THE HUMAN-INDUCED EARTHQUAKE DATABASE

Durham University [1]

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NAM

Induced Seismicity: A global overview from the *HiQuake* database

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IBERFAULT 2018
Alicante, Spain
12th June 2018

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Contents

Part 1: Introduction

Terminology

- *'Induced'* vs. *'Triggered'* earthquakes

Induced

Released energy predominantly of anthropogenic origin

Triggered

Released energy predominantly of natural origin

'Earthquake clock' advanced by humans

Terminology

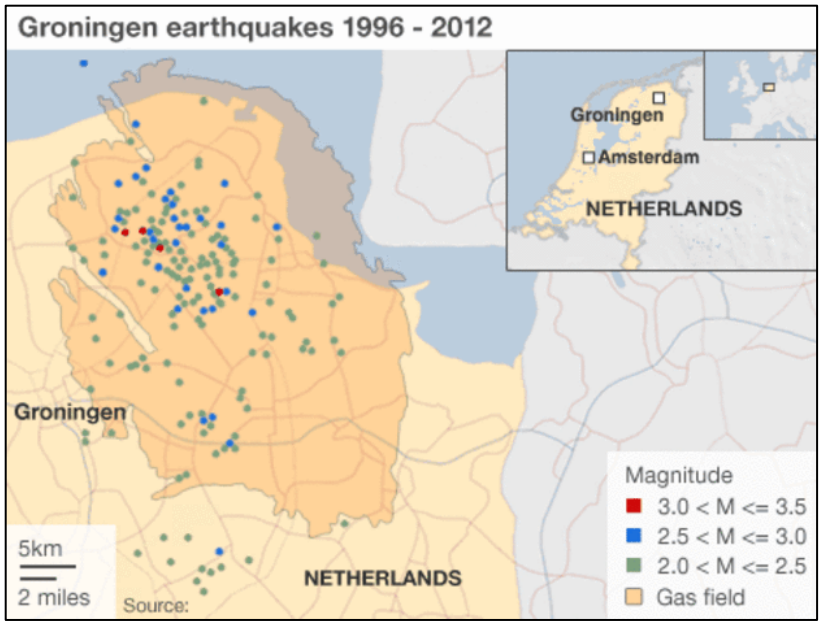
Induced – Human influence

Groningen

Nederlandse Aardolie Maatschappij BV

NAM

- Groningen gas field, The Netherlands
  - Production from 1963
  - 2.8 tcm gas in place
  - ~50% natural gas production in the Netherlands
- Induced earthquakes
  - First recorded in 1991
  - M_L 3.4 (16/08/2012)



http://www.bbc.co.uk/news/world-europe-22542982

Part 1

From denial to acceptance

Initial denial of induced earthquakes

Acceptance but ‘damage minimal’

Acceptance of earthquake numbers, magnitudes and damage increasing

September 2015 legal acceptance

Mitigation

- Invited expert workshop (March 2016)

- Maximum possible earthquake?

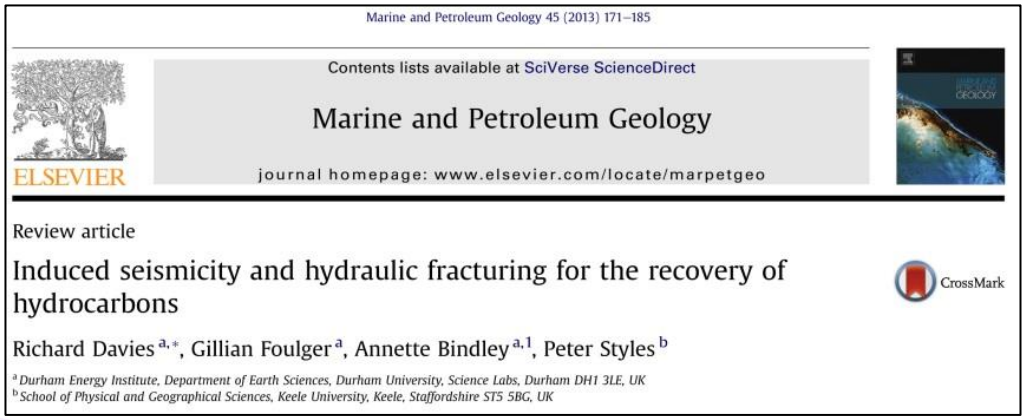
- Task: Update the ReFINE RESEARCHING FRACKING 2013 database

Part 1

ReFINE database

RESEARCHING FRACKING

- Published in 2013
- 198 examples of induced earthquakes with magnitudes ≥ 1
- 166 citations in 5 years



Marine and Petroleum Geology 45 (2013) 171–185

Contents lists available at SciVerse ScienceDirect

Marine and Petroleum Geology

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

Review article

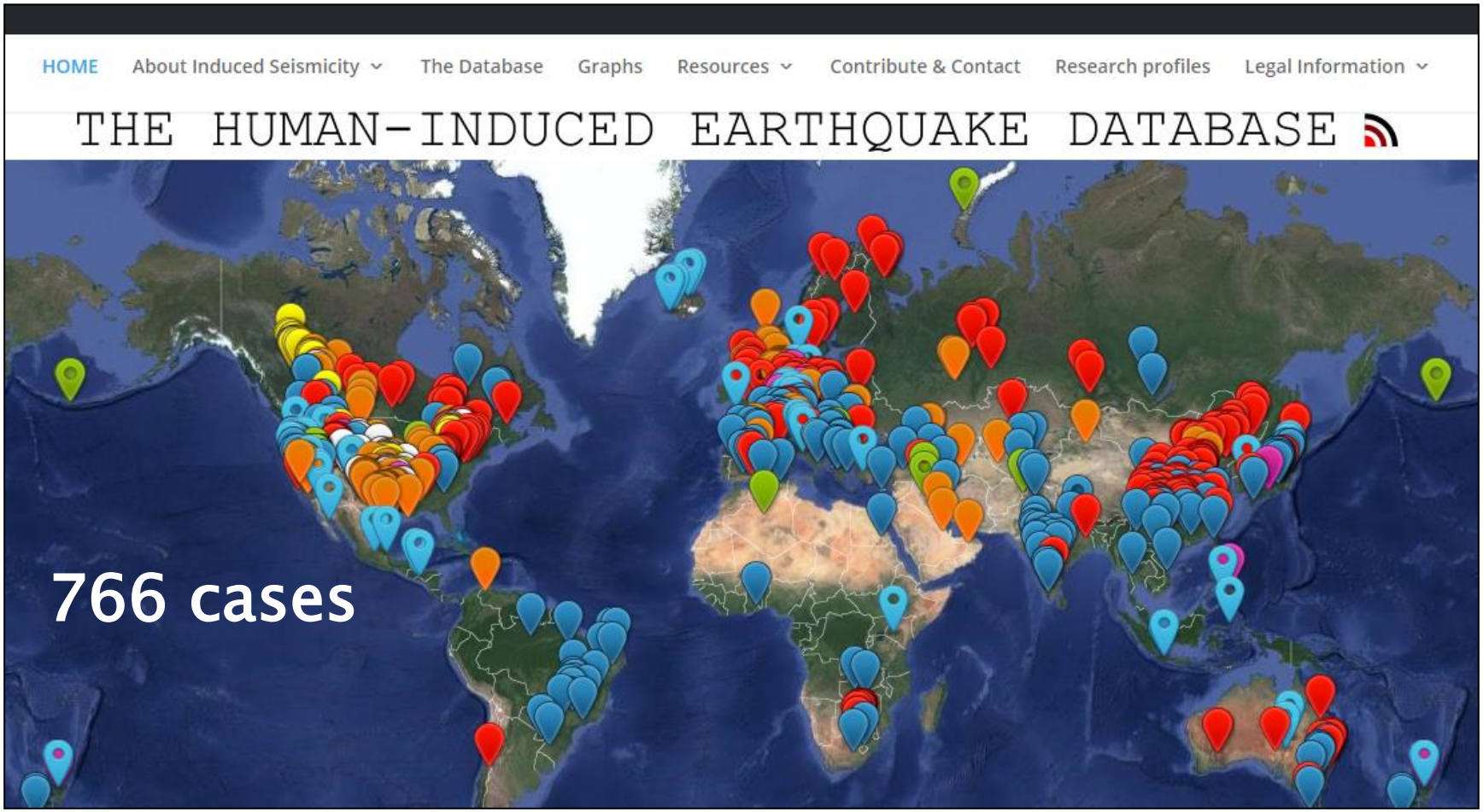
Induced seismicity and hydraulic fracturing for the recovery of hydrocarbons

Richard Davies [a,*], Gillian Foulger [a], Annette Bindley [a,1], Peter Styles [b]

[a] Durham Energy Institute, Department of Earth Sciences, Durham University, Science Labs, Durham DH1 3LE, UK
[b] School of Physical and Geographical Sciences, Keele University, Keele, Staffordshire ST5 5BG, UK

Part 1

HiQuake



www.inducedearthquakes.org

Part 1

What's included?

- **Any project** where induced earthquakes are scientifically proposed
- We don't base inclusion on our opinion

Part 1

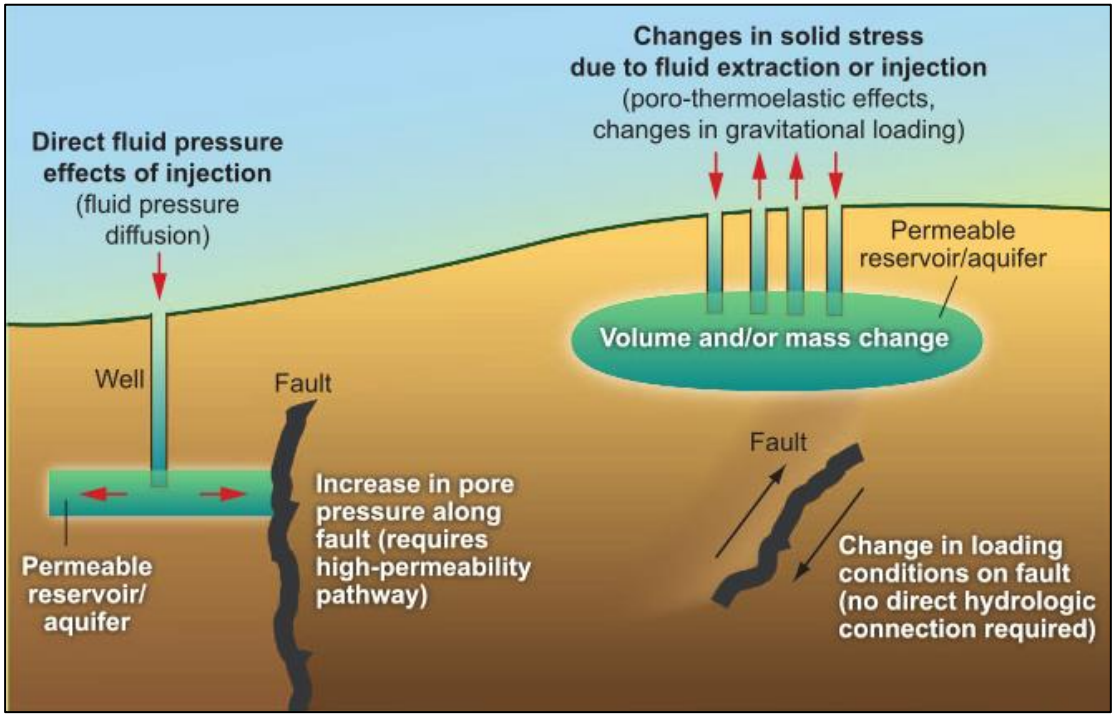
What's included?

- **Any project** where induced earthquakes are scientifically proposed
- We don't base inclusion on our opinion
- No religious or moral earthquakes included

Part 1

Part 2: Induced seismicity: Global Overview

Mechanisms of induction



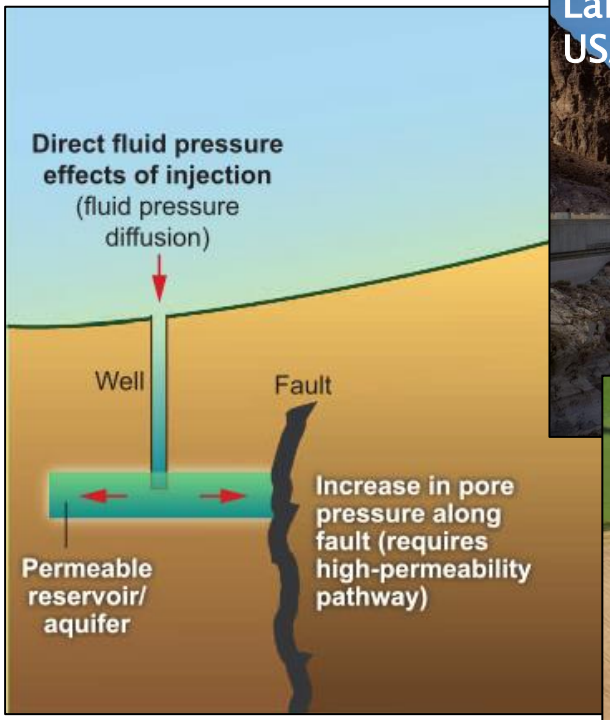
Ellsworth (2013)

