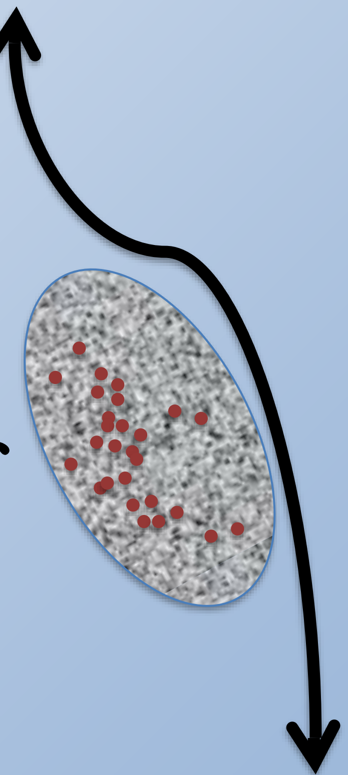
GEoREST Workshop on Induced Seismicity
Palma de Mallorca, Spain
11-13 March, 2024

HiQuake – a global database of human-induced earthquakes



Gillian R. Foulger

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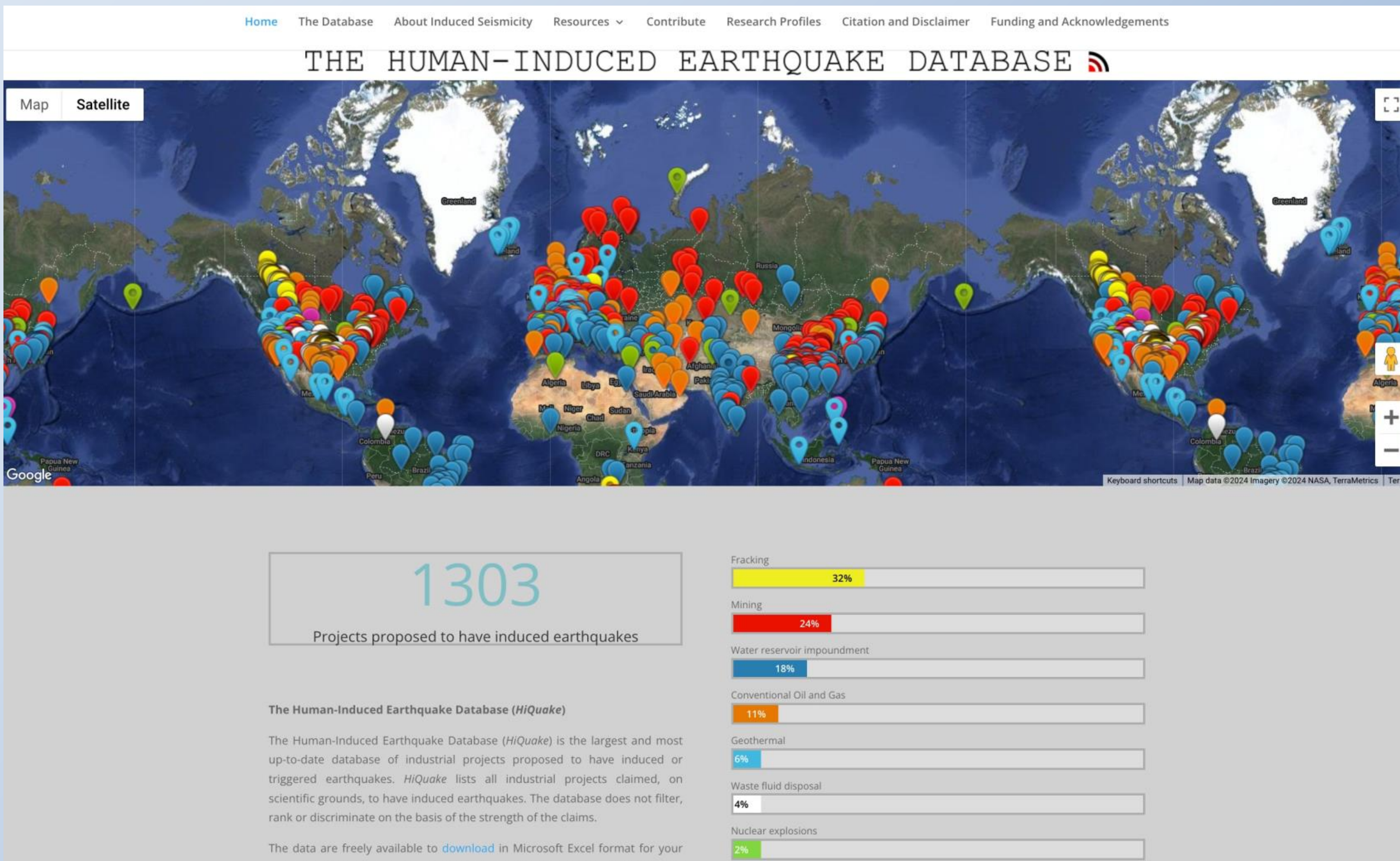
Groningen gas field, Netherlands (Holland)

- 10^{th} largest gas field in world
- 50% of all gas production in Netherlands
- 2019: decided to stop all production in 2022
- massive resource loss for The Netherlands
- Why? – Induced earthquakes

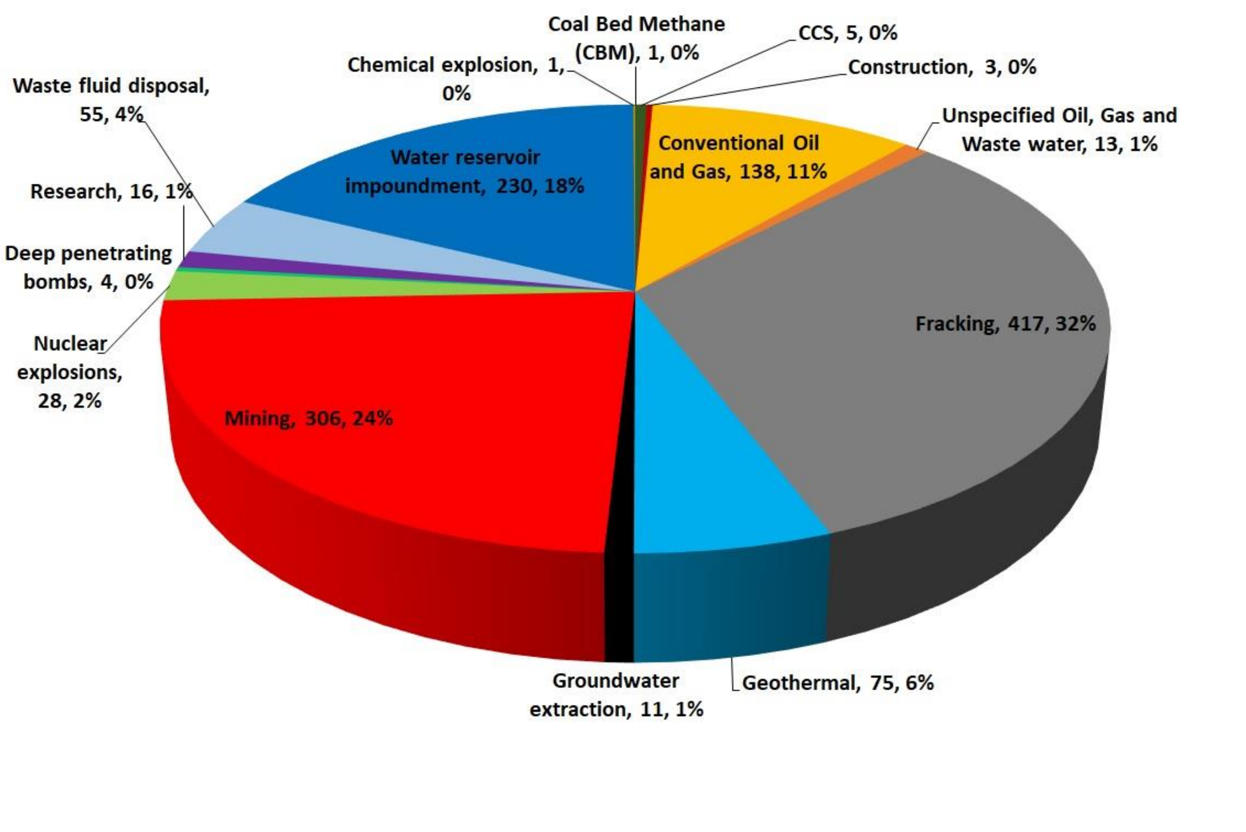
HiQuake

www.inducedearthquakes.org



HiQuake Database

- Freely available for download from: https://www.inducedearthquakes.org
- Currently 1303 cases
- A surprise: the huge range of processes

