SAND2020-13131C

Sandia National Laboratories

Operational and geological controls of hydro-mechanical coupling effects on induced earthquakes in Pohang, South Korea

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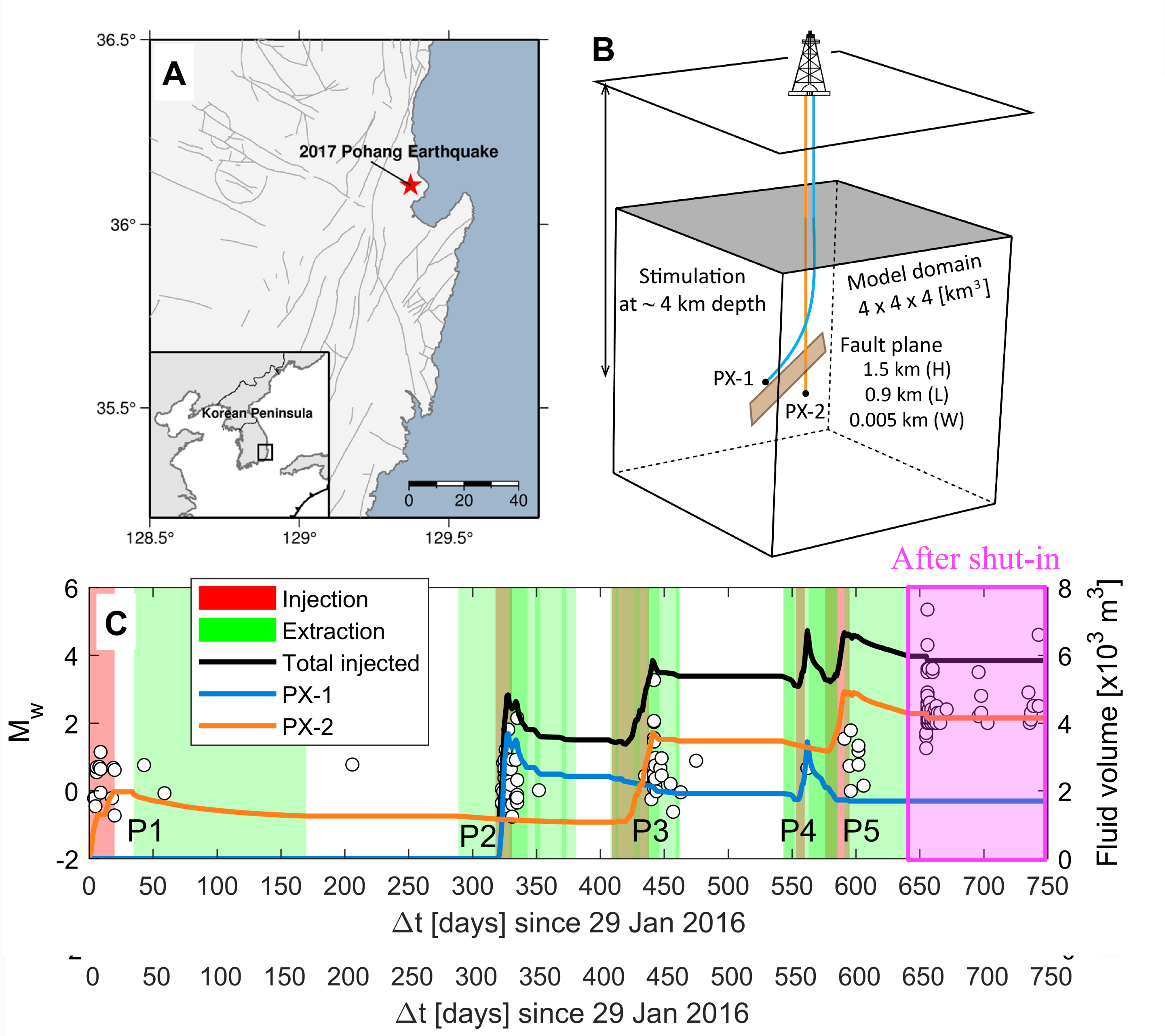
Abstract

