The evolution of induced seismicity sequences generated by long-term fluid injection

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Acknowledgements

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Natural
Environment
Research Council

Bristol and Oxford Passive Seismic
Research Consortium

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Exxon

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SPIRIT
ENERGY

TOTAL

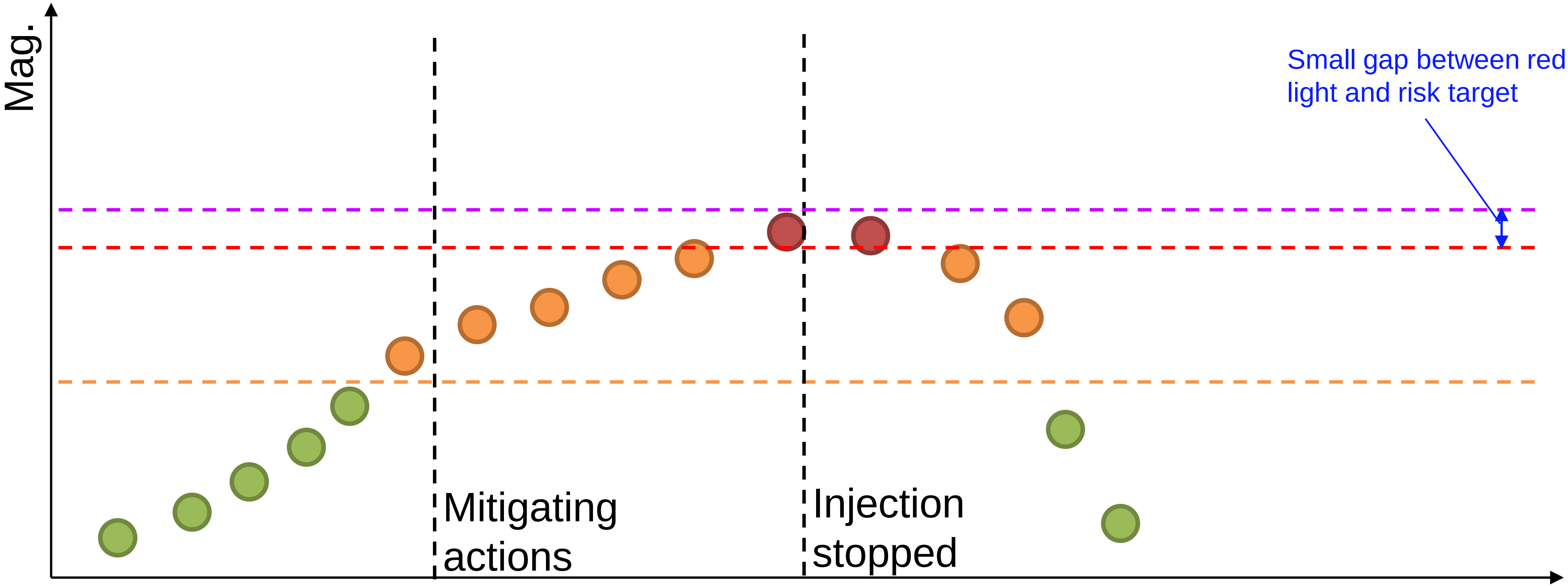
Motivation

Induced seismicity can have major impacts for subsurface indus

- Large events can cause damage to nearby buildings and infrastruct
- Smaller events, if felt by the public, cause significant levels of conce regulatory oversight, moratoria and outright closure of projects (and
- Many noteworthy examples:
  - Closure of Castor gas storage (20 km off the coast of Spain); s shale gas; significant reductions in WWD ops in Oklahoma; ab geothermal sites…
- Management of induced seismicity? Traffic Light Schemes

