On the physics-based processes behind production-induced seismicity in natural gas fields

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induSED seismicity

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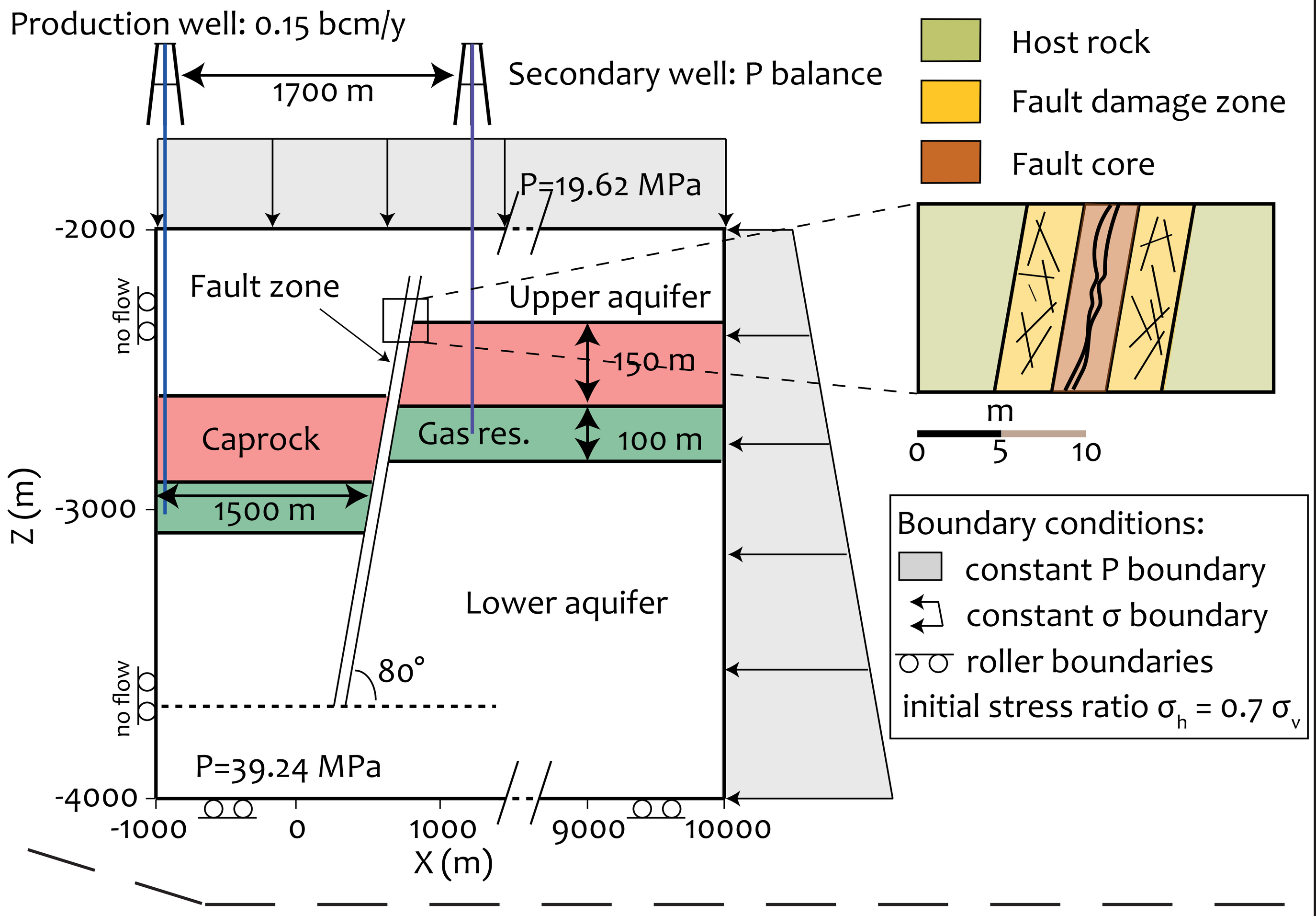
1 Introduction

