Fluid pressure drops during stimulation of segmented faults in deep geothermal reservoirs

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CHARACTERIZATION OF DEEP GEOTHERMAL SYSTEMS

1. Introduction

In this study we use the numerical simulator CFRAC to analyse pressure drops observed during stimulation of deep geothermal wells (Fig. 1). We develop a conceptual model of a fractured geothermal reservoir to analyse the conditions required to produce pressure drops and their consequences on the evolution of seismicity, fluid pressure, and fracture permeability throughout the system. For this, we combine two fracture sets, one able to be stimulated by shear mode fracturing and another one able to be stimulated by opening mode fracturing. With this combination, the pressure drop can be triggered by a seismic event in the shear-stimulated fracture that is hydraulically connected with an opening-mode fracture. Our results indicate that pressure drops are not produced by the new volume created by shear-dilatancy, but rather by the opening of the conjugated tensile fractures. Finally, our results show that natural fracture/splay fracture interaction can potentially explain the observed pressure drops at the Rittershoffen geothermal site.

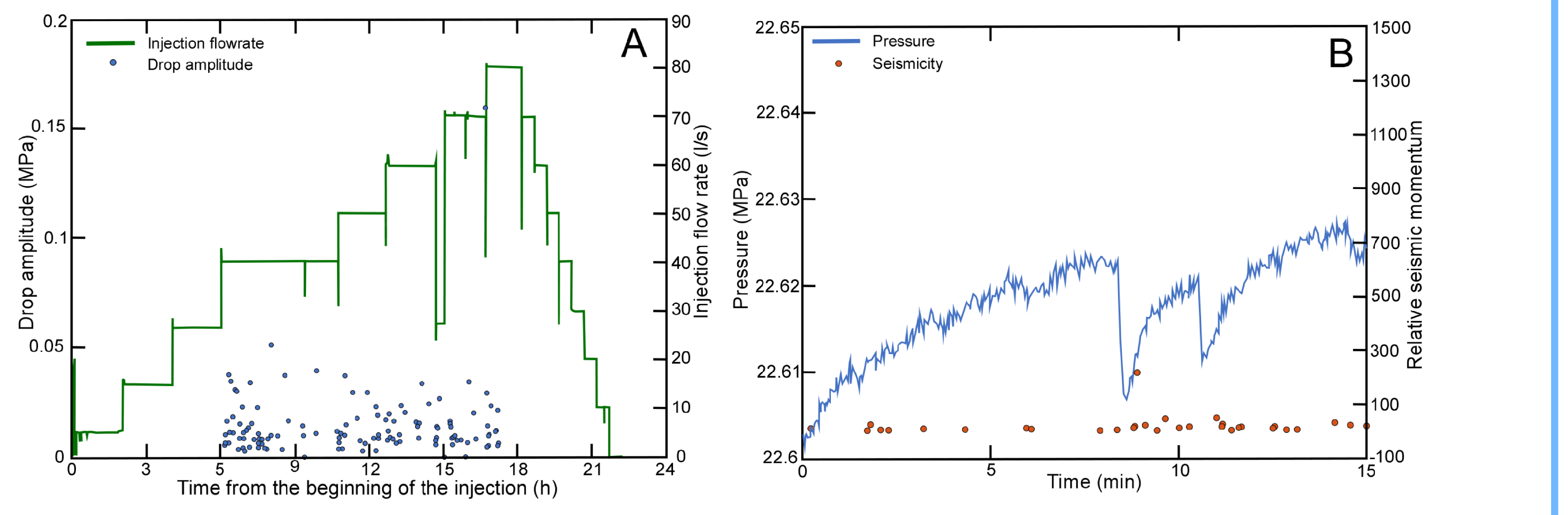


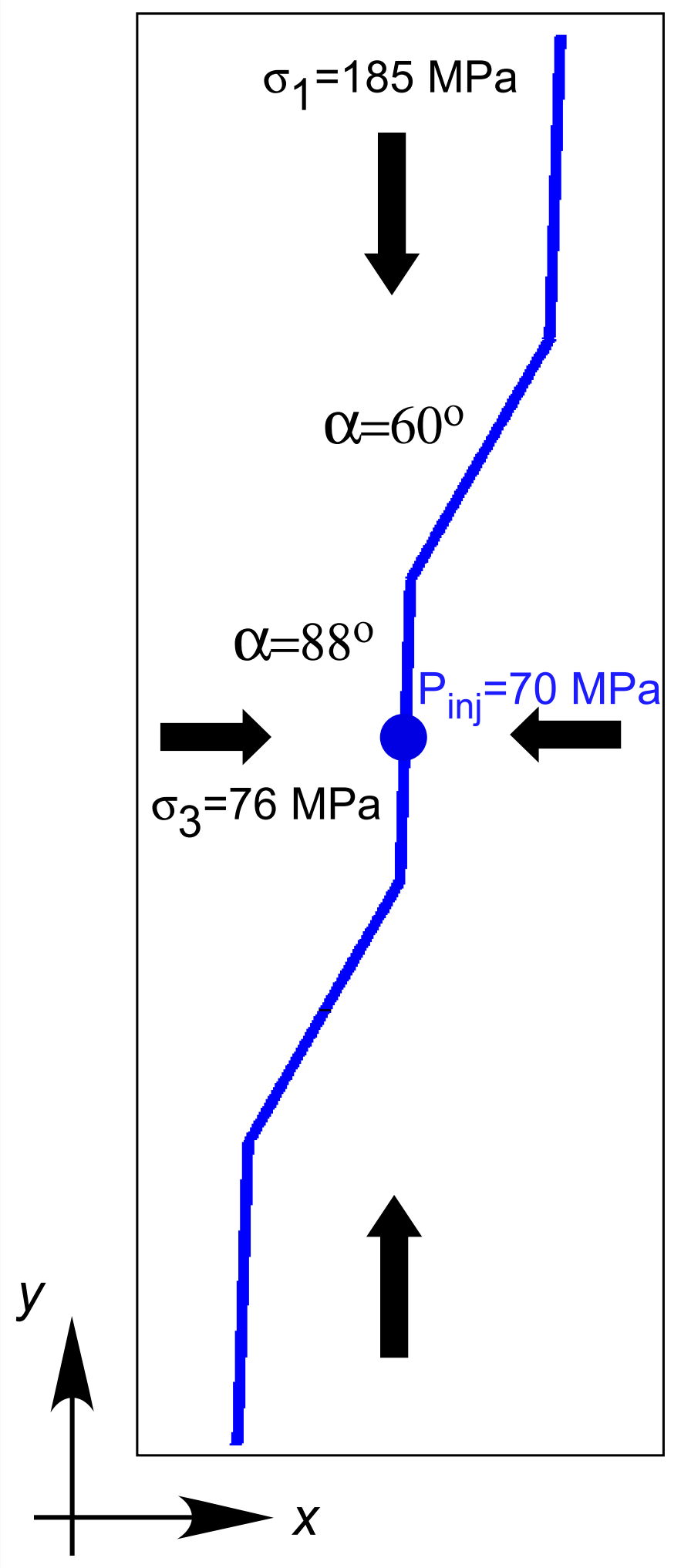
Figure 1. *(A) Injection flow rate and fluid pressure drop amplitude during fluid stimulation of the GRT1 well at the Rittershoffen geothermal reservoir. (B) A detail of the fluid pressure registered at well showing two examples of pressure drops and the associated seismicity swarm. Modified from Meyer et al. (2017).*

2. Methods

2D CFRAC-Boundary element code. Fully-coupled hydro-mechanical problem and the associated induced seismicity (McClure 2012).

