Simulation of induced seismicity associated with fluid injection in single fractures: influence on the fracture slip regime

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1. Introduction

The so-called Enhanced Geothermal Systems (EGS) are characterized by a stimulation phase that aims to increase fluid flow and heat transfer between wells by increasing the permeability and transmissibility of the reservoir. However, this technique induces low-magnitude seismicity that occasionally results in damage at the Earth's surface. Numerical simulations able to reproduce the hydro-thermo-mechanical behaviour of geological reservoirs are an essential tool for the evaluation and forecasting of induced seismicity in such systems. In this study, the numerical code CFRAC (e.g. McClure, 2012) is used to systematically evaluate how the orientation of fractures with respect to the maximum compressive stress (σ1) influences seismicity, the injection rate and the fracture sliding behaviour. After this, and seeing different sliding regimes in function of fracture orientation. Two characteristic sliding regimes were combined to see if the behaivour observed in single fractures is conservative for orientation change fractures.

2. Methods

The models were carried out with the discontinuous element code CFRAC (Complex ReseArch Code v 1.3; McClure, 2012).

- Fully coupled thermo-hydro-mechanical problem is solved for fractures, which can either open or slide, and the associated induced seismicity.
- A microseismic event is considered to begin when the sliding velocity along a fracture exceeds a reference velocity of 5 mm/s. A slip event is considered finished when the highest velocity in the fracture drops below 2.5 mm/s (McClure and Horne, 2011).
- Friction coefficient is evaluated using the rate and state friction law (e.g. Scholz, 2002).

3. Geometry and Model Set-up

The boundary conditions for all models were selected to be similar to those produced during the crisis of the Basel EGS reservoir (Häring et al., 2008). The geothermal reservoir was assumed to be at a depth of 4,500 m with a hydrostatic fluid pressure gradient. The principal stresses σ1 and σ3 were horizontal, while σ2 was vertical (i.e. strike-slip regime). The initial fracture properties and the rate-and-state frictional model were set with similar values than those by Gischig (2015) in his mechanical analysis of the Basel reservoir.

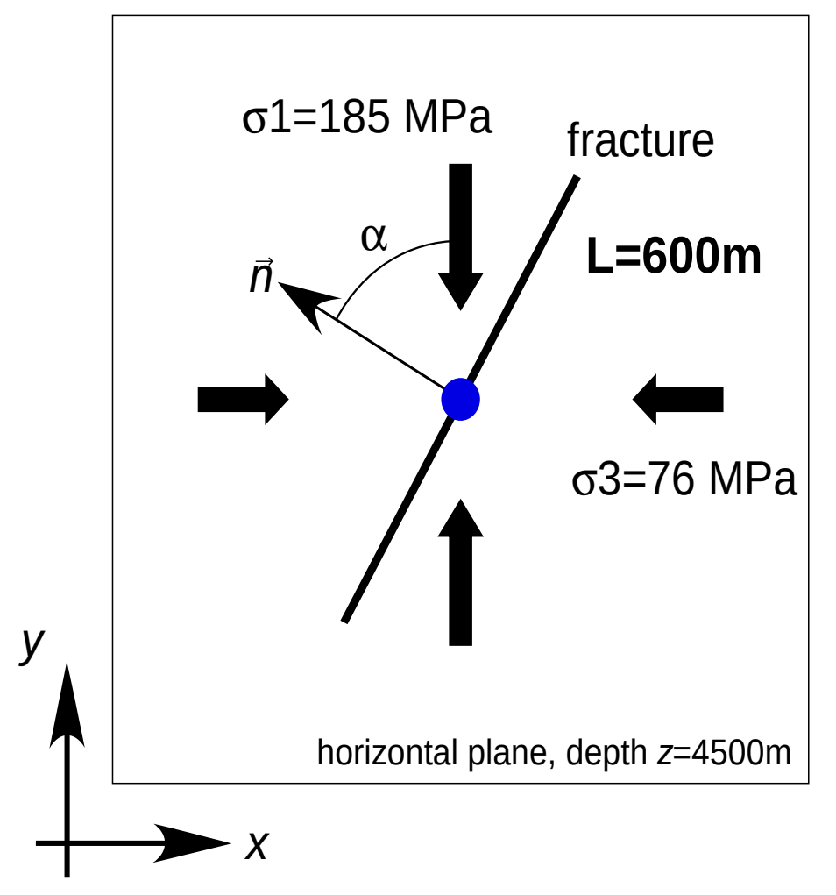

Figure 1. Setup of single fault models. The blue circle represents the injection point at middle of the fracture. Fracture orientation (α) was defined as the angle between the principal compressive stress σ1 and the fault normal.

