Long lasting seismic swarm and pore pressure decrease

(conventional gas production: Lacq, SW France (1969-2016)

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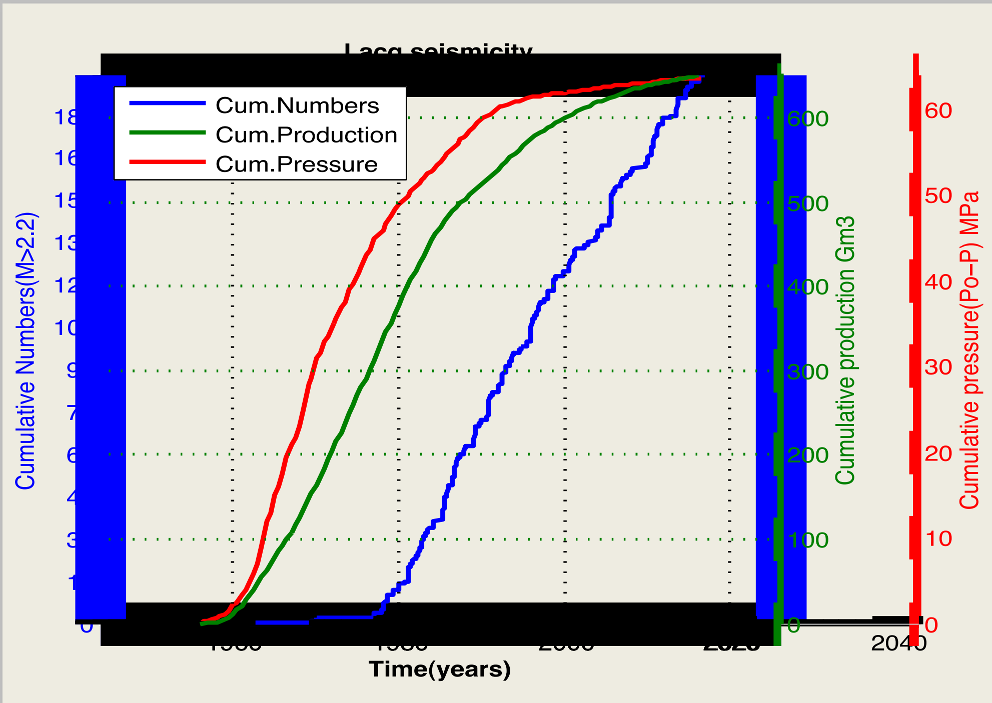

Gas pressure drop, production volume and cumulative seismicity

TOTAL COMMITTED TO BETTER ENERGY

Geopetrol

EC-EPOS (2015-2019)-IP
WP14 Anthropogenic seismicity

EPOS EUROPEAN PLATE OBSERVING SYSTEM

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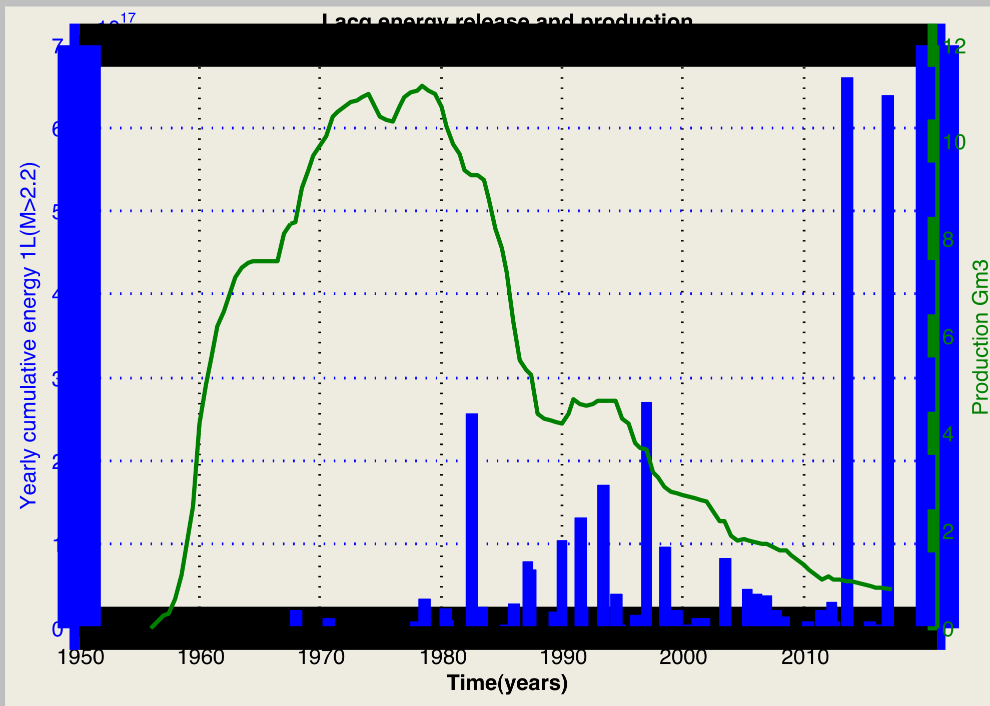
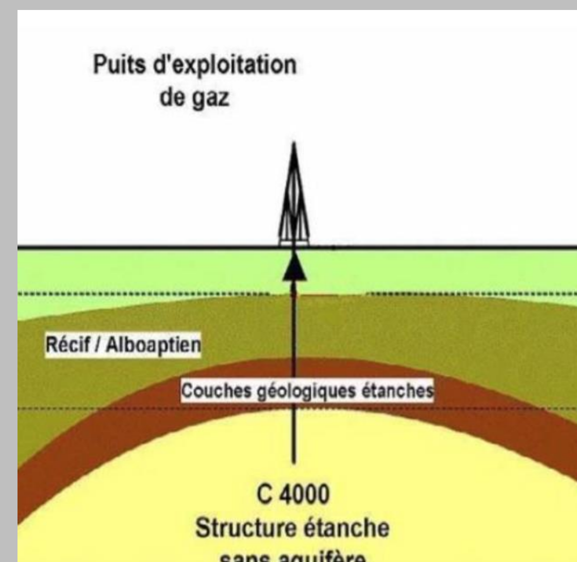


Gas production rate and seismic energy release rate over time

Mechanics of Lacq seismic swarm:

- seismicity onset ?
- seismicity end ?
- M_{max} ?



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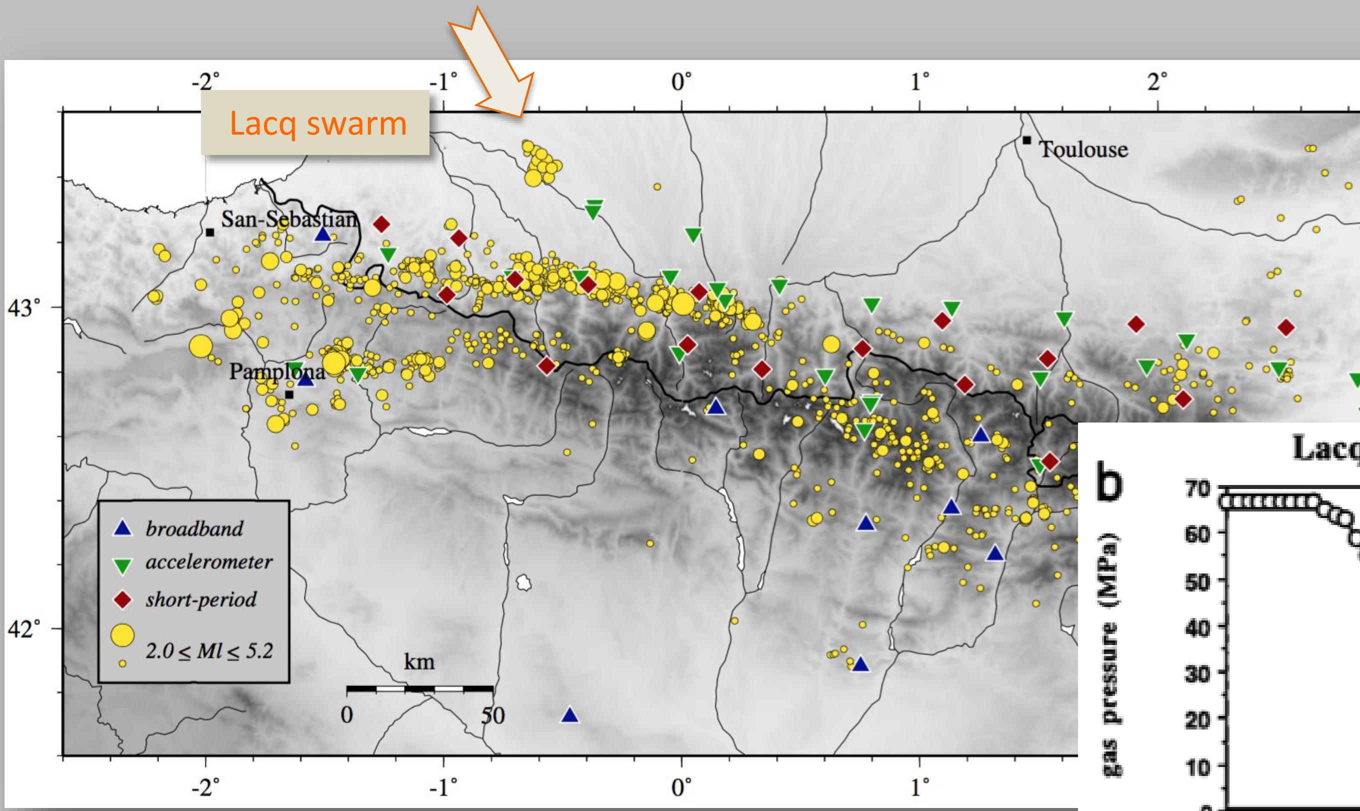
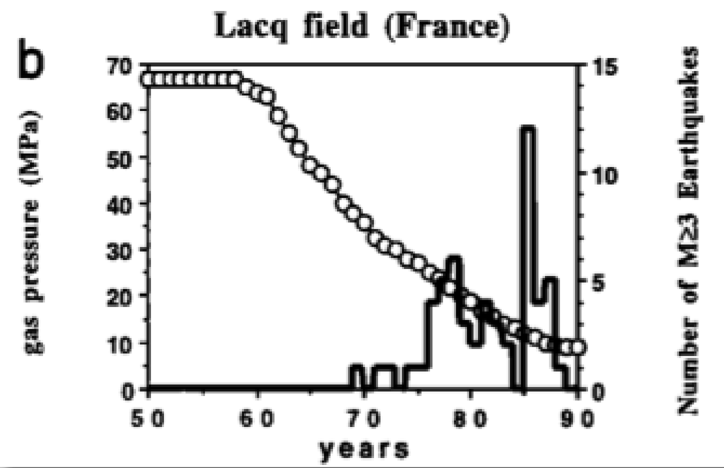


Pyrenees seismicity from regional network 1997-2010
Chevrot et al 2011



Seismicity pattern from local seismic network
e.g. Grasso and Wittlinger BSSA1990

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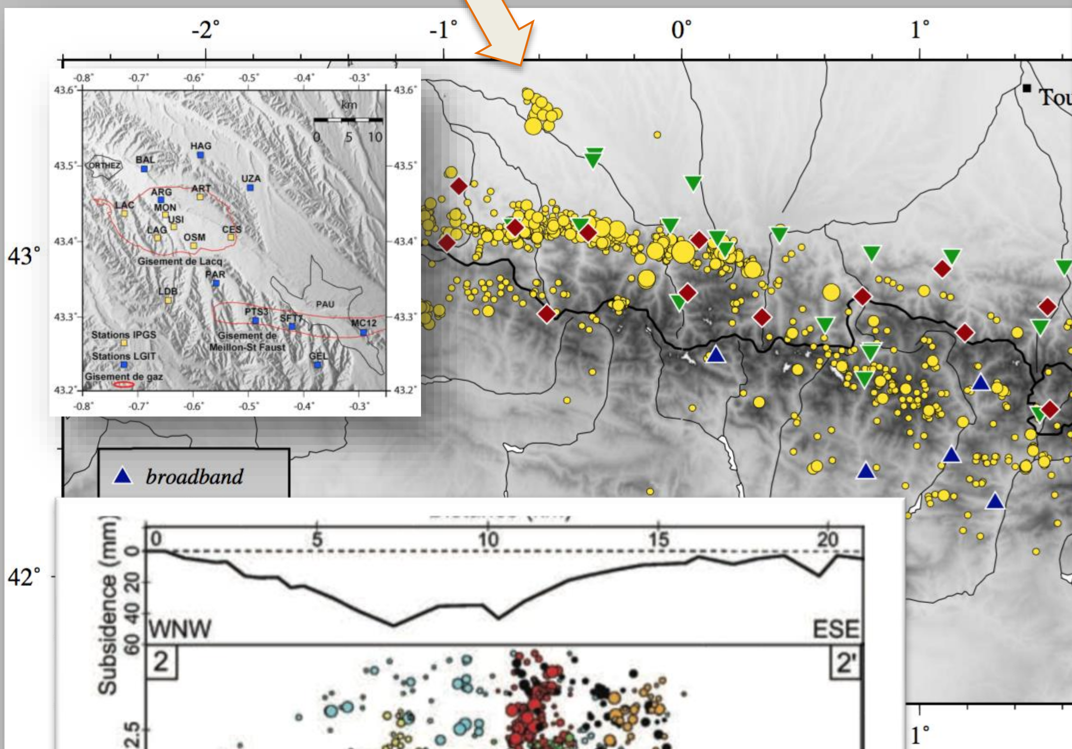
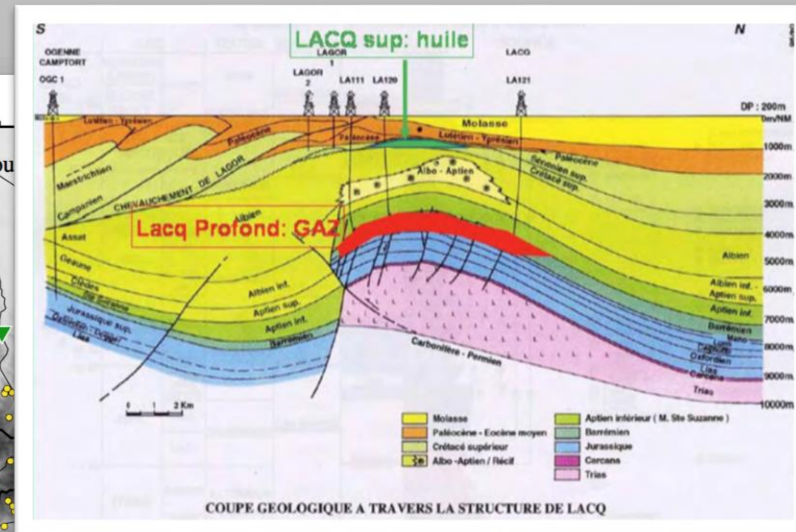
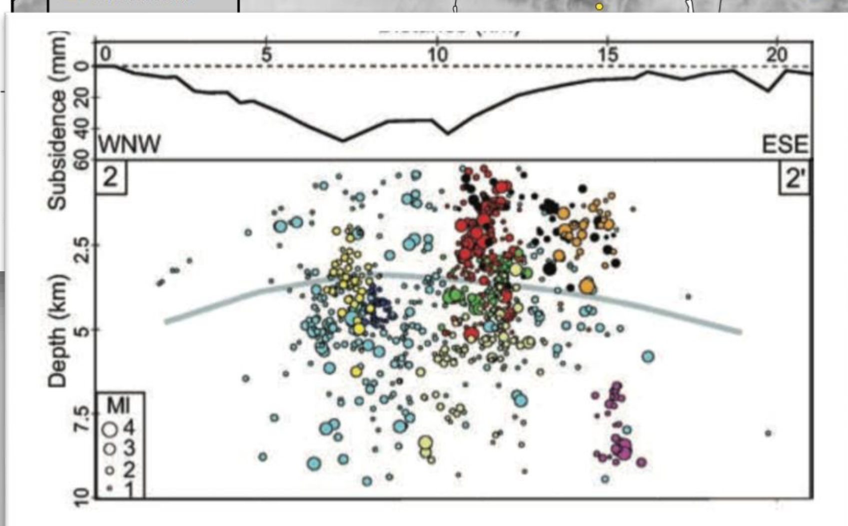
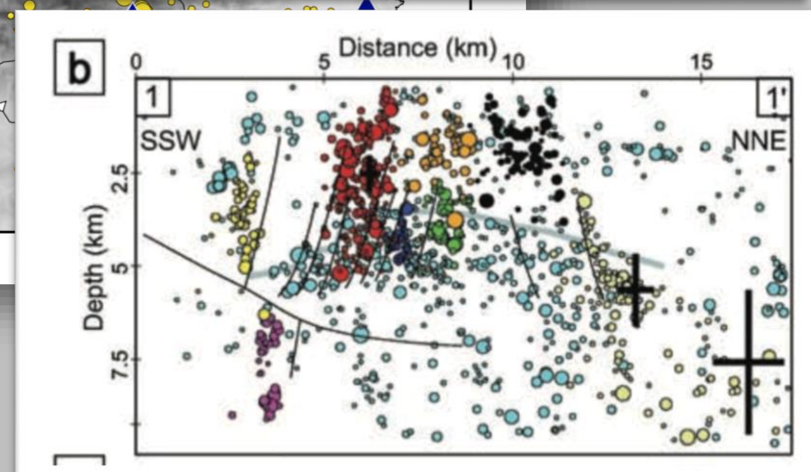




