2. Implement an outreach and communication program
3. Identify limits for ground vibration and noise
4. Monitor seismicity and ground motions
5. Quantify the hazard from natural and induced seismic events
6. Characterize the risk from induced seismic events
7. Develop risk-based mitigation plans

Case Study: EGS Demonstration Newberry Volcano, OR

- DOE Funded EGS demonstration project
  - 2010-2015

- Goals:
  - Demonstrate the development and operation of an **Engineered Geothermal System**
  - **Create EGS reservoir** around existing well NWG 55-29.
  - Stimulate **multiple fracture zones** using diverter technology.
  - Drill **production well** into mapped fracture network.
  - Complete **Circulation Test** of producer and injector.



Map of Project Site and the Davenport Newberry Unit Area. The Unit Area comprises Federal geothermal leases administered by the BLM with Davenport Newberry Holdings, LLC designated as the Unit operator for the purposes of exploration, development and operations

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U.S. Induced Seismicity Protocol for EGS: 7 Steps

1 Perform a preliminary screening evaluation

- Review relevant federal, state, and local laws and regulations.
- Determine the radius of influence within which there could be a negative impact.
- Identify potential impacts, including: physical damages, social disturbances, nuisance, economic disruption, and environmental impacts.
- Establish an approximate lower and upper bound of potential damage
- Classify the overall risk as one of the four described categories

I. Very Low:	II. Low:	III. Medium:	IV. High:
Proceed with planning.	Can proceed with planning, but may require additional analysis to confirm.	Probably should not proceed at this site, but additional analysis might support proceeding.	Do not proceed.

2 Implement an outreach and communication program

- Evaluate outreach needs
- Develop plans to approach community, stakeholders, regulators, and public safety officials.
- Develop a public relations plan to generate interest in the project from local media.
- Set up a local office in the community, ideally including technical displays for visitors.
- Initial public meeting and site visit that covers both technical and non-technical issues.
- Additional site visits during active drilling and in advance of the first stimulation.
- Etc…

Case Study: EGS Demonstration Newberry Volcano, OR

1 Perform a preliminary screening evaluation

- National Environmental Policy Act
- Noise Control Act, 42 U.S.C. § 4901
- Clean Water Act
- 2009 ORS Chapter 517, Mining and Mining Claims
- 2009 ORS § 540.350, Dams, Dikes and Other Hydraulic Works
- 2009 ORS Chapter 467, Noise Control
- 2009 ORS Section 197, Comprehensive Land Use Coordination
- 2009 ORS § 401.918, Emergency Management and Services, Seismic Safety Policy, Advisory Commission
- 2009 ORS § 467.120, Agricultural and Forestry Operations, Mining or Rock Processing
- 2009 ORS § 469.501, Energy Facility Siting, Construction, Operation and Retirement Standards
- Oregon Water Resources Department, Division 20, Dam Safety
- Oregon Department of Geology and Mineral Industries, Division 20, Geothermal Regulations
- Oregon Department of Geology and Mineral Regulations, Division 30, Oregon Mined Land Reclamation Act
- Oregon Department of Environmental Quality, Administrative Rules, Division 35, Noise Control Regulations
- Deschutes County Code (DCC), Chapter 8.08, Noise Control: County Noise Control Ordinances {C20}
- DCC Chapter 18: County Zoning {C20}
- DCC Chapter 23.76: County Comprehensive Plan, Energy {C20}
- City of La Pine, Comprehensive Plan, March 2010 {C20}

2 Implement an outreach and communication program

Phase	Type	Audience	When	Section
Pre-stimulation	Public Outreach and Professional Meetings, Presentations, and Discussions	Public, Media, Regulators, Politicians, Other Stakeholders	> 20 since Fall 2009	3.2.1; Appendix D
Pre-stimulation	Social Media and Websites Updates	Public	Weekly	3.2.1
Pre-stimulation	Local Newspaper Notice	Public	4 weeks prior to stimulation	3.2.1
Pre-stimulation	Informational kiosks at Lava Lands and Paulina Lake Visitor Centers	Public	Summer 2011	3.2.1
Pre-stimulation	Public Outreach Meetings	Public	After release of EA for public comment	3.2.1
Stimulation	Public Outreach Meetings	Public	Monthly	3.2.2
Stimulation	Social Media and Websites Updates	Public	Weekly	3.2.2
Stimulation	Daily stimulation and seismicity reports	DOE, BLM, FS, LBNL, PNSN	Daily	4.5
Stimulation	Exception Reports	DOE, BLM, FS, LBNL, PNSN	As required by triggers	5.2
Post-stimulation	Public Outreach Meetings	Public	At end of Phase II	3.2.3

