Insights into Rupture Physics from Induced Seismicity

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motivation

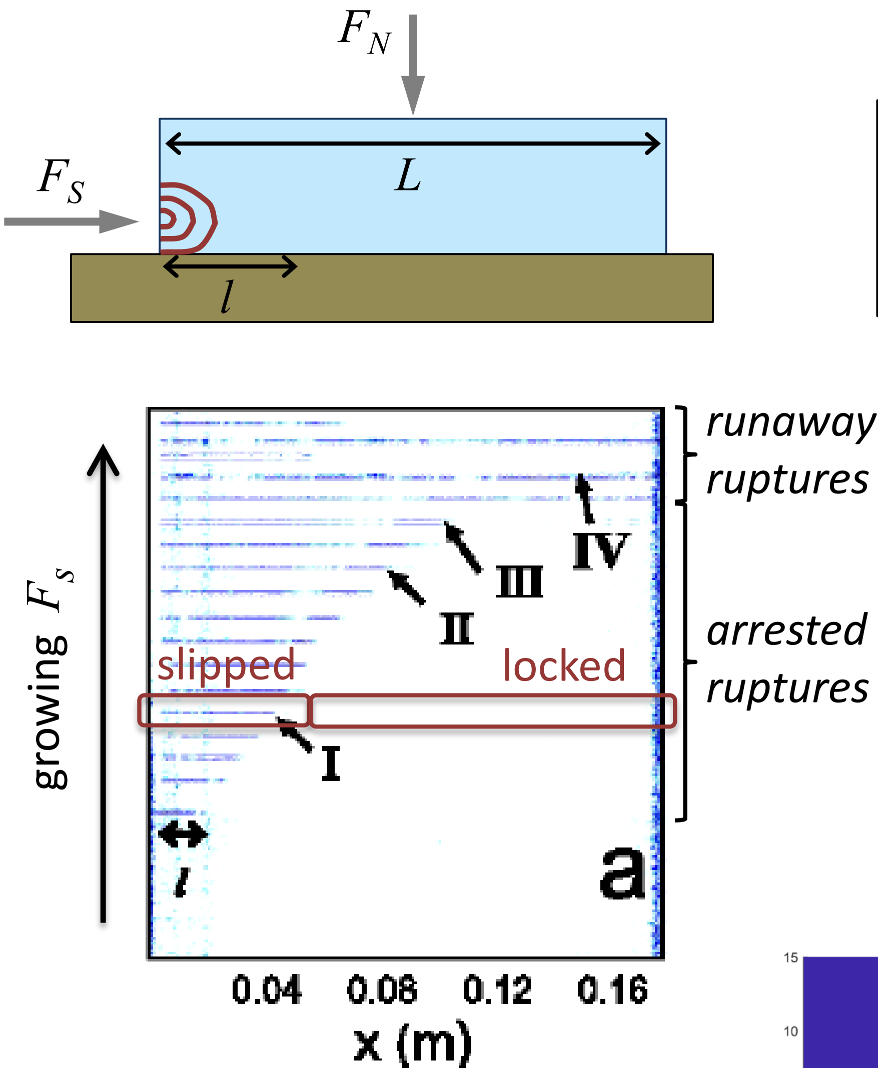
- naturally important to better understand
  what controls nucleation and size of earthquakes

- instead of adding complexity to the system,
  we focus on underlying physics

- theoretical models may provide
  insight into which parameters or processes are controlling
  nucleation, growth and arrest of ruptures