Induced seismicity due to natural gas exploitation has been observed at different sites around the world. Although these earthquakes are usually rather moderate in magnitude, they can be hazardous for mankind because of their shallow hypocenters. A well-known example is the Groningen gas field in the Netherlands, where a strong increase in induced seismicity during the last ten years has led the operators to significantly lower the production rates [1]. Given the high public impact, it is crucial to understand the underlying processes involved during natural gas production. In this work, we propose a single-fault model in 2D using the coupled hydro-mechanical simulator TOUGH-FLAC [2], which includes multi-phase fluid flow and poroelastic stress. The model allows us to simulate rupture on a fault plane from which we can calculate magnitudes for the induced eartquakes.

2 Model

We simulate reservoir depletion using a model consisting of **two permeable reservoir compartments offset by a fault zone** and covered by impermeable caprock. The fault zone consists of a damage zone and a low permeability fault core. We allow for **sudden slip on the fault core** using a strain-softening friction model.



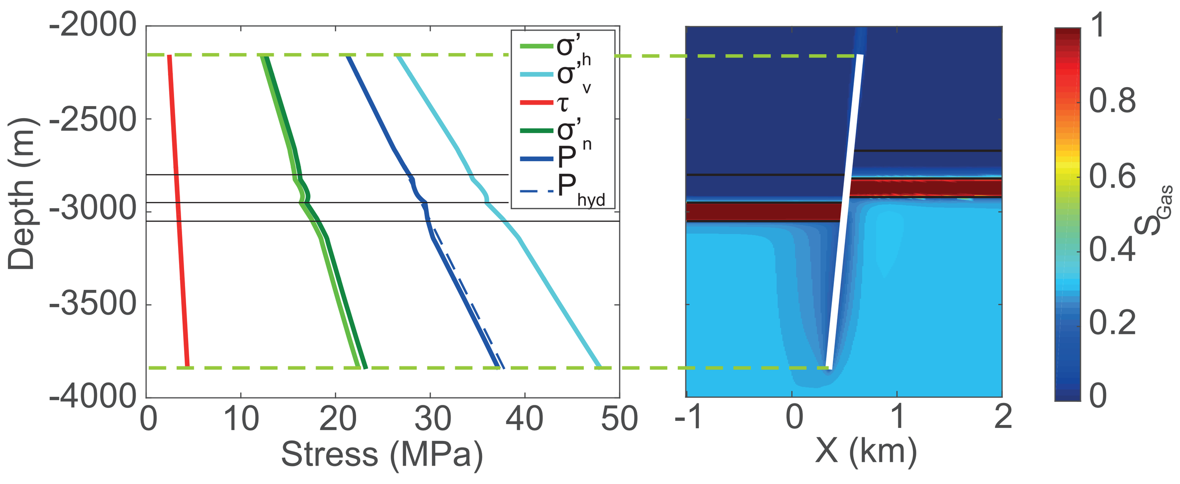
Mechanical and hydraulic parameters

Layer	E (GPa)	υ (-)	ρ (kg/m³)	φ (%)	κ (m²)
Upper aquifer	40	0.25	2260	10	10^{-14}
Reservoir	20	0.25	2260	16	10^{-13}*
Basal aquifer	40	0.25	2260	1	10^{-18}
Caprock	40	0.25	2260	1	10^{-21}
Damage zone	40	0.25	2260	10	10^{-17}*
Fault core	10	0.25	2260	10	10^{-19}*

* permeability is stress dependent in fault zone and gas reservoir [3, 4]