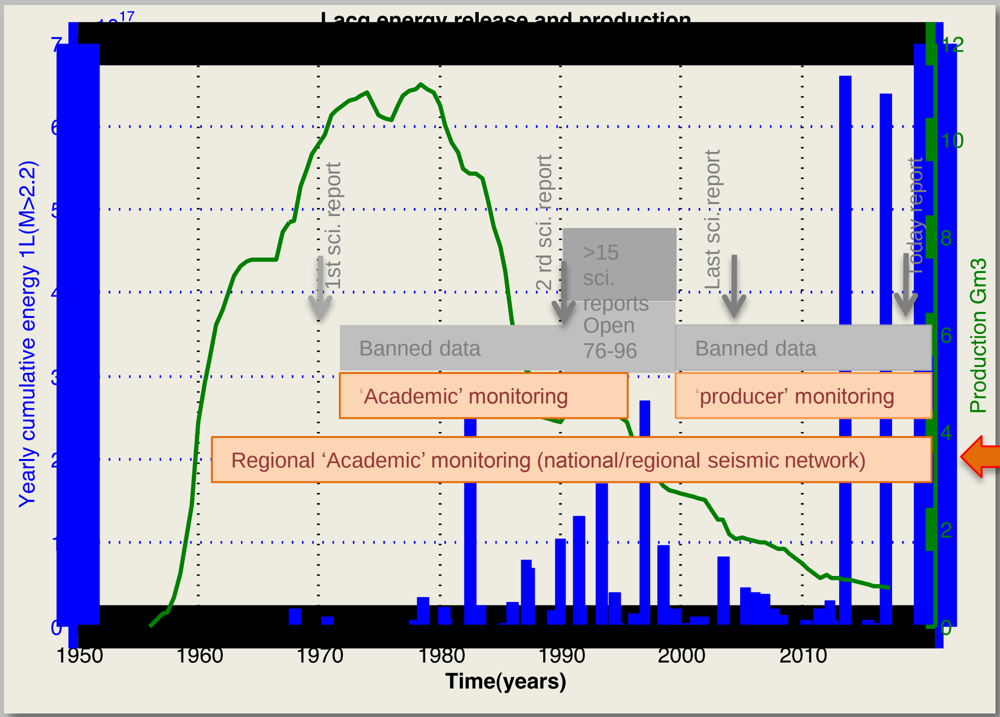




1976-1995 *bardainne et al GJI2008*

Long lasting seismic swarm and pore pressure decrease

(conventional gas production: Lacq, SW France (1969-2016)



SI-Hex data base (extended to 2016)
http://www.franceseisme.fr
Carra et al (2014)

This study
(1962_2016 data)

- Merging and aggregating seismic records (t_{obs}) in order to optimize location and magnitude => « homogeneous » magnitude over time

Local/regional monitoring – academic/producer monitoring

Close/open data set (seismicity, deformation, production)

EC-EPOS (2015-2019)-IP
WP14 Anthropogenic seismicity

Long lasting seismic swarm and pore pressure decrease

(conventional gas production: Lacq, SW France (1969-2016)

Data base :

- *completeness, robustness over time and space*
- *null hypothesis to compare with*

Observation :

- *production, pore pressure change*
- *Induced seismicity= f(Nbs, Magnitude, time, space)*
- *Regional Tectonic seismicity : endo- exo- genous interactions*

Mean field analysis:

- *<average> patterns*
- *susceptibility to forcing (field operation and earthquake)*

Possible Models and open questions :

- *seismicity onset*
- *seismicity history* — *f(oil-gas field operation) ?*
- *seismicity size*

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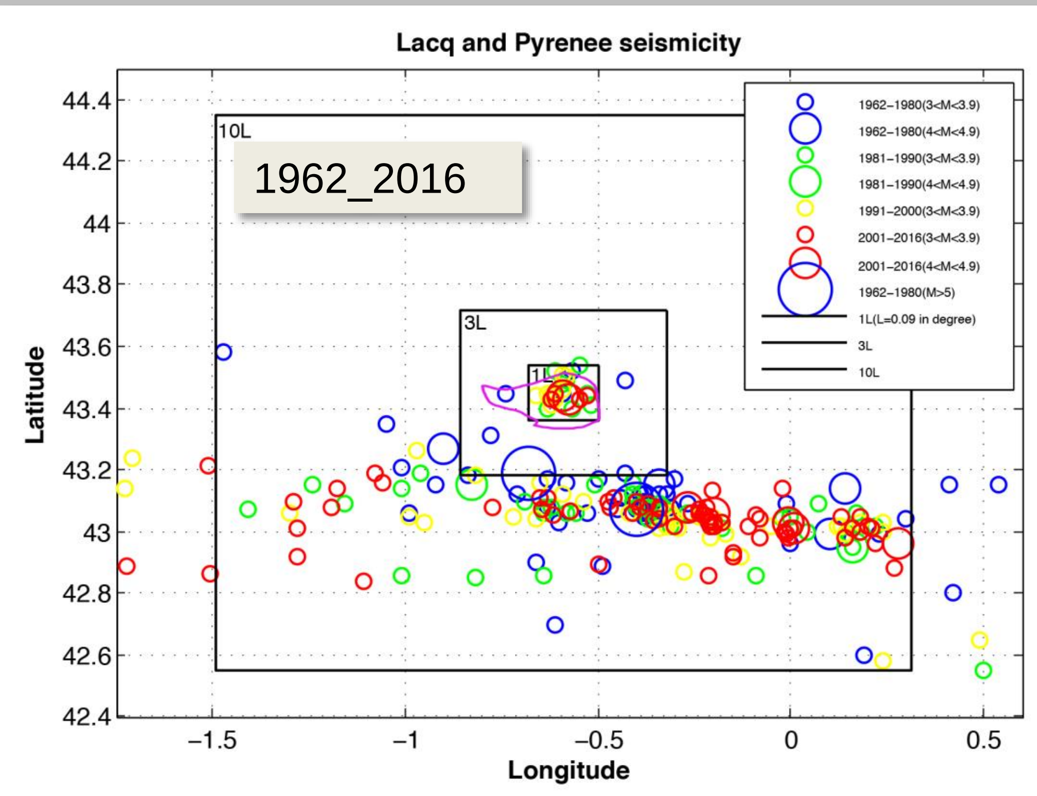
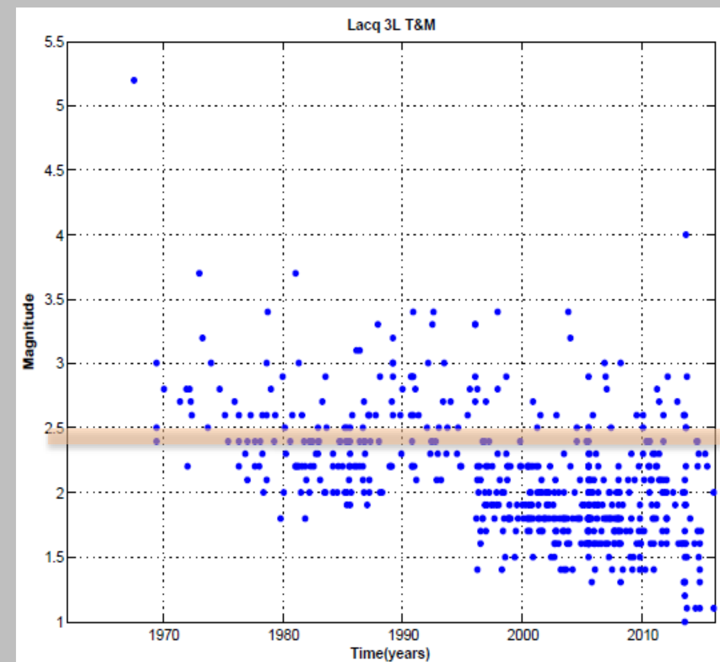
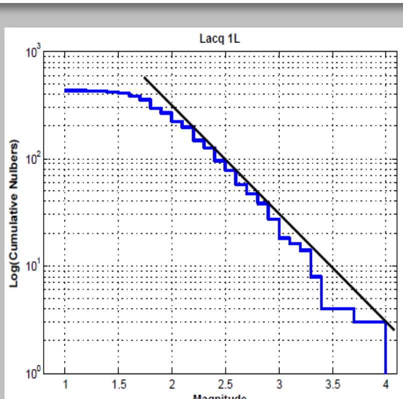
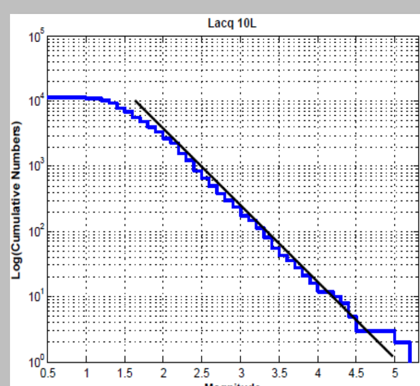
Seismicity Data: completeness and robustness over time





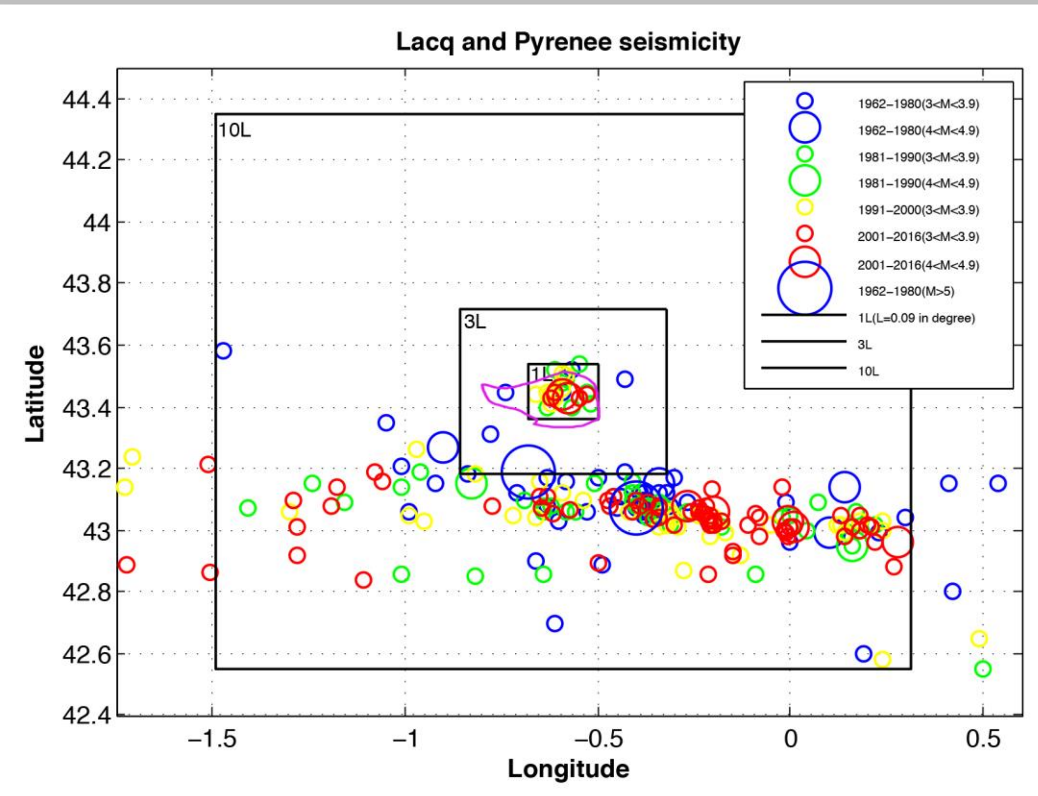
Evolution of network sensitivity over time



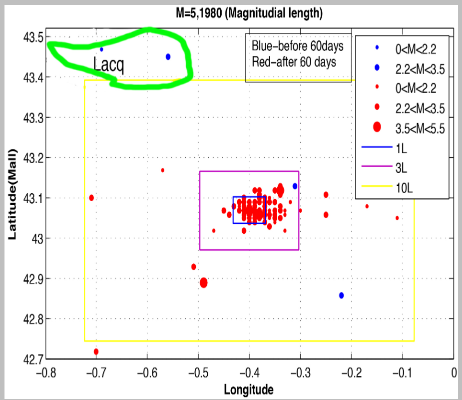


Null Hyptohesis, tectonic earthquake:
=> distance 10L
Lacq seismicity pattern:
=> distance 1-3L (near field)
(L: reservoir size)

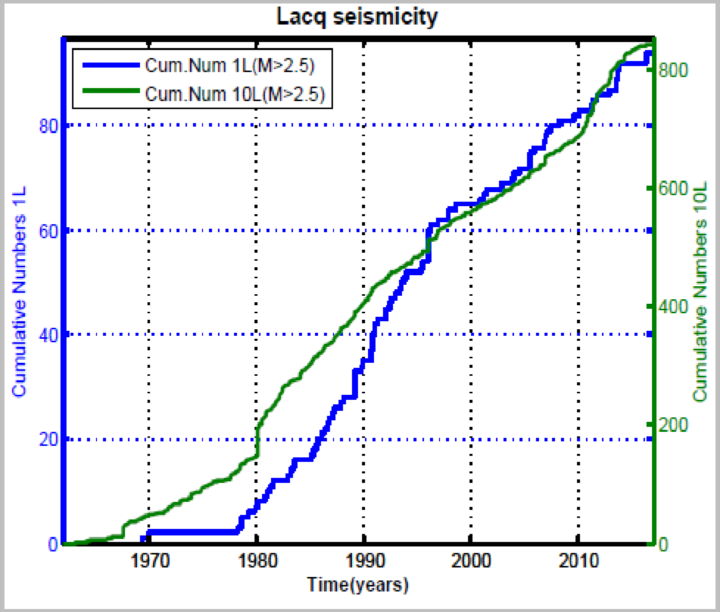
Seismicity Data: normalized distances



M : Fault length
-4 : 10 cm
-2 : 1 m
0 : 10 m
2 : 100 m
4 : 1 km
6 : 10 km



Tectonic aftershocks 1-3 L from mainshock



Null Hypotheses:

⇔ the reservoir acts as a (slow) mainshock and the triggered seismicity as aftershocks…

