Characteristics of Seismicity related to Hydro-Fracturing Review and Case Studies

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Overview

- PART I. A review on Hydro-Fracturing and Anthropogenic Seismicity
  - ✓ Introduction on Anthropogenic Seismicity
  - ✓ Introduction on Hydro-Fracking
  - ✓ Reported Cases
  - ✓ Mechanisms of IS (*Poroelasticity - Fault Reactivation*)
  - ✓ Characteristics of Fracking Seismicity
- PART II. Case Studies

  - Preese Hall (UK)

  - British Columbia (Canada)

  - Geothermal fields and associated induced seismicity: The Geysers (US), Case Study
- PART III. Conclusions

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Anthropogenic Seismicity

(or 'stimulated' according to McGarr and Simpson, 1997)

Triggered Seismicity

Regards large events (M>5.5) on nearby active tectonic faults, at a distance up to a few tens of kilometers.

Induced Seismicity

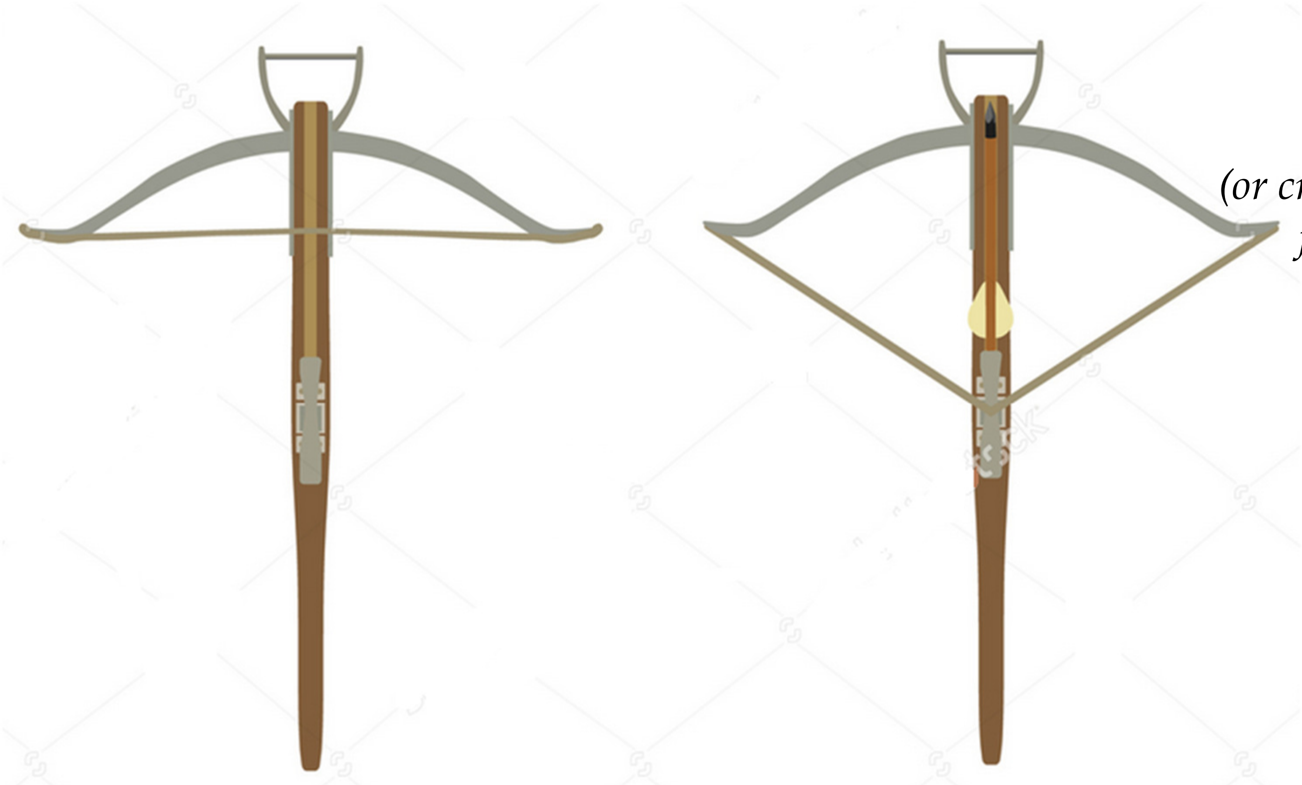
Most earthquakes concern small magnitude events (M<3.0) located in the vicinity of the activities themselves.

Loose Crossbow

(or unfavorable conditions for slip – potentially high but very localized stresses)

Pulling the trigger offers a tiny energy amount to the system <<<< 1Joule

Loose
Crossbow
(or unfavorable conditions for slip – potentially high but very localized stresses)



Stretched
Crossbow
(or critically pre-stressed fault, independently close to instability)

Pulling the trigger offers a tiny energy amount to the system <<<< 1Joule

The system releases huge amount of energy, several orders of magnitude larger than the 'trigger mechanism'. e.g. 130 Joules *(for bolt mass and initial velocity equal to 25g and 100m/s , respectively)*

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Anthropogenic Seismicity

(or 'stimulated' according to McGarr and Simpson, 1997)

Triggered Seismicity

It is caused by transient phenomena, concerning the nucleation of **a small region** of the rupture area, whereas the entire rupture is controlled by the background stress

Induced Seismicity

The nucleation process is **entirely** (e.g. in terms of rupture size, stress changes and energy released) controlled by its causative origin and would not occur otherwise

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HYDRAULIC FRACTURING

Induced Seismicity

The nucleation process is **entirely** (e.g. in terms of rupture size, stress changes and energy released) controlled by its causative origin and would not occur otherwise

FRACKING- fracture stimulating

Fracking
History

History

- Pioneered in 1947
- Used in 1.2 milion wells
- Modern day fracking since 1990s

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Fracking
History
Geology

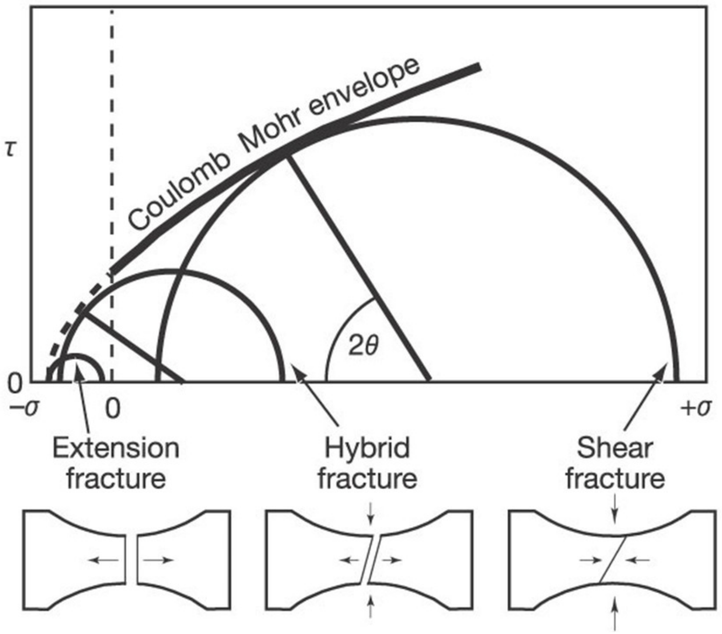

Diagram showing that for high differential stress (bigger stress circle, right), the rock will fail in shear, whereas for low differential stress (small circle, left) the failure mode will be tensile; http://www.nature.com/

Geology

- Permeability→porosity
- Local in situ stress field
- Rock strength
- Pore fluid pressure
- (temperature, elastic properties, pore water chemistry, loading rate)
- Mechanical (elastic) anisotropy

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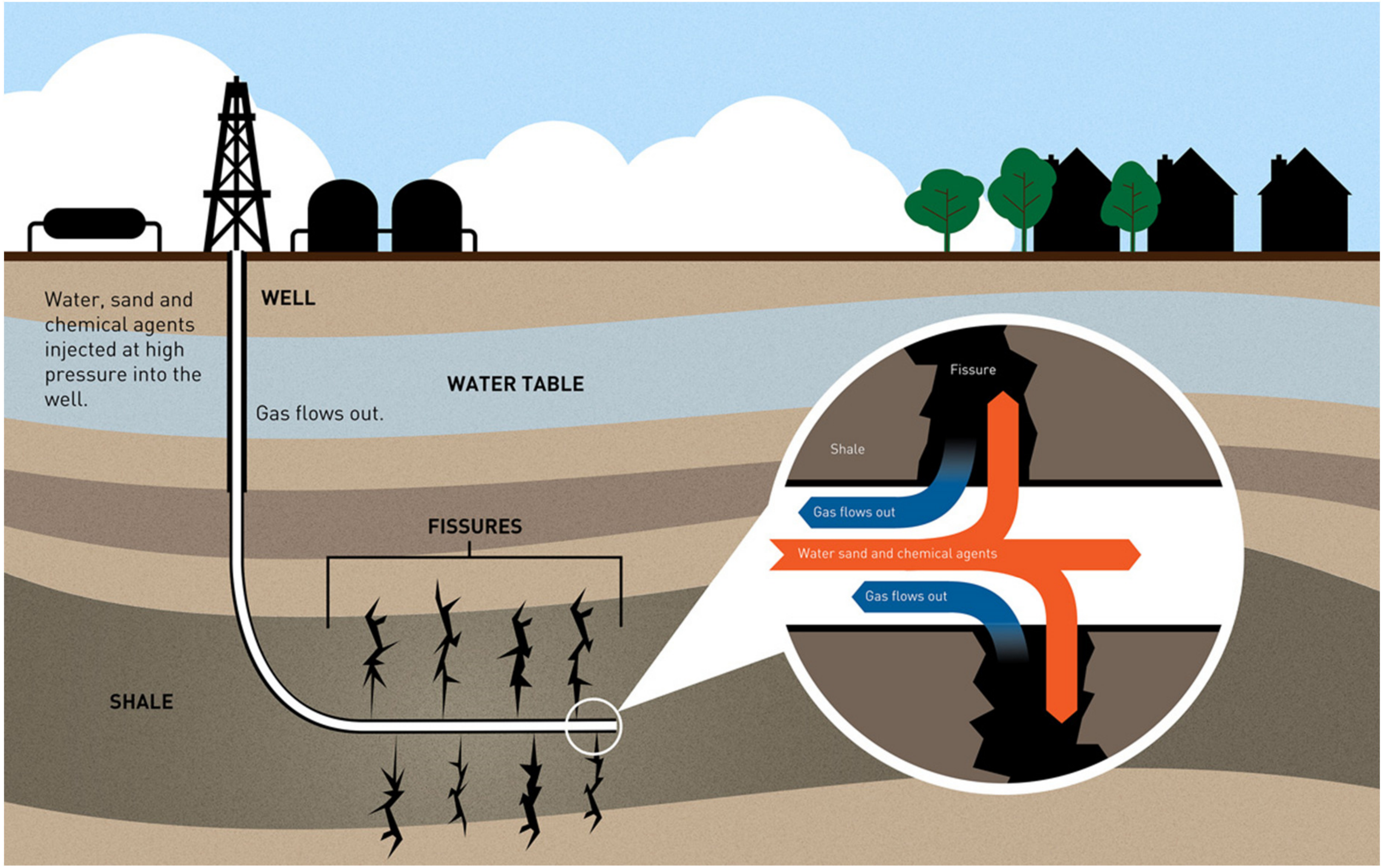
Fracking Process and Techniques



Schematic diagram showing the general features of a fracking operation; http://publisher.attn.com/

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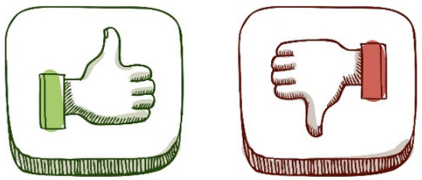
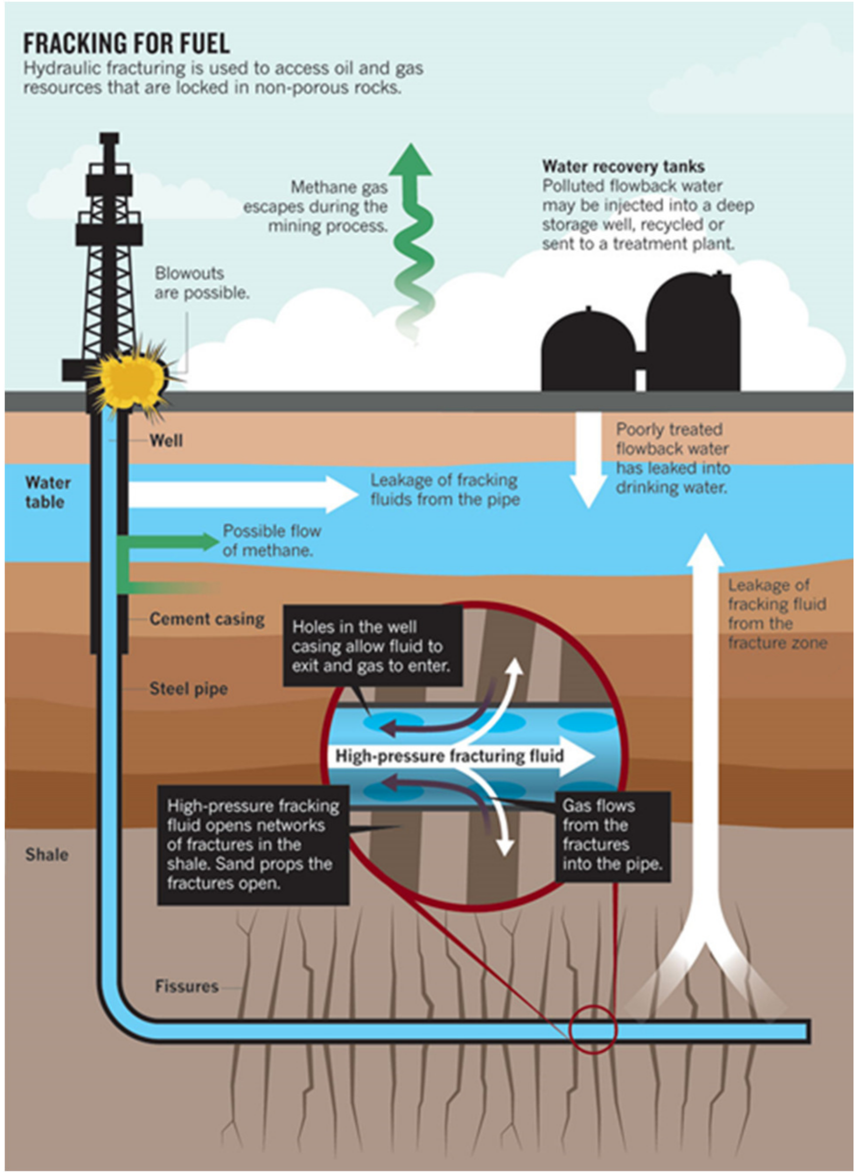
Fracking
Environmental Impact

Environmental impacts

- contamination of ground water, and possibly even drinking water, with natural gas and other chemicals;
- emissions of volatile components, such as CO_2 or methane, into the atmosphere;
- the leakage of contaminated drilling waste fluid from storage ponds.
- **Induced Seismicity**





Schematic diagram showing the general features of a fracking operation; NAGTWorkshops

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Seismicity Associated with Fracking

- Energy release is much less than the other kinds of IS (e.g. mining, reservoir impoundment)

- Intensity is likely to be smaller due to the greater depth at which shale gas is extracted compared with other IS technologies.

- Most of the induced events are not even felt on surface

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Fracking Comparison with other cases of induced seismicity

We subdivide the seismicity by likely trigger mechanism into:

<table>
<tr><th>Fracking</th><th>Mine subsidence</th><th>Oil and gas field depletion</th><th>Fluid injection for secondary oil recovery</th><th>Waste-water disposal</th></tr>
<tr><td rowspan="3">• Lancashire UK 2011 2.3 M_L
• Etsho and Kiwigana, Canada 3.8 M_L
• Eola Field Oklahoma 2.8 ML
• 4.6 M_L (2015) the highest one in Canada</td><td>These earthquakes range from M 1.6 to 5.6 .</td><td>In 1976, 1984 there were M 7.0 events at Gazli, Uzbekistan.</td><td>Magnitudes of earthquakes range from M 1.9 to 5.1. Example Ekofisk field (North Sea, UK).</td><td>Magnitudes of 2.0 to 5.3.</td></tr>
<tr><th>Solution mining</th><th>Enhanced Geothermal Systems operations</th><th>Reservoir impoundment</th><th>Groundwater extraction</th></tr>
<tr><td>That earthquake occurred in Attica (New York, USA) in 1929, and had a magnitude of M 5.3.</td><td>Basel, Switzerland EGS project . In total, 13,500 earthquakes were recorded, nine of which were of ML 2.5 or larger.</td><td>Magnitudes of recorded cases range from 1.0 to 7.9.</td><td>Mw 5.1 earthquake that occurred in Lorca, southeast Spain, 11th May 2011.</td></tr>
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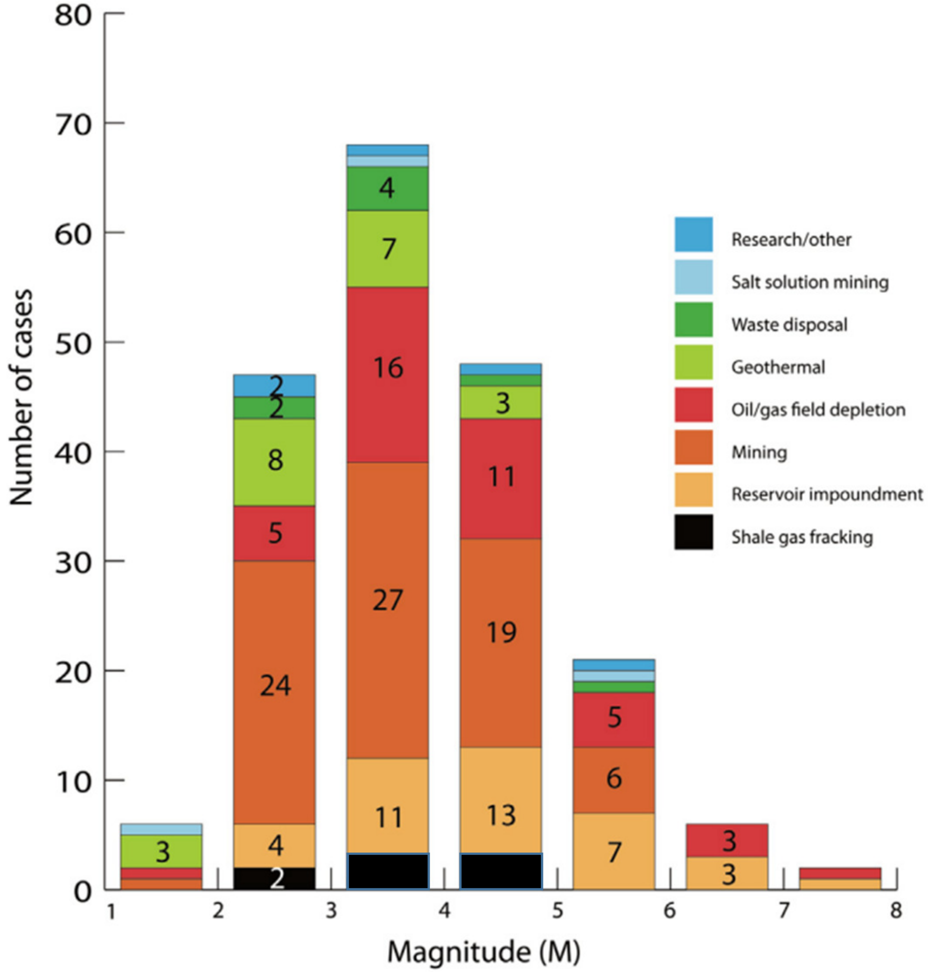
Fracking
Comparison with other cases of induced seismicity

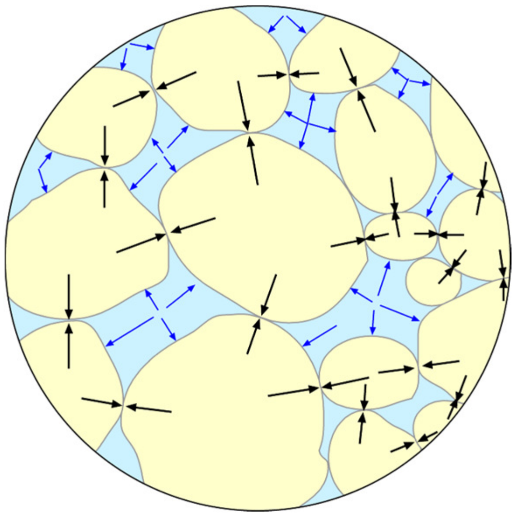


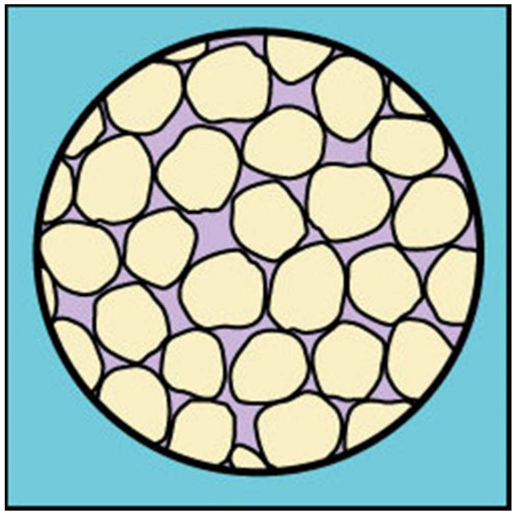
Frequency vs. magnitude for 198 published examples of induced seismicity (Modified from Davies et al., 2013)

Poroelasticity

The mechanical behavior of elastic solids strongly depend on whether they are saturated with water or are primarily dry.

Poroelasticity theory can explain a variety of phenomena associated with induced seismicity, over time periods ranging from hours to years.





