Variable permeability and stiffness in fault zones and their influence on slip

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Abstract

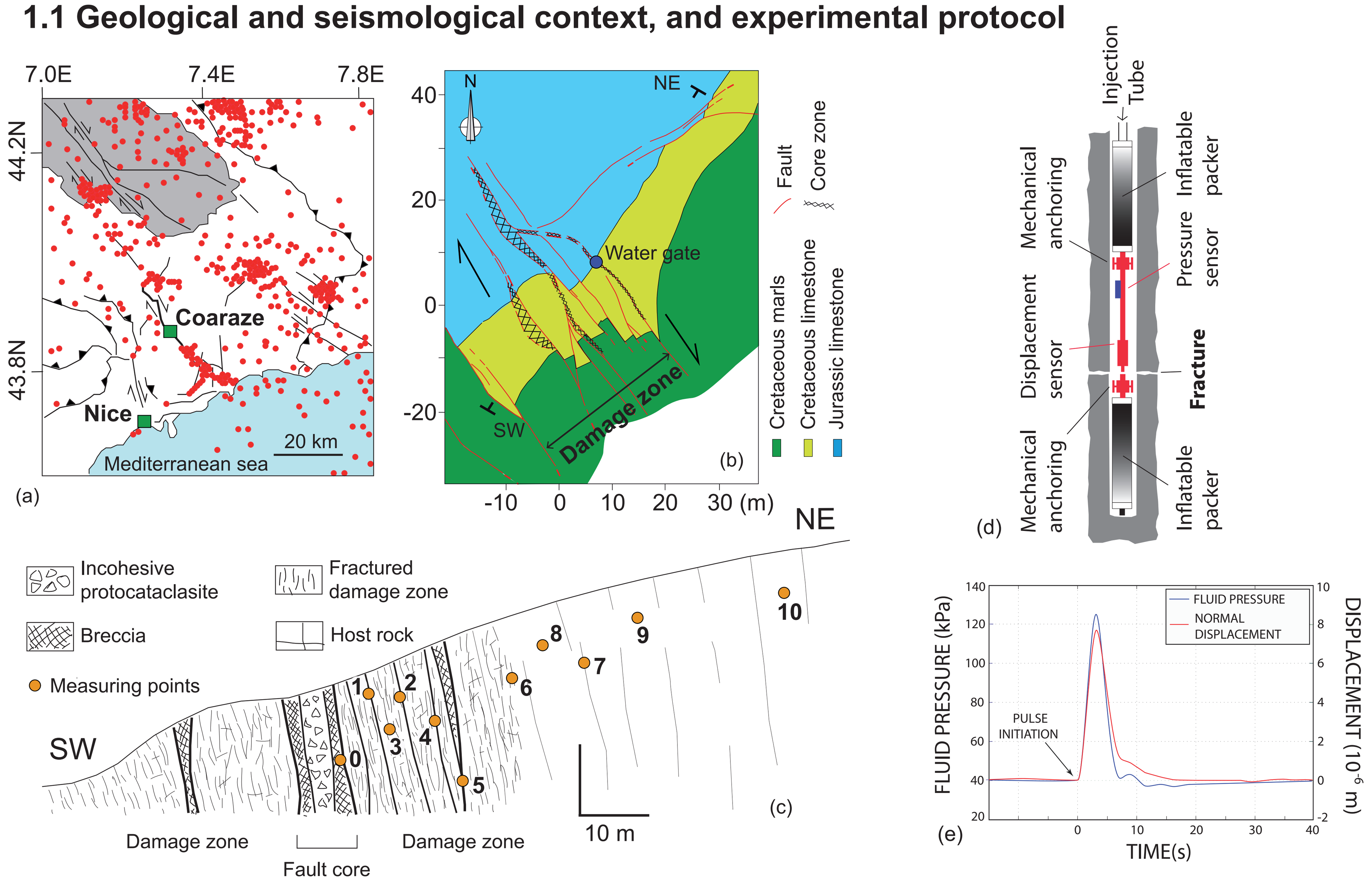
Fluid pressurization, a possible mechanism of fault weakening, exerts a critical control on earthquake rupture in the upper crust. One cause for this control is the presence of high fluid pressures inside the fault zone. However, the precise mechanisms relating high fluid pressures and fault rupture remain unclear. Here we measure the poroelastic properties of a fault zone, and then we use 2D hydromechanical models to show that effective stress changes induced by a transient pulse of fluid pressure along a fault zone with spatially variable material properties—conditions that are representative of natural faults—can be sufficient to produce large slip in the fault core, and fracturing in the surrounding damage volume. Rupture properties outside the limited source region are examined for ranges of values of the degree of material contrast across the fault. Our results indicate that the slip dimension is highly influenced by the contrasts of permeability and rigidity across the fault zone components, from the fault core through the various subzones of the fractured damage zone and to the less fractured host rock. Moreover, high fluid pressures may also develop locally off the narrow fault core, preferentially into the more permeable and less rigid parts of the damage zone, where the deformation is plastic, highlighting a possible mechanism for off-fault rupture. Finally, on faults with hydromechanical heterogeneities at the scale of the internal structure, the fluid pressure and rupture are highly asymmetric with propagation in a preferred direction, that is the more permeable and compliant material of the fault zones.