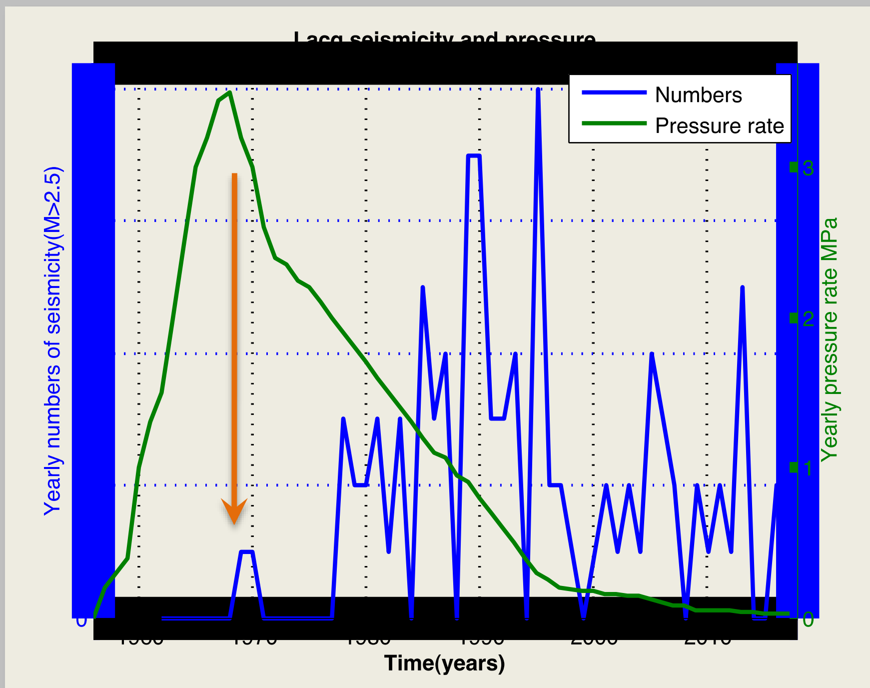
⇔ Tectonic quakes: distance 10L

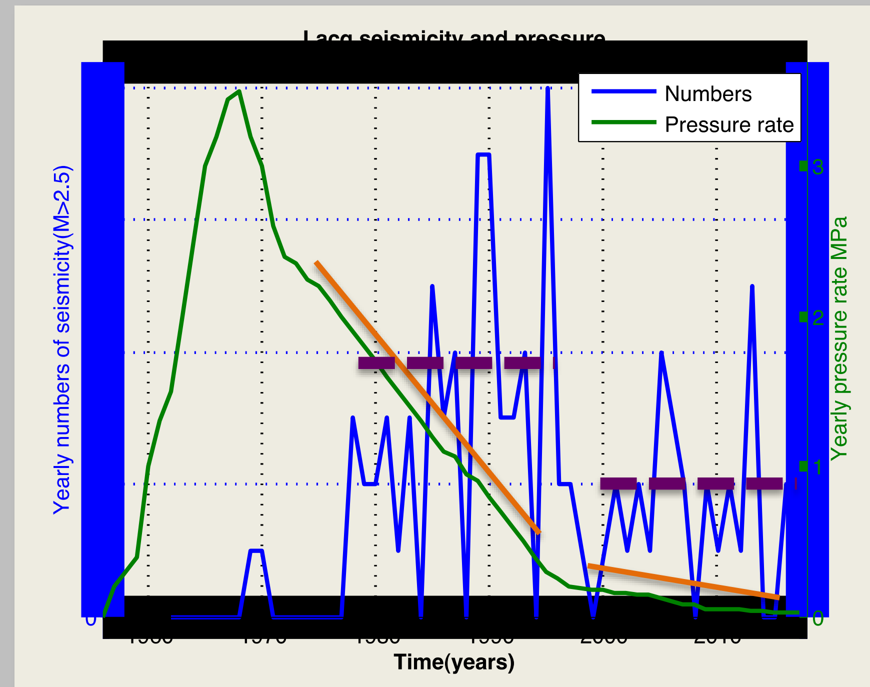
⇔ Lacq pattern : distance 1-3L

1970 - 1980 : ISR << TSR => ISR = sub-tectonic rate

1985 - 1995 : ISR > TSR = > ISR = super-tectonic rate

Observation: *pore pressure drop, seismicity rate*





Threshold response to stressing rate:
max stress rate ⇔ onset of seismicity ?

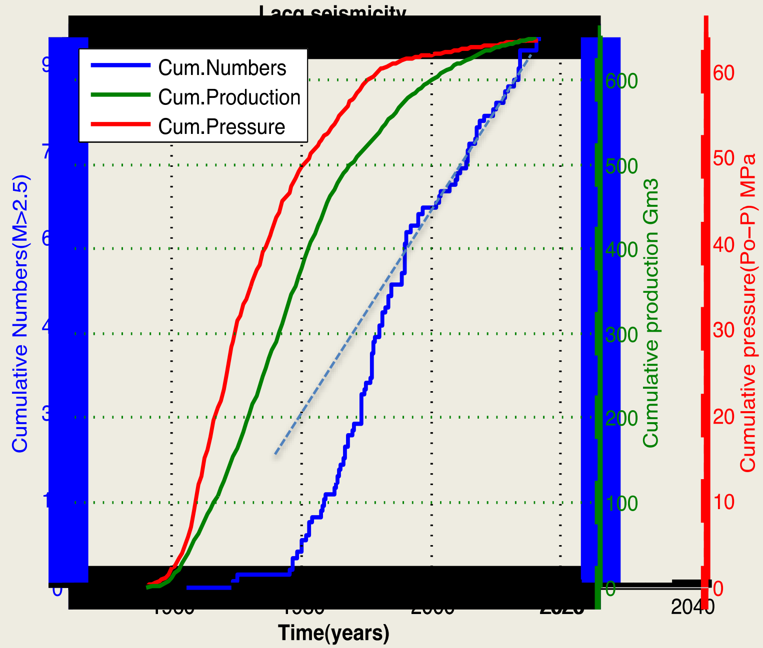
Seismicity rates and stressing rate :
$(\Delta N, \Delta p) / \Delta t_{(1985\text{-}1995)} > (\Delta N, \Delta p) / \Delta t_{(2000\text{-}2010)}$

Peak value $\Delta p/\Delta t$ 3.5 Mpa/yrs
$\Rightarrow$ $(\Delta\sigma/\Delta t)_{max}$ 0.01 Mpa/yrs (due to poro-elastic stress tranfer)
(Segall, 1989, Grasso, 1992, Segall et al 1994)

$\Delta p/\Delta t_{(1985\text{-}1995)} / \Delta p/\Delta t_{(2000\text{-}2010)} = 5$

$\langle \Delta N \rangle_{(1985\text{-}1995)} / \langle \Delta N \rangle_{(2000\text{-}2010)} = 2$

Observation: *pore pressure drop, production, seismicity*

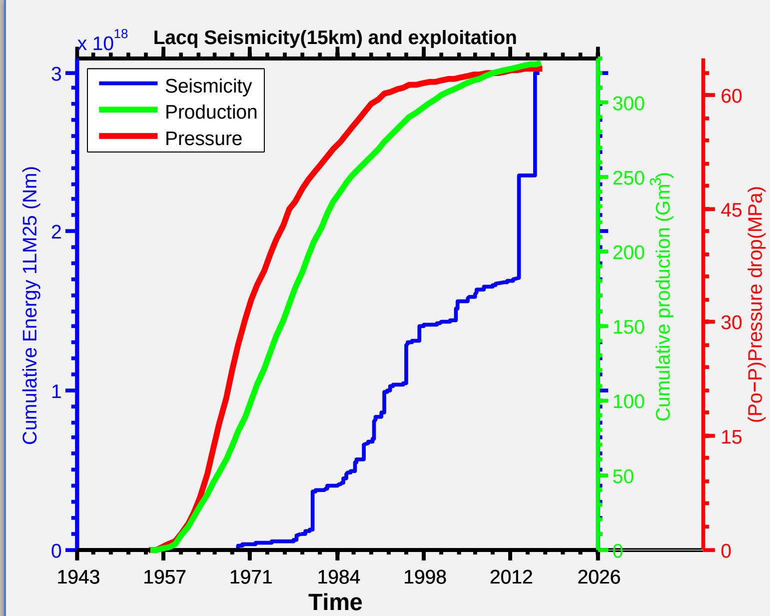


<=>

seismicity rates = f(stressing rate)
dN/dt = f(Δp/Δt)

seismic energy = f(?)

⇕



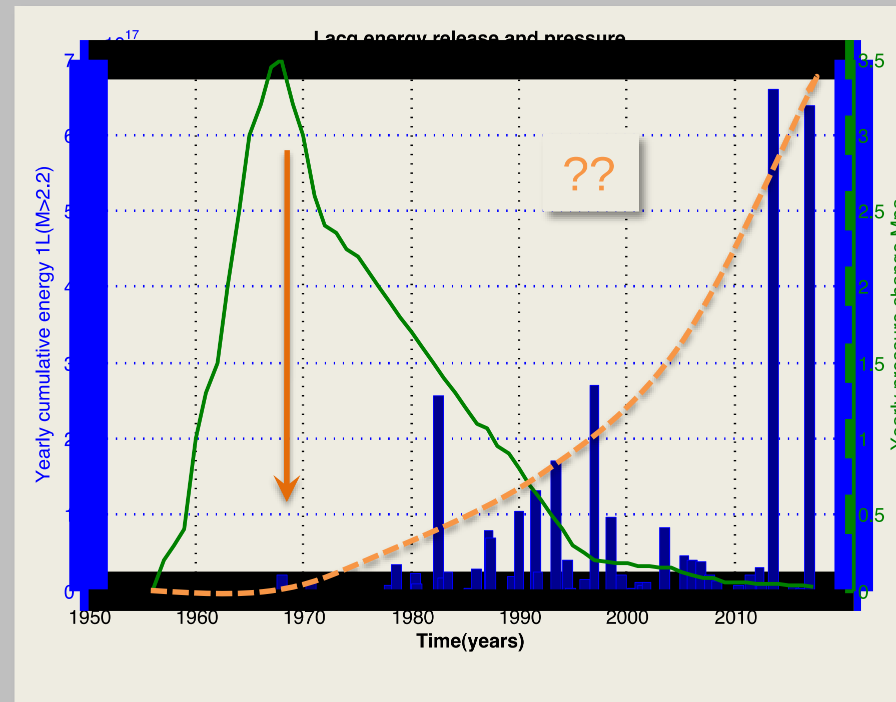
Depletion rate and production rate decrease
⇔ seismicity rate decrease

Observation: *pore pressure drop, seismicity*

Threshold response to poro-elastic stressing rate:

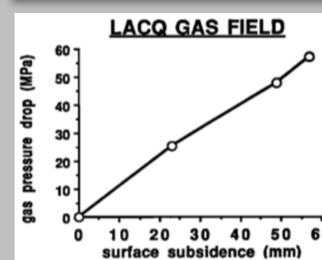
$(\Delta p/yrs)_{max}$ ⇔ onset of seismicity
Seismicity ⇔ non-deterministic cascading system ?

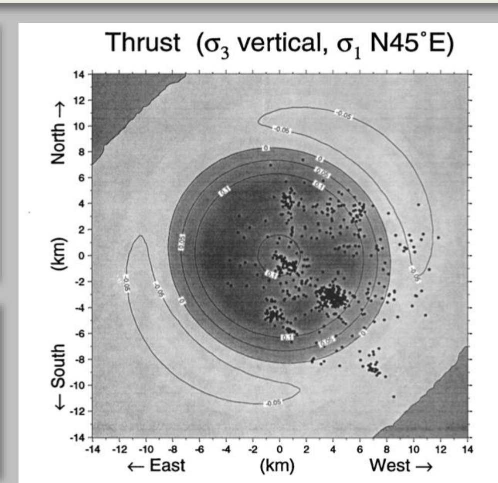
Impossible to understand/predict M_{max}=f(time) ?



Poro-elastic model
-succeed to predict eqs location i.e. the volume where stress changes ($\Delta\sigma^{+}_{max}$= 0.1 MPa)
- failed to control time–size patterns (M(t) and Mmax ?

Same context as tectonic earthquake:
we know the driving force (plate tectonic)…
But we fail to predict time size location of earthquakes

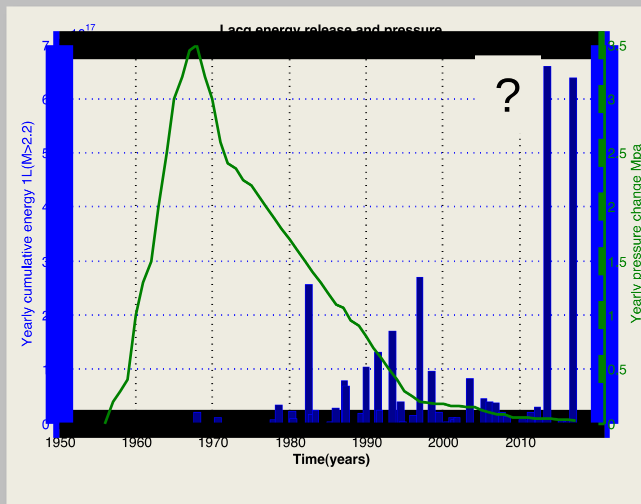


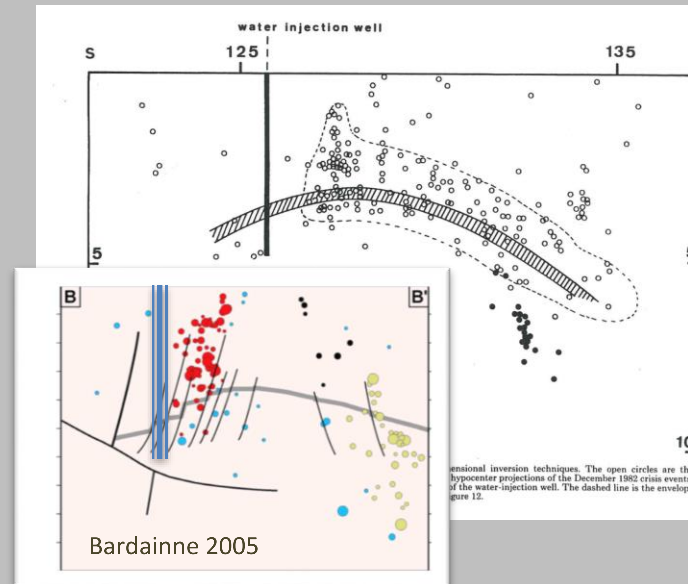


Lacq Poro-elasticity model
(Segall, Grasso, Mossop 1994)

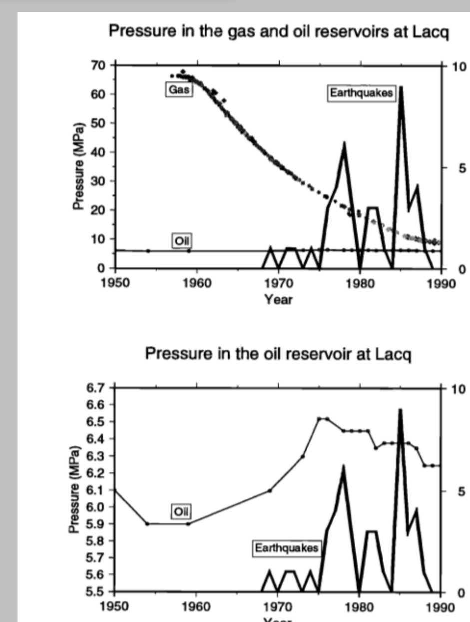
⇒ 90% of triggered seismicity within volume ($\Delta\sigma^{+}$)
⇒ $Area_{\Delta\sigma+}$ = control parameter for location similarly to mainshock- aftershock triggering