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Poroelasticity theory

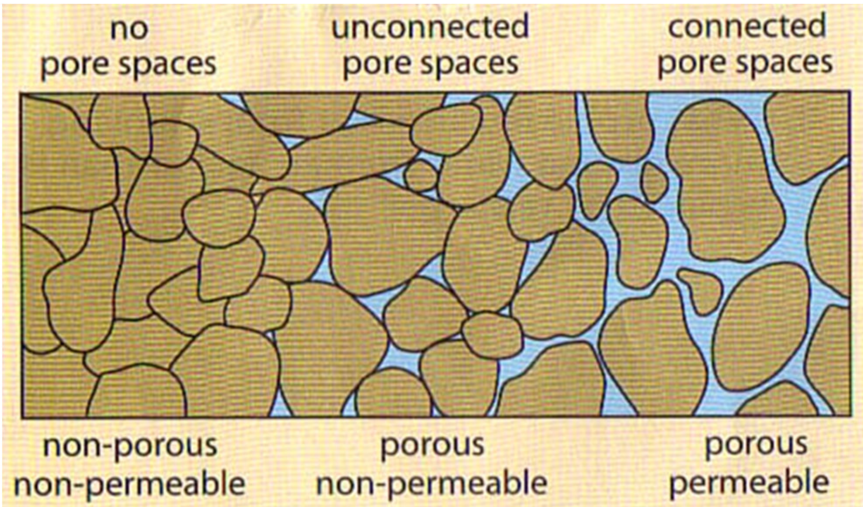
- **Three principal assumptions**:

  1. interconnected pore system uniformly saturated with fluid,

  2. total volume of the pore system is small compared to the volume of the rock as a whole,

  3. considered: **pore pressure**, **total stress** acting on the rock externally, **stresses acting on individual grains**.

- Fluid pressure pulses can move on greater distances in preexisting natural fracture systems.



Arizona State University

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Why does fault reactivation occur?

HYDRAULIC FRACTURING → pore pressure ↗ → effective normal stress ↘ →
→ SHEAR FAILURE

Effective stress according to *Terzaghi (1923)*:

$$\sigma_{ij} = S_{ij} - \delta_{ij} P_p$$

σ_{ij} – effective stress

S_{ij} – total stress acting on the rock externally

P_p – pore pressure

δ_{ij} – Kronecker delta → pore pressure influences only normal (not shear) components of stress tensor

Why does fault reactivation occur?

- Concept of effective normal stress *(Terzaghi, 1943)*: difference between total normal stress and pore pressure

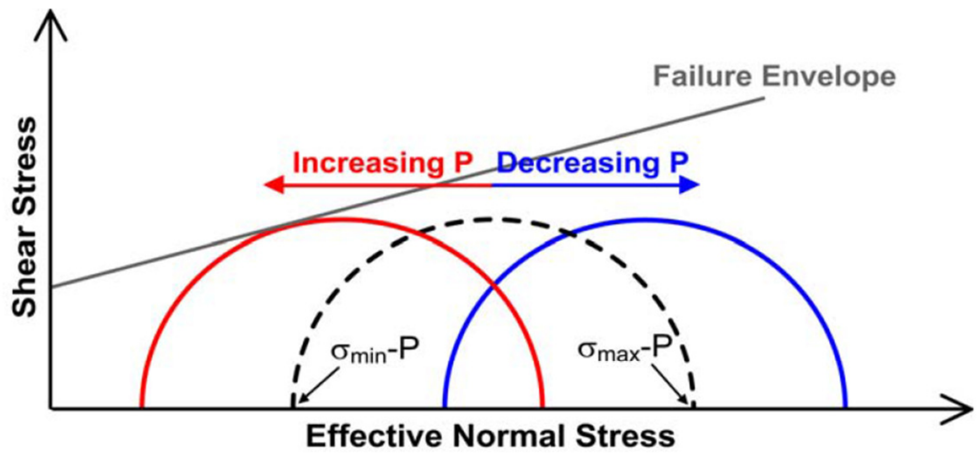

Figure 1-1. Mohr diagram, illustrating the effect of pore pressure change on the effective state of stress. σ_{max} and σ_{min} are equally influenced by the pore pressure, therefore the diameter of the Mohr circle is does not change. The dashed Mohr circle describes an initial state of stress, the red Mohr circle the effective state of stress after fluid injection, the blue Mohr circle the effective state of stress after depletion. During injection of fluid the Mohr circle shifts towards the failure envelope, thus failure becomes more likely. During fluid depletion, failure becomes more unlikely.

Altmann, 2010

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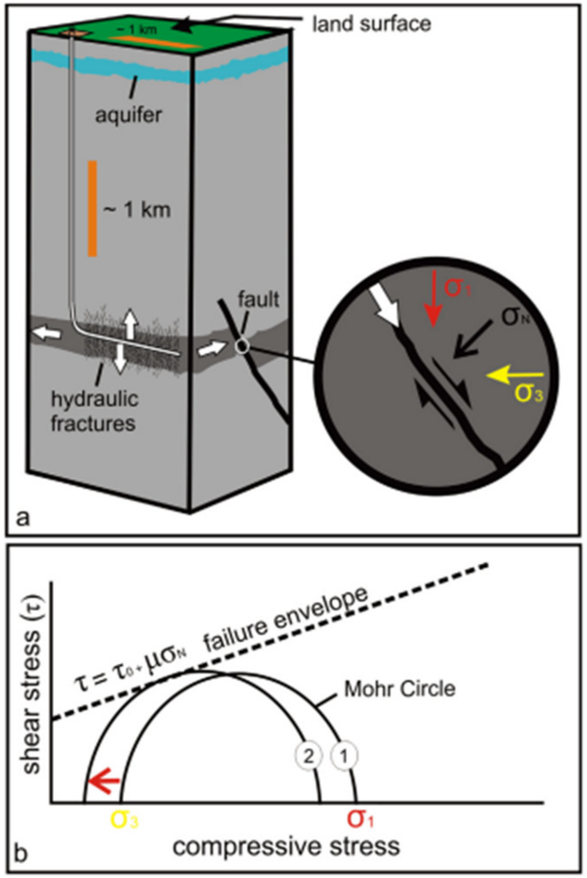
Why does fault reactivation occur?



Davies et al., 2013

A fault slips when the normal stress across a fault plane drops to a sufficiently low level that the **shear stress overcomes the static friction** on the fault surface (static friction = $\mu\sigma_N$).

A fault can be brought to a critical state either by:

- **increasing the shear stress**, e.g., by plate motions or surface loading,
- **decreasing the normal stress** that clamps the fault surfaces together. The latter could be caused by processes such as stretching, exhumation and erosion and by **increasing the fluid pressure in the fault zone**.

According to *Mulargia & Bizzarri, 2014* active faults can be triggered by fluid overpressures <0.1 MPa.

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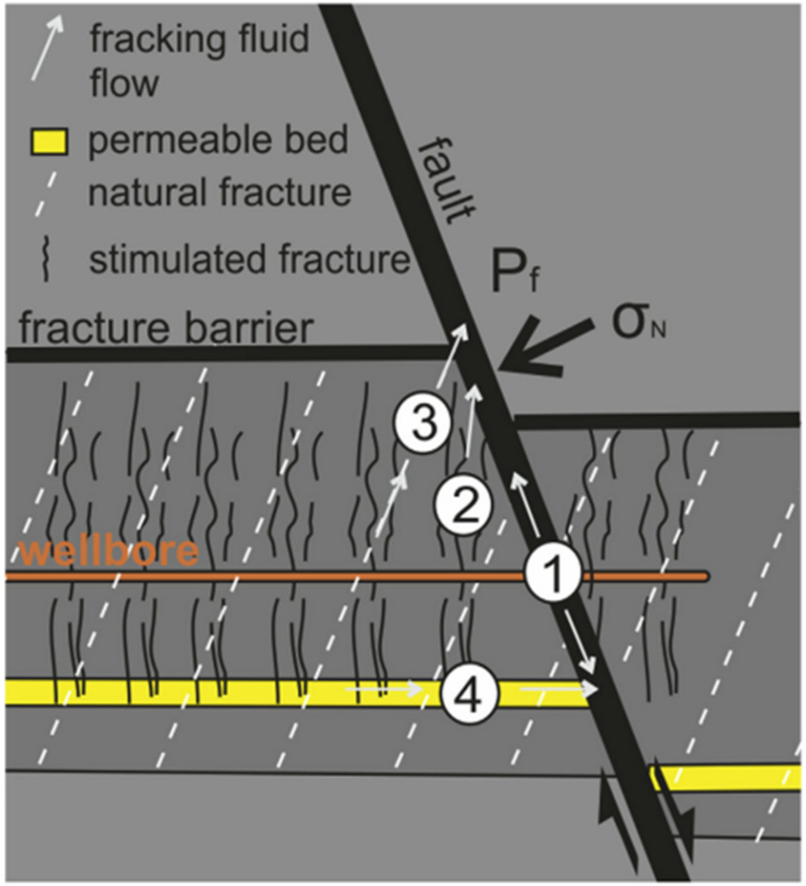
Why does fault reactivation occur?



Davies et al., 2013

Potential mechanisms for the transmission of a pore fluid pressure pulse or fluid into a fault to cause reactivation:

1 – direct injection into the fault,

2 – fluid flow through the stimulated hydraulic fractures,

3 – fluid flow through the existing fractures,

4 – fluid flow through permeable strata and along bedding planes.

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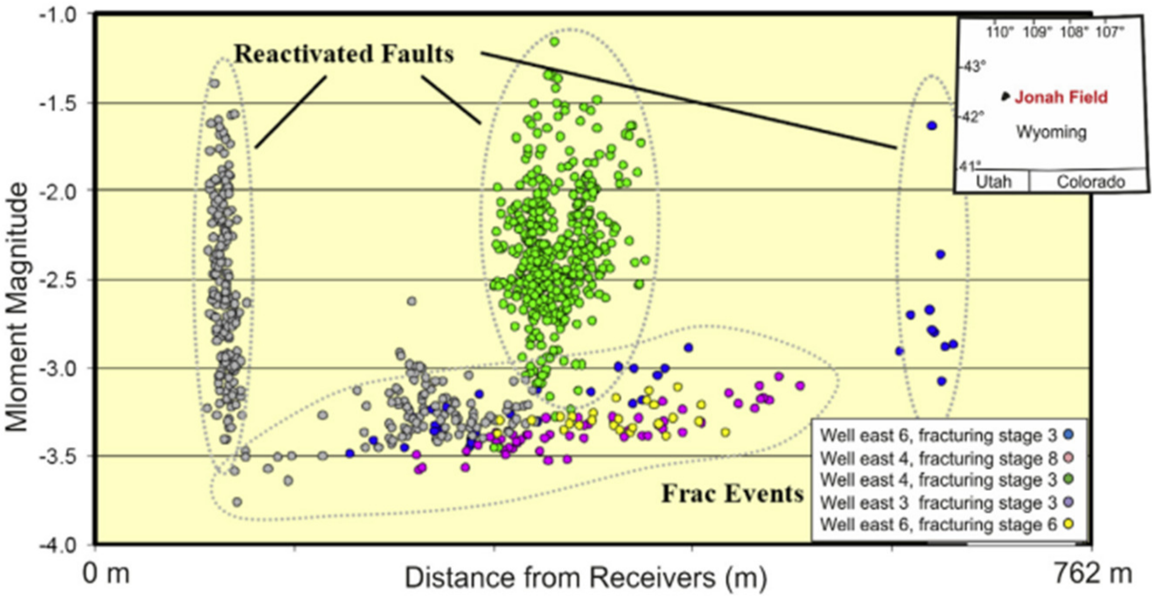
Seismicity caused by fault reactivation

- Identification on M_W(dist) plot:



Davies et al., 2013

M_W(dist) plot:

- **Anomalously large magnitudes,**
- **Clustering at specific distances** from well.

Other indicators of fault reactivation:

- **increase in the magnitude** of the microearthquakes **with time,**
- **sharp reduction in b-value** (calculated for a moving subset of events over the time that pumping took place),
- **significant increase in the normalized seismic energy** emitted (*Wessels et al., 2011*).

Seismicity caused by fault reactivation

- There is often a **time lag** of several hours between the **start of pumping** and **fault reactivation**:
  - ca 10h – Preese Hall,
  - ca 80min – Western Canada,
  - several hours – Horn River.

- The delay between pumping and the reactivation of some faults may in part be because the fault into which fluid is injected has **inherent storage and transmissibility characteristics**, or due to the time required for the **transmission of fluid pressure by pressure diffusion** and due to poroelasticity.

- Examples of fault reactivation during hydraulic fracturing:
  - **Etsho and Kiwigana Fields (Horn River, Canada) (M=3.8), 2011**
  - **Eola Field, Oklahoma, USA (M=2.8), 2011**
  - **Preese Hall, UK (M=2.3), 2011**
  - Montney Formation, BC, Canada → hydraulic fractures can terminate at faults (series of NW-SE faults)
  - Barnett Shale, USA → injection directly into faults
  - Jonah Field, Wyoming USA (M<-1.0) → new hydraulic fractures fed hydraulic fracturing fluid into a fault which consequently reactivated, fault 200 m from injection well

Characteristics of Fracking Induced Seismicity

Generally implies large but highly localized stresses

↓

Fresh fracture on small volumes of the bulk rock

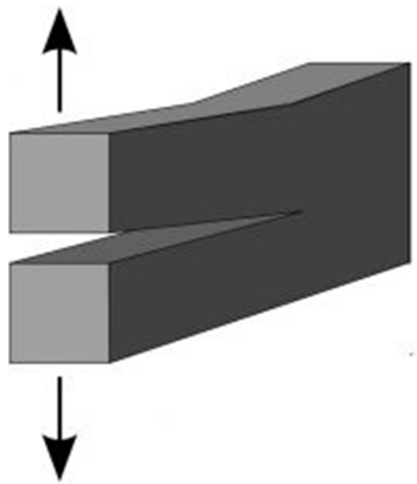
↓

Small size of events.

Fracturing Mechanisms (induced)

- Much of microseismicity associated with hydraulic fracturing, is unsurprisingly Mode-1 (Tensile) failures which have very low magnitudes, generally M_L<0.5 (reported very widely and used to map the progress of fractures)

- Fracking events usually demonstrate significant CLVD and ISO components



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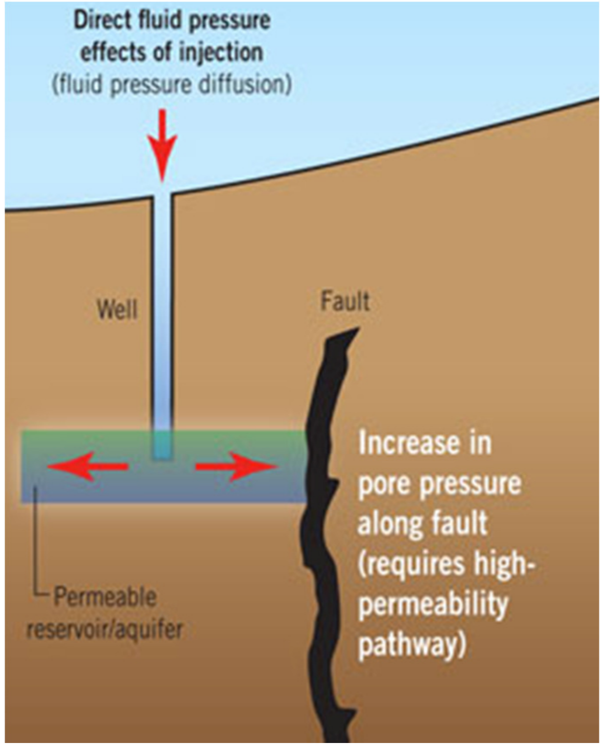
Fracturing Mechanisms (Triggered)

- Larger events are caused by fluid transmission and pore pressure changes
- Energy released is several orders of magnitude greater than the induced microseismicity energy
- Those events are highly DC



Elsworth, 2013

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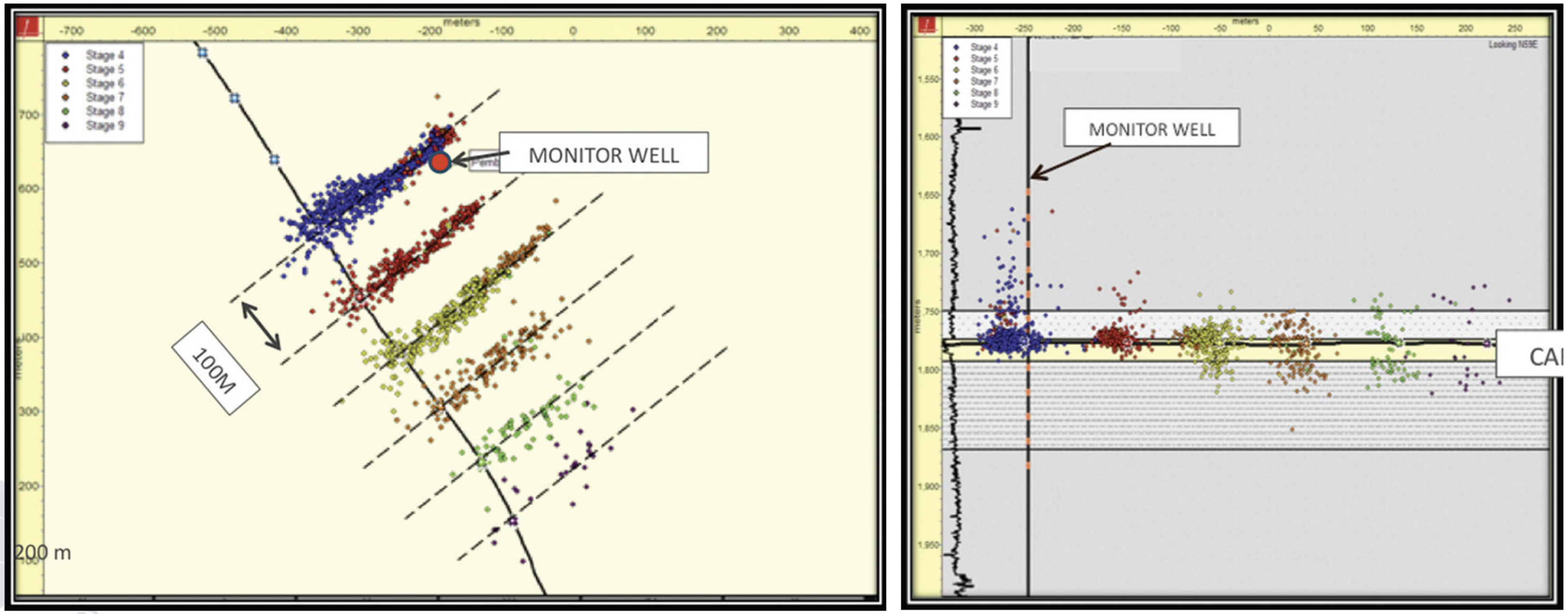
Seismicity

- Seismicity pattern generally reveals the distribution of fractures induced by the injected water.



Map view (left) and cross section (right) of fracking stages and seismicity from West Central Alberta, Canada

(Duhault, 2012)

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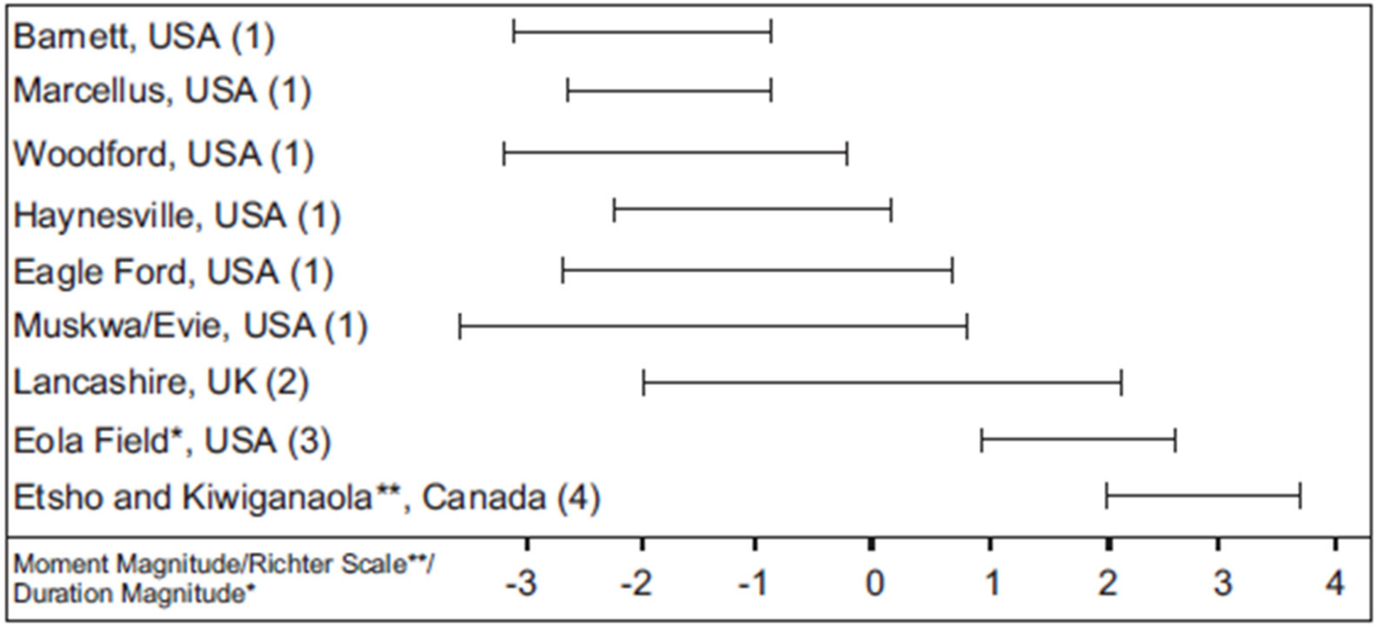
Magnitudes

- Update!!