U.S. Induced Seismicity Protocol for EGS: 7 Steps

3 Identify limits for ground vibration and noise

- Assess existing seismic conditions
- Review local ordinances
- Review building threshold cosmetic damage criteria
- Review structural damage criteria
- Assess human exposure to vibration
- Assess interference with industrial and institutional land uses
- Assess ground- borne noise

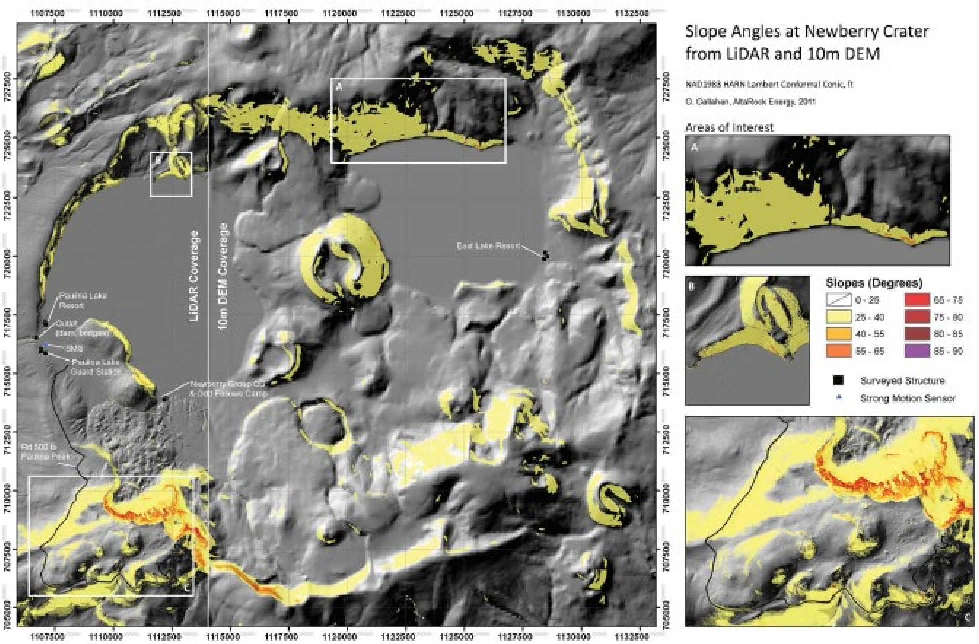
4 Monitor seismicity and ground motions

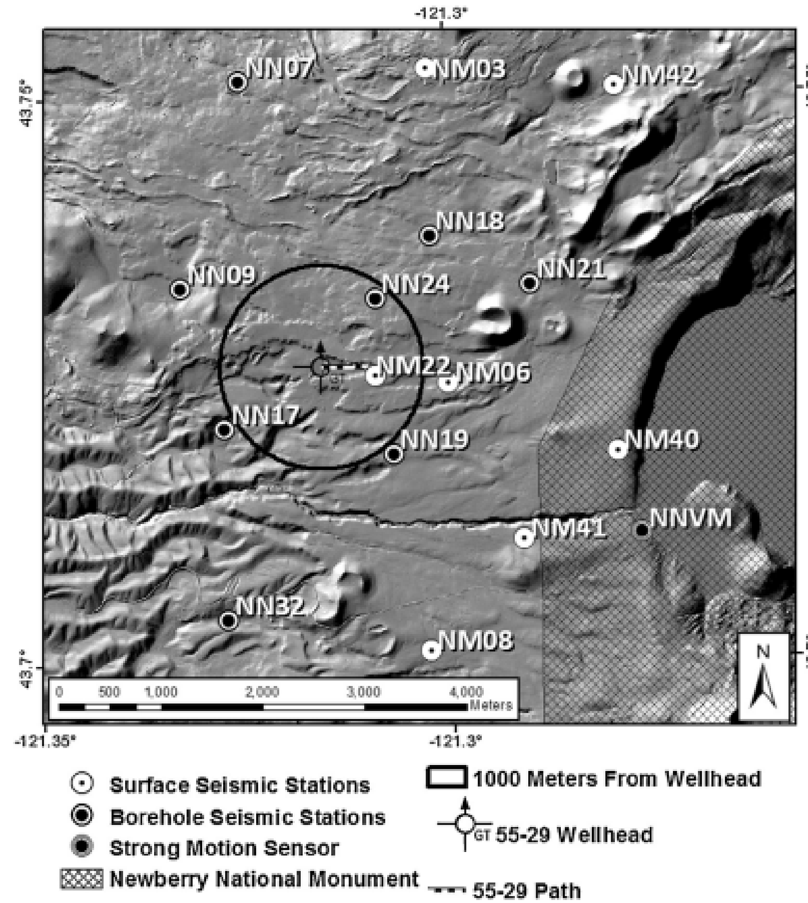
- Collect data to characterize background seismicity and faults
- At a minimum, determine location, magnitude and source mechanisms.
- Sustained monitoring throughout the injection activity