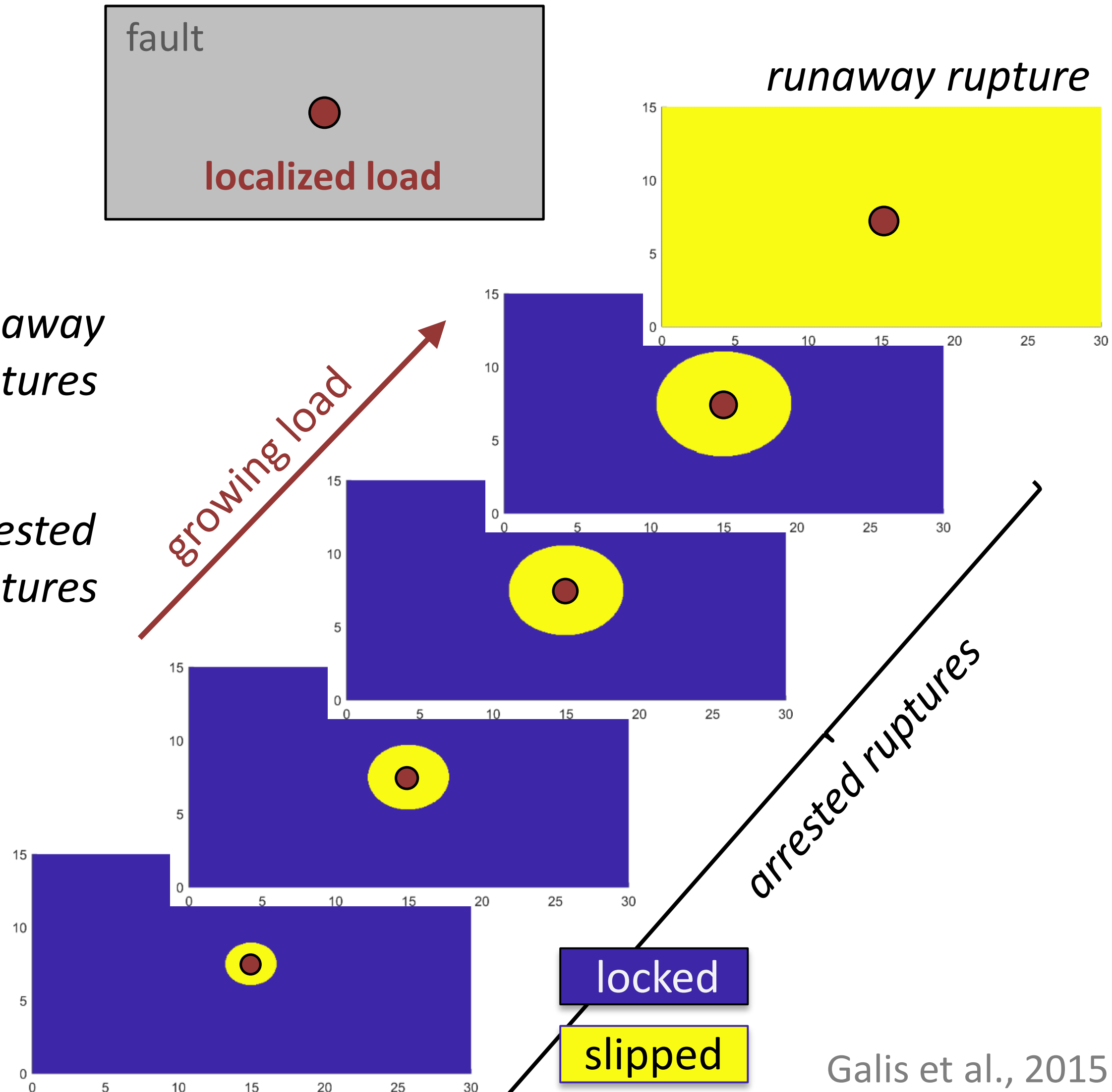
arrested and runaway ruptures

in **laboratory experiments**



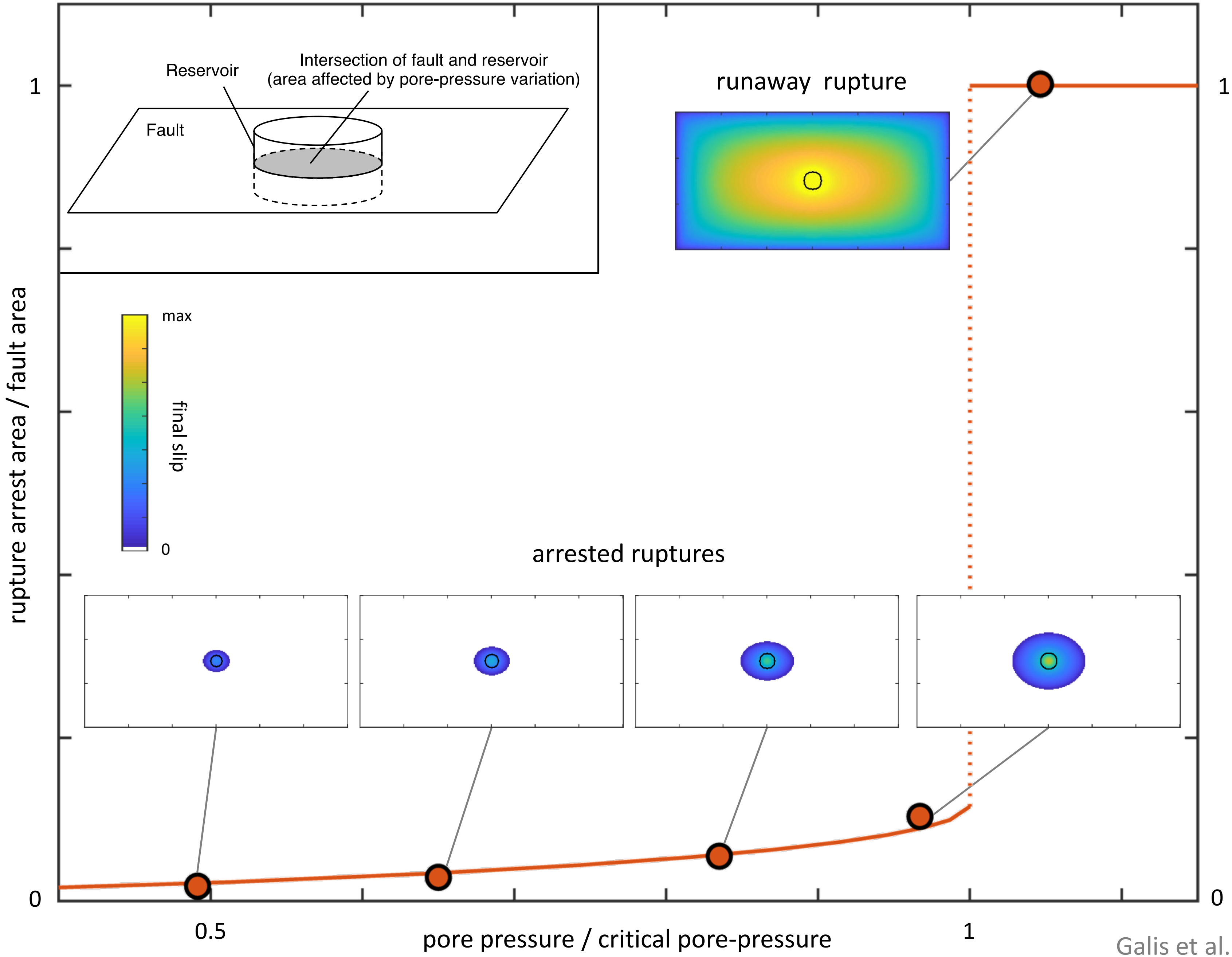
Rubinstein et al., 2007

in **our numerical simulations**
of spontaneous dynamic rupture propagation



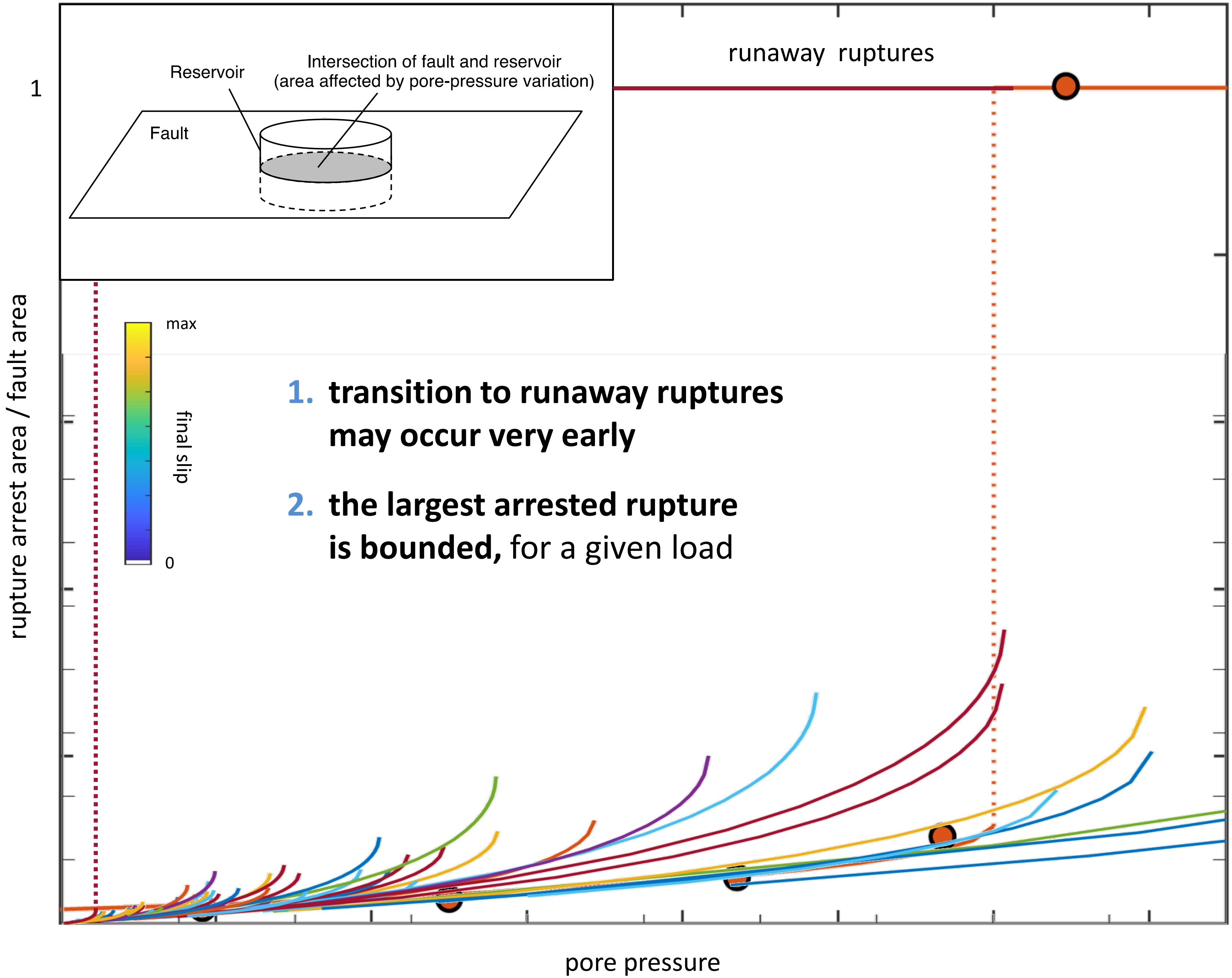
Galis et al., 2015

arrested ruptures and fluid-injection induced seismicity



Galis et al. 2017

the largest arrested rupture



physics-based estimate of size of the largest arrested rupture

$$M_0^{max\text{-}arr} \doteq \frac{0.4255}{\sqrt{\Delta\tau_0}}\left(\frac{\kappa\,\mu_d}{h}\right)\Delta V^{3/2} = \gamma.\Delta V^{3/2}$$

Two important approximations

- load due to pore-pressure inside the reservoir
  is approximated by a point force

- the pore-pressure change due to injected fluid is approximated
  by a response of fully saturated reservoir (following McGarr 2014)

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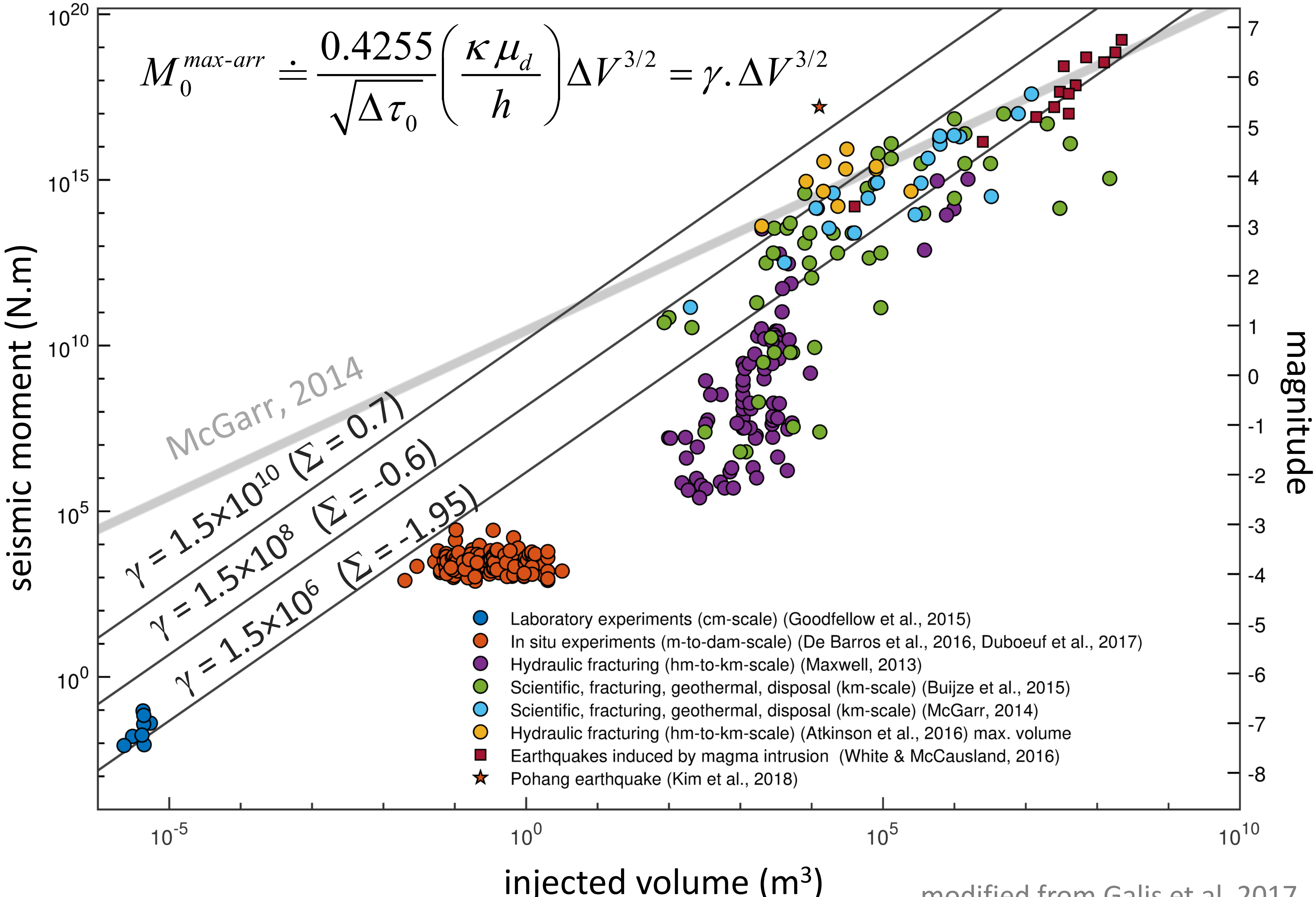