Complex interrelationships: production, pressure drop, injected volume / M_{max}





Grasso and Wittlinger BBSA90



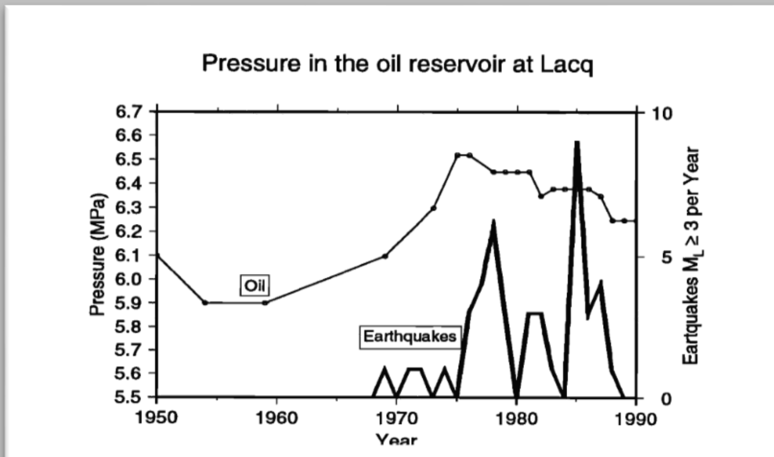
Segall Grasso Mossop JGR94

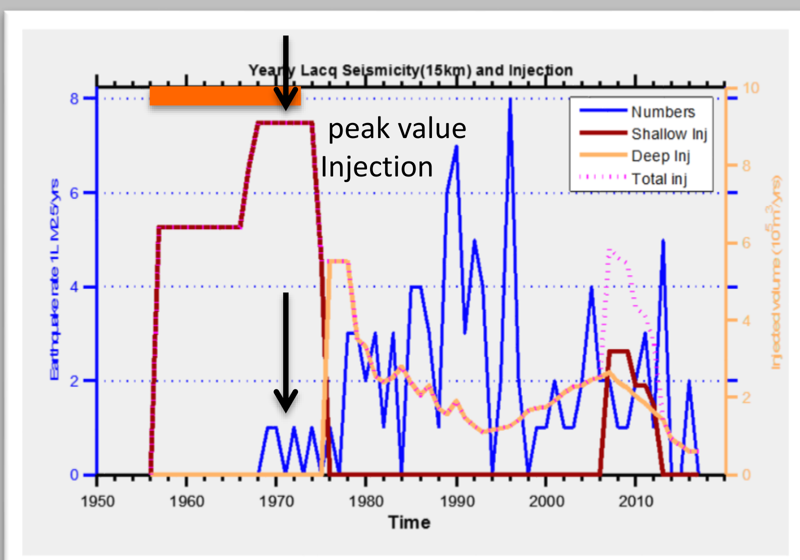
Injection was neglected/rejected as major driving the Lacq seismicity on the basis of too small pressure and volume changes and lack of comprehensive injection history.

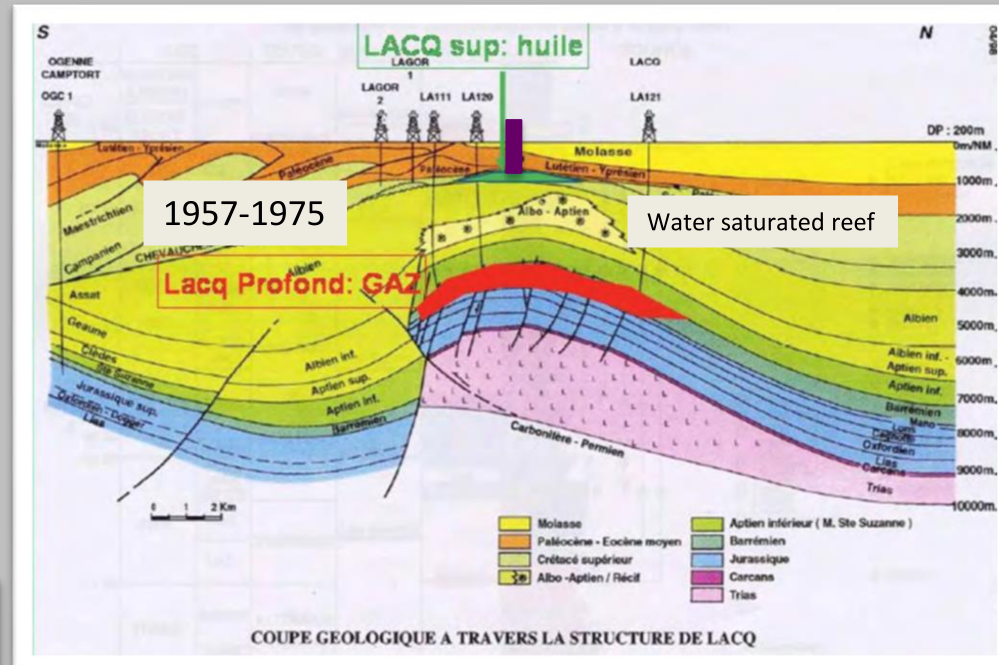
(e.g., Grasso and Wittlinger BBSA90, Maury et al. EG1992, Segall et al. 1994, Lahaie and Grasso 1999, Bardainne et al. 2008)

Complex interrelationships: production, pressure drop, injected volume / seismicity

Waste water disposal history: Shallow injection





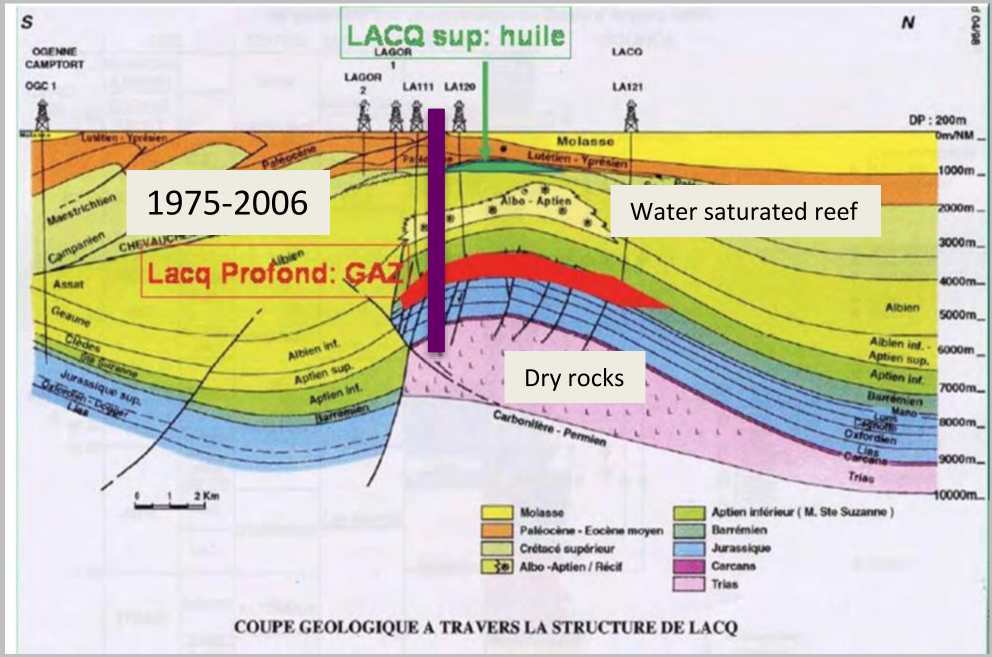


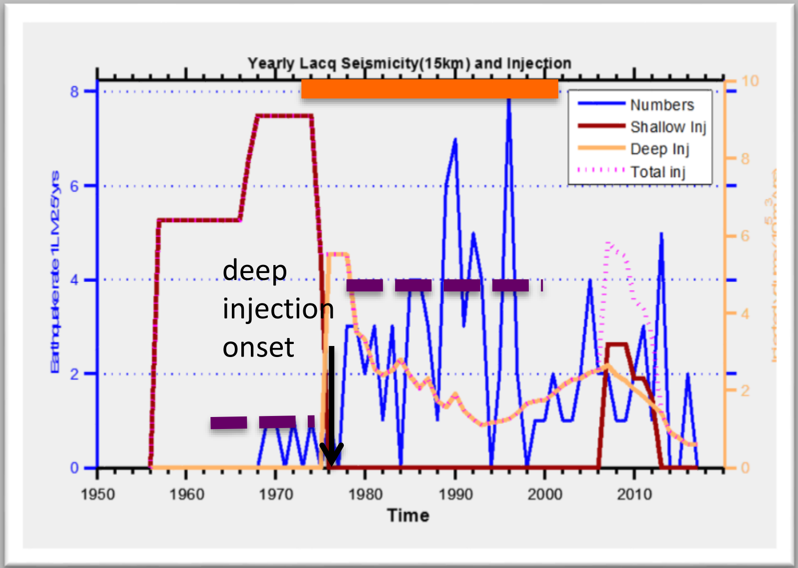
1967-1974: peak value for shallow injection
1969: onset of seismicity

Δp_{max} = 0.6 Mpa 1975 injection
$\Delta\sigma_{max}$ = 0.1 Mpa 1975 poro-elastic stressing

Complex interrelationships:
production, pressure drop, injected volume / seismicity

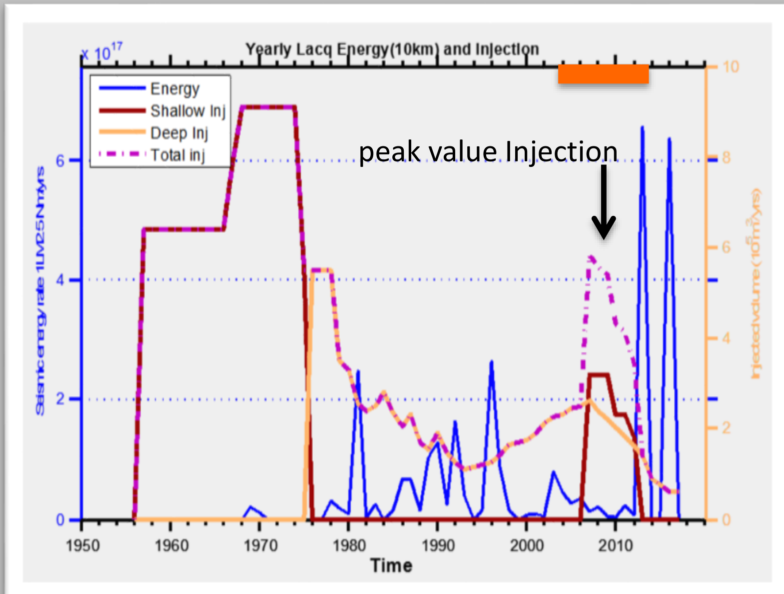
Waste water disposal history:
deep injection



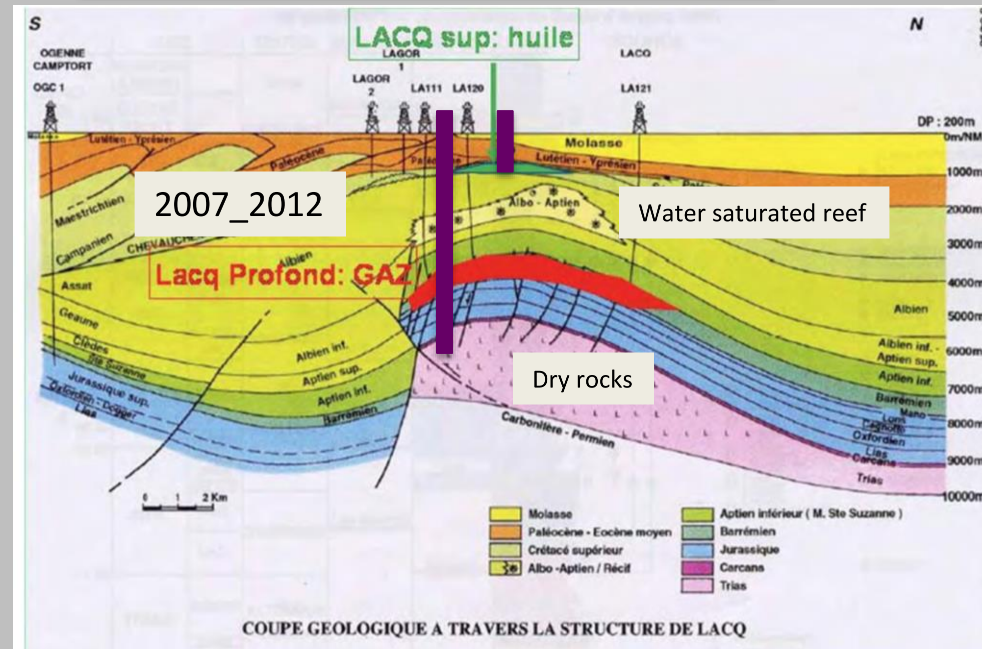


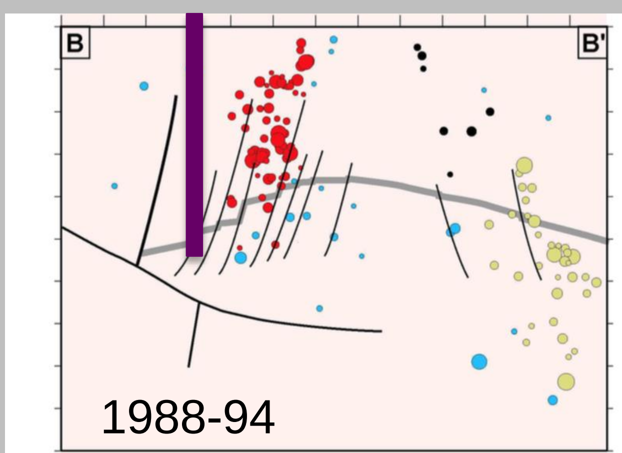
1975: onset of deep injection
1978: increase of seimicity rate

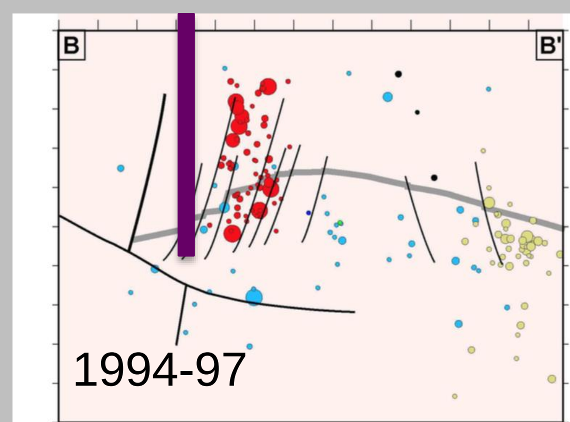
Complex interrelationships:
production, pressure drop, injected volume / seismicity



Waste water disposal history: deep + shallow injection



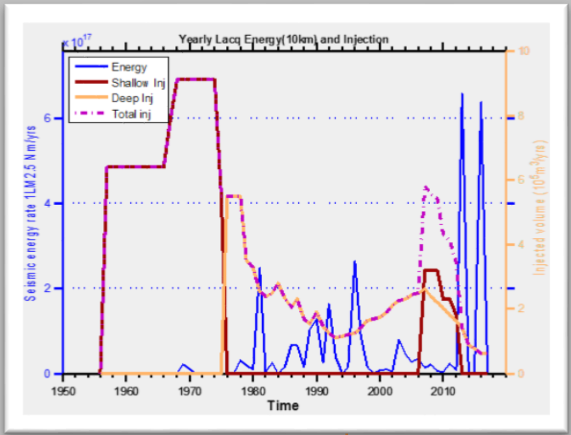


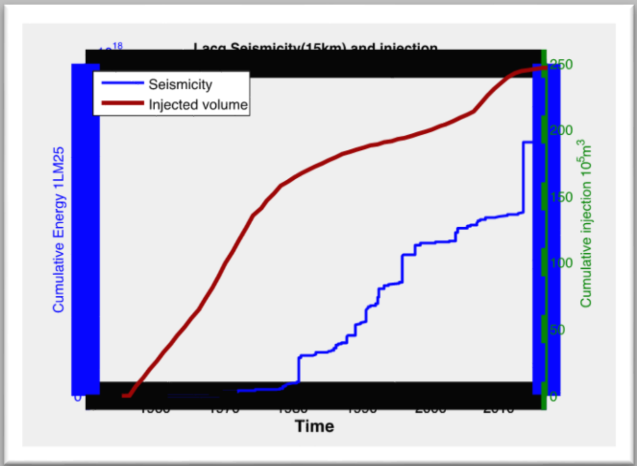


2006-2012:
deep + shallow injection
2013-2016:
M_{max}=4 (depth=7 km)