- British Columbia:

Several events with 2.0≤M≤4.6 have been recorded from 2013-2015

Strongest event: M_L=4.6, 17th August 2015, Montney, BC



Davies et al., 2013

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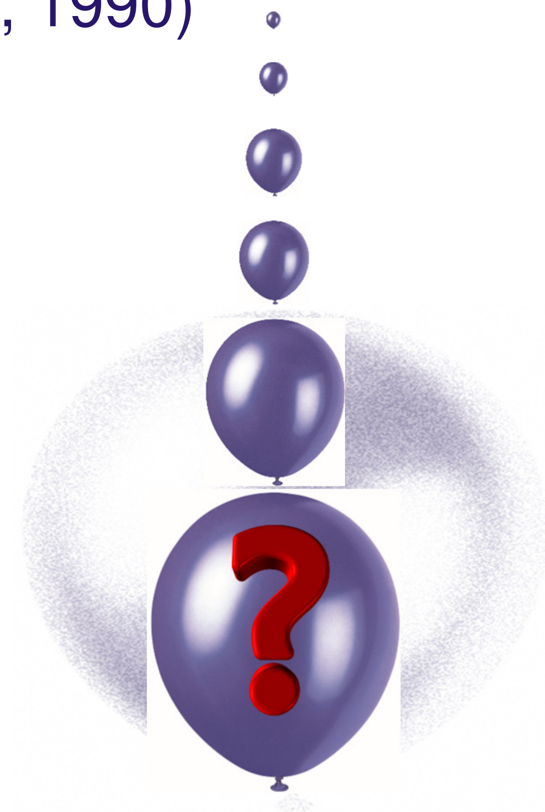
Magnitudes

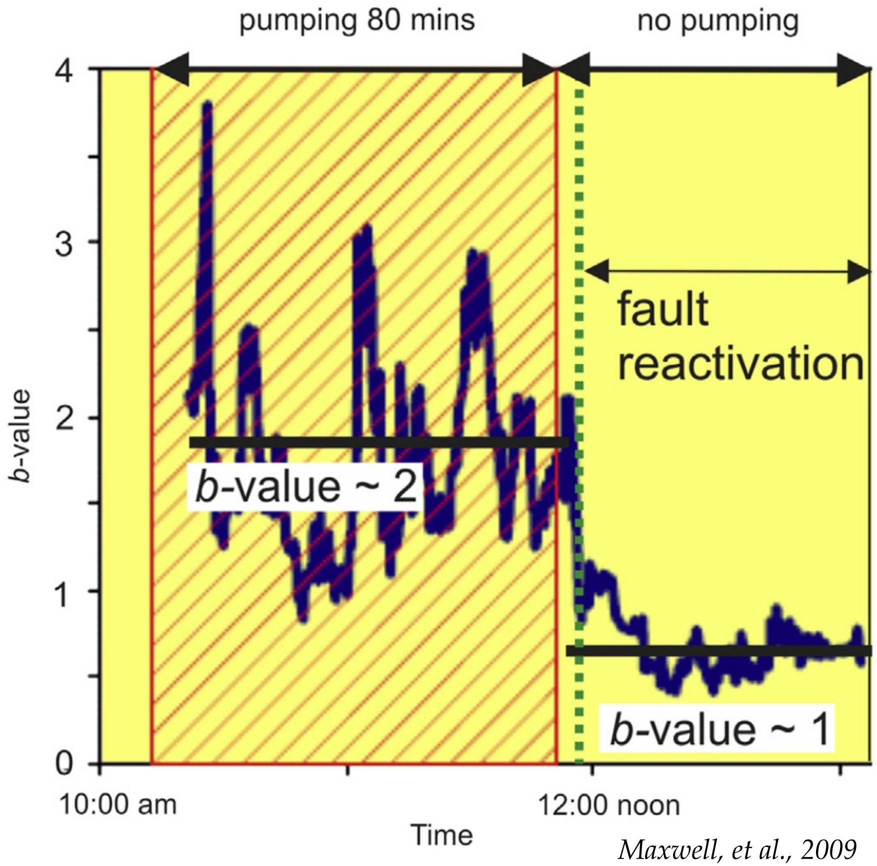
- Fracking maximum Magnitude event?

- 1979 M_{max}=1.9 (Nicholson and Wesson, 1990)
- 2009 M_{max}=2.3 Horn River Basin
- 2010 M_{max}=3.6 Horn River Basin
- 2011 M_{max}=3.8 Horn River Basin
- 2014 M_{max}=4.4 Montney
- 2015 M_{max}=4.6 Montney
- 2016 M_{max}=??
- 2020 M_{max}=??



b-values

- Fracking events usually demonstrate a b-value~2.0, whereas fault reactivation events have b-value~1.0 *(Maxwell et al., 2009; Kratz et al., 2012)*



Maxwell, et al., 2009

Technological Features

- **Factors affecting seismicity triggered by hydraulic fracturing (and magnitudes)**

a) Properties of Faults (dimensions, pre-stress status) and Shale (strength)

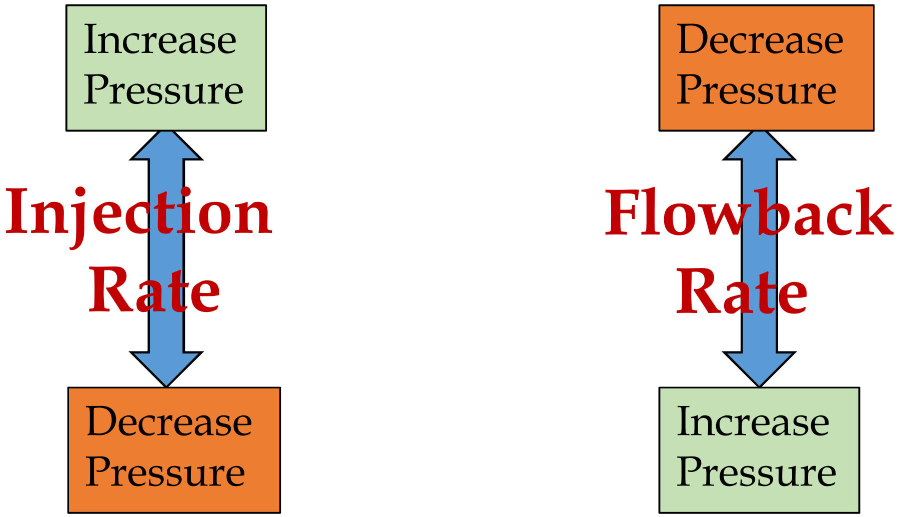
b) Pressure Constraints (Zoback, 2012)

- Pressurization takes place across a **limited volume** of rock, typically only a few hundred meters in any direction.
- Pressurization only takes place over a **limited timescale**, typically only a few hours.
- Pressure **dissipates into the surrounding** geology as more fractures are created, limiting the pressure that can build up.

Technological Features

Pressure in the well is a key determinant of induced seismicity, affected by:

- **The volume of injected fluid.** Larger volumes generate higher pressures.
- **The volume of flowback fluid** Approximately 25-75% (commonly close to 50%) of the hydraulic fracturing fluid used flows back after stimulation. Larger flowback volumes reduce the pressure.



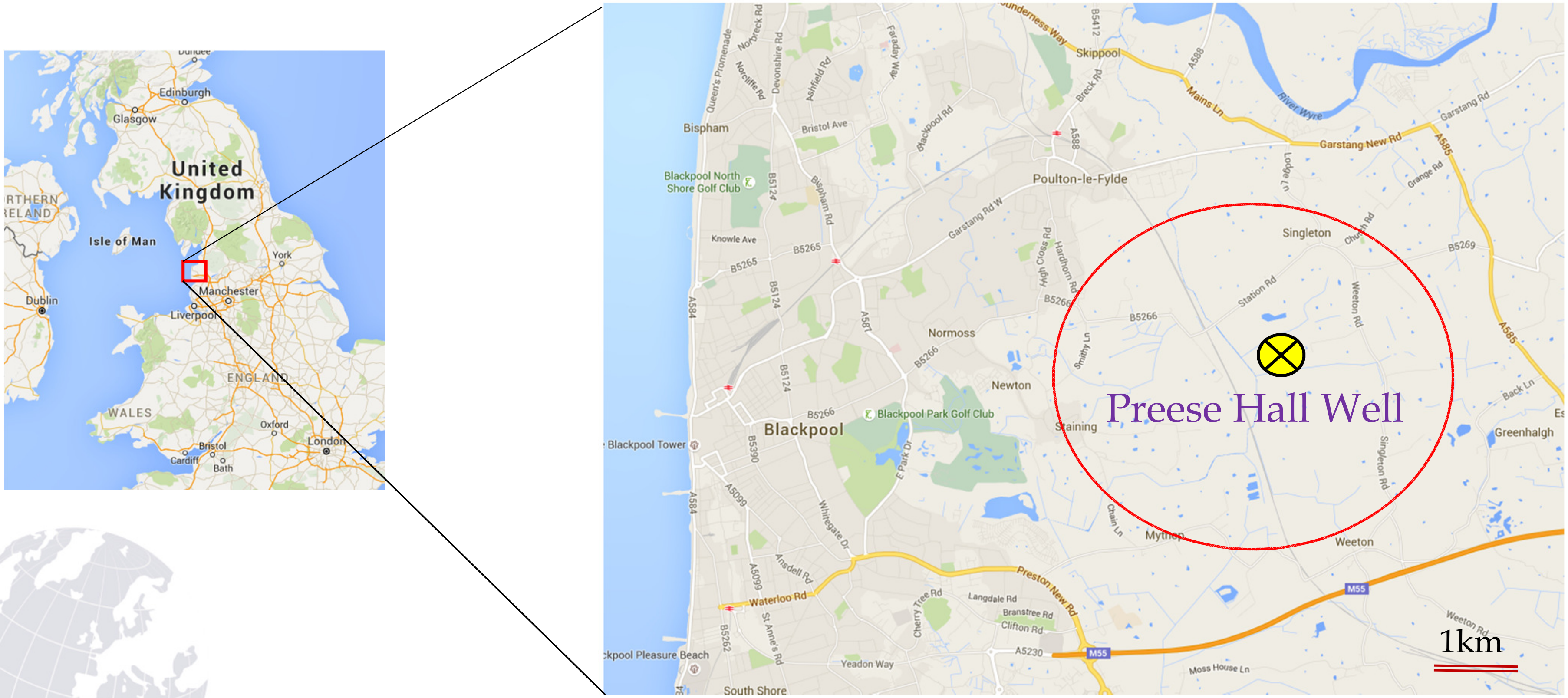
Part II. Case Studies

A) Preese Hall, Lancashire (UK)

B) Horn River Basin, British Columbia, (Canada)

C) The Geysers (US)

The Preese Hall, Lancashire (UK) Case Study



Background

- Low natural seismicity area (even for the UK standards).

- 1970, M_L=2.5, 5 km southwest of Blackpool.
- April 28th, 2009, M_L=3.7, ~30km north of Blackpool (Ulverston event) was also felt in the region.
- Historically, the largest seismic event in the region was the 1835 M_L=4.4 near Lancaster (~20km from Blackpool), maximum intensity of VI.

- No seismic events with M > 0 and waveforms similar to the reported events were recorded for one year and three months before March 30, 2011 *(Eisner et al., 2012)*.

Overview

In the spring of 2011, the first UK multi-stage fracking of a shale rock took place (by Cuadrilla) at Preese Hall, Lancashire, in a 1000m section of the Namurian Bowland Shale *(Wilson et al., 2015)*

- On 31st of March 11 events with M<1.5 were recorded
- On 1st of April an M_L=2.3 event occurred at 3.6km depth
- No further events of analogous size were detected – fracking recommenced.

(An M_L=2.3 event requires slip of up to 1 cm on a minimum rupture area of 10,000 m^2, ~56m radius)

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Overview

- On 27th of May an M_L=1.5 occurred and the operations were suspended

- A total of 52 events were detected between 31/3 and 02/08 2011

- Only 2 weak events (M_L<0) occurred after 27th of May

(July 30th, and August 2nd)

- Waveforms were similar to the 2 strongest events

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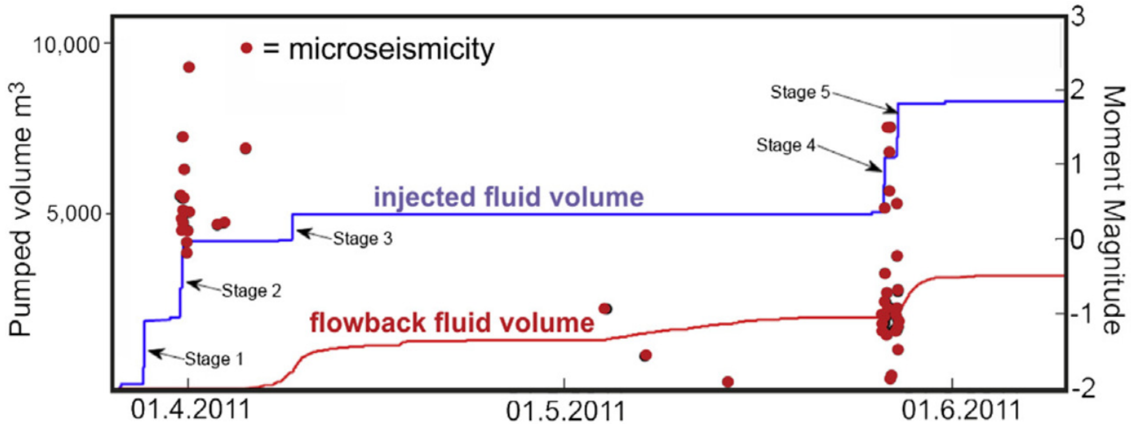
Technology

- Although six fracturing stages were planned at Preese Hall, Cuadrilla only completed five before ceasing its operations.
- Seismicity was only induced following hydraulic fracturing stages where larger volumes of fluid were injected and/or where there was little or no flowback of fluids (*de Pater and Baisch 2011*).



de Pater and Baisch 2011

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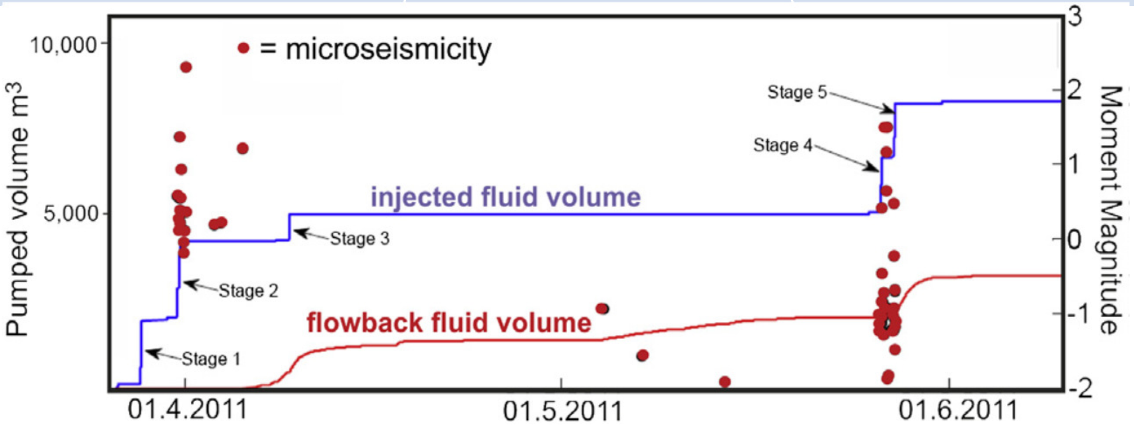
Technology

Stage	Injection Volume	Flowback Rate	Seismicity	M_{max}
1	Large	No	No	-
2	Large	No	14 events	2.3
Between 2-3	-	No/low	3 events	1.2
3	Small	High	No	-
Between 3-4	-	Low	3 events	-0.9
4	Large	Low	16 events	1.5
5	Large	High	14 events	0.5



de Pater and Baisch 2011

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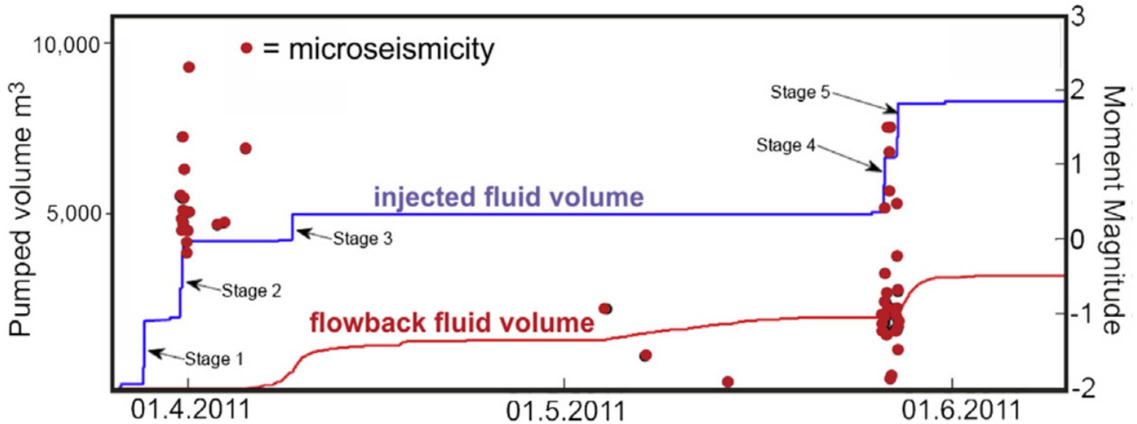
Technology

- In two of the hydraulic fracture treatments, in zones 2 and 4, the **largest earthquakes occurred approximately ten hours after the start of injection**, while the well was shut-in under high pressure.
- These events were preceded by **smaller events**, which started **immediately** after injection



de Pater and Baisch 2011

Monitoring

Seismicity is generally very weak and typically not recorded above the noise level by traditional surface seismometer networks. (M_C=0.4,)

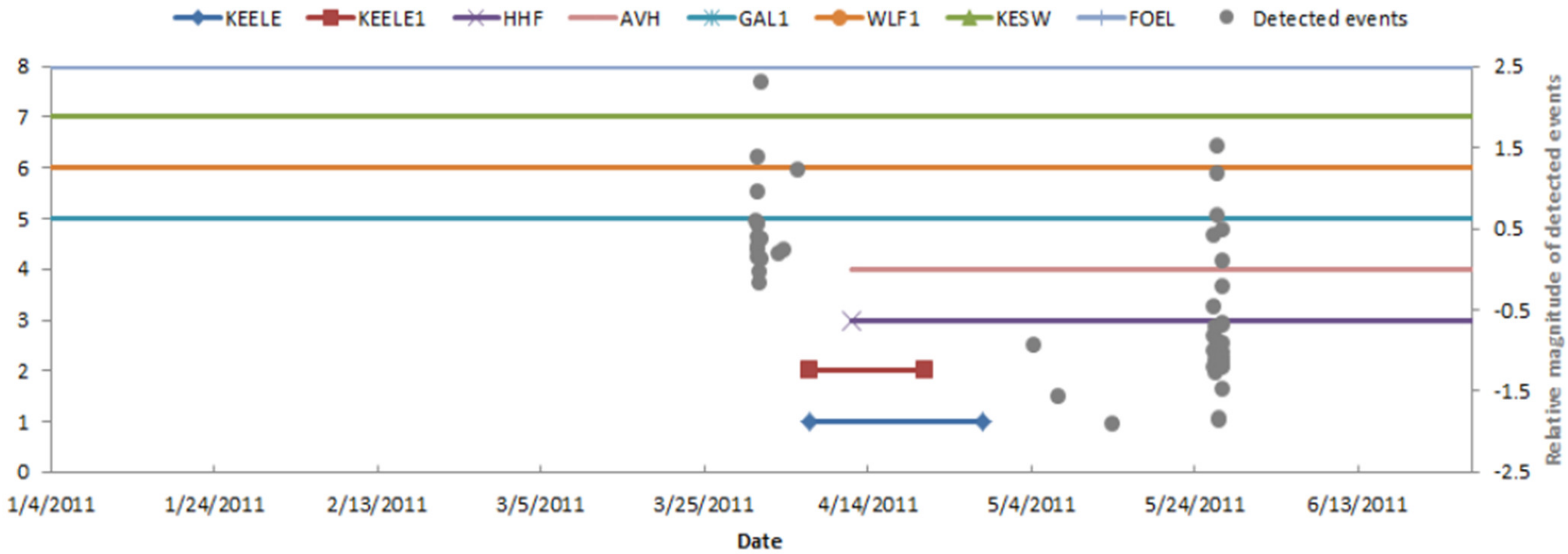


Figure 23: Availability of seismic stations over the treatment period vs date (in MM/DD/YYYY format). Local stations were installed after the first seismic event was reported by BGS (Seismik, 2011).

de Pater and Baisch 2011

Waveforms

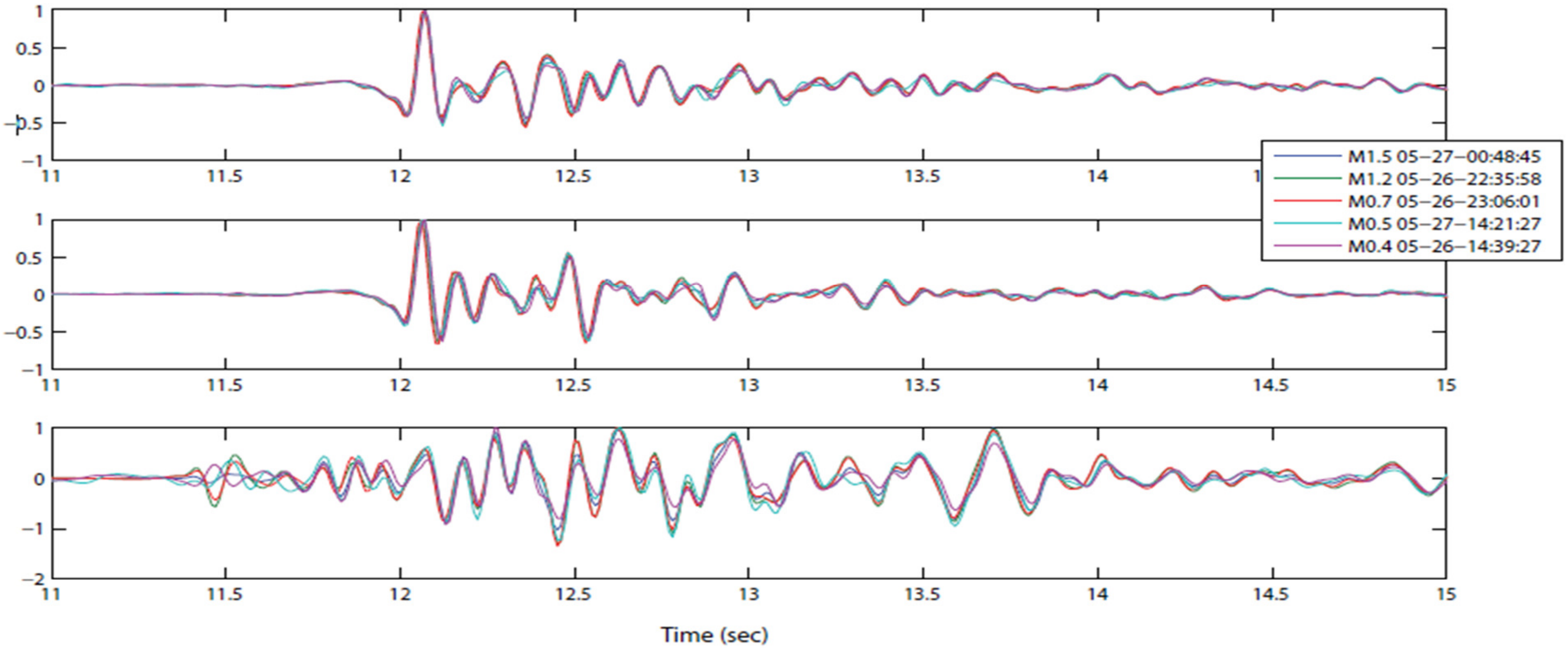


Figure 28: Traces of seismic events vs time, observed on the local station HHF, normalized on maximum amplitude. The two upper diagrams show the horizontal components, which picked up the shear waves and the lower diagram shows the vertical component with the compressional wave. The records are remarkably similar in shape, showing that all events originated from the same source plane.

de Pater and Baisch 2011

Waveforms

- Reported events of April 1, 2011 and May 27, 2011 show great similarity on the regional stations that recorded them, limiting the relative distance between the two events to less than 120 meters *(Eisner et al., 2012)*.