modified from Galis et al. 2017

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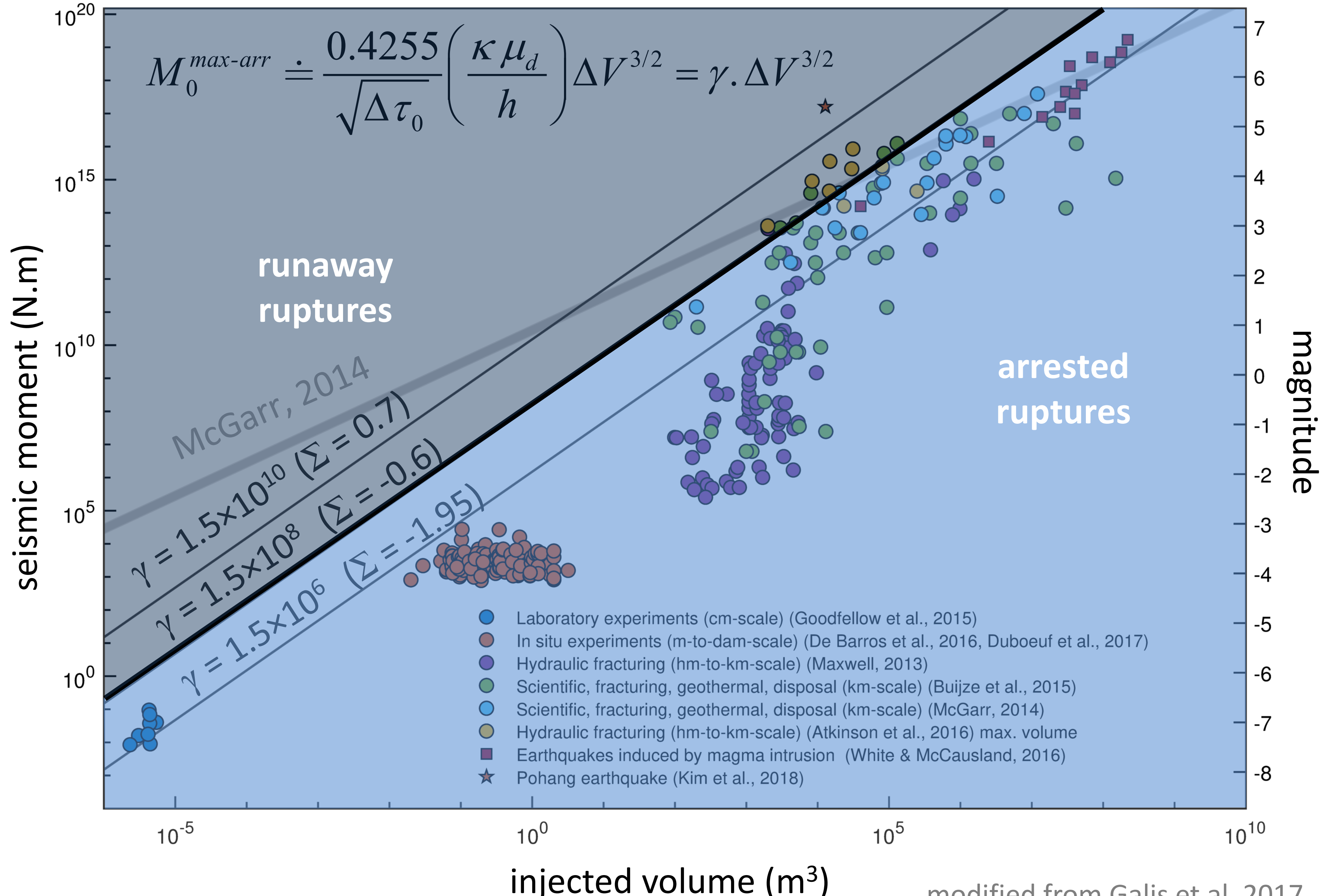

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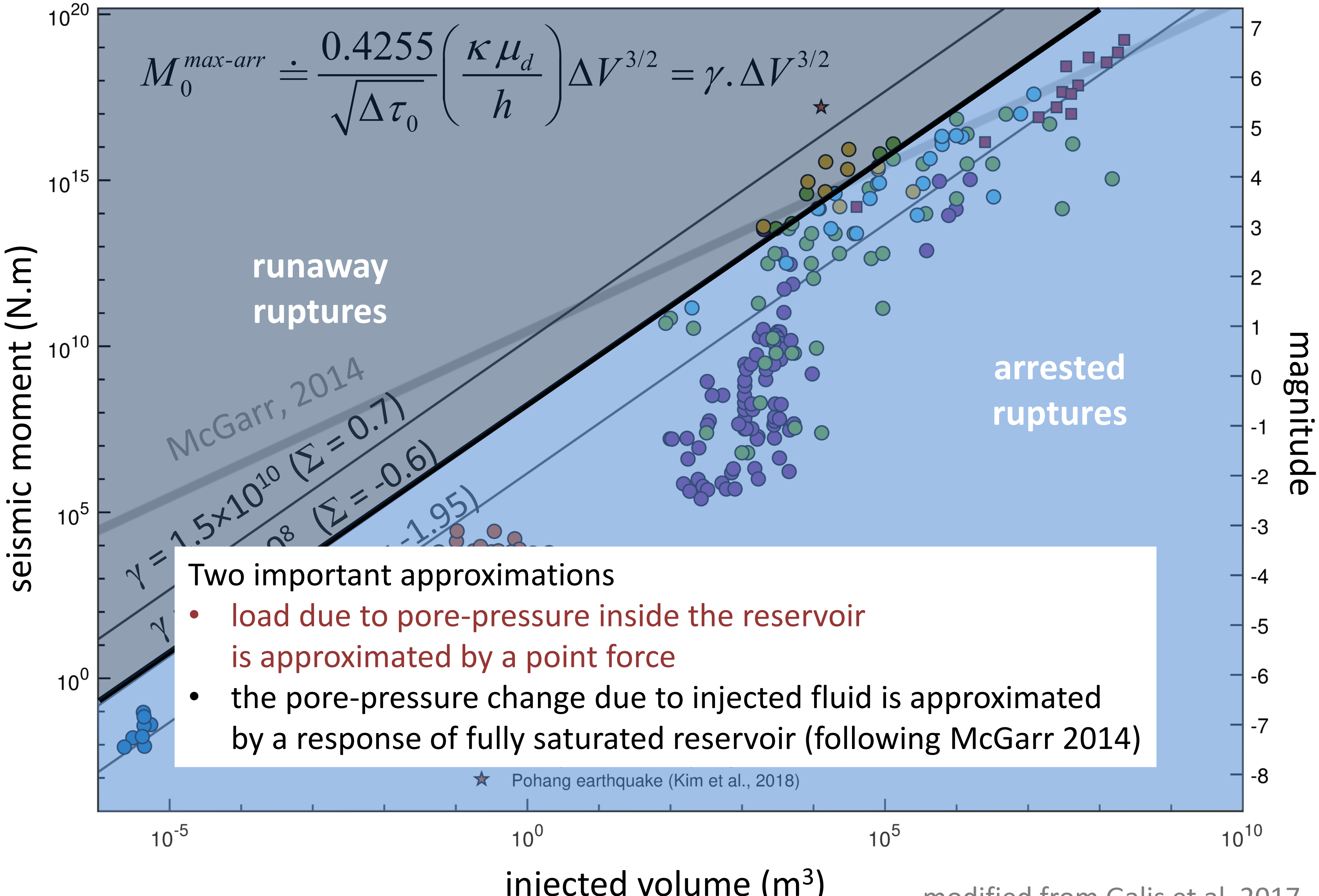
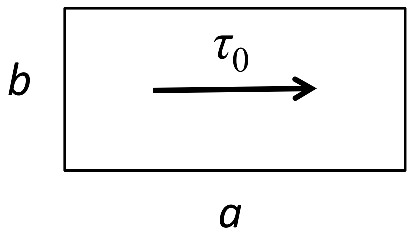
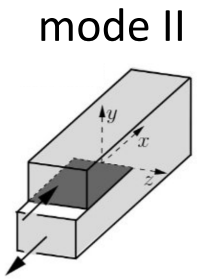
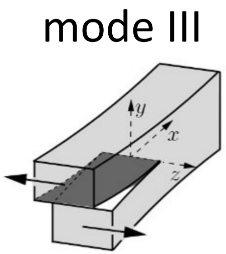


