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Pressure front interacting with a rate-and-state fault of heterogeneous permeability

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1 - Introduction

Many induced earthquake sequences could be seen as the rupture of brittle asperities along a fault zone, in response to fluid pressure changes generated by an injection at depth. Furthermore, the relocation of seismicity shows that these brittle patches only cluster on particular regions of the fault zone, which indicates that other portions of the fault are either creeping or not activated during the injection. This shearing behavior indicates heterogeneous permeability conditions within the fault zone. Here, we investigate the injection-induced seismic response of a heterogeneous fault plane featuring brittle asperities with low permeability embedded in higher permeability and ductile matrix.

2 - Modeling approach : coupling a hydromechanical and a quasi-dynamic earthquake model

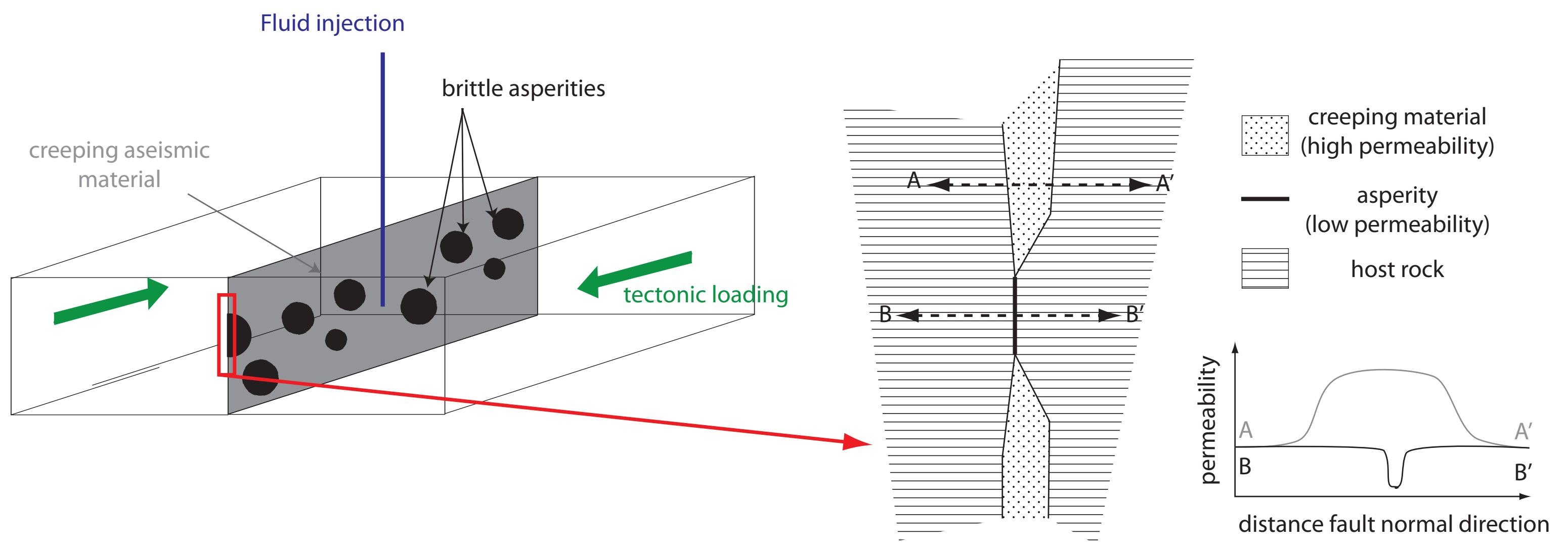

Fig 1 : Conceptual model assumed in this study. Earthquakes correspond to the rupture of brittle patches (asperities) embedded in a creeping matrix. A fluid injection is performed within such a prestressed fault system. We also assume an heterogeneous permeability within the system : during interseismic periods, asperities are locked and act as barriers to the flow. Creeping regions accumulate damage, and therefore present a higher permeability.