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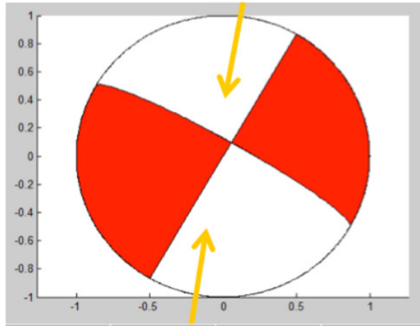
Geomechanical Features

(Summary of Findings from Baisch and Voros, 2011; Harper 2011; GMI, 2011; de Pater and Pellicier, 2011; de Pater and Basch, 2011; Green and Styles, 2012)

- The Bowland Shale consists of impermeable, hard rock
- Stresses are anisotropic. In-situ stress regime is strike-slip, implying a large S_{Hmax}-S_{hmin}.
- This stress difference obtained from minifrac pressure declines and image log break-outs is some 25-30MPa ≠ 2-4 MPa in US shale plays.
- Based on the seismic observations an M_{Lmax}=3 is estimated as a worst case scenario (de Pater and Baisch, 2011). An event of this size is not expected to provoke significant hazard.

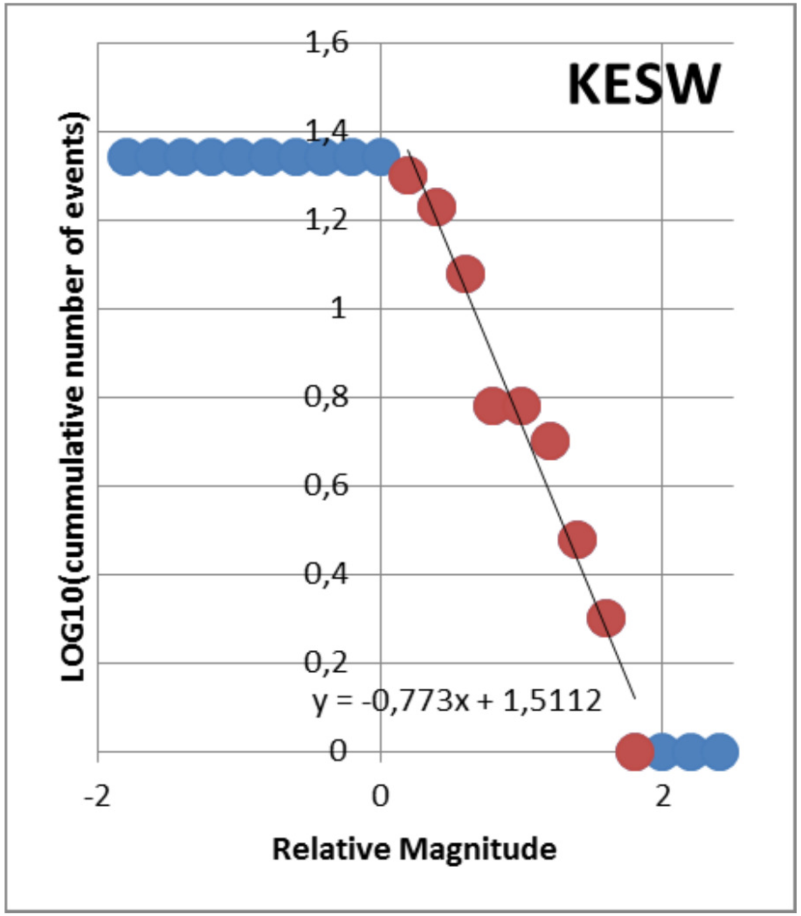


	Dip	Strike	Rake
Plane 1	85	**214**	-15
Plane 2	75	**305**	-175

Styles, 2012

b-values

- b=0.79±0.21 for Mc=0.4
- Surprisingly low b-value
- Considerably fewer observed than expected smaller events
- Very rapid activity rate decay observed after the largest events during stages 2 and 4 ≠ seismicity induced by fracturing in geothermal areas



Styles, 2012

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Interpretation

Seismicity depends on three factors concerning a fault that is:

- critically stressed
- transmissible so that it accepts large quantities of fluid
- brittle enough to fail seismically

All factors are considered very unlikely, classifying Preese Hall Stage 2 event, as a 'worst case scenario'.

(a crude probability estimate by de Pater and Baisch, 2011 is ~0.01%)

Risk Mitigation – Traffic Light System

- Traffic Light System *(de Pater and Baisch, 2011)*

o Magnitude smaller than M_L=0: regular operation

o Magnitude between M_L=0 and M_L=1.7: continue monitoring after the treatment until the seismicity rate falls below one event per day, for at least 2 days.

o Magnitude > M_L=1.7: stop pumping and bleed off the well, while continuing monitoring.

The maximum post-injection magnitude increase has been estimated to be 0.9 magnitude units (Q-con, 2011). M_L=1.7 is selected order to prevent the occurrence of an $M_{L,max}$ =2.6

Risk Mitigation – Traffic Light System

Green & Styles (2012)

- The M_{Lmax}=1.7 threshold, is considered as undesirably high.
- Based on this limit, no action would have been taken before the M_L=2.3 event on 1 April 2011.
- A lower limit of M_{Lmax}=0.5 is recommended instead.

Conclusions

- Similar waveforms, location and mechanism indicate a highly repeatable source (events originated from the same fault)
- Rapid decay of seismicity
- The events are located close to the point of injection and the timing clearly corresponds to the treatment schedule (fluid flow)
- The injected volume and flow-back timing are an important controlling factor in the level of seismicity

The Horn River Basin, British Columbia (Canada), Case Study

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BRITISH COLUMBIA (HORN RIVER BASIN), CANADA

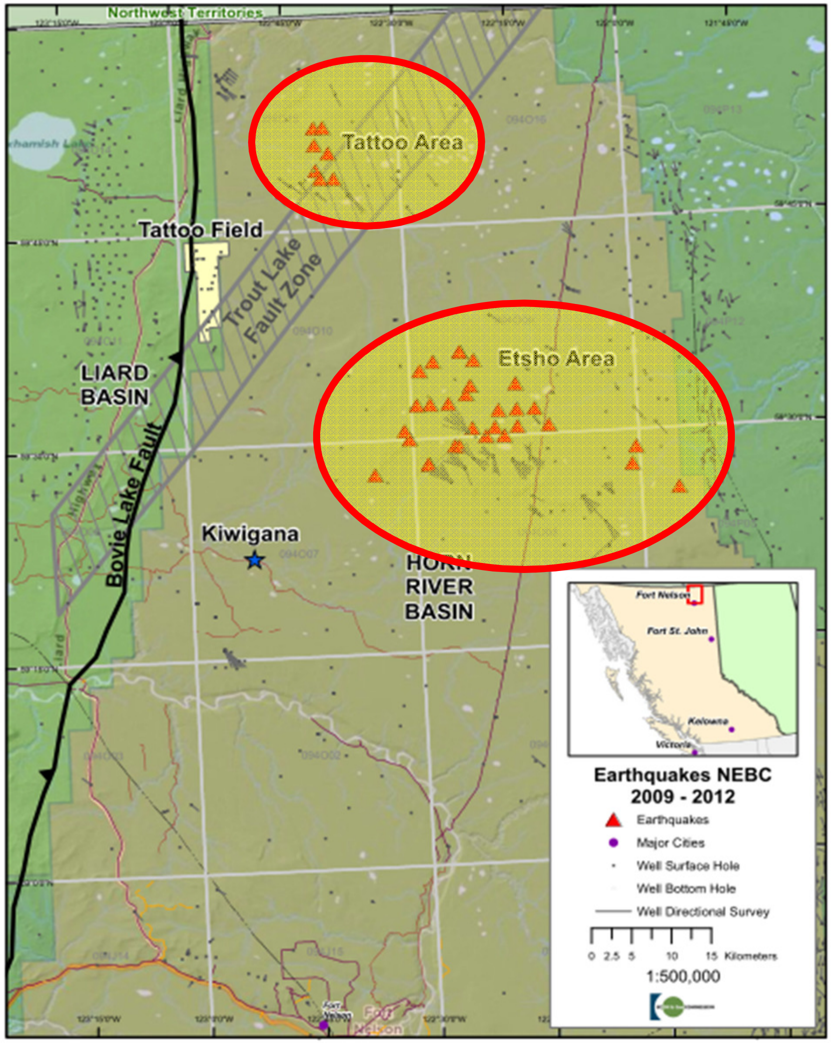
1985->NO DETECTED SEISMICITY PRIOR TO 2009

Event Summary

Natural Resources Canada (NRCan)

- Etsho area: 31 seismic events (April 2009- July 2011)
- Tatoo area: 7 seismic events (Dec.8-Dec. 13, 2011)
- Magnitudes:

  M_L 2.2-3.8



Location of Etsho, Tattoo and Kiwigana areas in the Horn River Basin, BC Oil and Gas Commission, Oil and Gas Commission open report, August 2012.

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Event Summary

Event #	Date	Time (UT)	Time (Pacific)	Correct Date	Lat	Long	Mag	Approximate Location
38	2011/12/13	13:17:32	5:17:32		59.84	-122.66	3.1ML	114 km N of Fort Nelson
37	2011/12/12	23:34:12	15:34:12		59.81	-122.68	3.1ML	110 km N of Fort Nelson
36	2011/12/12	07:59:22	23:59:22	12/11/2011	59.82	-122.69	2.9ML	112 km N of Fort Nelson
35	2011/12/11	09:15:57	1:15:57		59.85	-122.69	2.4ML	114 km N of Fort Nelson
34	2011/12/11	02:37:53	18:37:53	12/10/2011	59.87	-122.67	2.9ML	116 km N of Fort Nelson
33	2011/12/10	02:52:34	18:52:34	12/9/2011	59.87	-122.69	2.9ML	117 km N of Fort Nelson
32	2011/12/08	15:28:37	7:28:37		59.81	-122.65	2.8ML	111 km N of Fort Nelson
31	2011/07/14	10:40:32	2:40:32		59.51	-122.20	2.5ML	82 km NE of Fort Nelson
30	2011/07/07	22:46:37	14:46:37		59.49	-122.40	3.1ML	76 km NNE of Fort Nelson
29	2011/07/01	09:32:46	1:32:46		59.54	-122.49	2.6ML	81 km NNE of Fort Nelson
28	2011/06/26	13:17:02	5:17:02		59.56	-122.37	2.7ML	84 km NNE of Fort Nelson
27	2011/06/18	23:02:03	15:02:03		59.82	-121.47	2.8ML	132 km NE of Fort Nelson
26	2011/05/29	08:09:47	0:09:47		59.54	-122.46	3.1ML	81 km NNE of Fort Nelson
25	2011/05/20	06:22:34	22:22:24	5/19/2011	59.51	-122.52	3.0ML	78 km NNE of Fort Nelson
24	2011/05/19	13:13:43	5:13:43		59.47	-122.47	3.3ML	74 km NNE of Fort Nelson
23	2011/05/19	13:05:15	5:05:15		59.49	-122.41	3.8ML	76 km NNE of Fort Nelson
22	2011/05/10	14:16:03	6:16:03		59.51	-122.37	3.5ML	79 km NNE of Fort Nelson
21	2011/05/03	12:56:29	4:56:29		59.51	-122.32	3.2ML	80 km NNE of Fort Nelson
20	2011/04/30	13:27:30	5:27:30		59.46	-122.59	3.1ML	72 km N of Fort Nelson
19	2011/04/28	22:34:51	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]5ML	73 km NNE of Fort Nelson
18	2011/04/07	12:19:20	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]2ML	76 km NNE of Fort Nelson
17	2011/03/04	03:09:05	19:09:05	3/3/2011	59.50	-122.34	3.3ML	78 km NNE of Fort Nelson
16	2010/10/12	21:01:11	13:01:11		59.55	-122.38	3.4ML	83 km NNE of Fort Nelson
15	2010/10/12	19:19:44	11:19:44		59.53	-122.31	3.0ML	83 km NNE of Fort Nelson
14	2010/10/12	17:09:40	9:09:40		59.59	-122.45	3.4ML	87 km NNE of Fort Nelson
13	2010/10/09	10:00:31	2:00:31		59.54	-122.42	3.1ML	82 km NNE of Fort Nelson
12	2010/10/05	22:01:14	14:01:14		59.60	-122.39	3.6ML	88 km NNE of Fort Nelson
11	2010/10/05	13:30:28	5:30:28		59.53	-122.27	3.1ML	83 km NNE of Fort Nelson
10	2010/10/04	11:09:34	3:09:34		59.59	-122.36	2.9ML	88 km NNE of Fort Nelson
9	2010/10/03	08:06:50	0:06:50		59.56	-122.27	3.5ML	86 km NNE of Fort Nelson
8	2010/09/30	12:33:36	4:33:36		59.58	-122.48	3.0ML	85 km NNE of Fort Nelson
7	2010/09/30	12:31:43	4:31:43		59.60	-122.39	2.9ML	89 km NNE of Fort Nelson
6	2010/08/22	09:30:20	1:30:20		59.53	-122.23	2.4ML	84 km NE of Fort Nelson
5	2010/08/03	20:15:35	12:15:35		59.51	-122.27	2.7ML	81 km NNE of Fort Nelson
4	2010/06/11	22:25:19	14:25:19		59.50	-122.30	3.4ML	79 km NNE of Fort Nelson
3	2009/04/09	16:34:00	8:34:00		59.48	-122.01	2.2ML	83 km NE of Fort Nelson
2	2009/04/08	21:30:23	13:30:23		59.43	-121.92	2.3ML	82 km NE of Fort Nelson
1	2009/04/08	21:27:37	13:27:37		59.46	-122.02	2.3ML	81 km NE of Fort Nelson

reported as felt at surface

www.earthquakescanada.nrcan.gc.ca/

Table provides a summary of the events recorded by NRCan in the Etsho and Tattoo areas; Oil and Gas Commission open report, August 2012

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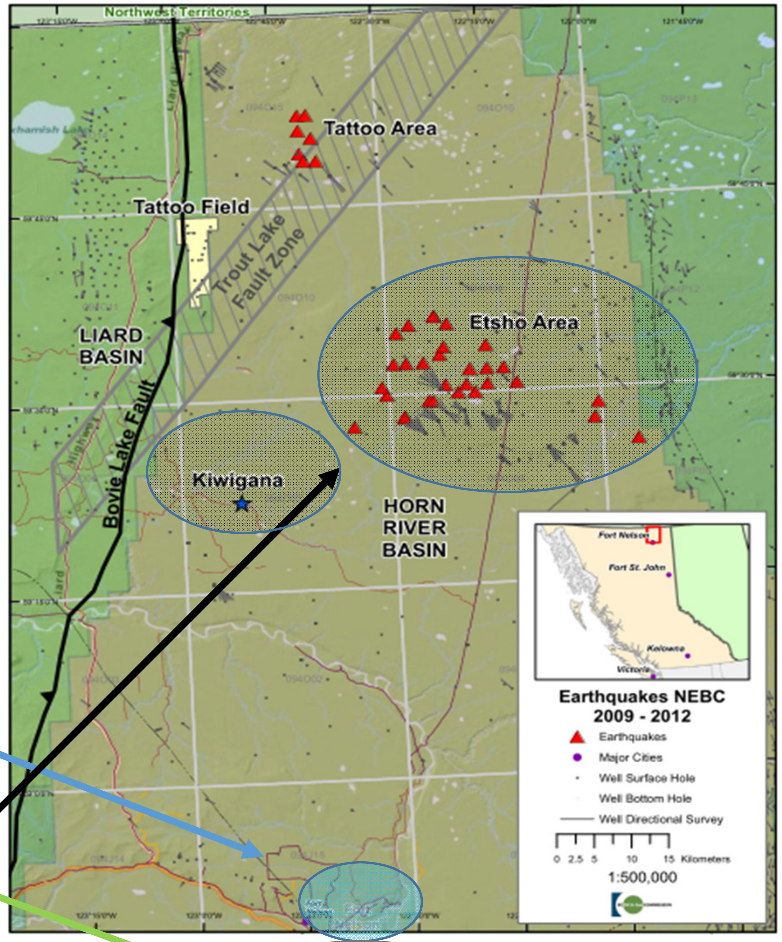
Station Coverage of the CNSN

The CNSN (Canadian National Seismograph Network) is designed to monitor moderate to strong magnitudes earthquakes that pose a risk to public safety and not to detect low magnitude induced seismicity.

- Epicenter uncertainty: 5-10km
- Focal Depth uncertainty: larger
- Stations:
  - **Fort Nelson seismograph station**
  - **The Bull Mountain (Hudson's Hope)**
- Additionally an operator deployed local array at Etsho and Kiwigana



300 km to the South

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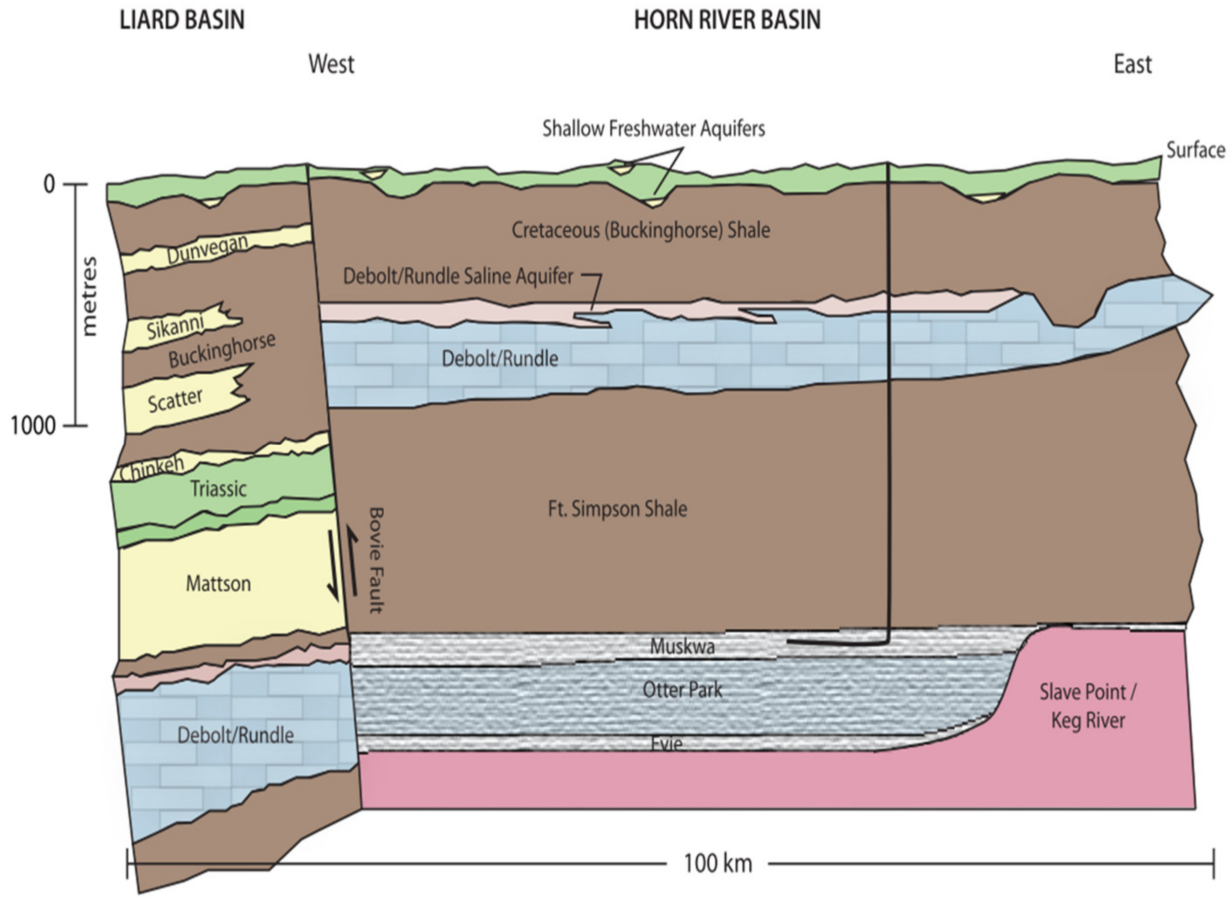
Geology of the Horn River Basin