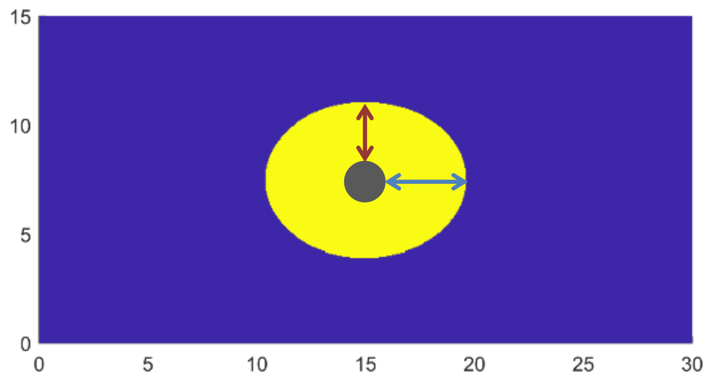
modified from Galis et al. 2017

effects of aspect ratio on size of arrested ruptures



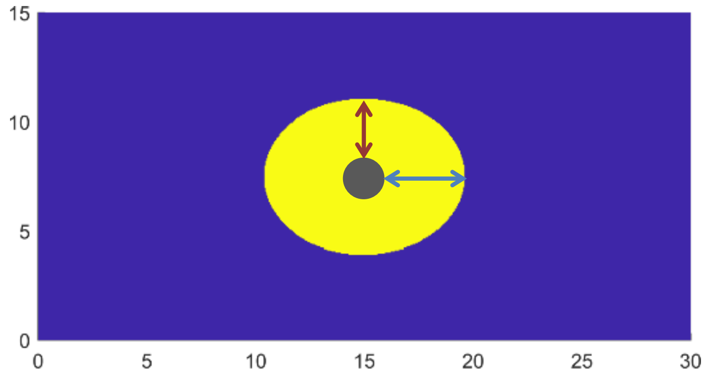






ruptured area
ruptured length in anti-plane direction
ruptured length in in-plane direction

effects of aspect ratio on size of arrested ruptures



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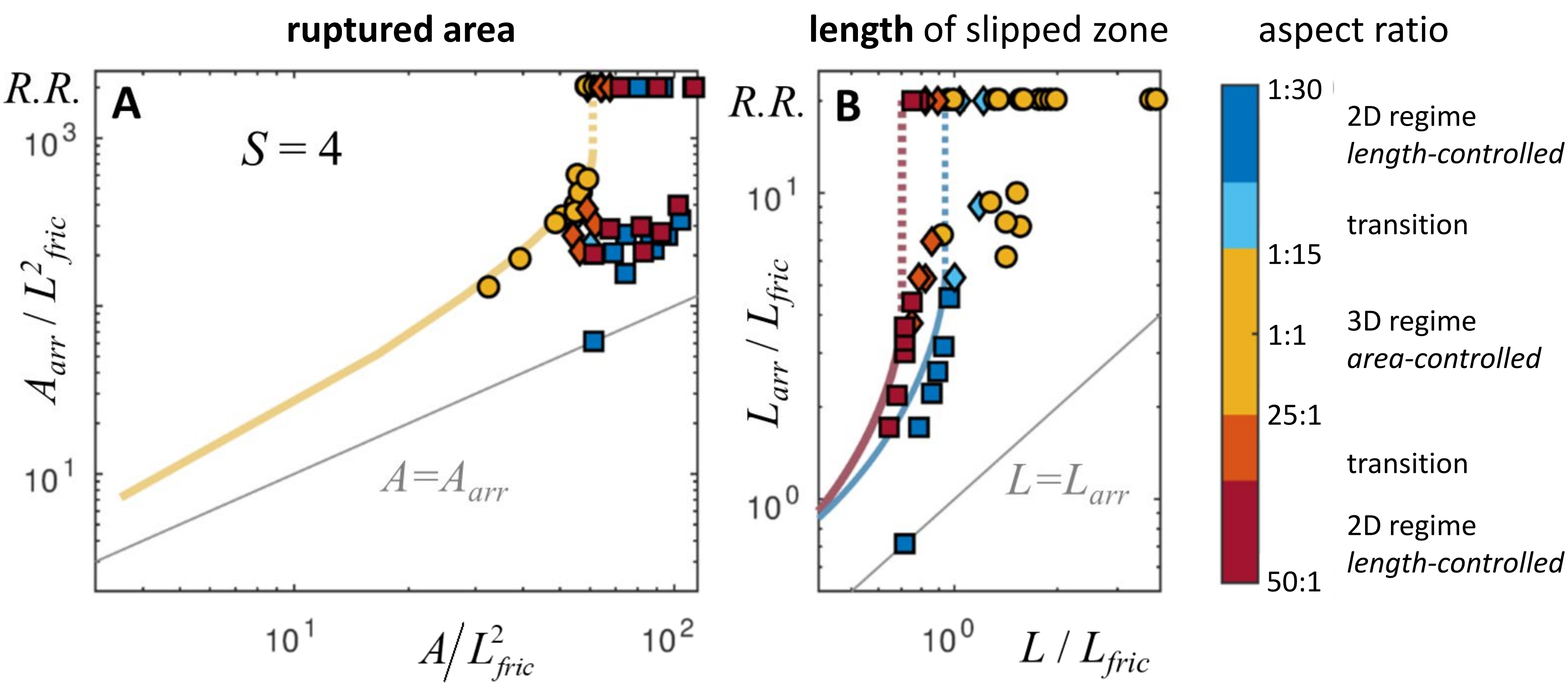

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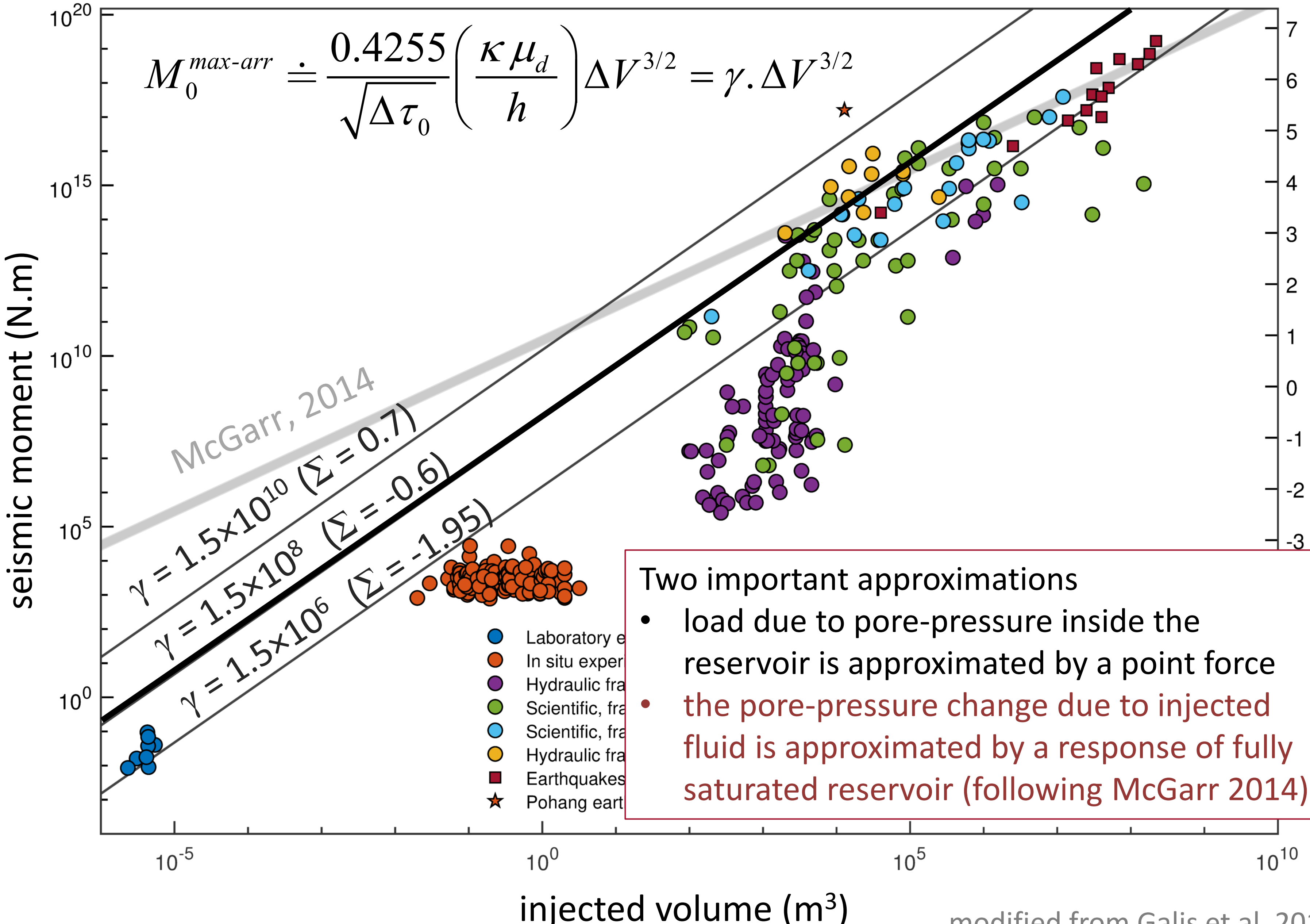