- Earthquake nucleation requires a change in stress on the fault

$$\tau_{crit} = \mu(\sigma_n - P) + S_o$$

Part 2

Pore pressure increase

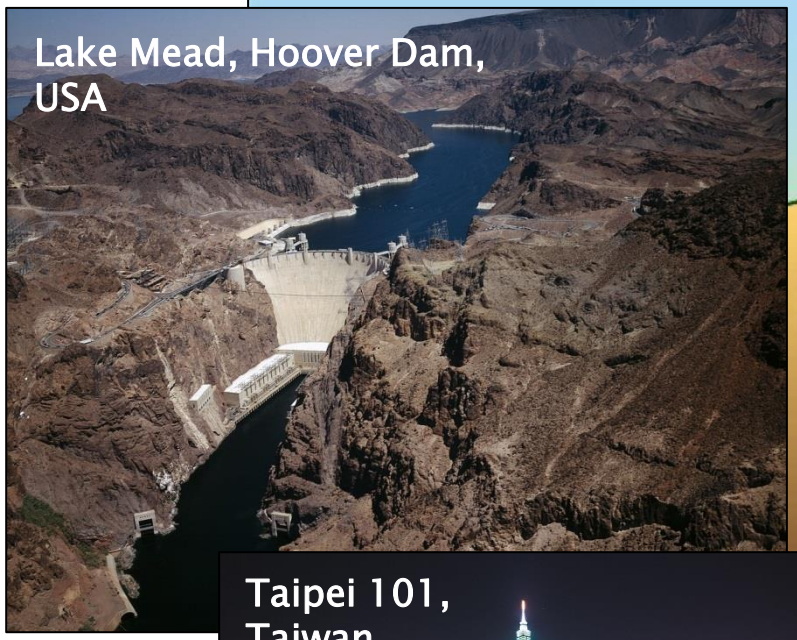


$$\tau_{crit} = \mu(\sigma_n - P) + S_o$$

Effective stress

Part 2

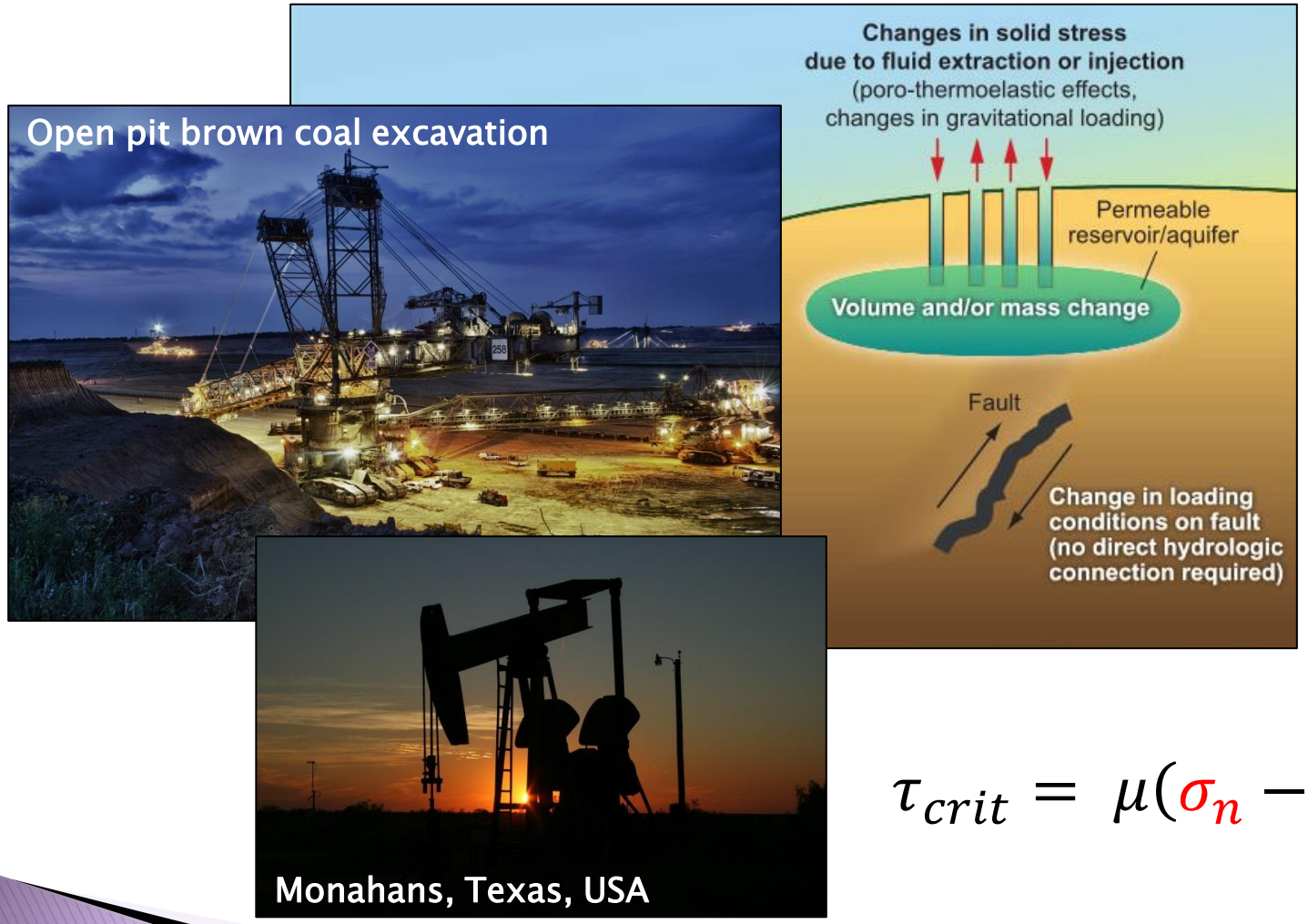
Loading



$$\tau_{crit} = \mu(\sigma_n - P) + S_o$$

Part 2

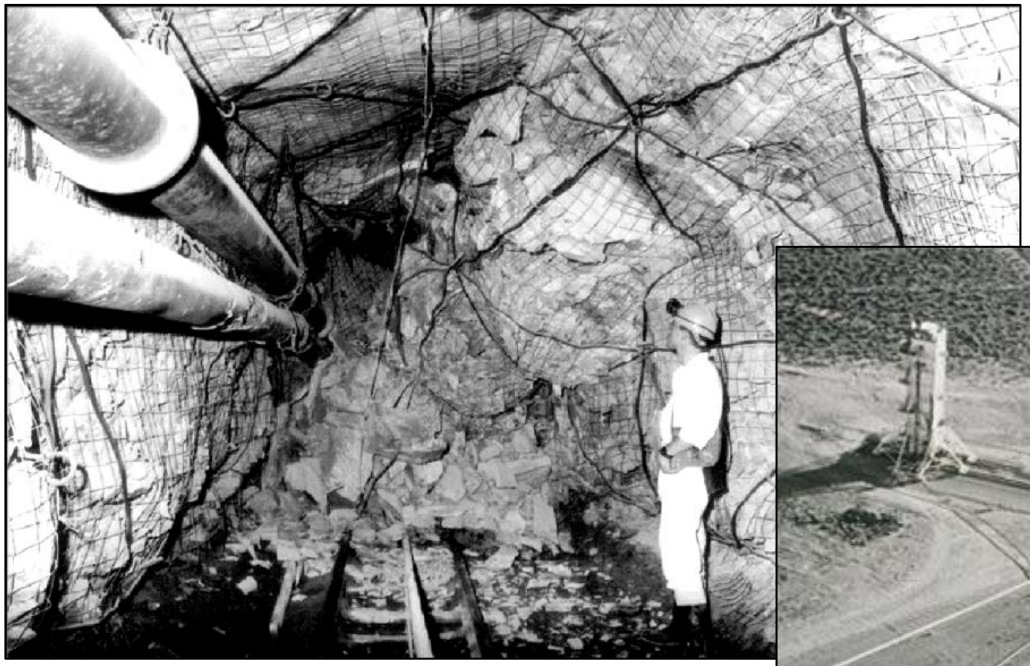
Unloading



$$\tau_{crit} = \mu(\sigma_n - P) + S_o$$

Part 2

Collapse



Durrheim (2010)
Photograph by W.D. Ortlepp

https://craighill.net

Part 2

Induced or natural?

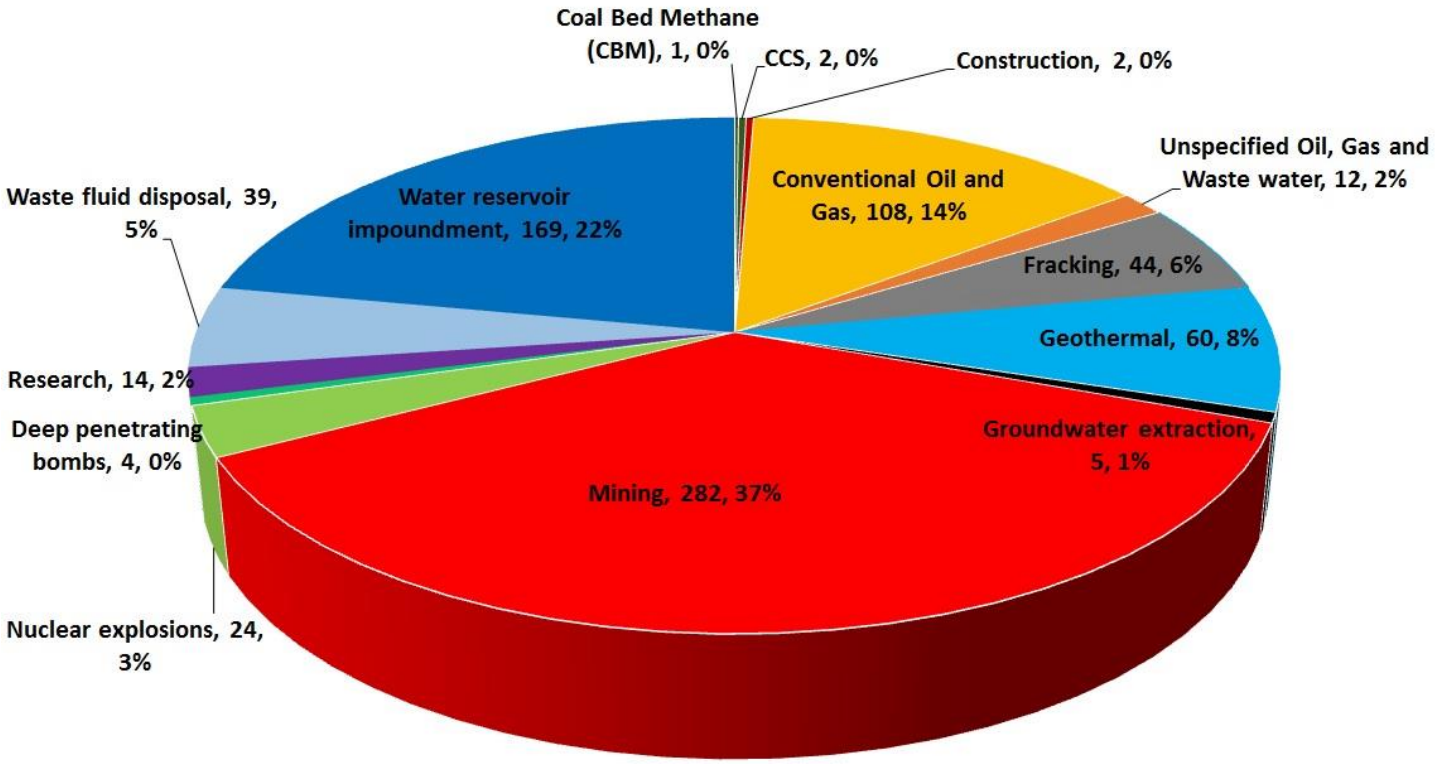
- Location
- Timing
- Historic seismicity (or lack of)
- Known faults

Davis and Frohlich (1993)

Question
Background Seismicity
1a Are large earthquakes ($M \geq 5.5$) known in the region (within several hundred km)?
1b Are earthquakes known near the injection site (within 20 km)
1c is rate of activity near the injection site (within 20 km) high?
Local Geology
2a Are faults mapped within 20 km of the site?
2b If so, are these faults known to be active?
2c Is the site near (within several hundred km of) tectonically active features?
State of Stress
3 Do stress measurements in the region suggest rock is close to failure?
Injection Practices
4a Are (proposed) injection practices sufficient for failure?
4b If injection has been ongoing at the site, is injection correlated with the occurrence of earthquakes?
4c Are nearby injection wells associated with earthquakes?