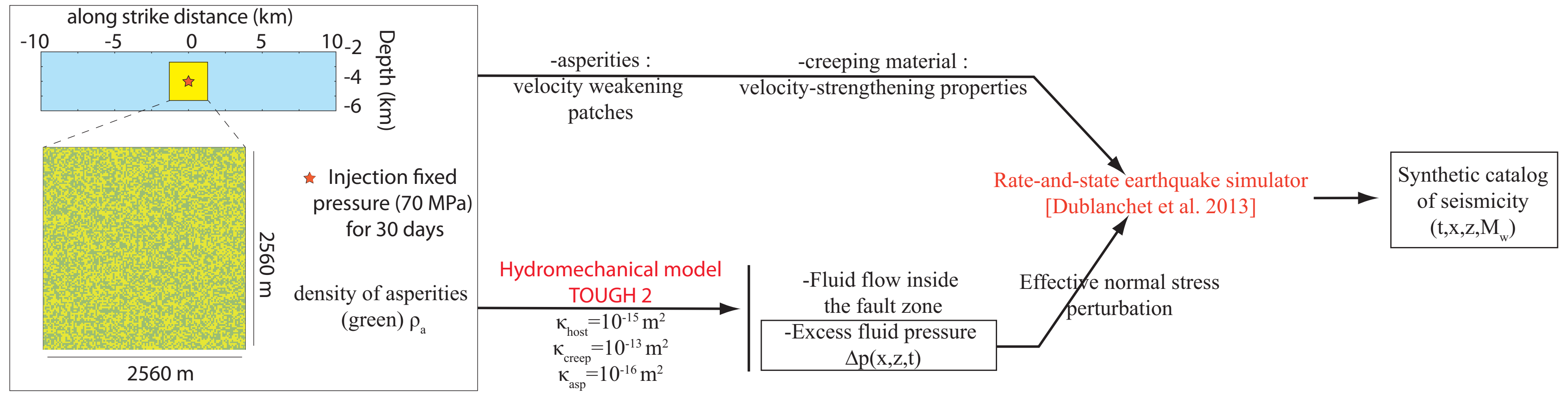

Fig 2 : Coupled modeling approach assumed in this study. From a given asperity distribution, a fluid flow is first computed with a hydromechanical model ***(Pruess* et al.*, 1999)***. *In a second step, the fault is modeled as a planar interface with frictional heterogeneities. The fluid pressure solution is used as a forcing term to compute seismicity.*

3 - Unpertubed behavior : the critical density of asperity ρ_a^*

The regimes of activity obtained in a rate-and-state asperity model are controlled by the density of asperities $\rho_a = S_{asp}/S_{tot}$ **(Dublanchet *et al.*, 2013a)**. The transition between a regime of uncorrelated activity and a regime of highly clustered swarms with large magnitude events occurs when the density of asperity exceeds a critical threshold ρ_a^* (Fig. 3). This is equivalent to an effective friction concept **(Dublanchet *et al.*, 2013b)**: if A is the spatially averaged rate-and-state $a-b$ parameter, we have

$\rho_a > \rho_a^* \equiv A < 0$ effective weakening behavior
$\rho_a < \rho_a^* \equiv A > 0$ effective strengthening behavior