Two important approximations

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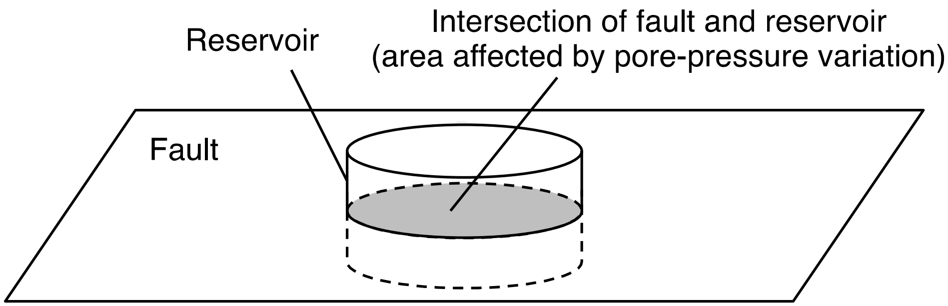
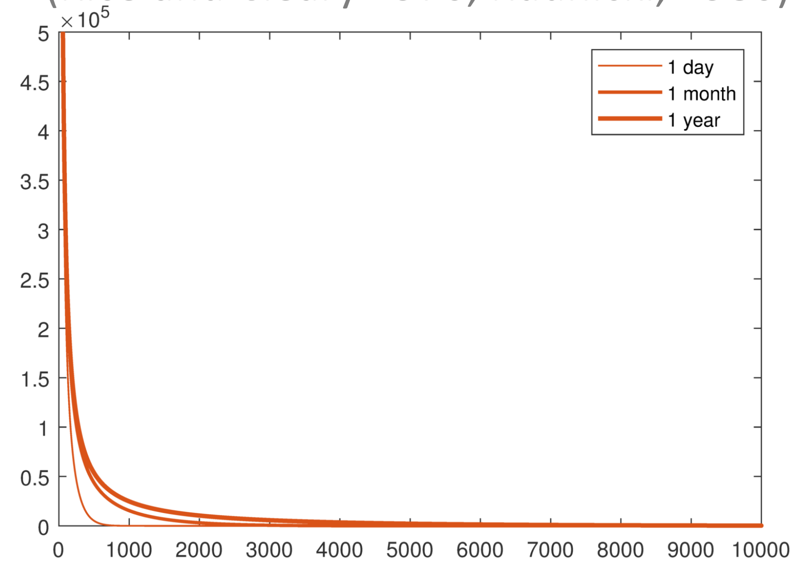
pore-pressure response to various sources



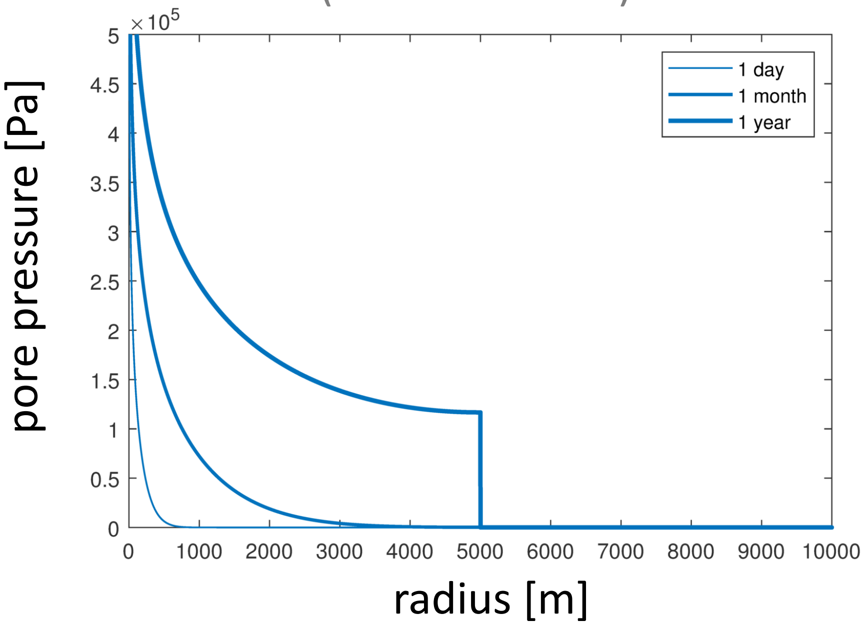
point source in 3D isotropic reservoir

(Rice and Cleary 1976, Rudnicki, 1986)



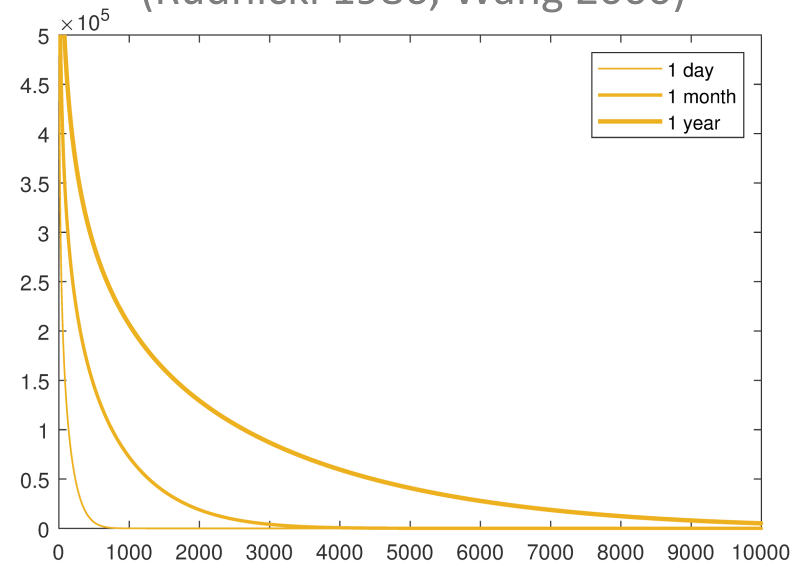
line source in cylindrical reservoir with no-flow boundaries

(Lee et al. 2003)

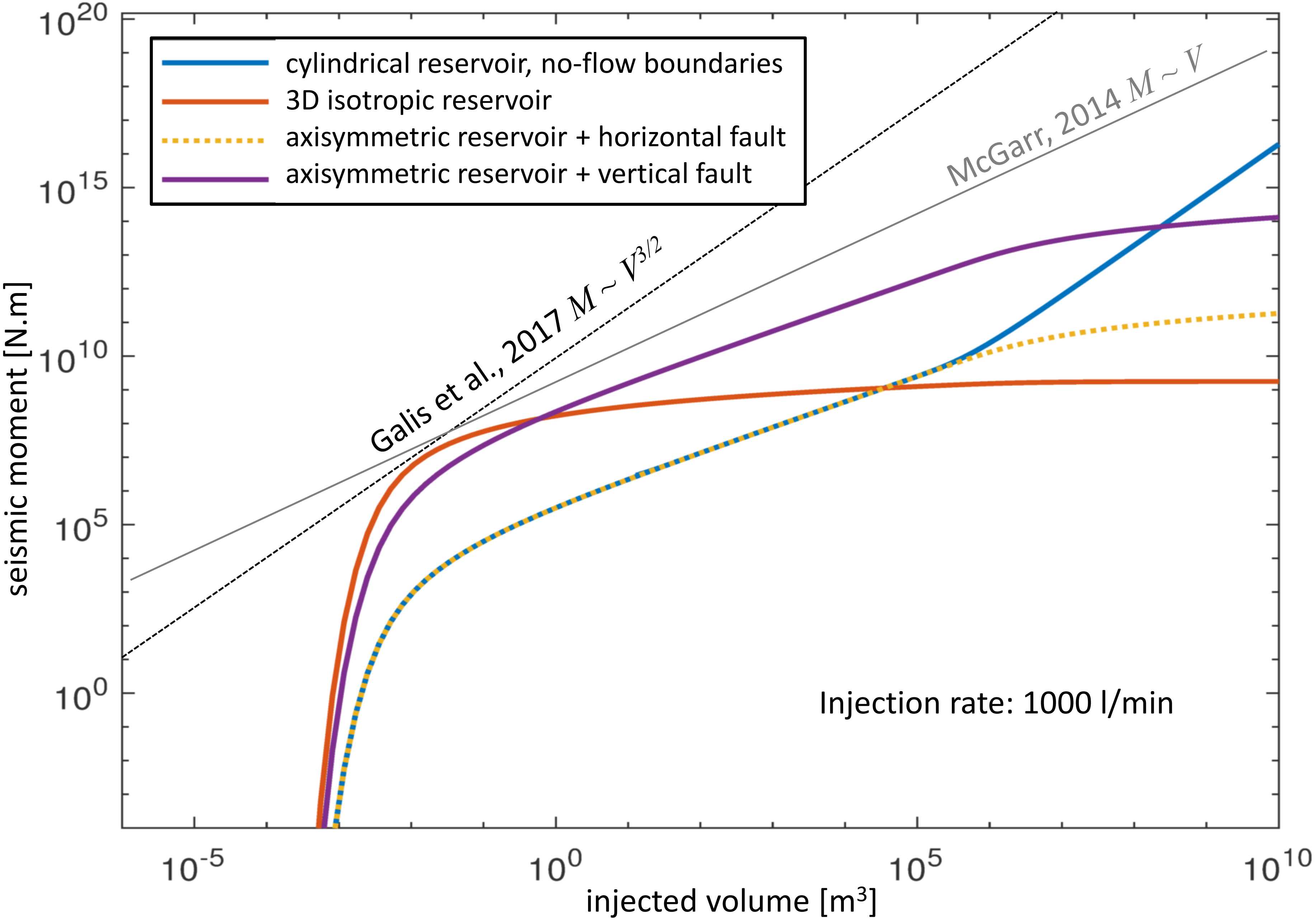


line source in a 2D axisymmetric reservoir

(Rudnicki 1986, Wang 2000)