Initial conditions

P is hydrostatic except at reservoir depth, where gas is present

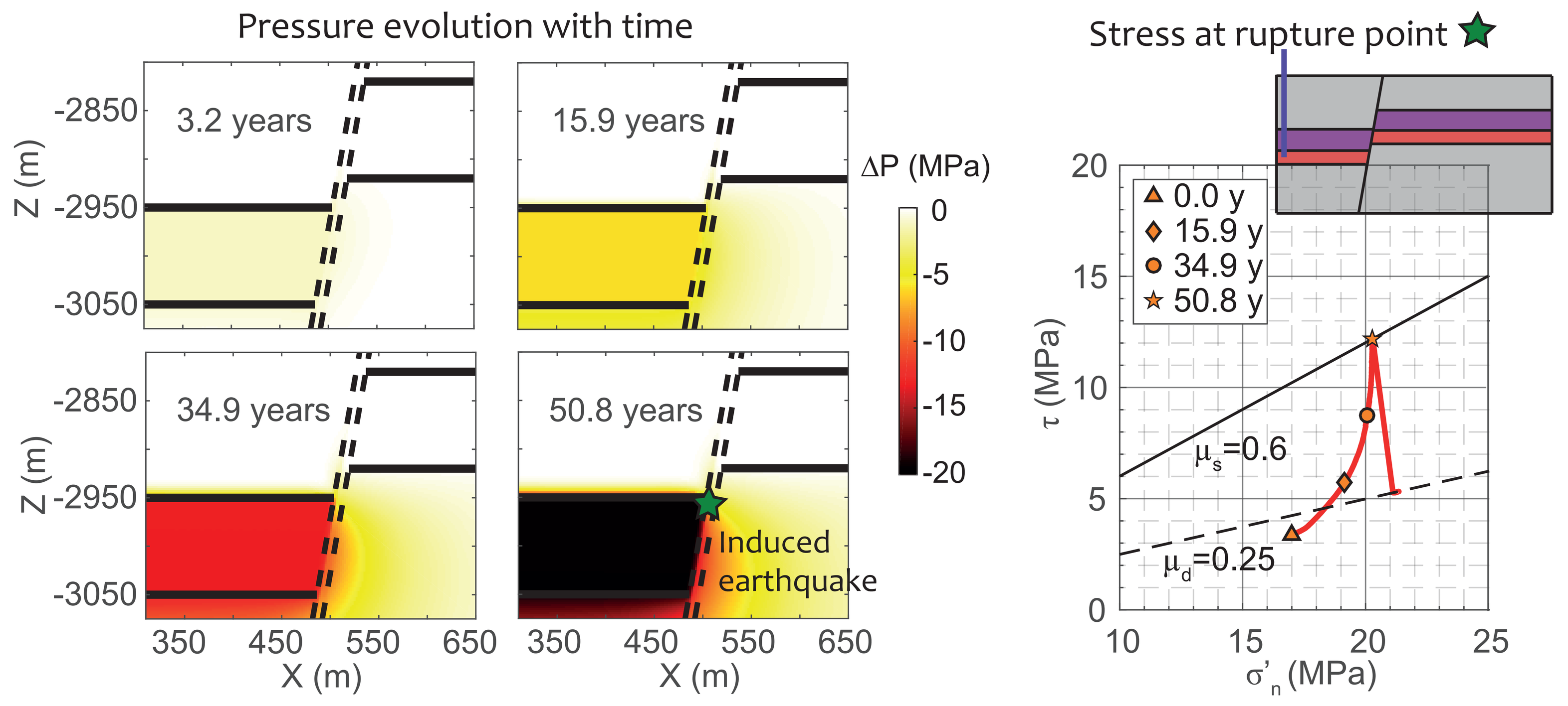


We consider 2 scenarios:
(i) **single well case**, where production occurs from the left model boundary at 3000 m depth
(ii) **multiple wells case**, where a secondary well produces from the right compartment to maintain similar pressure drop in both compartments

