Lecture 14

Triggered and Induced Seismicity

촉발 및 유발 지진

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Induced Seismicity
Importance

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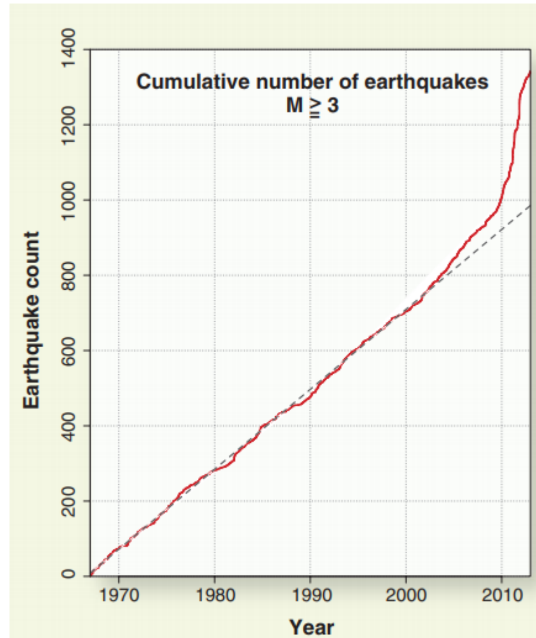
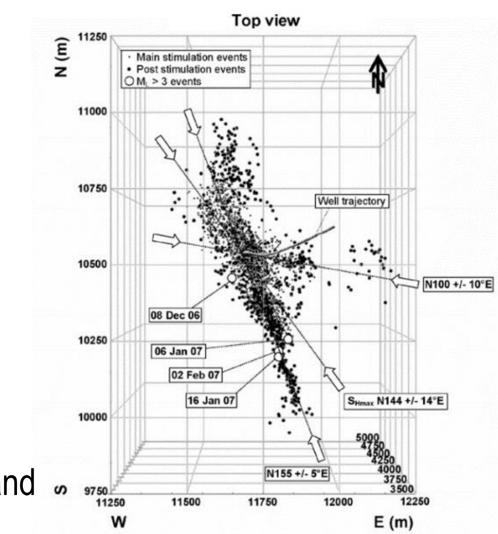
- Induced Seismicity
- Importance
- Definition
- Monitoring
- Mechanism
- Case study
- Management



Earthquakes with magnitude (M) ≥ 3 in the U.S. midcontinent, 1967–2012. After decades of a steady earthquake rate (average of 21 events/year), activity increased starting in 2001 and peaked at 188 earthquakes in 2011. Human-induced earthquakes are suspected to be partially responsible for the increase.

(Ellsworth, 2013)



Induced seismicity in Basel, Switzerland
(Haring et al., 2008)

Induced Seismicity
Definitions

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- Induced seismicity
  - Seismicity resulting from an activity that causes a stress change that is comparable in magnitude to the ambient shear stress acting on a fault to cause slip (McGarr et al., 2002)
  - Rupture (slip) was driven by the stress change over the full rupture plane (Dahm et al., 2015)
- Triggered seismicity
  - When the stress change is only a small fraction of the ambient level (McGarr et al., 2002)
  - Rupture (slip) initiation was driven by the stress change at the hypocenter of the earthquake (Dahm et al., 2015)
- Induced seismicity: all seismicity related to human activity (Foulger et al., 2017)

McGarr et al., 2002, Case Histories of induced and triggered seismicity, Int Handbook of earthquake and engineering seismology, vol 81A, 647-661
Dahm et al., 2015, Discrimination between induced, triggered, and natural earthquakes close to hydrocarbon reservoirs: A probabilistic approach based on the modeling of depletion-induced stress changes and seismological source parameters, J Geophys Res. Solid Earth, 120, 2491-2509
Foulger, G. R., et al. 2017. "Global review of human-induced earthquakes." Earth-Science Reviews. (in press) https://doi.org/10.1016/j.earscirev.2017.07.008

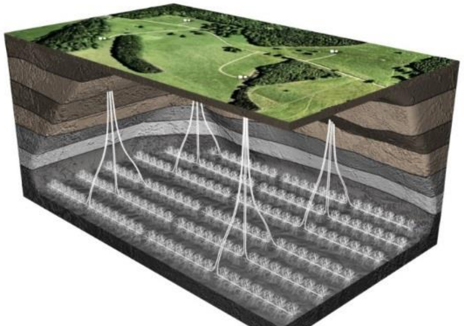
Induced Seismicity
Applications

Min,2012

Mining

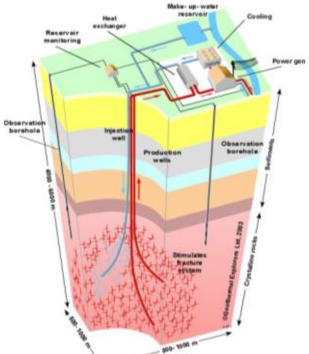
Induced Seismicity occur in various injection/excavation related applications

http://www.statoil.com/en/NewsAndMedia/News/2010/Pages/26MarMarcellus.aspx

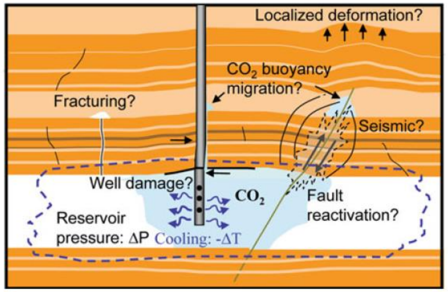


Hydraulic fracturing for shale gas development

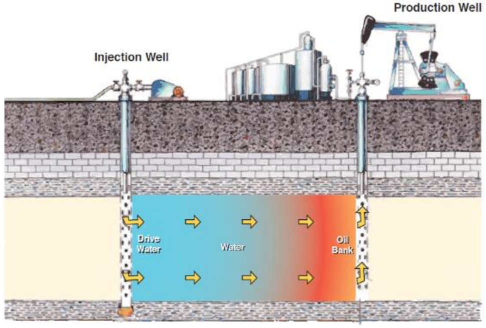
EGS Geothermal



Geothermal Explorer, 2010

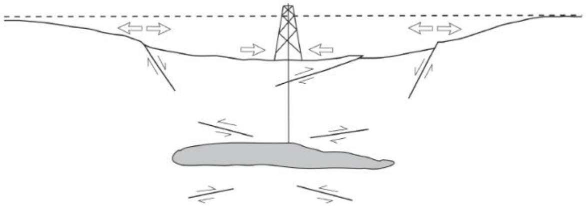


CO_2 underground storage (Rutqvist, 2012)



NRC, 2013

Enhanced Oil Recovery



Oil/gas production (Segall, 1989) & waste water injection

Induced Seismicity
Applications - Unconventional Hydraulic Fracturing

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- Marcellus Shale:
  - 10-30% of the injected fluid are produced back
  - 90% of produced fluid was re-used and 10% was reinjected in Class II well.
- Barnett Shale, Texas
  - Most of injected fluid were produced back
  - Only 5% were resued and 95% were injected into Class II well

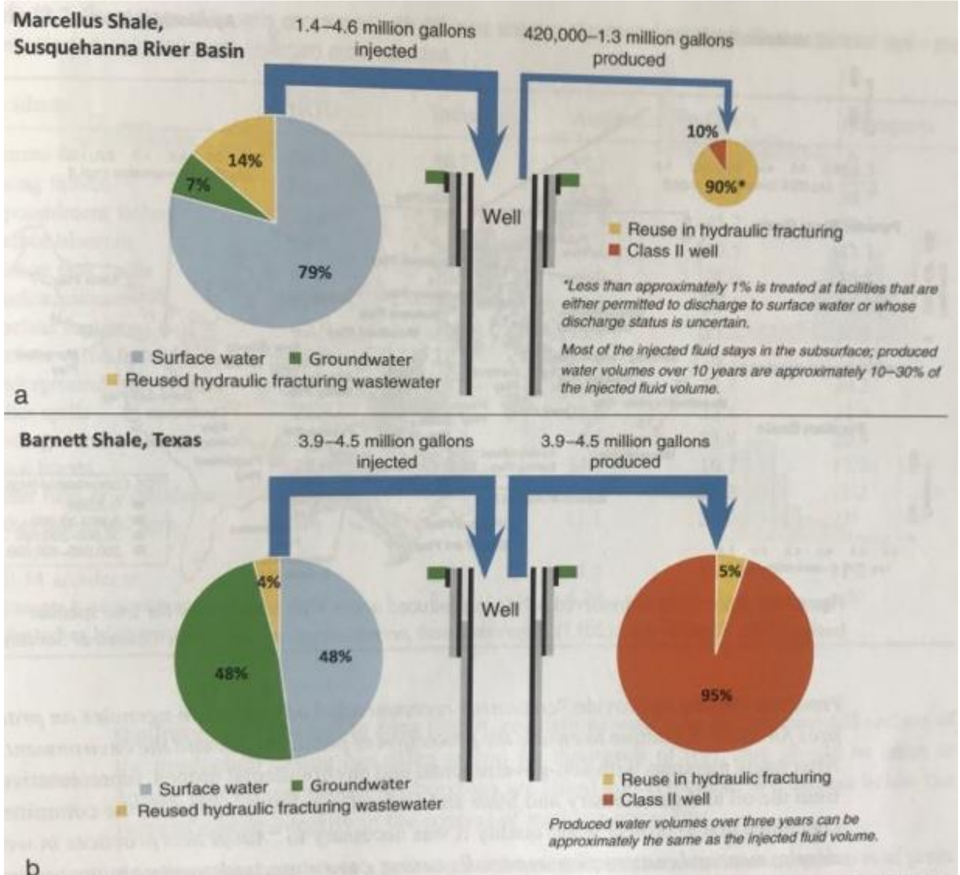


Figure 13.7 Water budgets illustrative of hydraulic fracturing water management practices in (a) the Marcellus shale in the Susquehanna River Basin between approximately 2008 and 2013 and (b) the Barnett shale in Texas between approximately 2011 and 2013. Class II wells are used to inject wastewater associated with oil and gas production underground and are regulated under the Underground Injection Control Program of the Safe Drinking Water Act. After EPA (2016).