The frictional resistance to slip is given by the Coulomb's law and the evolution of the friction coefficient was defined using a rate-and-state formulation (Segall 2010).

3. Geometry and Model Set-up



The geometry of the model consisted of a **single fracture defined by several linked segments with different orientations** with respect to the maximum compressive stress (σ1). Each individual fracture had a length of 60 m and was discretized into 20 cm-long elements (Fig. 2). A constant out-of-plane thickness of h=100m was considered for all models. **Fractures at α=60° are characterised by a critically loaded behaviour, with high associated seismicity** and ruptures that can propagate through the entirely fracture. On the other hand, **fractures at α=88° are characterised as having an aseismic orientation, with slow sliding velocities and unable to produce seismicity** (e.g. Gischig 2015; Piris et al. 2017). **We assumed strike-slip regime.**

SIMULATIONS EVALUATING:

- Injection segment orientation (60° or 88°). Moldel "60-88" and model "88-60" (Fig.2)
- Hydraulic fracture propagation as wing cracks on the 60° tips.
- Segment size (50m, 40m, 30m, 20m, 15m, 6m)
- Shear dilation angle (0°, 2.5°, 5°)
- With similar Rittershoffen configuration (Cornet et al. 2007; Baujard et al. 2017; Meyer et al. 2017) stress state (σ1=50 MPa, σ3= 29 MPa), initial fluid pressure of 23.7 MPa and constant injection pressure of 28 MPa. With different segment sizes (80m, 60m, 50m, 40m, 30m, 20m, 15m and 6m).

Figure 2. *The blue line represents the fracture configuration and the blue dot the injection point. Each fracture segment is 60 m long. Orientation and values of principal stresses and injection pressure (Pinj) are indicated.*