1. Evidence for poroelastic properties contrast across faults

(See Cappa et al., GRL, 2007; Guglielmi et al., 2008; Cappa et al., 2011 for details)

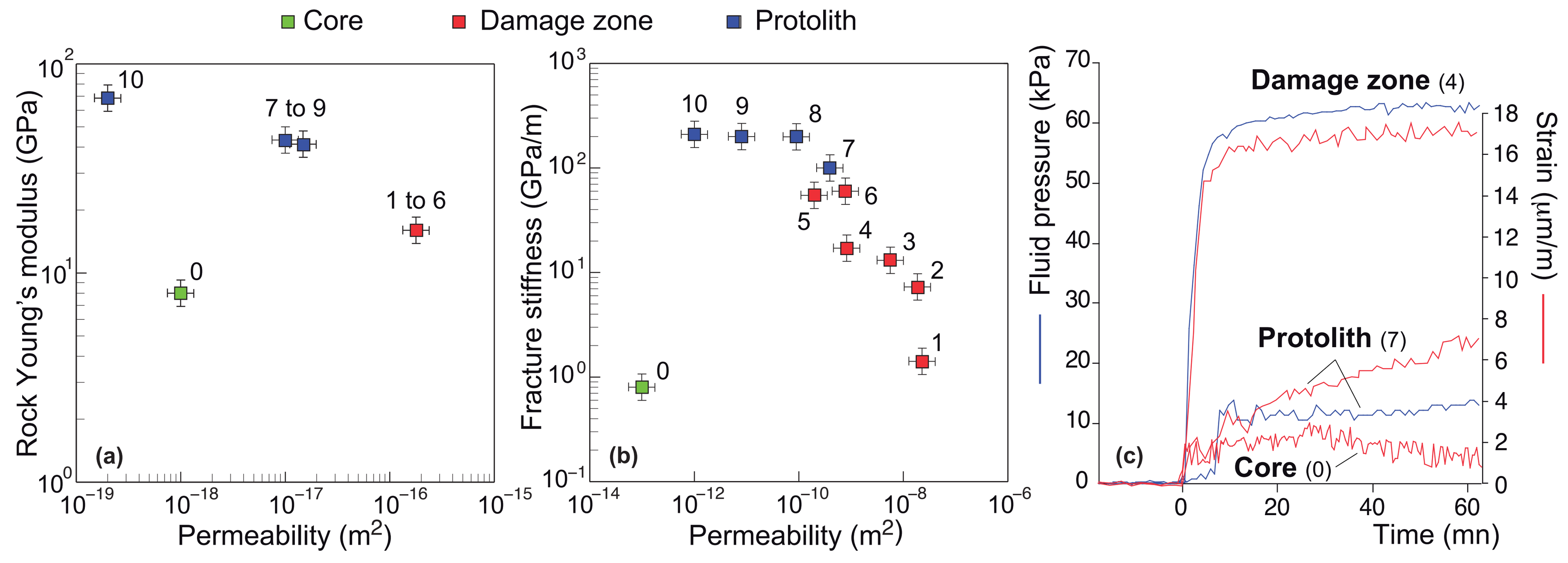
We examined the spatial distribution of permeability and rigidity in a strike-slip regional fault zone in low-porosity rocks, using poroelastic pulse tests that simultaneously measure fluid pressure and mechanical displacement. Data revealed the existence of a non-linear evolution between permeability and rigidity along the fault elements, with a high permeable and not-so-rigid damage zone coexisting with a low permeable and highly rigid protolith. The core has much lower permeability and rigidity by several orders of magnitude. Our data also showed that this variability in poroelastic properties imposes that fluids and strain are not uniformly distributed.