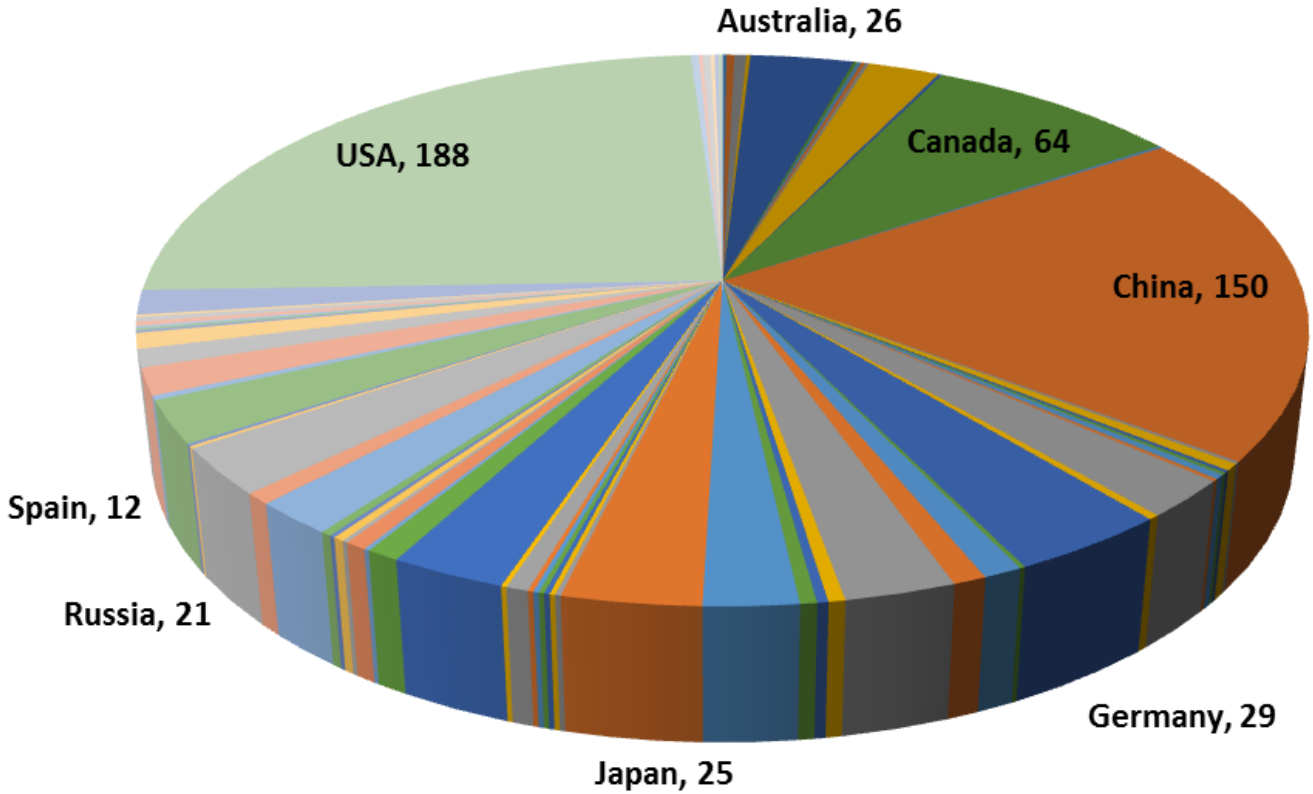
Project types

- 766 cases with reported induced seismicity

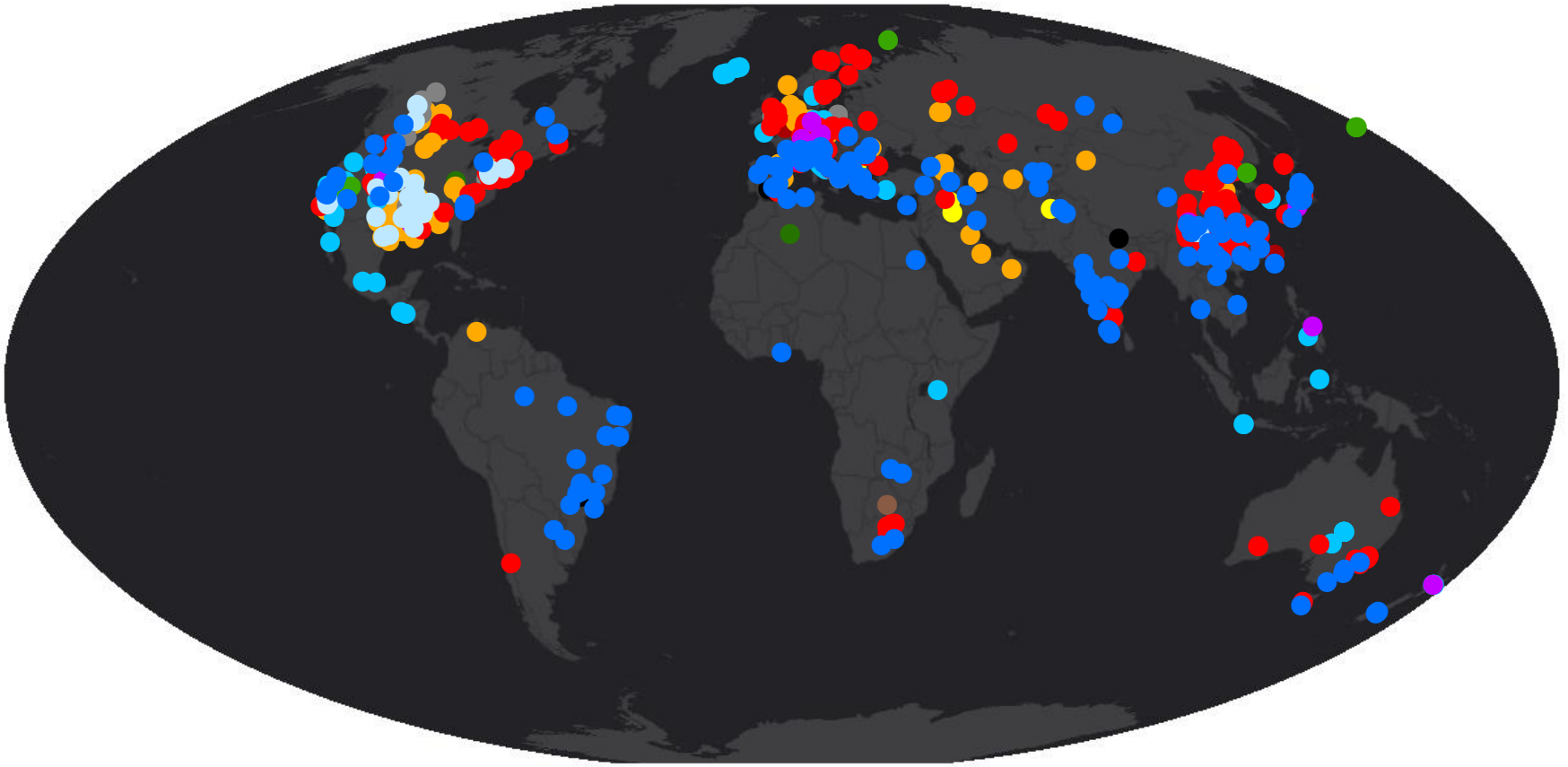


By country

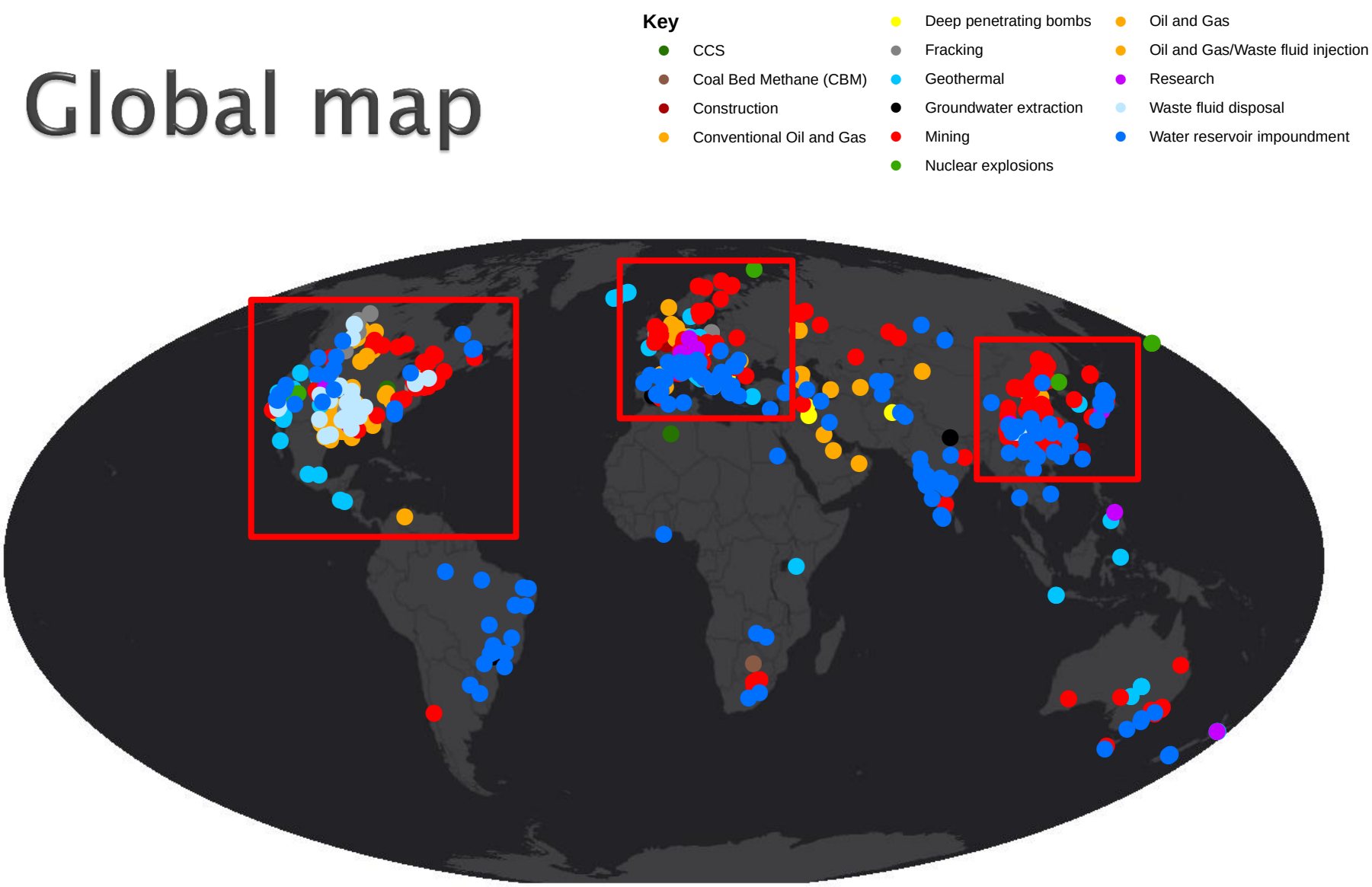
- 72 countries



Global map


Key
CCS
Coal Bed Methane (CBM)
Construction
Conventional Oil and Gas
Deep penetrating bombs
Fracking
Geothermal
Groundwater extraction
Mining
Nuclear explosions
Oil and Gas
Oil and Gas/Waste fluid injection
Research
Waste fluid disposal
Water reservoir impoundment

Global map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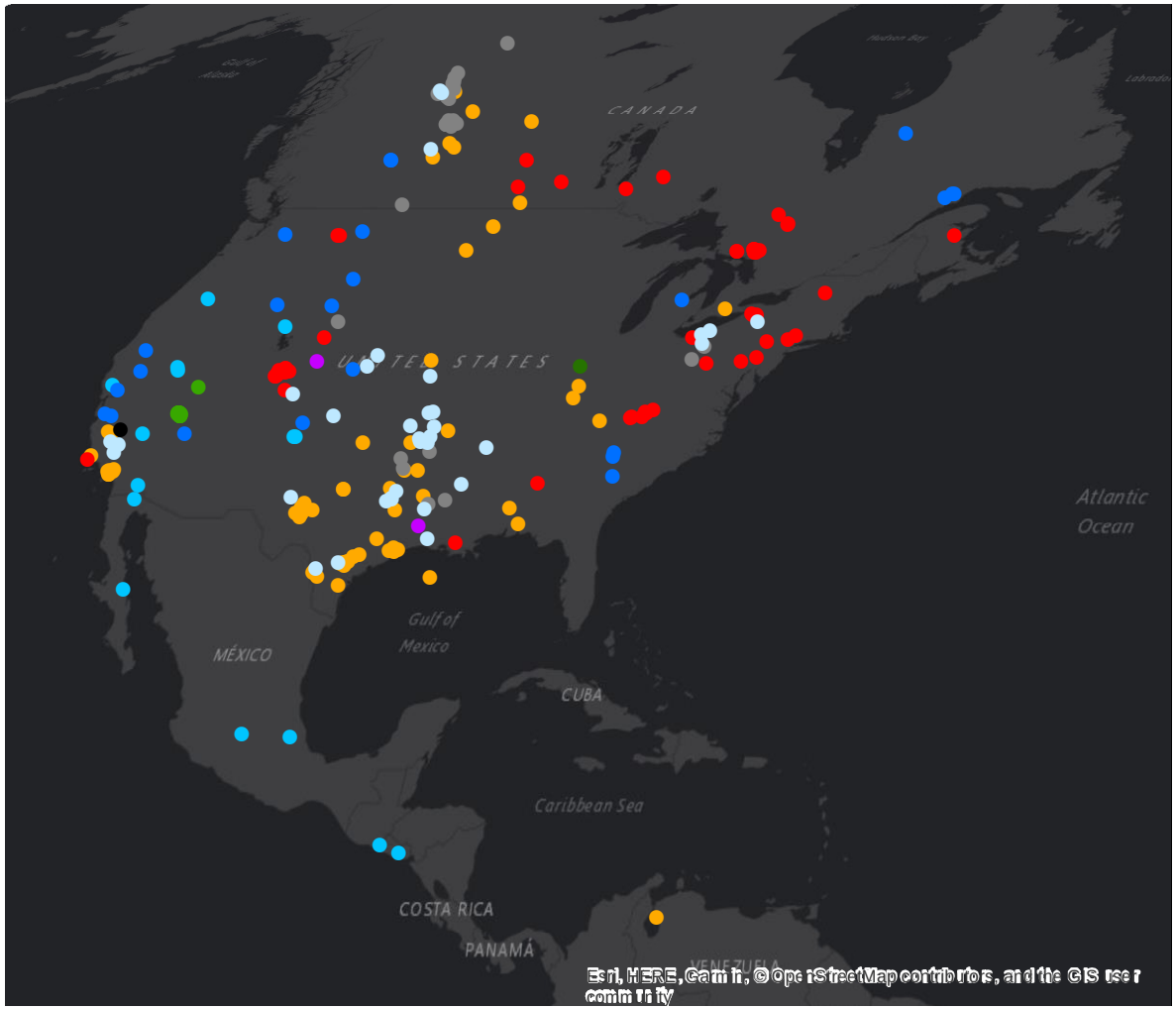
Water reservoir impoundment

North America

Key

- CCS
- Coal Bed Methane (CBM)
- Construction
- Conventional Oil and Gas
- Deep penetrating bombs
- Fracking
- Geothermal
- Groundwater extraction
- Mining
- Nuclear explosions
- Oil and Gas
- Oil and Gas/Waste fluid injection
- Research
- Waste fluid disposal
- Water reservoir impoundment

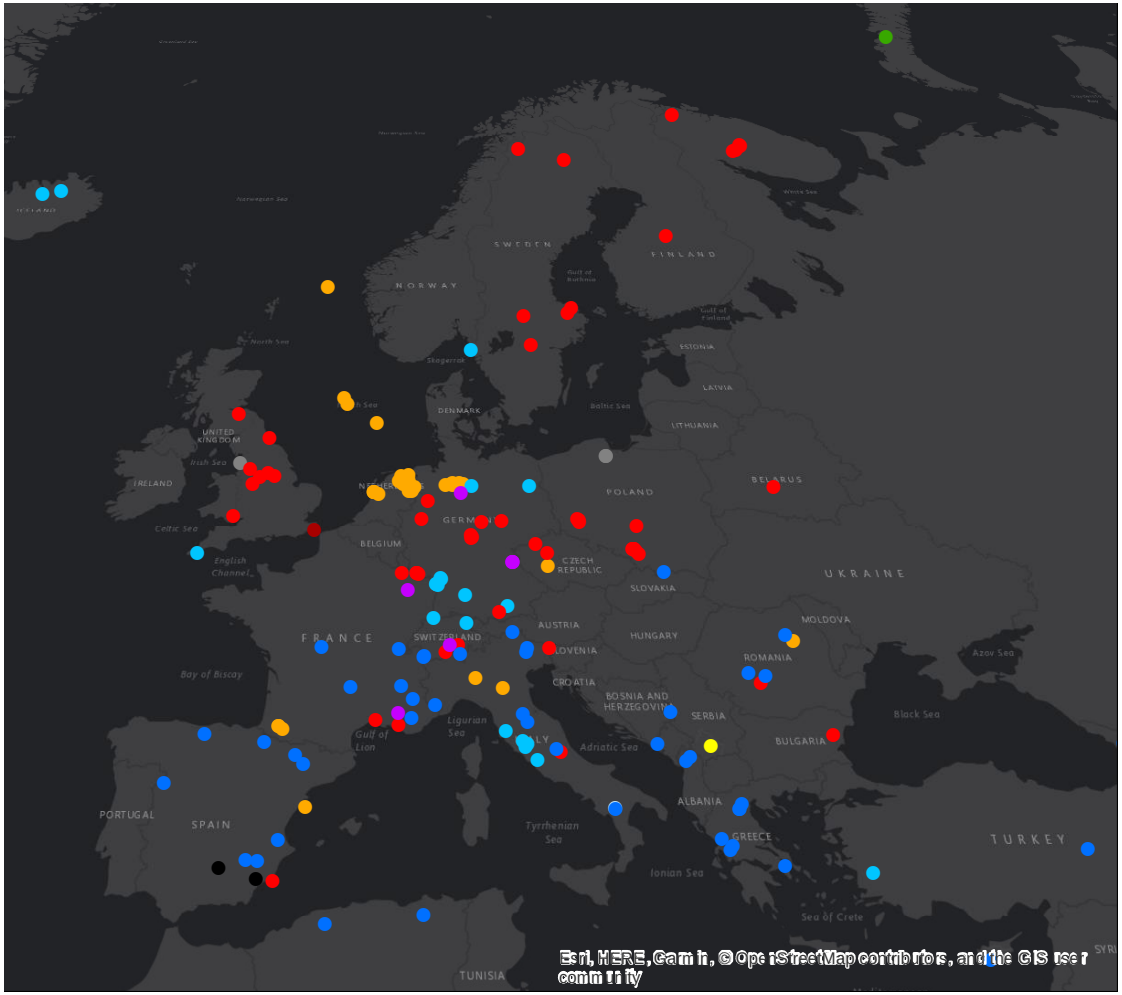


Part 2

Europe

Key

- CCS
- Coal Bed Methane (CBM)
- Construction
- Conventional Oil and Gas
- Deep penetrating bombs
- Fracking
- Geothermal
- Groundwater extraction
- Mining
- Nuclear explosions
- Oil and Gas
- Oil and Gas/Waste fluid injection
- Research
- Waste fluid disposal
- Water reservoir impoundment