- Basinal shales of Horn River:
  - (West) Bovie fault
  - (East) Keg River and Slave Point



Cross-section of Horn River Basin showing Muskwa, Otter Park and Evie formation shale gas targets. Horizontal wellbores target the Muskwa, Otter Park and Evie zones; Oil and Gas Commission open report, August 2012

BRITISH COLUMBIA (HORN RIVER BASIN), CANADA

- Duration: from February 2007 to late July 2011
- 14 different drilling pads
- 90 wells with more than 1600 fracking stage completion operations
- Multiple stages of slickwater and sand
- Cemented wells
- „Perf and plug” technique

Hydraulic Fracturing Etsho area

Pad Hydraulic Fracturing Statistics for Etsho (non-confidential pads). Minimum, maximum and average numbers are calculated from all pad data reviewed; Oil and Gas Commission open report, August 2012

Well Pad	Wells/Pad	Stages/ Well	HZ Completed (m)	Fluid/Well (m^3)	Sand/Well (Tonnes)	Avg Pump Rate (m^3/ minute)	Fracs/Pad	# of Seismic Events
b-100-G	5	5	1,176	11,505	710	12	26	0
c-1-J	9	16	1,837	52,429	3,072	14	147	0
b-76-K	13	15	1,752	58,386	2,454	15	180	1
d-70-J	7	14	1,391	53,800	2,692	15	74	3
d-1-D	7	27	2,727	138,005	5,484	15	176	6
c-34-L	9	18	2,200	63,000	3,200	15	162	7
b-63-K	14	23	2,452	107,738	4,505	14	347	13
Average	**8**	**17**	**1,846**	**61,612**	**3,107**	**13**	**149**	**3**
Min.	**4**	**5**	**1,176**	**11,505**	**710**	**8**	**26**	**0**
Max.	**16**	**27**	**2,727**	**138,005**	**5,484**	**15**	**347**	**13**

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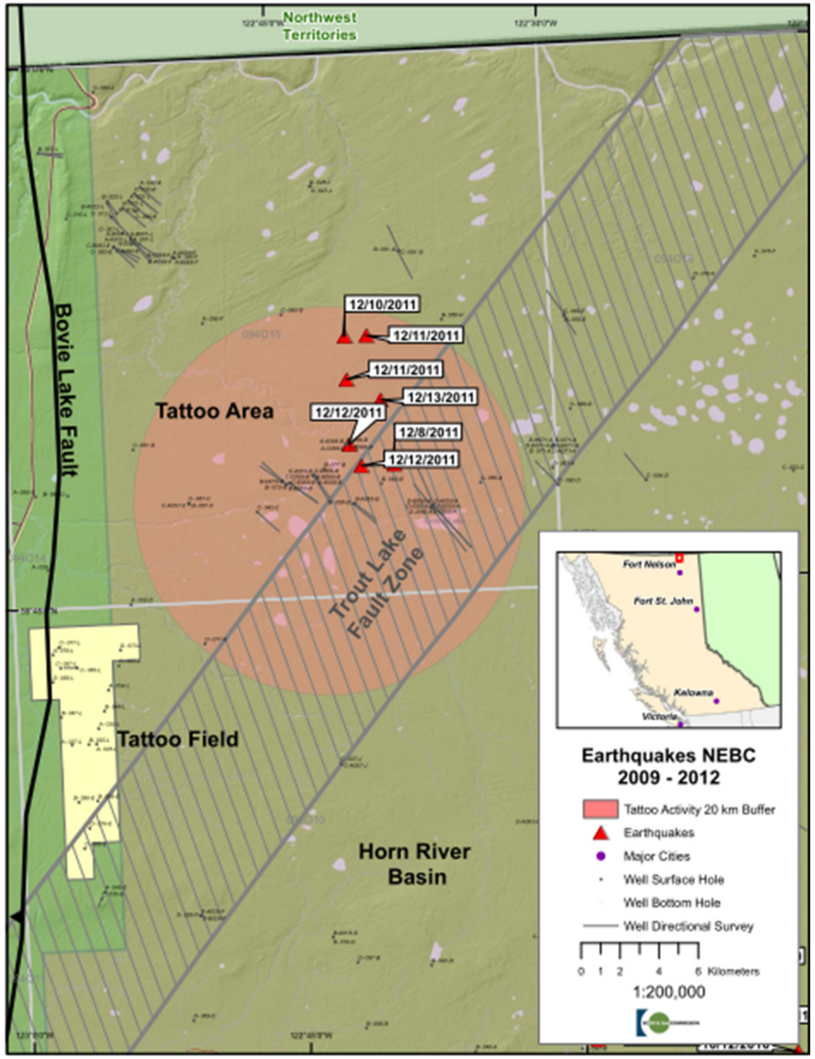
Induced Seismicity

- 17 of Etsho events lie within 10km radius circle
- 7 multi-lateral drilling pads within 10km radius circle
- 5 of them were conducting hydraulic fracturing operations when events occurred.

- All 7 of Tattoo events can be encompassed within 10km radius circle
- 2 multi-lateral drilling pads within 10km radius circle
- 1 of them was conducting hydraulic fracturing operations when events occurred.



Tattoo area NRCan event epicentres and Multi-Well Pads, locations shown within 20km buffer/10km radius shaded circle; Oil and Gas Commission open report, August 2012

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Operator Dense Array Deployments

Etsho	Kiwigana
• 20 seismographs • Operated from June 16 to Aug. 15, 2011 • Surrounding of d-1-D/94-O-8 pad	• 151 seismographs • Operated from Oct 25, 2011 to Jan. 27, 2012

BRITISH COLUMBIA (HORN RIVER BASIN), CANADA

Hydraulic Fracturing Seismicity

Etsho array:

- Magnitudes from M_L -0.8 to 3.0
- 216 related to fault movement (197 magnitude M_L 1.0-2.0, 19 magnitude M_L 2.0-3.0)
- b-value (0.5 to 1.0)
- For the same date range: 4 events recorded by CNSN (M_L 2.5-3.1)
- Events relocation: hypocentres within 200m, vertically and horizontally, within fracturing stages.
- TVD at the Etsho d-1-D pad: 2,650 to 2,889 metres,
- 69 magnitudes M_L 1.5 to 3.0 fall within the targeted formations. 66 of these occur between 2800 and 2870 metres.

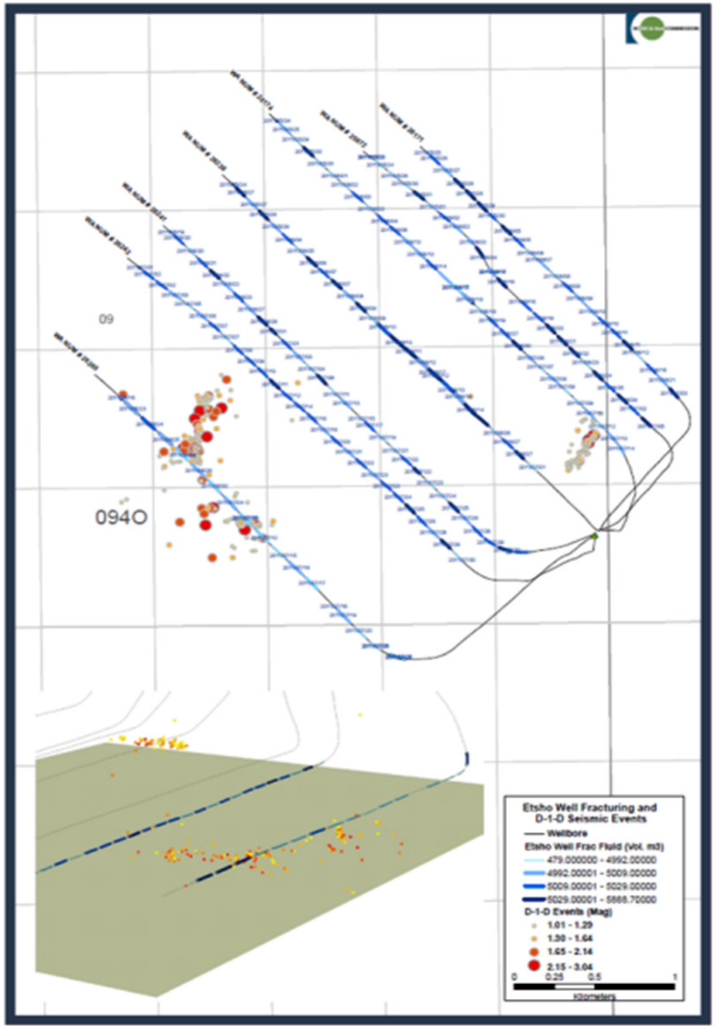

Diagram showing d-1-D wellbores and events >1.0. Wellbores are black lines and stages with relative injection volumes are thickened blue sections, ; Oil and Gas Commission open report, August 2012

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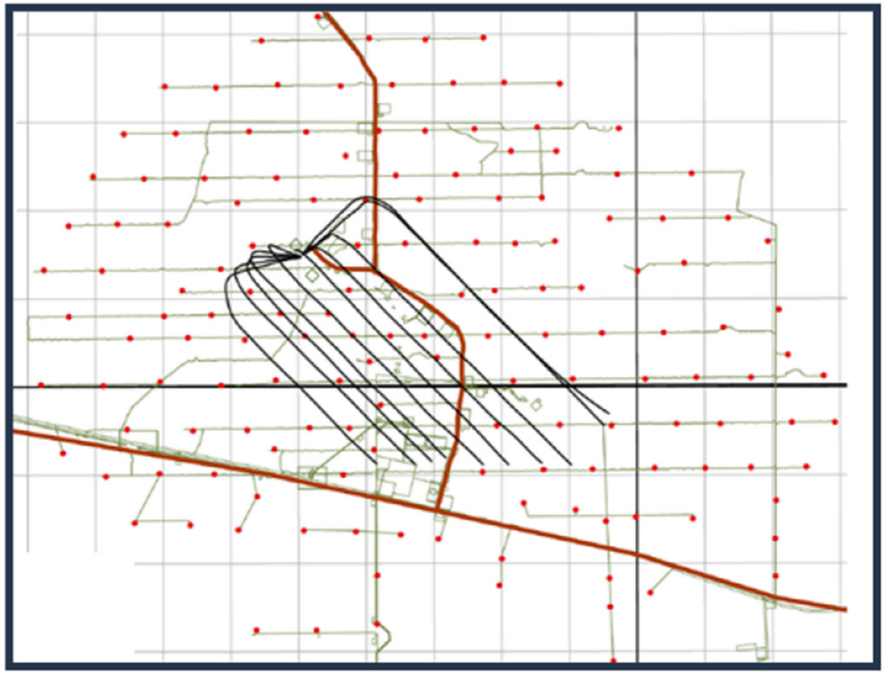
Hydraulic Fracturing Seismicity

Kiwigana array:

- Magnitudes from M_L -1.7 to 0.5 (Oct. 25, 2011-Jan.27, 2012)
- None of them detected by CNSN
- These events resulted from tensile failure and shear movement during the normal proces of hydraulic fracturing
- Additional 18 events, magnitude M_L 1.0 to 1.9, resulted from injection fluids triggering movement along pre-existing faults.



Map of Kiwigana dense array, surrounding c-15-D/94-O-7 pad, showing horizontal wellbores (black lines) and seismograph locations (red dots); Oil and Gas Commission open report, August 2012

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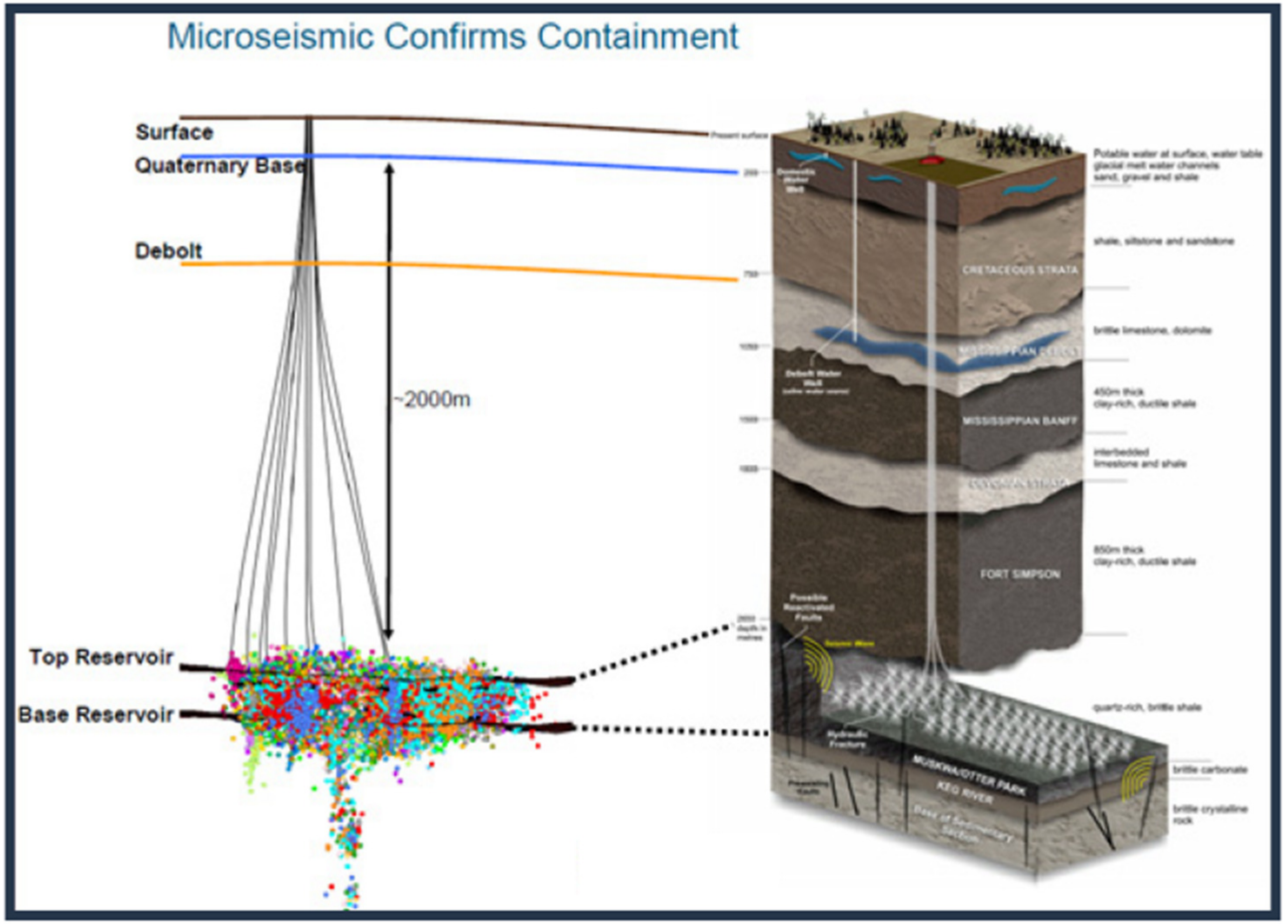
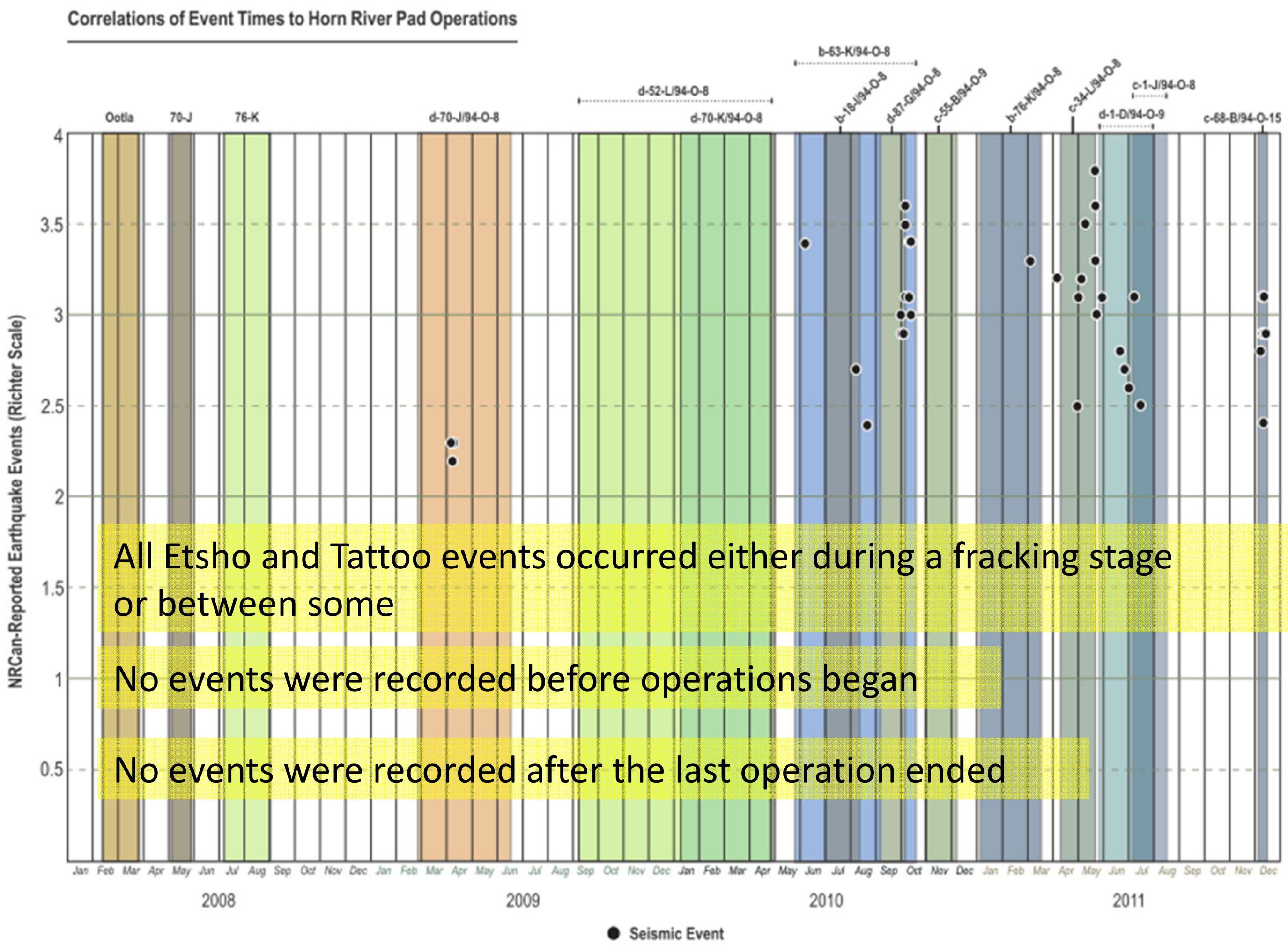
Hydraulic Fracturing Seismicity



Cumulative microseismic plot for Kiwigana, coloured dots indicate contained micro-seismicity events caused by tensile and shear failure of intact shale. Trail of coloured dots suggest reopening or movement of pre-existing fault. Generalized stratigraphic column to right, NRCan; Oil and Gas Commission open report, August 2012

BRITISH COLUMBIA (HORN RIVER BASIN), CANADA

Hydraulic Fracturing Timing vs Seismicity Event Timing



All Etsho and Tattoo events occurred either during a fracking stage or between some

No events were recorded before operations began

No events were recorded after the last operation ended

Timing of NRCan reported Events (black dots) vs. Magnitude. Timing of hydraulic fracturing operations (coloured columns) ; Oil and Gas Commission open report, August 2012

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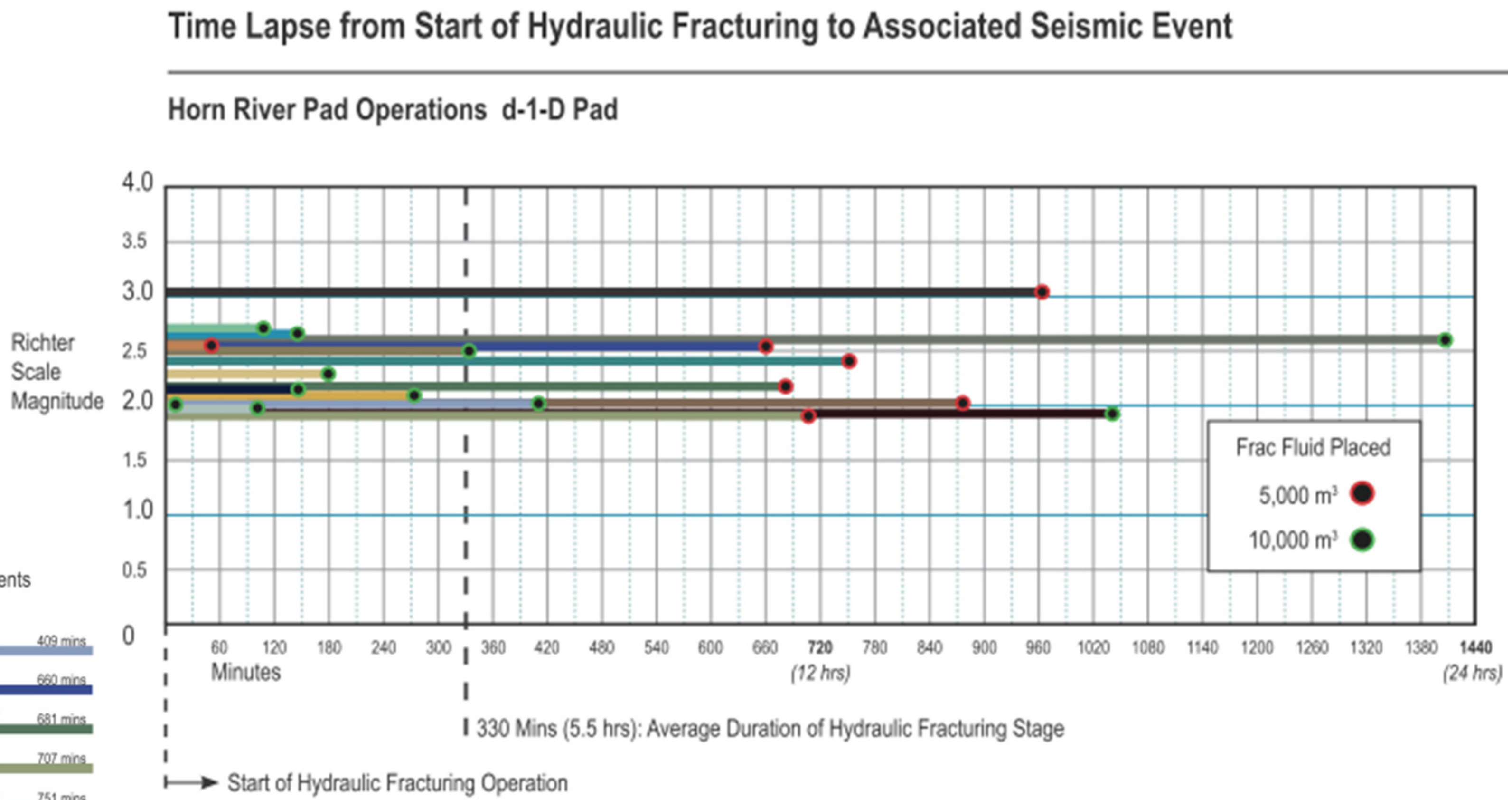
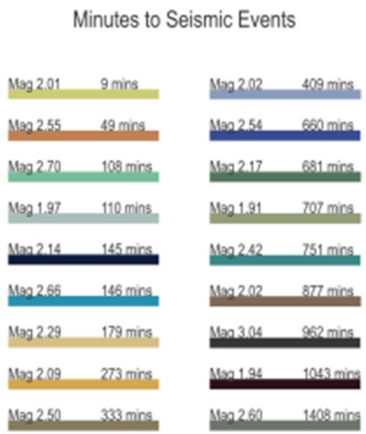
Hydraulic Fracturing