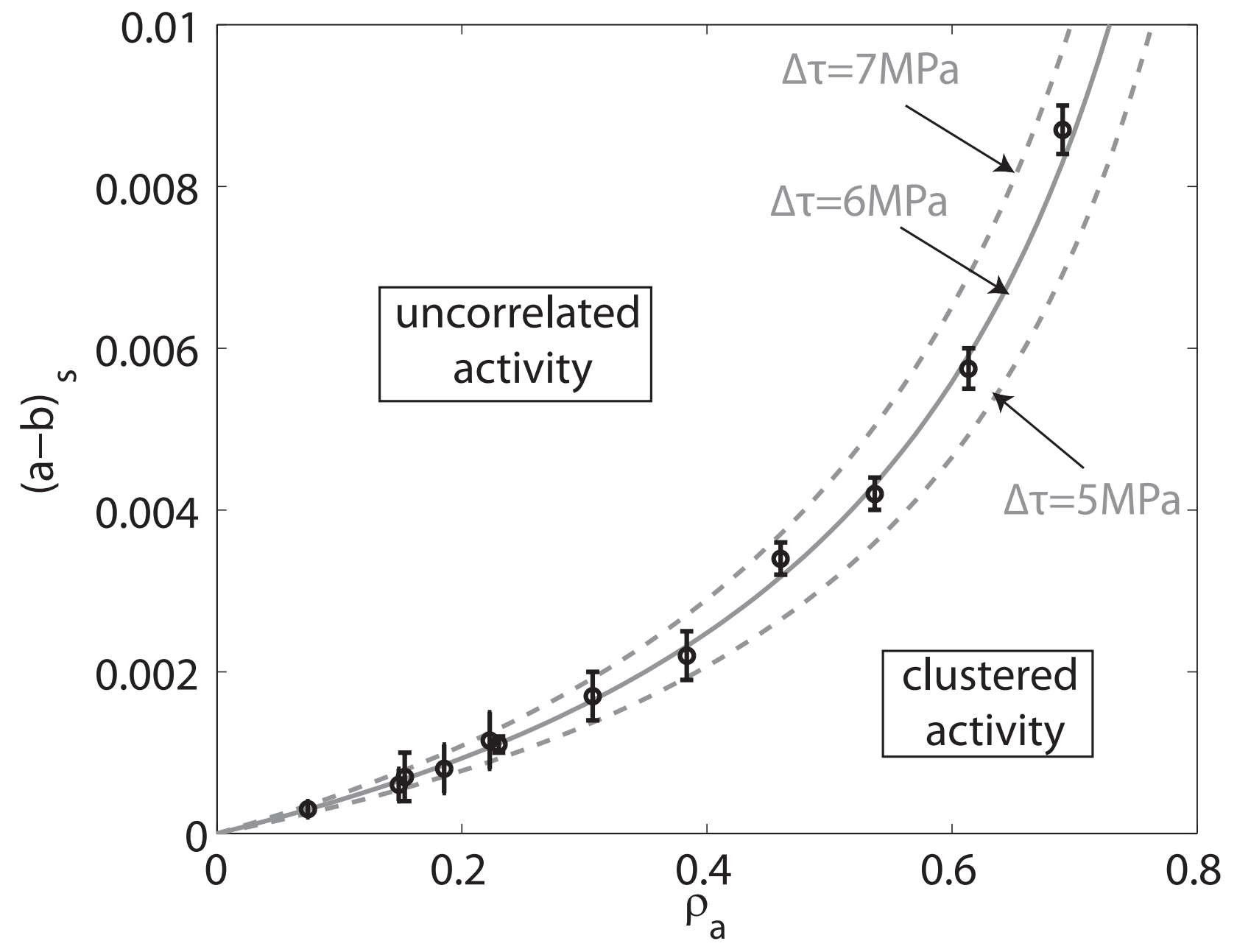

Fig. 3 : Transition between the regimes of seismicity of an asperity fault, in the density of asperity-steady state friction parameter diagram.

4 - Injection for subcritical density of asperities $\rho_a = 0.5 < \rho_a^*$

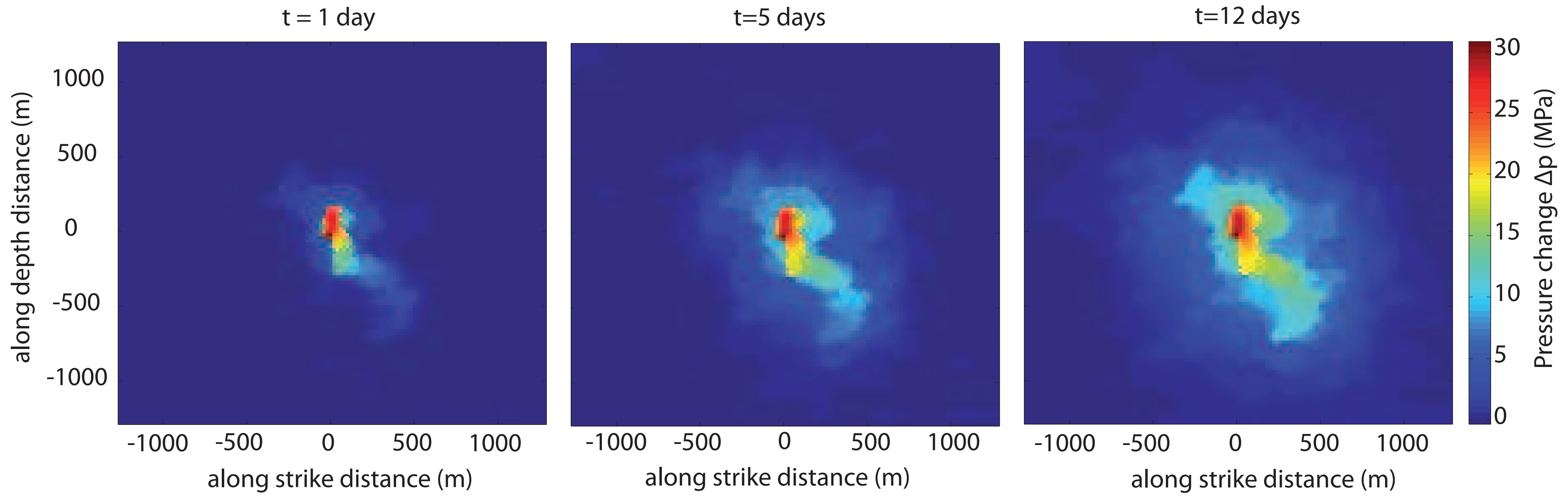

Fig. 4 : Excess fluid pressure Δp within the fault zone assumed, obtained with the hydromechanical model, for three different time steps. This solution is used as a perturbating term in the asperity model.