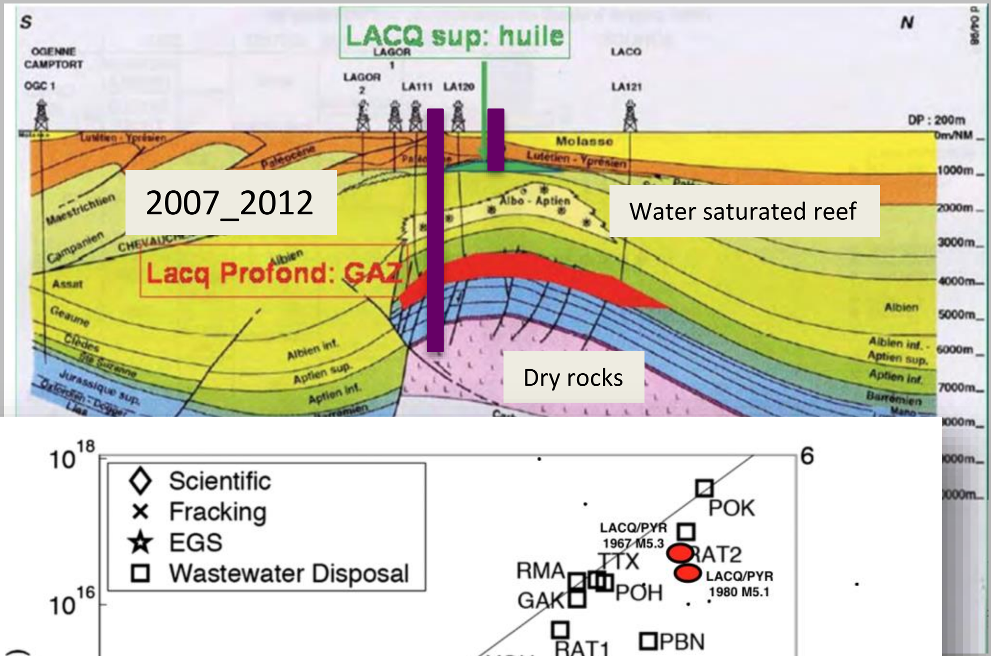
Data from bardainne 2005

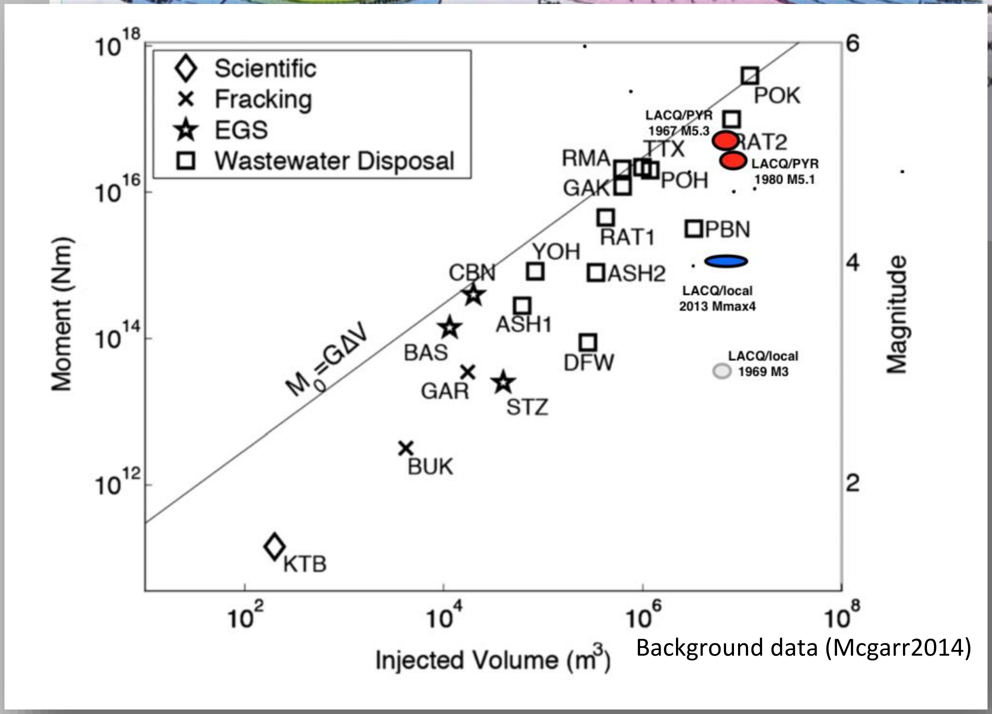
Complex interrelationships:
production, pressure drop, injected volume / seismicity





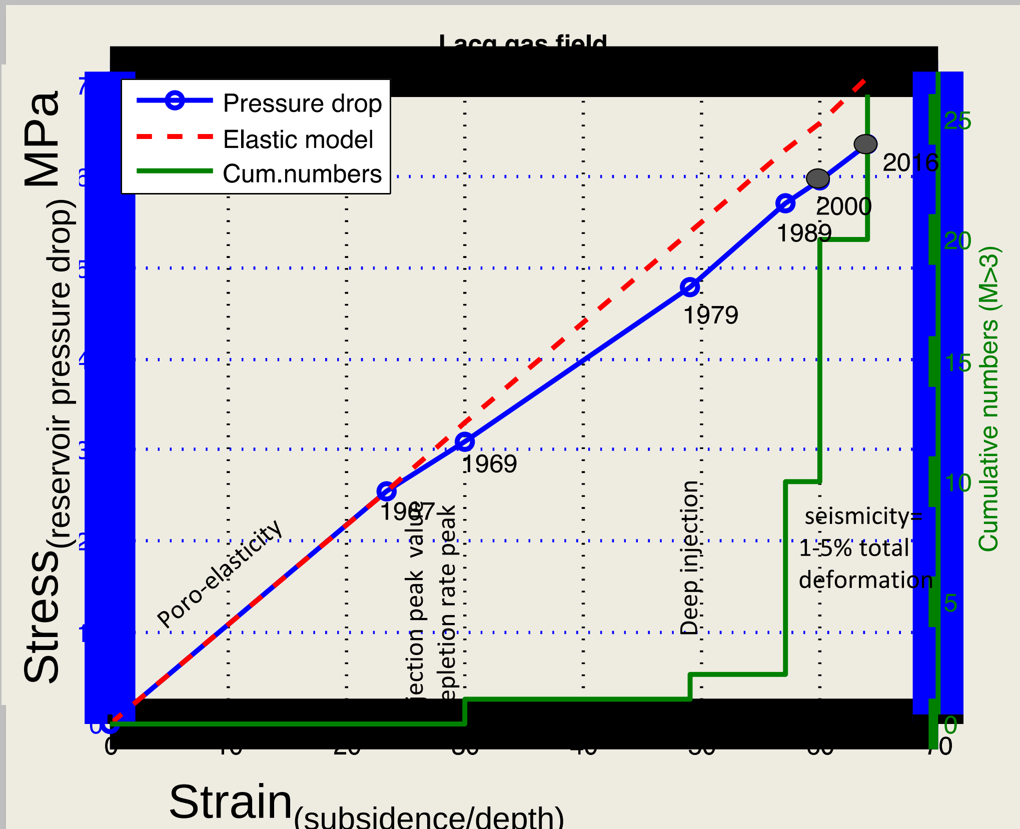
1957-2012 volume =
« Oklahoma- like » volumes





Background data (Mcgarr2014)

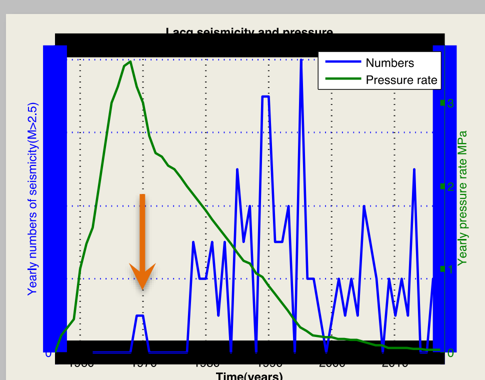
Trigger mechanics (conceptual)

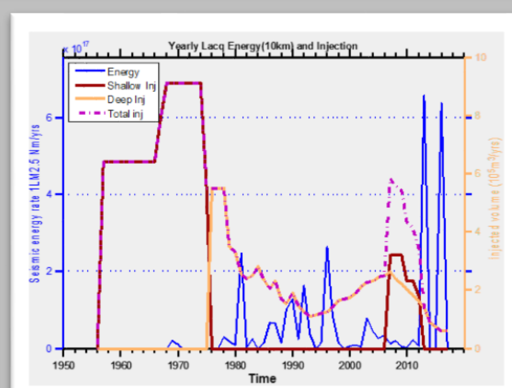


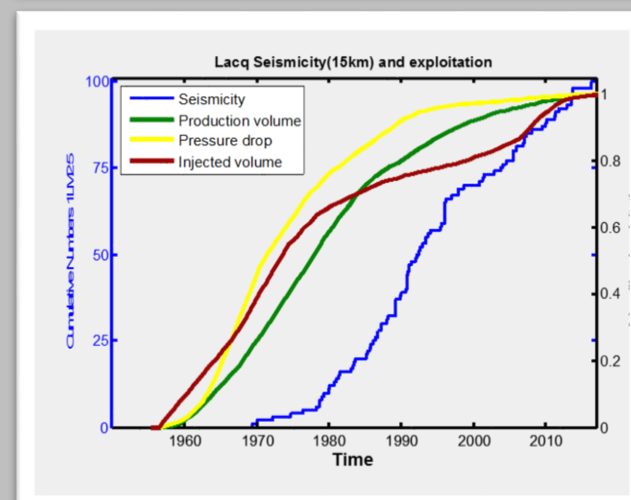
a) 1969: first earthquake as signature of departure from elastic response
= Onset of (seismic) brittle damage
- 1967 injection peak value
- 1969: $P_{reservoir} = P_{(hydrostatic)}$ at reservoir level
-1969 = peak value of $\Delta P/\Delta t$

b) 1975: onset of deep waste water injection, and change in depletion rate => seismcity rate change

c) 2007-2012: Deep + shallow injection
2013-2016 : Mmax=M4

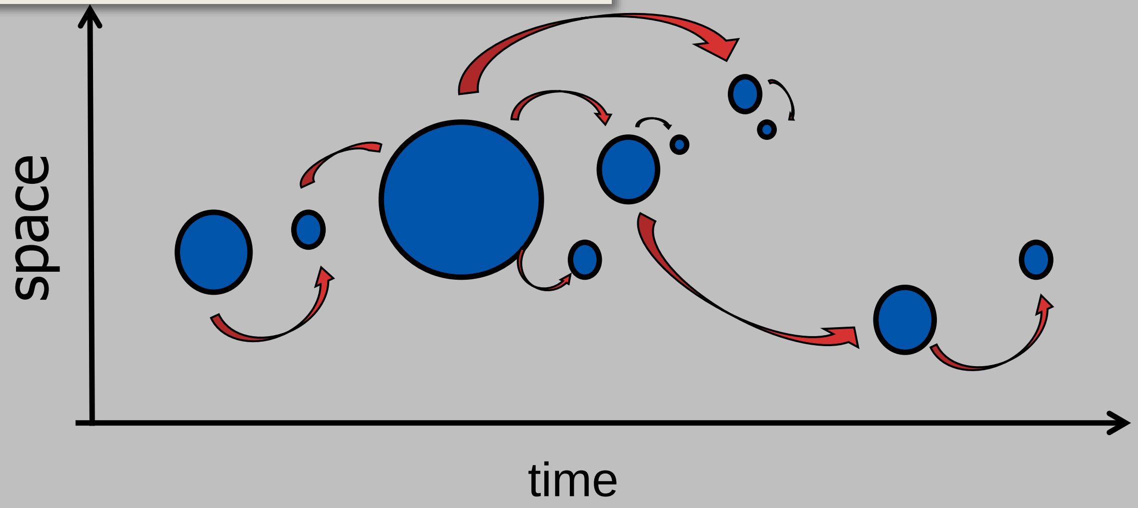


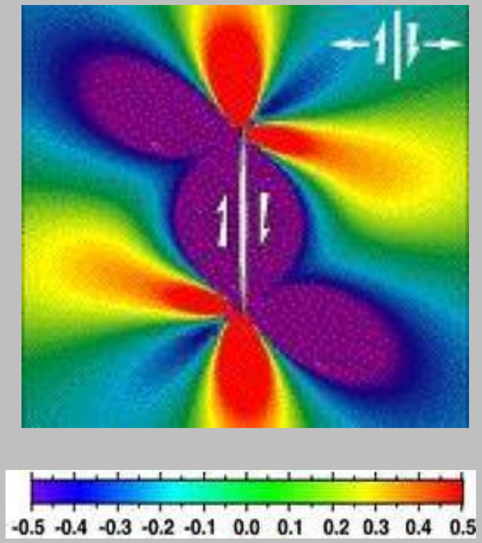




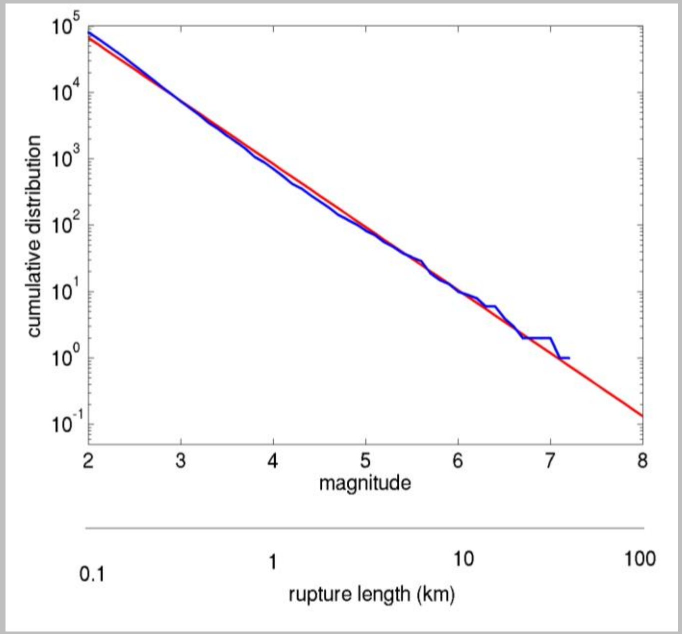
Tectonics and Anthropogenic seismic instabilities: M_{max}