Coupled poroelastic stressing and pore-pressure accumulation along pre-existing faults in deep basement contribute to recent occurrence of seismic events at subsurface energy exploration sites. Our coupled fluid-flow and geomechanical model describes the physical processes inducing seismicity corresponding to the sequential stimulation operations in Pohang, South Korea. Simulation results show that prolonged accumulation of poroelastic energy and pore pressure along a fault can nucleate seismic events larger than M_w3 even after terminating well operations. In particular the possibility of large seismic events can be increased by multiple-well operations with alternate injection and extraction that can enhance the degree of pore-pressure diffusion and subsequent stress transfer through a rigid and low-permeability rock to the fault. This study demonstrates that the proper mechanistic model and optimal well operations need to be accounted for to mitigate unexpected seismic hazards in the presence of the site-specific uncertainty such as hidden/undetected faults and stress regime.

Model Setting



- Total 6000 m3 of fluids was injected through PX-1 and PX-2
- Most of larger earthquakes occurred after shut-in of all stimulation wells

Coulomb Stress Change

$$\Delta\tau = \underbrace{(\Delta\tau_s + f\Delta\sigma_n)}_{\text{Poroelastic stress}} + \underbrace{f\Delta p}_{\text{Pore pressure}}$$

$\Delta\tau_s$ = shear stress change

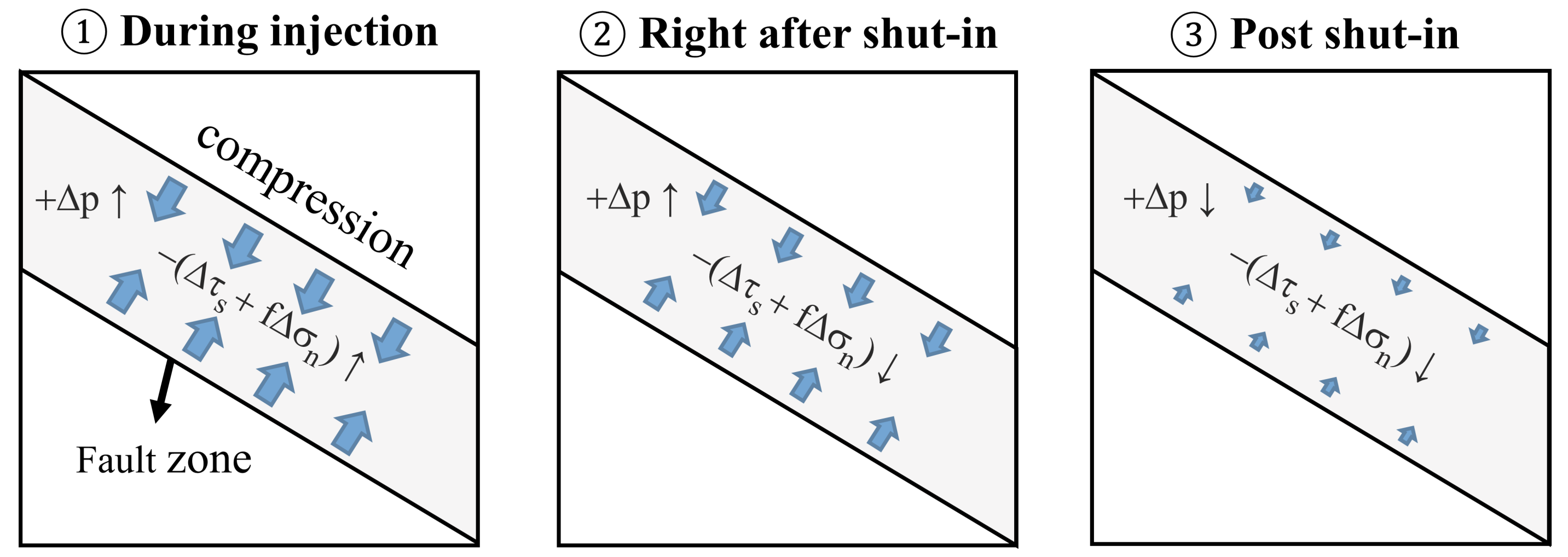
$\Delta\sigma_n$ = normal stress change

Δp = pore pressure change

- (+) values of each quantity imply that the fault plane is moved closer to failure