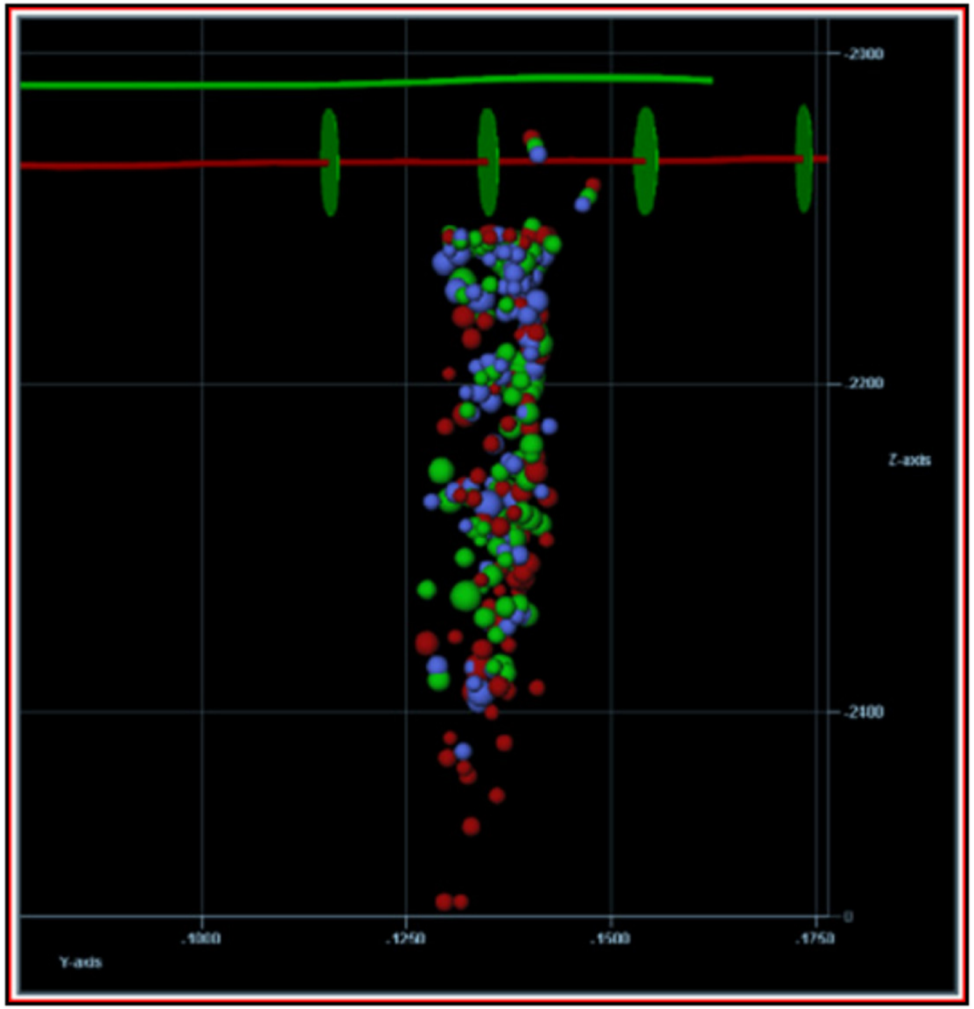
Timing of seismicity events, resulting from fluid injection at selected hydraulic fracturing stages. Green dots designate events linked to stages with 10,000 m^3 total 'Fracturing Fluid Placed' (two injections of 5000m^3 separated by one hour). Red dots are events linked to stages with 5,000 m^3 total 'Fracturing Fluid Placed'; Oil and Gas Commission open report, August 2012

BRITISH COLUMBIA (HORN RIVER BASIN), CANADA

Pre-Existing Faults

Etsho:

- All operators conducted two and three dimensional seismic surveys
- Fault mapping shows abundant faulting
- Faults were also interpreted from available microseismic plots



Micro-seismicity events (coloured circles) and hydraulic fracture stages (green ellipses) along horizontal wellbore legs, ; Oil and Gas Commission open report, August 2012

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Geothermal fields and associated induced seismicity: The Geysers (US), Case Study

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Seismicity associated with geothermal fields

- usually events have magnitudes below M_L=2, but there are some exceptions (see Table below)

Sites analysed in GEISER	M_{max}^{obs} (year)	Geology, rock type, stress	P_{max} (MPa)	Reservoir depth (km), fracture mechanism
The Geysers, California USA	4.6[a], 1982[c]	Metagraywacke SH–NE-SW[WSM]	7	3 km, cooling-induced shear slippage, since 1975
Berlin, El Salvador	4.4[a], 2003[c]	Young volcanic weak rock, SS + NF; SH–NNW-SSE	13	2 km, opening and closing of flowing fractures, since 1991
Cooper Basin, Australia	3.7[a], 2003	Granite with 3.6 km sediment cover, TF; SH–EW	68	4.1–4.4 km, slip on pre-existing sub-horizontal fractures, since 200
Alkmaar, NL	3.5[a], 2001	Sandstones, 2.6 to 3.1 km depth, SH–NW-SE[WSM]	18	2 km, reactivation Roer Valley Rift faults, gas production since 196
Basel, Switzerland	3.4[a], 2006[c]	Granite, Sh, 0.7SV, SH–N144°E ± 14°	30	4.4–4.8 km, pre-existing, en-echelon-type shear zone, since 2006
Soultz-sous-Forêts, France	2.9[a], 2003[c]	Granite, NF + SS, SH–N170°E	16	4.5–5.0 km (GPK3), single large tectonic fracture zone, since 1987
Paralana, Australia	2.5[a], 2.4[b], 2011[c]	Hybrid, granitic basement, 4 km sediment cover, TF	62	4 km, reverse fault events
Rosmanowes, Cornwall, UK	2.0[a], 1987	Carnmenellis granite batholite, SH–NW-SE[WSM]	16	2 km, system of natural fractures, since 1977
KTB, Germany	1.4[b], 1994	Gneiss, metagabbro SS (1–8 km); SH–N160°E	53	9.1 km, scientific wells, dilatant shear cracks, since 1987
Groß-Schönebeck, Germany	−1.0[b], 2007	Rotliegend sandstone, volcanic rock NF, SH–N18°E	60	4.1 km, only a total of 80 seismic events detected, doublet in 2007

Zang et al., 2014

- gradual migration from the vicinity of the borehole to distances farther from the borehole as fluid injection is progressing

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Seismicity associated with geothermal fields

- The maximum observed seismic magnitude increases with the volume of the fluid injected into the Earth's crust (*McGarr, 2014*).

- Early stimulation phase, close to injection well (near-field):
  - High pore pressures,
  - Many small events induced (high b-value),
  - Low stress drops,
  - Tensile character of events (significant volumetric component).

- Away from the injection well (far-field):
  - Lower pore pressure,
  - Events with big M more probable (lower b-value),
  - Higher stress drops,
  - Shear character of events.

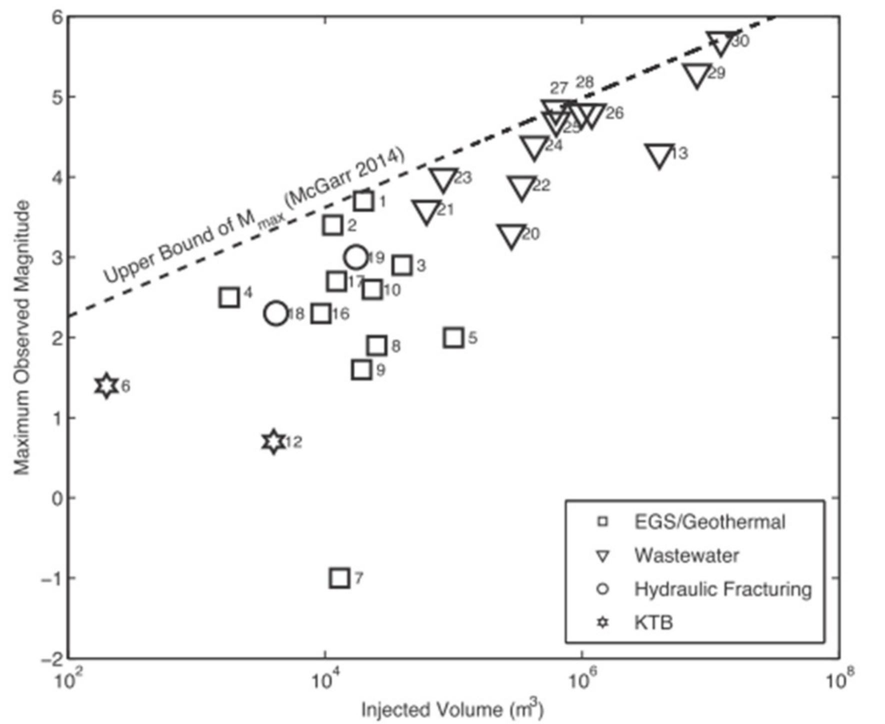

Fig. 1. Observed maximum magnitude of seismic events in geothermal operations (*squares*), wastewater disposal wells (*triangles*), hydraulic fracturing (*circles*), and fluid injection in the KTB scientific well (*stars*) as functions of volume of injected fluid. Numbers by symbols correspond to the order in which data are listed in Table 2.

Zang et al., 2014

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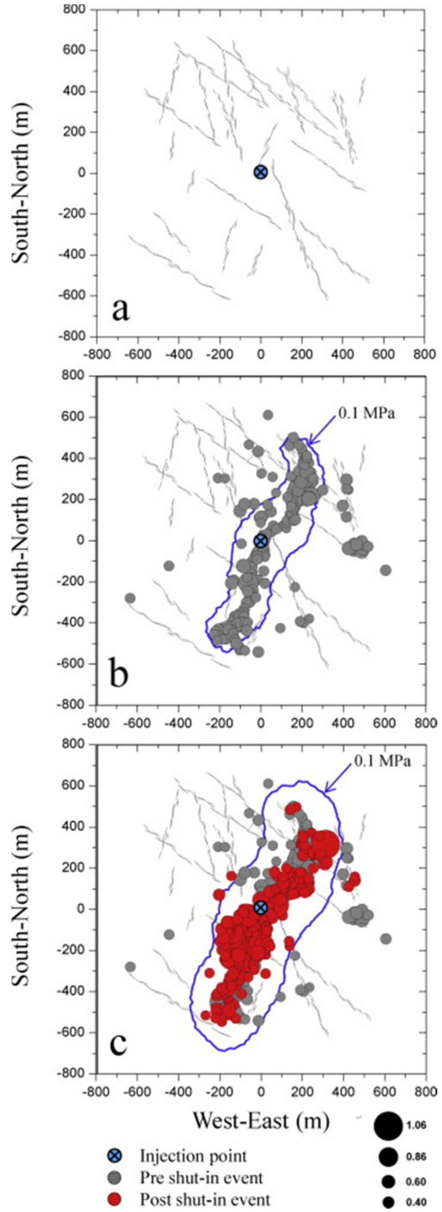
Seismicity associated with geothermal fields

- Higher probability for the occurrence of larger magnitude events (LME) at the periphery of the stimulated volume and during the later stages of the stimulation (especially after shut-in).
- Taking into account the short-term injections, EGS stimulations have in general shown a higher propensity to produce LME, compared to hydraulic fracturing in oil and gas operations.
- The width of the fluid-driven damage zone in naturally fractured crystalline rock is expected to be wider than that for sedimentary formations. If so, the seismic cloud induced by EGS stimulation should be narrower in weak compared to hard rocks.
- In crystalline reservoirs with multiple stimulation wells, seismicity is absent until the stress level of previous stimulations is exceeded (Kaiser Effect).



Discrete fracture network model with pore fluid flow algorithm.
Zang et al., 2014

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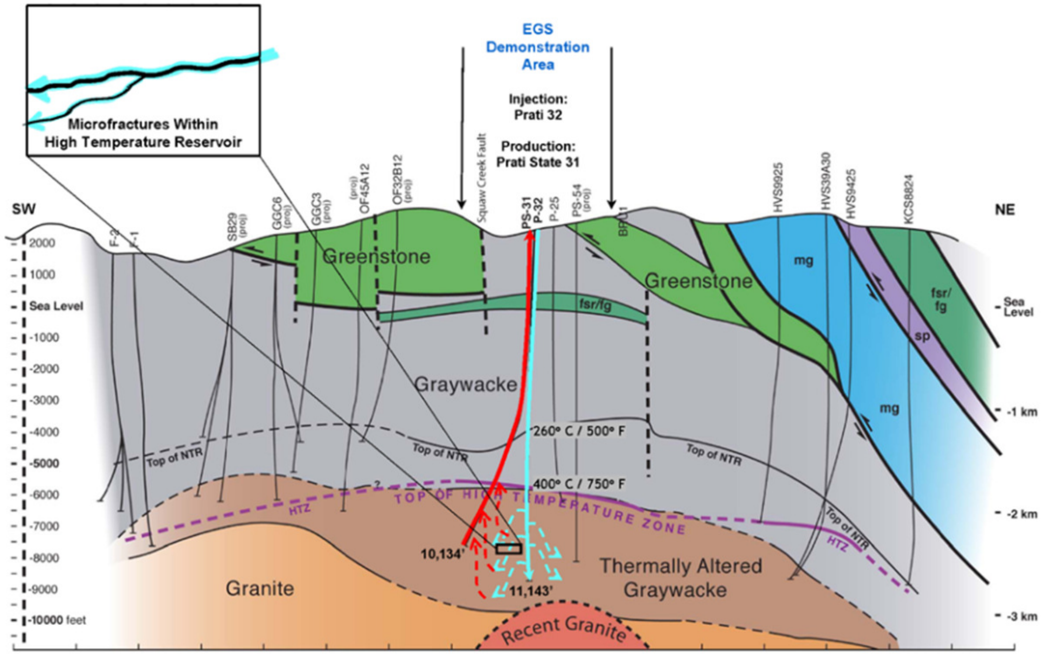
The Geysers geothermal field, California

- **The largest producing geothermal field** in the world with approximately 330 active steam production wells and 60 active water injection wells (*Brophy et al., 2010*)
- Production since 1960s, maximum production in 1987; later reservoir stimulation through the injection of large volumes of wastewater
- **Vapour-dominated** geothermal reservoir within a complex assemblage of **metamorphic rocks** (greywacke)
- Reservoir temperature ca **240°C** at 2 km depth, but exceeding **350°C** in the northwest Geysers at depths below ~2.75 km (high-temperature zone)
- Low total porosity of about 1-2%
- At TG, water is injected into the reservoir to prevent reservoir depletion. In this process, relatively **cool surface water falls freely into the injection** well resulting in significant volume reduction as the reservoir steam condenses. This causes **negative gauge pressure** at the wellhead, in contrast to active surface pumping commonly performed for reservoir stimulation with injection at elevated wellhead pressures (*Martinez-Garzon et al., 2014*)
- Seasonal tendency of injection (usually peak during winter months)



Rutqvist et al., 2013

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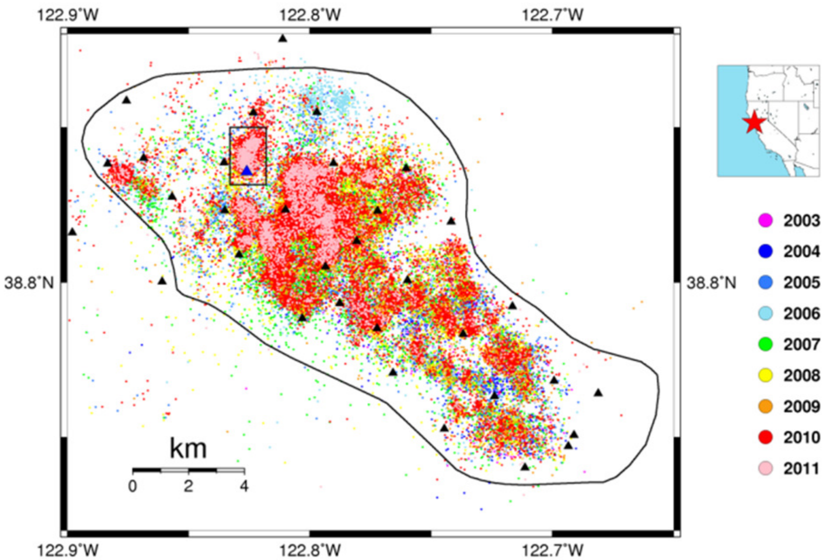
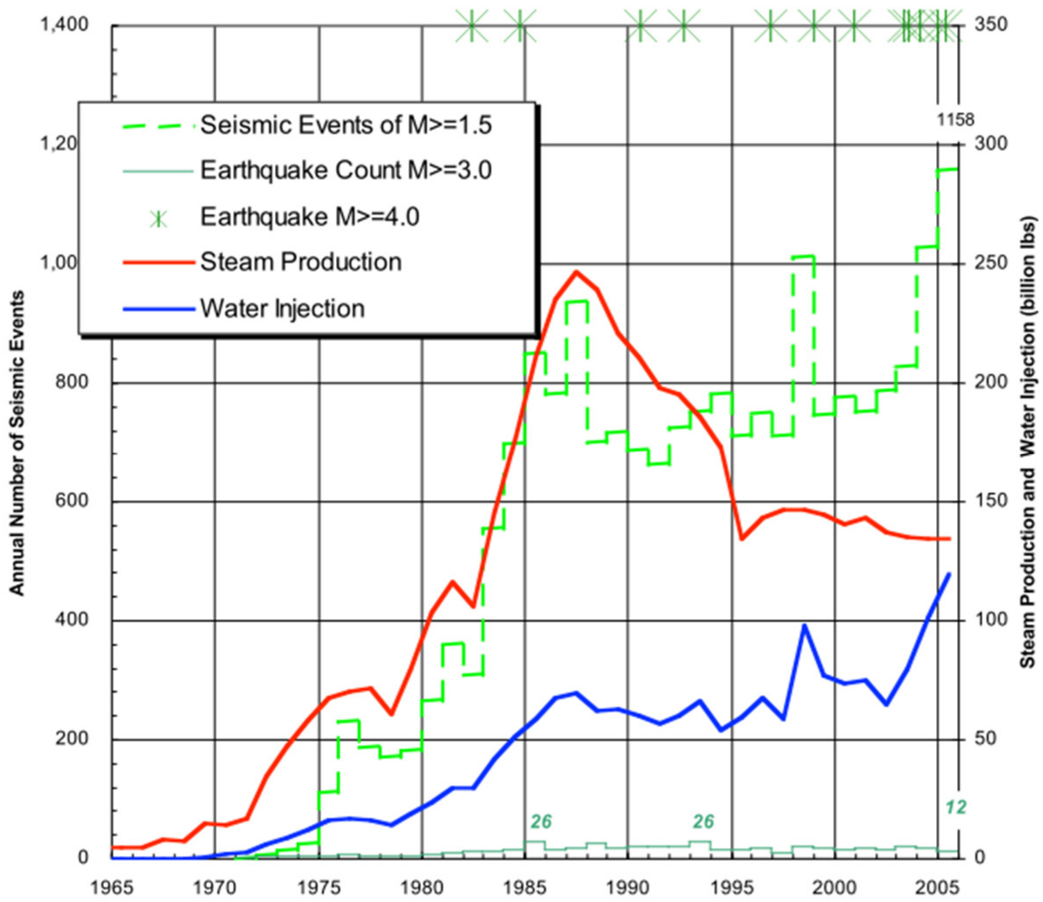
Seismicity at The Geysers

- According to USGS no events above magnitude 2 recorded before 1969
- The event of maximum magnitude M=4.6 was recorded in 1982
- Since a dense local seismic network was deployed in 2003, approximately 4000 seismic events per year with magnitudes, between 1.0 and 4.5 have been observed (*Martinez-Garzon et al., 2014*).