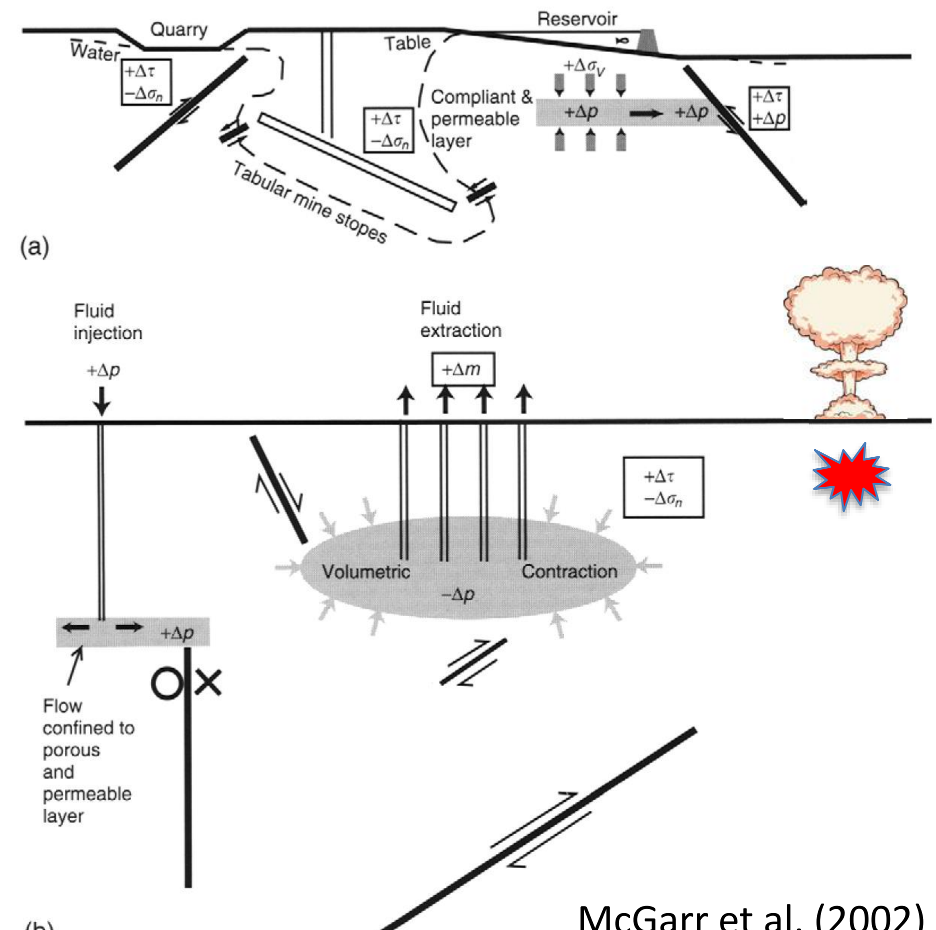


Environments of induced seismicity

- Surface operations
  - Adding mass
  - Removing mass
- Extraction from the subsurface
  - Groundwater extraction
  - Mining
  - Hydrocarbons
  - Geothermal production (heat/fluids)
- Injection into the subsurface
  - Liquid
  - Gas
- Explosions
  - Nuclear
  - Chemical

Individual cases:

Established → Speculative



McGarr et al. (2002)

Surface Operations

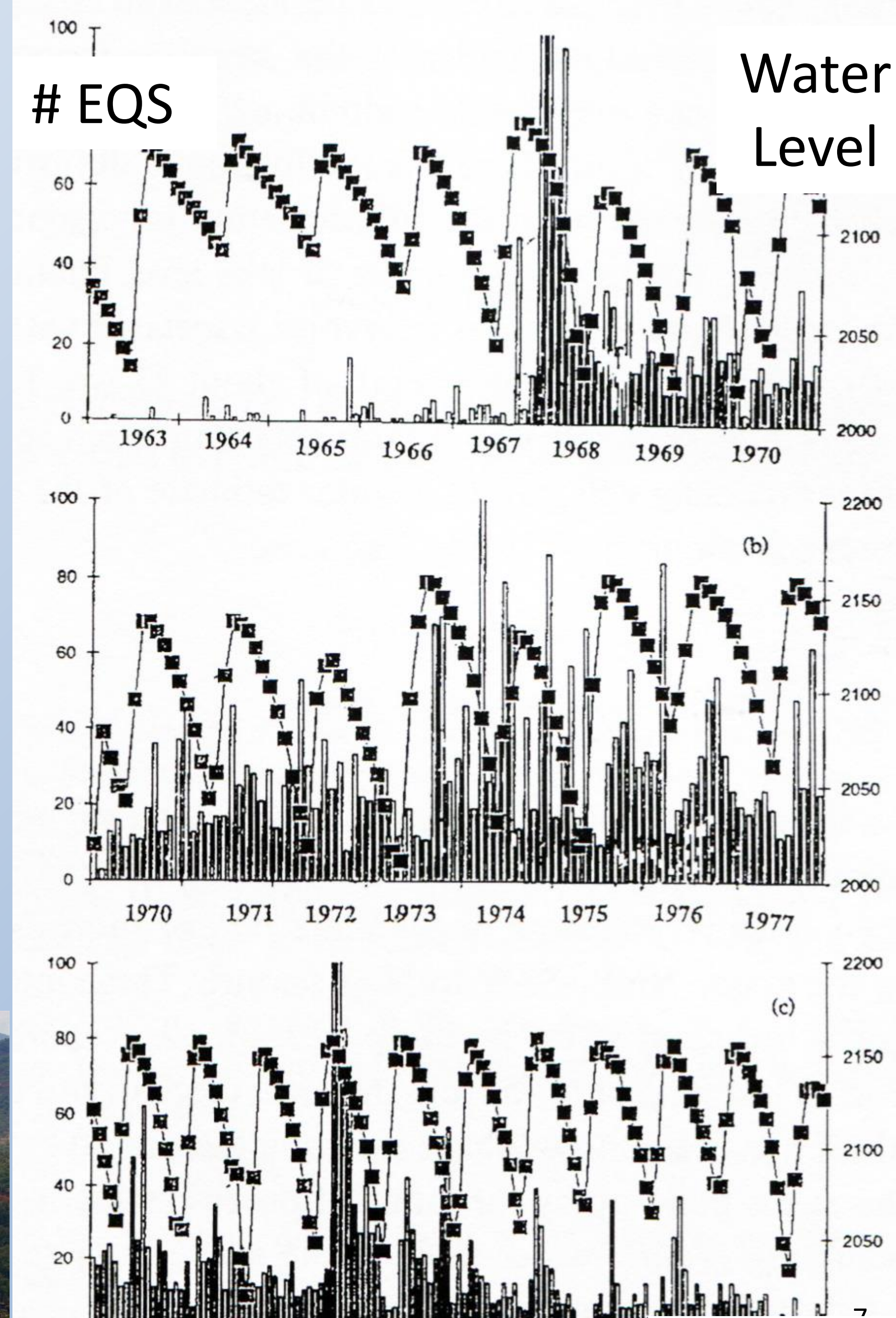
Water reservoirs

Open-cast mining

Erecting heavy buildings

Water reservoir example: Koyna dam, India

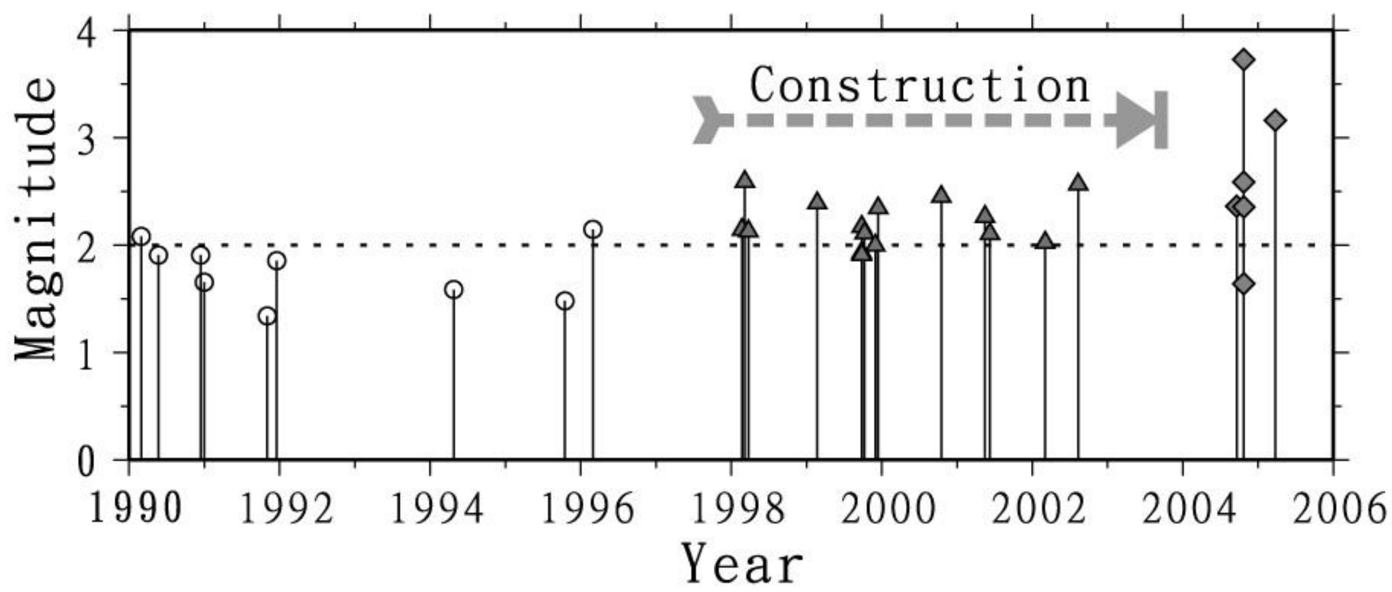
- Dam 103 m high, reservoir 75 m deep & 52 km long
- 1967 M 6.3, ~ 200 deaths & dam damaged
- Eqs M > 2 and reservoir water levels (feet) 1963 – 1986
- Large dams up to 140 m ~ 20% seismogenic



Talwani (1995)