The first models contained a 600 m long single isolated fracture embedded in a 2D space (Figure 1).

The **investigated parameter was the influence of the fracture orientation** (α, defined as the angle between the principal compressive stress σ1 and the fault normal) **on the induced seismicity, injection rates, sliding behaviour and fluid pressure accommodation.** 21 models were run with α ranging between 15° and 88° for 75 and 70 MPa.

Then, **two different orientations were combined to see if the parameters commented before for single schemes are conservative for geometry changes,** this model had 70 MPa as fluid injection.

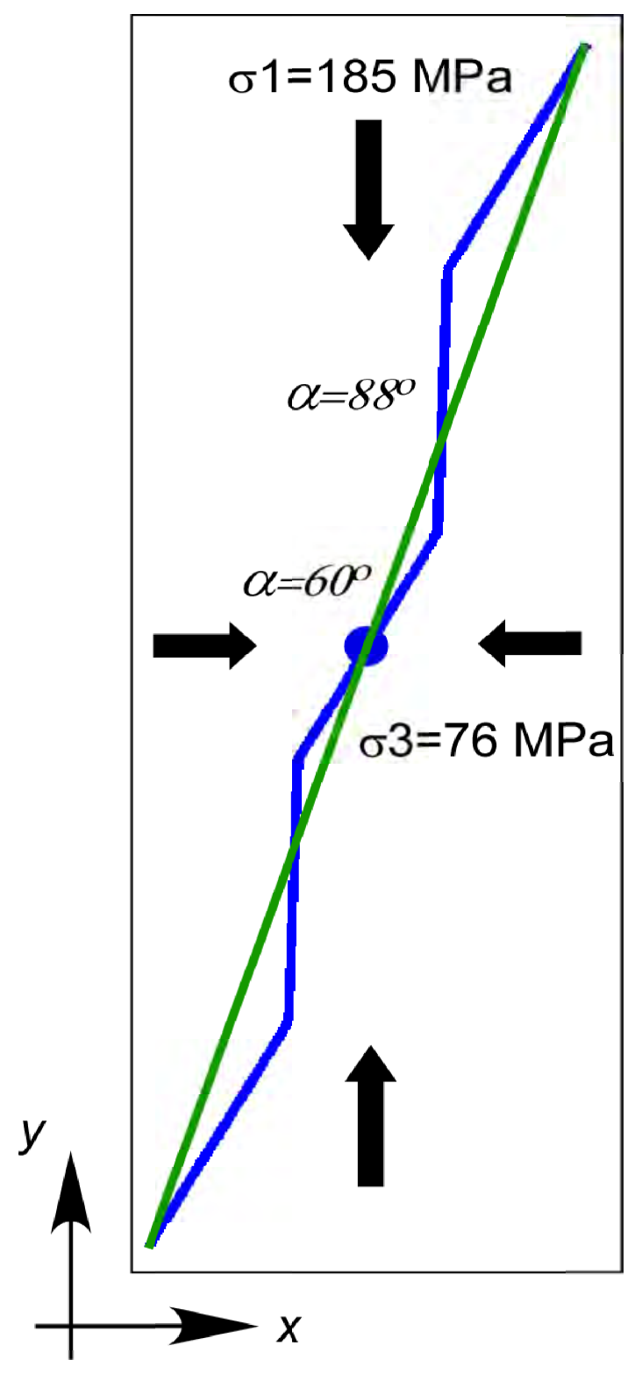

Figure 2. Setup of sigmoidal fault models. The blue circle represents the injection point at middle of the fracture. Fracture orientation (α) was defined as the angle between the principal compressive stress σ1 and the fault normal. The modelled fracture is showed in blue and the segments have 60m long. The green fracture would be the surrounding fracture.