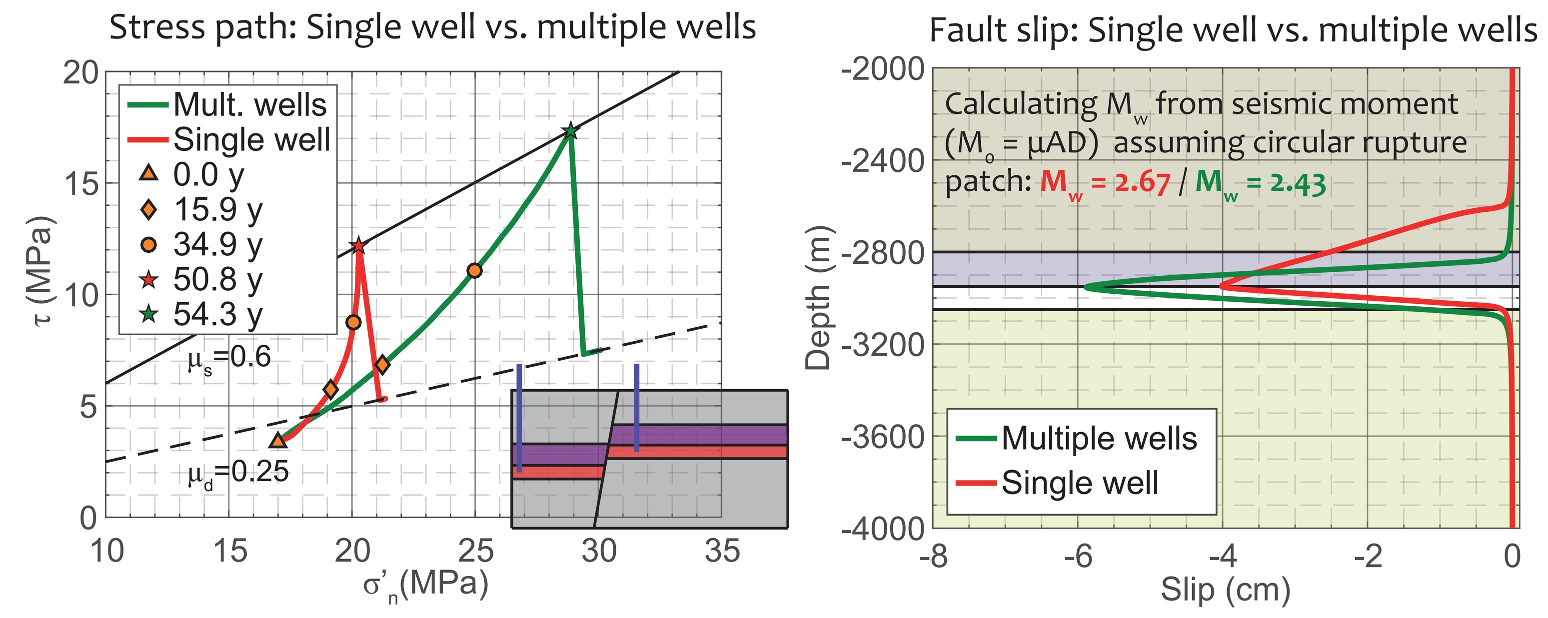
Subsequently, we test different scenarios to avoid fault reactivation:
(i) **shut-in of production well** after 40 y and 50 y, respectively
(ii) **re-injection of gas** into left compartment or into right compartment