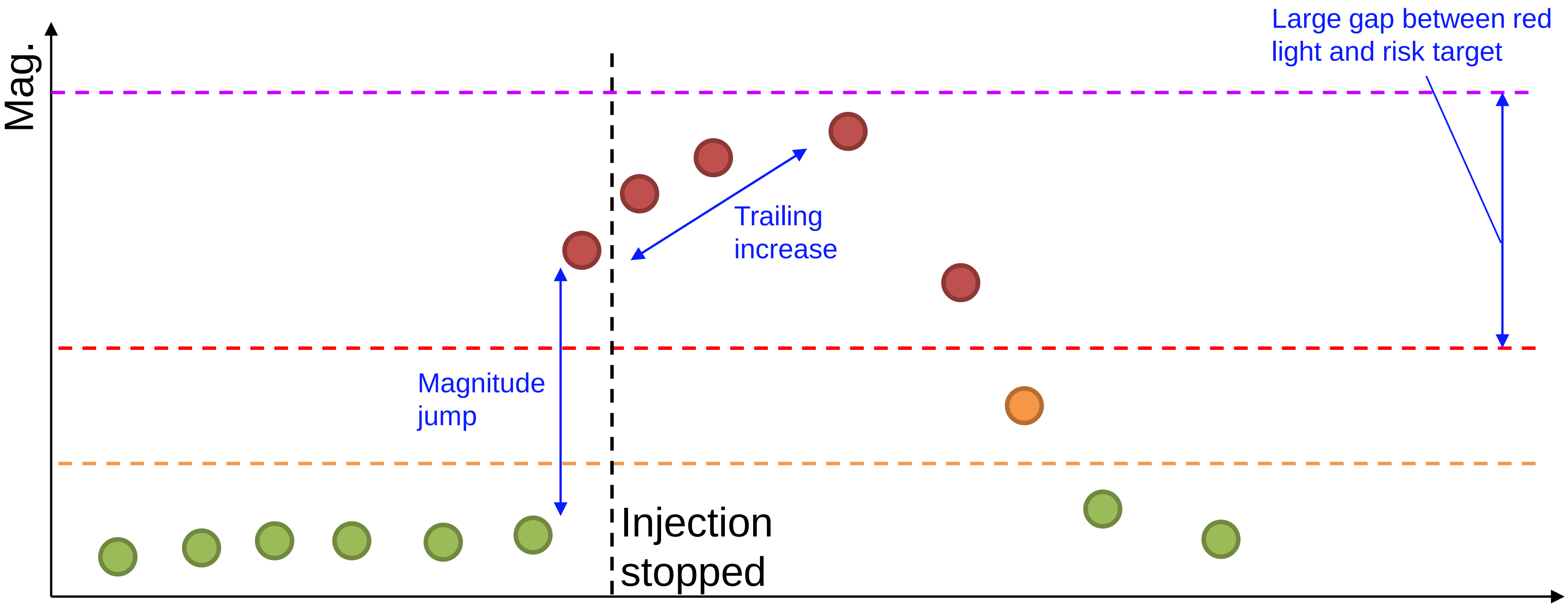
Traffic Light Systems

Green → yellow → red



Traffic Light Systems

Out of the blue, with trailing events



Key Questions

- Do the assumptions that underpin TLSs have evidential basis?
- How should we set red light thresholds relative to risk-based targets?
- Time-scales over which induced seismicity develops?
- What do the statistical properties of IS sequences tell us about underlying physical processes?

Data

Low-pressure long-term (LPLT) injection:

- Large volumes of fluid injected over long time-scales with low injection rates/pressures:
  - $V > 10^6$ m^3, $R < 1{,}000$ m^3/day, $P_I \approx P_f$.
  - Generally targeting high poro/perm sedimentary rocks (like CCS)
  - (compared to HF/geothermal stimulation): $V \approx 10^4$ m^3, $R \approx 500$ m^3/hour, $P_I \gg P_f$, targeting low-permeability rocks.

- Current technologies: primarily WWD.
- Future technologies: CCS; natural gas storage; H_2 storage.

- Using WWD cases as analogues to how induced seismicity might evolve at CCS/gas storage sites.