Erecting heavy buildings example:
Taipei 101, Taiwan

- Weight of building ~ 700,000 tonnes
- Increase in stress at base: ~ 0.47 MPa

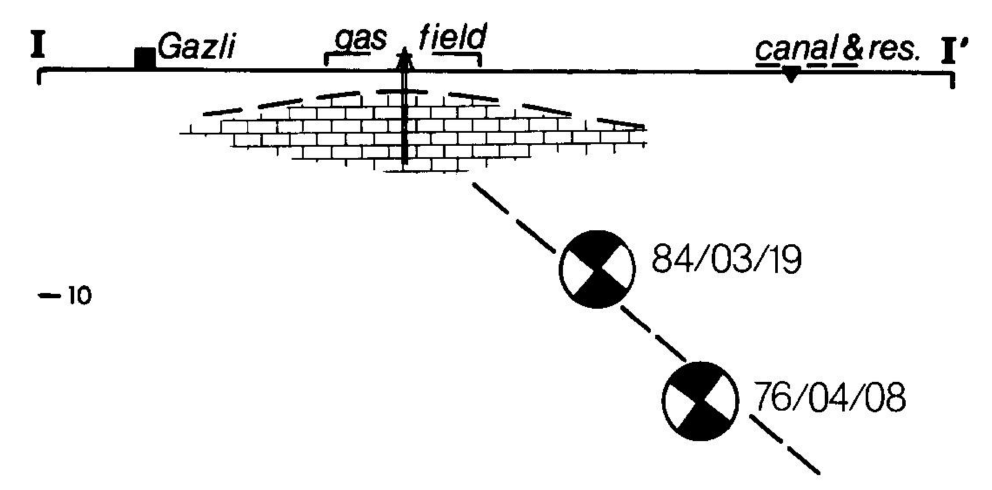


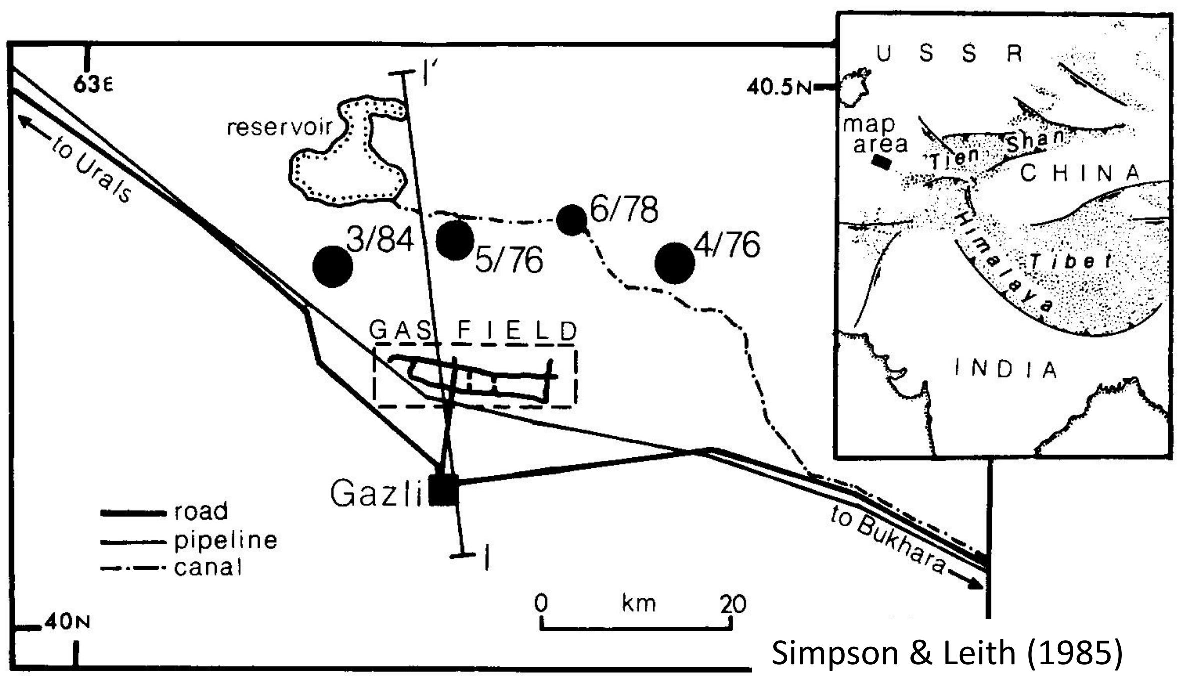
Extraction From the Subsurface

Oil & gas
Groundwater
Mining
Geothermal fluids

Oil & gas example:
Gazli, Uzbekistan

- 1966 – Large-scale gas production
  - 1976/8,
  - 1984 – 3 x M ~ 7
- 1 death, 100 injuries
- Pressure reduction ~ 5 MPa

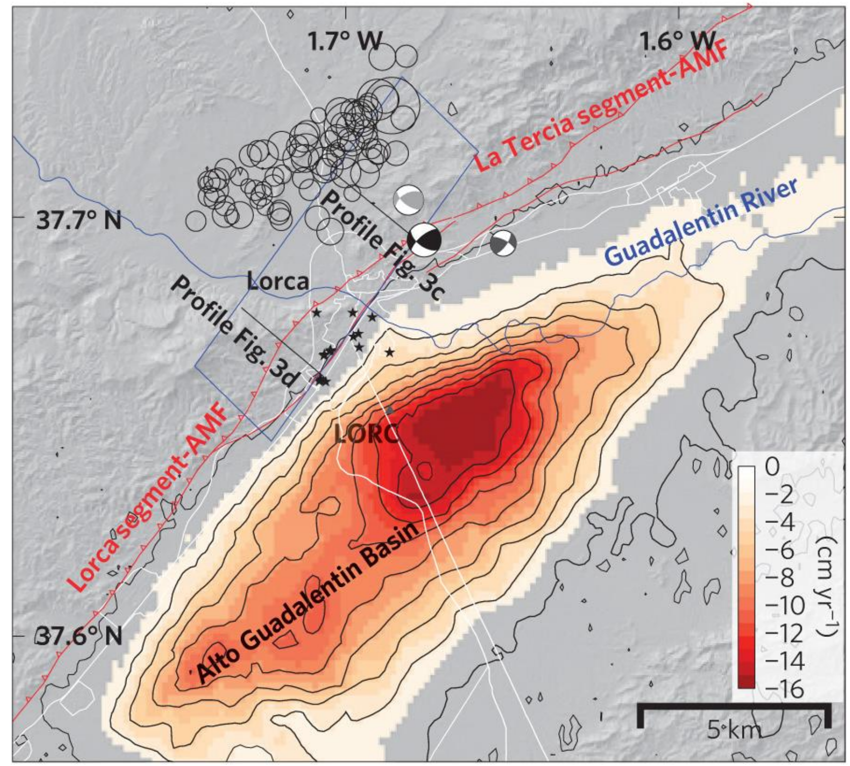


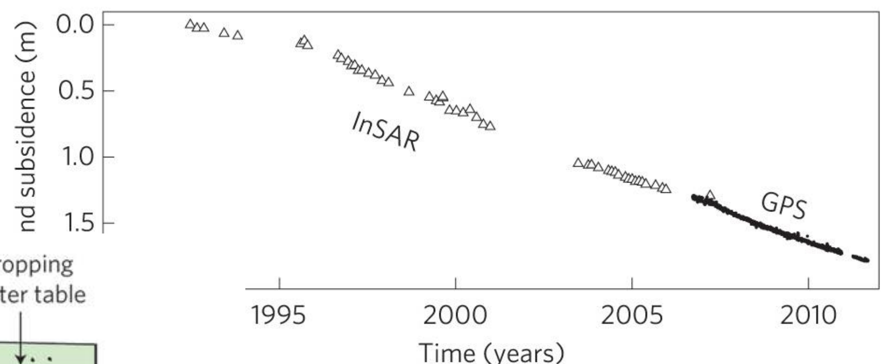


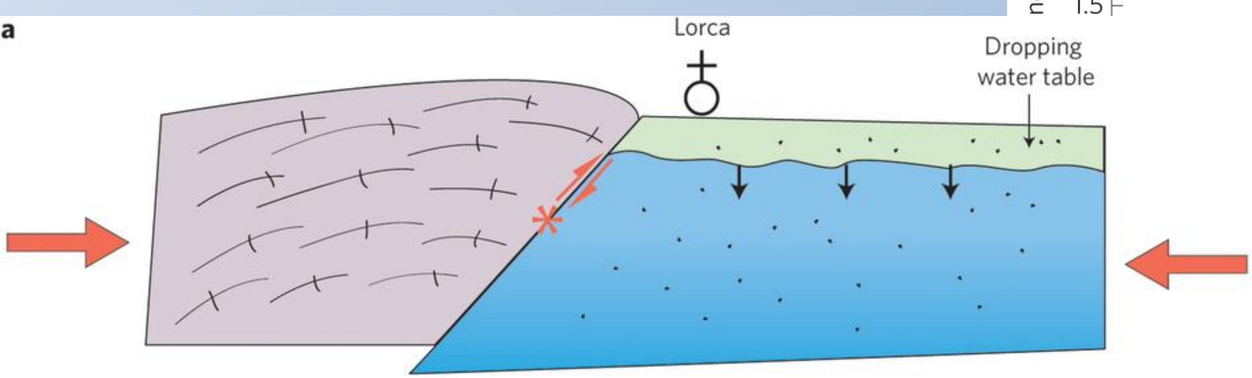
Simpson & Leith (1985)

Groundwater extraction example:
Lorca, Spain

- 2011 M_W 5.1
- Shallow, ~ 3 km depth, Alhama de Murcia Fault
- ~ 10 x 10 km fault area







González et al. (2012)

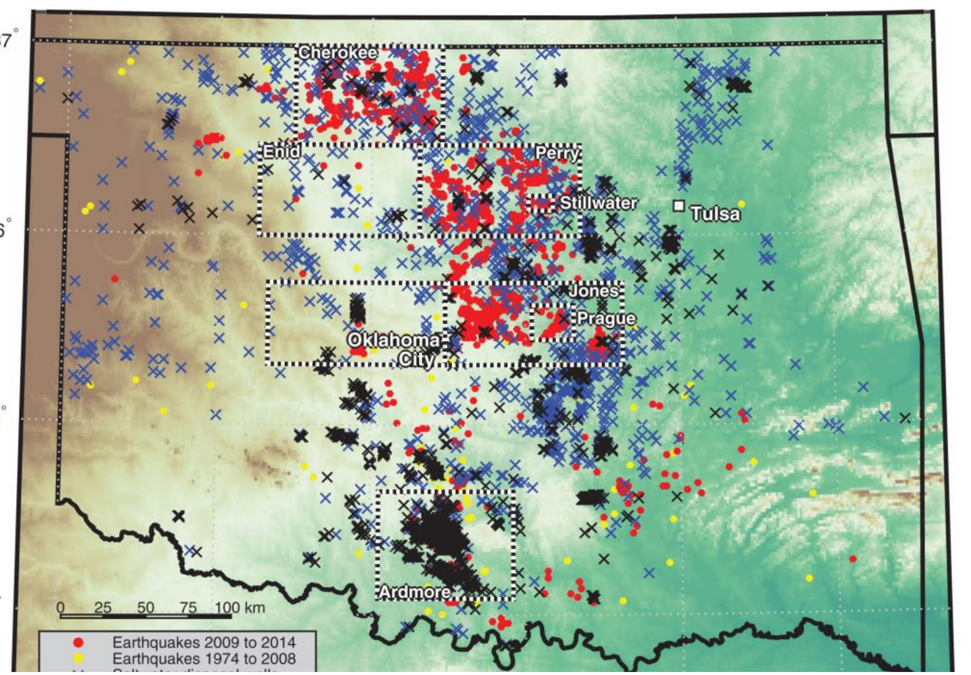
Lorca, Spain
9 people killed, 100s injured