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4. Results

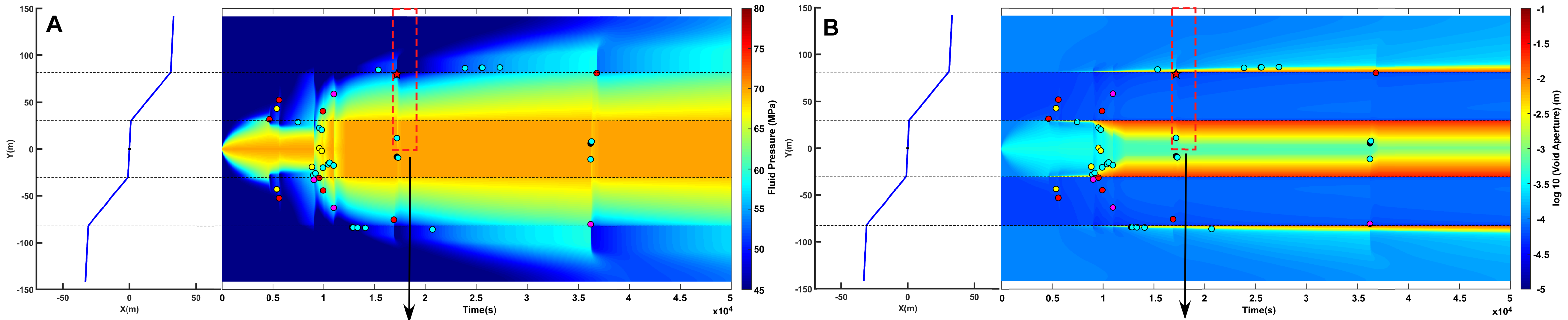


Figure 3. *Sketches of the simulated fracture network (blue lines on the left), and the evolution of **(A) fluid pressure and (B) fracture aperture** for the model "88-60". Dashed lines indicate the location of fracture segment intersections. Coloured points indicate the location of the earthquake hypocentres and magnitudes (cyan: M<0, green 0=M<1, yellow: 1=M<1.5, red: 1.5=M<2 and pink: M=2). The red dashed area indicates the data shown in Figures 5 and 6.*

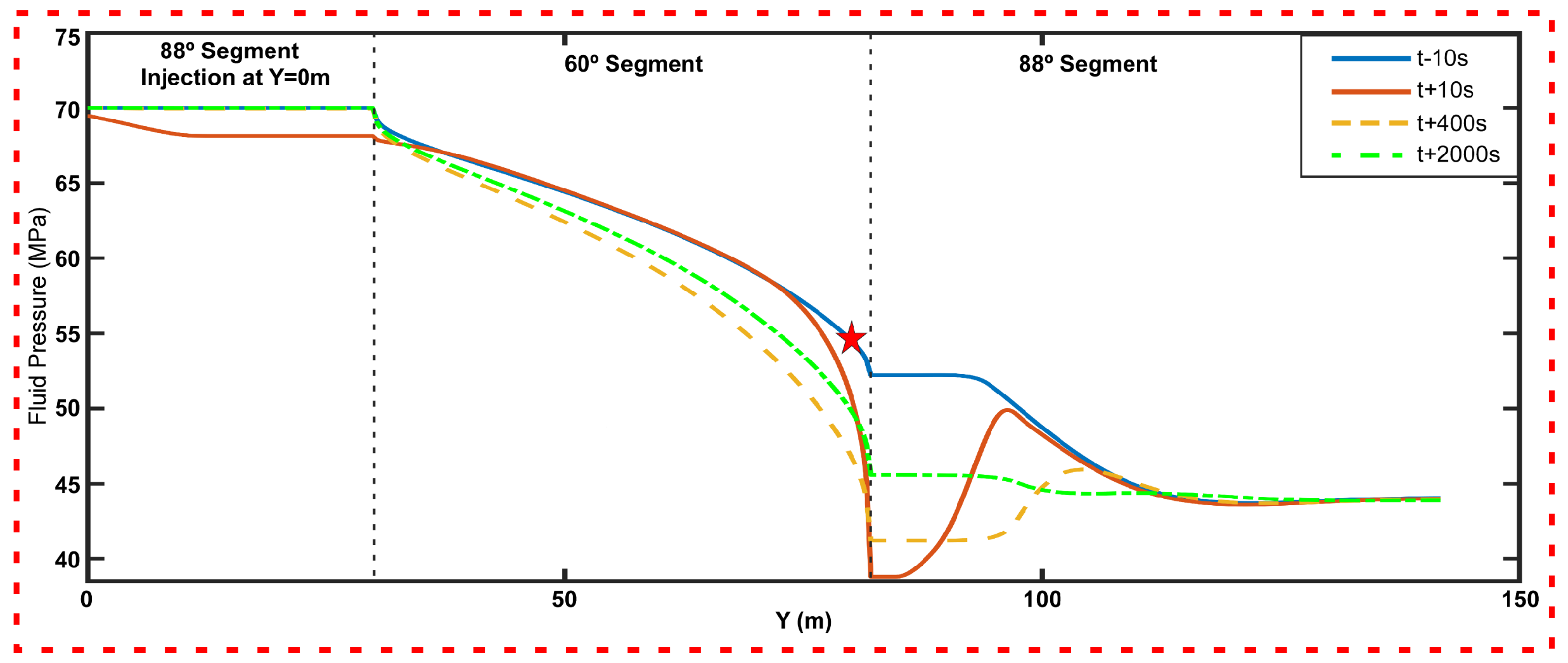


Figure 4. *Fluid pressure evolution with the distance to the well (Y) before (t-10s) and after (t+10s, t+400s and t+2000s) a seismic event (indicated by red star). The event corresponds to the red dashed area indicated in Fig. 3. Vertical dashed lines indicate the location of fracture segment intersections.*