3 Results and Discussion

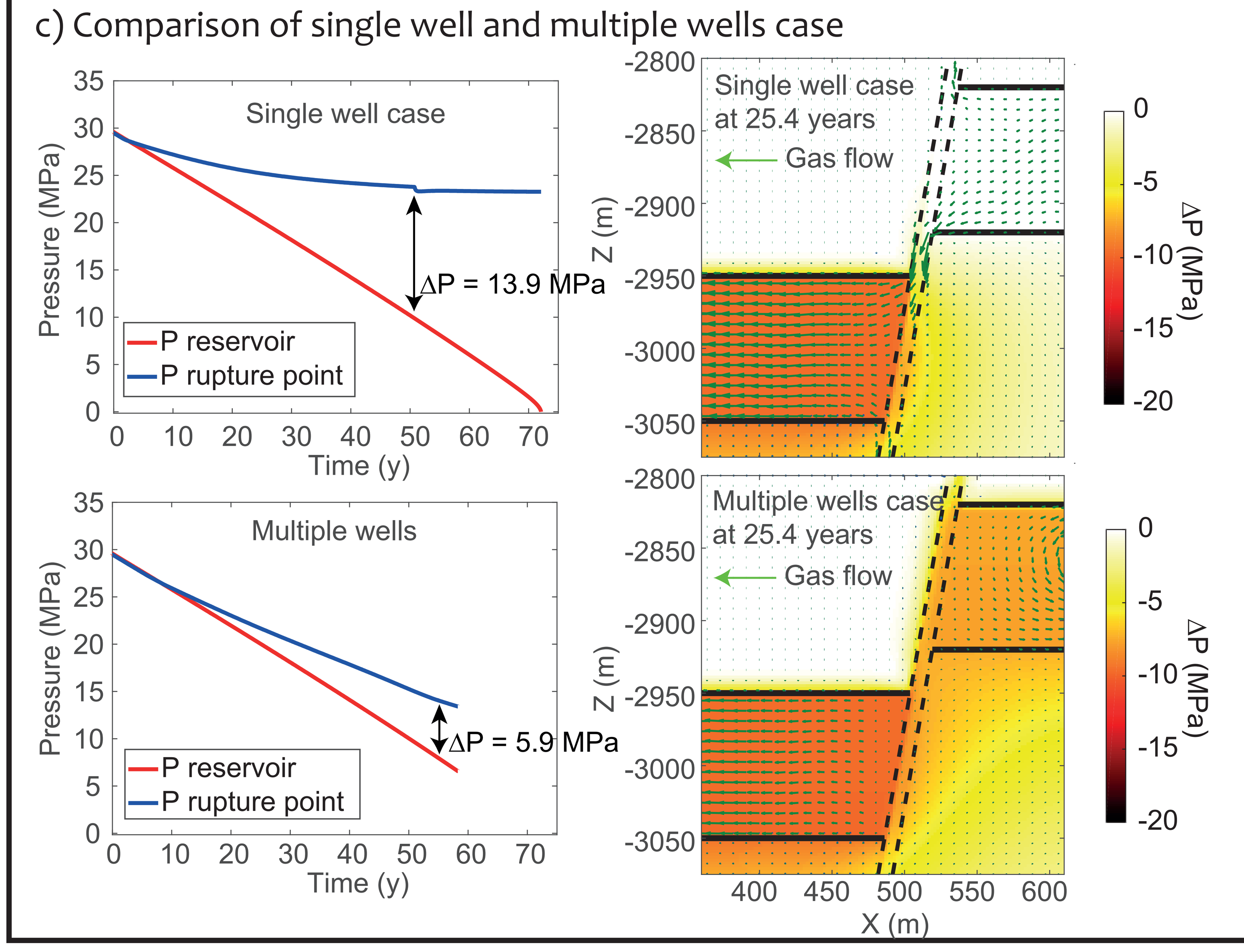
a) Single well case: Production in left compartment (0.15 bcm/y)