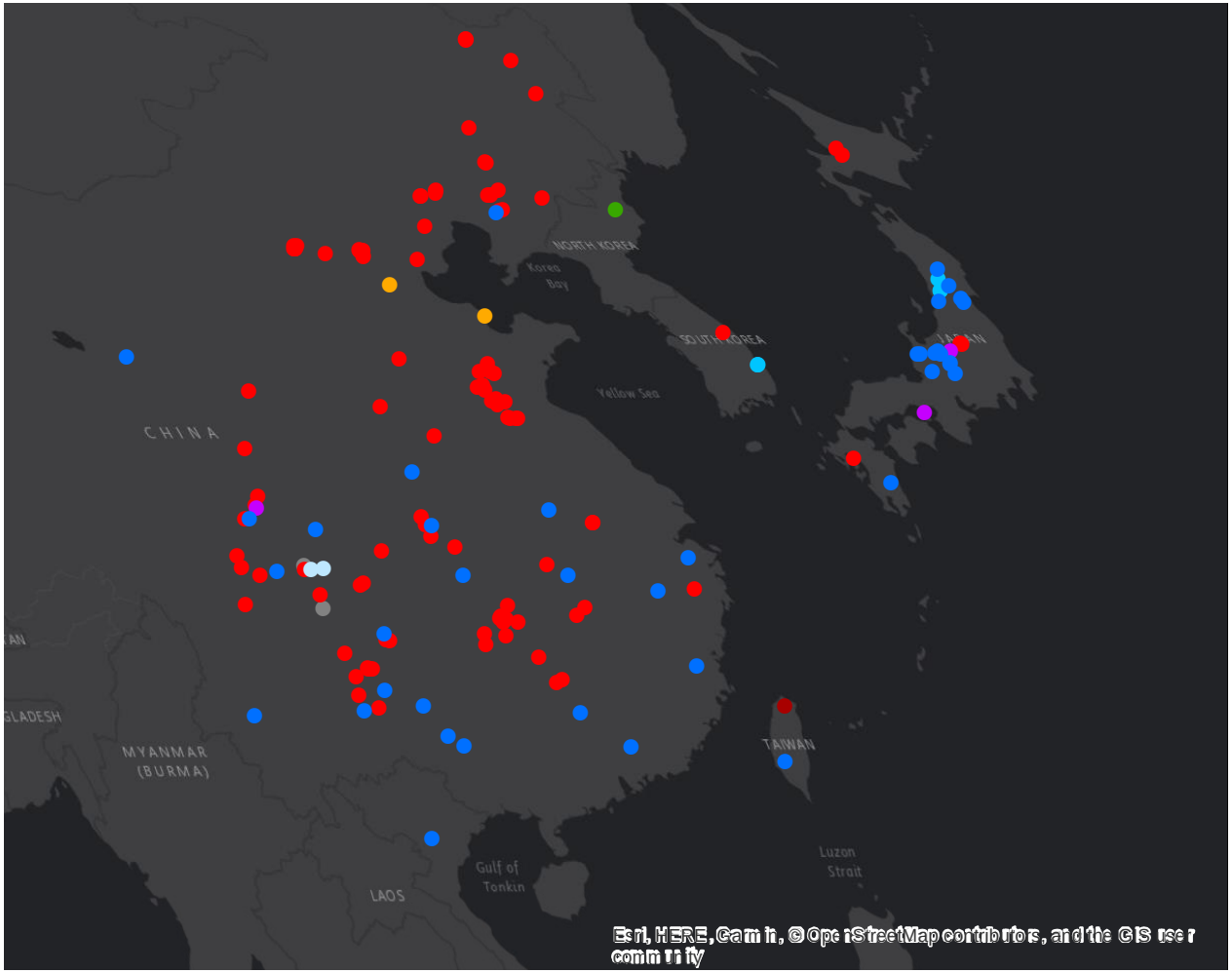


Part 2

Northeast Asia

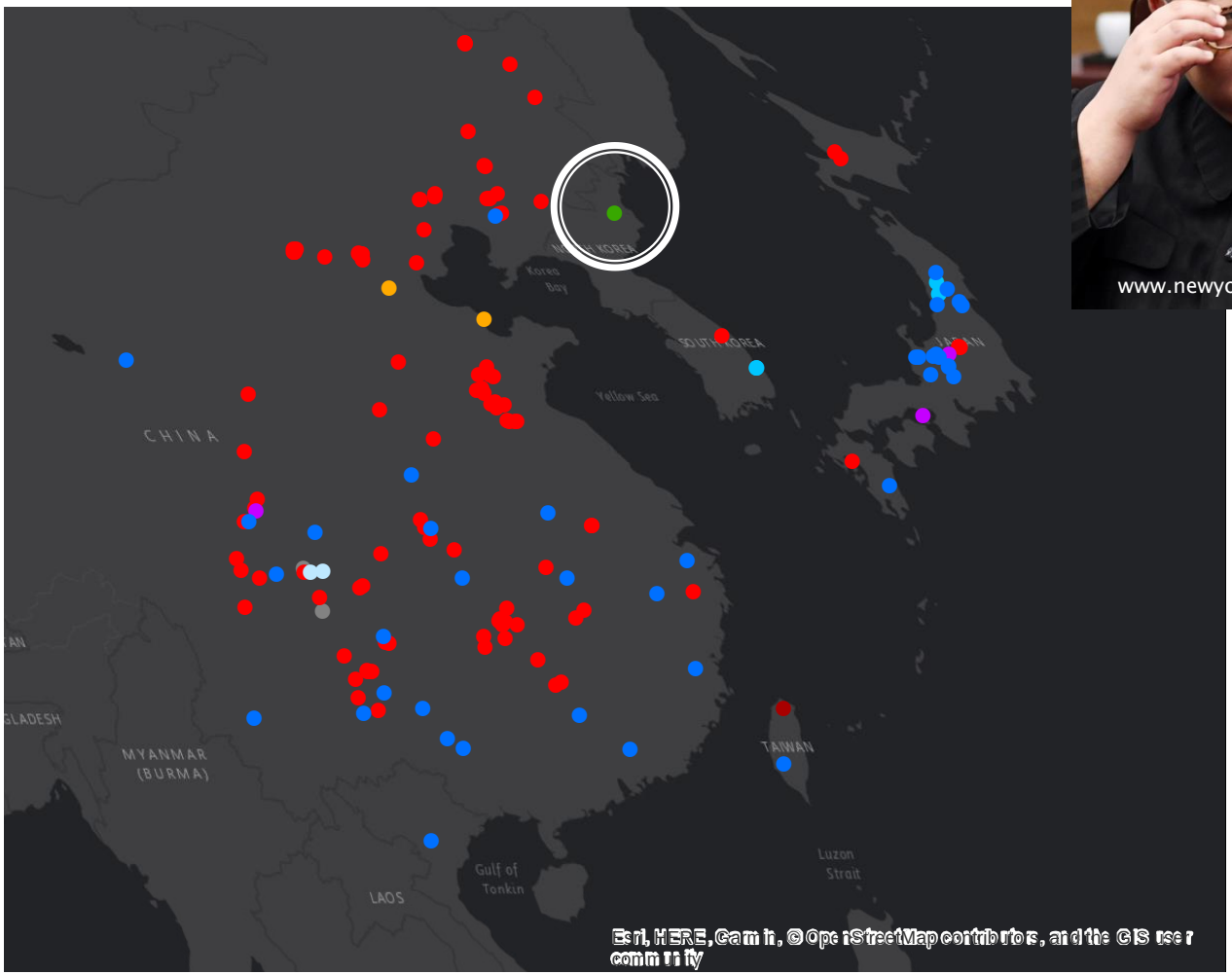
Key

- CCS
- Coal Bed Methane (CBM)
- Construction
- Conventional Oil and Gas
- Deep penetrating bombs
- Fracking
- Geothermal
- Groundwater extraction
- Mining
- Nuclear explosions
- Oil and Gas
- Oil and Gas/Waste fluid injection
- Research
- Waste fluid disposal
- Water reservoir impoundment