Zoback MD, Kohli AH, 2019, Unconventional Geomechanics, Cambridge Univ press

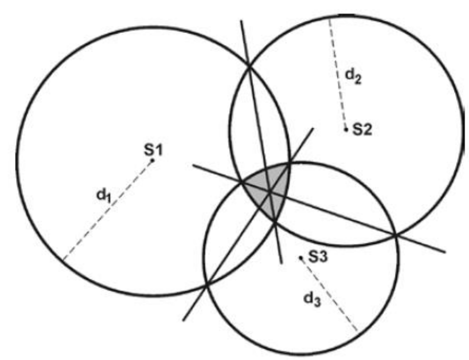
Induced Seismicity
Monitoring

- Active seismic monitoring
  - Use controlled sources such as explosives with known location and time
- Passive seismic monitoring
  - Make use of observation of either natural and anthropogenic earthquake data
- (Passive) Seismic monitoring is a key technology for characterizing the reservoir creation and protocol for underground mines
  - Improving resolution
  - Real-time processing

$$t_p = t_0 + \frac{x}{V_p}$$

$$t_s = t_0 + \frac{x}{V_s}$$

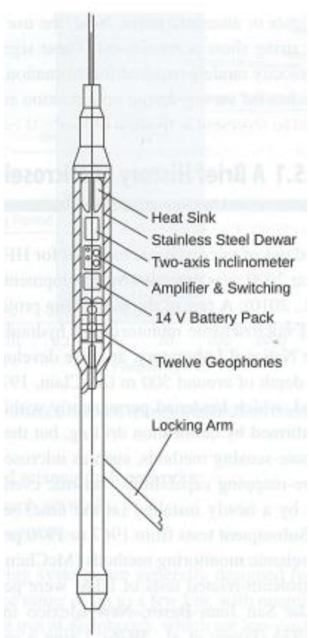
$$D = (t_s - t_p)\frac{V_p \cdot V_s}{V_p - V_s}$$



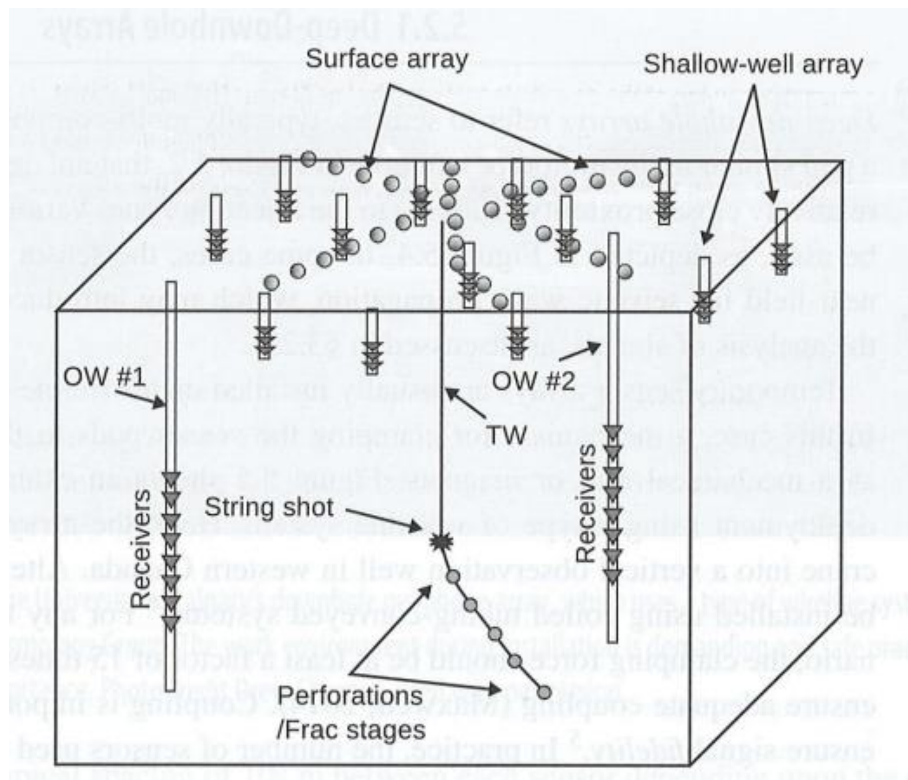
Zoback MD, Kohli AH, 2019, Unconventional Geomechanics, Cambridge Univ press

Induced Seismicity
Monitoring - Geophone

- Microseismic acquisition geometries typically used for hydraulic fracturing (OW: observation well, TW: Treatment well)



Deep downhole microseismic monitoring tool used in Fenton Hill geothermal project in 1976-1979



Zoback MD, Kohli AH, 2019, Unconventional Geomechanics, Cambridge Univ press

Induced Seismicity
Monitoring - Magnitude

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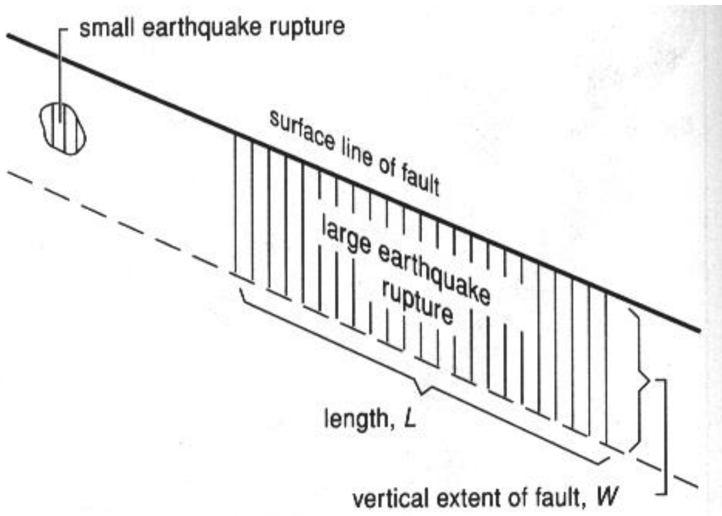
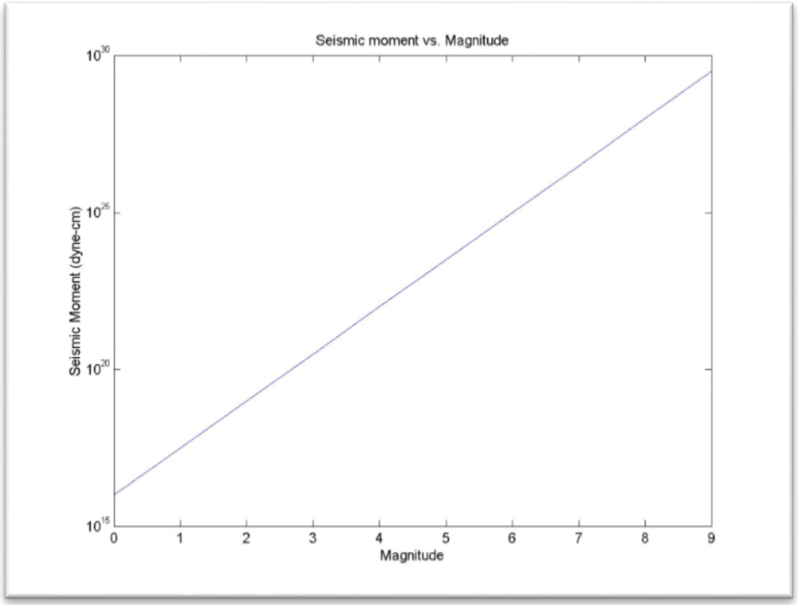
- Seismic Moment (Mo)

$$M_0 = \mu A d$$

- Relation between seismic moment (Energy) and moment magnitude

$$M_w = \frac{2}{3}\left[\log_{10} M_0(dyne - cm) - 16.0\right]$$





Induced Seismicity
Monitoring – earthquake statistics

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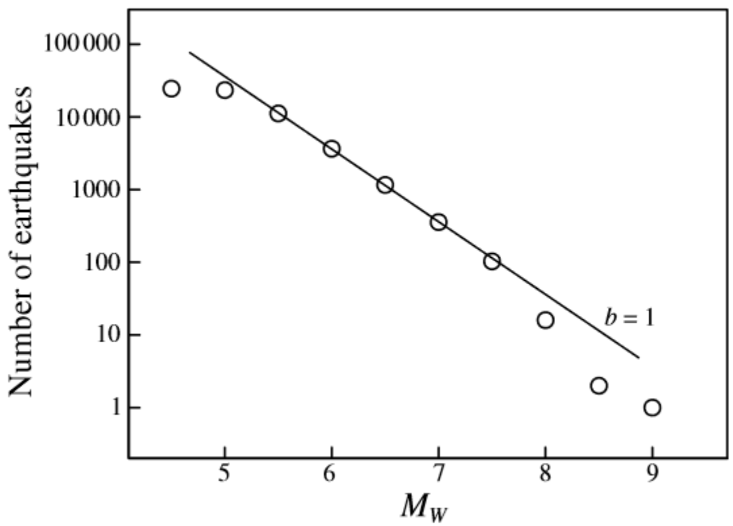
- Richter-Gutenberg Relationship

$$\log_{10} N = a - bM,$$

where N is the number of events with magnitudes greater than or equal to M. In this equation, a describes the total number of earthquakes, while the parameter b is called the *b-value* and measures the relative number of large quakes compared to small quakes. The b-value is generally found to lie between 0.8 and 1.2 for a wide variety of regions and different magnitude scales (for a review, see Utsu, 2002a).



Zoback MD, Kohli AH, 2019, Unconventional Geomechanics, Cambridge Univ press

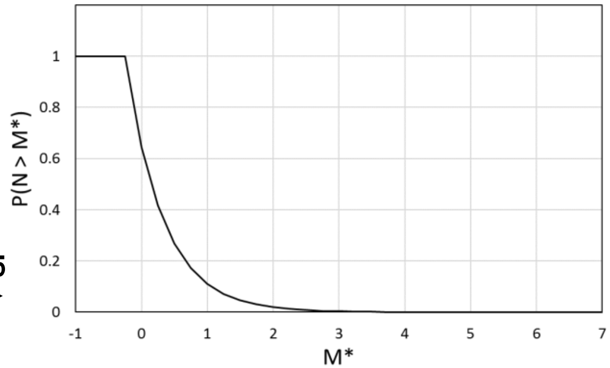
- Exceedance probability of Earthquake > M

- $Log(N > M^*) = a - bM^*$

- $N(> M^*) = 10^{a-bM^*}$ M_c: **magnitude completeness**

- $N_{total}(M > M_c) = 10^{a-bM_c}$

- $P\ (N > M^*) = \frac{N(>M^*)}{N_{total}} = 10^{-b(M^*-M_c)}$ **Example: a = 1.36, b = 0.762, M_c = -0.25** →



- Poisson distribution: 정해진 시간 안에 어떤 사건이 일어날 횟수에 대한 기댓값을 λ라고 했을 때, 그 사건이 n회 일어날 확률은 다음과 같다.