b) Multiple wells case: 2nd well to maintain equal ΔP in both compartments



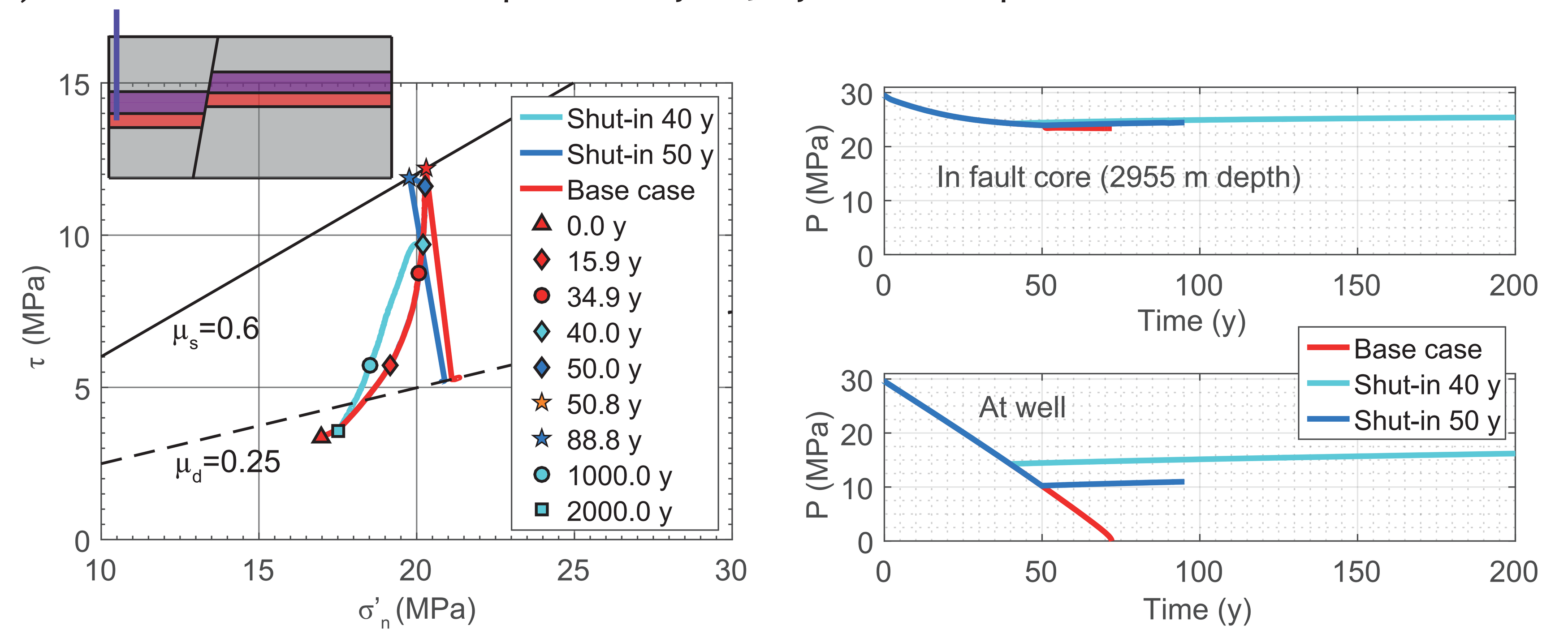
c) Comparison of single well and multiple wells case



- Single wells case: Stress path bent due to **poroelastic stress and gas inflow** into fault zone from right compartment
- Multiple wells case: **Stress path less bent** since fluid mainly flows out of fault zone
- **Induced earthquake slightly larger for single well case** (rupture is stopped at ~2800 m depth for multiple wells case)