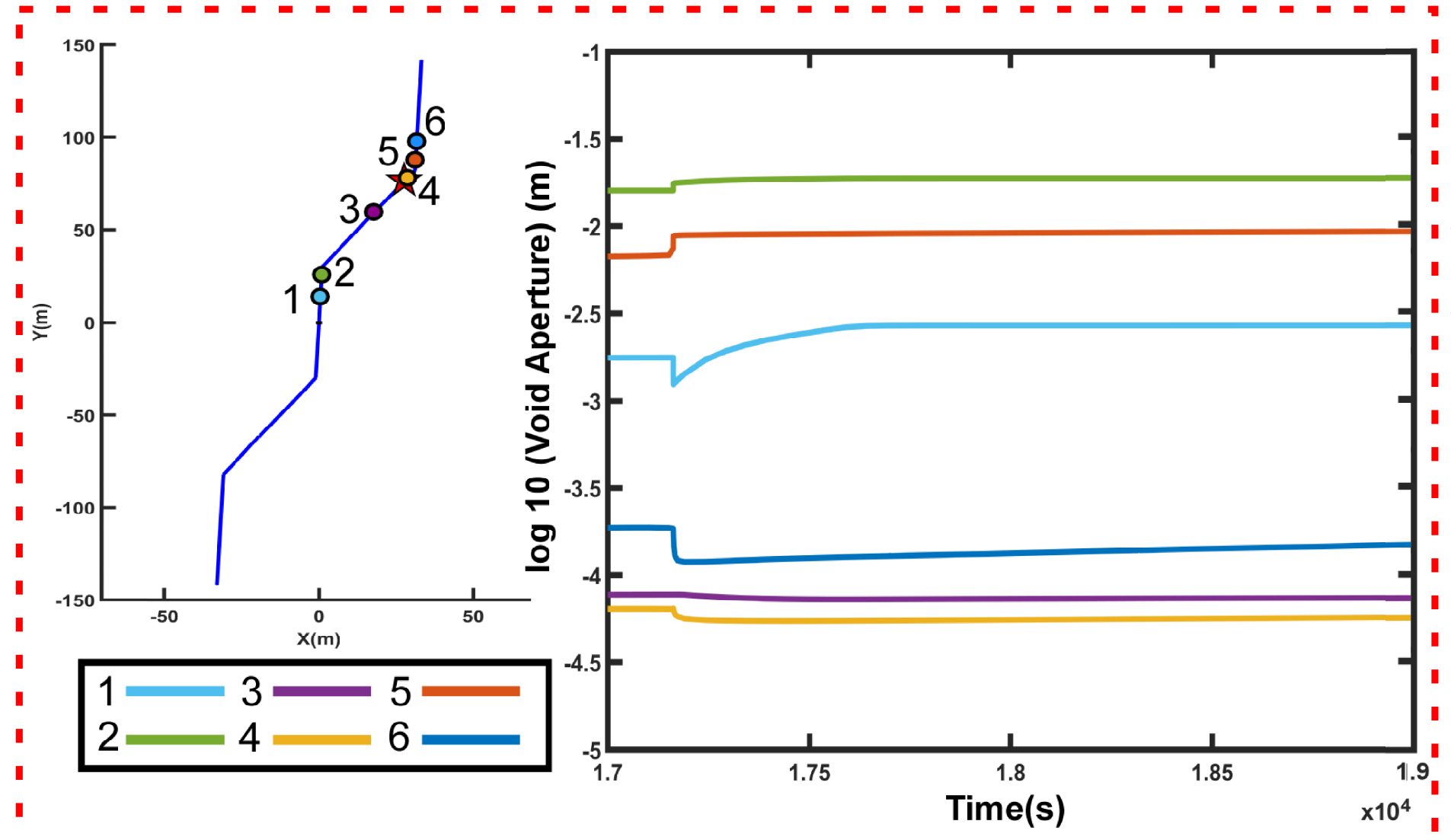


Figure 5. *Right, fracture network (in blue) and location of control points (coloured dots). Left, evolution of log 10 void aperture) of the control points through time. The time interval and region monitored by control points is indicated in Fig. 3 by the red dashed area.*