Site | Location	Year of onset	M_{MAX}	N	b	ΔM_{MAX}	ΔM_T	P_{Mmax} [%]	ΔT (First event) [days]	ΔT (Largest event) [days]	Reference
Castor | Spain	2013	4.0	3437	1.0	0.6	1.3	78	4	31	Cesca et al. (2021)
Puerto Gaitán | Colombia	2012	5.0	1637	0.9	0.5	0	87	1203	4312	Molina et al. (2020)
Rongchang | Sichuan	1980	5.6	3602	1.0	0.7	0	51	31	7014	Wang et al. (2020)
Hutubi | Xinjiang	2013	3.6	273	1.1	0.5	0	8	50	63	Tang et al. (2018)
Cordel | WCSB	1992	4.0	124	0.9	0.6	0	10	292	2008	Schultz et al. (2014)
Eagle West | WCSB	1984	4.3	91	0.8	0.5	0	36	1439	4920	Horner et al. (1994)
Graham | WCSB	2003	4.0	246	1.1	0.5	0	57	672	3194	Hosseini and Eaton (2018)
Musreau | WCSB	2018	3.9	85	0.8	0.5	0	41	251	633	Li et al. (2022)
Youngstown | Ohio	2011	4.1	282	0.9	1.3	1.3	94	15	369	Kim et al. (2013)
Greeley | Colorado	2013	3.3	1281	0.8	0.7	0	65	220	1316	Yeck et al. (2016)
Paradox Valley | Colorado	1989	4.4	6120	0.9	0.7	0	91	15	10108	Block et al. (2014)
Raton Basin | Colorado	1980	5.3	642	0.8	0.5	0	39	245	6139	Nakai et al. (2017)
Guy-Greenbrier | Arkansas	2009	4.7	1312	1.2	1.1	0	61	197	698	Horton (2012)
Cushing | Oklahoma	2012	5.0	501	1.1	1.3	0	74	781	2106	McGarr and Barbour (2017)
Fairview | Oklahoma	2014	5.1	2711	1.0	0.7	0	24	3096	3696	Goebel et al. (2017)
Guthrie-Langston | Oklahoma	2011	4.2	1993	1.1	0.7	0	34	2107	3152	Schoenball et al. (2018)
Pawnee | Oklahoma	2013	5.8	1525	1.1	2.1	0	33	1641	2802	Walter et al. (2017)
Prague | Oklahoma	2010	5.7	1014	0.8	0.9	0	13	6008	6883	Keranen et al. (2013)
Milan | Kansas	2014	4.9	277	0.9	1.5	0	17	199	469	Verdecchia et al. (2021)
Harper | Kansas	2014	4.3	466	0.8	0.5	0	18	846	946	Verdecchia et al. (2021)
Azle-Reno | Texas	2013	3.6	634	0.7	0.5	0	31	1624	1651	Hennings et al. (2021)
Dallas-Forth Worth | Texas	2008	3.2	64	0.6	0.3	0.2	90	60	2319	Hennings et al. (2021)
Irving | Texas	2014	3.9	818	0.8	0.5	0	30	2360	2624	Hennings et al. (2021)
Venus | Texas	2010	4.0	917	0.7	0.4	0	49	1178	3141	Hennings et al. (2021)
Timpson | Texas	2008	4.8	49	0.6	1.4	0	23	617	2116	Frohlich et al. (2014)
Cogdell | Texas	2009	4.3	285	1.1	0.5	0	38	2049	3906	Gan and Frohlich (2013)
Reeves | Texas	2018	4.9	208	0.6	1.3	0	32	809	1547	Skoumal et al. (2020b)