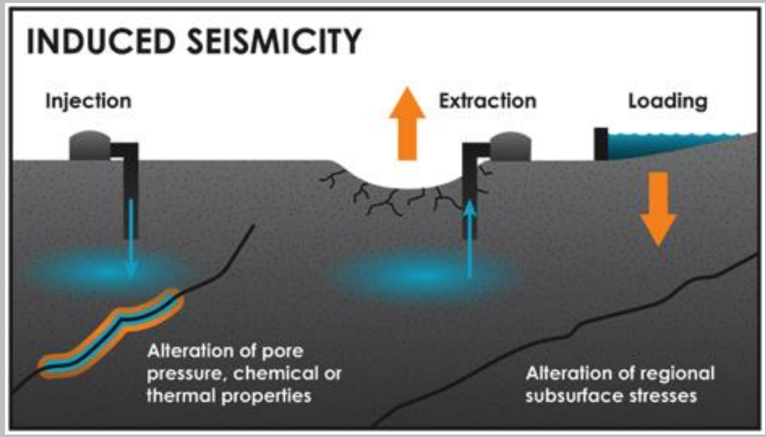
Tectonic earthquake framework





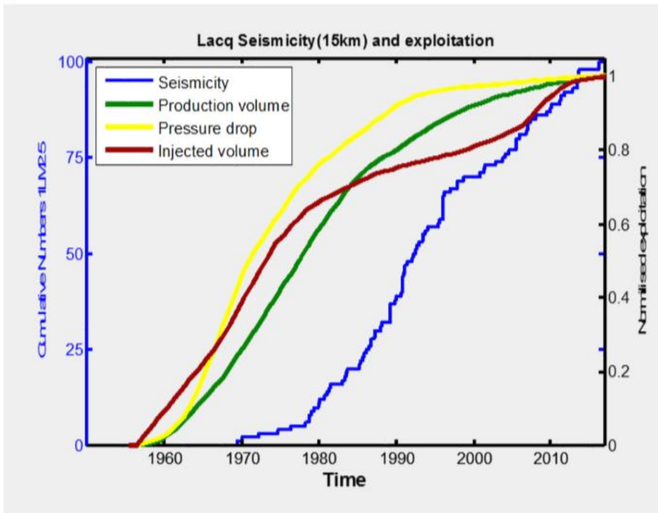
stress change (bar)





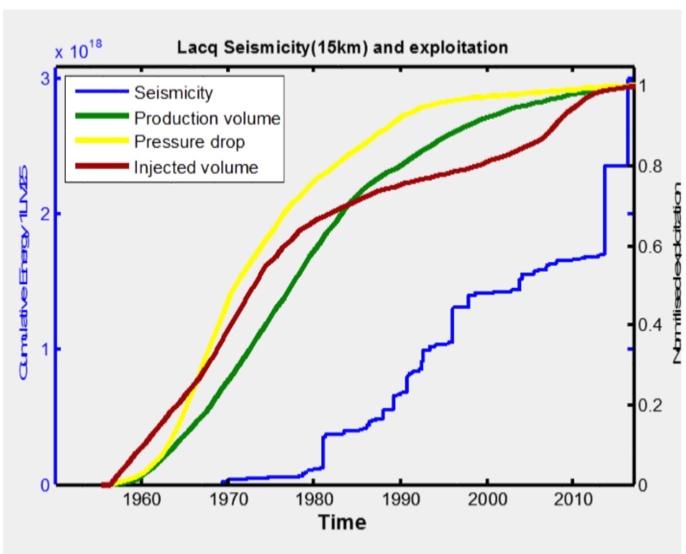
Anthropogenic earthquake framework

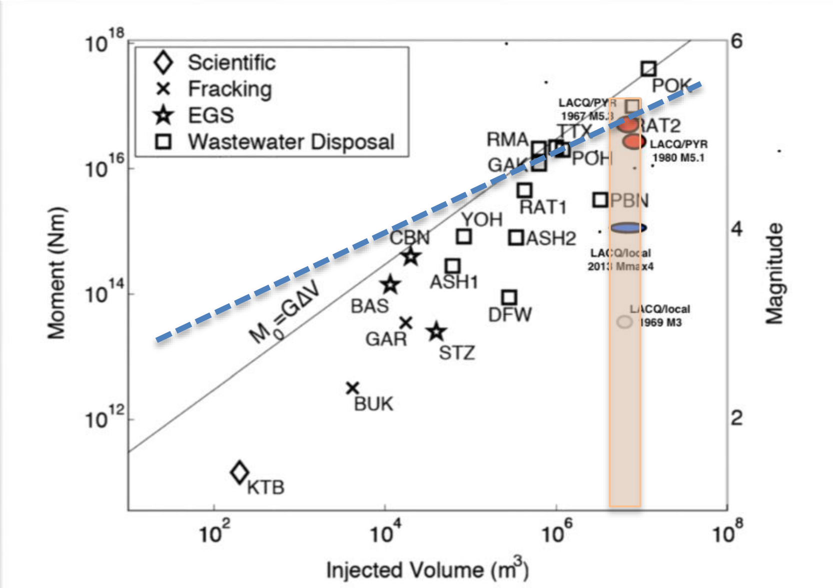
Production, pressure drop, injected volume / M_{max}



M_{max}: ?

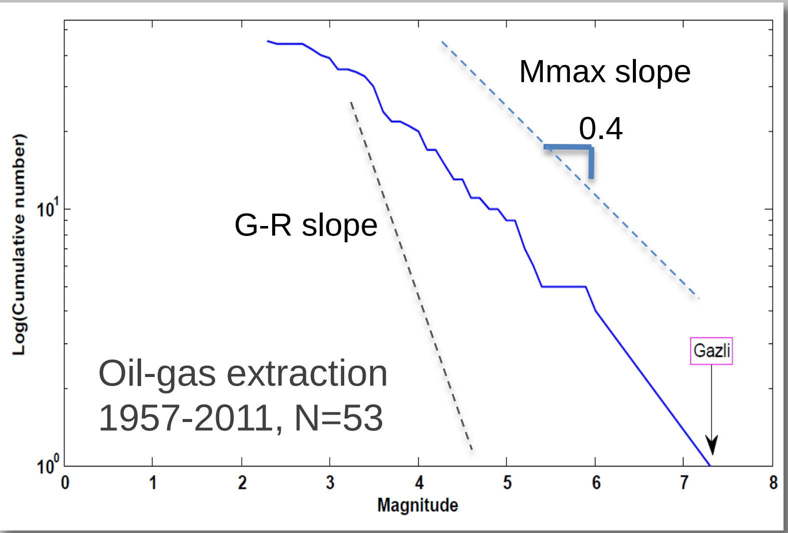
$M5^{+}$: As derived from injected volume





M_{max} distribution from conventional oil-gas extraction (world wide picture)

M_{max} frequency distribution



This is not a G-R distribution
(Mmax on different site)

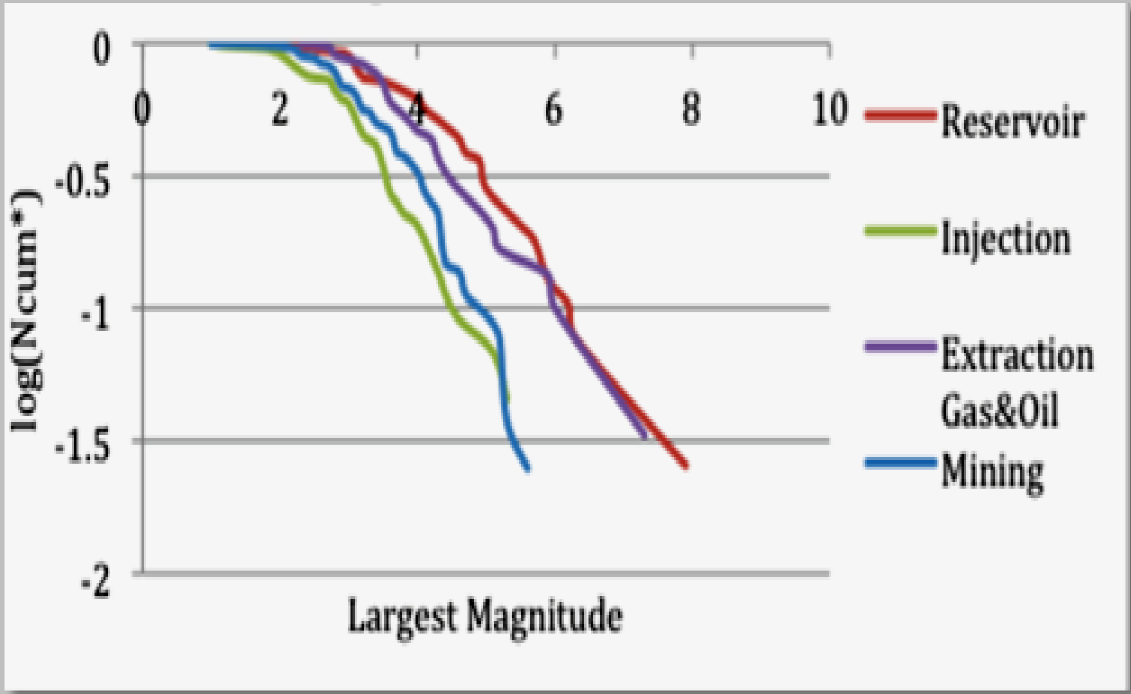
G-R distribution:
all earthquakes on given area

M_{max} distribution:
sampling M_{max} on different site
(e.g. record distribution,
Anderson et al. 2004, Krug 2007)

⇒(Power law) distribution of M_{max}
- Possible time independent M_{max} size prediction (before production starts)
- which control parameters for such a distribution (work in progress)

M_{max} distribution and geo-resource production types

Normalized frequency distributions

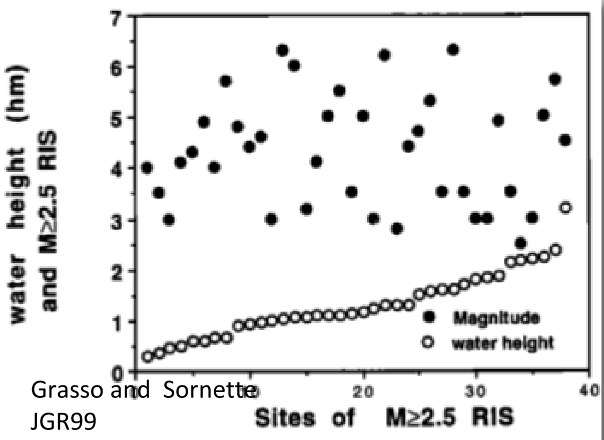


Modified from Davies et al 2014 data base

Impacted Area ($\Delta\sigma^+$)
for reservoir: 100 km^2

Impacted Area ($\Delta\sigma^+$)
for mining (and injection)
< 0.01-0.001 km^2 + fluid diffusion

Area $_{(\Delta\sigma +)}$ controls M_{max} rather than $\Delta\sigma^+$ value
(similarly to tectonic earthquake)



Grasso and Sornette
JGR99

Long lasting seismic swarm and pore pressure decrease

(conventional gas production: Lacq, SW France (1969-2016)

Production start : 1959

Seismicity Onset : 1969

peak value of $(-\Delta p/\Delta t)$ extraction

peak value of $(+\Delta p/\Delta t)$ injection

Production rate - depletion rate - seismicity : 1990-2010

N(t) decreases as production-pressure decreases

$(-\Delta p/\Delta t) \Leftrightarrow \langle \Delta N/\Delta t \rangle$

Eqs location: predicted by poro-elastic $\Delta\sigma^+$

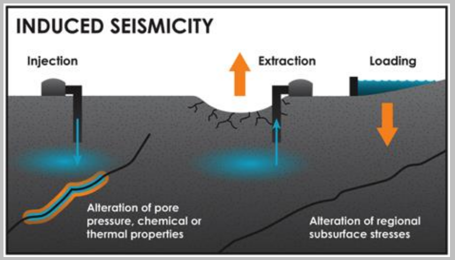
M_{max}: 2013-2016 M4,M4 ….(Injection driven)

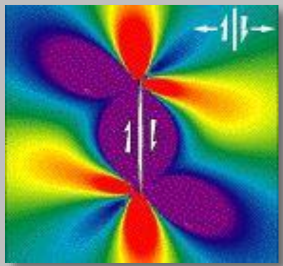
Aftershocks at the reservoir scale only:

$L_{reser.} = L_{M6}$, i.e. reservoir depletion as a slow MS)

Induced Rate / Tectonic rate => classification for IS

- M_{max} distribution bounded by perturbated volume size)





Data available on

EC-EPOS (2015-2019)-IP
WP14 Anthropogenic seismicity

QUAND L'HOMME FAIT TREMBLER LA TERRE

SCIENCES

L'exploitation du gaz de Lacq provoquerait des mini-séismes

Les étranges tremblements de terre des Landes

Plus de 800 secousses, certaines assez importantes, ont ébranlé la région depuis 20 ans. Une enquête, restée secrète depuis 1982, met en cause l'exploitation du gisement de gaz.

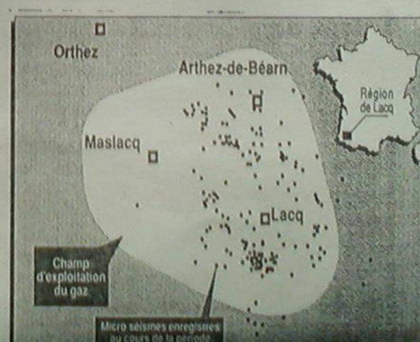
Le 24 novembre 1969, une première secousse sismique ébranle la région de Lacq (Pyrénées-Atlantiques). Magnitude : entre 3 et 4 sur l'échelle de Richter (1). Un an passe, avant un second séisme. Cette fois-ci, magnitude 4,2. Puis les secousses sismiques se multiplient, une en 1971, une la veille du jour de l'an 1972. Inquiétude au ministère de l'Industrie : la petite ville de Lacq doit sa notoriété au gaz du même nom, exploité par la compagnie Elf-Aquitaine, pas aux tremblements de terre. On

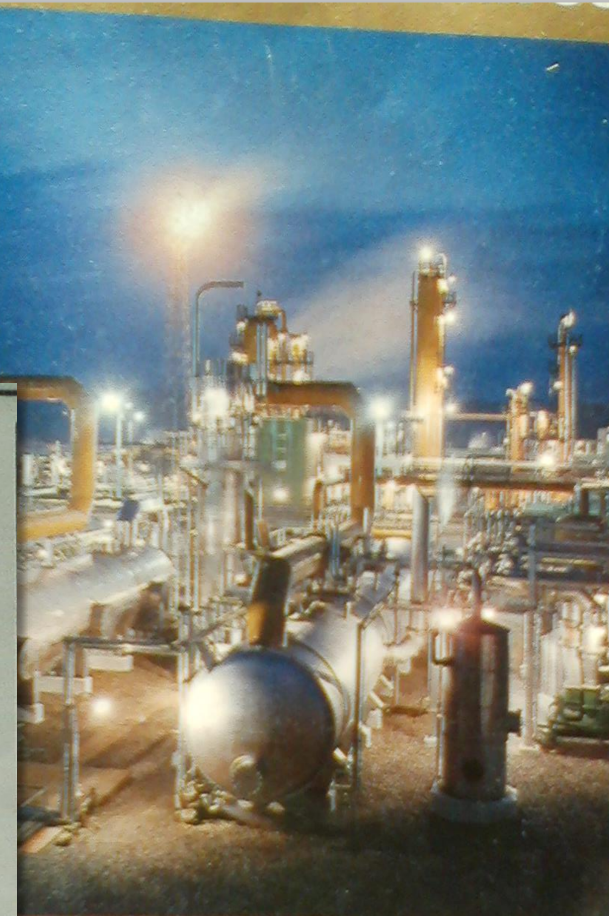
rasienne. Cette faille est une des plus actives de France, quand en 1967 un petit village proche de Lacq a tremblé, on a compté un mort, une quinzaine de blessés, et soixante-deux communes des alentours ont ressenti la secousse.

Mais si à la surface un tremblement de terre crée du désordre, le travail des failles répond en profondeur à des lois géophysiques précises. Or, en ce qui concerne Lacq, les géophysiciens sont d'abord restés perplexes, rien n'expliquait que la ville soit ainsi

des années 1980, le ministère de l'Industrie et Elf-Aquitaine ont appris que ces tremblements de terre étaient « artificiels », c'est-à-dire en relation directe avec l'exploitation du gisement, et qu'à l'époque personne ne pouvait prévoir l'évolution du problème, aucune information publique n'a filtré pour autant. Aujourd'hui encore, la direction générale d'Elf-Aquitaine ne désavoue pas l'étude, mais « *ne souhaite pas s'exprimer publiquement sur le sujet* ».