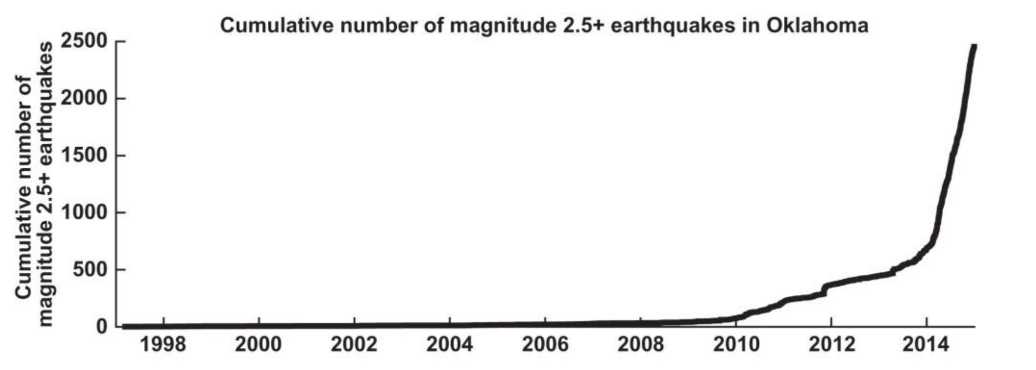
Injection Into the Subsurface

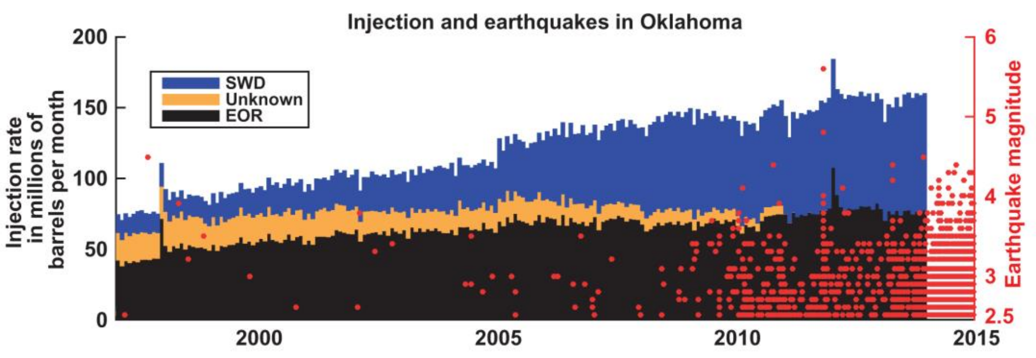
Wastewater disposal & enhanced oil recovery
Gas storage
Geothermal hydrofracturing
Carbon capture & storage
"Fracking"

Wastewater disposal & oil recovery example:
Oklahoma: Injection wells

- ~ 7,000 injection wells
  - Disposal of produced brine (dominant)
  - Enhanced oil recovery
  - Disposal of frack fluid
- Most injected in Arbuckle Group: carbonates/sandstones close to Precambrian crystalline basement

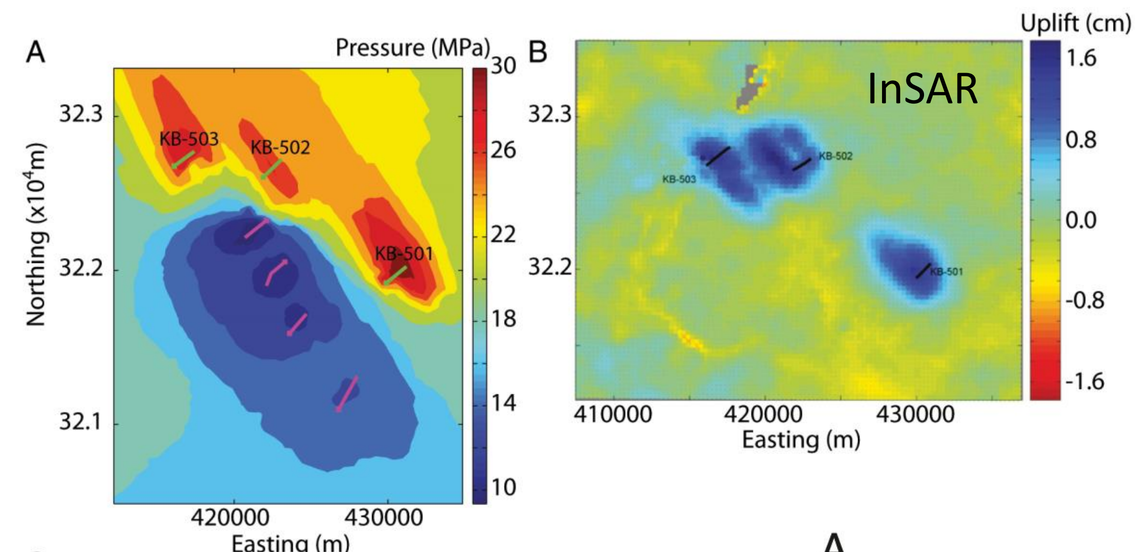


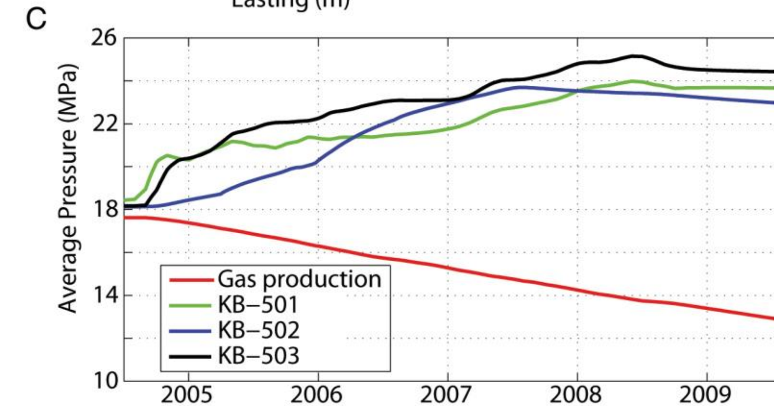


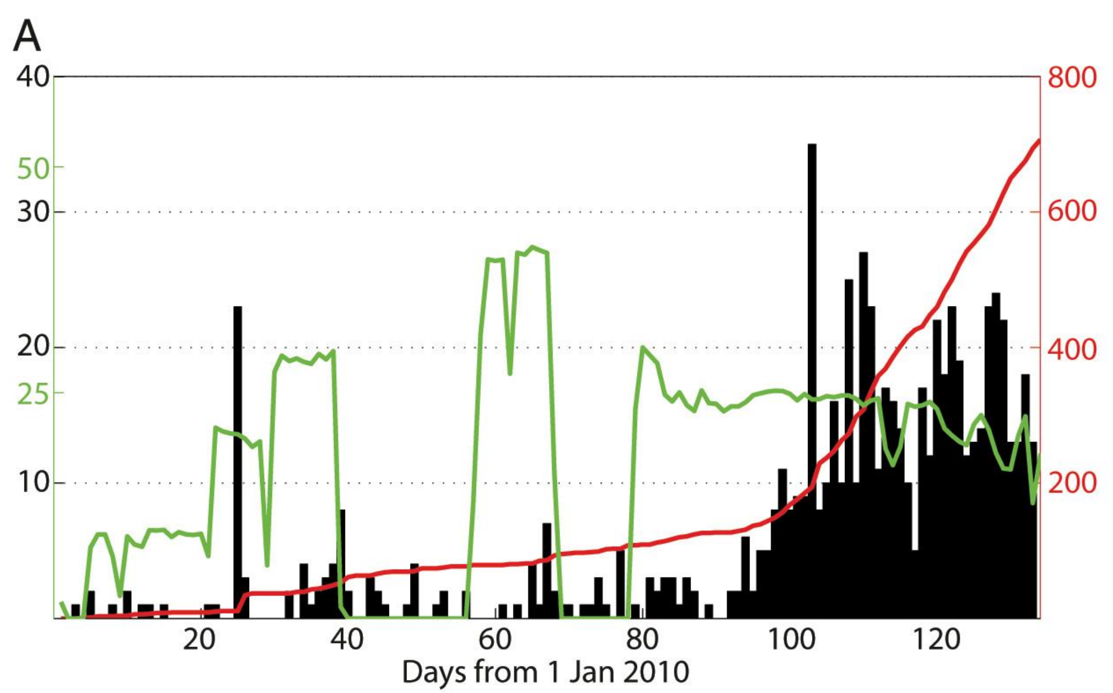


Walsh & Zoback (2015)