1.1 Geological and seismological context, and experimental protocol



(a) Regional tectonic framework of the Coaraze regional fault in southeastern France (seismicity is represented by the red circles);
(b) Geological map of the Coaraze fault zone; (c) Close-up view of the fault zone structure with measuring points (orange circles);
(d) Measurement device for the synchronous monitoring of (e) fluid pressure and fracture mechanical displacement.

1.2 Distribution of the hydraulic and mechanical properties along the fault zone, from the core through the damage zone to the protolith, and hydromechanical response

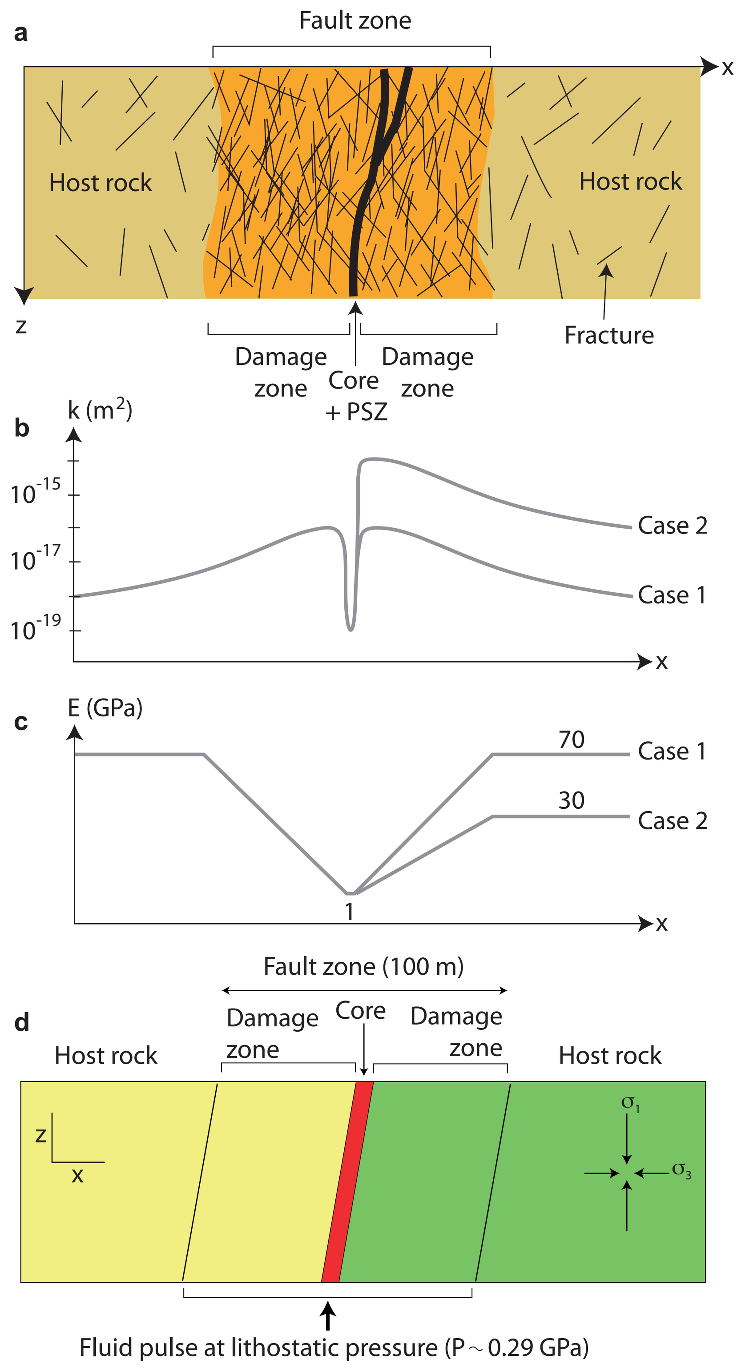


(a) Rock Young's modulus-versus-permeability; and, (b) Fracture stiffness-versus-permeability.
(c) Difference in the fluid pressure and mechanical displacement response between the core, the damage zone and the protolith during a 60-minutes long pressurization (measuring points are 0, 4 and 7, see Fig. 1c for location).