Case Study: EGS Demonstration Newberry Volcano, OR

3 Identify limits for ground vibration and noise

4 Monitor seismicity and ground motions





U.S. Induced Seismicity Protocol for EGS: 7 Steps

5 Quantify the hazard from natural and induced seismic events

- Estimate the Baseline Hazard from Natural Seismicity
  - PSHA
- Estimate the Hazard from Induced Seismicity
  - Ground motion prediction model
  - DSHA

6 Characterize the risk from induced seismic events

- Characterize the ground motion at each location within the area potentially impacted
- Identify the assets that could be adversely affected and that could contribute to the total risk.
- Characterize the damage potential (vulnerability) from the risk contributors.
- Estimate the risk.
- Map the results

Case Study: EGS Demonstration Newberry Volcano, OR

5 Quantify the hazard from natural and induced seismic events

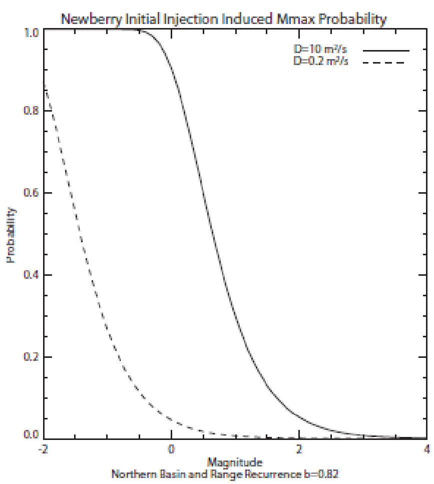
6 Characterize the risk from induced seismic events

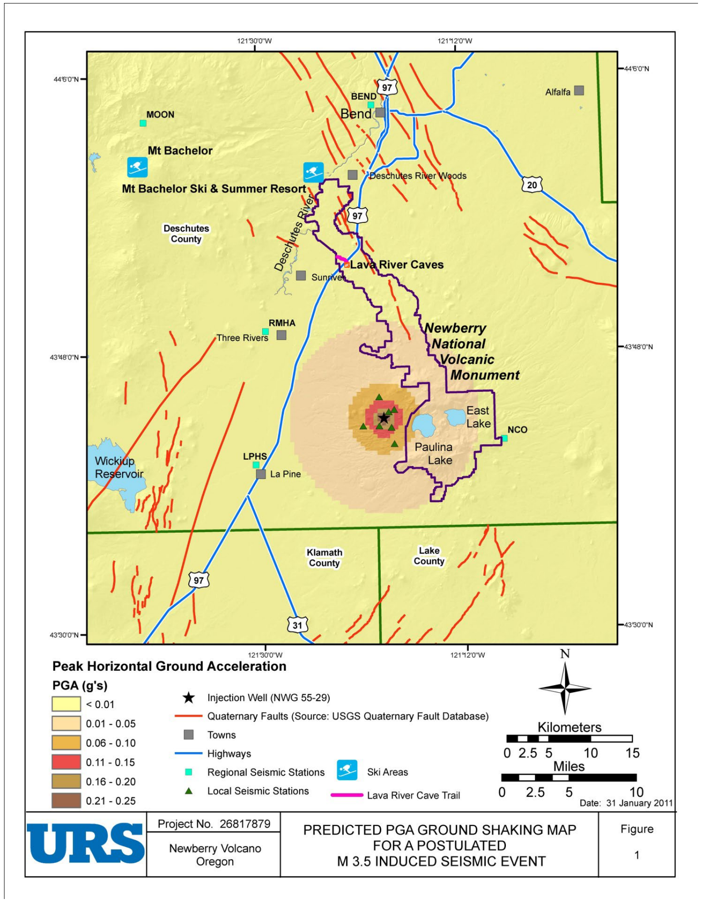
Table 3-3. Summary table for the three deterministic approaches used to estimate M_{max}. Only highest M_{max} estimated by each method is shown in this table. M_{max} based on a wider range of input values shown in Appendix E.