- $f(n;\lambda) = \frac{\lambda^n e^{-\lambda}}{n!}$

- $\lambda = N_{total} * P\ (N > M^*) = (10^{a-bM_c})(10^{-b(M^*-M_c)}) = 10^{a-bM^*}$

- $f(0;\lambda) = e^{-\lambda} = e^{-(10^{a-bM^*})}$ **: Probability that no event of M > M***

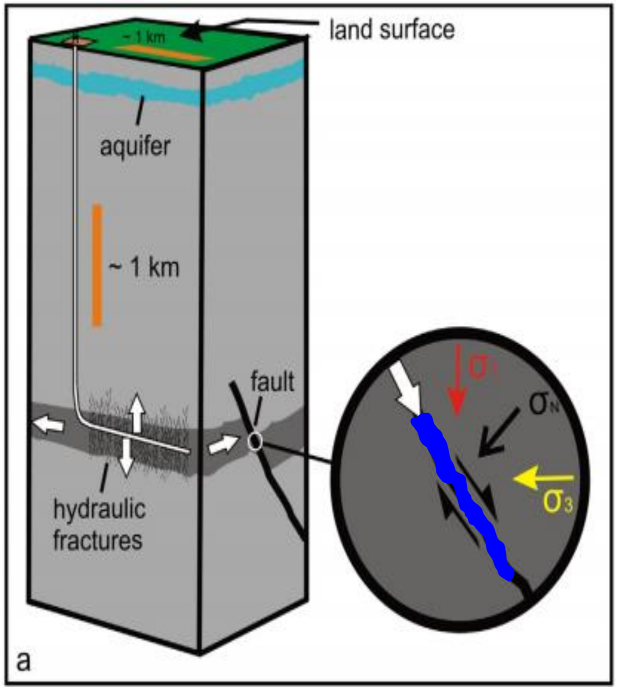
- $1 - f(0;\lambda) = 1 - e^{-\lambda} = 1 - e^{-(10^{a-bM^*})}$ **: Probability that at least one event of M > M***

= Exceedance probability

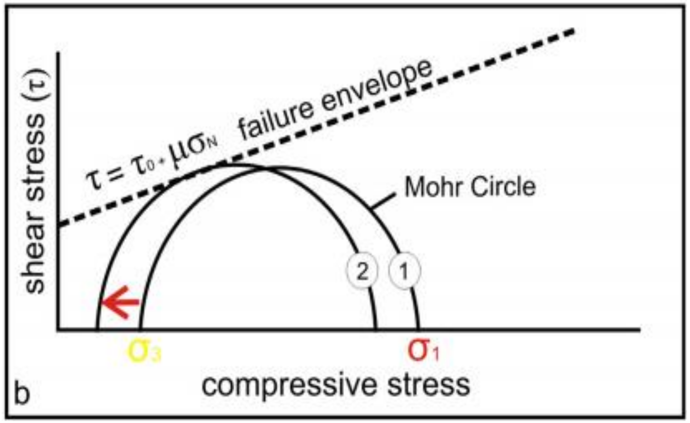
Induced Seismicity
Mechanism

- Cause of induced seismicity

<Fluid injection to hot reservoir> **<Mohr circles representing in-situ stress state>**



(Richard Davies, 2013)



Change of Mohr Circle

(a) Pore pressure increase

(b) Temperature drop

(c) Fluid extraction/Depletion

(d) Fault interface degradation

Change of Coulomb Failure criterion

Induced Seismicity
Mechanism – Coulomb Failure Function

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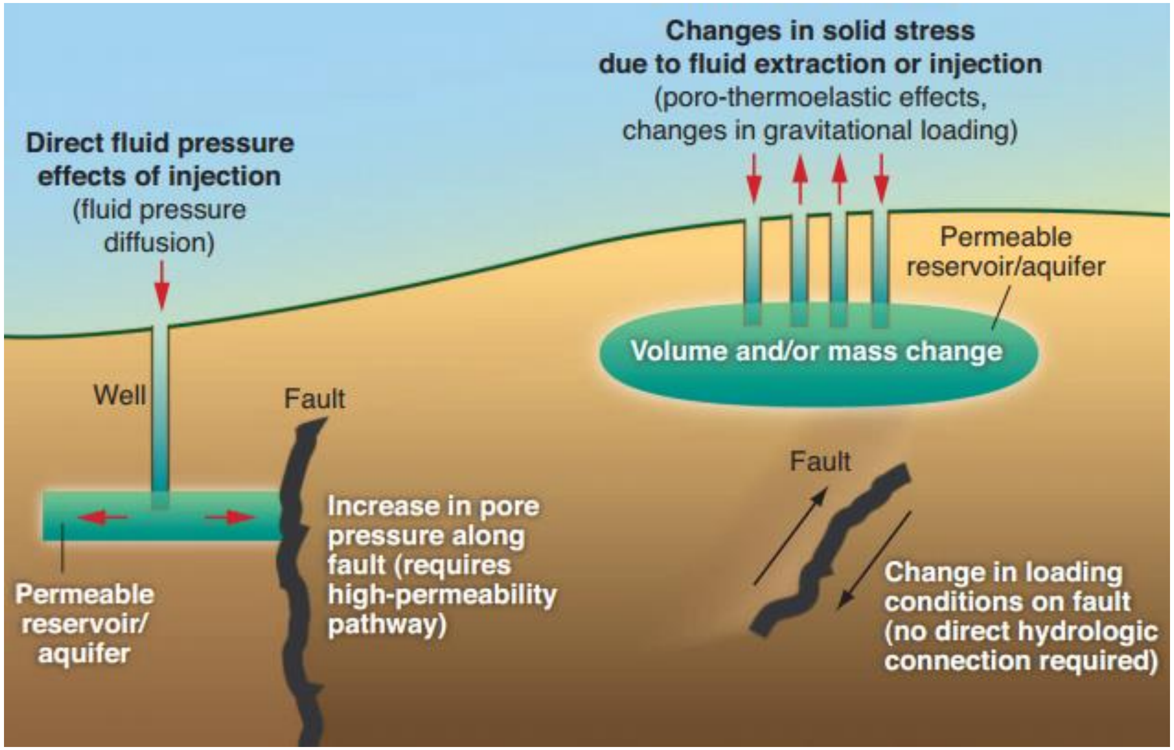
- Direct pore pressure effect and poroelastic stress
- Coulomb Failure Function
  - (+) means more likelihood of failure

$$\mathrm{CFF} = \tau - \mu \sigma_{\mathrm{n}} \qquad CFF = \tau - \mu(S_n - P_p)$$



Induced Seismicity
Mechanism – Applications

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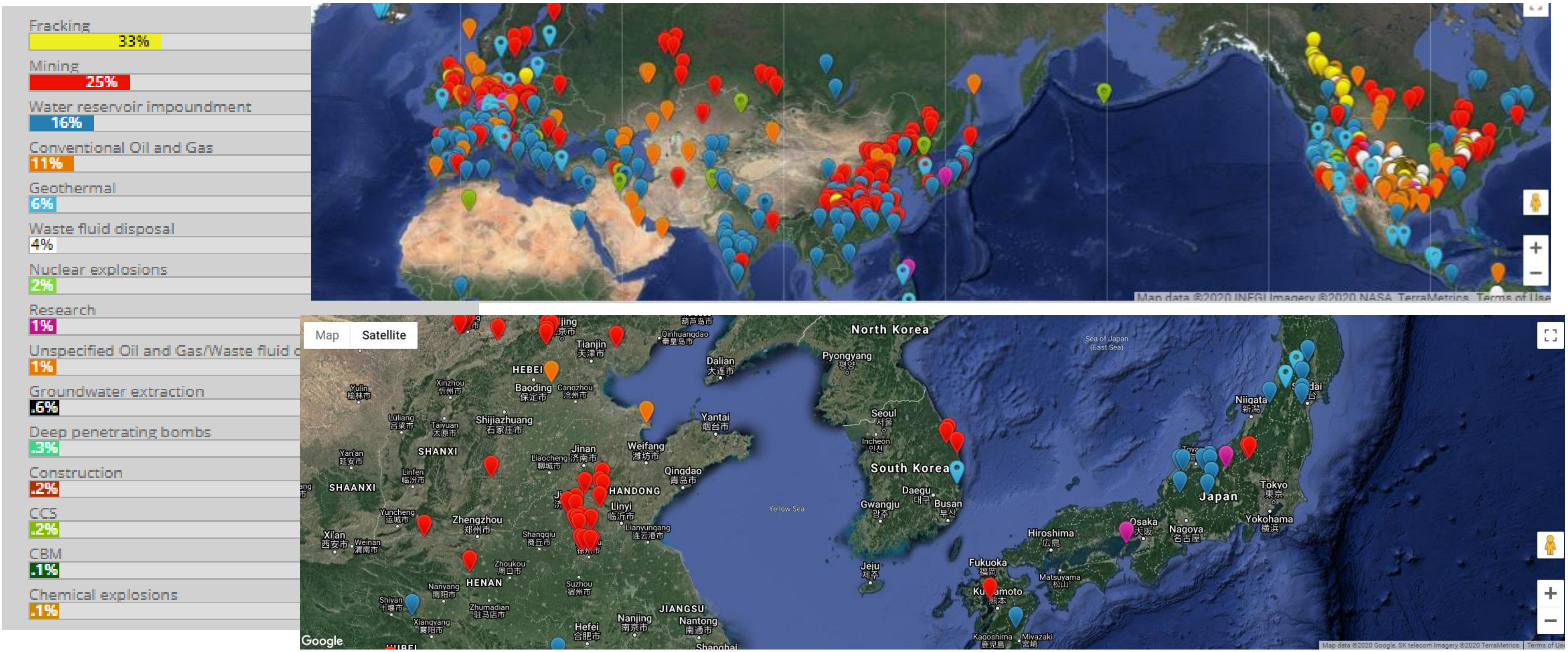
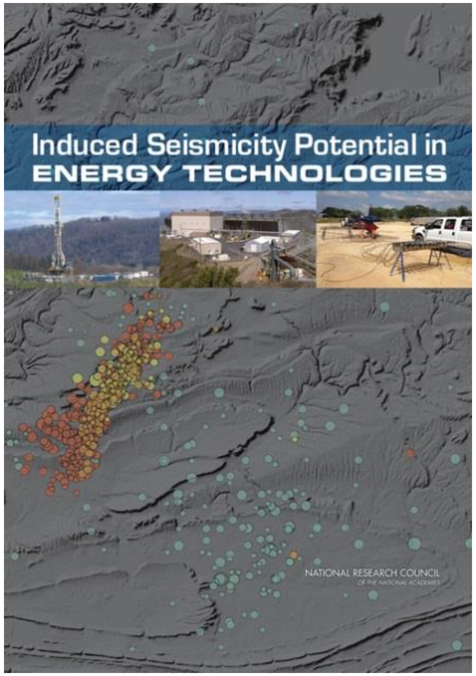
- Human Induced Earthquakes Database (1,184 projects, usually M>2.0)
  - http://inducedearthquakes.org/
  - Hydraulic fraturing (33%), Mining (25%), Water impoundment (16%), petroleum (11%), geothermal (6%)



Induced Seismicity
Mechanism – Applications: CO2 storage



US National Research Council (2013)

- …Because even small- to moderate-sized earthquakes threaten the seal integrity of CO2 repositories, in this context, large-scale CCS is a risky, and likely unsuccessful, strategy for significantly reducing greenhouse gas emissions… (Zoback & Gorelick, 2012)


PNAS
PERSPECTIVE

Earthquake triggering and large-scale geologic storage of carbon dioxide

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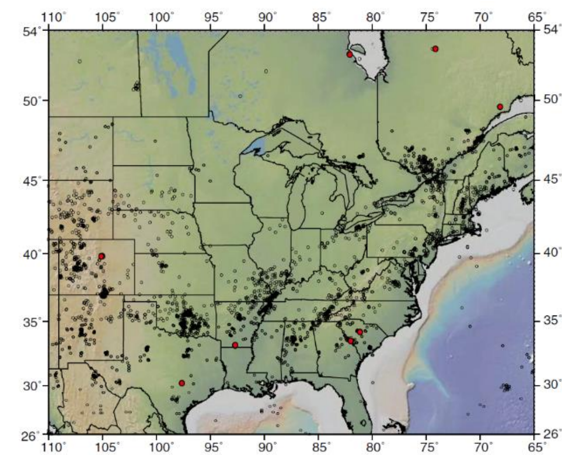
Departments of [a]Geophysics and [b]Environmental Earth System Science, Stanford University, Stanford, CA 94305

Edited by Pamela A. Matson, Stanford University, Stanford, CA, and approved May 4, 2012 (received for review March 27, 2012)