Carbon capture & storage example:
In Salah, Algeria







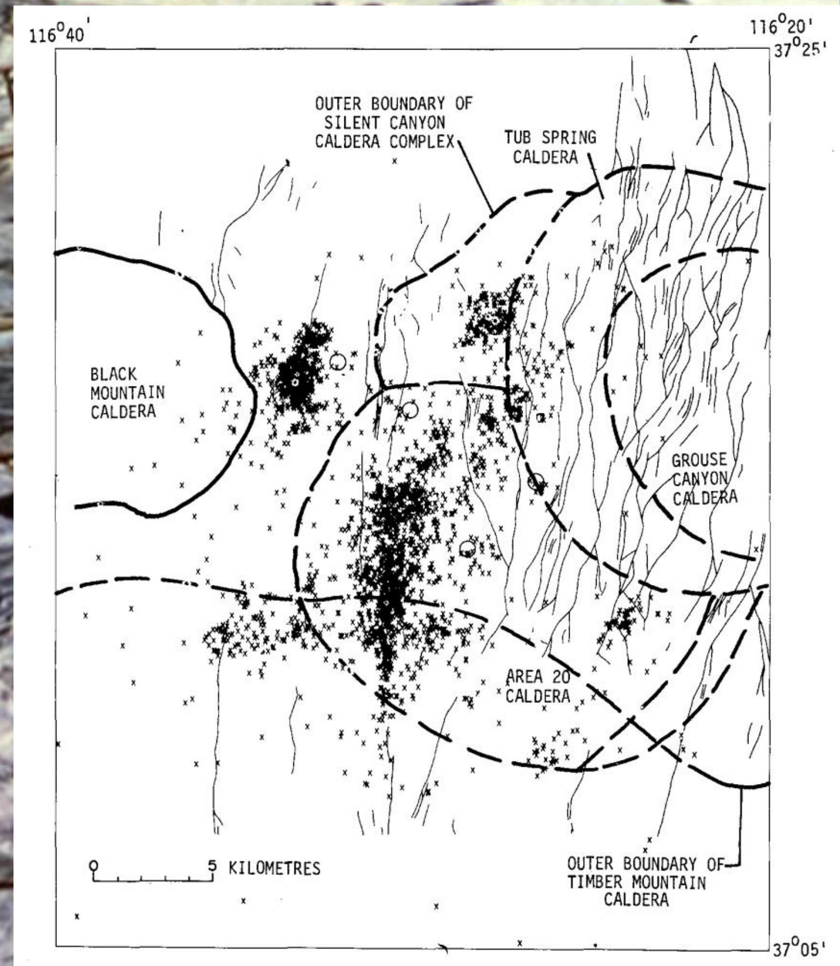
Verdon et al. (2013)

Explosions

Nuclear

Chemical

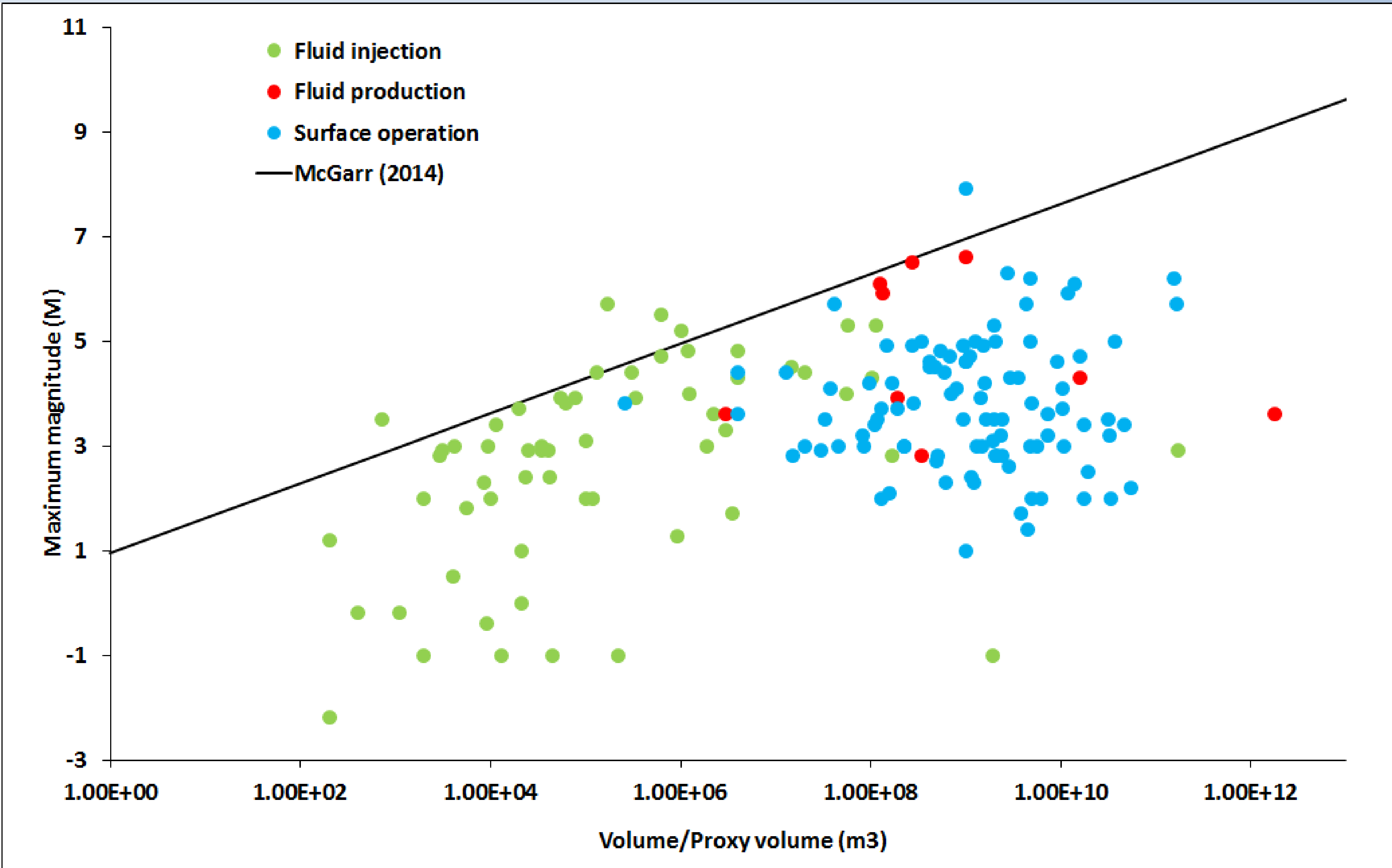
Nevada test site



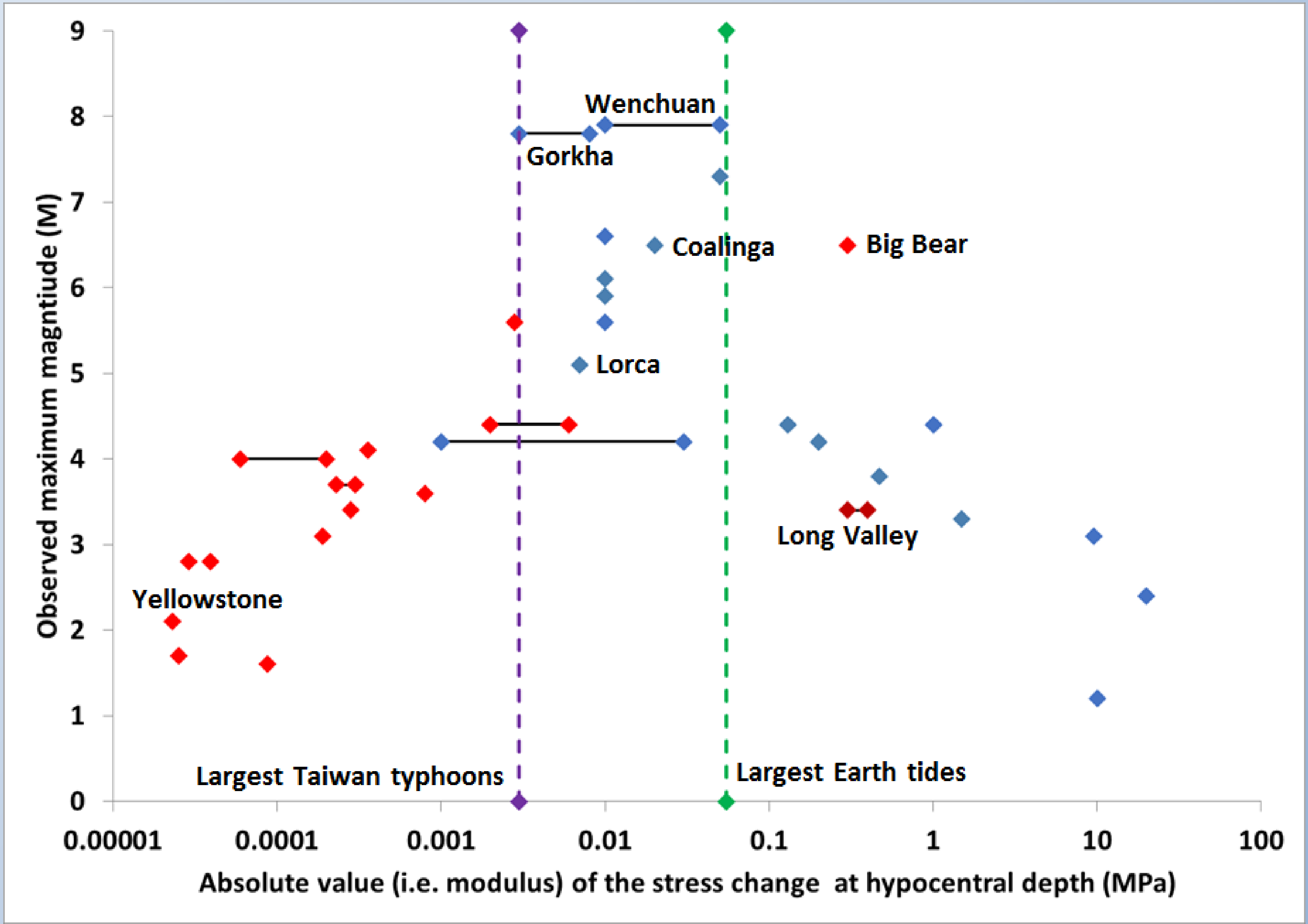
Chemical explosions

– currently no credible claims

How big earthquakes?
All Projects – M_{max} vs. Volume



Stress vs. M_{MAX}



How reliable are the cases in *HiQuake?*

Problems

- Starting problem: No way of knowing if a proposal of human-induction correct or not
  - Upfront decision: – include all proposals
  - Opinion on reliability user's responsibility
- Ending problem: Stakeholders wanted guidance on reliability of cases
  - But a non-verifiable post-dictive problem!
  - necessitated expert-opinion approach – will be bias and noise
  - We focused on reducing both bias and noise

How to assess the strength of cases?