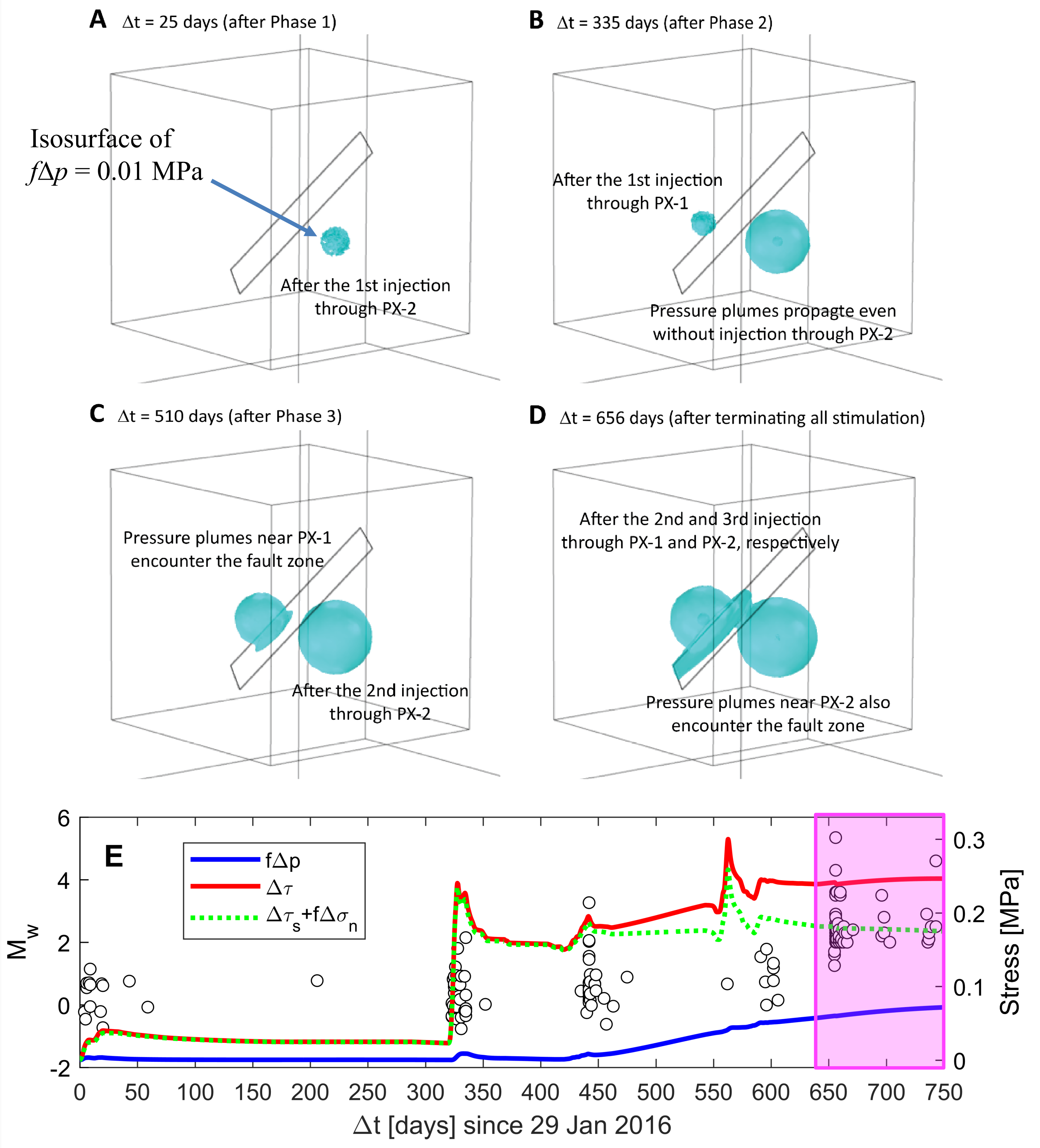
Poroelastic Coupling Mechanism

Pore pressure change ⇄ Rock deformation



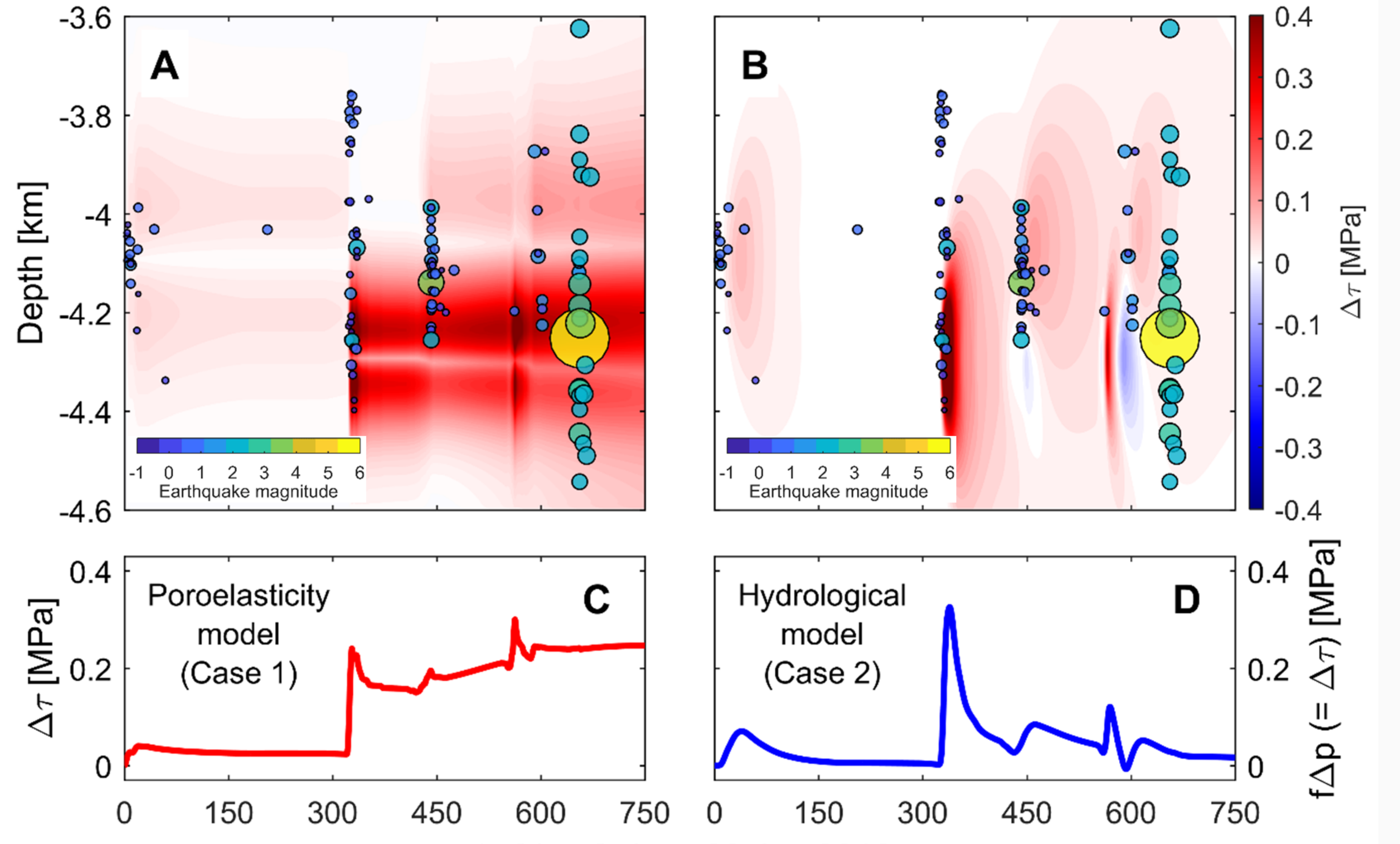
Chang et al. (2018) *BSSA*

Modeling Results



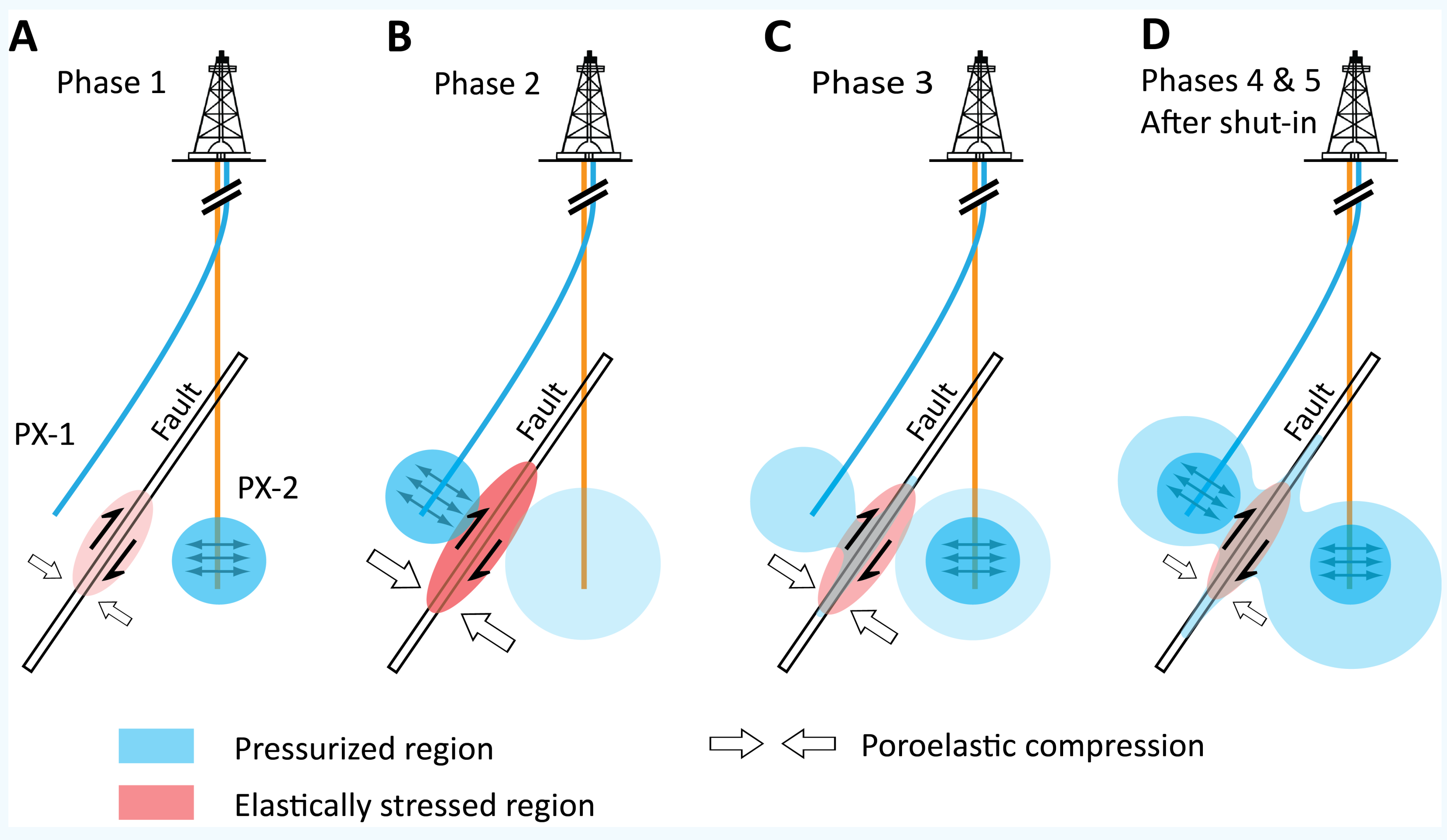
- Near-instant poroelastic stressing causes early seismic events.
- Delayed pore-pressure diffusion, due to low-permeability of basement, results in gradual increases of Δτ along the fault.

Coupled vs. Uncoupled



Chang et al. (2020) *Sci. Rep.*

Sequences of Potential Mechanisms



(A)During Phase 1, when the first injection started at PX-2: pore pressure started to diffuse into the surrounding basement rock, but poroelastic compression causes shearing on the fault plane immediately.

(B) During Phase 2, when the first injection started at PX-1: the expansion of pressurized regions at both sides of the fault plane gives stronger poroelastic stressing, but still we don't have pore-pressure diffusion into the fault.

(C) During Phase 3, when second injection started at PX-2: fluids injected at PX-1 start to penetrate into the fault due to the closer distance of PX-1 to the fault.

(D) During Phases 4–5 and after shut-in: Continuous poroelastic stressing and gradual diffusion of pore-pressure accumulate energy along the fault, consequently inducing moderate to large earthquakes including the $M_w5.5$ main event.

This work is supported by the Laboratory Directed Research and Development program at Sandia National Laboratories. Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.