effects of pore-pressure models on size of the largest arrested rupture



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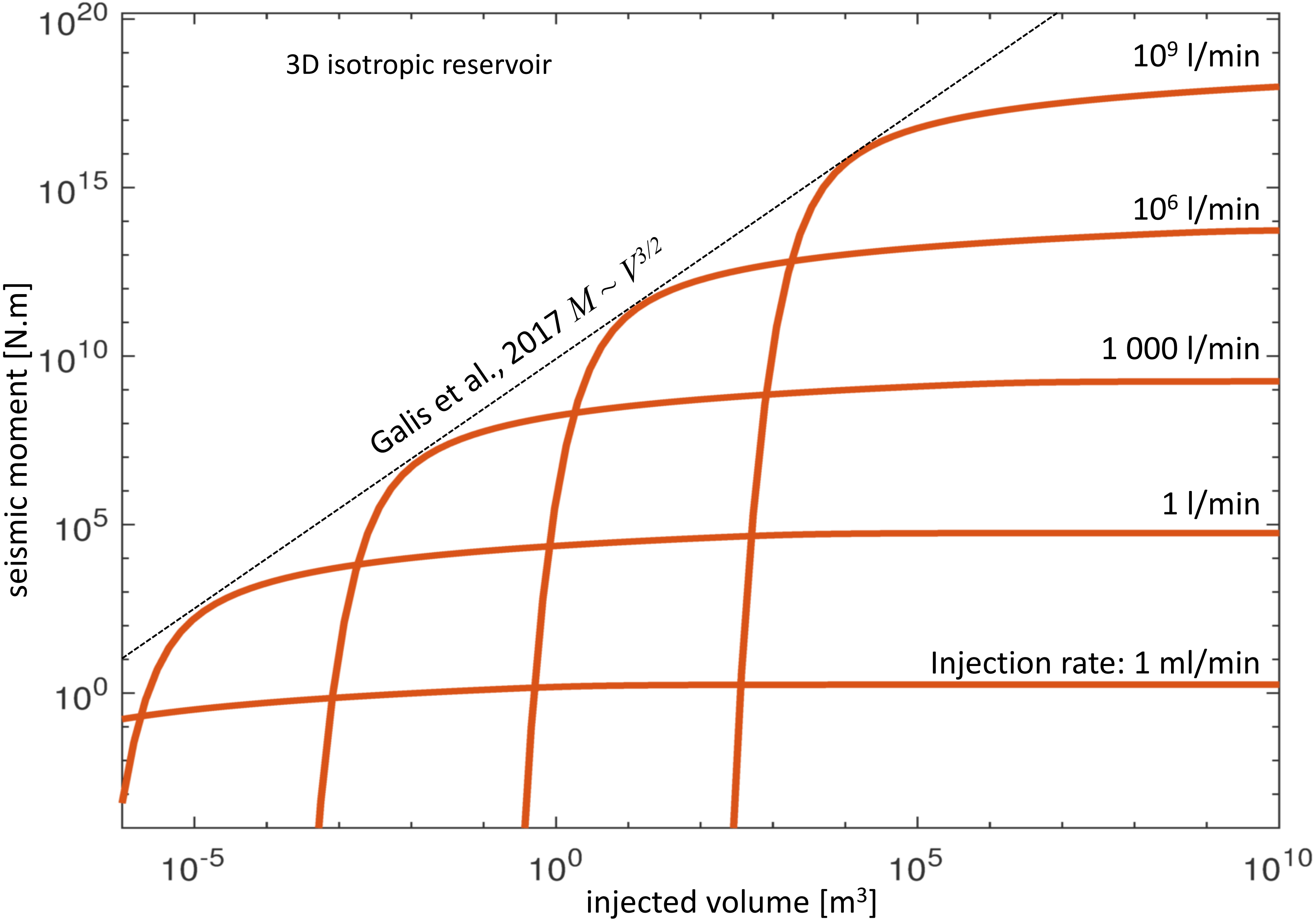

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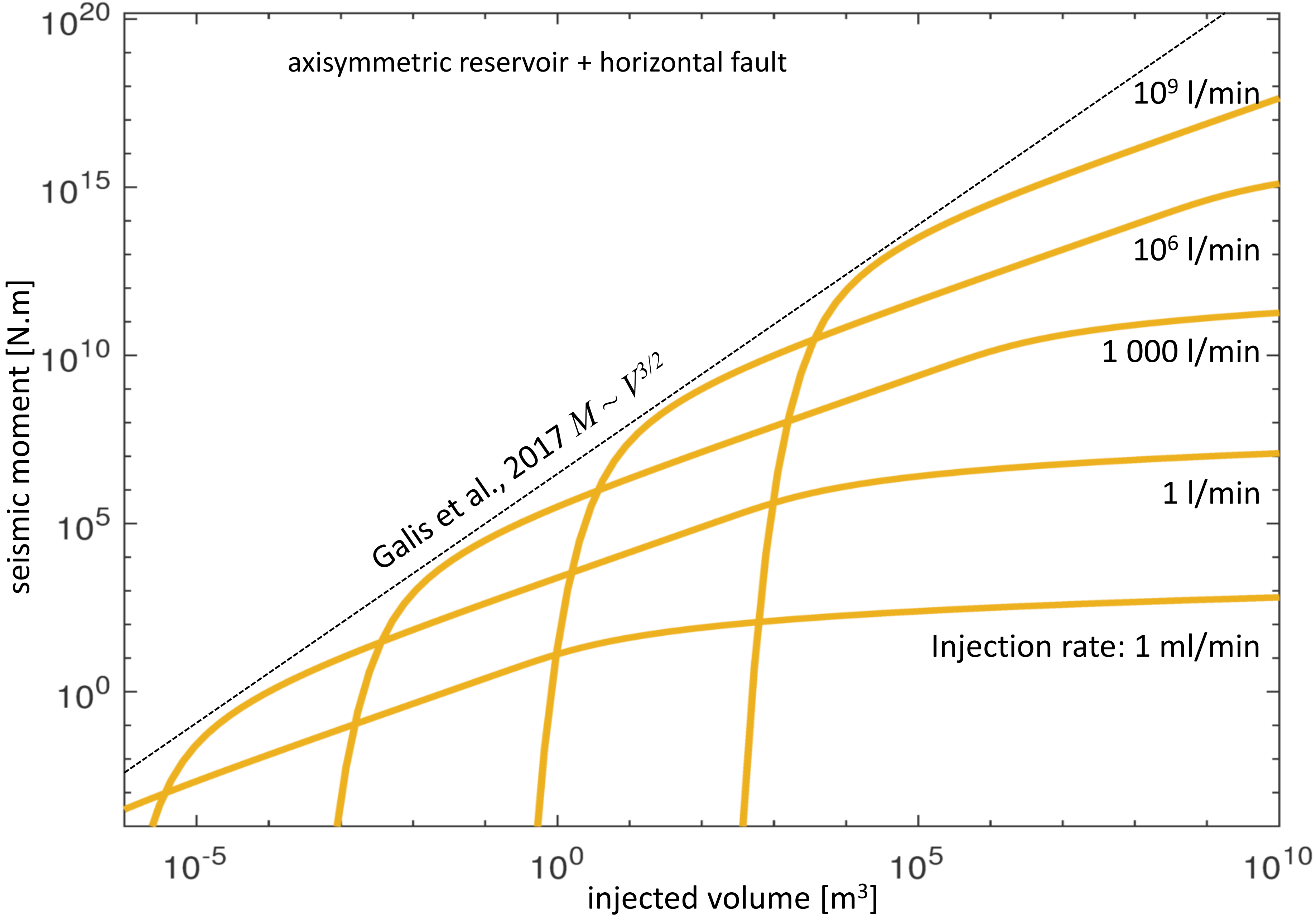

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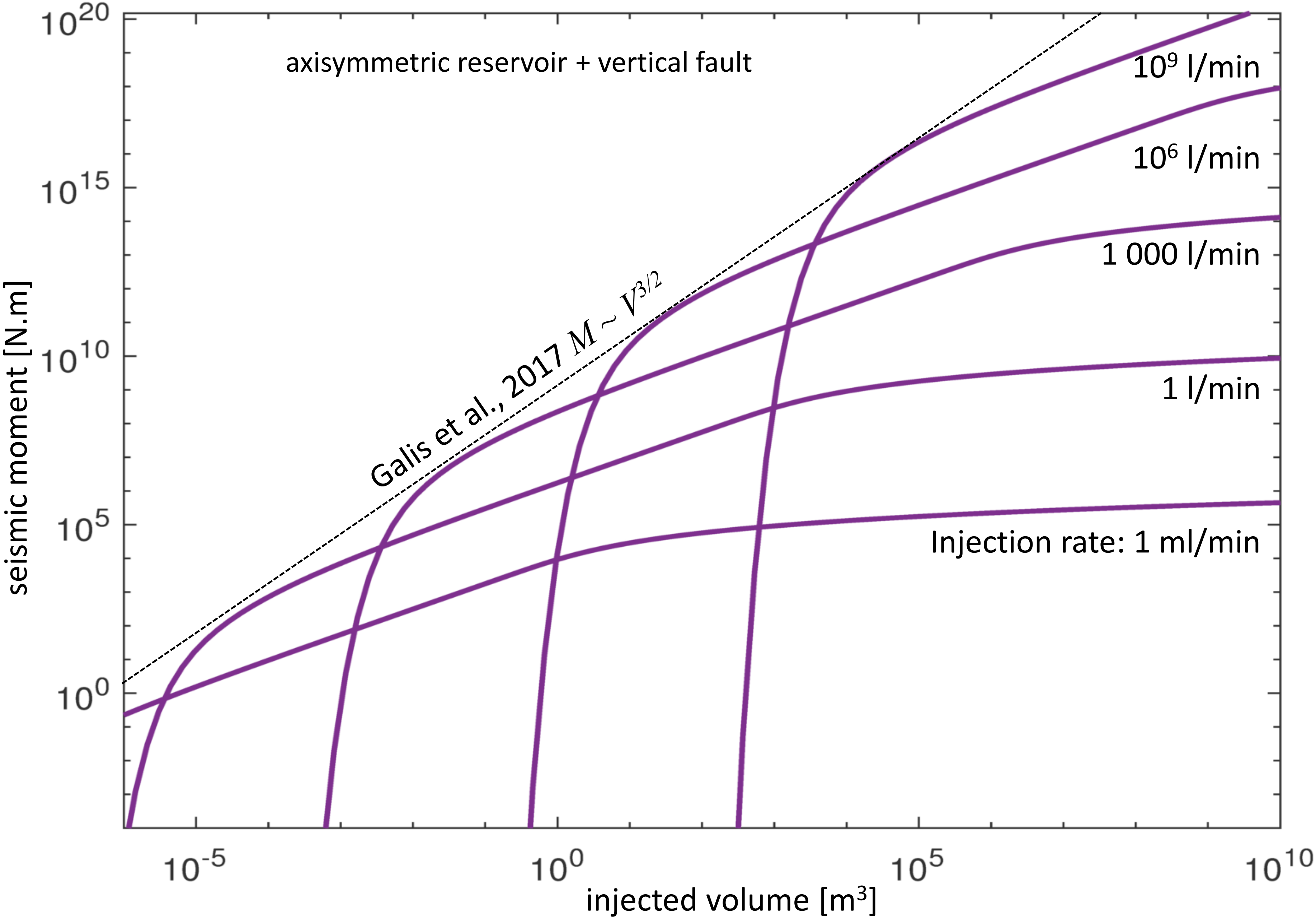