Viegas & Hutchings, 2011



Majer & Peterson, 2006

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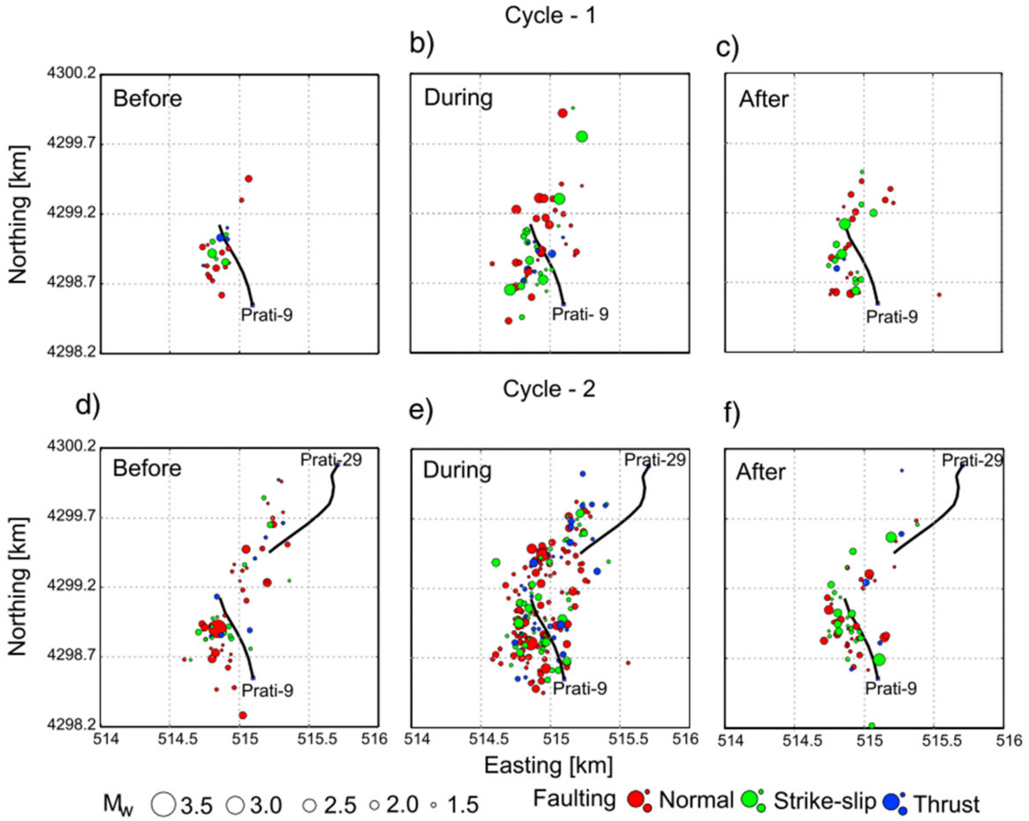
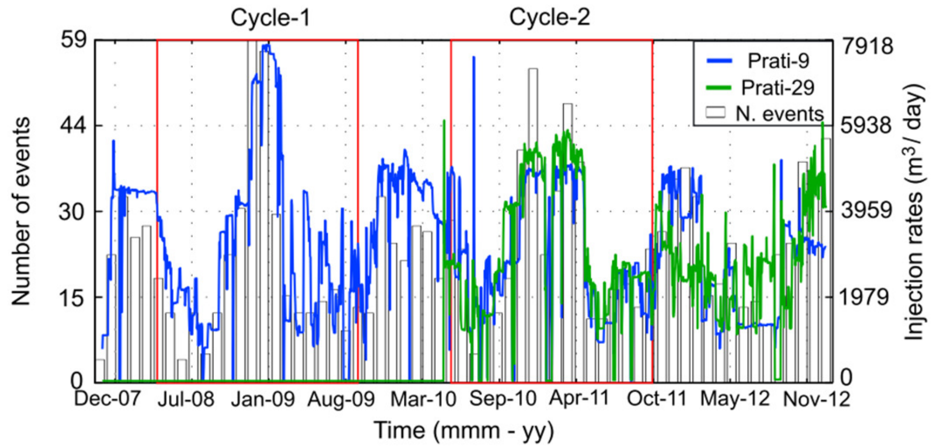
Analysis of seismicity cluster in Northwestern Geysers

- Clear correlation between the monthly seismicity rate and injection rate for both wells



Martinez-Garzon et al., 2014



Martinez-Garzon et al., 2014

- During injection:
  - Decrease of b-value,
  - Increase in relative amount of strike-slip and thrust events,
  - Increase in average distance from injection well (pulsation of seismic cloud).

- Long axis of cloud ellipsoid is subparallel with S_{HMax}
- Aligned strike-slip events suggest the presence of a previously unknown local fault, which is favorably oriented with respect to the regional stress field.

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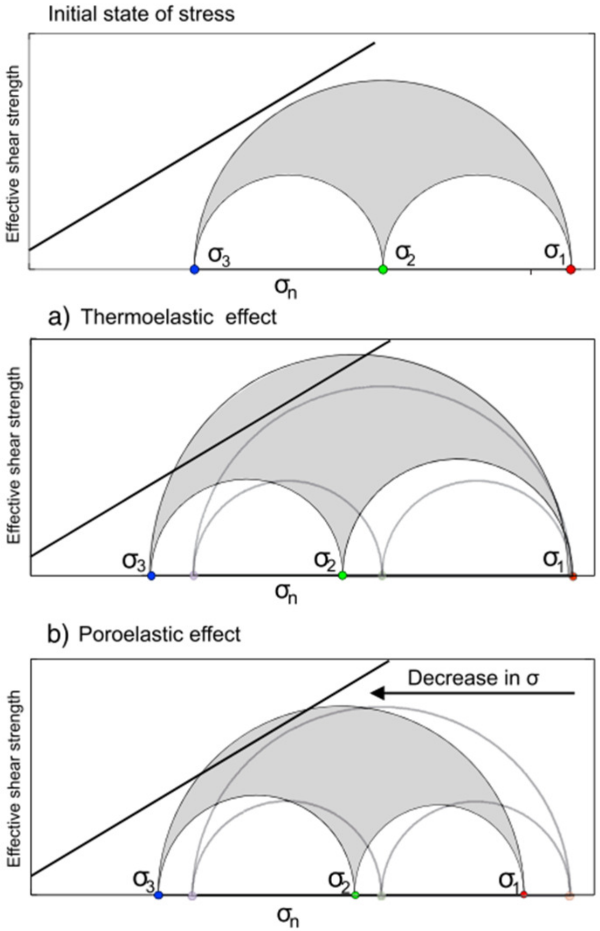
Analysis of seismicity cluster in Northwestern Geysers



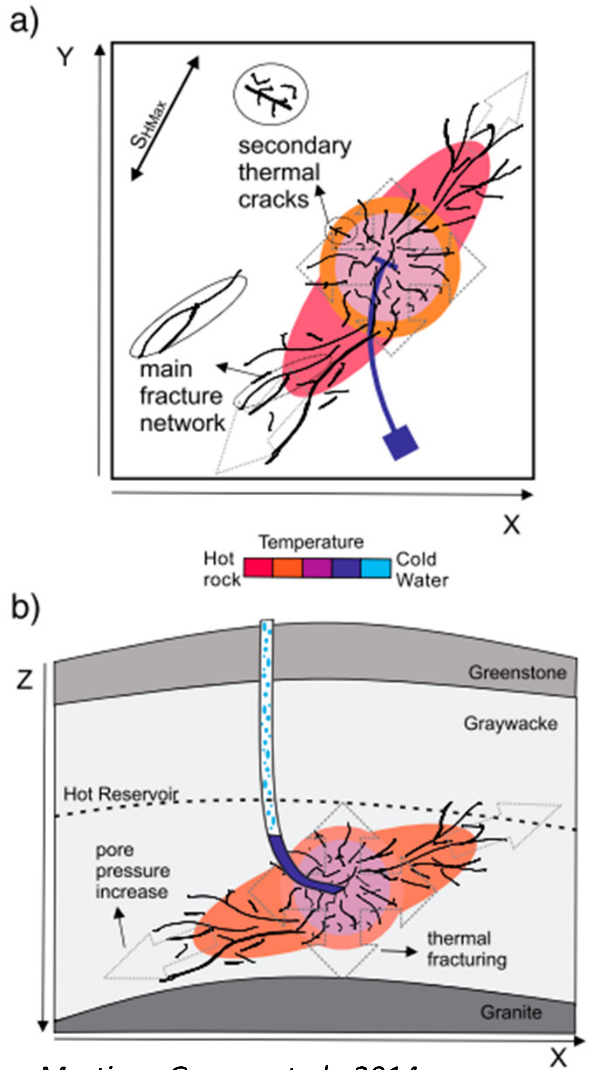
Martinez-Garzon et al., 2014

Processes inducing seismicity:

- **THERMOELASTIC** effects → **dominate in the proximity of the well** regardless of the injection stage, estimated thermally induced stress magnitude of approximately -26 MPa from strong thermal contraction at the wellbore wall but **attenuates rapidly with distance**
- **POROELASTIC** effects (pore pressure diffusion) → **dominate at some distance from the well** and **during peak fluid injections**, estimated pore pressure difference of about 1 MPa between peak injection and pre/post injection periods (capable of inducing seismicity)

Thermoelastic effect (volumetric contraction of rock due to cooling) occurs near the injection well. Causes **decrease of horizontal stresses** (σ2 and σ3 in normal faulting regime).

Pore pressure diffuses further from the well through the main fracture network. Causes **decrease of all princpial stresses** (σ1 , σ2 and σ3).



Martinez-Garzon et al., 2014

Part III. Conclusions

- *'the process of hydraulic fracturing as presently implemented for shale gas recovery does not pose a high risk for inducing felt seismic events'*

(National Research Council of the National Academies, June 2012)

- After hundreds of thousands of fracturing operations, only few examples of felt seismicity have been documented.

- The likelihood of inducing felt seismicity by hydraulic fracturing is thus extremely small but cannot be ruled out. *(Davies et al., 2013)*

- Future Findings ????

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SUPPLEMENTARY MATERIAL

Did Injection Induce Earthquakes?

7 criteria (Davis and Frohlich, 1993)

1) Background Seismicity

Are these events the first known earthquakes of this character in the region?

2) Temporal Correlation

Is there a clear correlation between injection and seismicity?

3) Spatial Correlation

a) Are the epicenters near wells (within 5 km)?

b) Do some earthquakes occur at or near injection depths?

c) If not, are there known geologic structures, that may channel flow to sites of earthquakes?

4) injection Practices

a) Are changes in fluid pressure at well bottoms sufficient to encourage seismicity?

b) Are changes in fluid pressure at hypocentral locations sufficient to encourage seismicity?

<u>Will</u> Injection Induce Earthquakes?

10 criteria (Davis and Frohlich, 1993)

1) Background Seismicity

a) Are large earthquakes ($M \geq 5.5$) known in the region (within several hundred km)?

b) Are earthquakes known near the injection site (within 20km)

c) Is rate of activity near the injection site (within 20km) high?

2) Local Geology

a) Are faults mapped within 20km of the site?

b) If so, are these faults known to be active?

c) Is the site near (within several hundred km of) tectonically active features?

3) State of Stress

Do stress measurements in the region suggest rock is close to failure?

4) Injection Practices

a) Are (proposed) injection practices sufficient for failure?

b) If injection has been ongoing at the site, is injection correlated with the occurrence of earthquakes?

c) Are nearby injection wells associated with earthquakes?

Poroelasticity

- Principal Assumptions in Poroelasticity Theory (Zoback, 2007):
  - There is an interconnected pore system uniformly saturated with fluid.
  - $V_{pore\ system} << V_{rock}$
  - We consider pore pressures and total stresses in terms of statistically averaged uniform values.

- An increase of fluid pressure causes the medium to expand just as an increase of temperature causes a similar expansion.

Poroelasticity - Coupling

- 1) Solid-to-fluid coupling occurs when a change in applied stress produces a change in fluid pressure or fluid mass.
- 2) Fluid-to-solid coupling occurs when a change in fluid pressure or fluid mass produces a change in the volume of the porous material (Wang, 2000).

Technological Features (induced events) *(different results)*

- Although there are sparse data and uncertainties, there is enough information to conclude that there is a lack of correlation between M_w and either the rate or volume of injection. (*Warpinski et al., 2012*)

- The largest magnitudes occur at relatively modest rates and volumes – more related to location than to the treatment parameters. (*Warpinski et al., 2012*)

Monitoring

- Events with magnitude greater than 0.25 could be reliably detected on relatively noisy stations (at least 4 stations)
- Events with magnitude greater than -0.6 can be reliably detected on more quiet stations (Eisner et al., 2012).
- The catalog is considered complete above M_L=0.4

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Interpretation

- ✓ The earthquake activity was caused by direct fluid injection into an adjacent fault zone during the treatments.
- ✓ The fluid injection reduced the normal stress on the fault, causing it to fail repeatedly in a series of small earthquakes.

Risk Mitigation

(Summary of Findings from Baisch and Voros, 2011; Harper 2011; GMI, 2011; de Pater and Pellicier, 2011)

- A conservative estimate of the minimum size of earthquake that could cause damage is M_L=2.6, based on German DIN4150 standards. This should be the maximum allowable limit for seismic activity.

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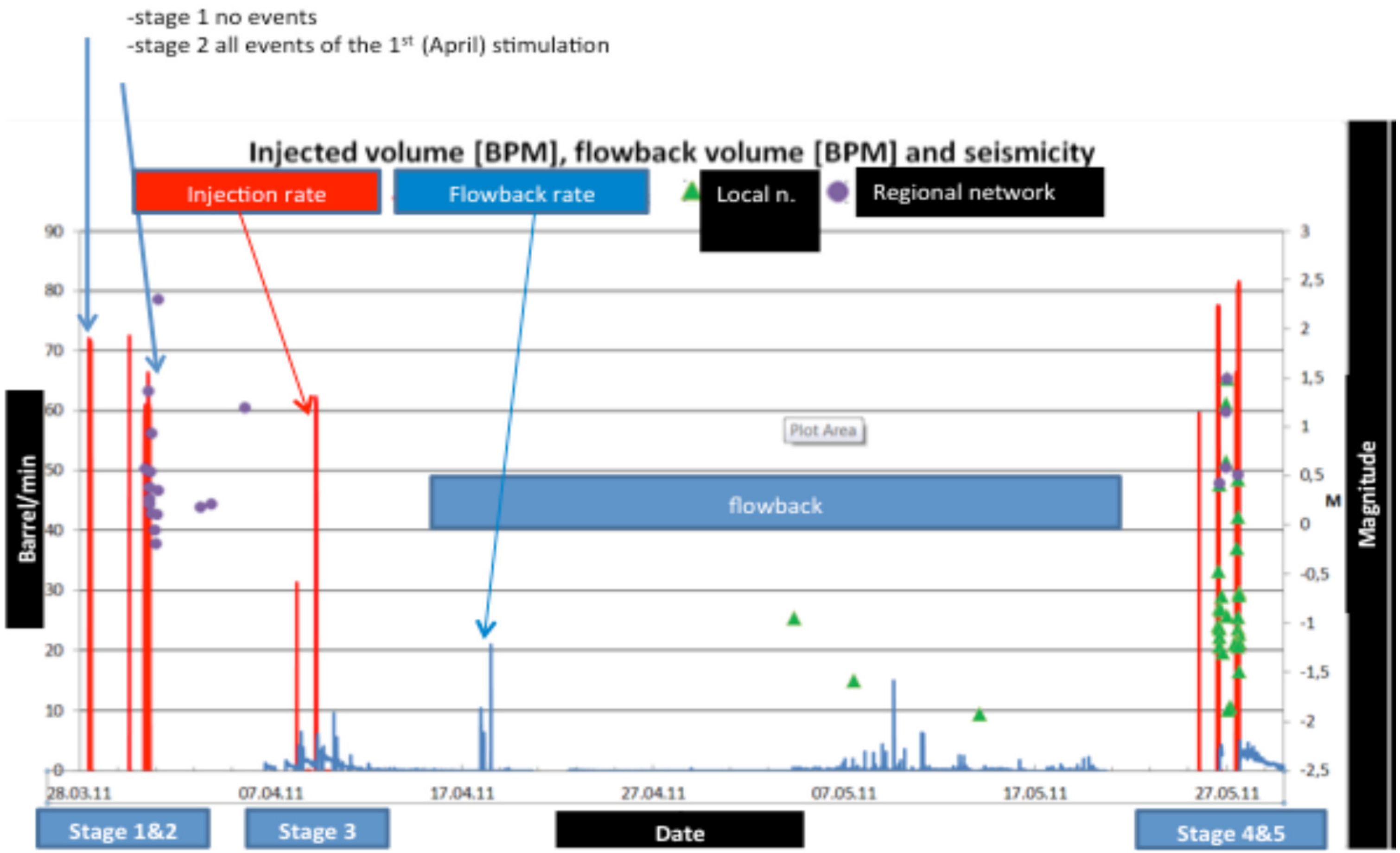
The Preese Hall, Lancashire (UK) Case Study



Styles, 2012

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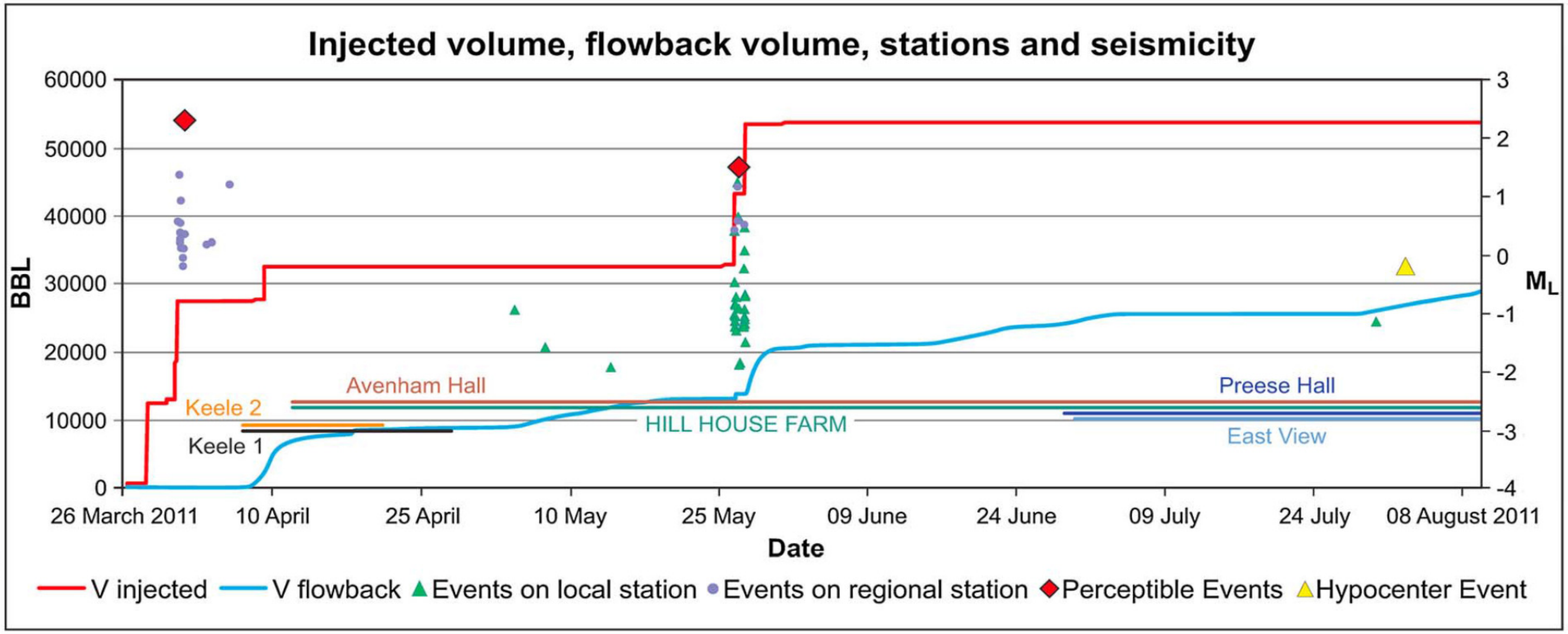
The Preese Hall, Lancashire (UK) Case Study



Styles, 2012

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Waveforms

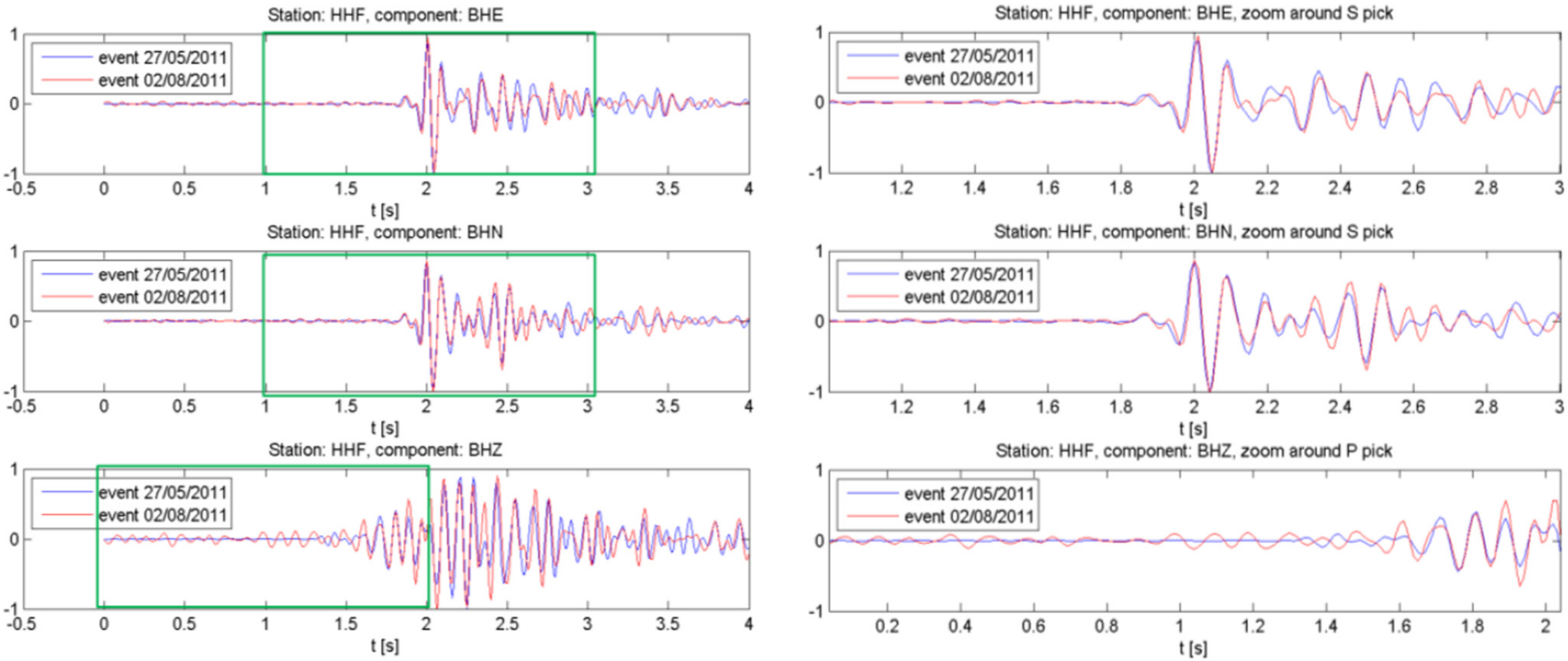

Figure 13. Filtered waveforms of the May 27, 2011 and August 2, 2011 events at station HHF. The green rectangles in the left plots are enlarged in the right plots. Waveforms start 2 seconds before the S-wave pick. The waveforms are aligned on the S-wave pick. Each trace is normalized to its maximum.