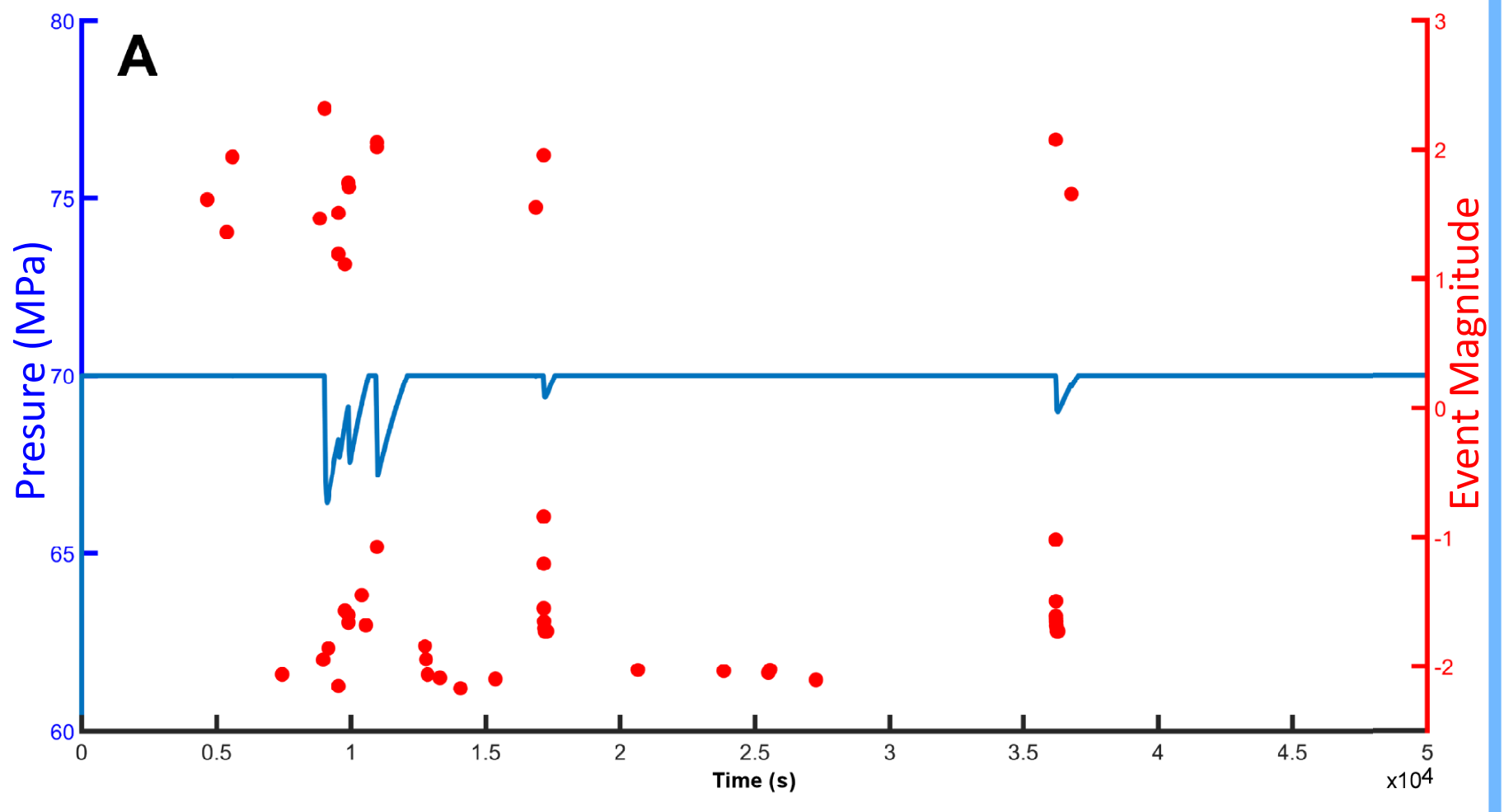


Figure 6. *Variation of the fluid pressure in the well. Magnitude of the seismic events are indicated by red circles. In general, events with larger magnitudes are linked to fluid pressure drops in well, although swarm of low magnitude earthquakes are observed after pressure drops.*