4. Results

SINGLE FRACTURE MODELS

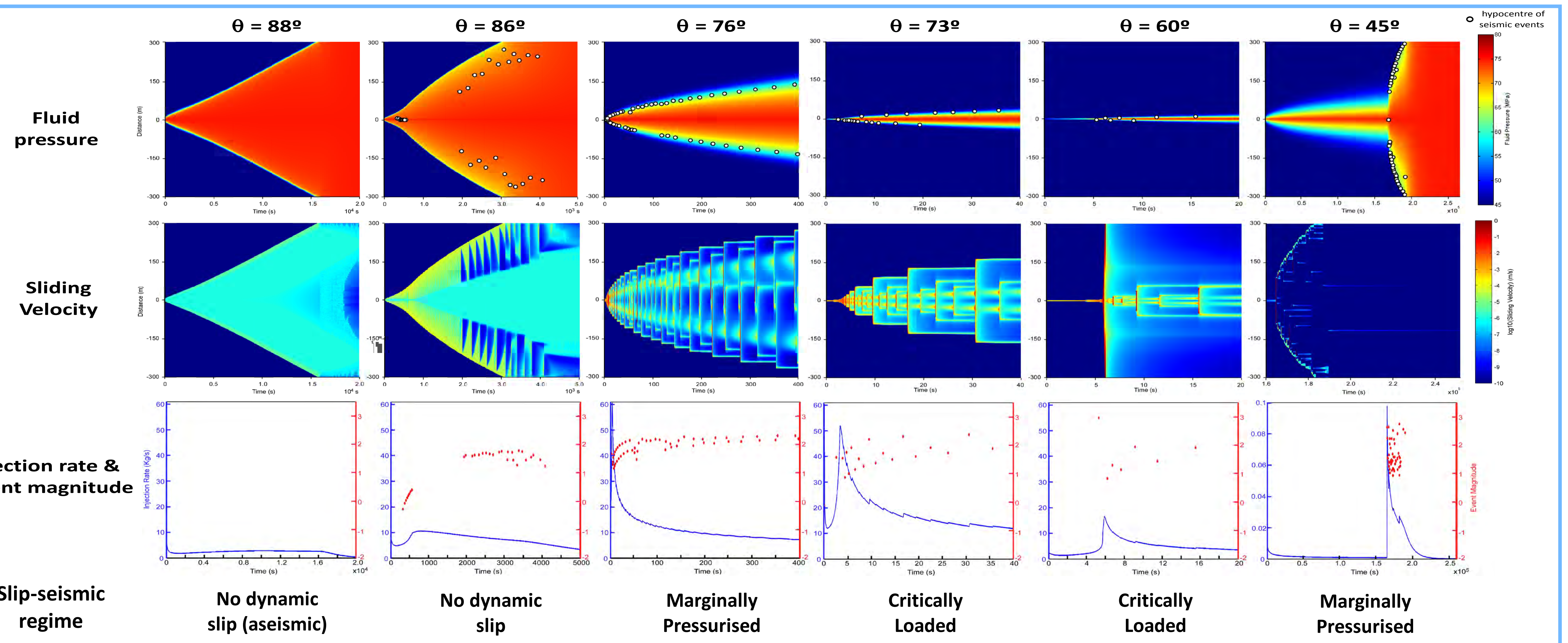

Figure 3. Fluid pressure (MPa), sliding velocity (m/s), injection rate (kg/s) and event magnitude evolution along fracture distance and time elapsed (s) for injection pressure of 75 MPa. White points indicate hypocentre of seismic events. The observed slip-seismic regime is also indicated.