Part 2

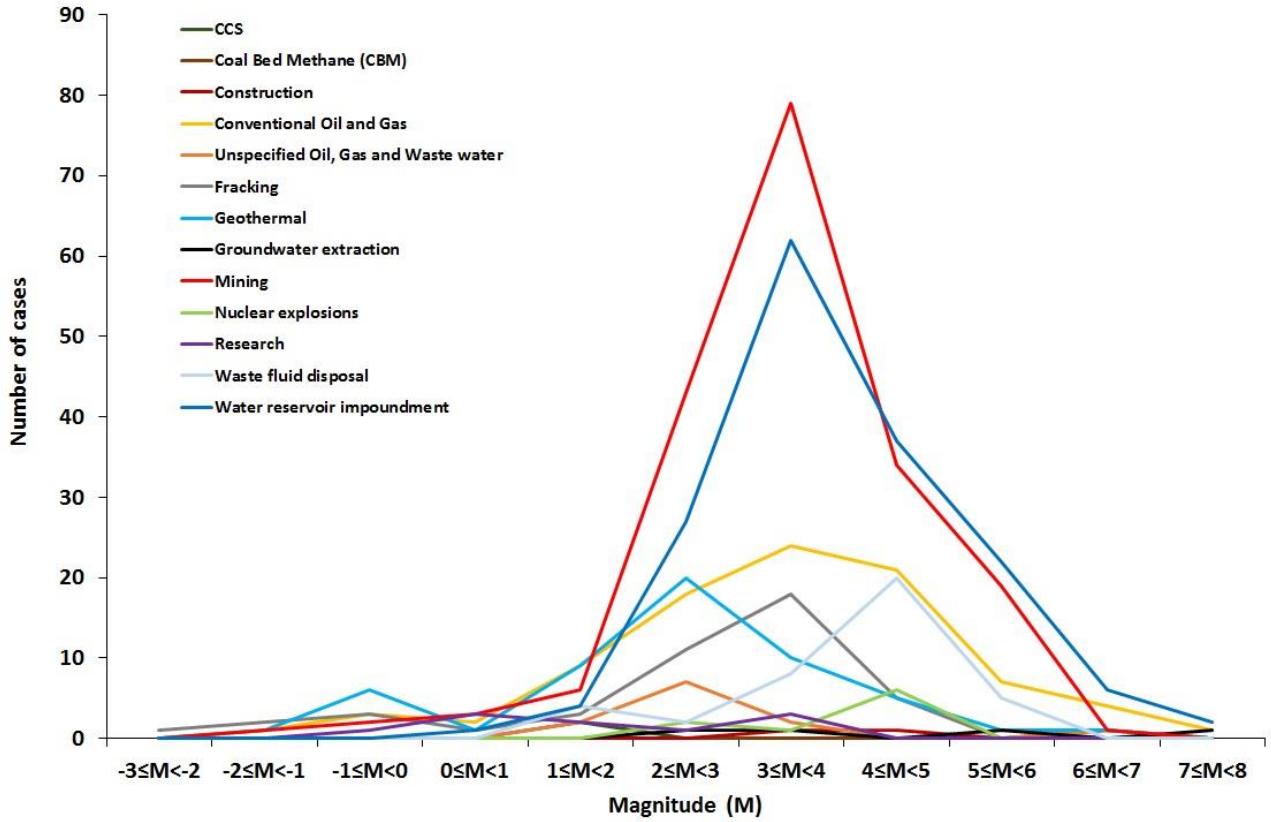
Northeast Asia



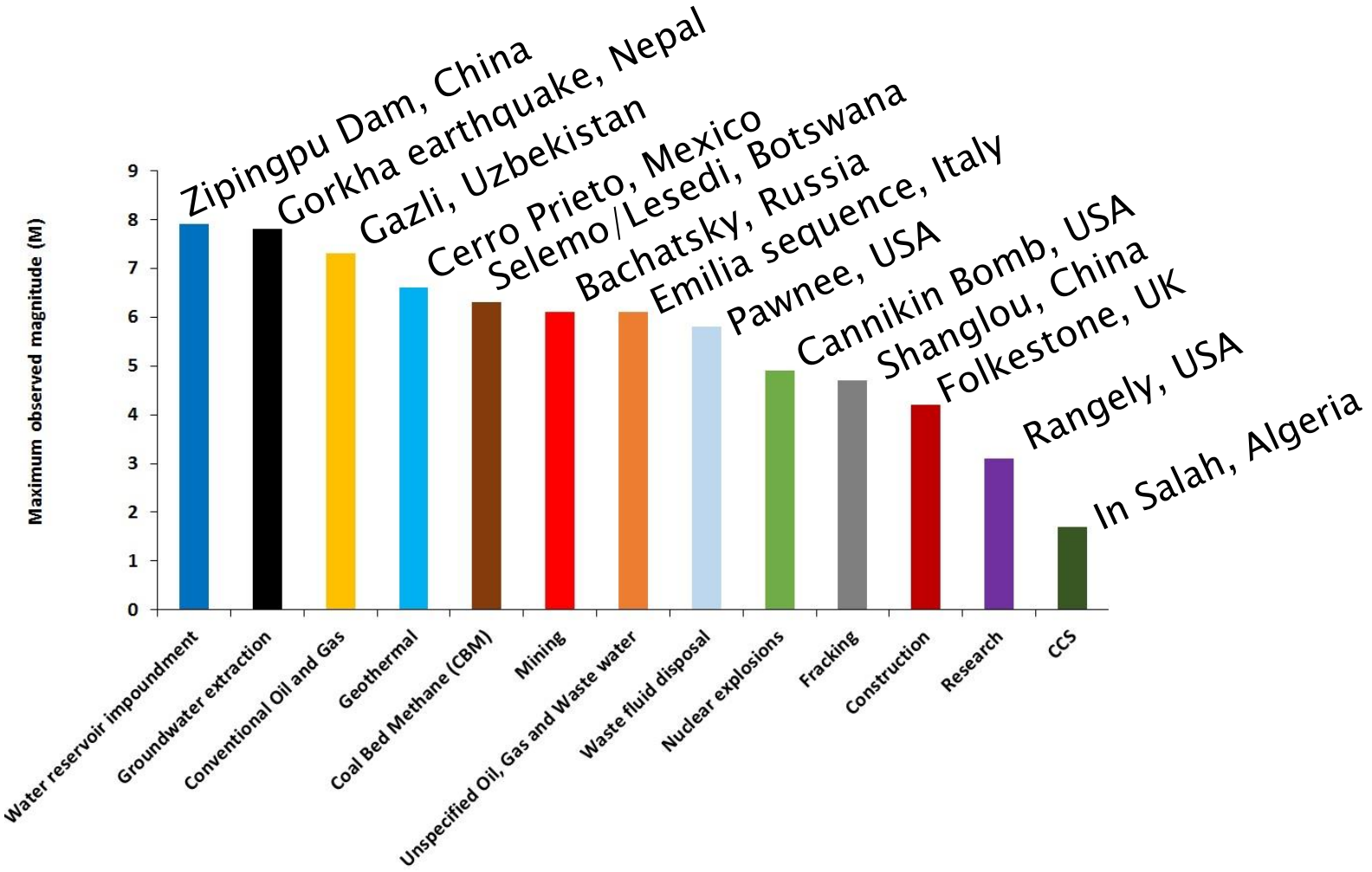
Part 2

M_{max} range

- Most commonly reported M_{max} value $3 \leq M < 4$

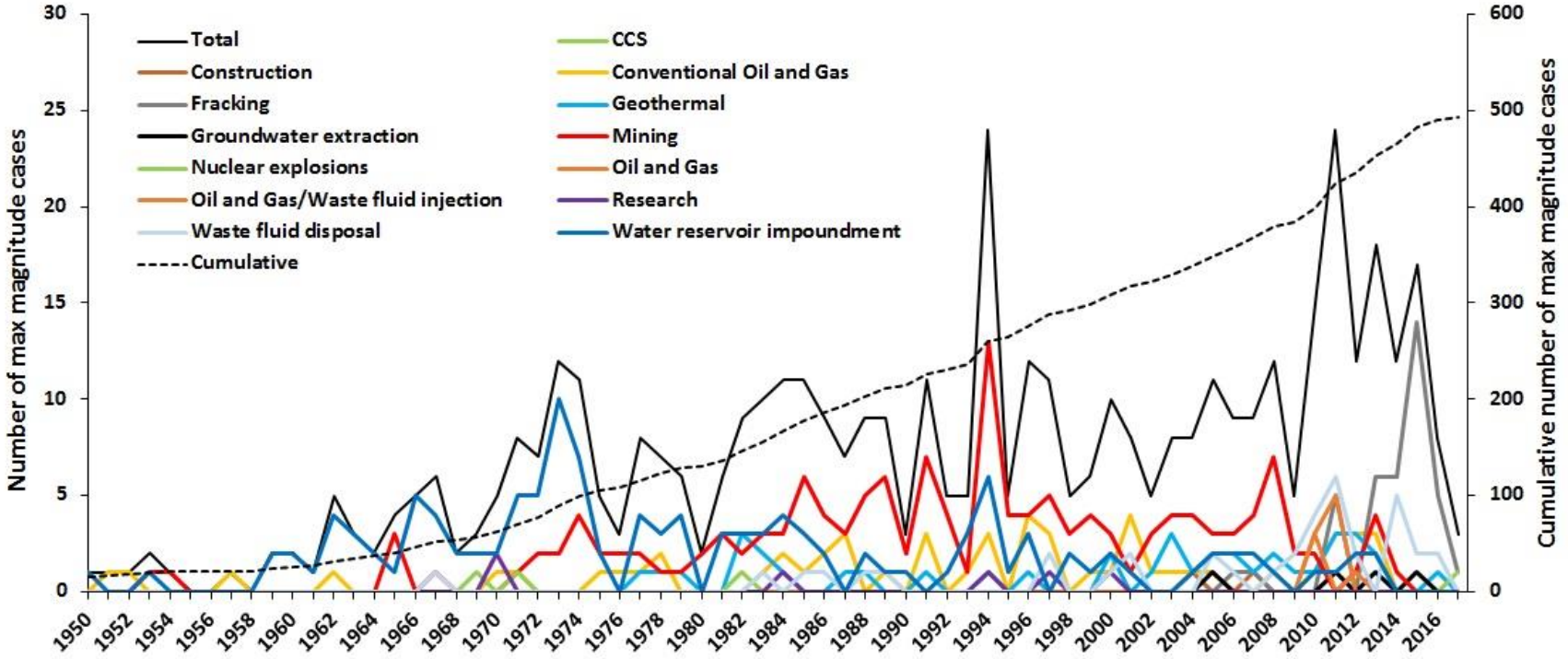


Maximum M_{max} for project types



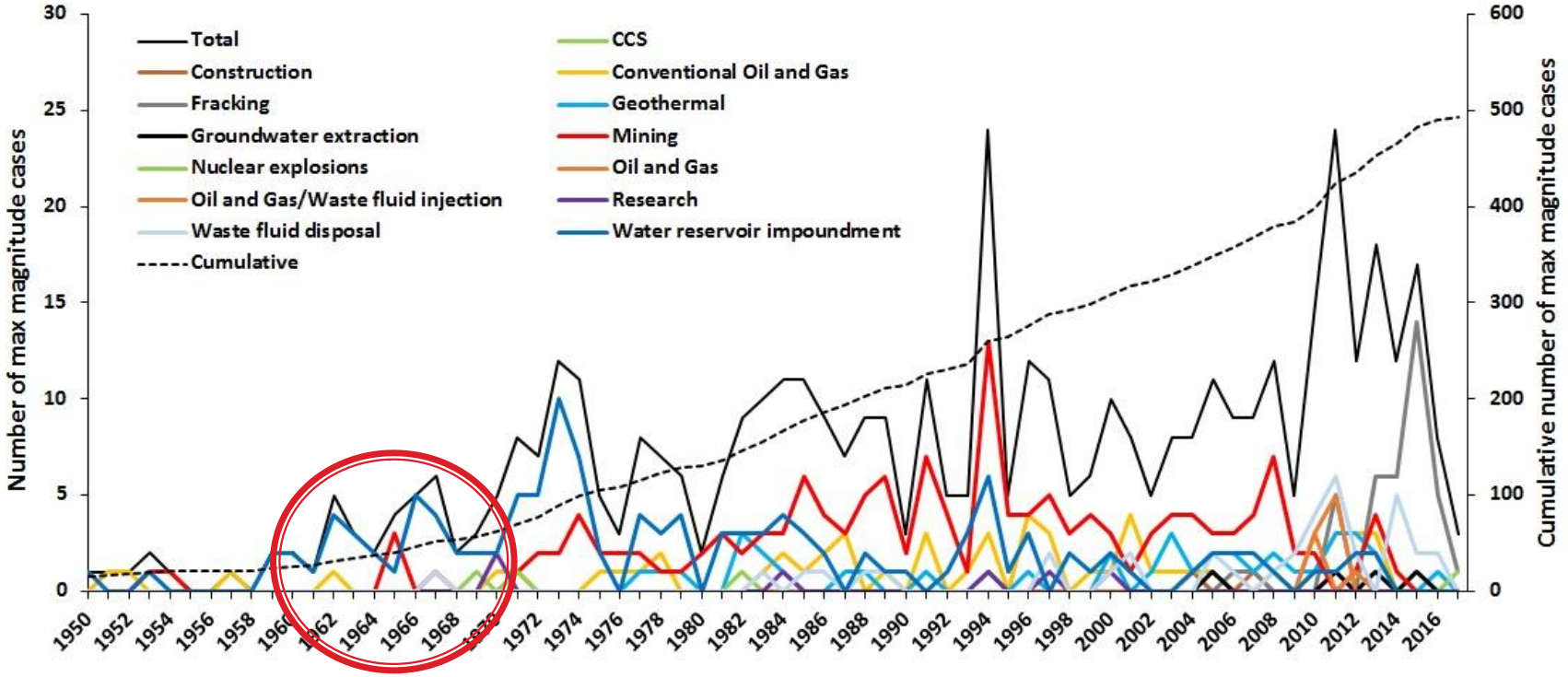
Part 2

Induced earthquake sequences through time



Part 2

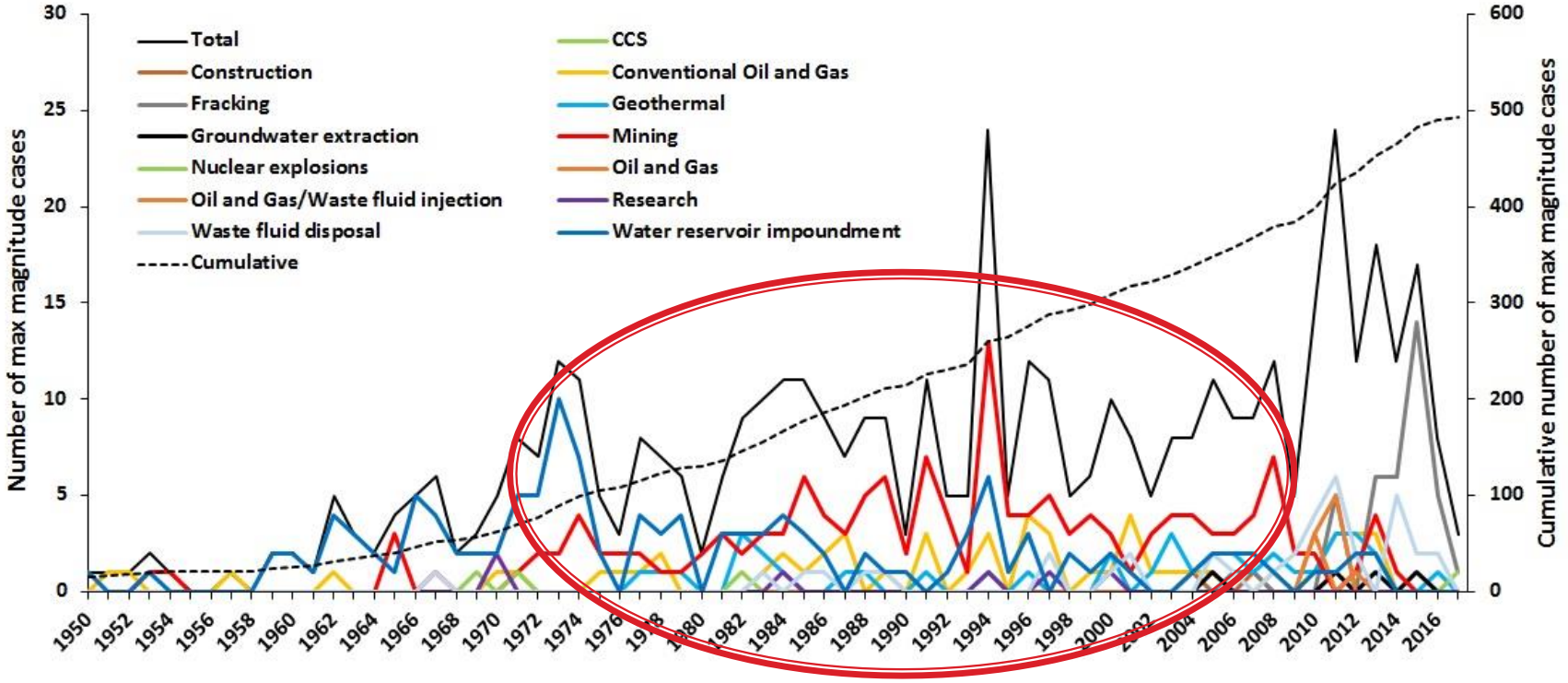
Induced earthquake sequences through time



Initial rise of induced seismicity

Part 2

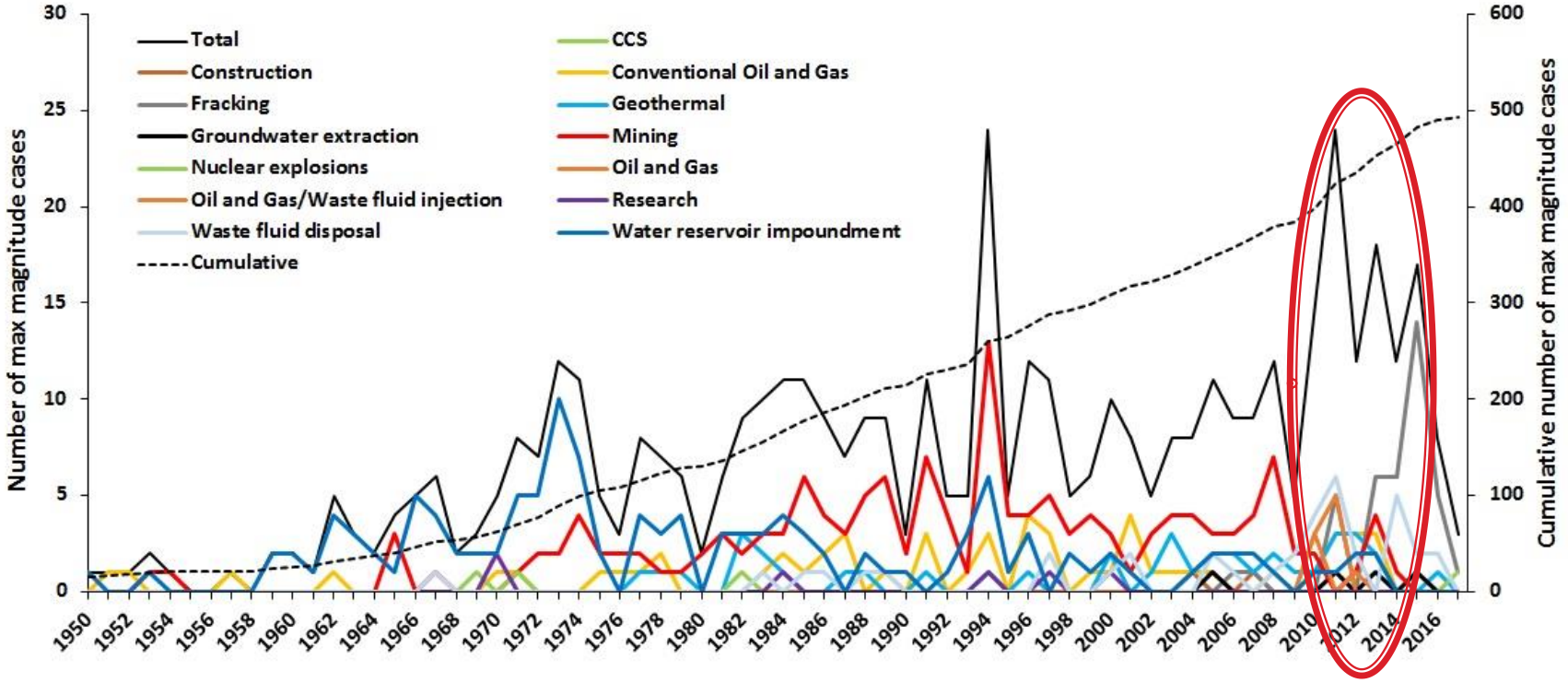
Induced earthquakes through time



Reporting approximately constant?

Part 2

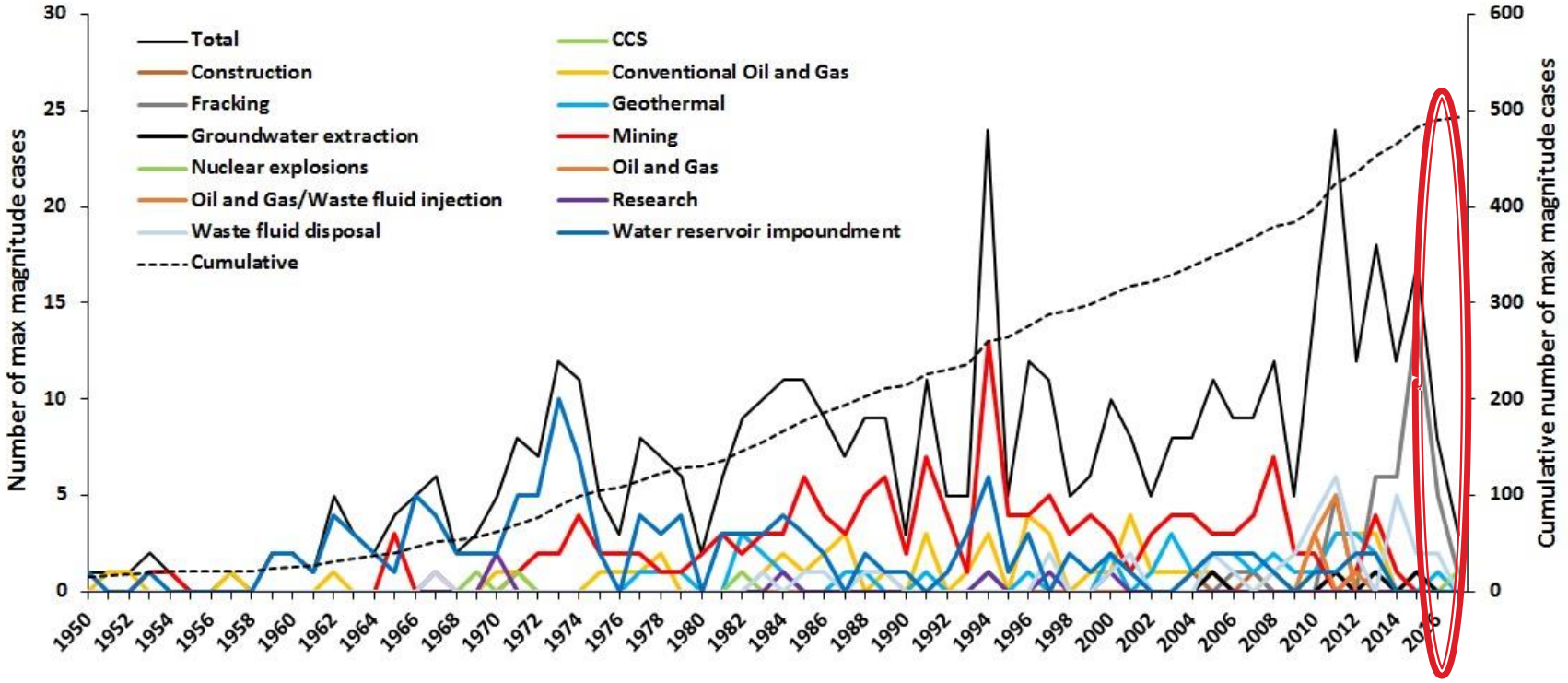
Induced earthquakes through time



Second rise of induced seismicity

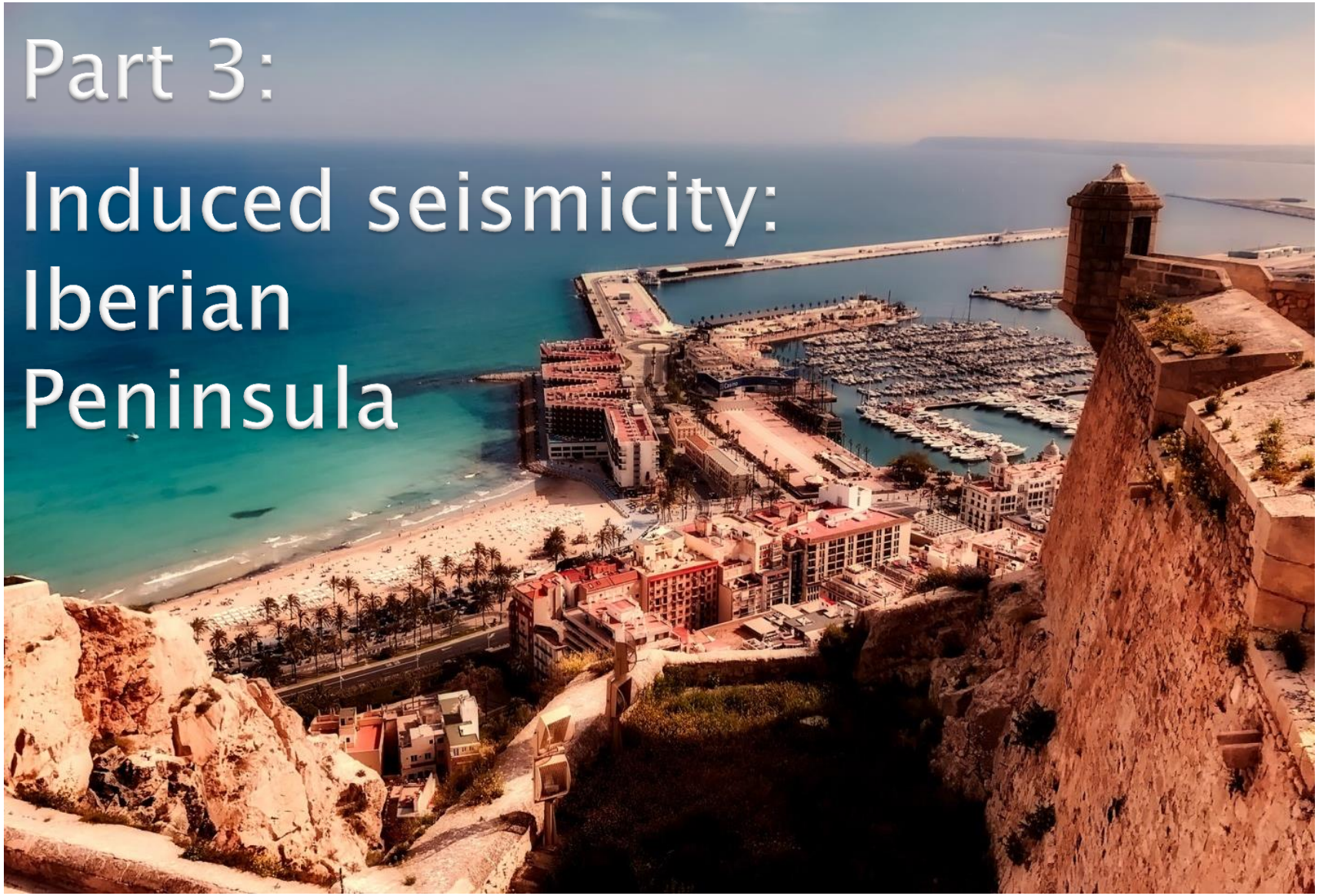
Part 2

Induced earthquakes through time



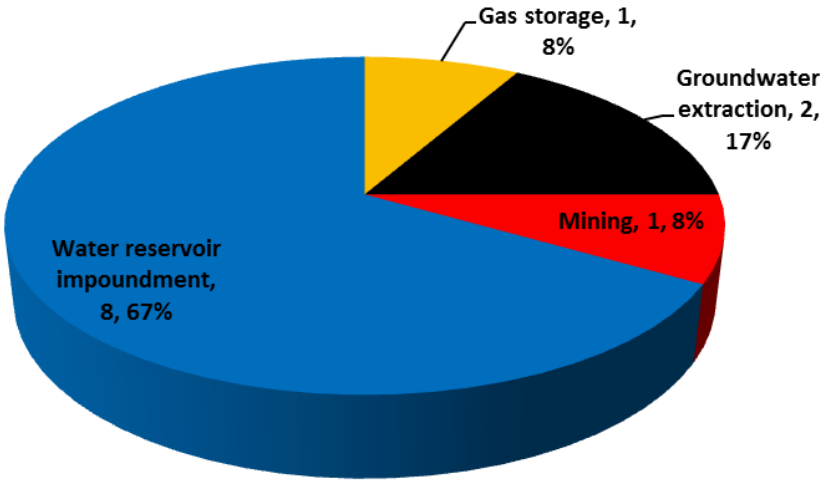
Reporting catch up?
More regional-based studies?