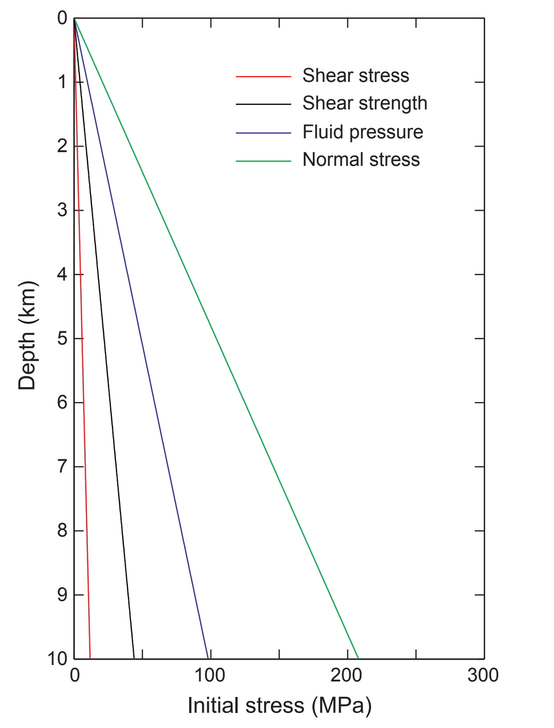
2. Hydromechanical modeling of fault rupture

(See Cappa, 2009 and 2011 for details)