Technique	Characteristics	Highest M_{max}
Brune (1970)[1]	Dynamic stress drop, 500 m (1640 ft) radius, 3 MPa stress drop	3.89
McGarr (1976)[2]	Injected volume of 30,545 m^3 (8 million gallons)	3.24
Leonard (2010)[3]	Based on fault area 1000 m (3280 ft) strike length and 1473 m (4833 ft) vertical extent limited by shallow (3.5 km) brittle-ductile transition	3.98

Table 3-4. Calculated Probability of Event Occurrence

Event Magnitude	Event Probability	
	Minimum	Maximum
>1	0.7%	40%
>2	0.1%	6%
>3	0.01%	0.8%
>4	0.002%	0.09%





U.S. Induced Seismicity Protocol for EGS: 7 Steps

7 Develop risk-based mitigation plans

- Direct mitigation: "traffic light" system (Bommer, 2006 & Majer et al.)
  - RED—the lower bound of the red zone is the level of ground shaking at which damage to buildings in the area is expected to set in. *Pumping suspended immediately.*
  - AMBER—the amber zone was defined by ground-motion levels at which people would be aware of the seismic activity associated with the stimulation, but damage would be unlikely. *Pumping proceeds with caution, possibly at reduced flow rates, and observations are intensified.*
  - GREEN—the green zone was defined by levels of ground motion that are either below the threshold of general detectability or, at higher ground-motion levels, at occurrence rates lower than the already-established background activity level in the area. *Pumping operations proceed as planned.*
- Indirect mitigation:
  - Seismic monitoring
  - Increased outreach
  - Community support / compensation
- Liability and Insurance

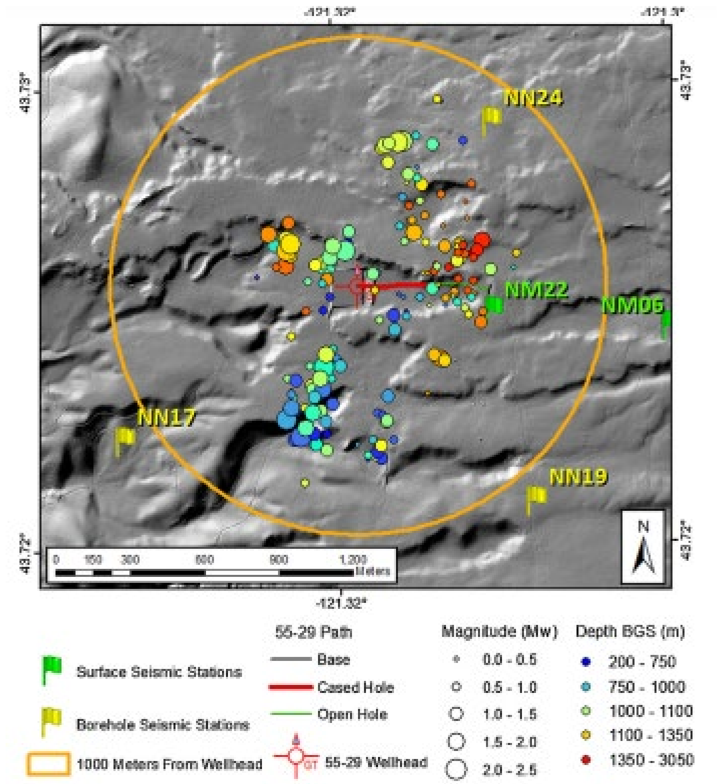
Case Study: EGS Demonstration Newberry Volcano, OR

7 Develop risk-based mitigation plans

Event Level and Characteristics		Field Operation	Communication
Start	• Regulator approval • MSA/SMS active	1) Initiate stimulation plan 2) Conduct step-rate test	1) Notify pubic 2) Initiate real-time data feed 3) Initiate daily report
Outlier Alert	• r > 1000m • Z < 6000 ft • NNVM < 500m	1a) M > 2 Apply diverter 1b) M < 2 Confirm, then apply diverter 2) No flow or pressure increase 3) Assess result for 24 hours	1) Issue outlier report
No Flow Increase	• M 2.0 to 2.6 within 3 km	1) No flow or pressure increase	1) Issue trigger report
Decrease Flow	• M 2.7 to 3.4 within 3 km • PGA: 0.014 to 0.028 g	1) Reduce flow to reduce pressure in 250 psi steps 3) Wait 12 hours	1) Issue trigger report 2) All phone notifications 3) Implement USFS site restrictions 4) Solicit damage reports
Stop Injection – Flow Well	• M ≥ 3.5 within 3 km • PGA ≥ 0.028 g	1) Stop injection 2) Flow to surface	1) Issue trigger report 2) All phone notifications 3) Implement USFS site restrictions 4) Solicit damage reports