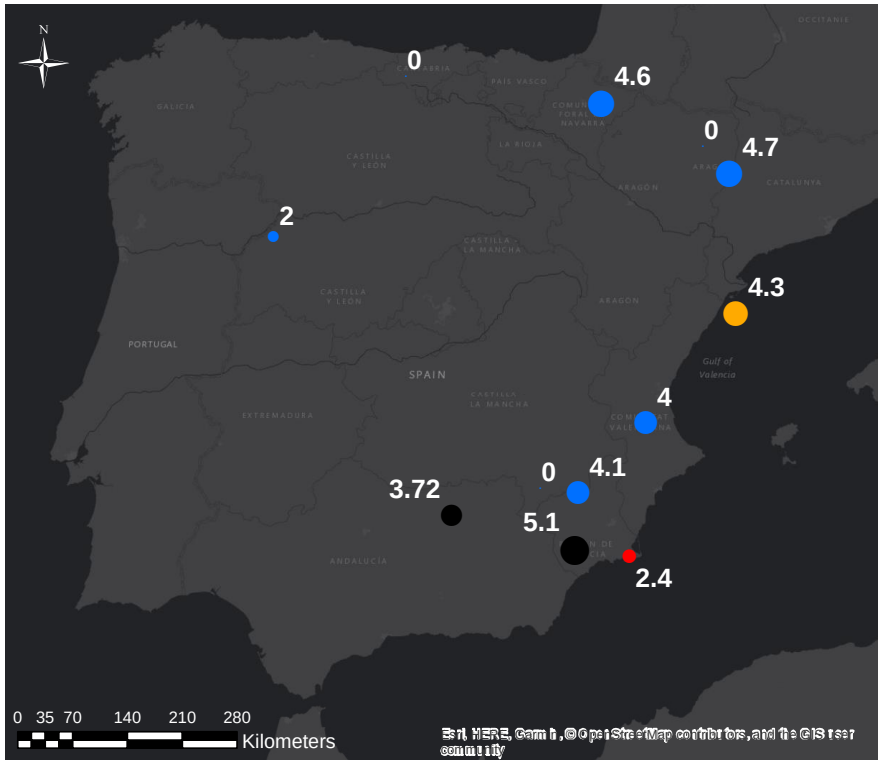
Part 2


Part 3:
Induced seismicity:
Iberian
Peninsula

Overview

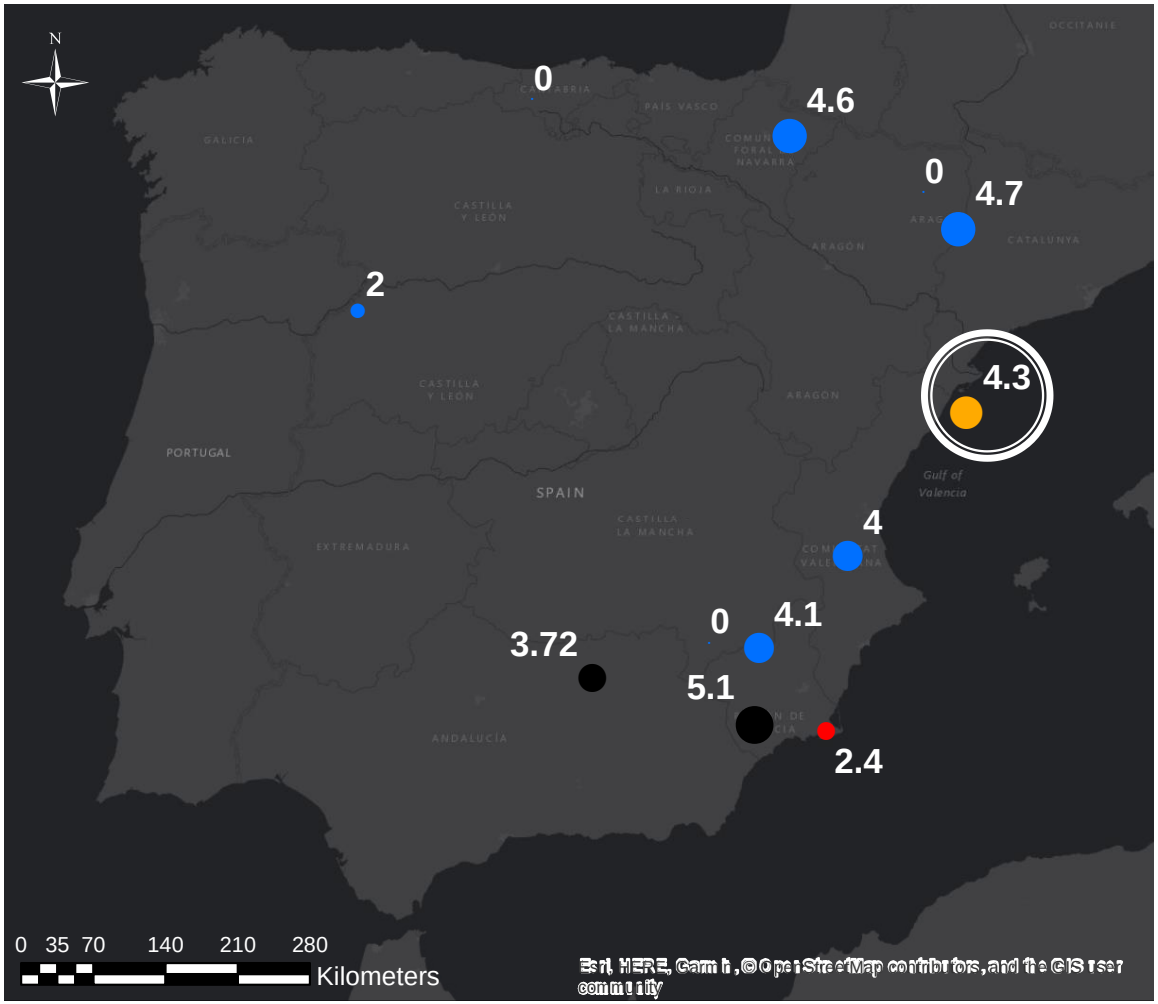
- 12 cases
- M_{max} 5.1





Part 3

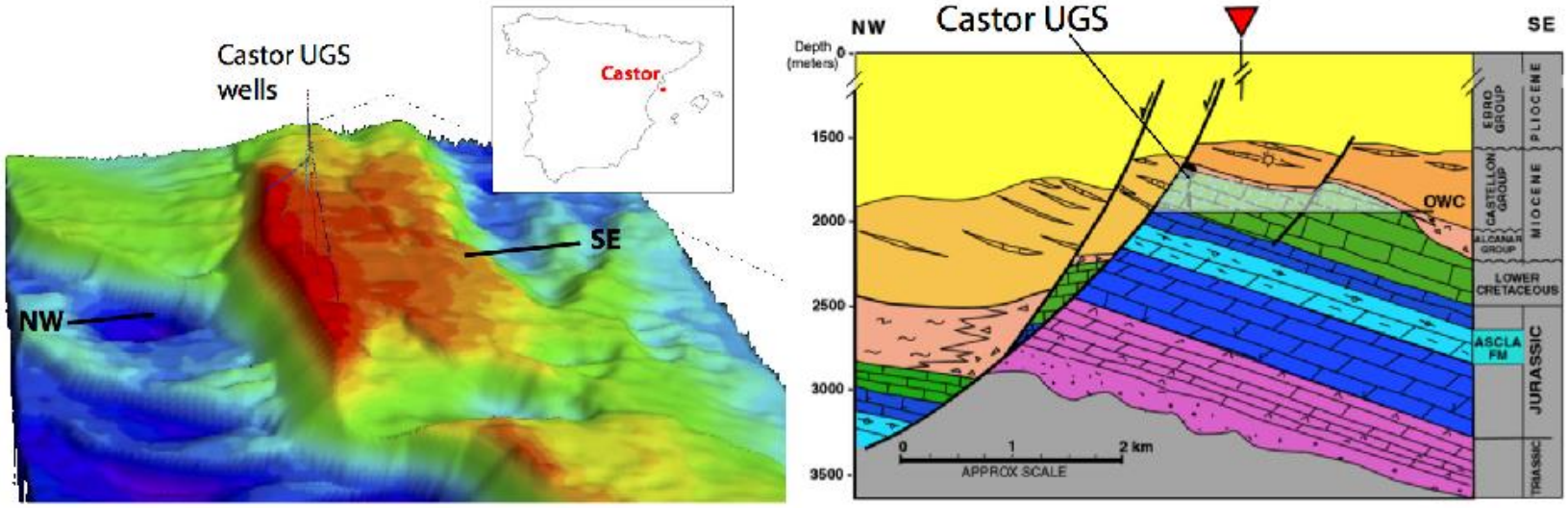
Castor – Gas storage



Part 3

Castor – Gas storage

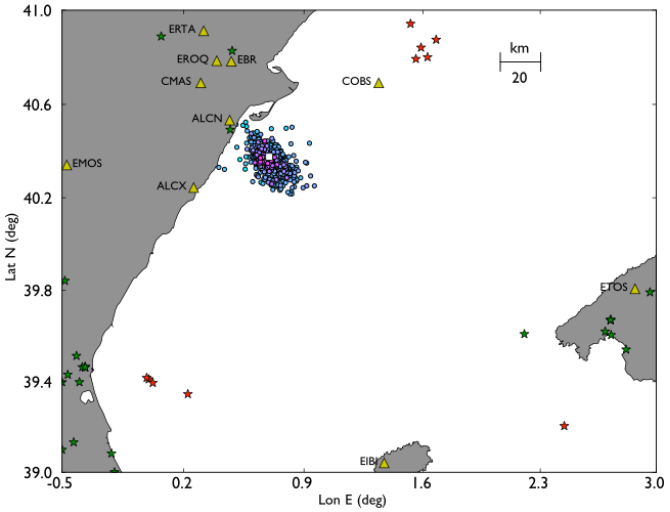
- Offshore facility in depleted Amposta oil field
- 25% Spain's gas storage needs

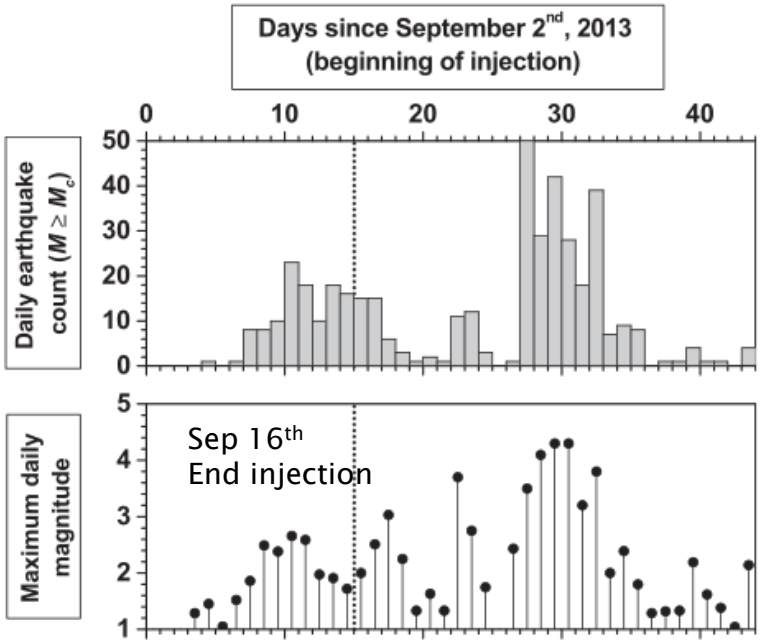


del Potro and Diez (2015)

Castor – Gas storage

- No seismicity associated with initial injection (June 2013)
- Seismicity started with last stage of cushion gas injection (5th September 2013)
- M_W 4.3

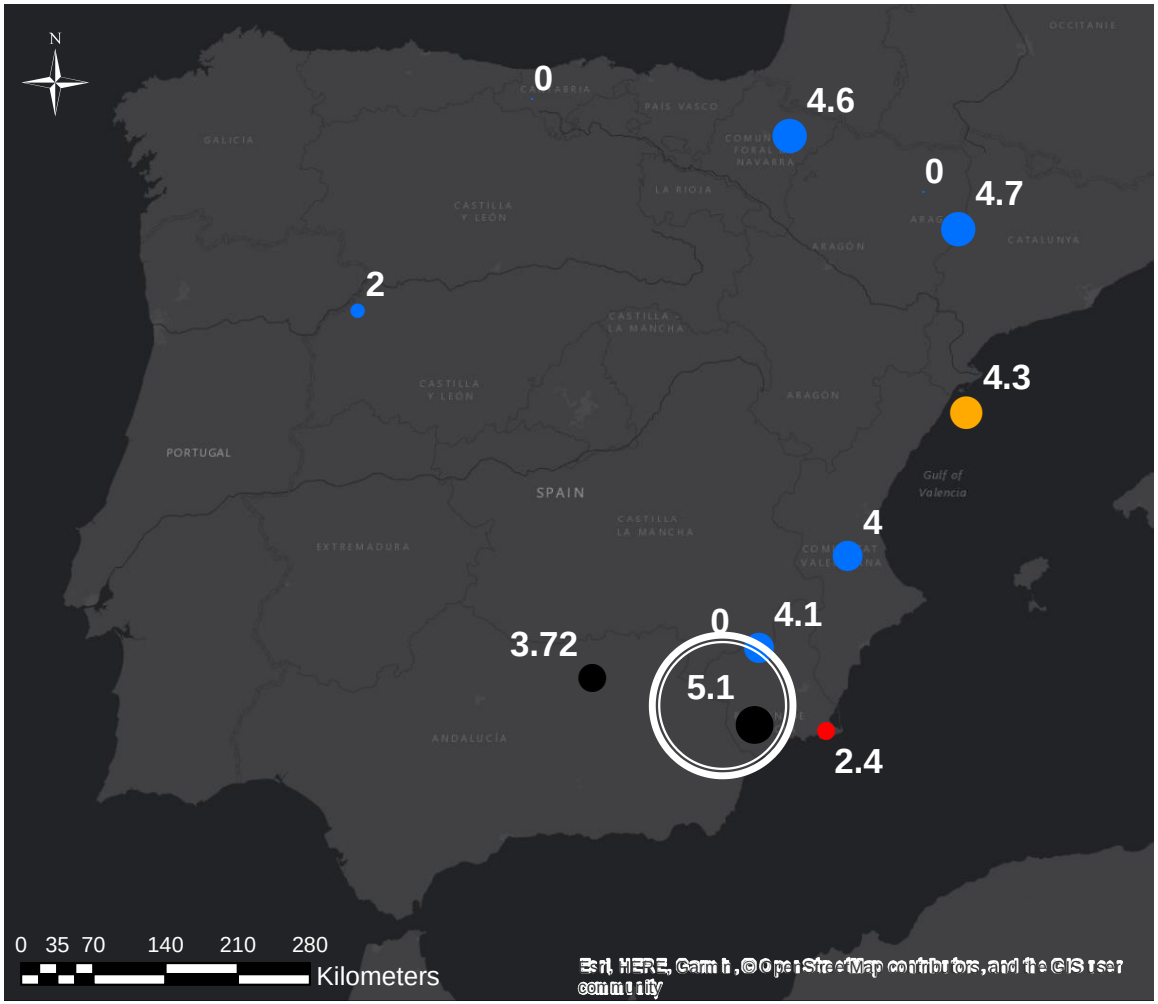




Cesca et al. (2014)

Part 3

Lorca – Groundwater extraction



Part 3

Lorca – Groundwater extraction

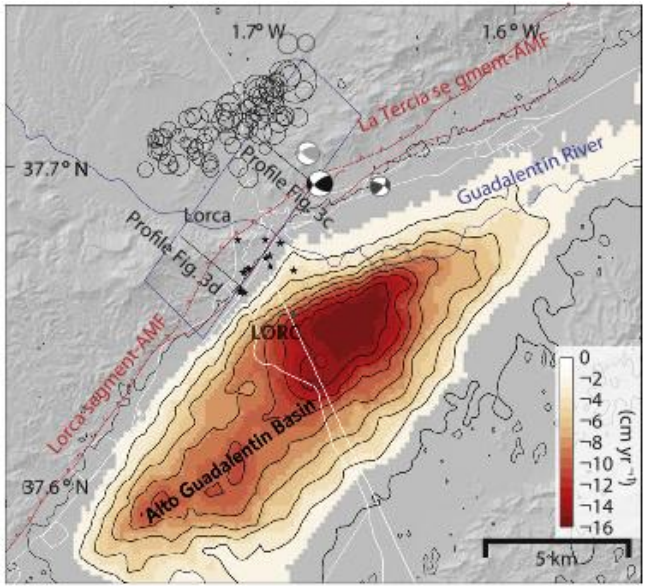
- M_W 5.1 (11th May 2011)
- 9 deaths, injuries, infrastructure damaged
- Hypocentre ~3 km deep
- Palaeoseismology at SW tip suggests M_W 7 is possible (*Ortuño et al.*, 2012)