Rankin Inlet
Great Slave L.
Bear Lake
British Columbia
Fort Chipewyan
CANADA
Churchill
Hudson Bay
Inukjuak
Prince Rupert
Alberta
Fort McMurray
Manitoba
Grande Prairie
Saskatchewan
Thompson
Labrador City
Prince George
Edmonton
Flin Flon
Red Deer
Prince Albert
L. Winnipeg
Kamloops
Saskatoon
Quebec
Vancouver
Calgary
Ontario
Moosonee
Victoria
Regina
Washington
Seattle
Swift Current
Spokane
Brandon
Winnipeg
Amos
Timmins
Quebec
Maine
Vancouver
Williston
Grand Forks
Minnesota
Lake Superior
Portland
Helena
North Dakota
Duluth
Montreal
Montana
Ottawa
Butte
Bismarck
Concord
Idaho
Oregon
South Dakota
St. Paul
Wisconsin
Lake Huron
Boise
Minneapolis
Toronto
Rochester
Twin Falls
Milwaukee
Lake Michigan
Buffalo
Hartford
Wyoming
Detroit
Michigan
Lake Erie
Iowa
Salt Lake City
Scottsbluff
Reno
Nebraska
Chicago
New York
Cheyenne
Omaha
Illinois
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Tennessee
North Carolina
Santa Fe
Los Angeles
Arizona
Oklahoma
Charlotte
Albuquerque
Memphis
San Diego
Phoenix
Little Rock
Columbia
South Carolina
Mexicali
New Mexico
Arkansas
Birmingham
Atlanta
Tucson
Mississippi
Alabama
Georgia
Jackson
Texas
Jacksonville
Tallahassee
Hermosillo
Austin
Baton Rouge
Louisiana
New Orleans
Florida
Chihuahua
Orlando
San Antonio
Houston
Tampa
West Palm Beach
MEXICO
Rio Grande
Monterrey
Nassau

Magnitude Jumps and Trailing Events

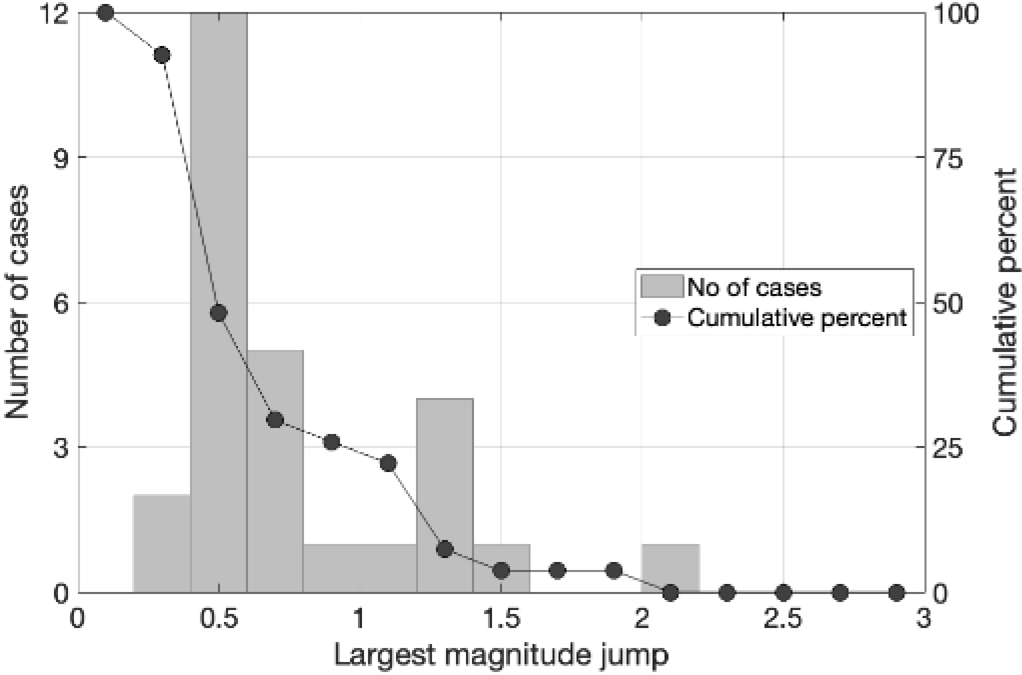
Magnitude Jumps:

- In most cases, $\Delta M_{MAX} < 1.0$ magnitude units, and in only 1 case was $\Delta M_{MAX} > 1.5$ magnitude units.