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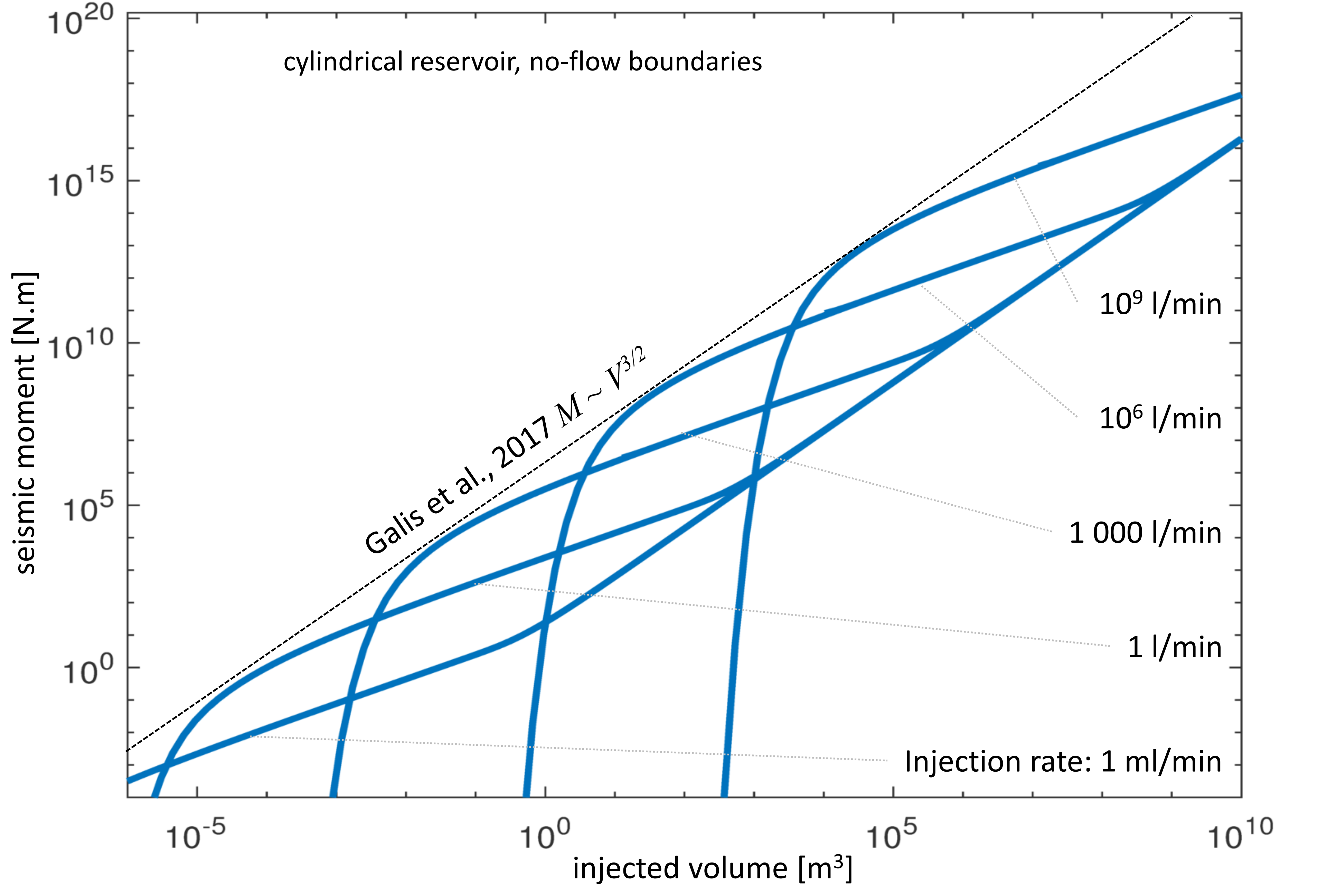
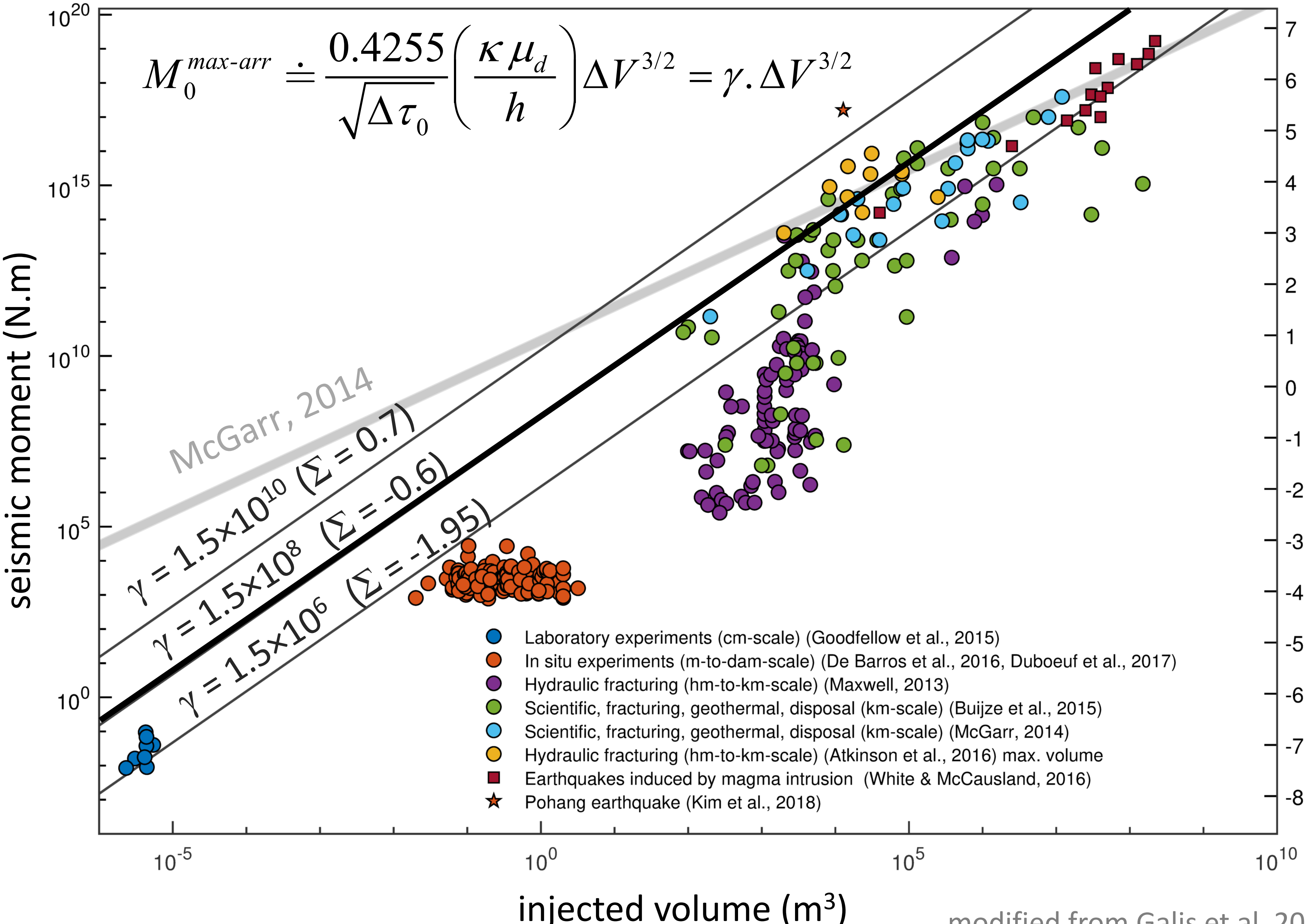


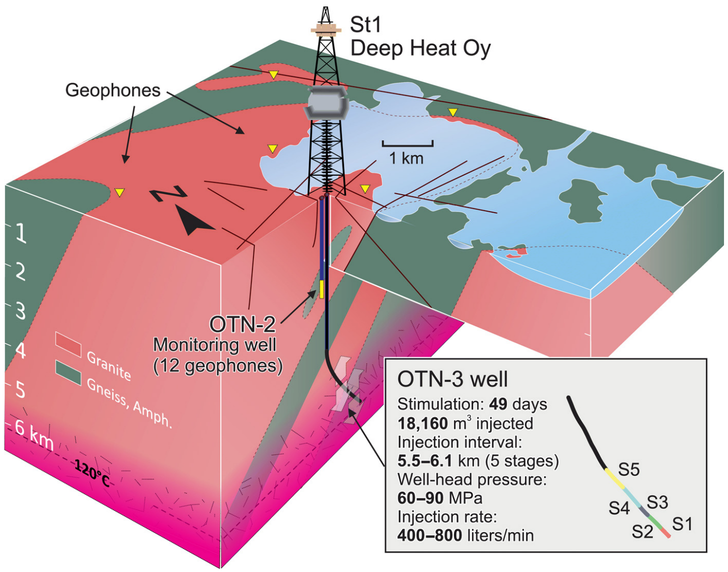
physics-based estimate of size of the largest arrested rupture