https://en.wikipedia.org/wiki/2011_Lorca_earthquake

Part 3

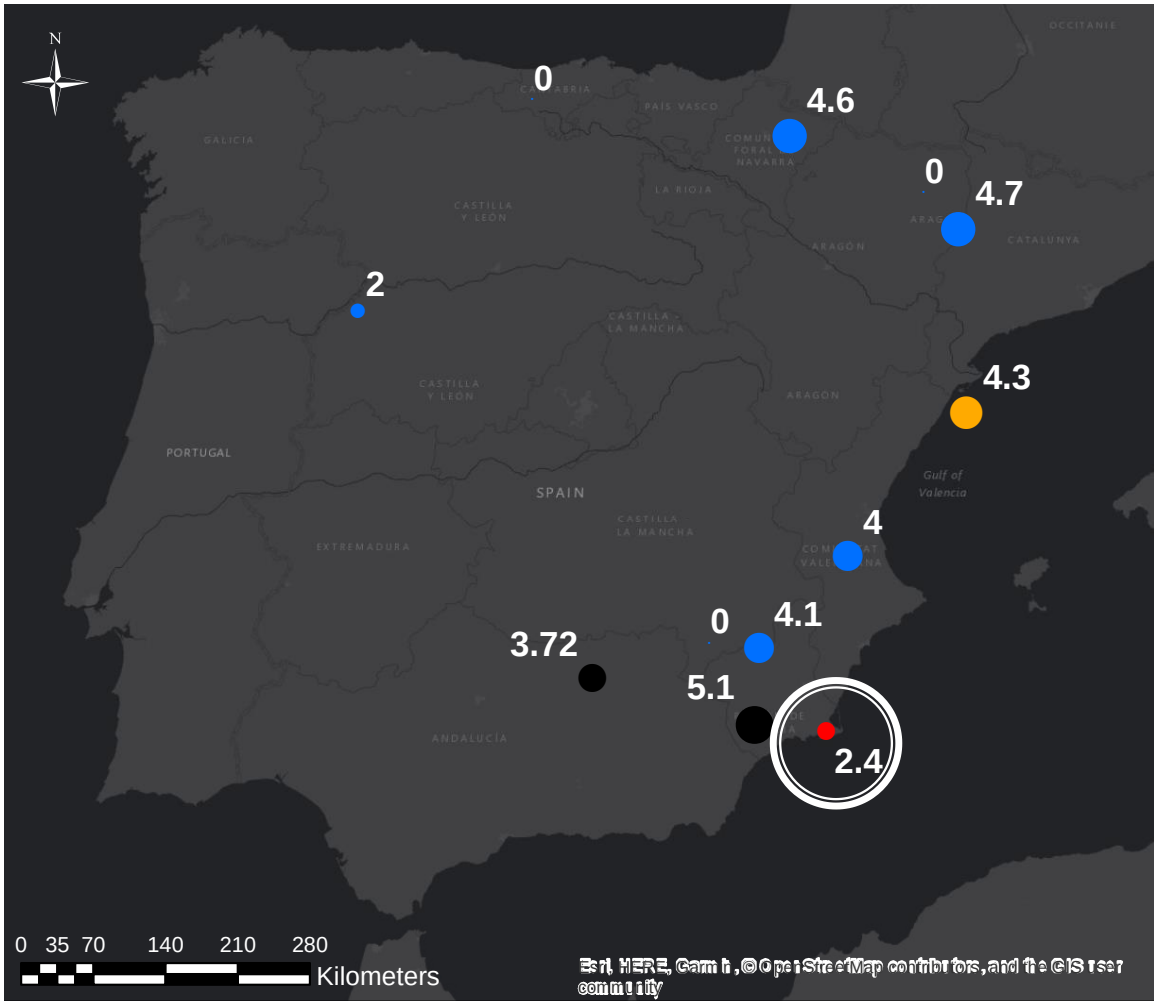
Lorca – Groundwater extraction

- Water table lowered >250 m (1960–2010)
- Surface subsidence >10 cm/yr (1960–2010)
- Fault slip deficit of ~12 cm
- Unloading released deficit



González et al. (2012)

Lo Tacón – Mine collapse



Part 3

Lo Tacón – Mine collapse

- M_W 2.4 (2nd May 1998)
- Torre Pacheco earthquake

⬇

Mine collapse?

- Subsidence in Lo Tacón

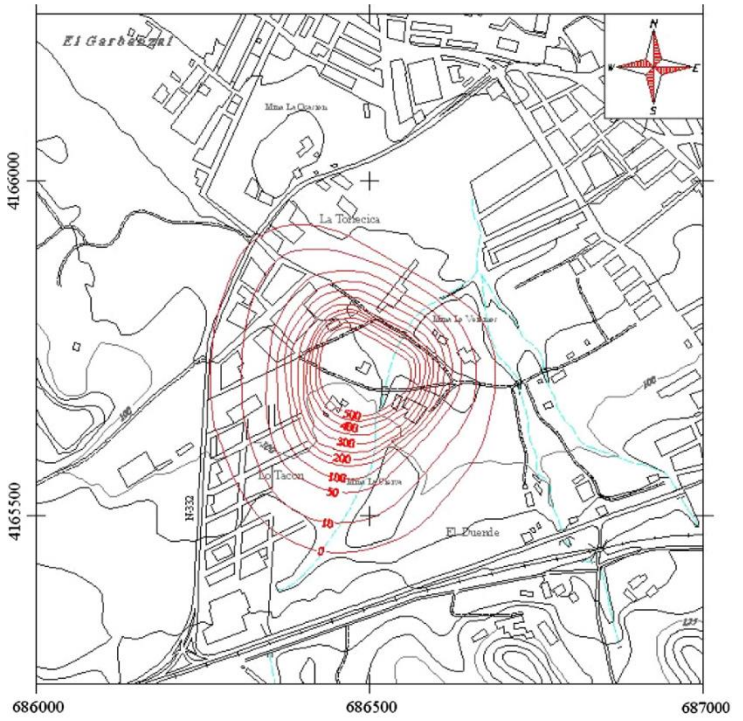


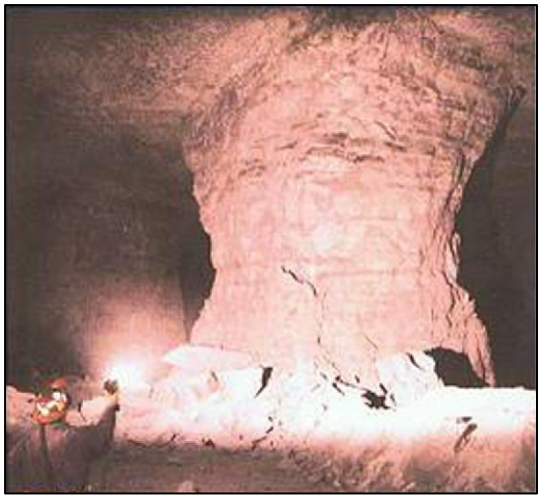
Fig. 7. Subsidence map.

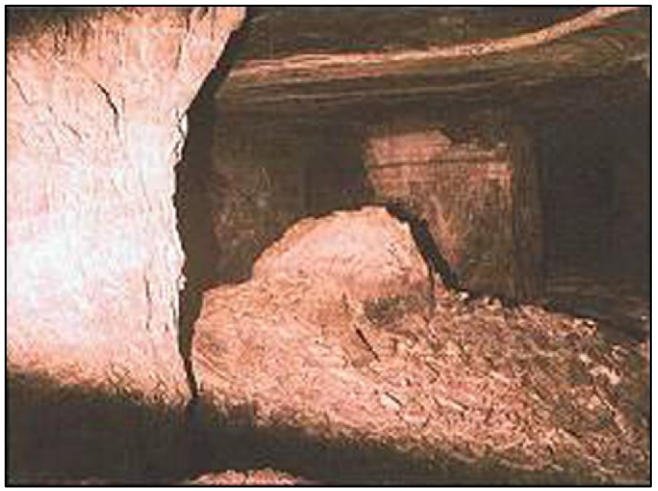
Alvarez-Garcia et al. (2013)

Part 3

Lo Tacón – Mine collapse

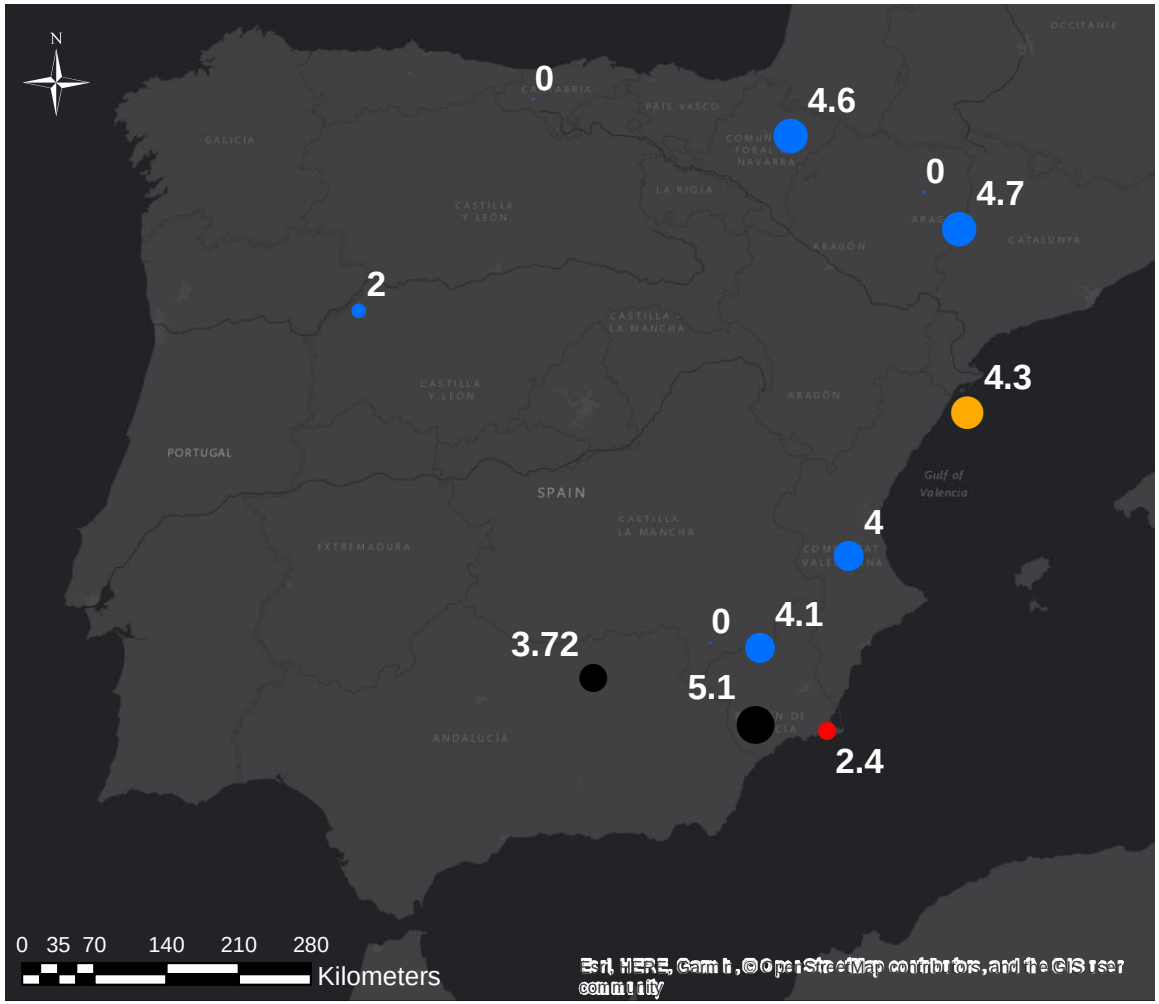
- Mine collapse was the earthquake
- Cascading pillar failure (CPF)





Alvarez-Garcia et al. (2013)

Surface water reservoirs

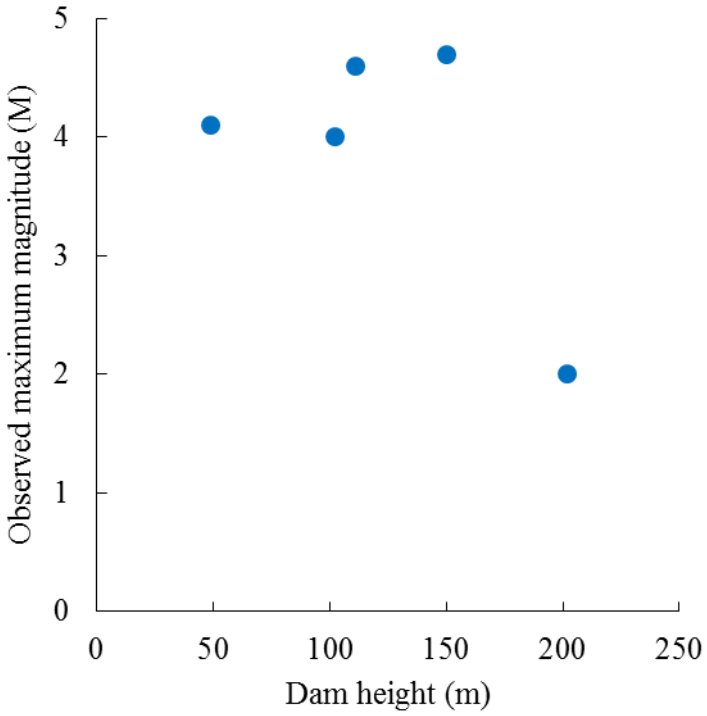


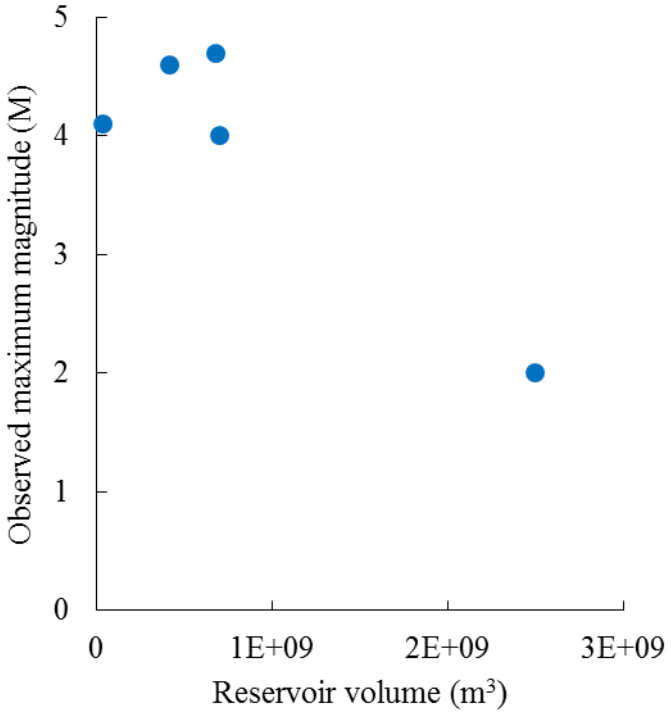
Part 3

Surface water reservoirs

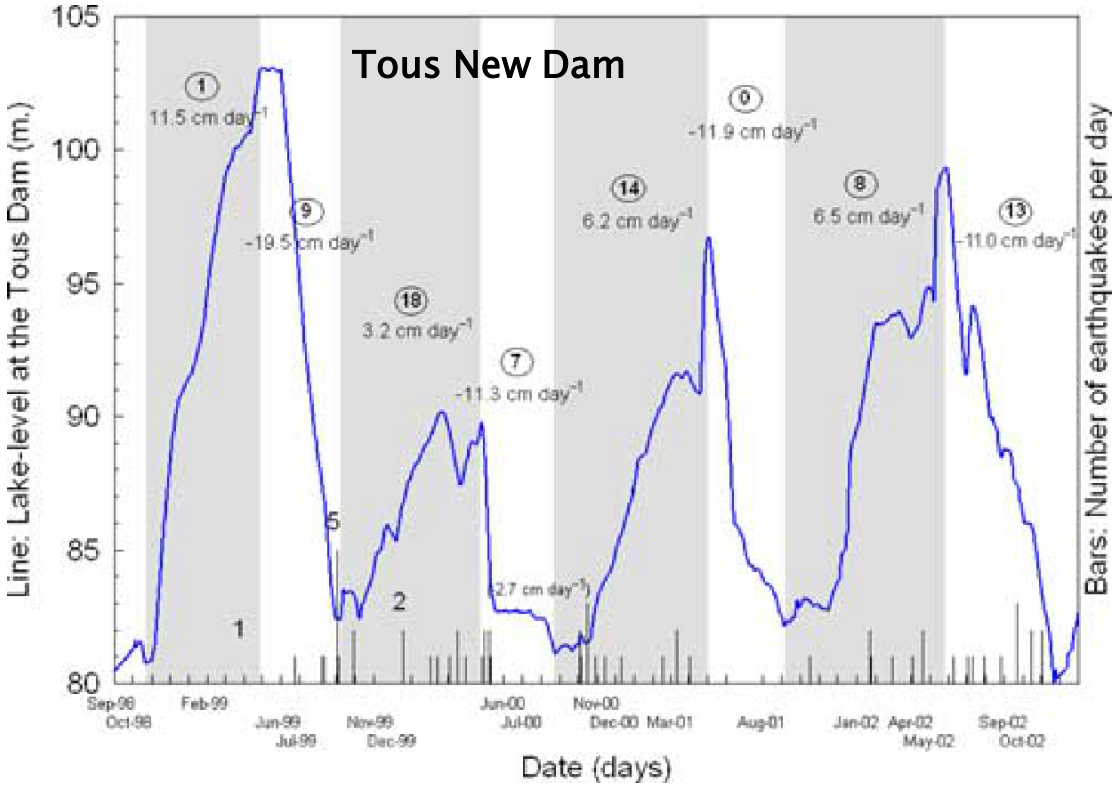
Dam or reservoir name	M_{max}	Year
Canelles	4.7	1962
Itoiz	4.6	2004
Camarillas	4.1	1964
Tous New	4	2000
Almendra	2	1972
Cenajo		1973
El Grado		
La Cohilla		1975