- To reduce bias among expert opinions – use questionnaires
- History of questionnaires:
  - Davis & Frohlich [1993]
  - Davis et al. [1995]
  - Frohlich et al. [2016]
  - Verdon et al. [2019]

Example: Davis & Frohlich [1993]

Designed for fluid injection 7 questions ≥ 5 yes = probably induced 4 yes = ambiguous ≤ 3 yes = unlikely to be induced
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 the time of injection and the times of seismic activity?
3a. Spatial correlation: Are epicenters near the wells?
3b. Spatial correlation: Do some earthquakes occur at depths comparable to the depth of injection?
3c. Local geology: If some earthquakes occur away from wells, are there known geologic structures that may channel fluid flow to the sites of the earthquakes?
4a. Injection practices: Are changes in fluid pressure sufficient to encourage seismic or aseismic failure at the bottom of the well?
4b. Injection practices: Are changes in fluid pressure sufficient to encourage seismic or aseismic failure at the hypocentral locations?

Example: Davis & Frohlich [199]

Designed for fluid injection 7 questions ≥ 5 yes = probably in 4 yes = ambiguou ≤ 3 yes = unlikely to be in
1. Background seismicity: Are these events the first known ea region?
2. Temporal correlation: Is there a clear correlation between the seismic activity?
3a. Spatial correlation: Are epicenters near the wells?
3b. Spatial correlation: Do some earthquakes occur at depths compar the depth of injection?
3c. Local geology: If some earthquakes occur away from wells, are there known geologic structures that may channel fluid flow to the sites of the earthquakes?
4a. Injection practices: Are changes in fluid pressure sufficient to encourage seismic or aseismic failure at the bottom of the well?
4b. Injection practices: Are changes in fluid pressure sufficient to encourage seismic or aseismic failure at the hypocentral locations?

Problems:

– subjective
– narrow
– restricted
– ...etc.

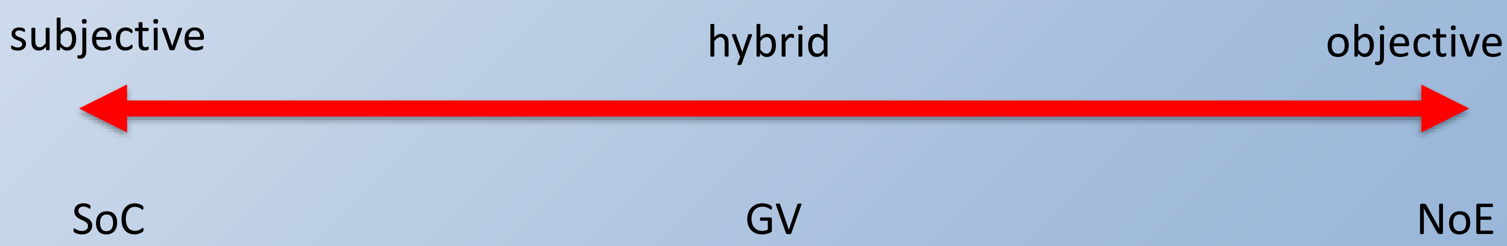
Project to assess the reliability of cases

Goal: Produce the best possible gradings for all the cases in *HiQuake*

1. Design & trial suite of questionnaire schemes
2. Develop a final, generic scheme – E-PIE
3. Apply to all cases in *HiQuake*

Phase 1: Design & trial schemes

- Three questionnaire schemes developed:
  - "Strength of Case" (SoC; "quick") scheme – subjective
  - "Generic Verdon" (GV) scheme – hybrid
  - "Number of Evidence" (NoE) scheme – objective



Strength of Case (SoC; “quick”) scheme

- Subjective

1	Case very weak/highly unlikely
2	Case weak/unlikely
3	Case moderate/plausible
4	Case strong/likely
5	Case very strong/highly likely

Generic Verdon (GV) scheme

- Hybrid, 7 questions

6.	Is there a plausible mechanism to have caused the events?	
a.	No significant pore-pressure increase or decrease occurred that can be linked in a plausible manner to the event hypocentral position	-5
b.	Some pore-pressure or poroelastic stress change occurred (increase in pore-pressure or positive Coulomb Failure Stress [CFS]>0.1 MPa, or a decrease in pore pressure of > 1 MPa) that can be linked in a plausible manner to the event hypocentral position	+2
c.	A large pore-pressure or poroelastic stress change occurred (increase in pore pressure or positive CFS >1 MPa, or a decrease in pore pressure of > 5 MPa) that can be linked in a plausible manner to the event hypocentral position	+5

6. Do the non-seismic data, e.g. pore-pressure changes, support the suggested induction process?	
a. The non-seismic data provide little or no support for the proposed induction process	−5
b. The non-seismic data support the proposed induction process to some extent	2
c. The non-seismic data support the proposed induction process strongly	5

Verdon J.P., Baptie B.J., Bommer J.J. (2019) An Improved Framework for Discriminating Seismicity Induced by Industrial Activities from Natural Earthquakes. *Seismol Res Lett* **90**: 1592-1611

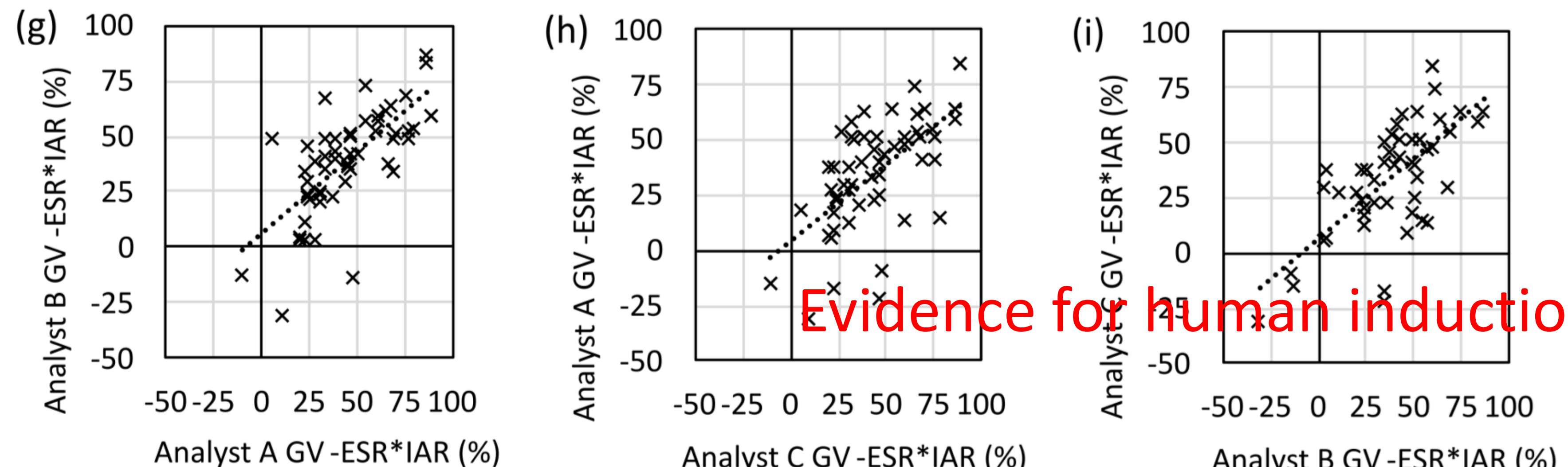
Number of Evidence (NoE) scheme

- Objective

1. Background seismicity
2. Epicentral location
3. Hypocentral depth
4. Temporal correlations
5. Physical model
6. Stress: industrial
7. Swarm/aftershock activity
8. Stress
9. Earthquake magnitude
10. b-value
11. Total number of earthquakes
12. Focal mechanisms
13. Direct nucleation effects observed
14. Surface deformation

Generic Verdon *vs.* Strength of Case (“quick”)

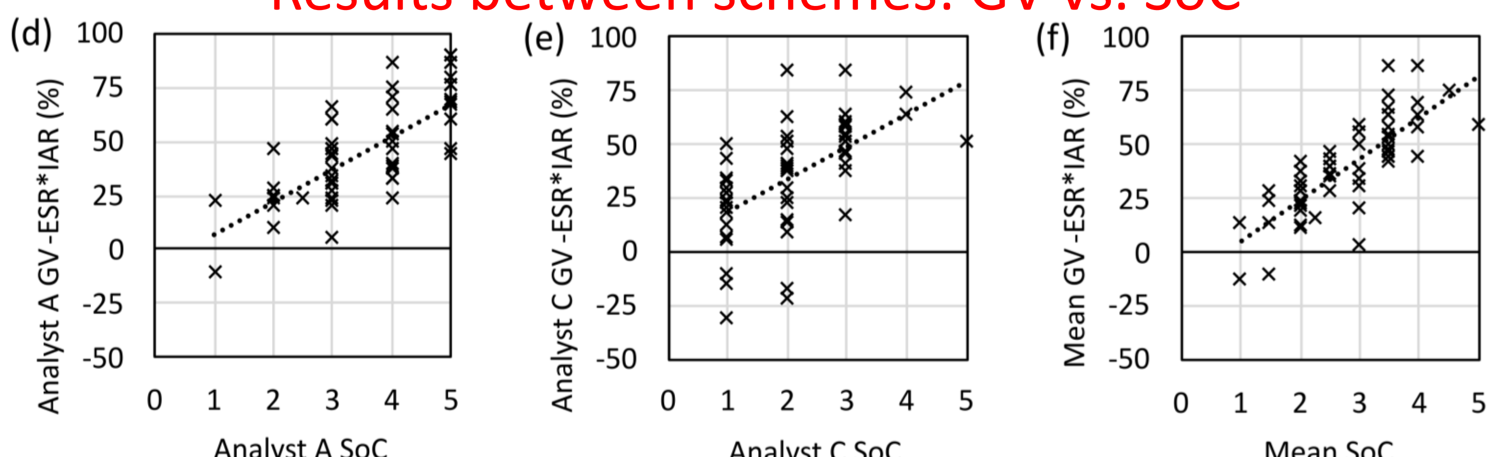
Results between analysts



Evidence for human induction

r = 0.70 r = 0.62 r = 0.68

Results between schemes: GV vs. SoC



r = 0.73 r = 0.58 r = 0.79

Application to "natural" earthquakes

Evidence for human induction

Case	Generic Verdon (%)	Strength of Case (%)	Number of Evidence (%)
Reykjanes Peninsula, Iceland	-17 -35	20 20	0 0
Coso geothermal field, California	-24 -29	20 20	0 0
Lombok, Italy (2018)	-52 -34	20 20	0 0
Tbilisi, Georgia (2002)	26 -34	20 20	0 0