ALTAROCK ENERGY INC

Newberry EGS Enhanced Geothermal Systems DEMONSTRATION



Other Existing I.S. Protocols

Framework	Majer et al. 2012	Majer et al. 2013	Bommer et al., 2015	Wiemer et al., 2015	SED risk governance workflow (Sections 6-10)
Scope	geo-thermal	geo-thermal	all induced seismicity	geother-mal	geothermal
Country of application	USA	USA	generic	Switzer-land	Switzerland
Preliminary screening	brief	detailed	-	-	detailed
Seismic hazard					
Assessment					
• Empirical seismic haz-ard study	brief	detailed	brief	brief	brief
• Probabilistic seismic hazard study	brief	detailed	brief	brief	brief
• Secondary hazards	brief	brief	brief	-	brief
Management					
• Seismic monitoring	brief	detailed	brief	brief	brief
• Magnitude-based traf-fic light systems	brief	brief	brief	brief	brief
• Risk-based traffic light systems	brief	brief	brief	brief	brief
• Adaptive risk-based traffic light systems	-	-	brief	brief	brief
Seismic risk (exposure and vulnerability of structures and population)					
Assessment					
• Macroseisimic intensi-ty- or engineering-based risk study	brief	detailed	detailed	-	brief
Management					
• Building monitoring	-	detailed	brief	-	brief
• Insurance and liability	brief	brief	brief	-	brief
• Structural retrofitting	-	-	detailed	-	brief
• Relocation of the pop-ulation	-	-	brief	-	-

Geothermal Risk of Induced Seismicity Diagnosis (GRID)

- Trutnevyte & Wiemer (2017) → Geothermal Risk of Induced seismicity Diagnosis (GRID)
- GRID scores are:
  - derived from indicators that describe concern about seismic hazard, risk (in terms of secondary hazards, exposure and vulnerability), and social context.
  - dependent on, but not exactly proportional to, the level of seismic hazard or risk.
  - reflect the concern level rather than hazard or risk level, meaning that higher concern requires more thorough risk governance
- adopted in the Swiss "Good Practice Guide for Managing Induced Seismicity in Deep Geothermal Projects in Switzerland."

GRID Indicators

- Evaluated by at least three parties:
  - the project operator,
  - the licensing regulator/authority,
  - independent experts
- Assigned values of:
  - 0 (little concern)
  - 1 (medium concern)
  - 2 (high concern)
- The licensing authority/regulator decides final category of the project based on GRID scores

SEISMIC HAZARD CONCERN	0 (little concern)	1 (medium concern)	2 (high concern)
Depth of the reservoir	< 1 km	1 - 3 km	> 3 km
Cumulative injection volume during stimulation	<1,000m³	1,000-10,000m³	>10,000m³
Daily injection or extraction volume during operation	<1,000m³/day injection or <5,000m³/day extraction	1,000-10,000m³/day injection or 5,000-50,000m³/day extraction	>10,000m³/day injection or >50,000m³/day extraction
Rock type	Sediments	Within 500 meters from the crystalline basement	Crystalline
Separation between back-ground and induced seismici-ty	≤0.6 m/s² dimensioning value a_{gd} from SIA (2003), defined as maximum PGA on Ground Class A of natural seismicity with a 475-year return period*	<1.3 m/s² dimensioning value a_{gd} from SIA (2003)*	≥1.3 m/s² dimensioning value a_{gd} from SIA (2003)*
Fluid injection pressure	<0.1MPa	0.1-1MPa	>1MPa
Distance to known and potentially active faults with length greater than 3 km	>5 km	2-5 km	<2km
CONCERN ABOUT SECOND-ARY HAZARDS, EXPOSURE AND VULNERABILITY (within a radius of 5 km)	0 (little concern)	1 (medium concern)	2 (high concern)
Local site amplification (within a radius of 5 km)**	No buildings or infrastructure on soft soils (Ground Class D, E, F in SIA (2003))	<10% of buildings or infra-structure on soft soils (Ground Class D, E, F in SIA (2003))	≥10% of buildings or infrastructure on soft soils (Ground Class D, E, F in SIA (2003))
Exposed population (within a radius of 5 km)	Remote (<100 inhabitants)	Rural (100-20,000 inhabit-ants)	Urban (>20,000 inhabitants)
Industrial or commercial activity (within a radius of 5 km)	Low activity	Medium activity (≥1 enter-prise with 100-499 employ-ees or ≥1 industrial installa-tion of a particular value)	High activity (≥5 enterprises with 100-499 employees or >1 enterprise with over 500 employees or ≥2 industrial installation of a particular value)
Importance of buildings and infrastructure (within a radius of 5 km)	No buildings or infrastructure of Class II or III, as defined in SIA (2003)	Buildings or infrastructure of Class II (SIA, 2003); no build-ings or infrastructures of Class III (SIA, 2003)	Buildings and infrastructure of Class III (SIA, 2003)
Infrastructures with consid-erable environmental risk (within a radius of 5 km)	None	-	One or more
Unreinforced cultural herit-age (within a radius of 5 km)	<5% buildings listed as important local, regional or national herit-age sites	5-10% buildings listed as important local, regional or national heritage sites	>10% buildings listed as important local, regional or national heritage sites; or any buildings listed as important international heritage sites
Susceptibility to secondary hazards (within a radius of 5 km)	Very low	Exists	High
SOCIAL CONCERN	0 (little concern)	1 (medium concern)	2 (high concern)
Potential for concern in the general population	None	Exists	Significant
Vulnerable or strongly opposing stakeholders	None	Exist	Significant
Negative experiences with similar projects	None	Exist	Significant
Lack of trust in the project operators or authorities	None	Exists	Significant
Benefits to the local commu-nity	Direct benefits with or without monetary compensation	Monetary compensation only	None