Trailing Events:

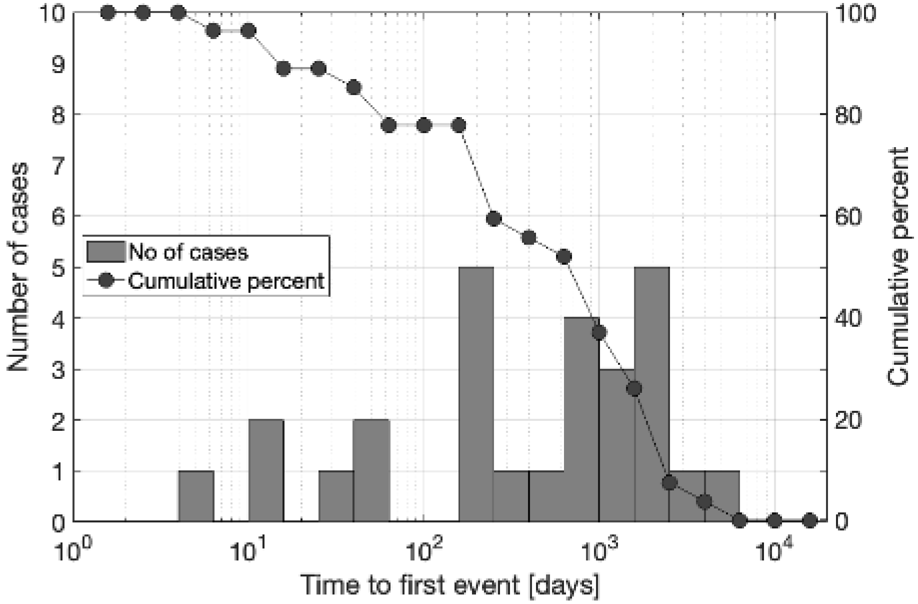
- Few cases with trailing events – in most cases injection did not stop after large events.
- For cases that did stop (Castor; Youngstown; DFW), trailing event increases were c. 1.0 mag. units, and occurred within 2 weeks (similar to HF observations)

Distribution of magnitude jumps:

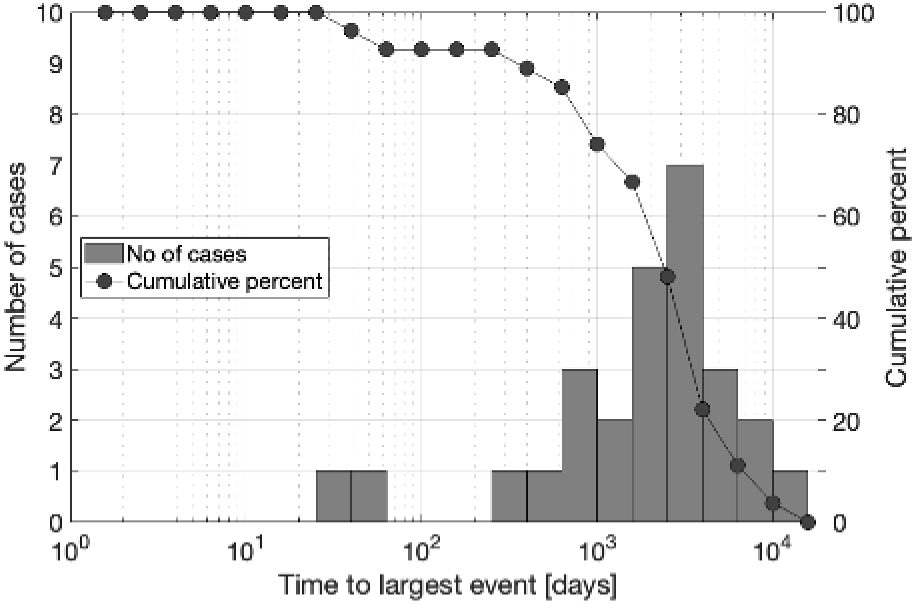


Timescales for Seismicity Onset

Time to first event



Time to biggest event



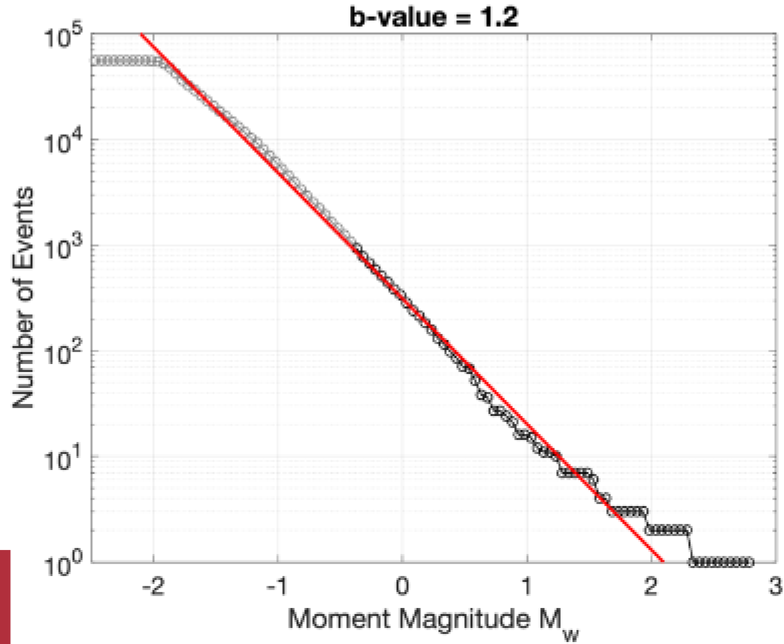
Random Occurrence of M_{MAX}?

Van der Elst (2016):

- Once a fault is triggered, event magnitudes are drawn at random from a G-R distribution.
- Occurrence of M_{MAX} event will be random within the sequence
- M_{MAX} event could occur early within the sequence, meaning that TLSs cannot prevent these events.

Verdon and Bommer (2021):

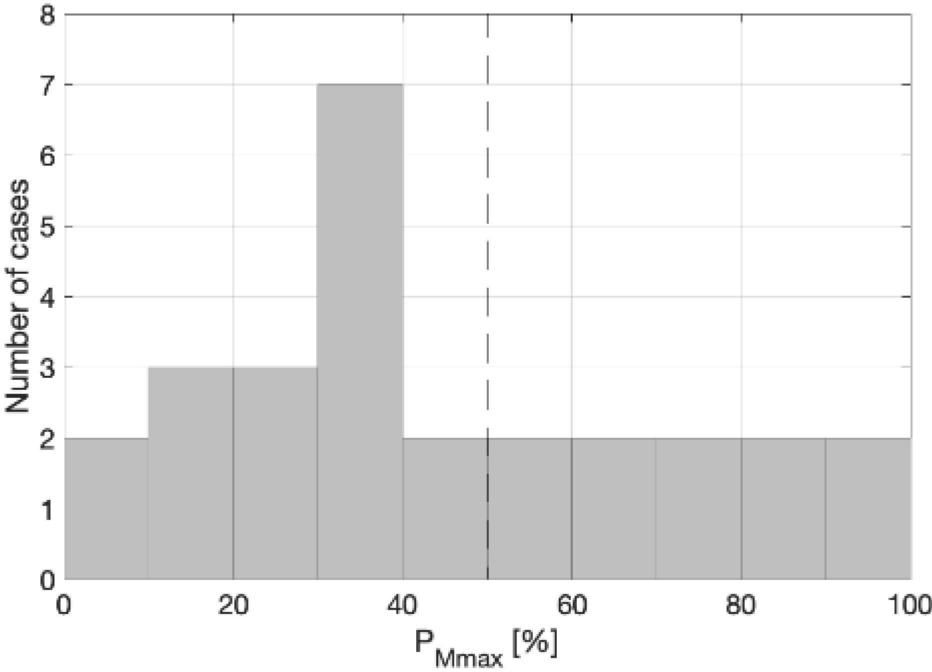
- Subsurface perturbation grows with time, hence event magnitudes will grow with time. M_{MAX} events will occur towards the end of a sequence.
- TLSs can therefore be used to mitigate hazard.



Random Occurrence of M_{MAX}?