Despite its enormous cost, large-scale carbon capture and storage (CCS) is considered a viable strategy for significantly reducing CO_2 emissions associated with coal-based electrical power generation and other industrial sources of CO_2 [Intergovernmental Panel on Climate Change (2005) IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change, eds Metz B, et al. (Cambridge Univ Press, Cambridge, UK); Szulczewski ML, et al. (2012) *Proc Natl Acad Sci USA* 109:5185–5189]. We argue here that there is a high probability that earthquakes will be triggered by injection of large volumes of CO_2 into the brittle rocks commonly found in continental interiors. Because even small- to moderate-sized earthquakes threaten the seal integrity of CO_2 repositories, in this context, large-scale CCS is a risky, and likely unsuccessful, strategy for significantly reducing greenhouse gas emissions.

carbon sequestration | climate change | triggered earthquakes



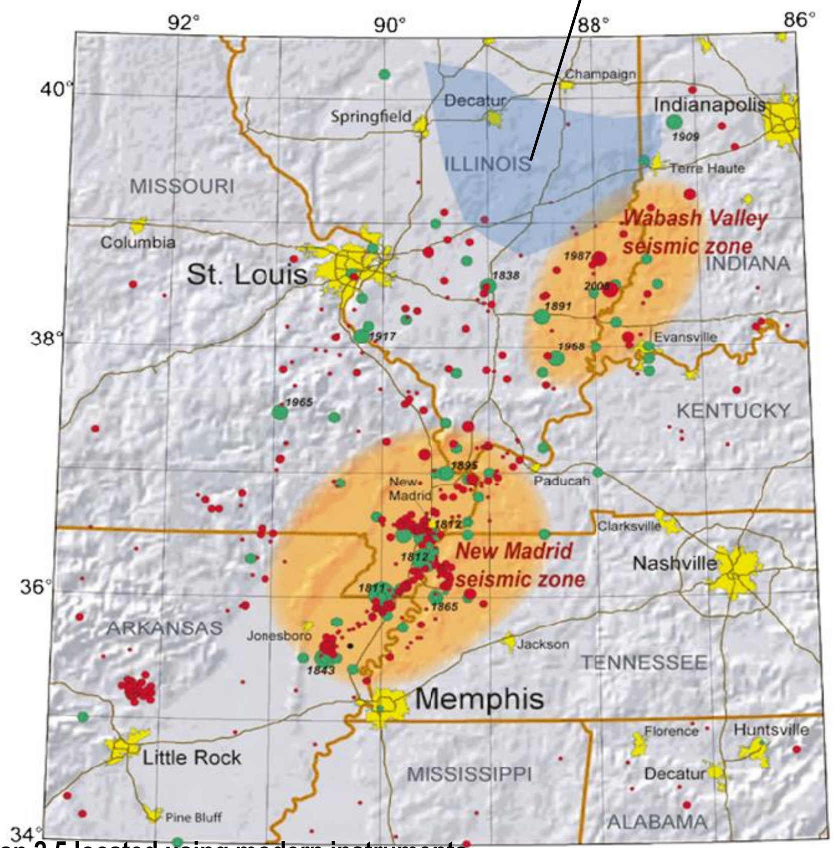
Earthquake >3 in the US (• : induced EQ M4-5)

Zoback MD & Gorelick SM, Earthquake triggering and large-scale geologic storage of carbon dioxide, Proc National Academy of Science of the USA (PNAS), June 2012, www.pnas.org/cgi/doi/10.1073/pnas.1202473109, cited by 427 times (google scholar, 26 June 2018)

Induced Seismicity
Mechanism – Applications: CO2 storage

- 지중은 많은 경우 임계응력상태→지중저장에 의한 수 MPa의 공극압 변화 → 지진
- Illinois Mt Simon 사암지대
- M>2.5
- 매년 1억톤 주입후 40년 후 : 수 MPa의 공극압 증가

공극압 증가지역



Red circles indicate earthquakes that occurred from 1974 to 2002 with magnitudes larger than 2.5 located using modern instruments. Green circles denote earthquakes that occurred be- fore 1974. Larger earthquakes are represented by larger circles.

Zoback & Gorelick, 2012

Induced Seismicity
Mechanism – Applications: CO2 storage

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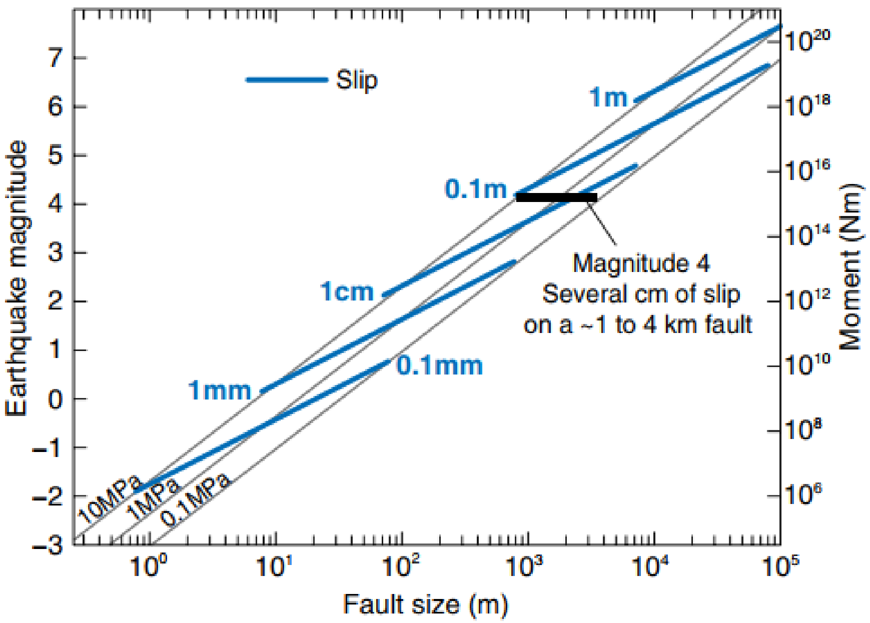


Fig. 2. Relationships among various scaling parameters for earthquakes. The larger the earthquake, the larger the fault and amount of slip, depending on the stress drop in a particular earthquake. Observational data indicate that earthquake stress drops range between 0.1 and 10 MPa.

Zoback MD & Gorelick SM, Earthquake triggering and large-scale geologic storage of carbon dioxide, Proc National Academy of Science of the USA (PNAS), June 2012, www.pnas.org/cgi/doi/10.1073/pnas.1202473109, cited by 427 times (google scholar, 26 June 2018)

Induced Seismicity
Mechanisms - McGarr's M_{max}-ΔV relationship

- Maximum earthquake magnitude is proportional to the injected fluid volume

$$M_o(\max) = G\Delta V$$

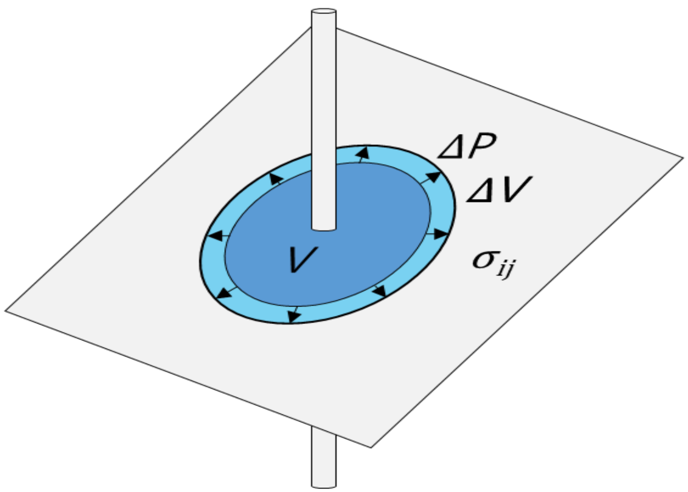
$M_o(\max)$: maximum seismic moment
G : shear modulus of reservoir
ΔV : total injected fluid

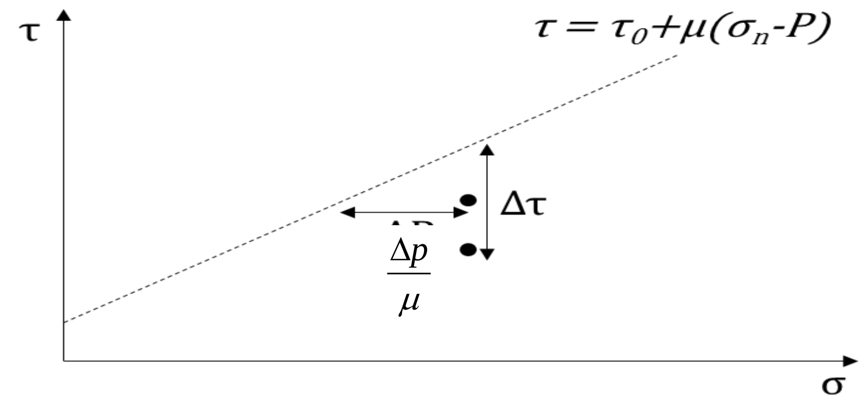
- Assumptions
  - The formation is either seismogenic or there is hydraulic communication between injection interval and seismogenic regions
  - Before injection, fault are stress within a seismic stress drop (Δτ) of the failure
  - Rock mass is fully saturated before injection
  - The seismic response follow the Gutenberg and Richter relationship
  - The induced earthquakes are localized to the region where the crust has been weakened due to fluid injection

McGarr, A. (2014). "Maximum magnitude earthquakes induced by fluid injection." Journal of Geophysical Research: Solid Earth 119(2): 1008-1019.

Induced Seismicity
Mechanisms - McGarr's M_{max}-ΔV relationship

- Derivation





$$1)\ \Delta P = \frac{3\lambda + 2G}{3}\frac{\Delta V}{V} \qquad 2)\ \Delta P = \frac{\Delta\tau}{2\mu} \qquad 3)\ \Delta\varepsilon_{ij} = \frac{1}{2GV}\sum M_{ij} \rightarrow \Delta\tau = \frac{1}{V}\sum M_0$$

$$\sum M_0 = \frac{2\mu(3\lambda+2G)}{3}\Delta V = 2G\Delta V \ (\text{if } \lambda = G, \mu = 0.6)$$

$$1)\ logM_0 = 1.5M + 9.05$$
$$2)\ logN = a - bM$$

$$M_{0(max)} = \frac{(1.5-b)}{b}\frac{2\mu(3\lambda+2G)}{3}\Delta V = G\Delta V \ (if\ b = 1, \lambda = G, \mu = 0.6)$$