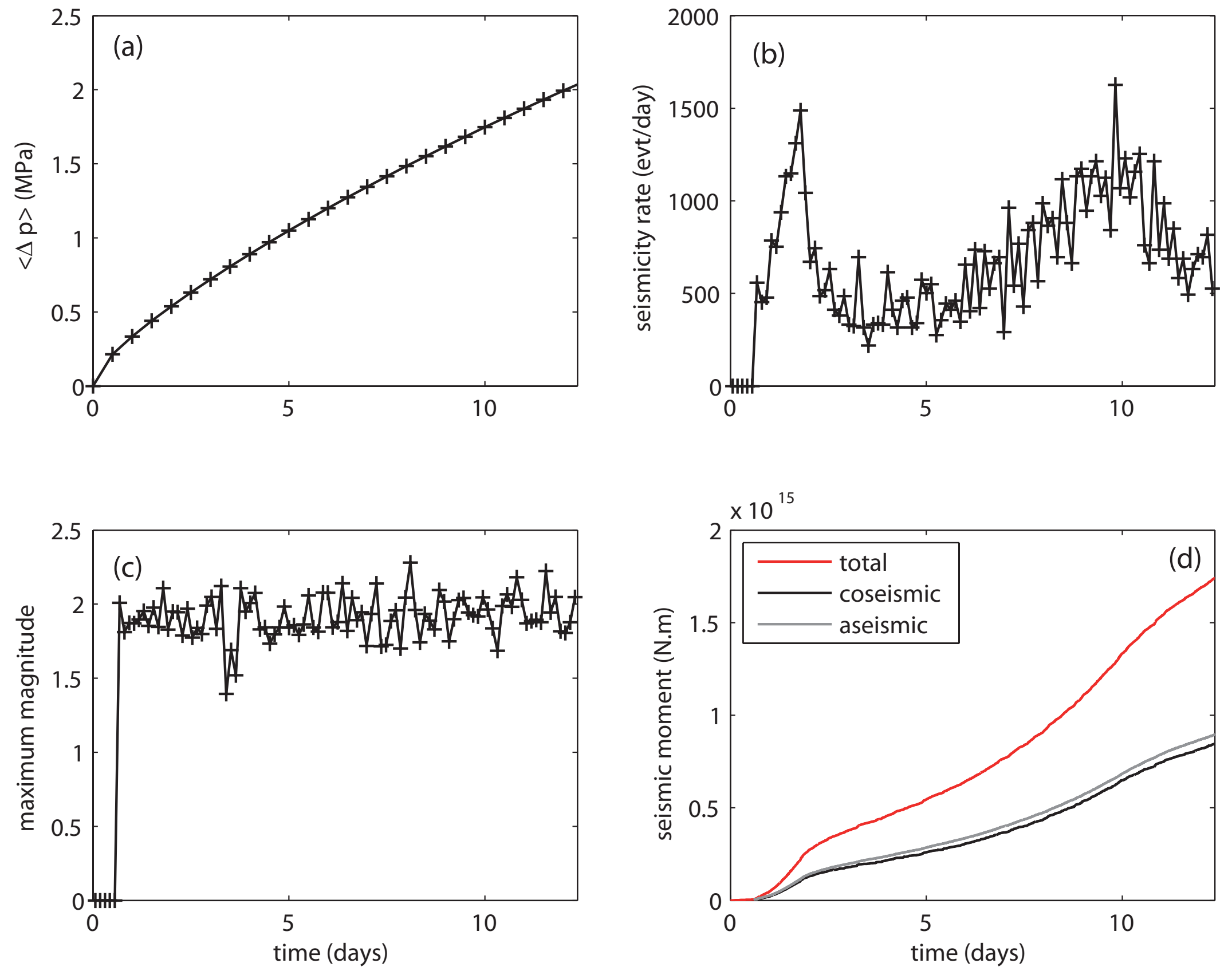

Fig. 5 : (a) Spatially averaged fluid pressure excess associated with the injection $< \Delta p >$ as a function of time during the injection. (b) Seismicity rate generated on the fault segment during the injection. (c) Maximum magnitude as a function of time during the injection. (d) Seismic moment (total, coseismic, and aseismic) released by the fault segment during the injection.