Application to “natural” earthquakes

Evidence for human induction

Case	Generic Verdon (%)	Strength of Case (%)	Number of Evidence (%)
Reykjanes Peninsula, Iceland	-17	20	0
	-35	20	0
Coso geothermal field, California	-24	20	0
	-29	20	0
Lombok, Italy (2018)	-52	20	0
	-34	20	0
Tbilisi, Georgia (2002)	26	20	0
	-34	20	0

Phase 2: Develop a final, generic scheme

E-PIE

(Evaluating Proposals of human-Induced Earthquakes)

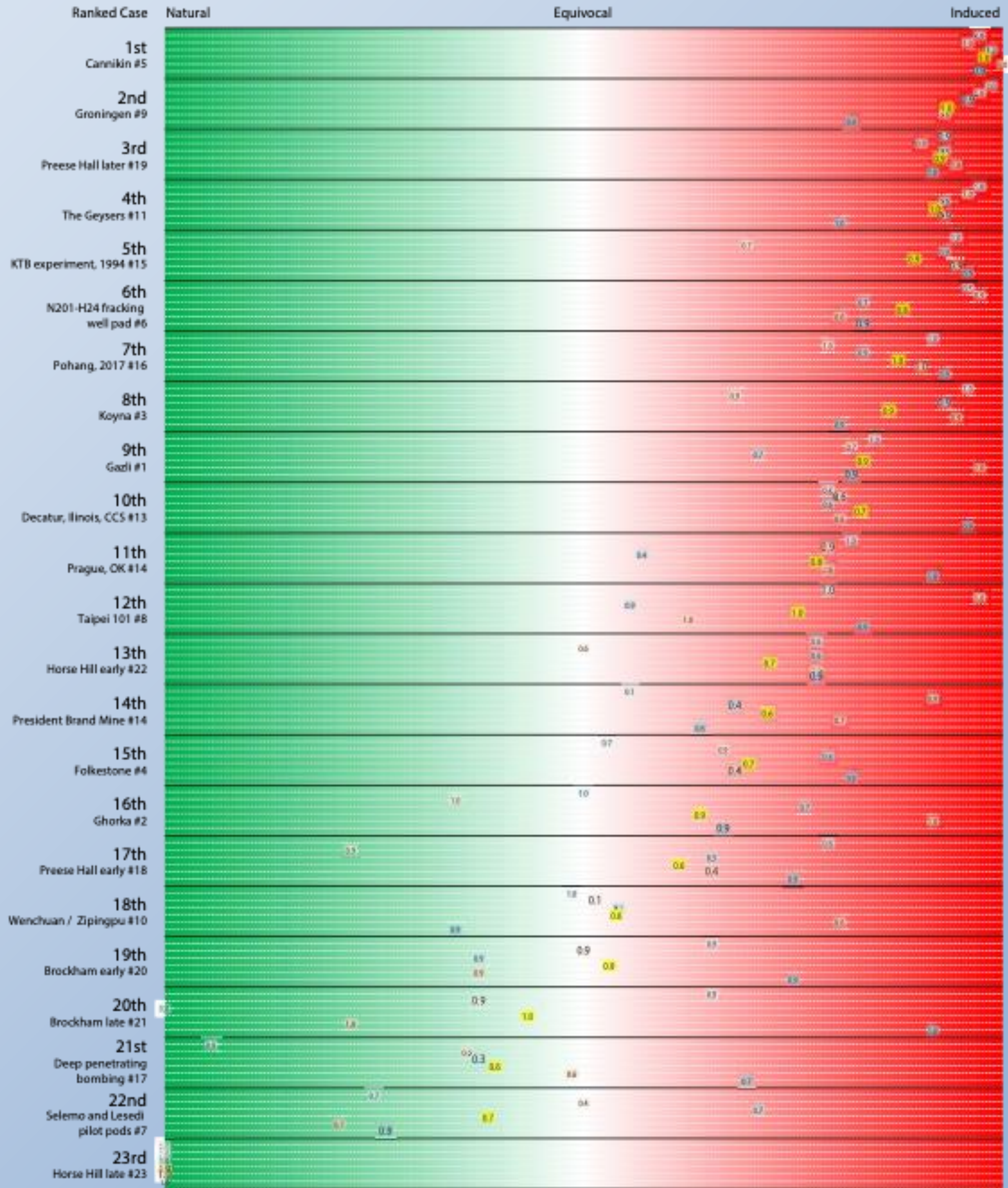
Phase 2: E-PIE generic scheme

9 questions

Orientation	
How plausible is the proposed induction mechanism? • Is it a well-established phenomenon? • Is it reported for multiple localities? **How wide, in space and time, is the range of likely environmental modulation?** • Only near-field, rapid response to operations likely • Up to medium-field, medium-term response to operations likely • Out to far-field, delayed response to operations likely	
Proposed-induced earthquakes (PIEs)	
1. PIEs–temporal: Did the PIE sequence onset before, during or after the industrial activity?	10
a. Insufficient information available	
b. The PIE sequence began before the onset of the industrial activity	Exit
c. The PIE sequence began while the industrial activity was minimal OR after its cessation	
d. The PIE sequence began while the industrial activity was substantial	
2. PIEs–epicenters: Is there spatial collocation between the PIEs and the likely area of environmental modulation by the industrial activity?	100
a. Insufficient information available	
b. The PIEs are outside the likely area of environmental modulation by the industrial activity	
c. The PIEs are peripheral to the likely area of environmental modulation by the industrial activity	
d. The PIEs are within the likely area of environmental modulation by the industrial activity	
3. PIEs–hypocenters: Is there spatial collocation between the PIEs and the likely volume of environmental modulation by the industrial activity?	100
a. Insufficient information available	
b. The PIEs are beneath the likely volume of environmental modulation by the industrial activity	
c. The PIEs are peripheral to the base of the likely volume of environmental modulation by the industrial activity	
d. The PIEs are within the likely volume of environmental modulation by the industrial activity	
4. PIEs–temporal: Is there temporal correlation between the PIEs and specific industrial events?	100
a. Insufficient information available	
b. There is little or no temporal correlation between the PIEs and specific industrial events	
c. There is weak temporal correlation between the PIEs and specific industrial events	
d. There is strong temporal correlation between the PIEs and specific industrial events	

Pre-industrial earthquakes	
5. Pre-industrial earthquakes–epicenters: Is there evidence for pre-industrial earthquakes at or near the site of the PIEs?	10
a. Insufficient information available	
b. Pre-industrial earthquakes occurred at or near the site of the PIEs	
c. Pre-industrial earthquakes occurred in the wider region around the site of the PIEs	
d. Pre-industrial earthquakes did not occur at or near the site of the PIEs or in the wider region around it	
6. Pre-industrial earthquakes–hypocenters: Is there evidence for pre-industrial earthquakes in the same volume as the PIEs?	10
a. Insufficient information available	
b. Pre-industrial earthquakes occurred at or near the site of the PIEs at similar or shallower depths	
c. Pre-industrial earthquakes occurred in the wider region around the site of the PIEs at similar or shallower depths	
d. Pre-industrial earthquakes did not occur at or near the site of the PIEs or in the wider region around it at similar or shallower depths	
Additional data	
7. Focal mechanisms: Are the focal mechanisms consistent with a natural and/or induced earthquake cause?	10
a. Insufficient information available	
b. The focal mechanisms ARE consistent with the regional stress and NOT consistent with the proposed induction mechanism	
c. The focal mechanisms ARE consistent with the regional stress and ARE consistent with the proposed induction mechanism OR The focal mechanisms are NOT consistent with the regional stress and NOT consistent with the proposed induction mechanism	
d. The focal mechanisms are NOT consistent with the regional stress and ARE consistent with the proposed induction mechanism	
8. Other–seismic data: Are there other seismic data to support a natural or induced cause, *e.g.*, swarm, foreshock-aftershock pattern, b-value, total number of earthquakes, stress release corresponding to the earthquake magnitude or seismicity?	10
a. Insufficient information available	
b. Other seismic data support a natural origin	
c. Other seismic data are equivocal	
d. Other seismic data support an induced origin	
9. Other–non-seismic data: Are there non-seismic data that support a natural or induced cause, *e.g.*, direct nucleation effects, precursory surface deformation?	10
a. Insufficient information available	
b. The non-seismic data support a natural origin	
c. The non-seismic data are equivocal	
d. The non-seismic data support an induced origin	