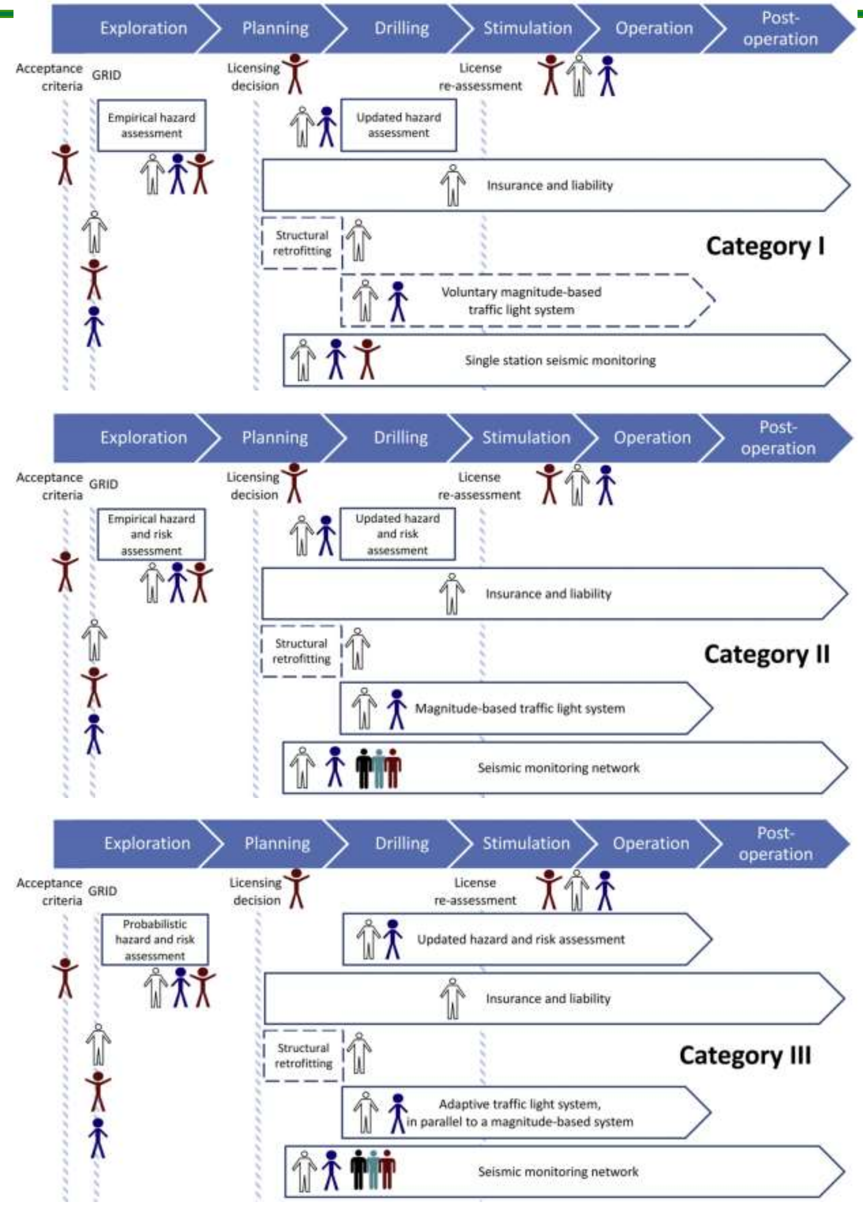
GRID Categories

Category 0:
- Induced seismic hazard, risk and social concerns very low or absent
- no dedicated induced seismicity risk governance is needed.