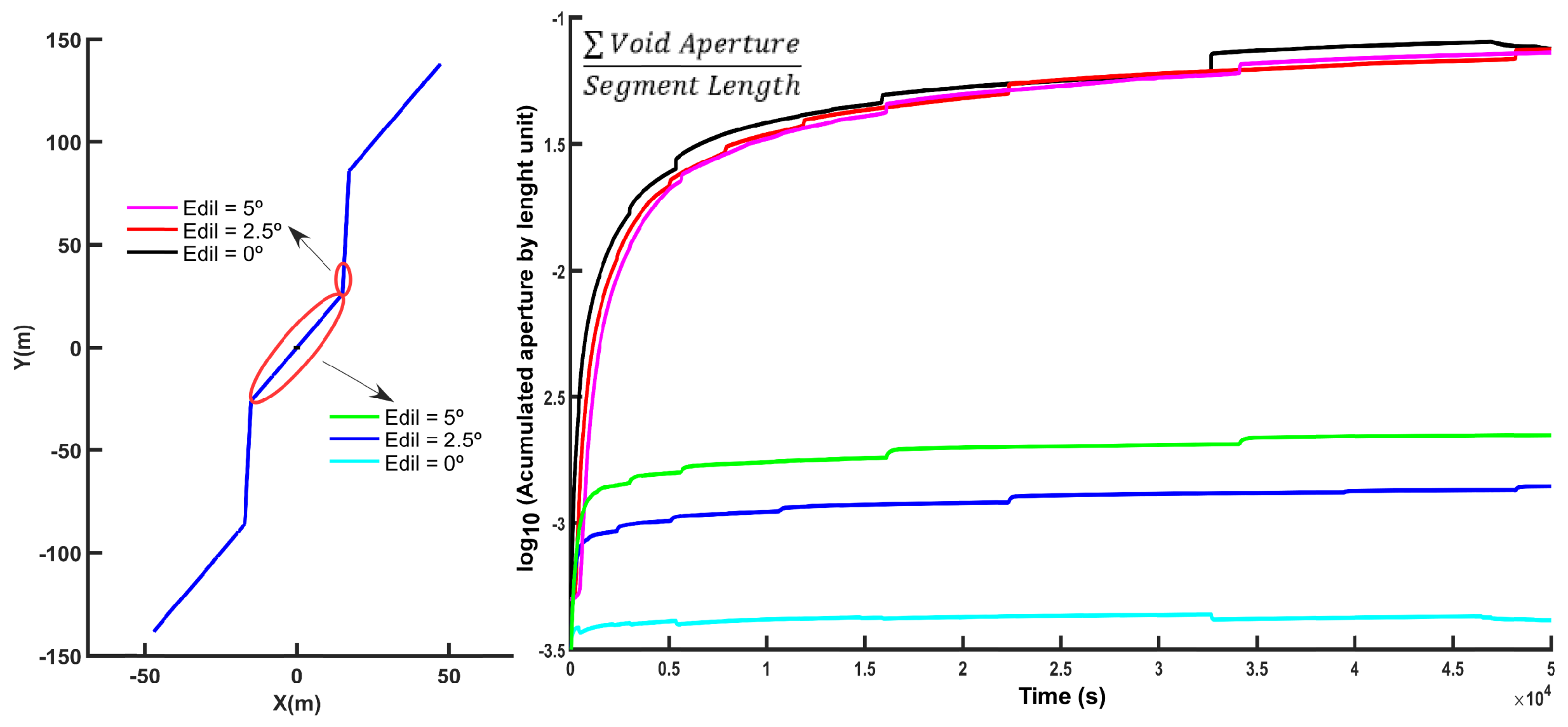


Figure 7. *Accumulated aperture by length unit in the injection seismic segment and in the opening region of the aseismic segment with different dilation angles (0º, 2.5º and 5º) for the "60-88" model. The sharp steps in the accumulated aperture were correlated with seismic events.*

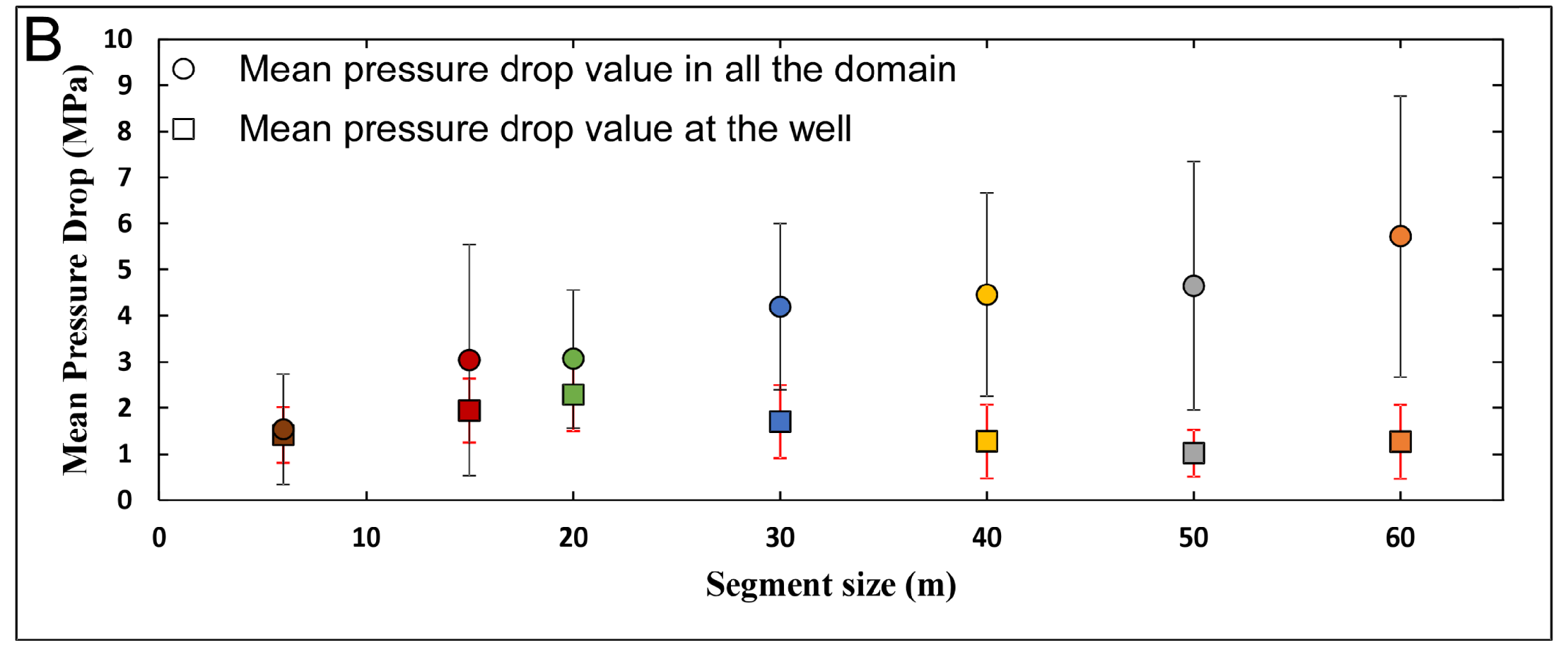


Figure 8. *Mean pressure drop values observed for all the simulation domain (circles) and felt in the well (squares) for different segment sizes. Error bars indicate the standard deviation.*