SIGMOIDAL FRACTURE MODEL

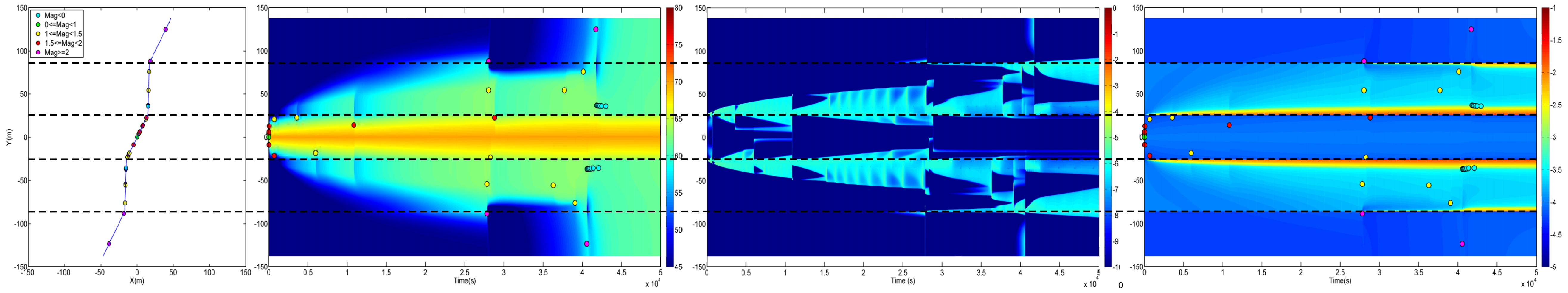

Figure 4. Event magnitude, fluid pressure (MPa), sliding velocity ($\log_{10}$ (m/s)) and void aperture ($\log_{10}$ (m)) along fracture distance and time elapsed (s). Coloured points indicate hypocentre of seismic events.

5. Discussion

The results show that the seismic behaviour during injection is strongly influenced by the fracture orientation, at least for single-fracture cases (Piris et al ., 2017). **Three main seismic regimes can clearly be distinguished:**

1) The first types are events that do not require a large fluid overpressure patch on the fracture before the onset and nucleation of a seismic event. A small perturbation of strength is enough to produce a critical load and fracture reactivation. The size of the rupture surface is larger than the size of the pressurised patch, and therefore, slip along the fracture can expand outside of the pressurised front leading to situations of uncontrolled rupture propagation. The fractures oriented between 50°<α<76° follow this behaviour for both injection pressures 75 MPa and 70 MPa.

2) The second type of response is defined by fracture orientations that require longer injection times before the onset of fracture slip. In this case, the onset of dynamic slip requires that a large part of the fracture is first uniformly pressurised. Seismic events in this case are not located near the injection point, but into the pressurised front. They are characterised by high slip velocities and surface run-outs that can expand outside of the pressurised region, but are still able to produce rupture surface along the whole fracture distance. This implies that, although the dynamic slip behaviour is efficient and there is weakening of the friction coefficient, the residual friction must be high enough to arrest and stabilise the perturbation. The fracture orientation ranges between 76°<α<86° and 45°<α<50° for injection pressure of 75 MPa and 76°<α<84° and 48°<α<50° for 70 MPa as injection pressure follow this behaviour.

3) Finally, a third case with the fracture oriented α>85° and α>84° for injection pressures of 75 MPa and 70 MPa respectivelly, can be defined. In this case, dynamic slip is not observed and fracture propagation is arrested due to the increase of the dynamic friction coefficient during the raise of the slip velocity. The accommodation of loading, and therefore the accommodation of a finite displacement along the fracture, takes place by means of slow motion events (i.e. low-magnitude seismicity) or by aseismic flow (i.e. at velocities lower than the predefined by the threshold for seismic events).

These three slip regimes are coherent with the analytical model by Garagash and Germanovich (2012) on the nucleation and arrest of dynamic slip on a pressurised fault and numerical simulations by Gischig (2015). Garagash and Germanovich (2012) proposed a different way for predicting the slip regime behaviour using a diagram defined by the understress versus the overpressure (Fig. 5).

In the sigmoidal fracture, critically loaded regime and stable regime (no slip) where combined. The main result is that the **critical regime induces events and aperture in the stable regime segments**, which for single cases did not show seismicity. The apertures generated in the aseismic segments (88°) by the seismic slides (in the 60° segments), produce pressure drops in the segment where the event was produced and in the adjacent ones.