Category I:
- Perturbations of the stress field may be expected
- damaging events are very unlikely
- no significant social concern

Category II:
- Induced seismicity is possible
- damaging events and social concern cannot be excluded

Category III:
- Induced seismicity is likely
- damaging events and significant social concerns are possible and require thorough risk governance measures
- Seismicity will certainly occur and felt events are likely



Conclusions

- Induced seismicity issues are not new in energy industries
- General causes of earthquakes related to fluid injection (e.g., EGS) are known and can be mitigated
  - Continued R&D is critical : Increased understanding of the physics of induced seismicity will enable development of more robust mitigation and control procedures
  - Large base of available technology and expertise to draw upon to address issues
- Successful utilization of induced microseismicity is critical to successful energy extraction and mitigation activities
  - Negative issues can be mitigated and the risk will be low compared to benefits
- Continue to develop and update engineering guides/protocols that identifies means to accurately assess risk and mitigate unacceptable seismicity

Supplemental Slides

EGS vs Oil and Gas / Wastewater Injection

- Advanced seismic monitoring required
- Map major faults with intention of avoiding them
- Injection and circulation to equalize pressure
- Follow the DOE Protocol to minimize and closely monitor any seismicity

	Injected Volume (gallons/minute)	No. of Wells in Target Area	Duration of Injection
Oklahoma	~800 thousand	Thousands	Years
EGS – Fallon NV	~0.8	3	Weeks/Days
Difference	1 million times less	1000 times less	10-100 times less

Types of Fractures relevant to EGS*:

Dilational fractures/joints:

- Two rough surfaces with normal displacement continuity (moved away from each other perpendicular to the surfaces)

Shear fractures/faults:

- Shear displacement continuities move parallel to each other . Relative movement is either:
    1. Perpendicular to the fracture front
    2. Parallel to the fracture front

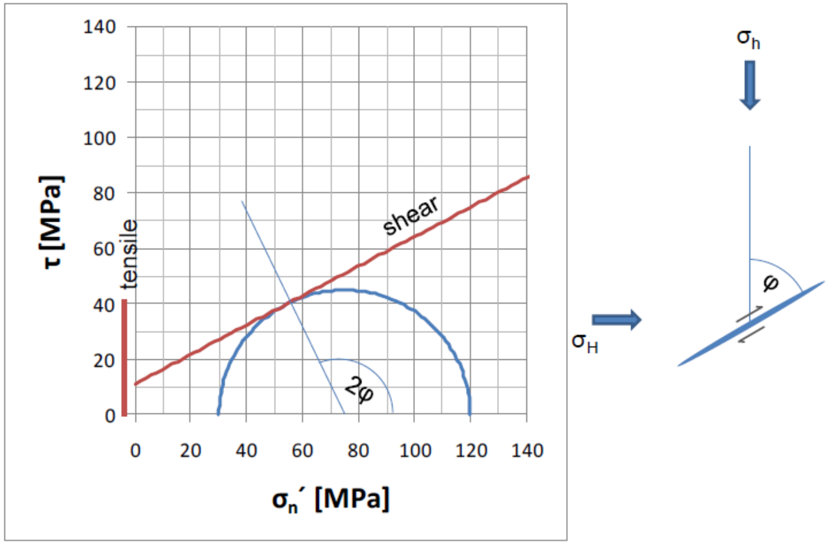
Mixed mode:

- Combination of the above

Fracture Mechanisms:

Fluid is injected into a rock mass at or below the fracture opening pressure (or minimum principal stress).

Shear deformation is induced in favorably oriented natural fractures in the rock mass → ***increases the permeability*** of the rock