- M_{MAX} events are not randomly (uniformly) distributed within sequences.
- However, M_{MAX} events are not at the end of the sequences.
- In general, seismicity builds, peaks and then levels off or subsides.
- Exhaustion of tectonic strain? After a certain number of induced events, faults have nothing left to give, so seismicity subsides.
- Size of perturbation through time? ΔP reaches a steady state as injection continues?

When in the sequence does the largest event occur:



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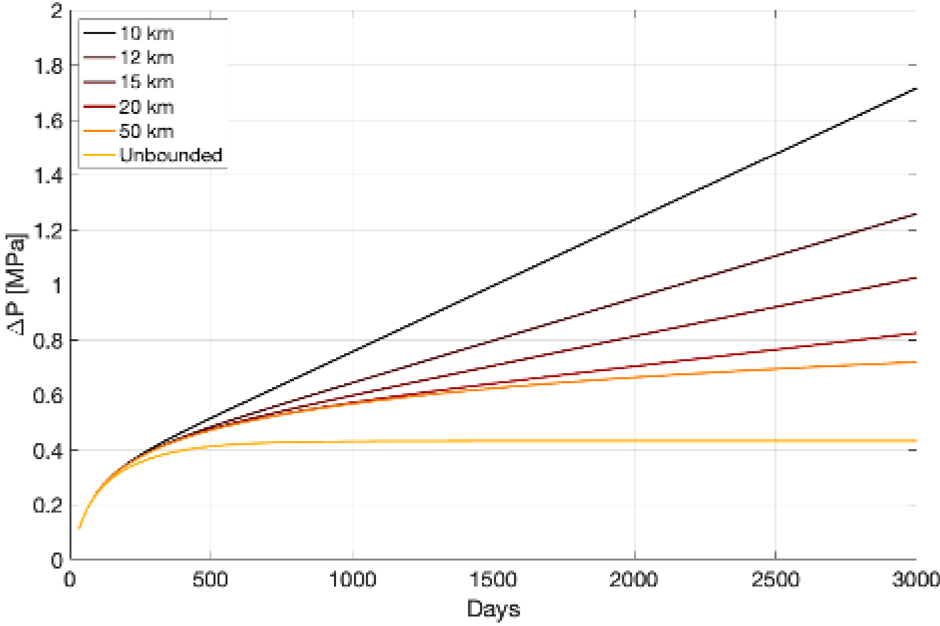
Pressure change (simple injection models)



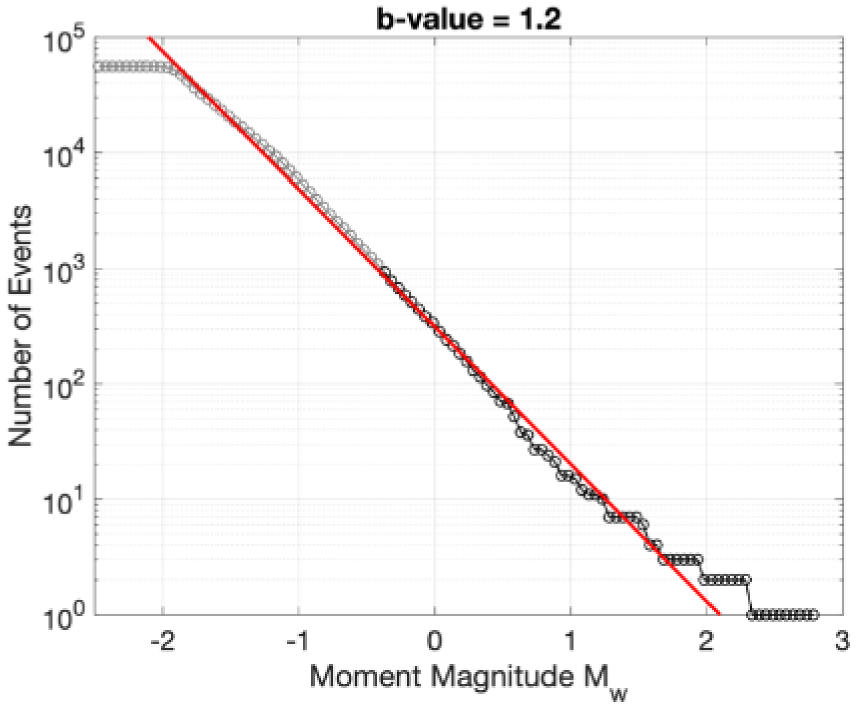
Are ΔM_{MAX} values G-R distributed?