Les phénomènes de trem-





...lusif A Lacq, Elf ...trembler la terre

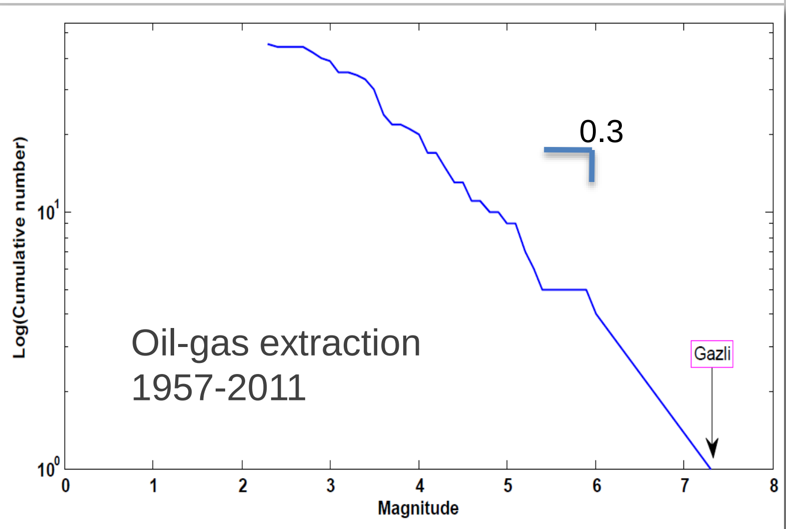
...sation" or "fault" attaching to an earthquake. The court cases ...lving earthquakes and liability deal almost exclusively with two ...tions: whether the damage resulted from faulty construction or ...her the damage was covered by insurance. The parties do not ...ion the "cause" of the earthquake.

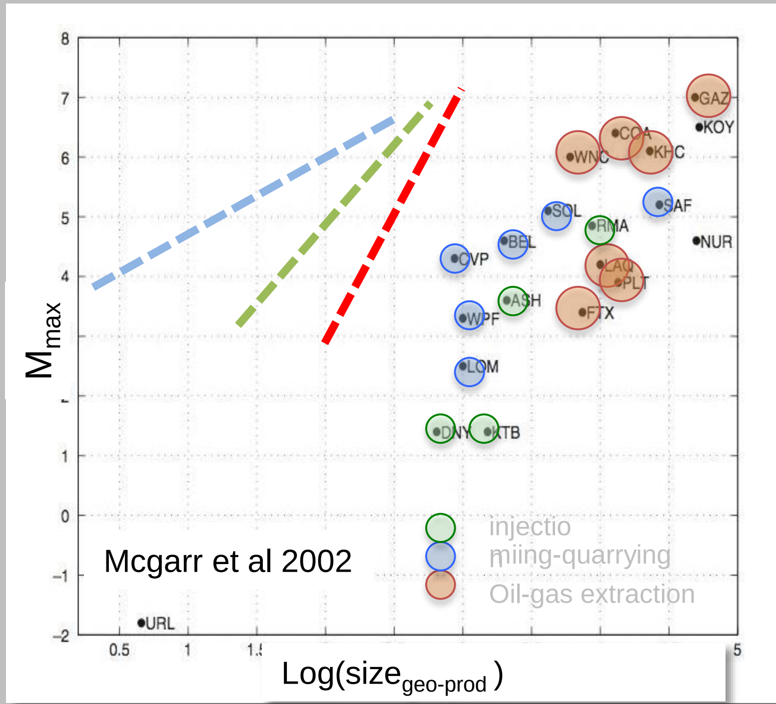
There are a few reported federal cases that mention the possibili... earthquakes being caused by reservoirs, waste injection wells or ...sions. In these cases the courts were reviewing nuclear power plant licensing procedures and the adequacy of environmental impact statements for dams and nuclear weapons tests. The Oklahoma Supreme Court also once reviewed the permit for a salt water ... the plaintiff believed the well would increase

schatzalp-17

M_{max} distribution and geo-resource production type

M_{max} frequency distributions





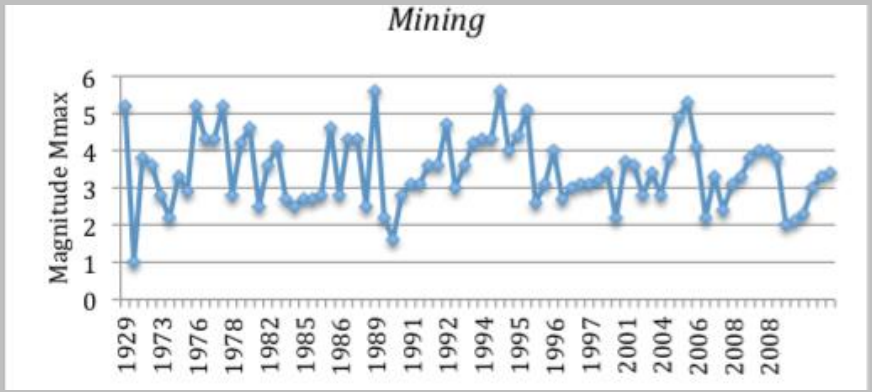
- M_{max} driven by the size of perturbated area ($\Delta\sigma$) , rather than $\Delta\sigma_{max}$ value

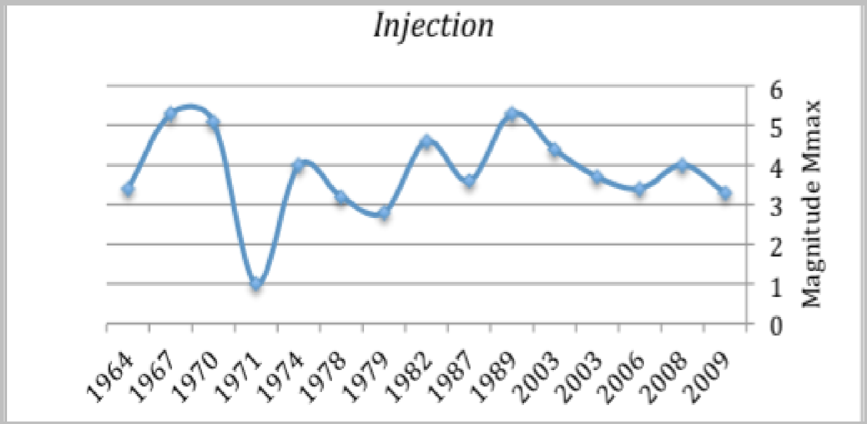
- The larger the area where the stress changes,
  => the larger the triggered earthquake rate
  => the largest the possible M_{max}

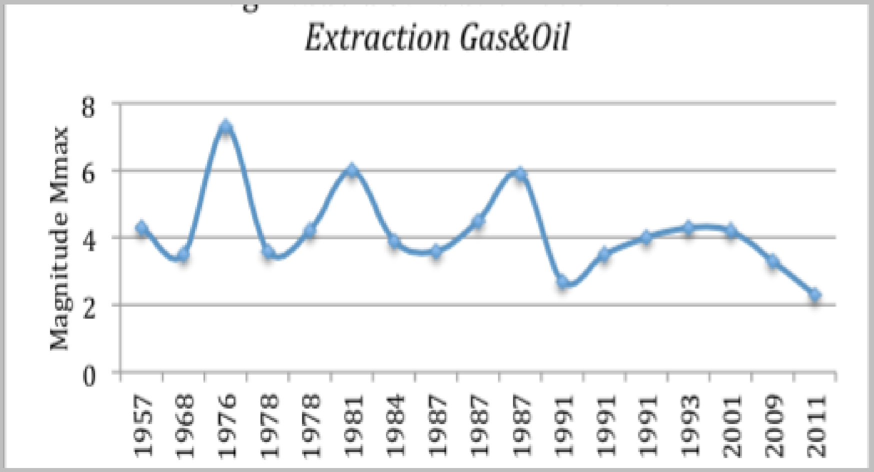
- Anthropogenic events as aftershocks of geo-resource production

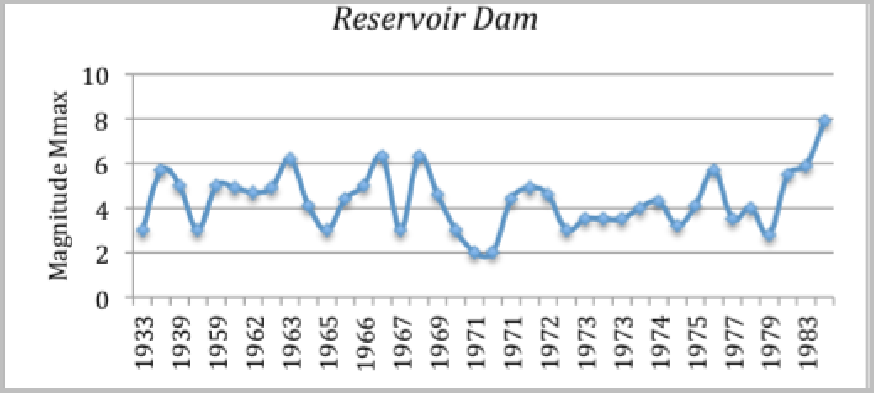
(in the same framework as tectonics eqs (e.g. $N_{after} = 10^{-bM}$, $M_{max} = M_{ms}$- cte))

M_{max} for induced seismicity: Worldwide pictures









Modified from Davies et al 2014 data base

→On each site : Mmax → sorted by geo-resource exploitation types
→we define 4 categories :
Mining, *Injection (all types)*, *Gas&Oil Extraction*, *Reservoir Dam*

séisme = rupture/glissement d'une faille

glissement sur la faille et magnitude (M) :

- M = -4 : glissement de 0,003 mm
- M = -2 : glissement de 0,03 mm
- M = 0 : glissement de 0,3 mm
- M = 2 : glissement de 3 mm
- M = 4 : glissement de 30 mm
- M = 6 : glissement de 300 mm

Ressenti

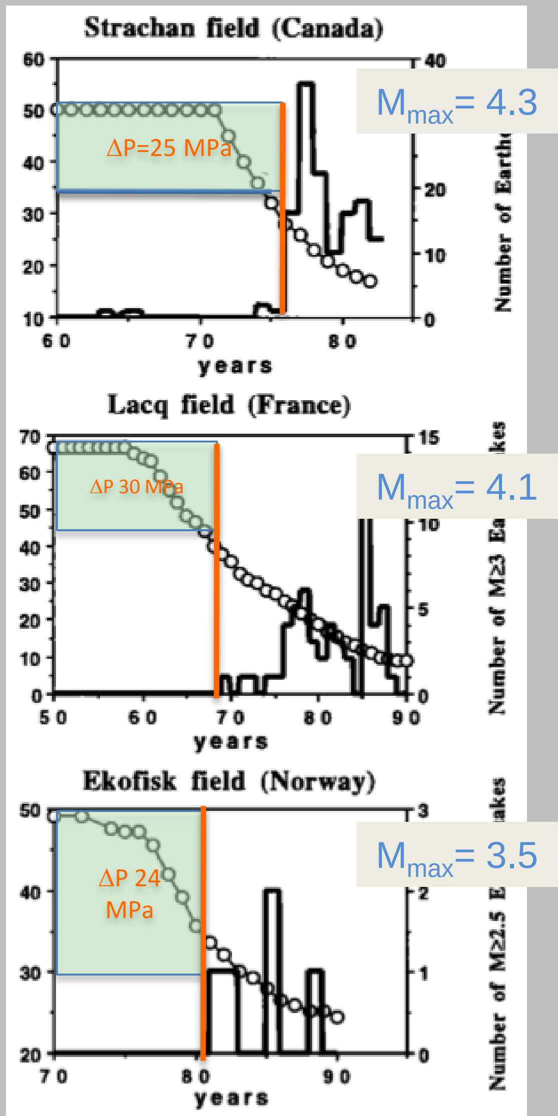
longueur de la faille et magnitude (M) :

- M = -4 : faille de 10 cm de long
- M = -2 : faille de 1 m de long
- M = 0 : faille de 10 m de long
- M = 2 : faille de 100 m de long
- M = 4 : faille de 1 km de long
- M = 6 : faille de 10 km de long

Ressenti

Trigger mechanics (conceptual)

Reservoir Pressure



time

Poro-elasticity model
(Segall, Grasso, Mossop 1994)

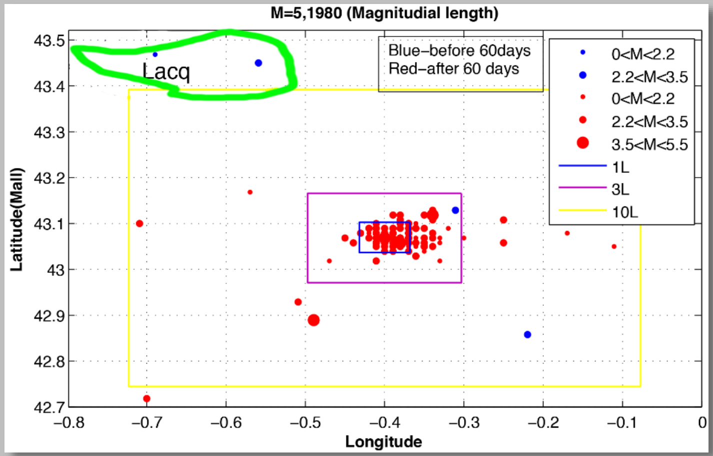
$\Rightarrow \langle \Delta p_{(reservoir)} \min \rangle = 20\text{-}30$ MPa
$\Rightarrow \langle \Delta \sigma_{(caprocks)} \min \rangle = 0.01\text{-}0.5$ MPa

$\Rightarrow \Delta p/dt_{(reservoir)} \max = 5$ MPa/yr (Lacq)
$\Rightarrow \Delta \sigma/dt_{(caprocks)} \max = 0.01$ MPa/yr (Lacq)

$$\Delta\sigma_{max} = [(1-2\nu)/2\pi(1-\nu)]\ \Delta p\ F_{max}(a/D),$$
$$\Delta\sigma_{max} = -0.1\ (T/D)\ \Delta p\ F_{max}(a/D)$$

a, T, D : radius, thickness, Depth of reservoir
(segall 1989, grasso 1992)

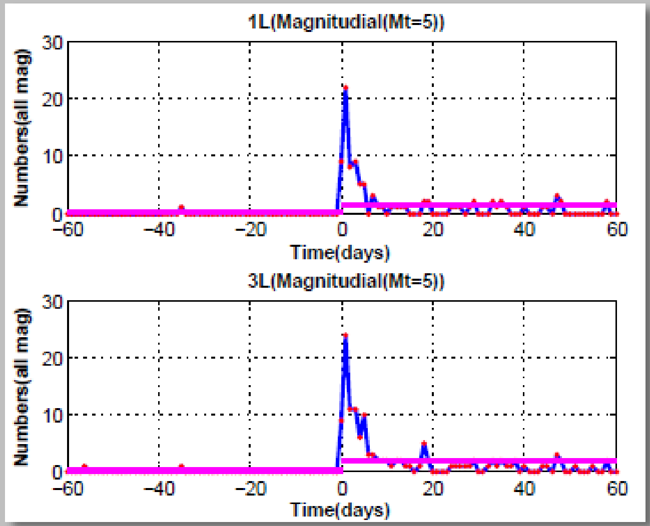
Complexity of Anthropogenic seismic instabilities: *susceptibility to forcing*



response to exogenous stressing rate

M5 1980
(distance)$_{Lacq}$= 10L to M5
⇒ Lack of dynamic triggering on Lacq field by regional M5