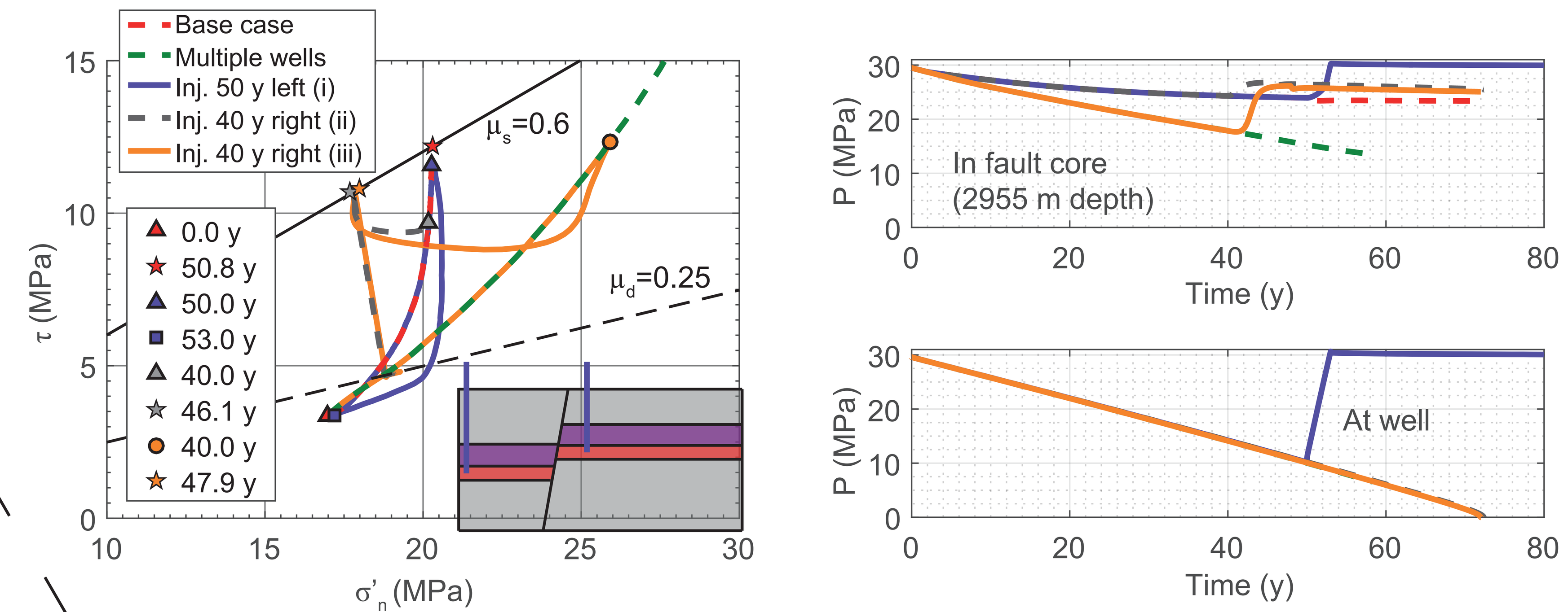
4 Avoiding fault reactivation

a) Well shut-in: Production stop after 40 y or 50 y in left compartment



- Shut-in after 40 y: reduction in effective normal stress and shear stress -> **fault is stabilised.**
- Shut-in after 50 y: Fault is so close to rupture that production stop **cannot avoid fault reactivation.**

b) Re-injection: (i) After 50 y in left compartment, (ii) after 40 y in right compartement (single well production at left side), (iii) after 40 y in right compartment (double well production)



- Injection in left compartment after 50 y: Shear stress decreases immediately -> **fault is stabilised.**
- Injection in right compartment: Gas flows from right into left compartment through fault zone and increases P in fault zone -> effective normal stress decreases -> **fault is destabilised.**

Re-injection into neighbouring reservoir compartment does not prevent earthquake!

5 Conclusions

- Poroelasticity and **fluid flow has strong influence on evolution of stress** in fault (bending of stress path due to fluid inflow)
- **Reactivation of fault zone earlier when fluid flow is included,** because effective normal stress is reduced and rupture occurs at lower shear stress
- Production with two wells in neighbouring compartments does not avoid fault reactivation, since **offset of reservoirs causes shear stress to increase**
- Shut-in of production well avoids fault reactivation unless a highly stressed fault is present (**earthquake can be induced decades after production stop**)
- Re-injection into reservoir does only **prevent fault from being reactivated when injection occurs in reservoir under depletion** and **not when injection occurs in neighbouring compartment** (fluid flow from right to left compartment causes fault reactivation)

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