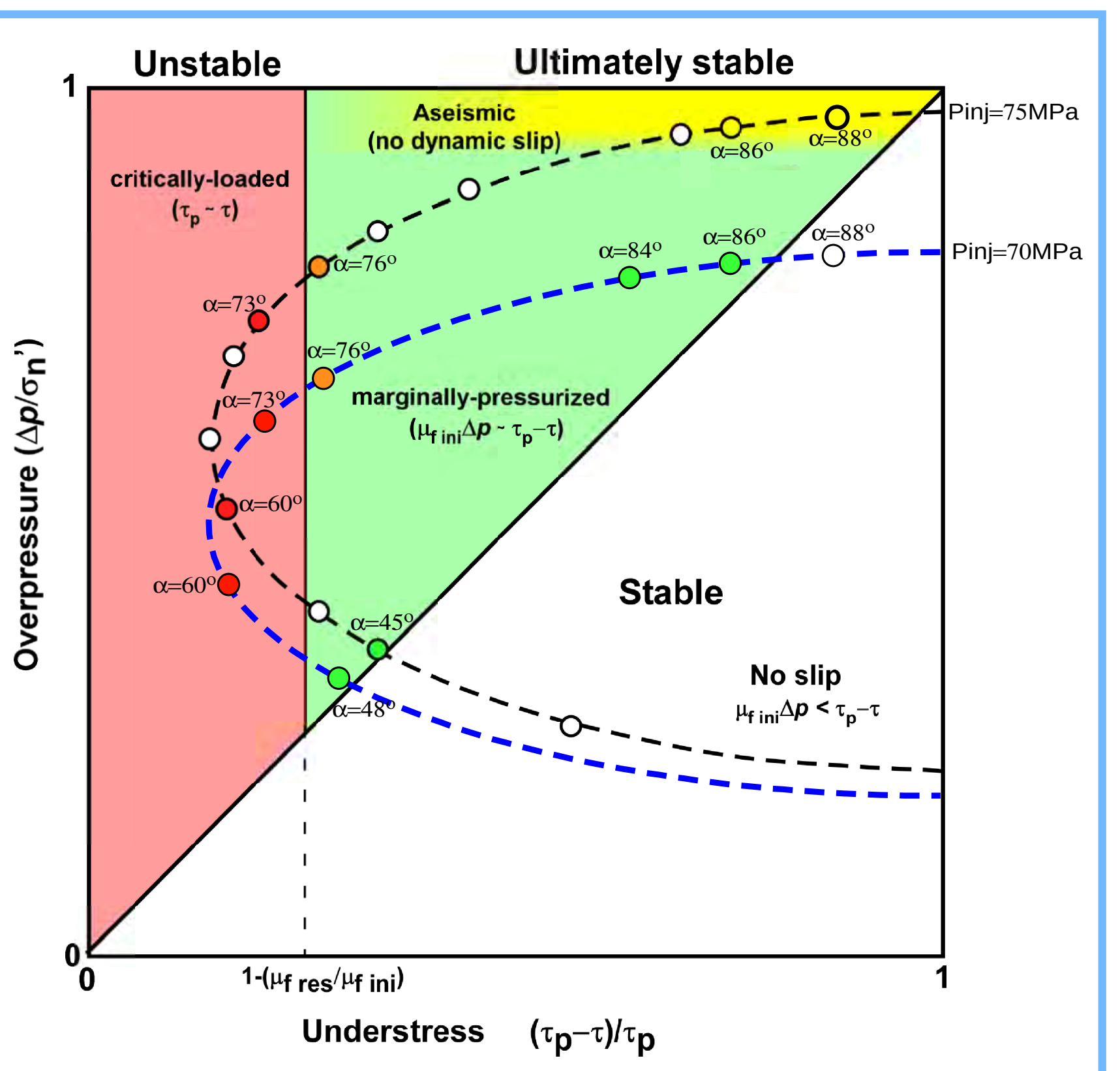

Figure 5. Different slip regimes as a function of the overpressure and understress field. The dashed lines represents the evolution trajectory as a function of the fracture orientation (from α=0º to α=90º) for both injection pressures. Coloured points are characteristic orientations for each sliding regime. Δp is the fluid pressure increment, σ'_n is the effective normal stress, τ_p is the critical shear stress to slip and τ the shear stress on a plane.

6. Conclusions

- **The orientation of single fractures with respect to the stress field is a key factor controlling induced seismicity. For the conditions simulated in the models, three different slip regimes were observed: (1) critically loaded regime, (2) marginally pressurised regime and (3) no dynamic slip or aseismic.**
- **The production of seismic events, sliding regime and fluid pressure distribution vary according to the slip regime or fracture orientation.**
- **Our numerical simulations are in agreement with the analytic solution proposed by Garagash and Garmanovich (2012).**
- **The sliding regimens combination in the same fracture, show as a determined segment can modify the other one.**

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