Induced Seismicity
Mechanisms – Seismicity vs. Injected volume

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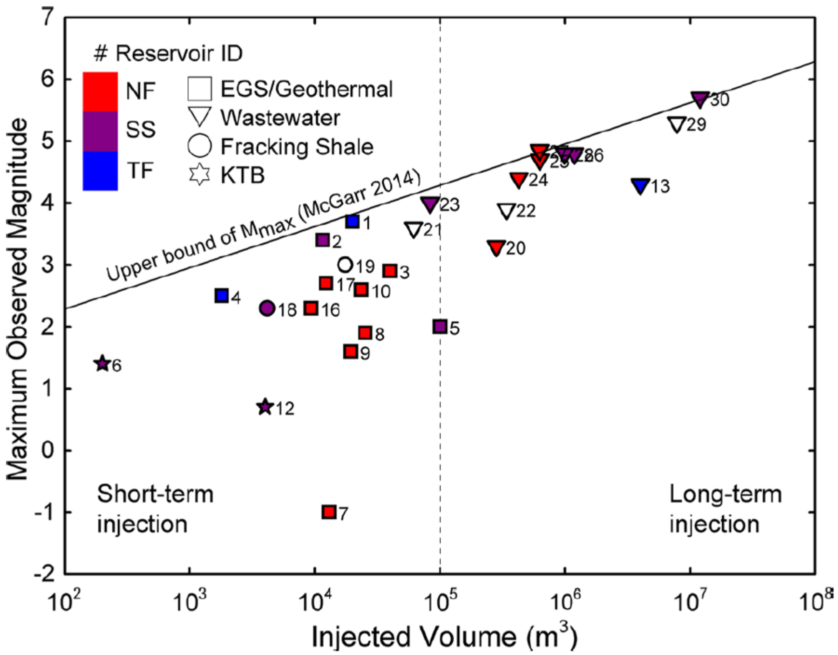
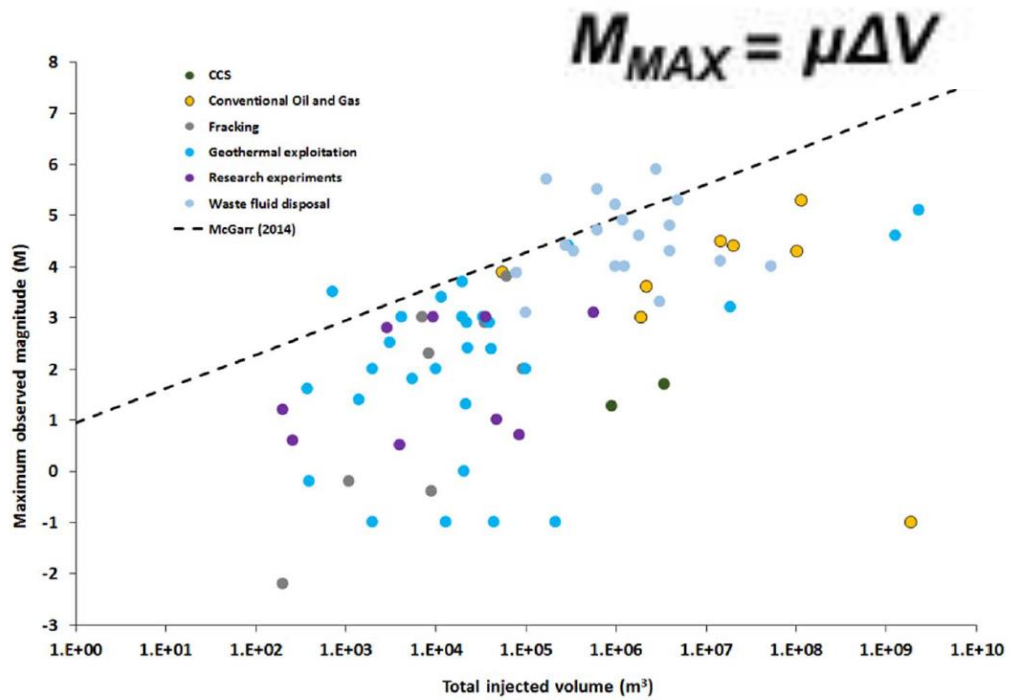
- McGarr's relationship between maximum seismic magnitude and total injected volume works, *however, there are some outliers*.



Maximum seismic moment and magnitude as functions of total volume of injected fluid from the start of injection until the time of the largest induced earthquake (Zang et al., 2018)



MMAX vs. total injected volume for the 69 cases of induced seismicity for which data are available (Foulger et al., 2017)

Zang A, Zimmermann G, Hofmann H, Stephansson O, Min KB, Kim KY, 2018, How to Reduce Fluid-Injection-Induced Seismicity, *Rock Mechanics and Rock Engineering*, in pressu

McGarr, A. (2014). "Maximum magnitude earthquakes induced by fluid injection." Journal of Geophysical Research: Solid Earth 119(2): 1008-1019.

Foulger, G. R., et al. (2017). "Global review of human-induced earthquakes." Earth-Science Reviews. (in press) https://doi.org/10.1016/j.earscirev.2017.07.008

Induced Seismicity
Mechanisms - McGarr's M_{max}-ΔV relationship

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- Comparison with 18 cases (scientific, hydraulic fracturing, EGS, wastewater disposal)

[Maximum moment and magnitude vs Injected volume]

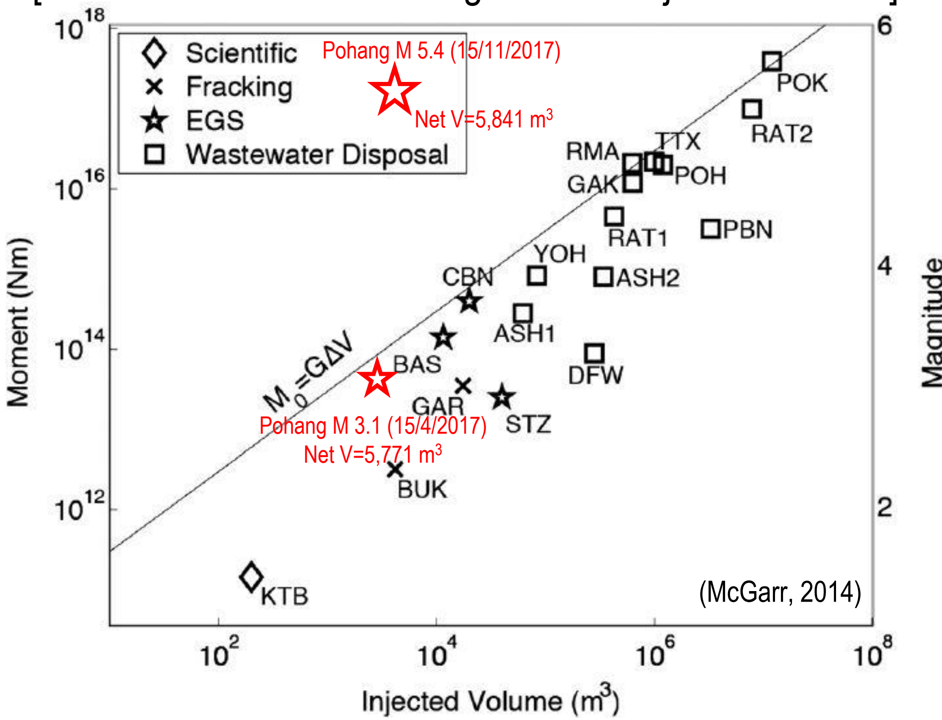

Table 1. Maximum Seismic Moments M_0(Max) and Total Injected Volumes ΔV

Event	M_0(max) (N m)	ΔV (m^3)	Type[a]	M	Location
KTB[b]	1.43e11	200	scientific	1.4	eastern Bavaria, Germany
BUK[c]	3.2e12	4.17e3	frak	2.3	Bowland shale, UK
GAR[d]	3.5e13	1.75e4	frak	3.0	Garvin County, OK
STZ[e]	2.51e13	3.98e4	egs	2.9	Soultz, France
DFW[f]	8.9e13	2.82e5	wd	3.3	Dallas-Fort Worth Airport, TX
BAS[e]	1.41e14	1.15e4	egs	3.4	Basel, Switzerland
ASH[g]	2.82e14	6.17e4	wd	3.6	Ashtabula, OH, July, 1987
CBN[e]	3.98e14	2.0e4	egs	3.7	Cooper Basin, Australia
ASH[g]	8.0e14	3.4e5	wd	3.9	Ashtabula, OH, January 2001
YOH[h]	8.3e14	8.34e4	wd	4.0	Youngstown, OH
PBN[i]	3.16e15	3.287e6	wd	4.3	Paradox Valley, CO
RAT1[j]	4.5e15	4.26e5	wd	4.4	Raton Basin, CO, September 2001
GAK[k]	1.2e16	6.29e5	wd	4.7	Guy, AR
POH[l]	2.0e16	1.19e6	wd	4.8	Painesville, OH
RMA[m]	2.1e16	6.25e5	wd	4.85	Denver, CO
TTX[n]	2.21e16	9.91e5	wd	4.8	Timpson, TX
RAT2[o]	1.0e17	7.84e6	wd	5.3	Raton Basin, CO, August 2011
POK[p]	3.92e17	1.20e7	wd	5.7	Prague, OK

[a] frak = hydraulic fracturing; egs = enhanced geothermal system; wd = wastewater disposal.
[b] *Zoback and Harjes* [1997].
[c] *De Pater and Baisch* [2011].
[d] *Holland* [2013].
[e] *Majer et al.* [2007] and *Baisch et al.* [2006].
[f] *Frohlich et al.* [2011].
[g] *Seeber et al.* [2004] and *Nicholson and Wesson* [1990].
[h] *Ohio Department of Natural Resources* [2012] and *Kim* [2013].
[i] *Ake et al.* [2005].
[j] *Meremonte et al.* [2002].
[k] *Horton* [2012].
[l] *Nicholson et al.* [1988].
[m] *Herrmann et al.* [1981] and *Hsieh and Bredehoeft* [1981].
[n] *Frohlich et al.* [2013].
[o] J. L. Rubinstein et al. (manuscript submitted for publication, 2013).
[p] *Keranen et al.* [2013].

Induced Seismicity
Mechanisms – depletion induced seismicity

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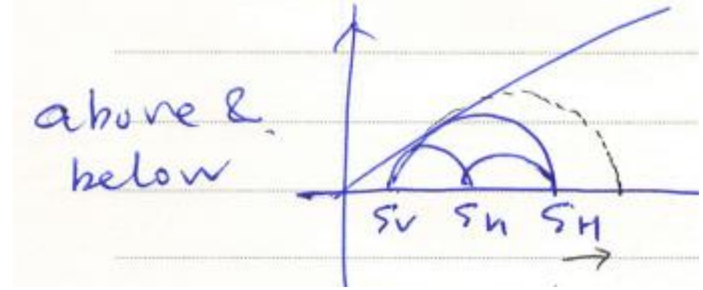
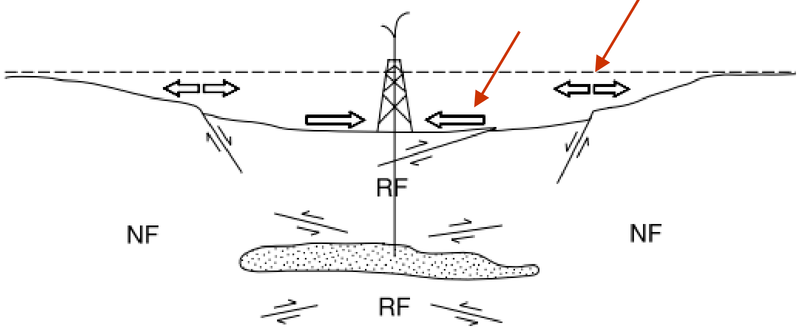
- Stresses around the reservoir
  - Reverse faulting at the top/below
  - Normal faulting at the side
  - (Normal faulting within the reservoir)