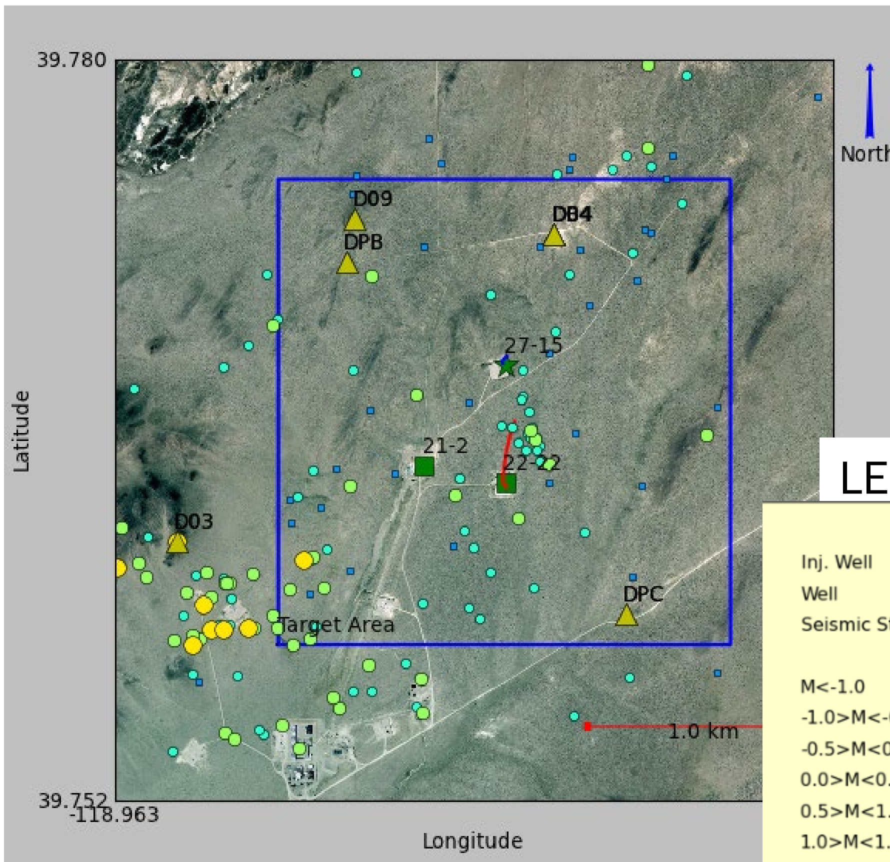


*Rock Fractures and Fluid Flow: Contemporary Understanding and Applications, Committee on Fracture Characterization and Fluid Flow, National Research Council, ISBN: 0-309-56348-8, 568 pages, 6 x 9, (1996).

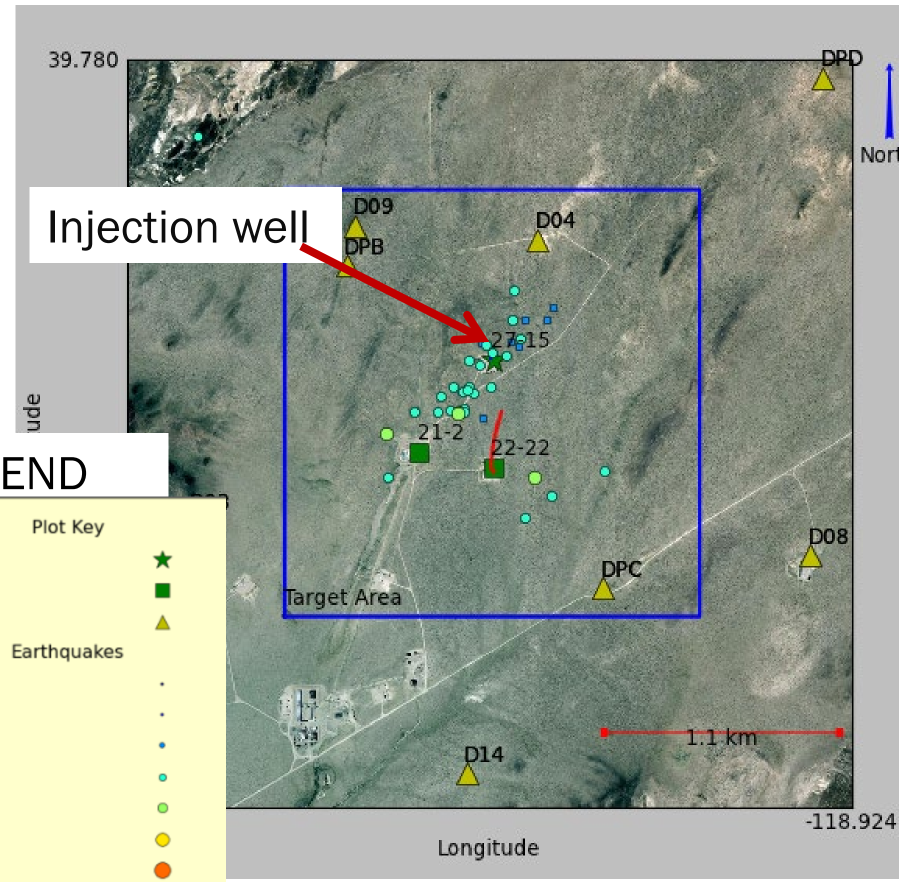
Desert Peak:

Low-Magnitude Events Between Injection and Production Wells

2 Years Before EGS Injection



12 Days During and After EGS Injection



LEGEND

Largest event M 1.0

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Brady's Hot Springs:

No Events Related to EGS Injection

3 Years Before EGS Injection

14 Days During and After EGS Injection