Phase 2: E-PIE test on 23 cases

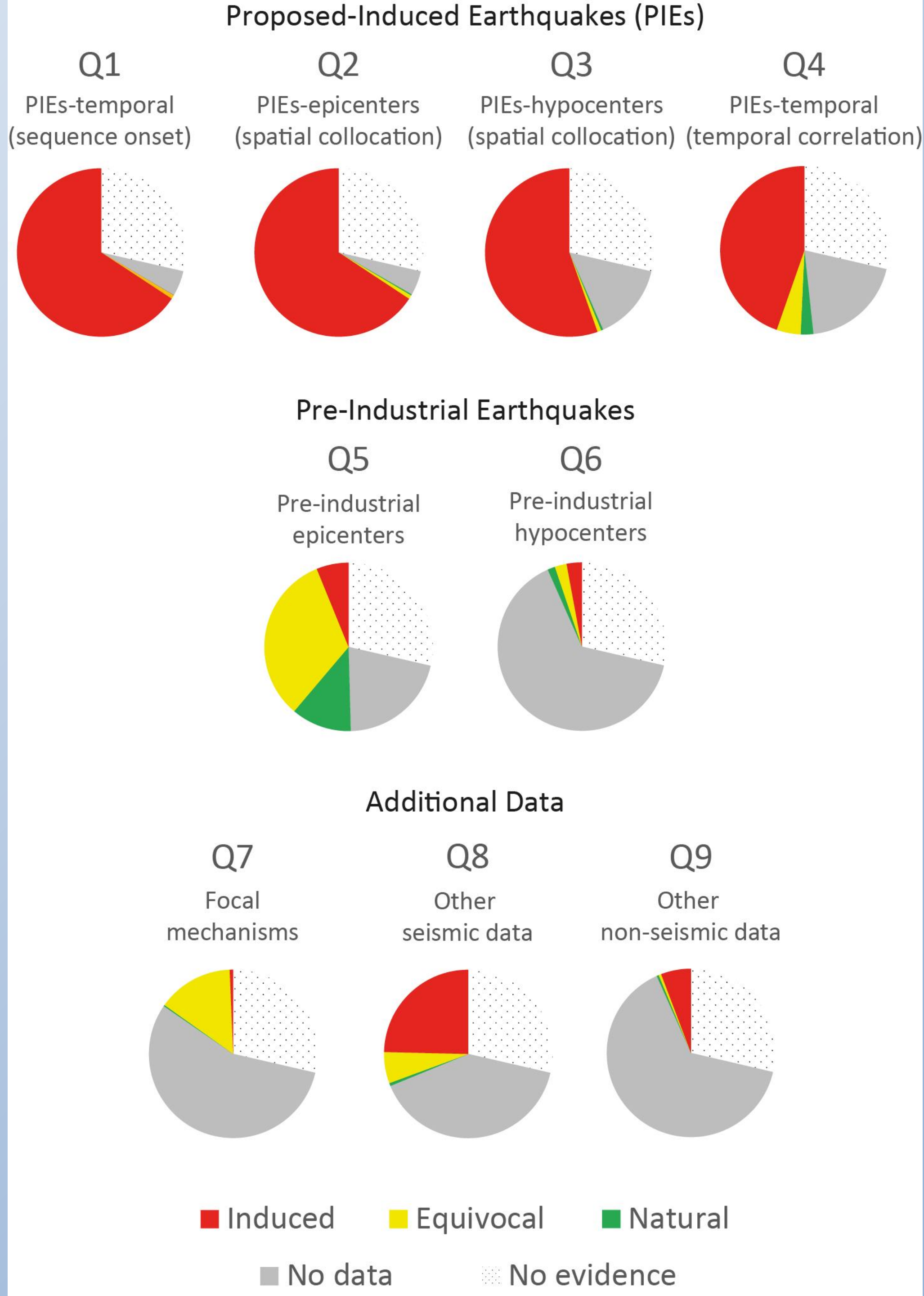


Phase 3: Apply E-PIE to all cases in *HiQuake*

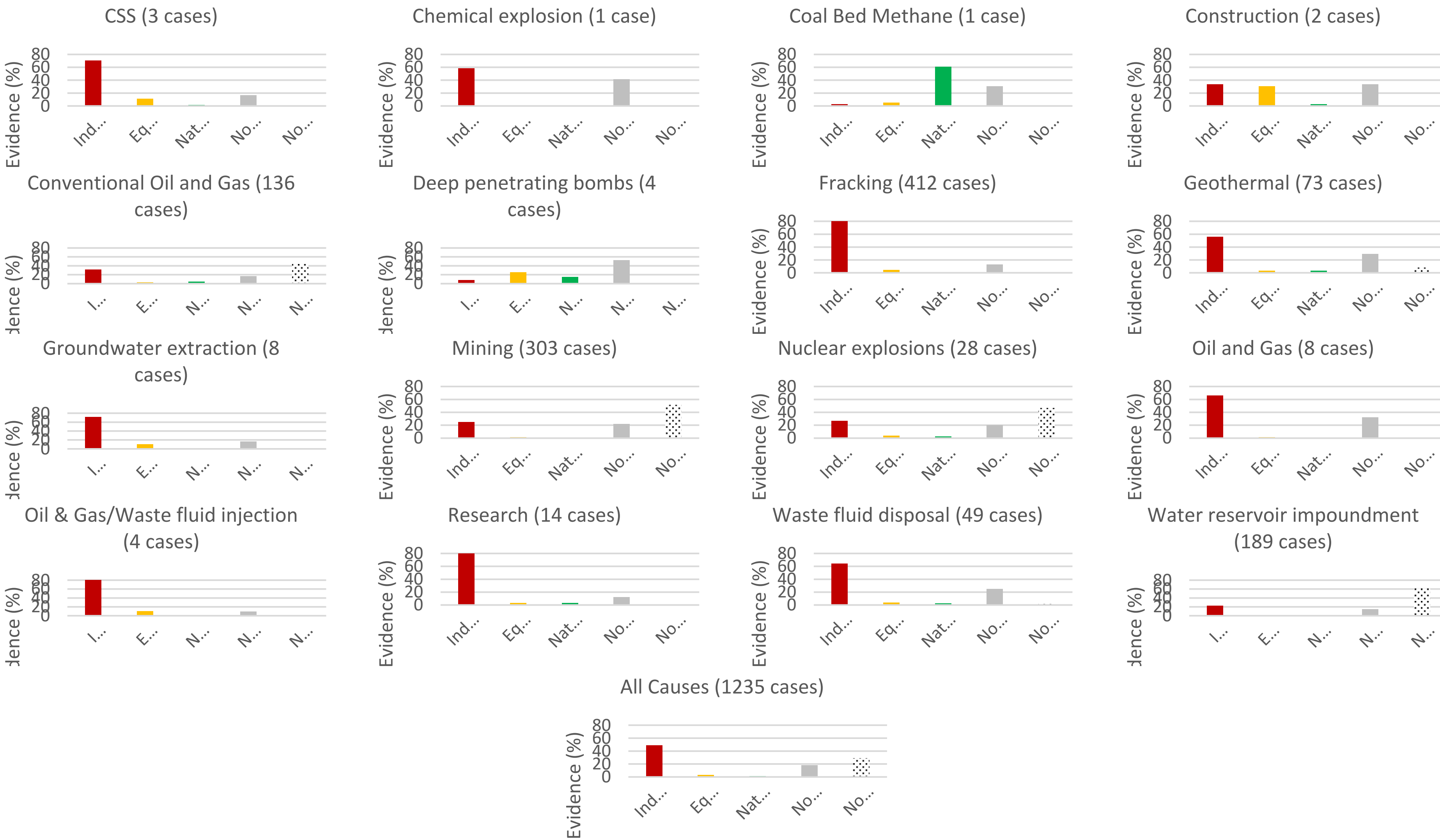
Done by a single analyst over a 20-month period

Took ~ 1,000 hours of time

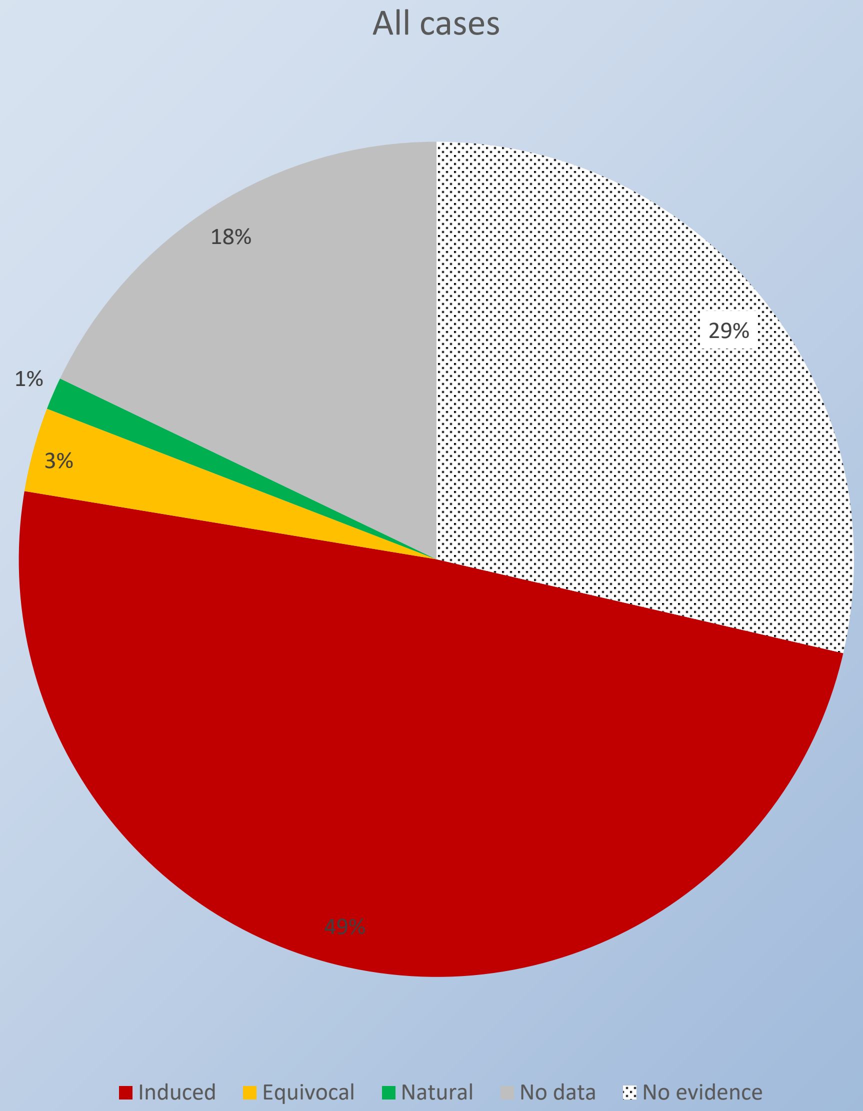
Results by question



Results by induction mechanism



Weighted responses to Qs – all cases



Cluster analysis suggests 97% in *HiQuake* likely to be induced

Resources

www.inducedearthquakes.org

Earth-Science Reviews 178 (2018) 438–514

Contents lists available at ScienceDirect

Earth-Science Reviews

journal homepage: www.elsevier.com/locate/earscirev

Invited review

Global review of human-induced earthquakes

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- Foulger, G.R., Wilkinson, M.W., Wilson, M.P., Mhana, N., Tezel, T., Gluyas, J.G., 2023. Human-induced earthquakes: E-PIE-a generic tool for Evaluating Proposals of Induced Earthquakes, *J. Seismol.* 27, 21-44.

- Wilkinson, M.W., Mhana, N., Wilson, M.P., Foulger, G.R., Tezel, T., Gluyas, J.G., Applying the E-PIE scheme to the HiQuake database: An Objective Assessment of Proposed Evidence for Known Cases of Induced Seismicity. in preparation.

That's all folks