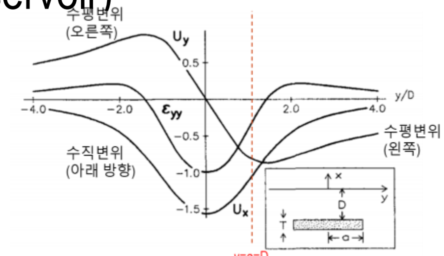
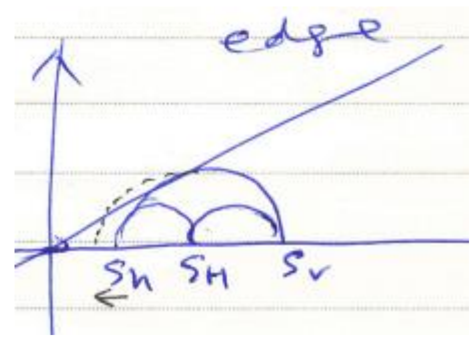
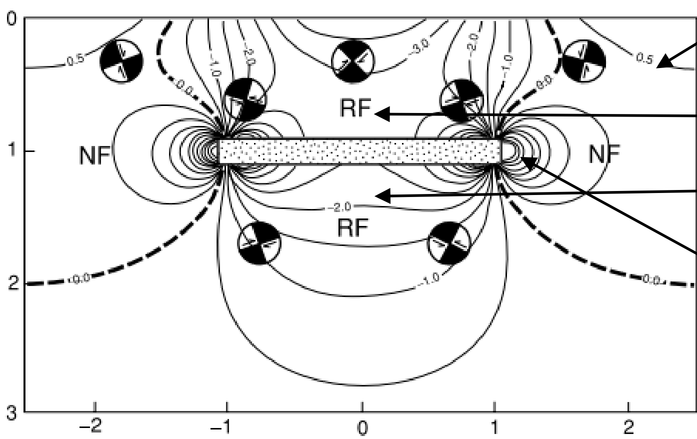


Figure 5. Calculated surface displacements u_x, u_y, and strain ϵ_{yy} (extension positive) for a/D = 1.0. Geometry is shown in inset. Displacements are normalized by $2(1+\nu_u)BT\Delta m(t)/3\pi\rho_o$, strains by $2(1+\nu_u)BT\Delta m(t)/3\pi\rho_o D$.



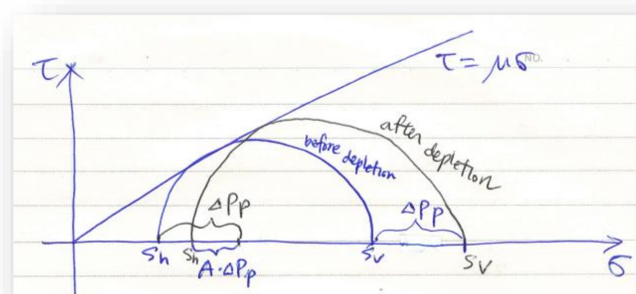


Relative change of horizontal stress. Notice: Tension (+)

Compression

Compression

tension



Segall, 1989, Earthquakes triggered by fluid extraction, Geology, 17:942-946

Induced Seismicity

Mechanisms – Seismicity vs. injection pressure

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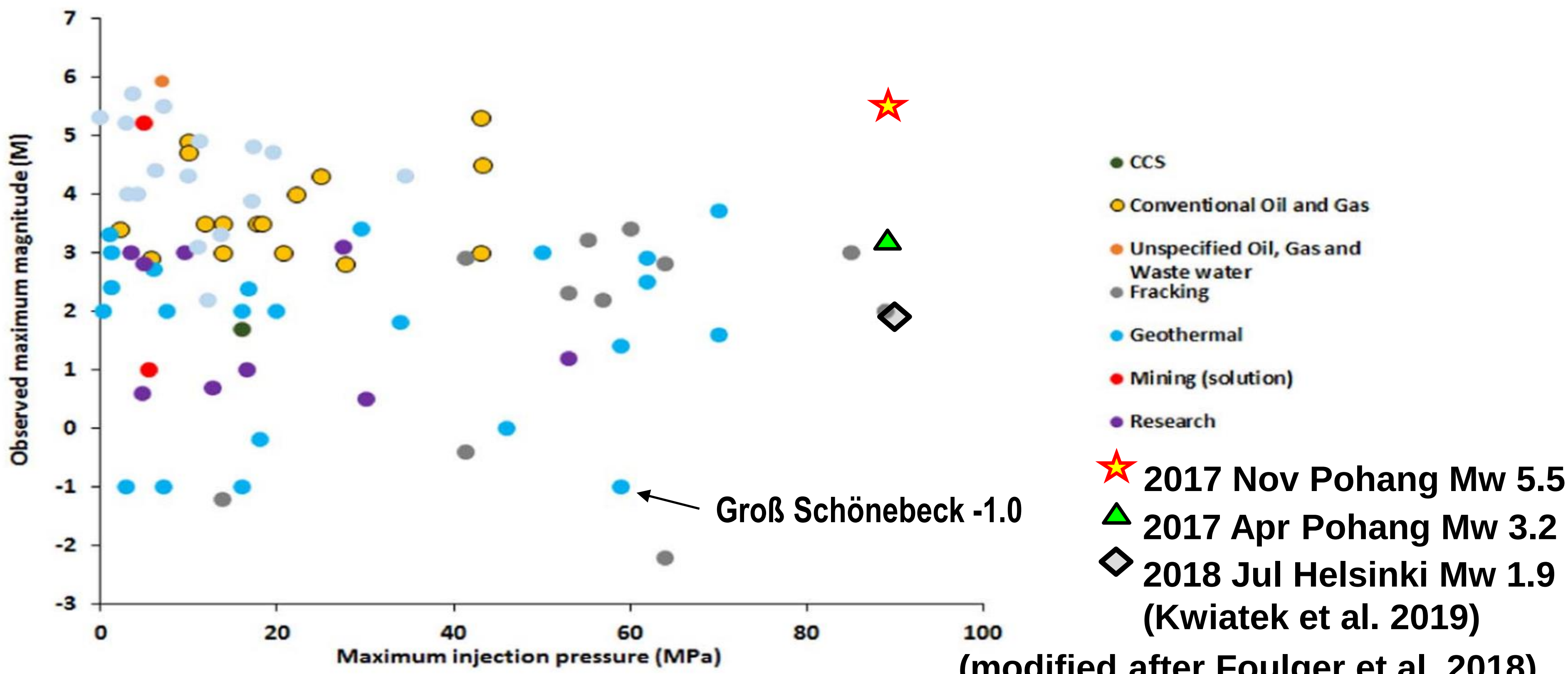
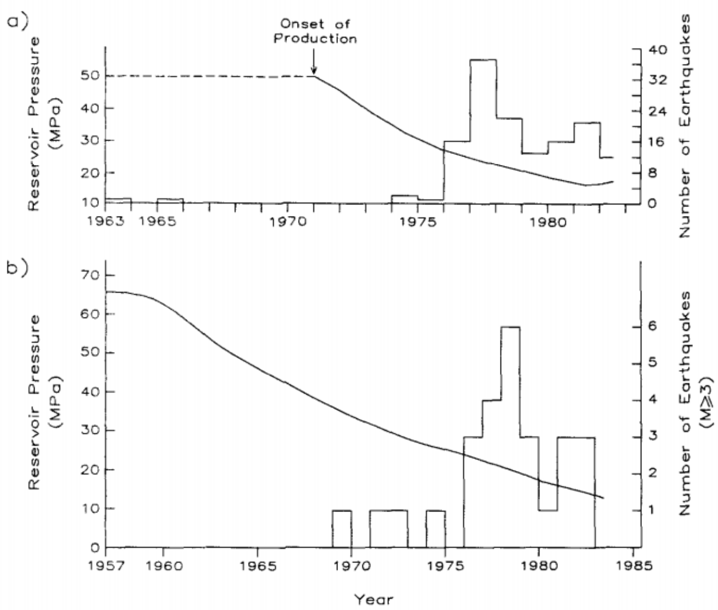
- The relationship between M_{max} and maximum injection pressure seems to be mildly related*, however, this has to be interpreted with caution (perm, injectivity…)*



(modified after Foulger et al. 2018)

- Withdrawal of fluid can induce faulting in reservoir



Strachan field in Alberta (Canada). Average static bottomhole pressure at 2.8 km

Pau basin (France). M >3 earthquakes and average reservoir pressure

Number ot earthquakes recorded per year and decline in average reservoir pressure (Segall, 1989)

Segall, 1989, Earthquakes triggered by fluid extraction, Geology, 17:942-946

Induced Seismicity
Examples: Basel EGS project (2006)

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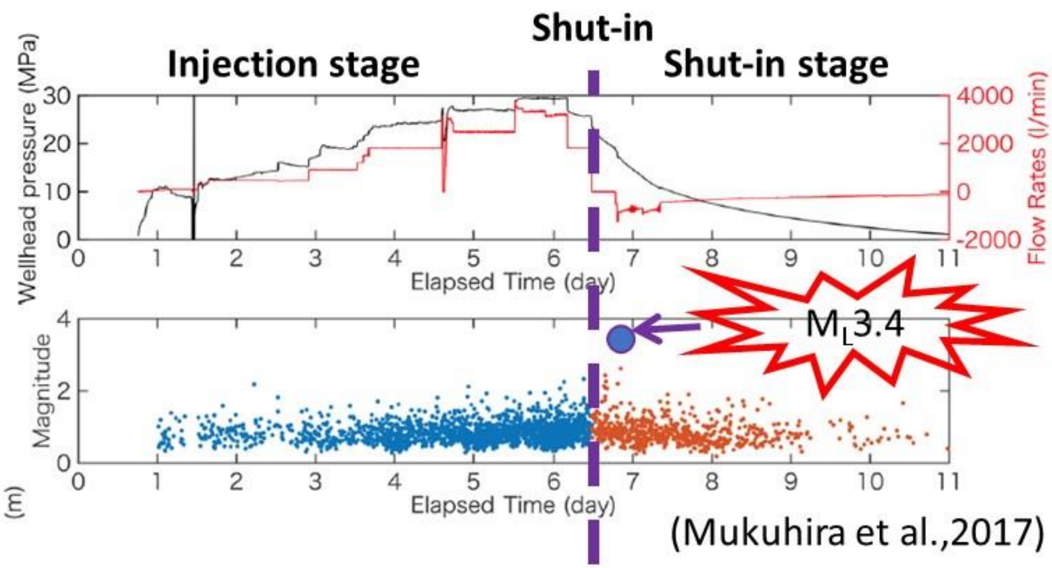
- Basel Deep Heat Mining project (2006)
  - Borehole at 5 km, Injection: 11,570m3
  - Maximum seismicity: ML 3.4 (5 hours after shut-in)
  - The project was suspended immediately, and closed permanently after 3 years
  - Property damage: 7 million swiss franc

