We simulate an earthquake rupture through a 3-D Finite Difference algorithm using the Traction-At-Slip-Nodes Fault Boundary Condition. The dynamic rupture propagation is governed by an assigned constitutive law, which controls the breakdown processes within the cohesive zone. Seismic slip on faults produces temperature perturbations. Fault heating is controlled by the mechanical properties of the fault surface and by the rheological properties of the gouge layer. We modeled the temperature evolution on the fault through the heat flow equation and we coupled these thermal variations with the fluid pressure changes by using the Darcy’s law for fluid flow in porous media and the continuity equation of fluid mass in a solid. We assume that the increase of temperature does not change the accepted R&K constitutive parameters during the dynamic instability. To model the temporal variations of effective normal stress we consider a constant porosity within the slip zone and the evolution equation for the state variable proposed by Linker and Dieterich (1992, JGR, 97). Finally, we link this constitutive model with the evolution law for porosity proposed by Segal and Rice (1995, JGR, 101).

The goal of this study is to investigate dynamic fault weakening caused by shear heating and thermal pressurization of pore fluids. We show how these phenomena may complicate the dynamic rupture evolution and affect dynamic fault strength. Our simulations reveal that the effect of frictional heating and temperature increase strongly depend on the thickness of the slip zone. Thus, our 3-D simulations confirm that thermal pressurization is a viable mechanism to explain earthquake ruptures.

### Abstract

Thermal pressurization model in 3-D dynamic spontaneous rupture model with cohesive zone

We simulate an earthquake rupture through a 3-D Finite Difference algorithm using the Traction-At-Slip-Nodes Fault Boundary Condition. The dynamic rupture propagation is governed by an assigned constitutive law, which controls the breakdown processes within the cohesive zone. Seismic slip on faults produces temperature perturbations. Fault heating is controlled by the mechanical properties of the fault surface and by the rheological properties of the gouge layer. We modeled the temperature evolution on the fault through the heat flow equation and we coupled these thermal variations with the fluid pressure changes by using the Darcy’s law for fluid flow in porous media and the continuity equation of fluid mass in a solid. We assume that the increase of temperature does not change the accepted R&K constitutive parameters during the dynamic instability. To model the temporal variations of effective normal stress we consider a constant porosity within the slip zone and the evolution equation for the state variable proposed by Linker and Dieterich (1992, JGR, 97). Finally, we link this constitutive model with the evolution law for porosity proposed by Segal and Rice (1995, JGR, 101).

The goal of this study is to investigate dynamic fault weakening caused by shear heating and thermal pressurization of pore fluids. We show how these phenomena may complicate the dynamic rupture evolution and affect dynamic fault strength. Our simulations reveal that the effect of frictional heating and temperature increase strongly depend on the thickness of the slip zone. Thus, our 3-D simulations confirm that thermal pressurization is a viable mechanism to explain earthquake ruptures.

### Conclusion

In this work we have made the following goals:

1. Thermal pressurization modifies the shape of the rupture front (see Figure 1 and Figure 2).
2. The breakdown stress drop (\(\Delta\sigma\)) increases for decreasing values of the slip zone thickness \(2w\) and hydraulic diffusivity \(\chi\).
3. Both \(w\) and \(\chi\) affect the weakening.
4. The equivalent characteristic slip-weakening distance \(\delta_w\) increases for decreasing \(w\) and \(\eta\).
5. Fluid pressure and normal stress variations modify the state variable evolution.
6. Evolution law does matter (see Figure 5).
7. Variable porosity makes it possible to identify \(\delta_w\) and \(\Delta\sigma\) (see Figure 6).
8. Healing and short slip durations with thermal pressurization reduces the final temperature increase due to fault slip, while the instantaneous temperature increase is similar to a crack like solution.
9. In dry conditions, for 60 cm of total fault slip, we obtain thermal variations from 35 °C (\(w = 35\) mm) to 1000 °C (\(w = 10\) mm). In wet conditions, for 1 m of total fault slip thermal variations are from 32 °C (\(w = 35\) mm) to 850 °C (\(w = 10\) mm). Therefore we demonstrate that the thermal pressurization may partially explain the heat flux paradox, as proposed by Sibson (1973, Nature, 243; 2003, ESSA, 93).

### Variable Porosity

If the porosity \(\Phi\) is not constant over the dynamic process, the generalized solution for the thermal pressurization problem is:

\[
\frac{\partial\Phi}{\partial t} = \frac{1}{\varepsilon} \nabla \cdot \left( \frac{\nabla p}{\kappa} \right) - \frac{1}{\varepsilon} \nabla \cdot \left( \frac{\nabla q}{\lambda} \right)
\]

assuming for simplicity that \(\varepsilon = 1\).

### Variable Porosity

In Figure 6 we plot the results for a case in which the porosity evolution is expressed by Segal and Rice (1995):

\[
\Phi(t) = \Phi_0 \left( \frac{t}{t_0} \right)^{-n}
\]

where \(\Phi_0\) is the initial porosity, \(n\) is a parameter that controls the rate of porosity decrease.

### Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<td>(\varepsilon)</td>
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<tr>
<td>(\Phi_0)</td>
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</table>

### Figure 1

Thermal Pressurization Model

We couple the thermal variations with the fluid pressure changes by using the Darcy’s law for fluid flow in porous media and a constitutive law for the cohesive zone that is anisotropic and non-linear. We assume a linear temperature dependence of the friction coefficient and a non-linear stress dependence of the effective normal stress.

\[
\mu = \mu_0 \left( 1 - \frac{\theta}{\theta_0} \right)
\]

\[
\tau = \tau_0 \left( 1 - \frac{\theta}{\theta_0} \right)^n
\]

where \(\mu_0\) and \(\tau_0\) are the reference friction coefficient and stress, \(\theta\) is the temperature, \(\theta_0\) is the reference temperature, and \(n\) is a parameter that controls the rate of porosity decrease.

### Figure 2

Effects of Gouge Layer Thickness and Hydraulic Diffusivity

In all the numerical experiments presented in this work we assume for simplicity that the slip zone (or the gouge layer) thickness \(2w\) is uniform over the whole fault surface. We show in Figure 3 the effects of the variable \(w\) (from 30 \(\mu\)m to 0.3 m) and of a variable hydraulic diffusivity \(\chi\) (variable permeability) over the range between 2.5e-20 and 1.5e-15 m²/s for the solutions for a fault obeying to SW law. In Figure 6 we have reported the same comparison for the RD case. Blue curves represent the reference (Dry) case, in which the fluid effects are not considered.

### Variable Porosity

If the porosity \(\Phi\) is not constant over the dynamic process, the generalized solution for the thermal pressurization problem is:

\[
\frac{\partial\Phi}{\partial t} = \frac{1}{\varepsilon} \nabla \cdot \left( \frac{\nabla p}{\kappa} \right) - \frac{1}{\varepsilon} \nabla \cdot \left( \frac{\nabla q}{\lambda} \right)
\]

assuming for simplicity that \(\varepsilon = 1\).