2.1. Modeling Set-up

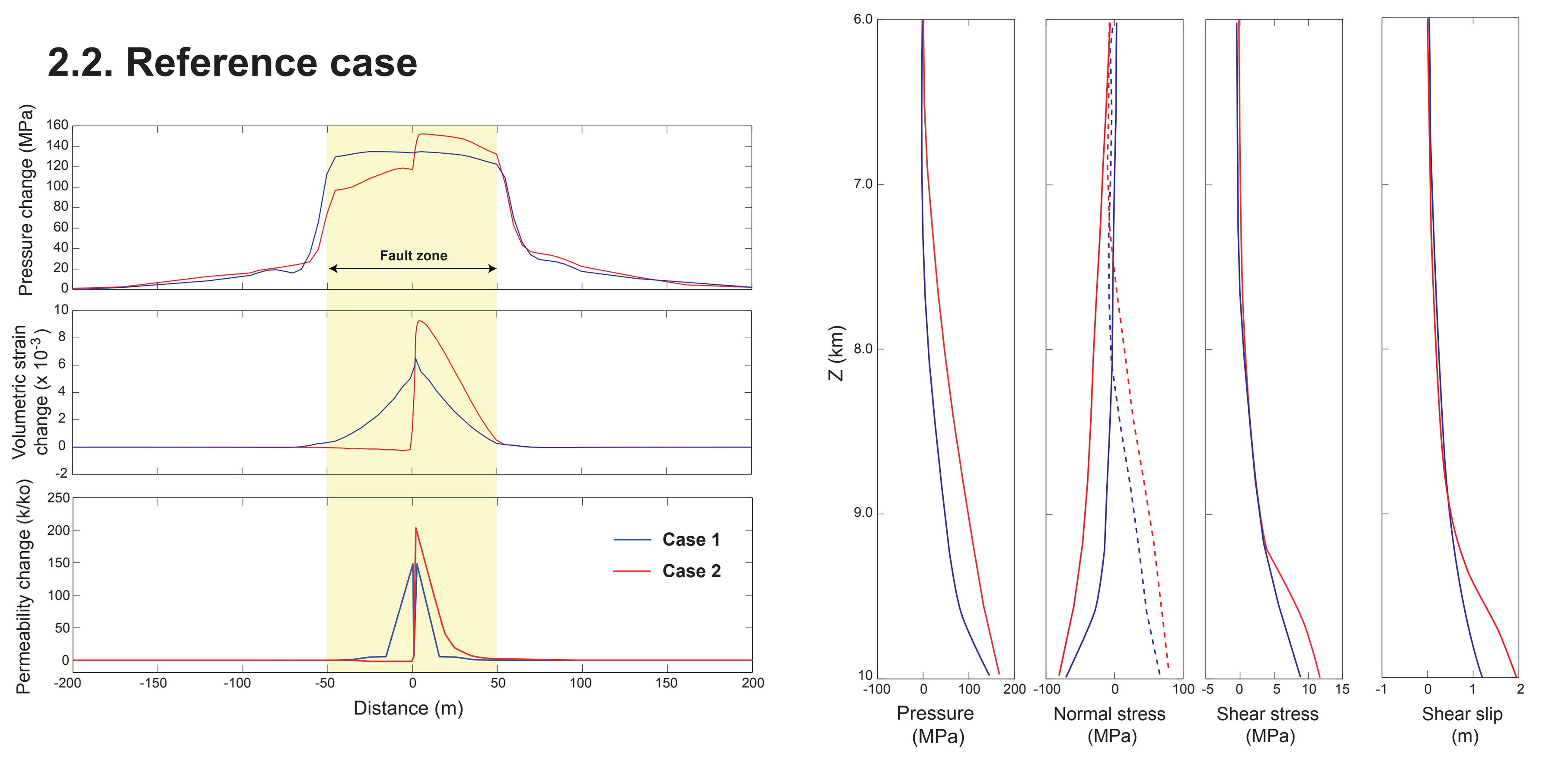


Model of fault zone structure and properties.
(a) Schematic diagram of the structure across a fault zone illustrating relationships between the principal slip zone (PSZ in grey), fault core (in black), and damage zones (in orange); and model of the distribution of permeability in (b) and Young's modulus in (c). In the damage zone, the fracture density decreases with distance to a regional background level. (d) Model of the hydromechanical interaction between the fault zone elements, that is, from the fault core through the damage zone and to the host rock. The fault dip angle is of 80° towards the right side of the model. The fault core is represented by a thin zone (Young's modulus E = 1 GPa, Poisson ratio ν = 0.3, density ρ = 3000 kg m, cohesion c = 0, static friction coefficient μ_s = 0.4, zero stress porosity ϕ_0= 0.1, zero stress permeability k_0 = 10-17 m). The PSZ is represented by an interface with a Coulomb friction law inside the fault core. The damage zone is divided in several parallel subzones with properties varying gradually as seen in (b) and (c). In case 1, the properties are symmetrically distributed on each sides of the fault core, whereas in case 2, the right side (in green) of the fault core is more permeable and less rigid than the left side (in yellow).