Eisner et al., 2012

Waveforms

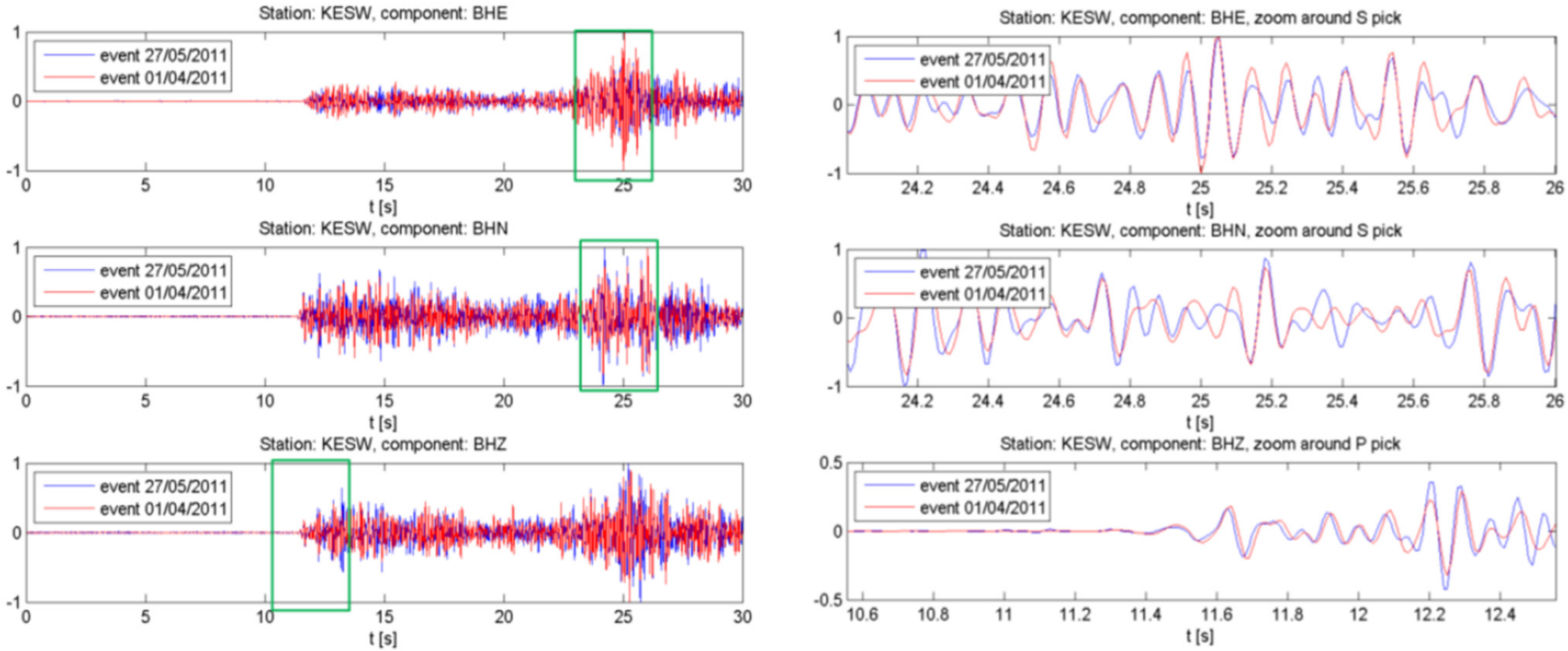

Figure 9. Filtered waveforms of the April 1, 2011 and May 27, 2011 events at station KESW. The green rectangles in the left plots are enlarged in the right plots. Waveforms start 25 seconds before the approximate S-pick. The waveforms are aligned on the S-pick and the difference on the P-pick is about 0.02 s. Each trace is normalized to its maximum.

Eisner et al., 2012

Risk Mitigation (conclusions?)

- Reduction of the treatment volume (Q-con, 2011),
- Aggressive flowback following hydraulic fracture treatments (Q-con, 2011),
- Seismic real-time monitoring in combination with a properly adjusted “traffic light system”.

de Pater and Baisch, 2011

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Fault

- The causative fault has not actually been identified, and more generally that there is only a limited understanding of the fault systems in the basin.
- The fault may be at a distance of up to a few hundred meters from the well-bore, but that fluid was able to flow into the fault through bedding planes in the reservoir that opened during stimulation as a result of the high pressures *(Green et al., 2012)*

Technology

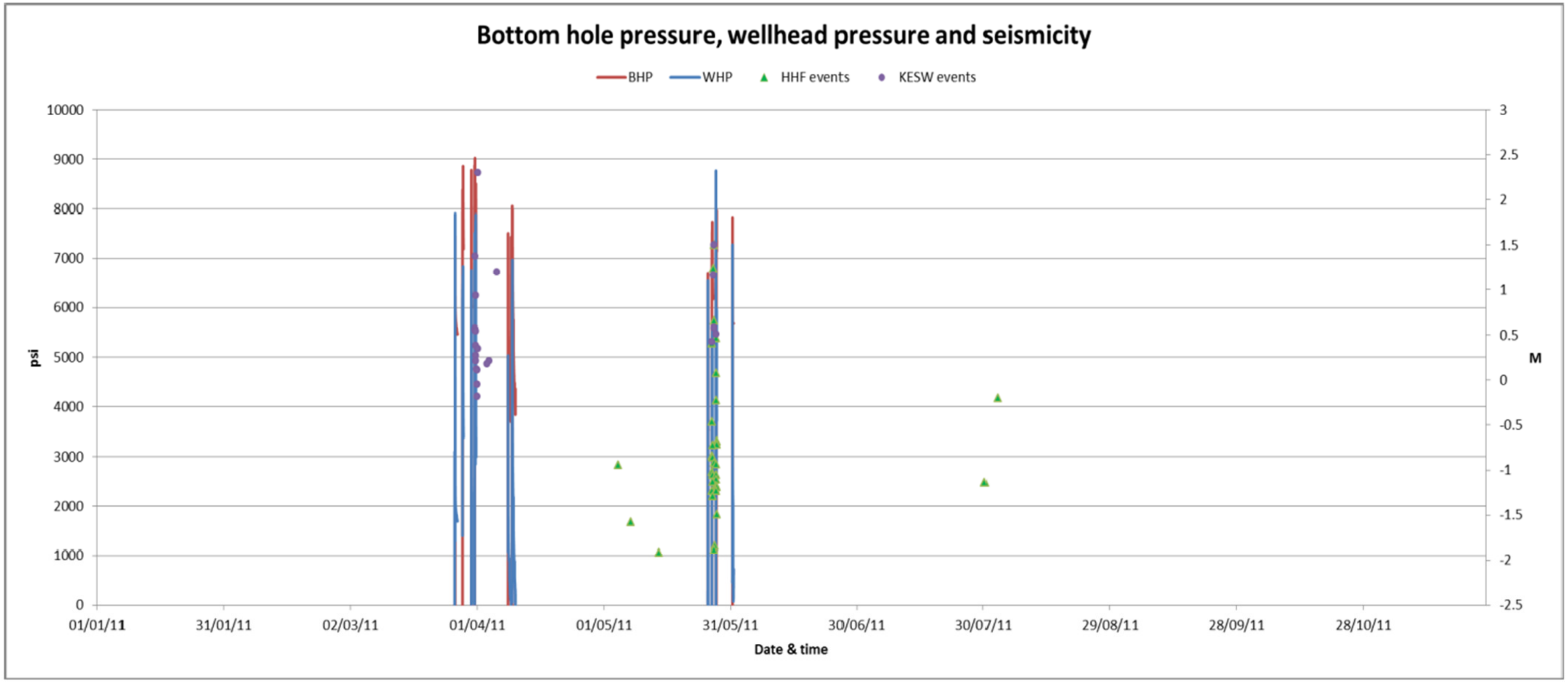


Figure 18. Bottom hole pressure (BHP) and wellhead pressure (WHP) in the exploration well Preese Hall. Events detected by KESW and by HHF are represented by the origin time and magnitude relative to the May 27, 2011 master event. The station HHF was operating since April 12, 2011 but is able to record much smaller events.

Eisner et al., 2012

Technology

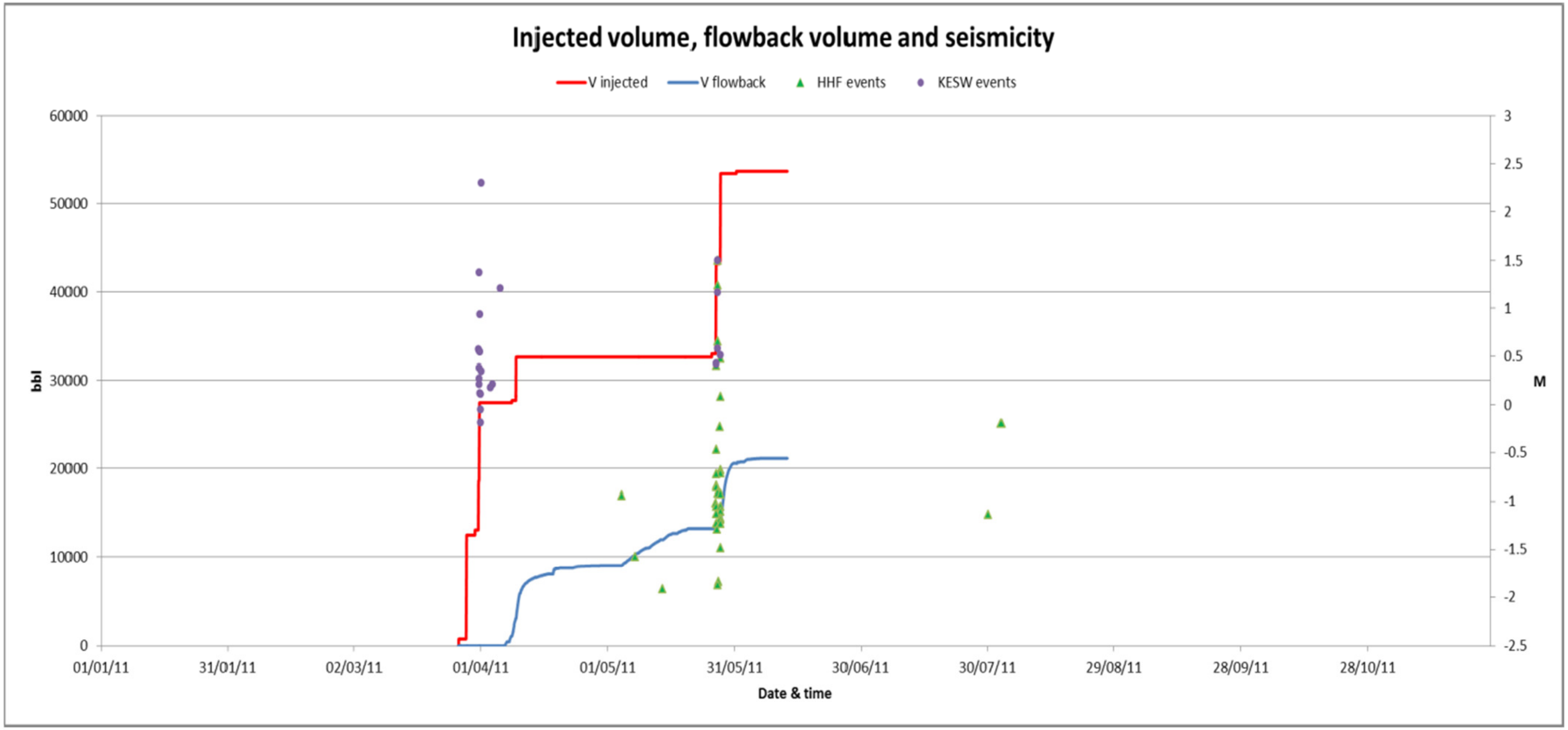
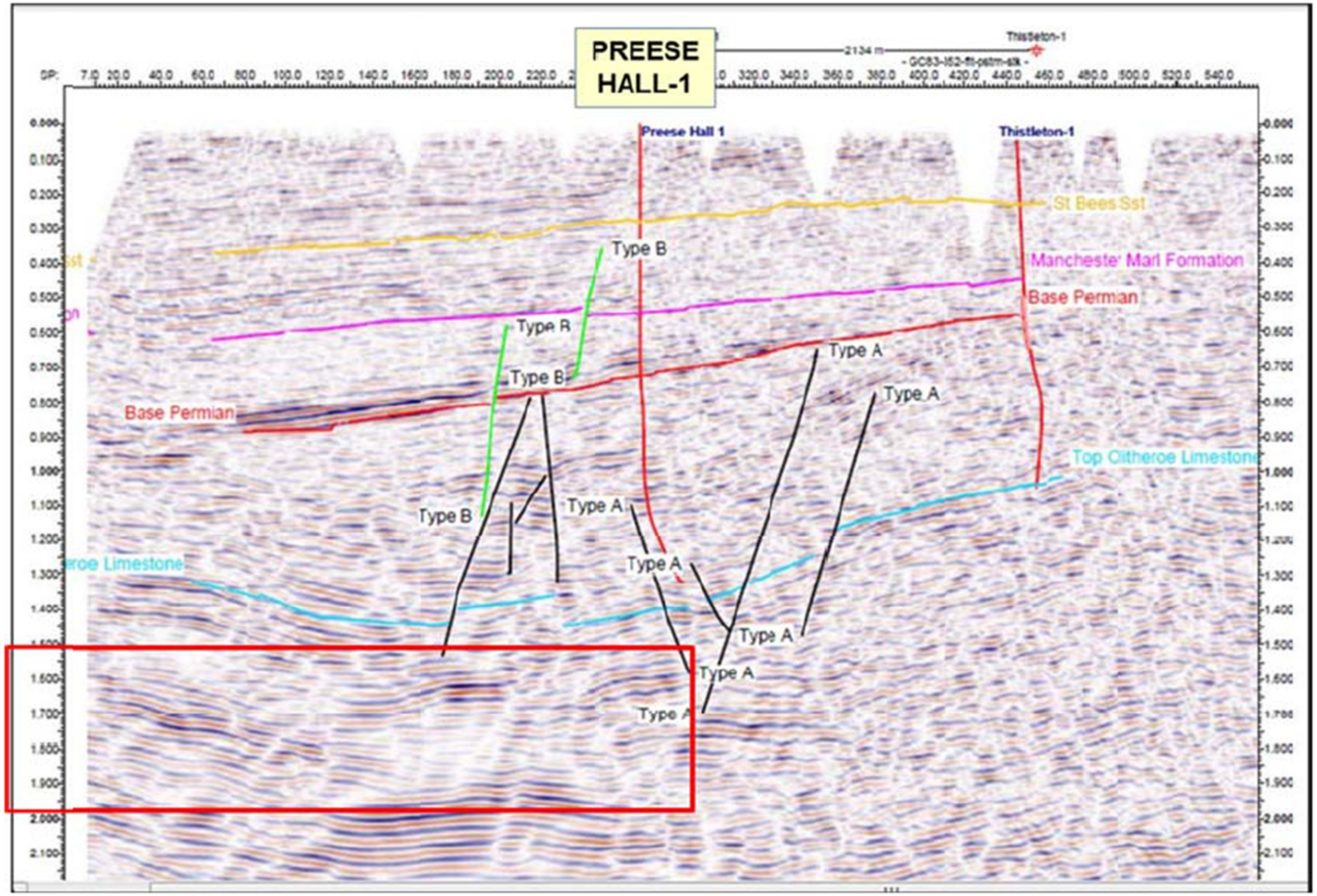


Figure 20. Injected volume and flowback volume in the exploration well Preese Hall. Events detected by KESW and by HHF.

Eisner et al., 2012

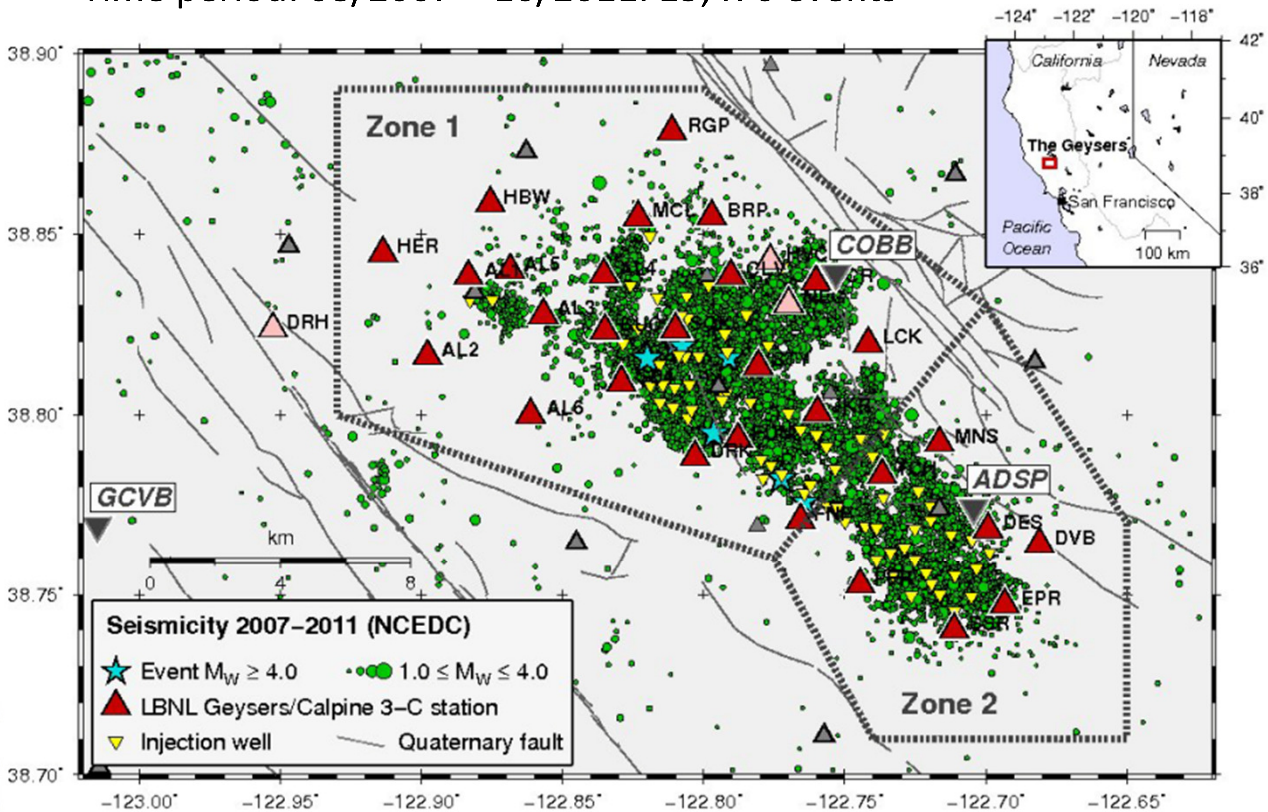
Figure XI-4: Seismic Reflection Line Showing Suspected Active Faults Near The Preese Hall-1 Well In The Bowland Sub-basin

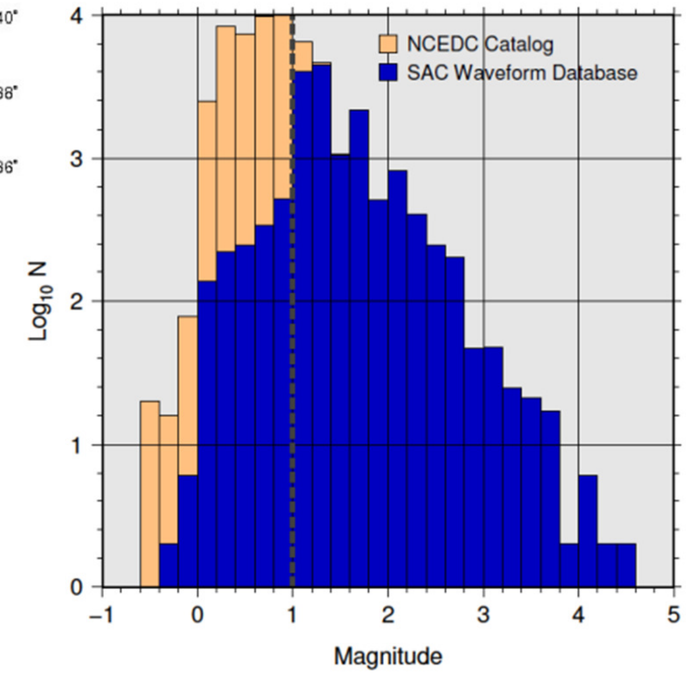


Source: de Pater and Baisch, 2011

The Geysers

Time period: 08/2007 – 10/2011. 15,476 events





Orefice et al., 2013

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