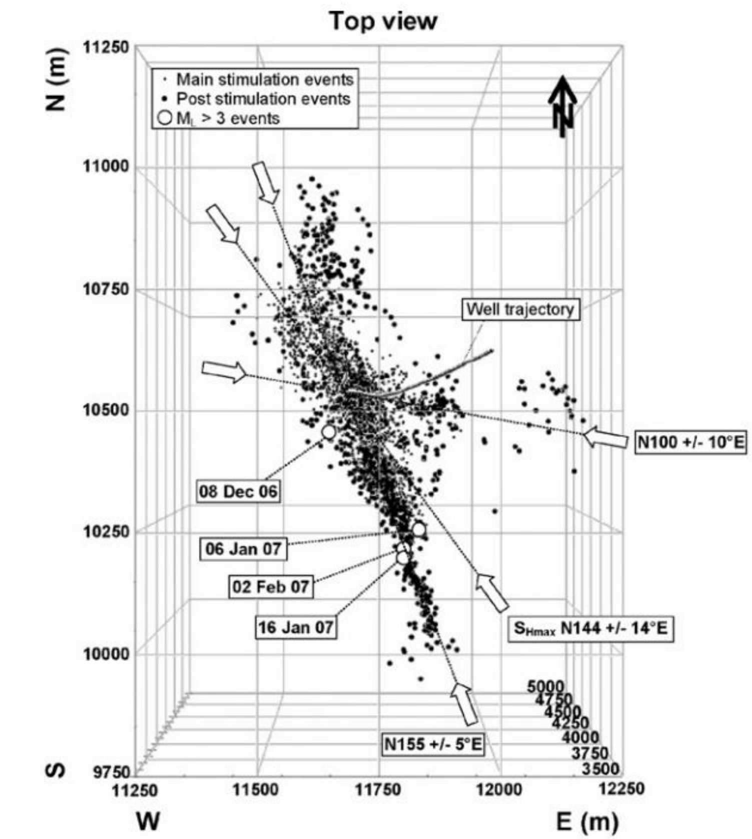


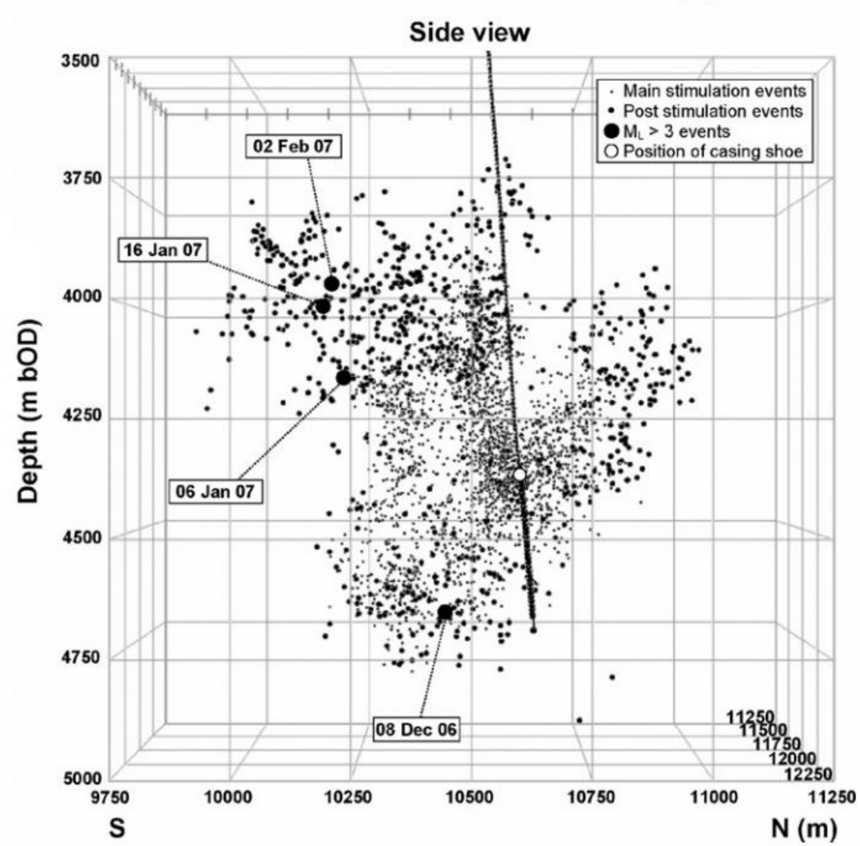
(Mukuhira et al.,2017)

Häring, M. O., et al. (2008). "Characterisation of the Basel 1 enhanced geothermal system." Geothermics 37(5): 469-495.

Induced Seismicity
Examples: Basel EGS project (2006)

- Microseismicity during main stimulation and post stimulations





Häring, M. O., et al. (2008). "Characterisation of the Basel 1 enhanced geothermal system." Geothermics 37(5): 469-495.

Induced Seismicity
Management – Induced seismicity Protocol

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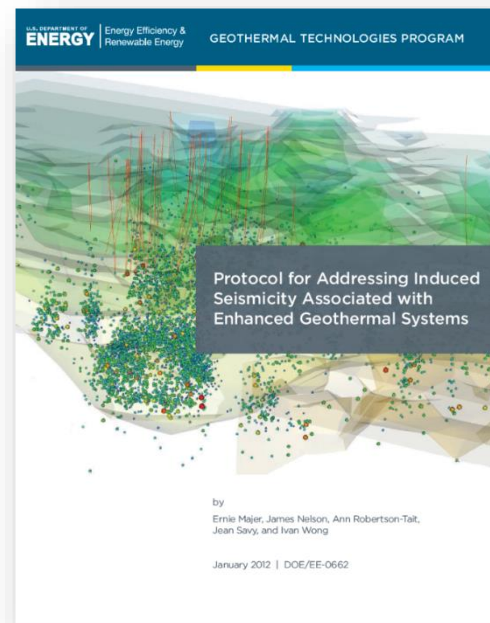
- Composed of seven steps for management of EGS (Majer et al., 2012)
- Pohang EGS project also applied this protocol (Kim et al., 2018)

Steps	Contents
Step 1	Perform a preliminary screening evaluation
Step 2	Implement an outreach and communication program
Step 3	Review and select criteria for ground vibration and noise
Step 4	Establish seismic monitoring
Step 5	Quantify the hazard from natural and induced seismic events
Step 6	Characterize the risk of induced seismic events
Step 7	Develop risk-based mitigation plan



Majer et al., 2012, Protocol for addressing induced seismicity associated with Enhanced Geothermal Systems, US DOE/EE-0662
Kwang-Il Kim, Ki-Bok Min*, Kwang-Yeom Kim, Jae-Won Choi, Kern-Shin Yoon, Woon Sang Yoon, Byungjoon Yoon, Tae Jong Lee, Yoonho Song, Protocol for induced microseismicity in the first Enhanced Geothermal System Project in Pohang, Korea. Sustainable and Renewable Energy Review 91, 1182-1191

Induced Seismicity
Management – Traffic Light System

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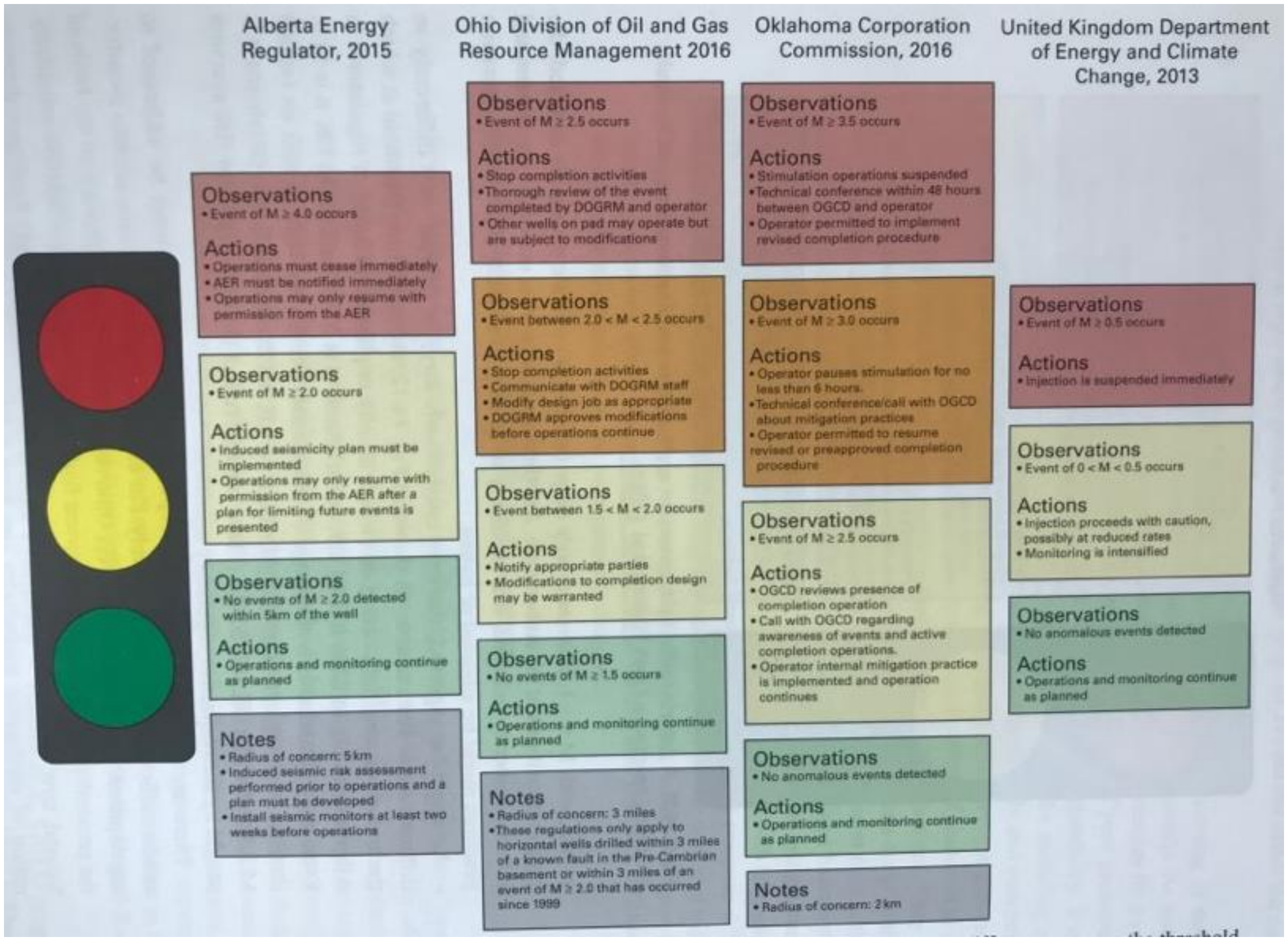
- Traffic Light Systems used in different applications



Zoback MD, Kohli AH, 2019, Unconventional Geomechanics, Cambridge Univ press

Induced Seismicity
Management – Traffic Light System

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- Step 7. Develop risk based mitigation plan – Traffic Light System
  - Firstly suggested in Bérlin, El Salvador (Bommer et al., 2006) and Basel (Häring et al., 2008)
  - Pohang EGS project
    - M_L 2.0 or 2.5 used as maximum criteria (Kim et al., 2018)

M_L	Stage	Pumping	Injection pressure	Report	PGV (cm/s)
	Stage 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 hall, MOTIE, KETEP)	
2.0					2.0
	Stage 4	Stop	Bleed off excess pressure	Alarm to H.S. team Report to research institutions (SNU, KICT, KIGAM, POSCO, INNOGEO)	
1.7					1.0
	Stage 3	Reduction or stop	Reduction or constant pressure	Alarm to H.S. team (H.S. team, M.S. monitoring team, Boards of NEXGEO)	
1.4					0.5
	Stage 2	Constant flow rate	Constant pressure	Report to hydraulic stimulation team (H.S. team, M.S. monitoring team)	
1.0					0.08
	Stage 1	Regular operation	Regular operation	Regular report (Microseismicity monitoring team)	

* Flow rate and injection pressure would be regulated dependently during hydraulic stimulation.
* Axis of M_L and PGV do not correspond to one-to-one each other.