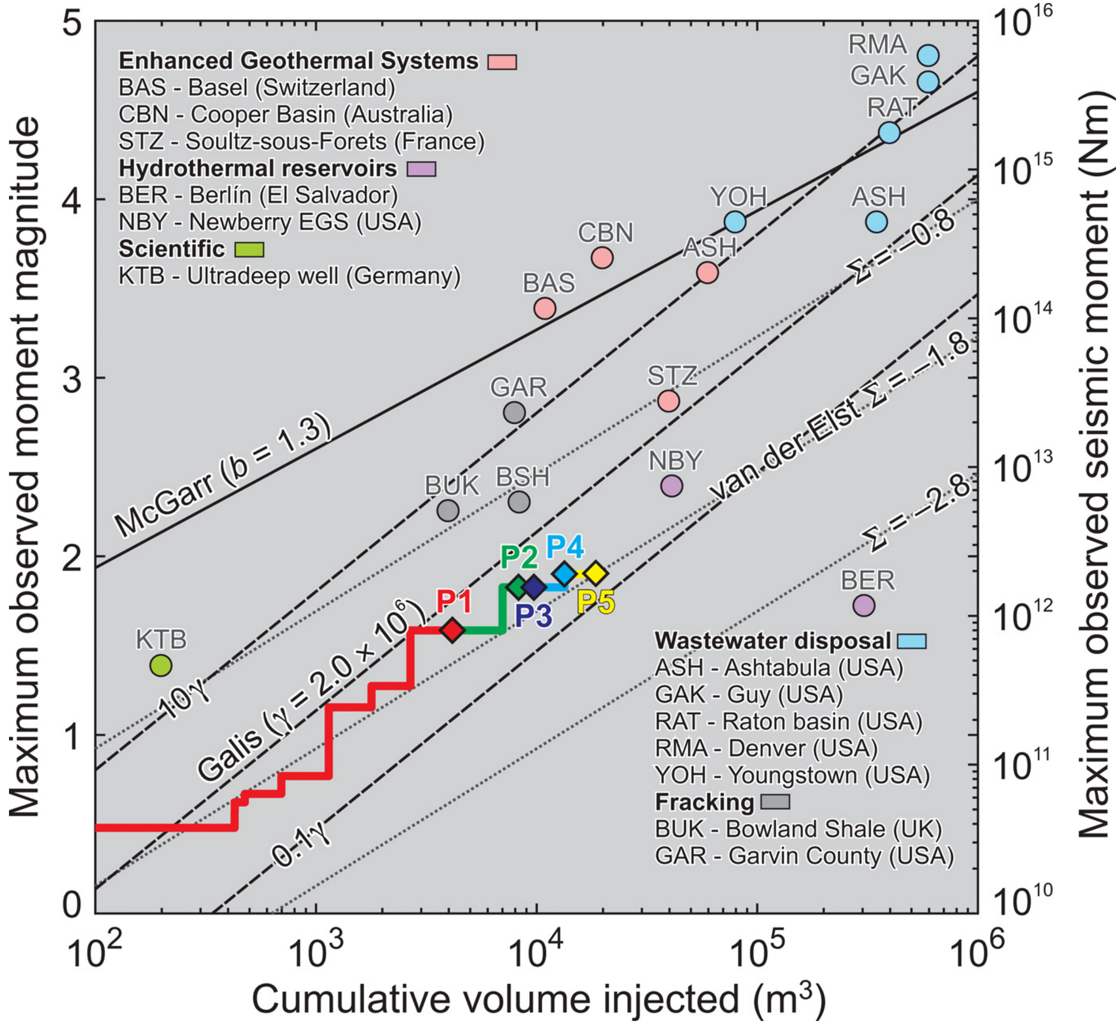


modified from Galis et al. 2017

Can the estimate of the largest arrested rupture be useful?

Development of an enhanced geothermal reservoir near Helsinki, Finland
Kwiatek et al., 2019





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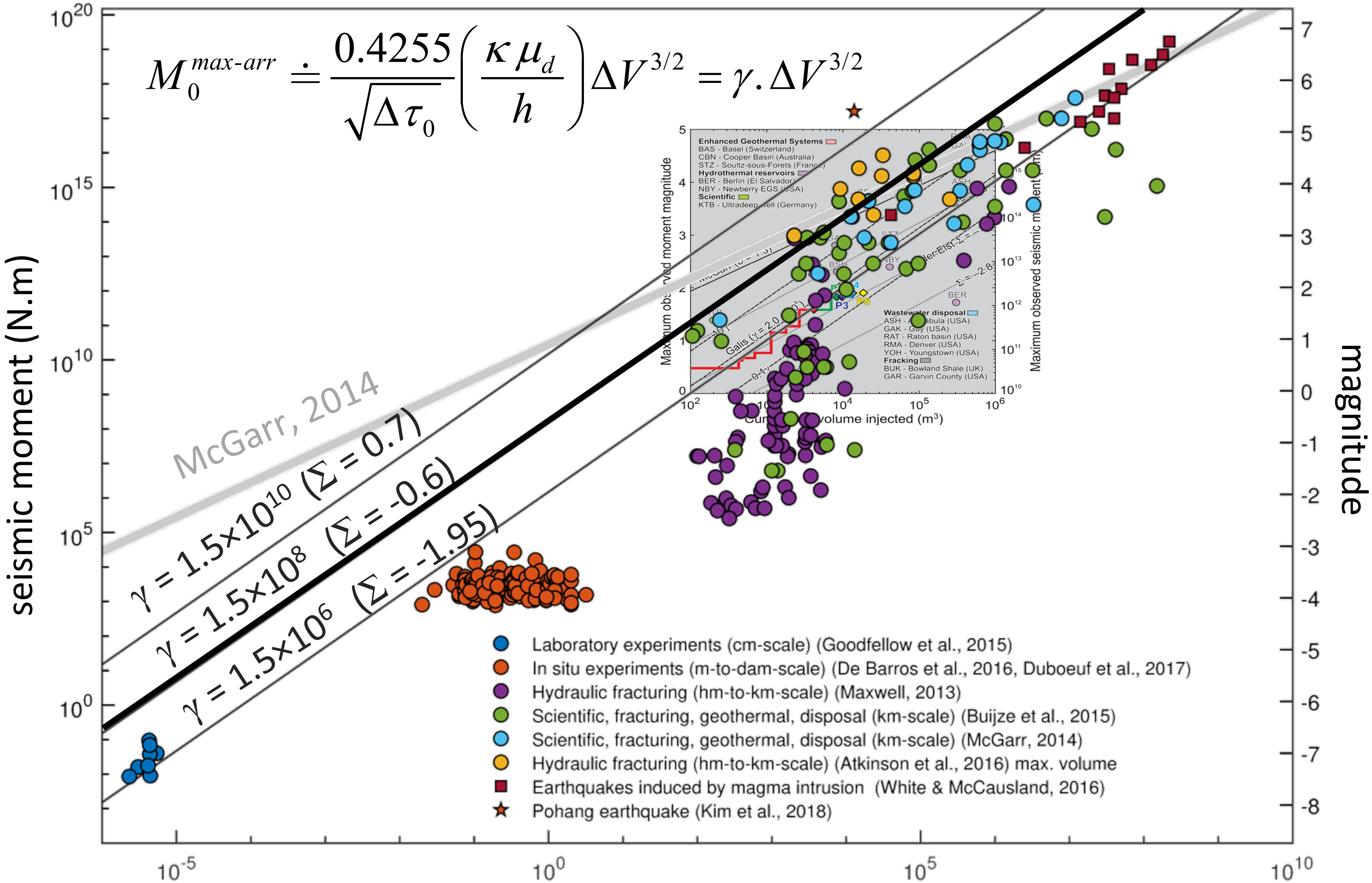

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conclusions

- we have **derived a physics-based estimate** of seismic moment of the largest arrested rupture, $M_{max\text{-}arr}$
- assuming injection into a saturated reservoir, we have found that $\boldsymbol{M_{max\text{-}arr}}$ **grows as** $\boldsymbol{\sim V^{3/2}}$
- **the slope of 3/2 is a rather robust feature** that remains preserved for elongated reservoirs with broad range of aspect ratios as well as for ensembles of reservoirs with various pore-pressure models
- **consistency of our model with observations** across broad range of scales for fluid-injection induced seismicity **suggests that our model captures underlying physics**
- because induced earthquakes, particularly the largest ones, release accumulated tectonic deformation, **concept of our model should be applicable also to natural tectonic earthquakes**
- however, due to poorly constrained conditions at the time of nucleation, application to natural earthquakes **remains a task for future…**

Galis, Ampuero, Cappa, Mai, 2017
Induced seismicity provides insight into why earthquake ruptures stop
Science Advances, 3(12), eaap7528
advances.sciencemag.org/content/3/12/eaap7528

Galis, Ampuero, Mai, Kristek, 2019
Initiation and arrest of earthquake ruptures due to
elongated overstressed regions
Geophysical Journal International, 217
academic.oup.com/gji/article-abstract/217/3/1783/5322168

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Thank you