5. Discussion

PRESSURE DROP TRIGGERING MECHANISMS

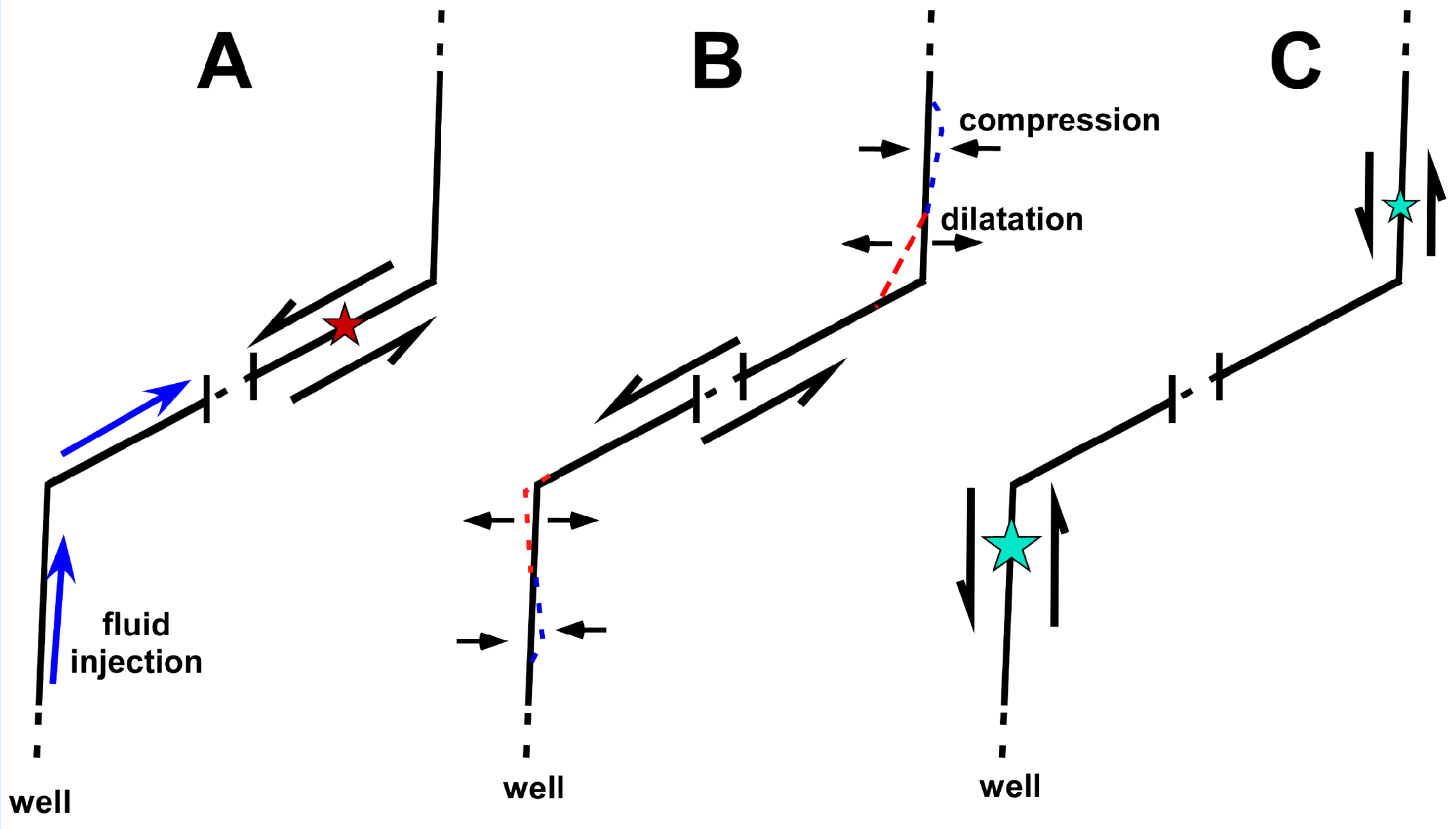
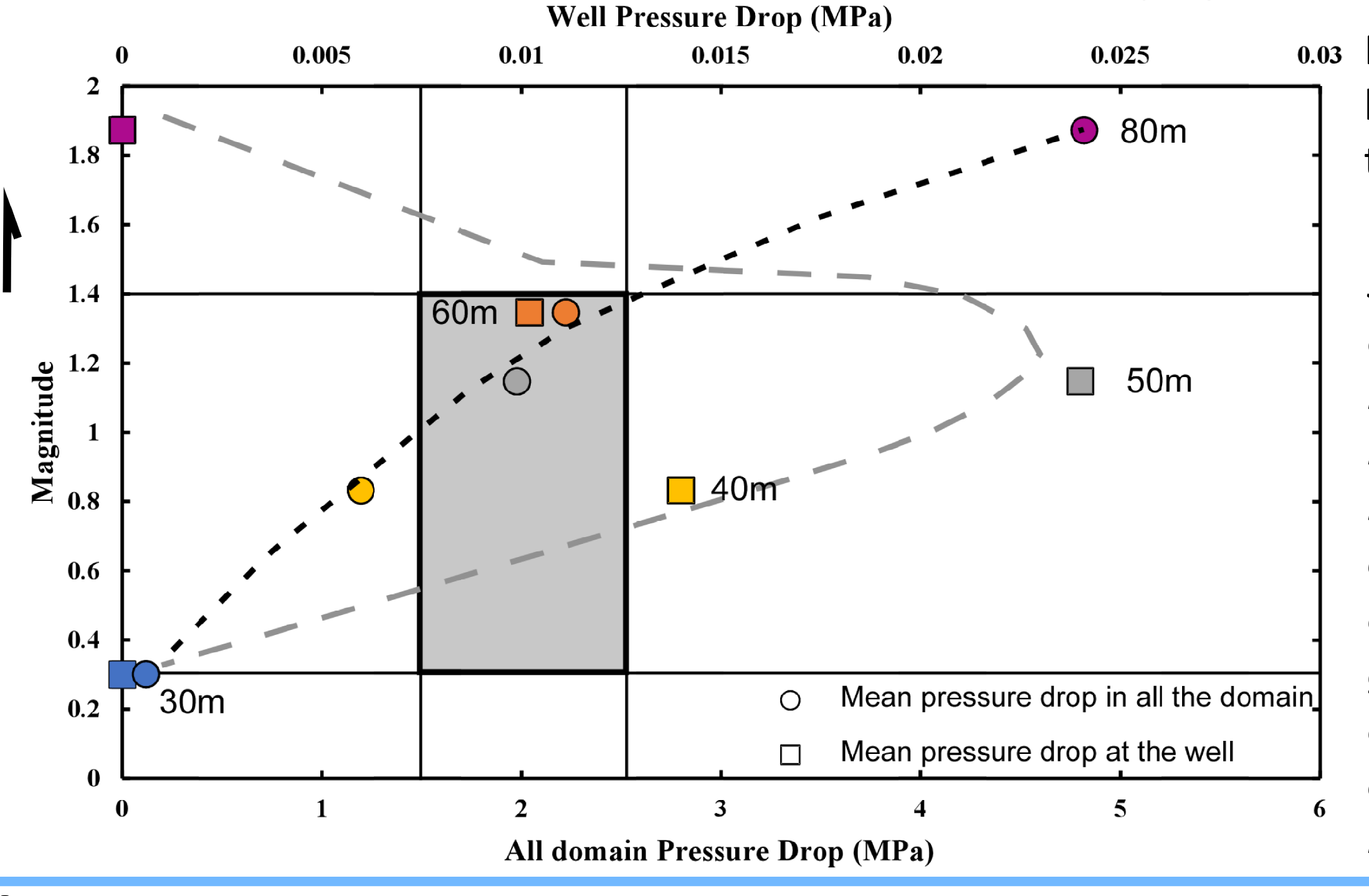