Kwang-Il Kim, Ki-Bok Min*, Kwang-Yeom Kim, Jae-Won Choi, Kern-Shin Yoon, Woon Sang Yoon, Byungjoon Yoon, Tae Jong Lee, Yoonho Song, Protocol for induced microseismicity in the first Enhanced Geothermal System Project in Pohang, Korea. Sustainable and Renewable Energy Review 91, 1182-1191

Induced Seismicity
Management – Outreach and Communication

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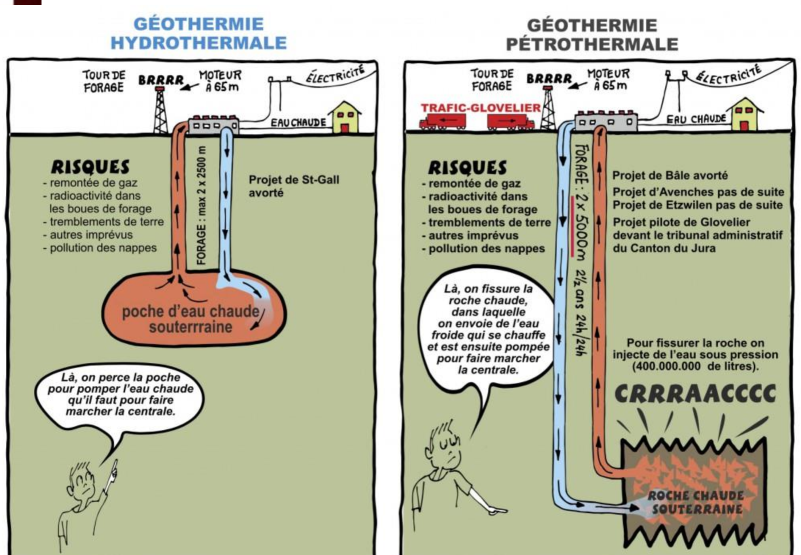
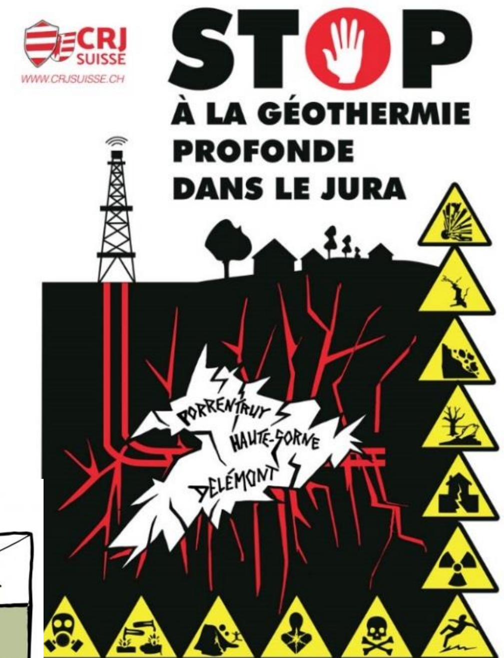
- Public engagement is a critical components for energy related project
- http://crjsuisse.ch/
  - https://youtu.be/bPNrRXvCHsM





Poster against EGS in Haute-Sorne, Switzerland

Induced Seismicity
Management – Outreach and Communication

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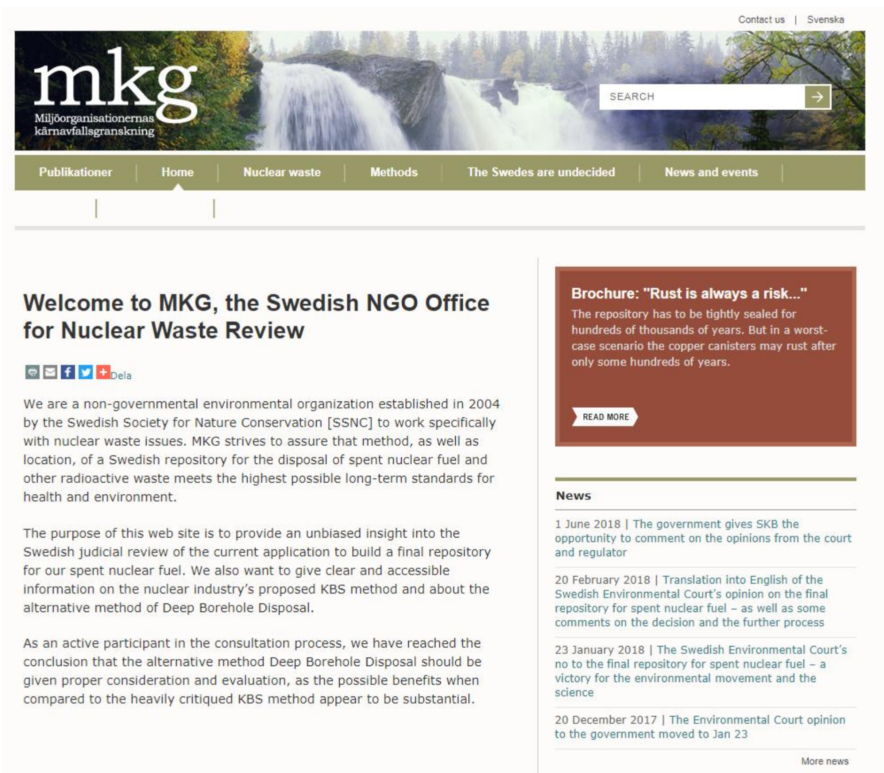
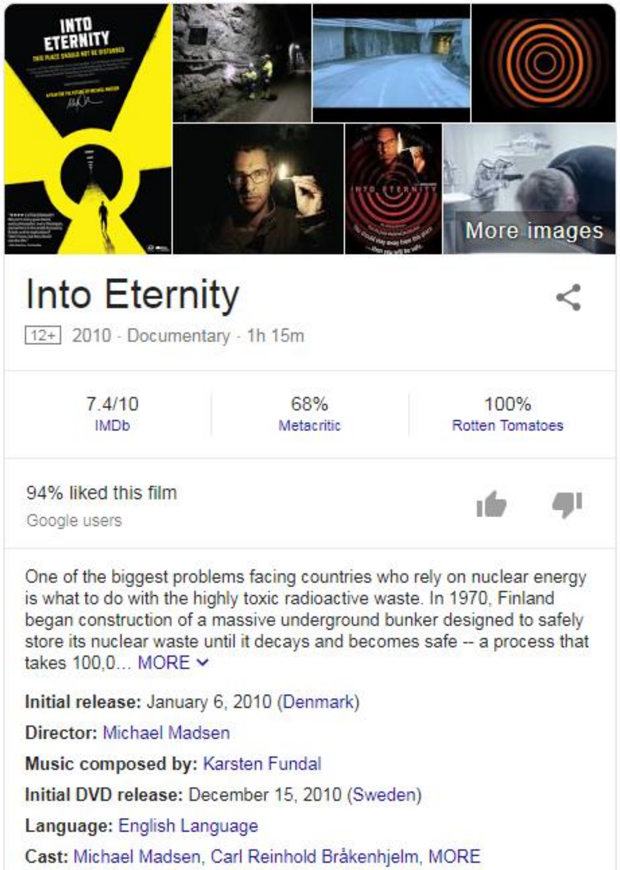
- A case from geological repository for nuclear waste in Sweden and Finland
  - Transparency is the key for implementation of underground energy applications





Induced Seismicity
Management – change of injection scheme

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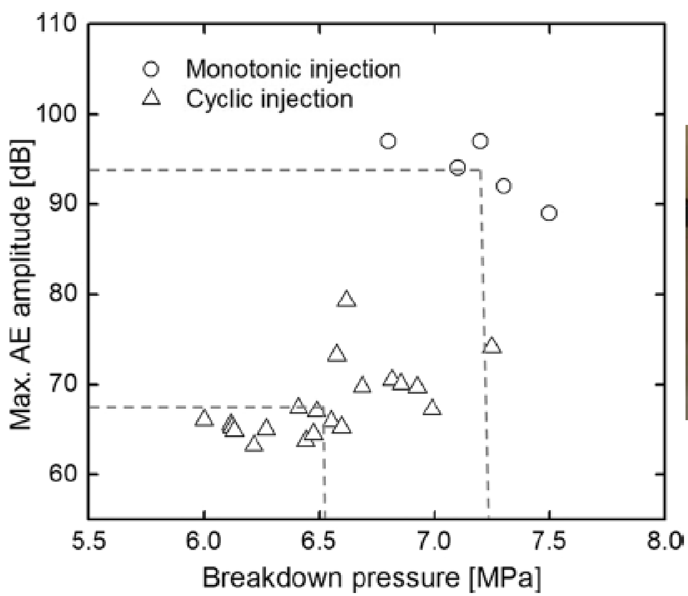
- Reductions of the induced seismicity in the lab and underground research lab scale are observed (Zang et al., 2018), *however, appropriate validation in reservoir scale remains to be achieved.*

Lab scale (KICT)



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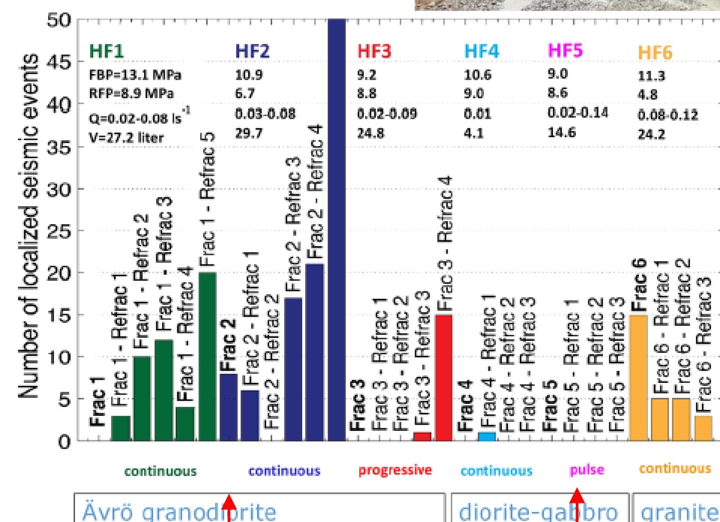

Continuous inejction

Cyclic injection

Zang A, Zimmermann G, Hofmann H, Stephansson O, Min KB, Kim KY, 2018, How to Reduce Fluid-Injection-Induced Seismicity, *Rock Mechanics and Rock Engineering*, in press

Induced Seismicity
Discrimination between natural and induced

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- Davis and Frorich's criteria (1993)

Questions		Not induced	Induced
Background Seismicity	Are these events the first known earthquakes of this character in the region?	No	Yes
Temporal Correlation	Is there a clear temporal correlation between injection and seismicity?	No	Yes
Spatial Correlation	Are **epicenters** near wells (within 5km)?	No	Yes
	Do some earthquakes occur at or near injection **depths**?	No	Yes
	If not, are there **known geologic structures** that may channel flow to sites of earthquakes?	No	Yes
Injection Practices	Are changes in **fluid pressure at well bottoms** sufficient to encourage seismicity?	No	Yes
	Are changes in **fluid pressure at hypocentral locations** sufficient to encourage seismicity?	No	Yes

Davis SD and Frohlich C, 1993, Did (or will) fluid injection cause earthquakes? – criteria for a rational assessment, Seismological Research Letters, Vol. 64(3-4):207-224