No evidence for exogenous M5 triggering pattern
⇒ low susceptibility to high frequency
⇒ (Lahaie-Grasso JGR99)

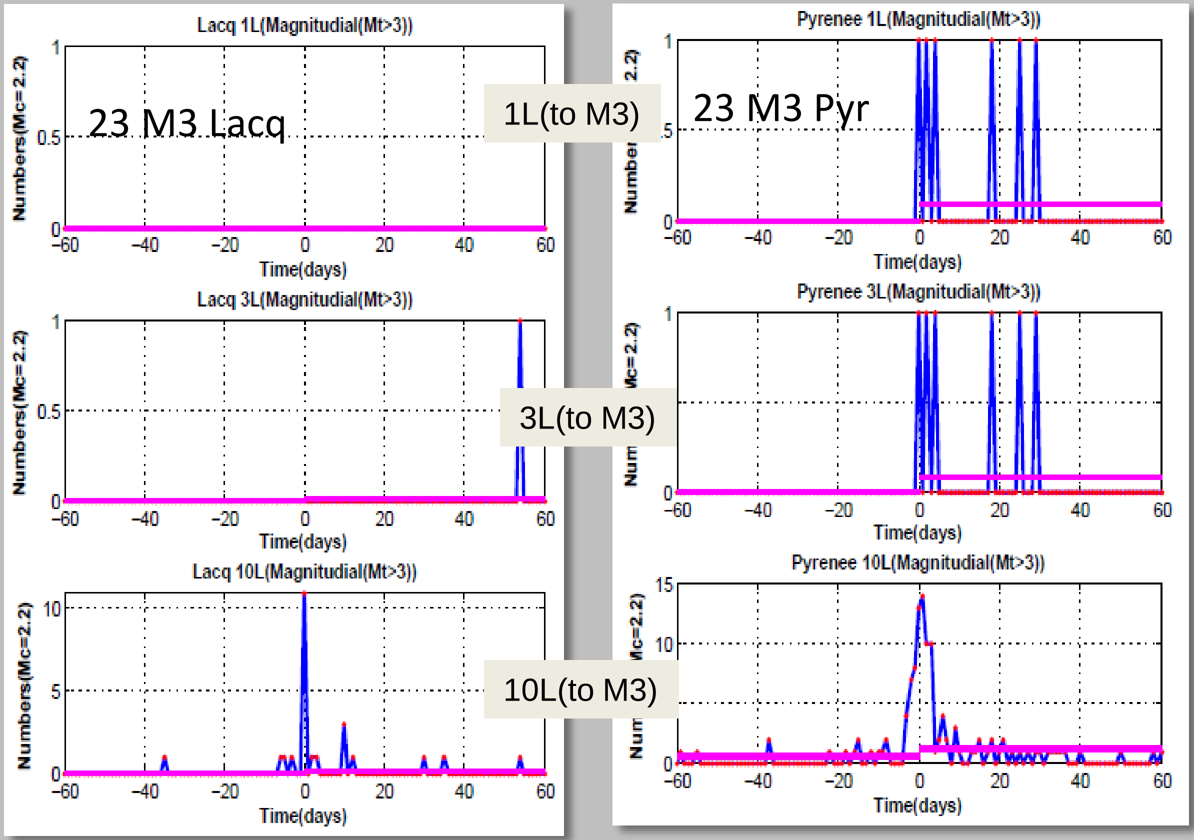


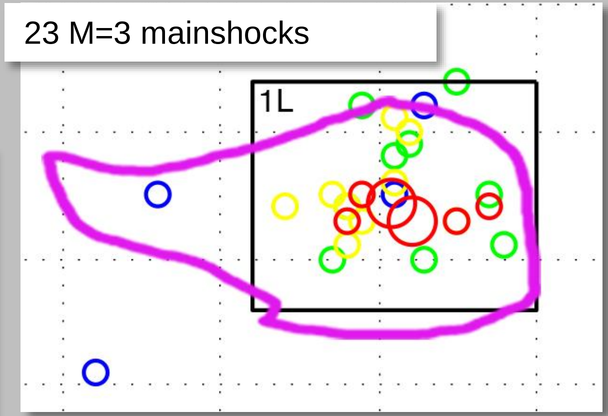
M5 1980, distance= 1-3L
Regular aftershock sequence

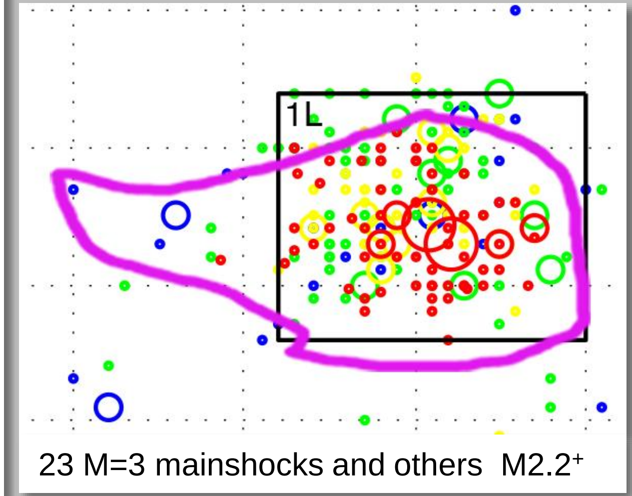
M : Fault length
-4 : 10 cm
-2 : 1 m
0 : 10 m
2 : 100 m
4 : 1 km
6 : 10 km

Complexity of Anthropogenic seismic instabilities: *susceptibility to forcing*

Stack on 23 M=3 aftershock sequences







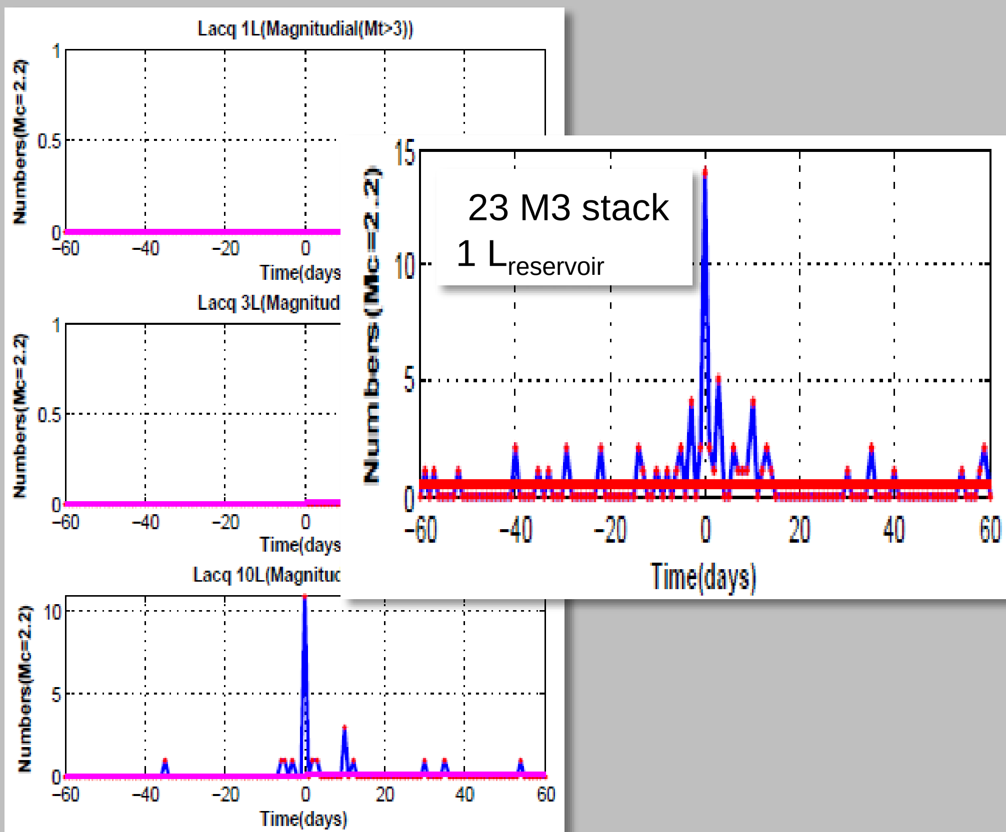
Deficit of Lacq aftershock productivity for M3 (1_3L) relatively to M3 Pyrenees counterpart.

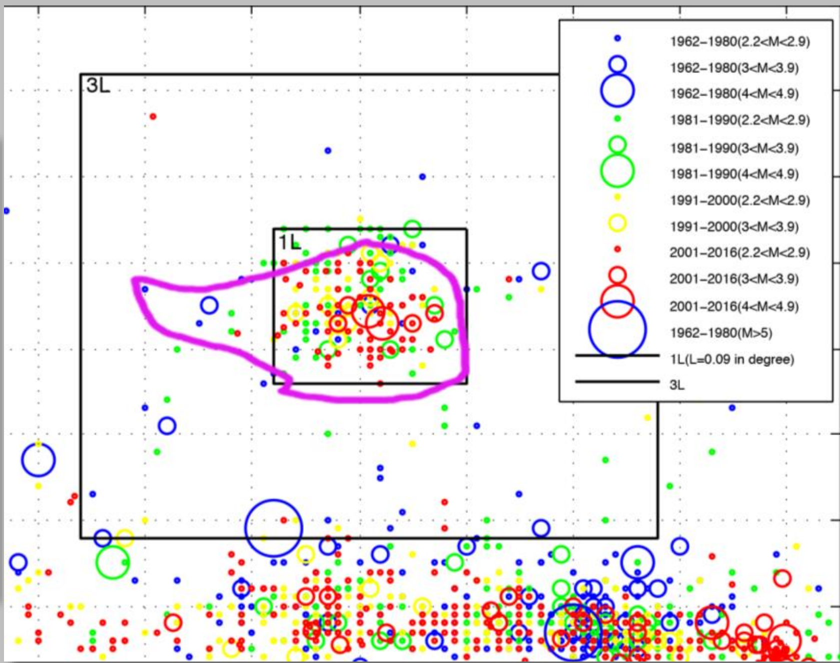
M : Fault length
-4 : 10 cm
-2 : 1 m
0 : 10 m
2 : 100 m
4 : 1 km
6 : 10 km

Complexity of Anthropogenic seismic instabilities: *susceptibility to forcing*

Stack on 23 M3 mainshocks :

susceptibility to endogenous triggering

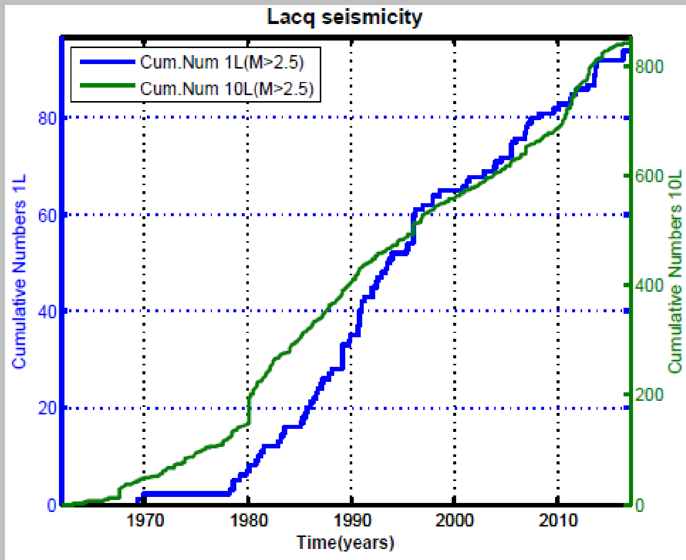




- a regular aftershock productivity at the reservoir scale ($L_{reservoir}$ = L_{M6})
(i.e. reservoir depletion as a slow mainshock)

M : Fault length
-4 : 10 cm
-2 : 1 m
0 : 10 m
2 : 100 m
4 : 1 km
6 : 10 km

Complexity of Anthropogenic seismic instabilities: *induced/tectonic eqs rate*



Induced seismicity rate: IR (1L box)

Tectonic seismicity rate: TR (10L box)

Seismicity rate :

1970 - 1980 : IR << TR
1985 - 1995 : IR > TR
2000 - 2010 : IR = TR
2015 - : ?

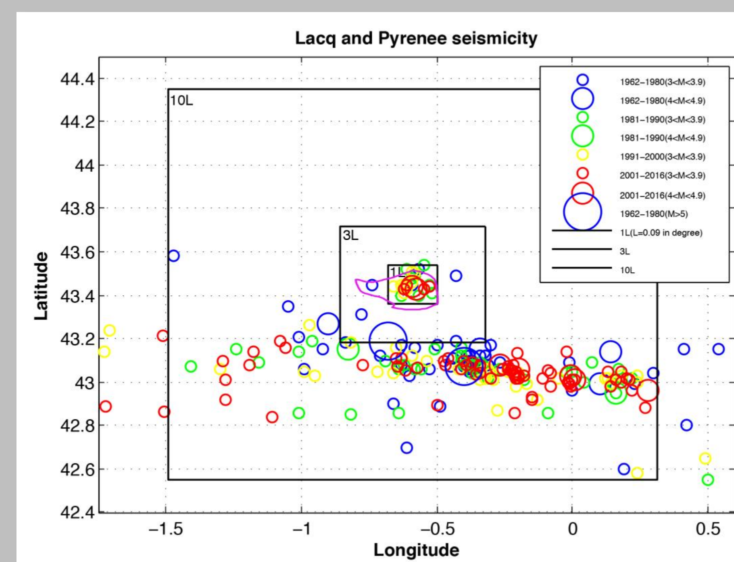
Seismicity rate :

$N_{(earthquake)}$ = Background + $interaction_{(aftershocks)}$

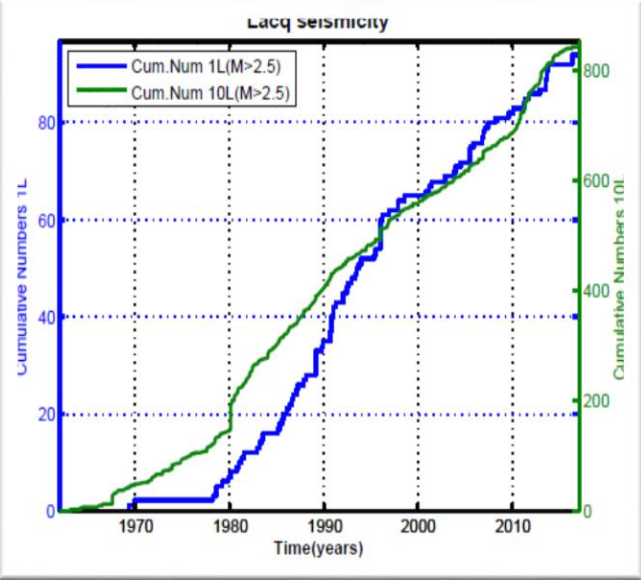
(e.g. point process model (Kagan, 80; Helmstetter et al.03))

New classes for induced seismicity as IR/TR ratio ?

IR/TR < 1 => sub- tectonic rate
IR/TR > 1 => super- tectonic rate
close to volcano swarm setting
(e.g. Touati et al. PRL2009; Traversa and Grasso, BSSA09, BSSA10)
<=> $(IR)_{Background}$ to estimate $(TR)_{Background}$



Complexity of seismic instabilities: *induced/tectonic eqs rate*



Induced seismicity rate: IR
Tectonic seismicity rate: TR

Seismicity rate : 1L 10L

1970 - 1980 : IR << TR sub-tectonic rate
1985 - 1995 : IR > TR super-tectonic rate

Seismicity rate :
$N_{(earthquake)}$ = Background + $interaction_{(aftershocks)}$

with Interaction $_{(lacq\ aftershock)}$ << 0

Close to volcano swarm setting
(e.g. Traversa and Grasso, BSSA09, BSSA10; Touati et al. PRL2009)

- $(IR)_{Background}$ to estimate $(TR)_{Background}$