Figure 9. *Sketch representing the different processes involved in a fluid pressure drop. A. Start of the pressure drop process, in which a seismic event is produced at the seismic segment (red star), with arrows indicating the sliding direction. B. Dynamic aperture (red dashed lines) and closure (blue dashed lines) on the aseismic tips connected with the seismic segment. C. Low-magnitude events at the aseismic tips occur to accommodate the opening generated. Seismicity is higher in the already pressurised segment than the new stimulated segment (blue stars).*

RITTERSHOFFEN COMPARISON



For this setup, pressure drops and seismic magnitudes are lower than those previously described, as stress magnitudes are substantially lower.

Figure 10. *Mean seismic magnitude against mean pressure drop in all the domain (circle symbols, lower x axis) and at the well (square symbols, upper x axis). Each colour represents a different segment size, ranging from 30 to 80 m. Pressure drops were not observed in models with length size lower than 30m. The black dashed curve indicates the general tendency of pressure drops measured in all the domain, while the grey dashed curve represents the general tendency of pressure drops at the well. The dashed area indicates the range of pressure drops and seismic events observed during stimulation in the Rittershoffen reservoir (Meyer et al., 2017).*

6. Conclusions

1. The results suggest that two fracture sets can influence pressure drops: one system able to be stimulated by shear (that will produce seismic events) and another one able to be stimulated by opening mode fracturing (that will be aseismic).

2. In the simulations, a pressure drop can be triggered by a seismic event in a shear-stimulated fracture that is hydraulically connected with a tensile or opening-mode fracture. The pressure drop is not produced by the new volume created by dilatancy, but rather by the opening of the conjugated tensile fracture.

3. This tensile fracture set may be part of the preexisting fracture network, or be developed as a hydrofracture during the stimulation phase. However, in our simulations no pressure drops are observed during hydraulic fracture propagation at the tips of a preexisting fracture.