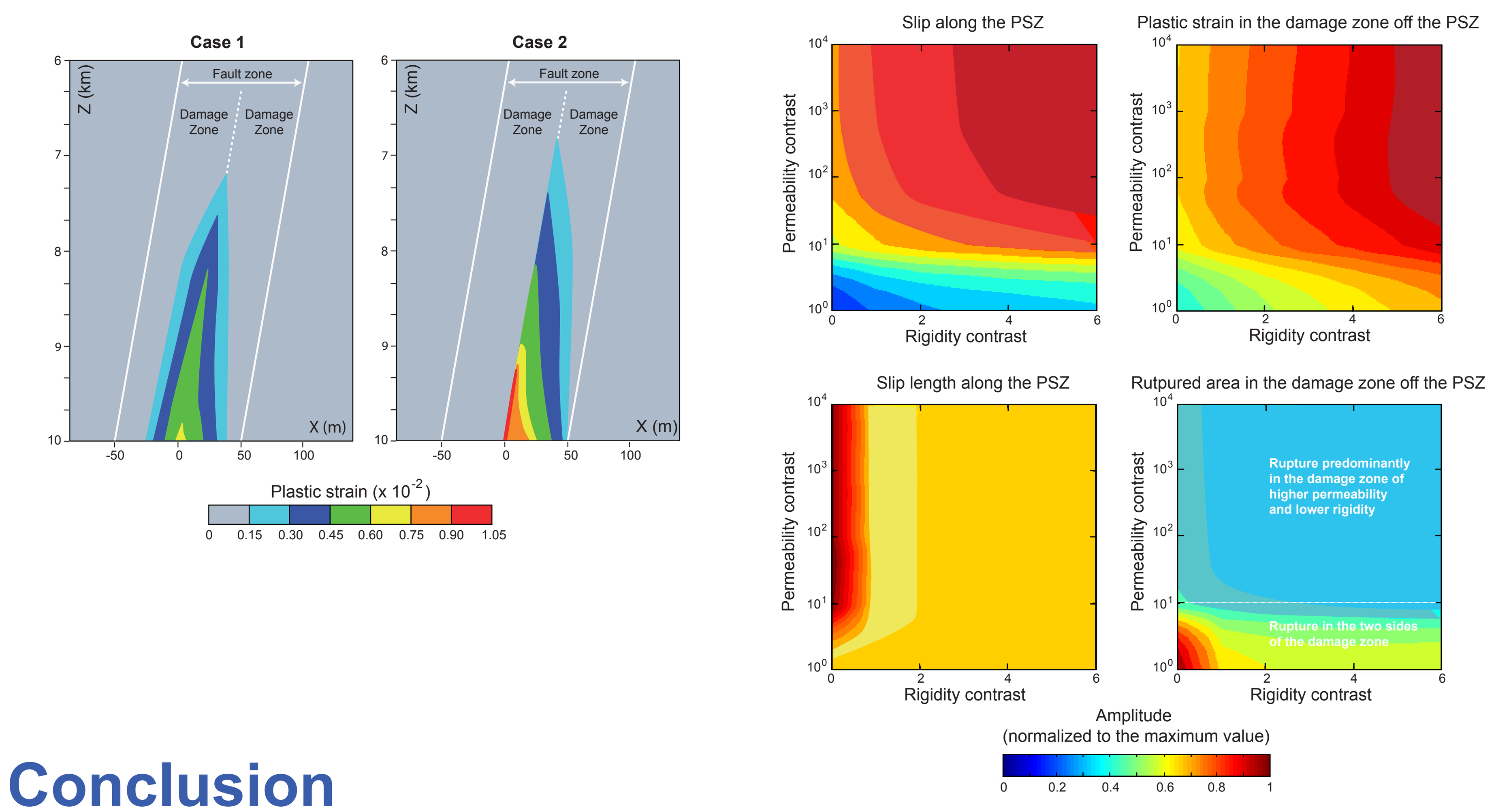


Initial fluid pressure and stress distribution with depth

2.2. Reference case



2.3. Off-fault plasticity and Sensitivity study



3. Conclusion

- Our in situ data indicate the existence of a strong contrast of poroelastic properties across a fault zone ;

- A variety of fluid pressure/strain response was observed, with a highly deformable damage zone acting as a channel and trap for fluids, and a dry core whose deformation is much smaller and controlled by poroelastic stressing in the damage zone ;

- Using hydromechanical models, we also found that the properties contrast significantly changes the amount of slip along the fault and plastic strain off the fault, and consequently, the degree of rupture asymmetry. This asymmetry is manifested by larger off-fault plasticity in the less rigid and more permeable side of the fault ;

- A consequence of rupture on a fault with contrasted properties could be the result of a heterogeneous spatial earthquake distribution and coseismic deformation through volume rather than a single ruptured plane.

References

Cappa F., 2009. Modeling fluid transfer and slip in a fault zone when integrating heterogenous hydromechanical characteristics in its internal structure. Geophys J Int, 178, 1357–1362, doi : 10.1111/j.1365-246X.2009.04291.

Cappa F., 2011. Influence of hydromechanical heterogeneities of fault zones on earthquake ruptures. Geophys J Int, 185, 1049-1058, doi: 10.1111/j.1365-246X.2011.04994.x

Cappa F., Guglielmi Y., and Virieux J., 2007. Stress and fluid transfer in a fault zone due to overpressures in the seismogenic crust. Geophys Res Lett, 34, L05301, doi:10.1029/2006GL028980.

Cappa F., Guglielmi Y., and Jeanne P., 2011. Evidence for poroelastic properties contrast across faults and implications for earthquakes rupture, Geophys Res Lett, submitted

Guglielmi Y., Cappa F., Amitrano D., 2008. High-definition analysis of fluid-induced seismicity related to the mesoscale hydromechanical properties of a fault zone. Geophys Res Lett, 35, L06306, doi:10.1029/2007GL033087.