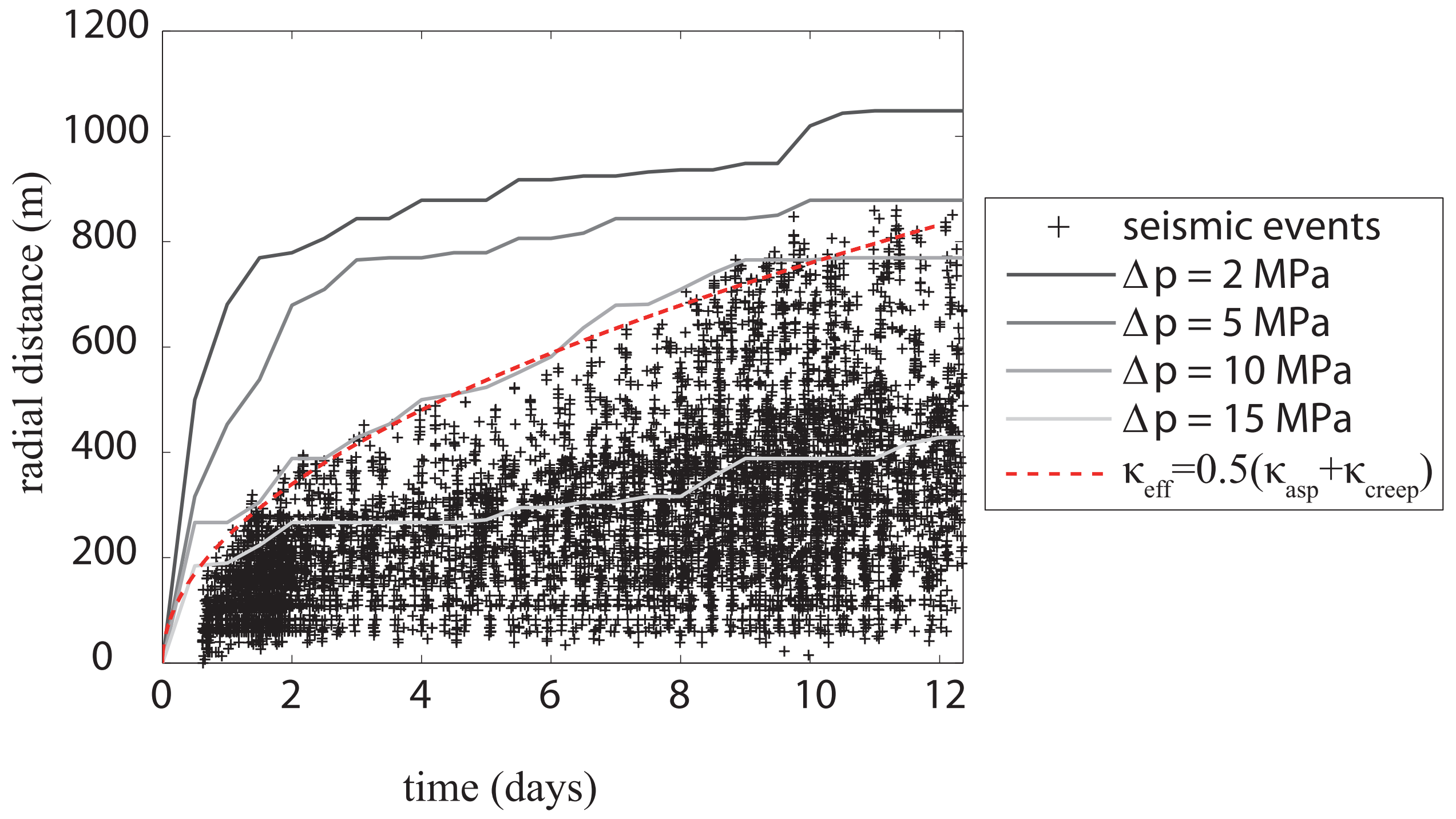

Fig. 6 : Distance to the injection point for each event (black crosses) recorded on the fault segment during the injection. Solid gray lines correspond to the maximum extent of a particular fluid pressure level Δp, computed from the injection point at each time step of the injection. The dotted red line is the effective diffusion curve for the fluid flow.

5 - Conclusions

In this study we proposed a new method to compute the injection-induced seismic response of a heterogeneous fault zone, which couples a hydromechanical model and an asperity model based on laboratory derived rate-and-state friction laws. This approach allows to quantify the amount of seismic vs. aseismic deformation generated by the fluid injection, to quantify the relative importance of static interaction and fluid effects in the triggering of seismicity, and to investigate the physical conditions leading to large magnitude events. For stable fault conditions (subcritical density of asperities), the seismicity could be used to track the fluid at depth.

References

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