H_0: once a fault activates, event magnitudes are drawn randomly from an underlying G-R distribution:

- If so, Δ*M* values will also be G-R distributed

H_1: Perturbation increases through time, so events get larger systematically:

- If so, large jumps will be under-represented in the Δ*M* distribution

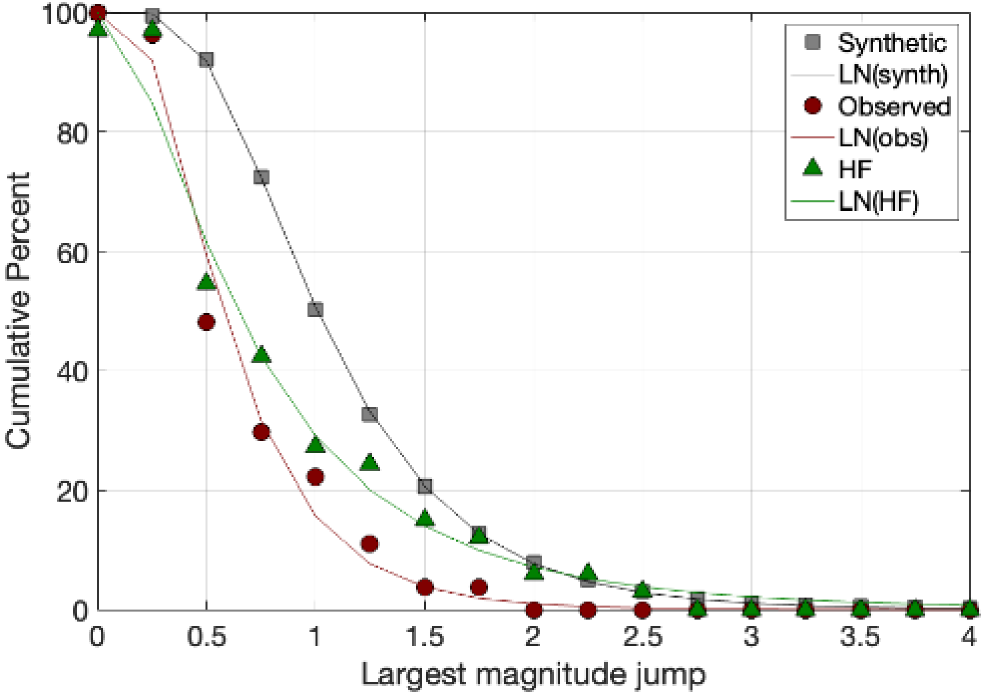


Are ΔM_{MAX} values G-R distributed?

We test this by comparing our observed ΔM distributions with those produced by random sampling of the G-R relationship

- LPLT and HF observations have similar distributions, which are clearly lower than synthetic values.
- **Growth of magnitudes is systematic and gradual, not random from G-R!**

Distribution of magnitude jumps:



Conclusions

- Magnitude jumps are typically < 1.5 magnitude units for LPLT injection. Red-light thresholds should be set c. 1.5 magnitude units below the risk-based threshold (i.e., the magnitude that is to be avoided).
- Onset of seismicity is variable: some cases within days, other cases not for several years. Monitoring must continue through the duration of a project.
- M_{MAX} does not occur at random. Sequences tend to build, peak, and then stabilise or subside. Links to how ΔP evolves during injection?
- Observed magnitude jumps are not consistent with random draws from G-R. Large magnitude jumps are under-represented. Magnitudes evolve sequentially with time.

Thanks!

Any questions, comments or suggestions?

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