Surface water reservoirs



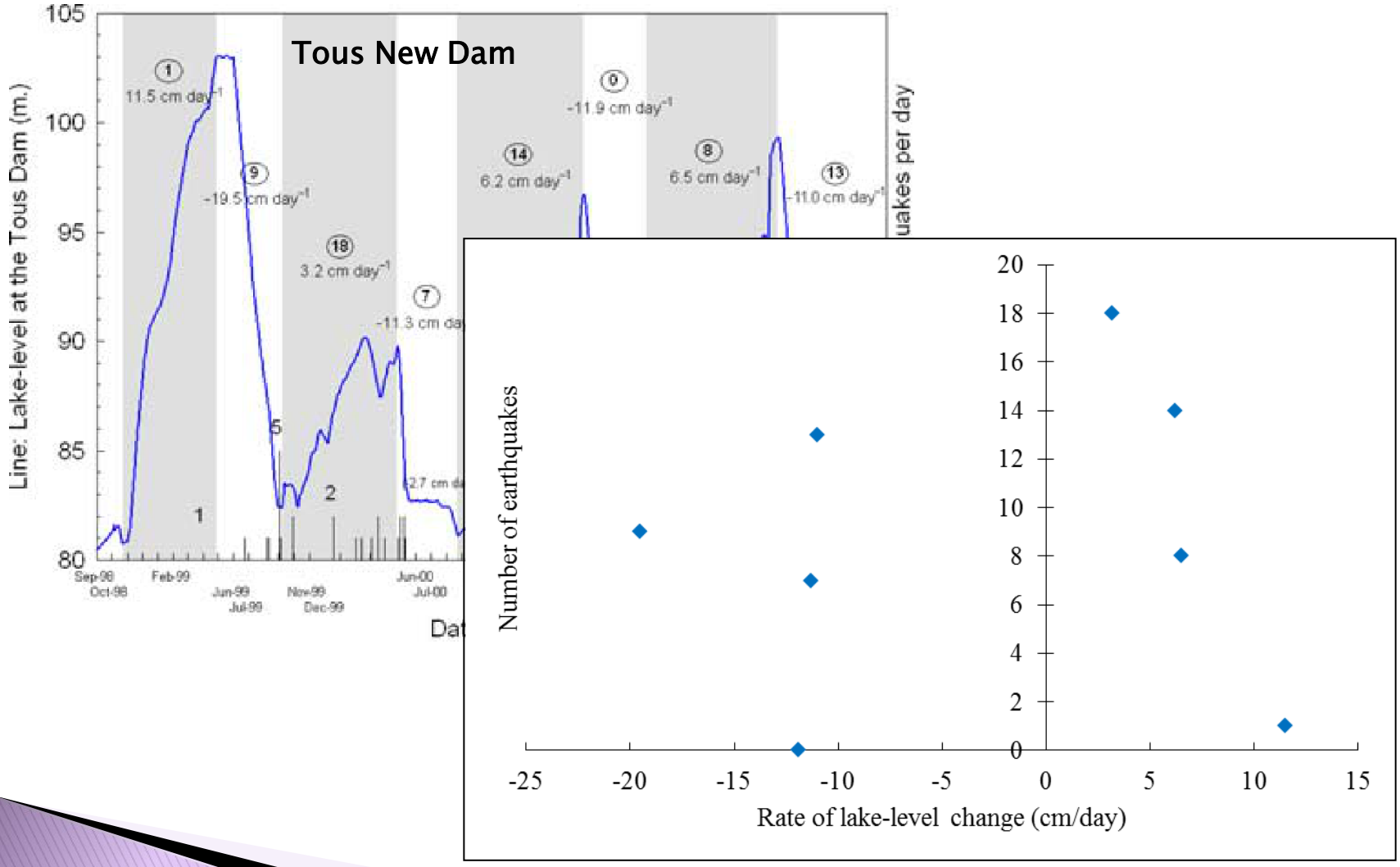


Surface water reservoirs



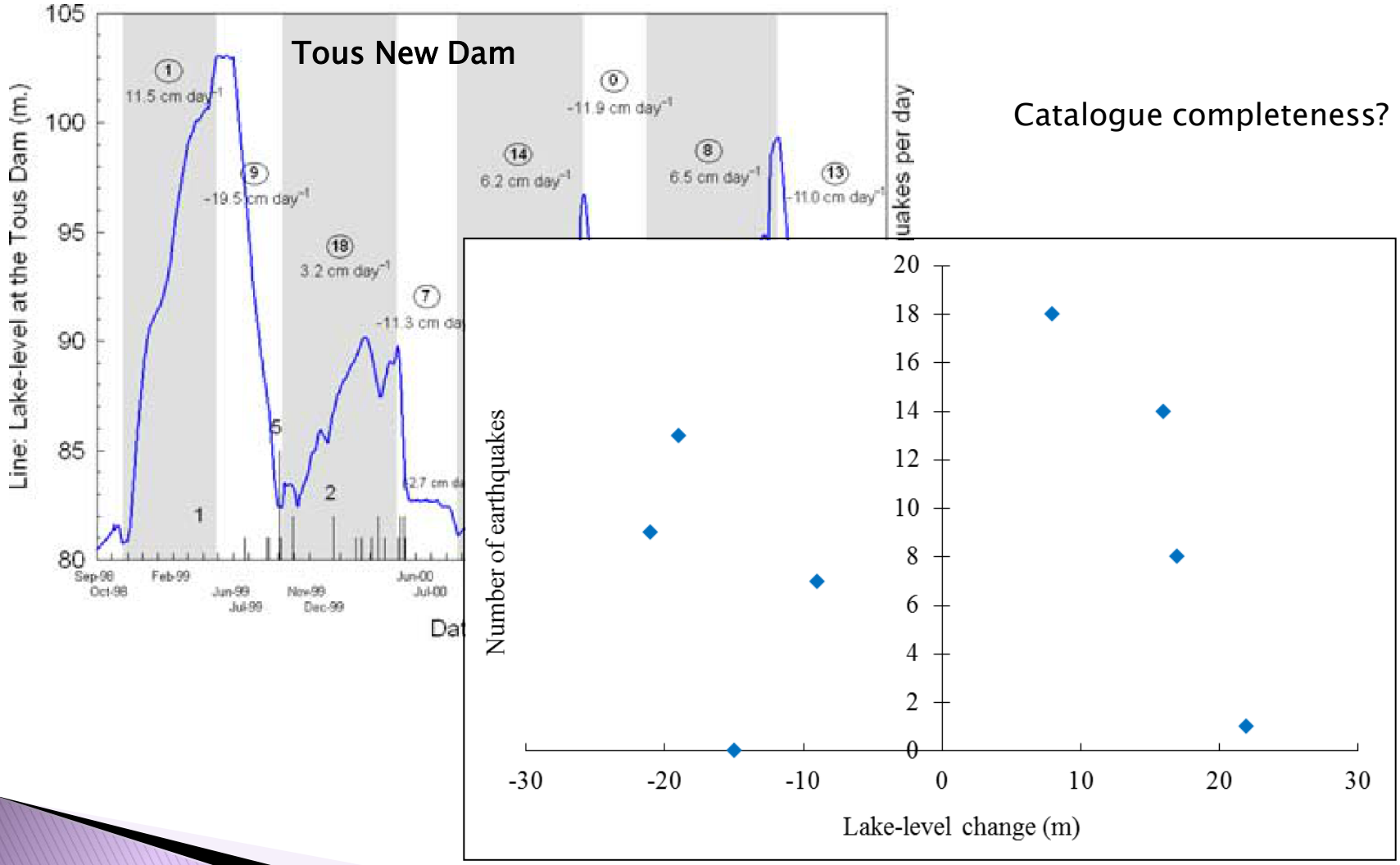
Torcal et al. (2005)

Surface water reservoirs



Part 3

Surface water reservoirs



Catalogue completeness?

Part 3


Part 4:
Society and induced seismicity

Society's response to induced seismicity

- M_W 4.6, Canada, not reported to be felt (*Atkinson et al.*, 2016)
- M_L 2.3 and M_L 1.5 smallest felt fracking-induced earthquake (*BGS*, 2016)

⬇

- 1.5 year moratorium
- Public outrage and protest

http://www.dailymail.co.uk/news

The ‘disconnect’

- Does society today realise where…

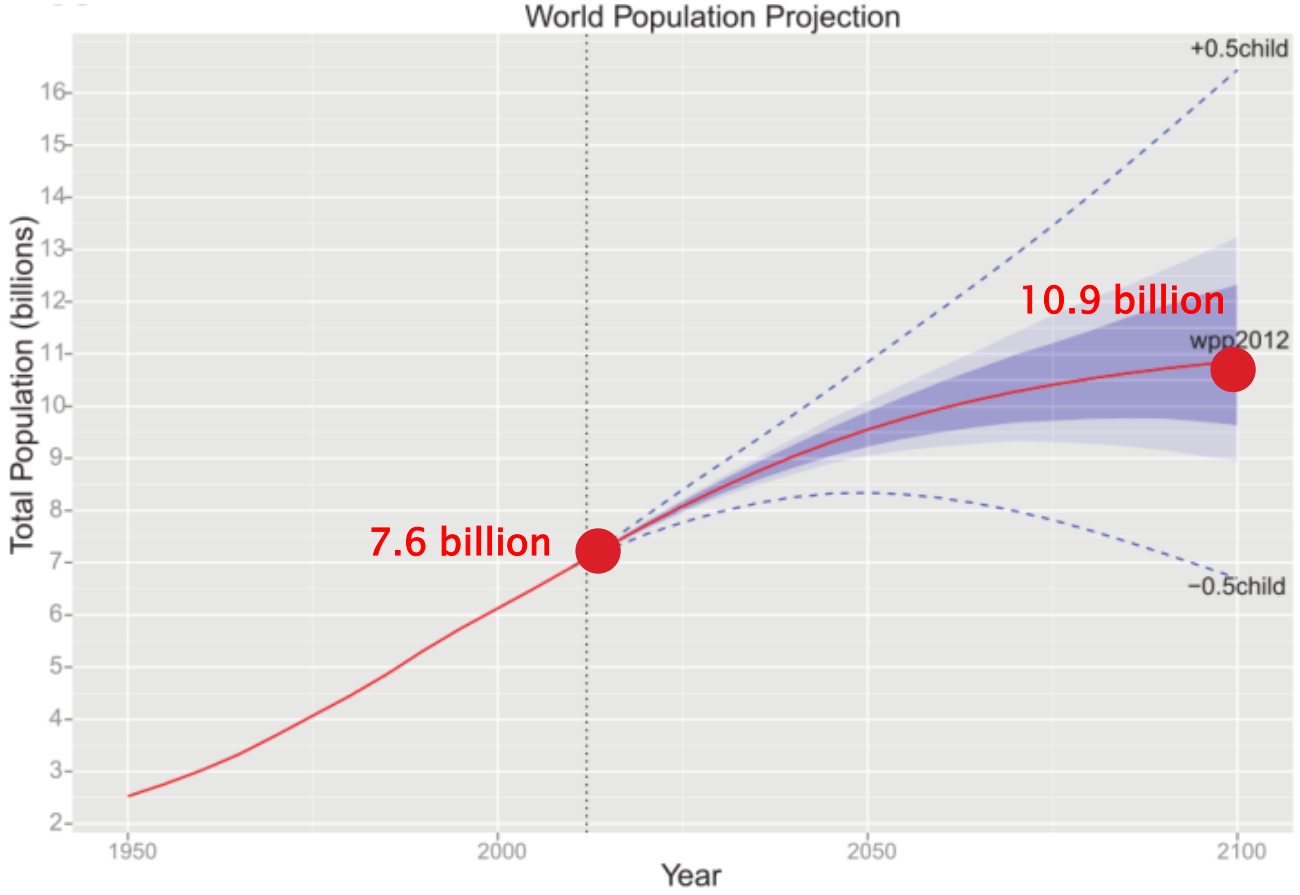
Where petrol comes from?

Electricity comes from?

The materials needed for renewables come from?

The materials in our phones come from?

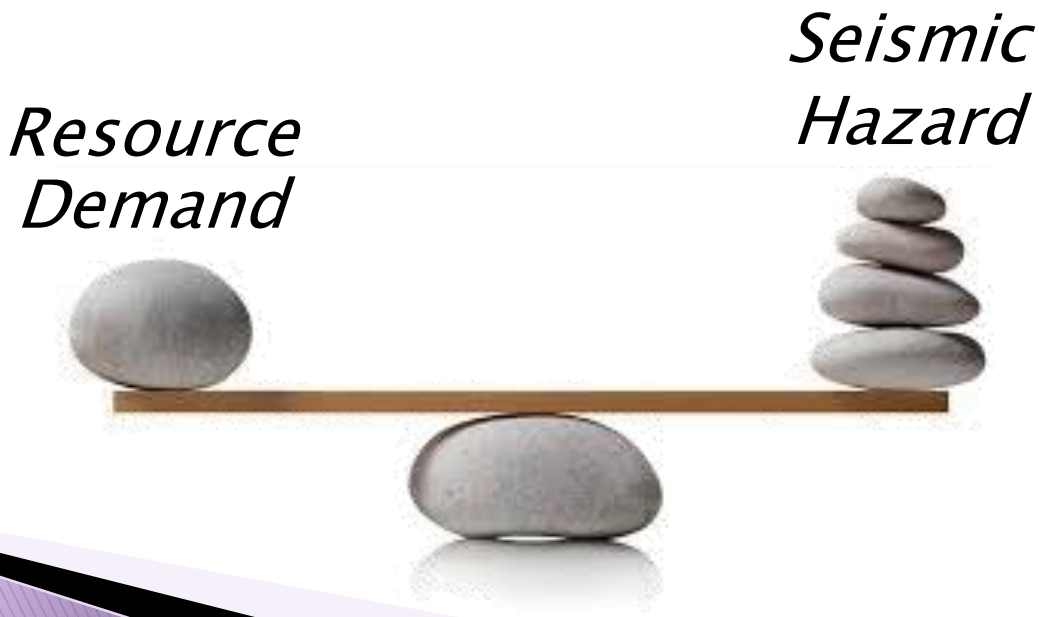
World population →Resource demand



Gerland et al. (2014)

The ‘balance’

- We don’t want induced earthquakes to be a hazard or social problem…
- But we all use electricity, metals, plastics, petrol, etc.



The role of geoscientists

- Observation
- Investigation
- Mitigation

- Education
- Cooperation

?

Neutrality is key

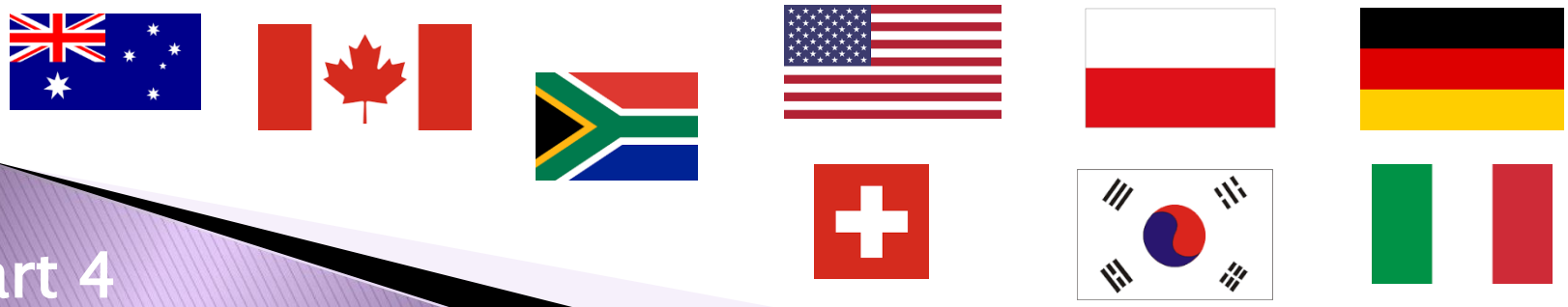
Facts not opinions

Role of *HiQuake*

- Context
- Educational resource
- Scientific resource
- Start collaborations
- Manage impact of induced seismicity on society?

Current success of *HiQuake*

- ~116,000 website hits since January 2017
- Significant media coverage
  (Nature, National Geographic, BBC, etc.)
- Top 10 Google hits for “induced earthquakes”
- Praise from global scientific community



Summary

- *HiQuake* currently contains 766 projects and is the largest and most up-to-date database of its kind
- Recent years have seen an increase in reported injection-induced earthquakes but…
- Induced earthquakes caused by more human activities than generally appreciated
- Proposed induced seismicity in Iberian Peninsula dominated by surface water reservoirs
- Balance needed between resource demand and seismic hazard
- Geoscientists have a key role in cooperation and education

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NAM

Thank you

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