Simulation of frictional heat generation due to underground motion

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1. Introduction

Frictional energy generated during an earthquake has been well studied in the last decades and quite a few laboratory experiments have been carried out recently with the objective to quantify and describe this type of energy in a better way. In our research we modelled the temperature rise during a simulated seismic event a using the ANSYS® Mechanical software.

Most material properties change in function of the temperature. In our case is important to understand the behavior of these properties in a faulting zone. Big changes on underground temperature could generate instabilities on surrounding fault zones, becoming a nucleation point for small earthquakes.

Objectives:

- Simulate a **microearthquake.** ($M_w < 3$) thermal budget produced by a modeled millimetric normal fault.
- Study the characteristic of heat generation due to friction by changing relevant model parameters.

2. Background and Numerical Approach.

The model uses a cylindrical geometry, simulating the conditions of a triaxial test

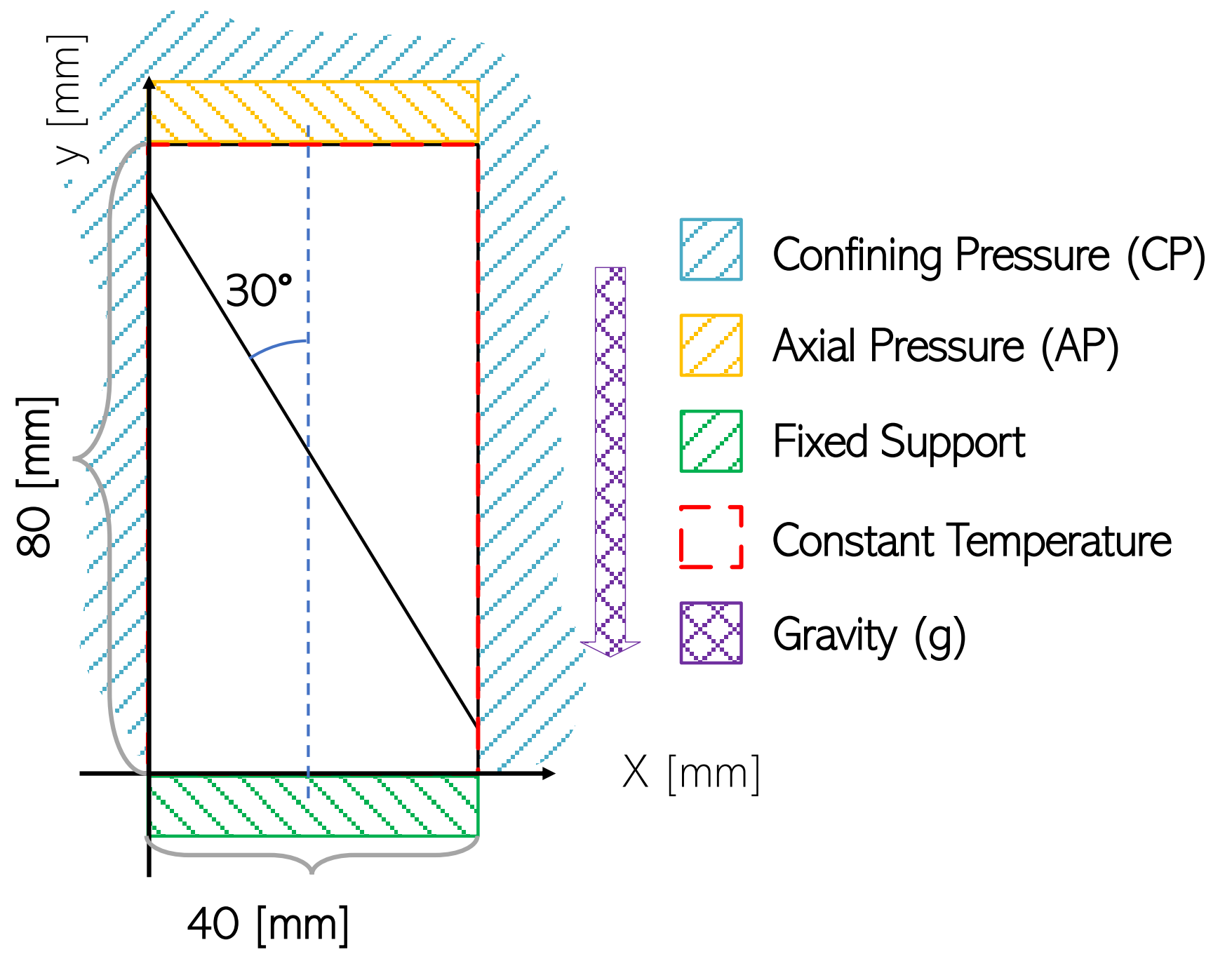

FIGURE 1: model diagram showing the main parameters considered in the simulation

The simulation is based on the studies of Aubry et al., (2018) and Passélegue et al., (2016).

Simplifications

- The current model does not consider fracture, neither deformation.
- The friction acts as a function of time.
- The current model applies only for dry faults.

2.1. Friction coefficient drop

The faulting model used is the Mohr-Coulomb criterium.

$$\tau_{lim} = \mu P + b \tag{1}$$

To overcome the limit shear stress and generate motion axial pressure is applied and continuously increased until faulting,
Knowing that the limit shear stress is related to the **friction coefficient (μ)** we reduce it as a function of time.

To originate the fault motion, we vary the friction coefficient in a small time period (0.01[s]), from 0.6 to 0.47; keeping a constant confining and axial pressure.

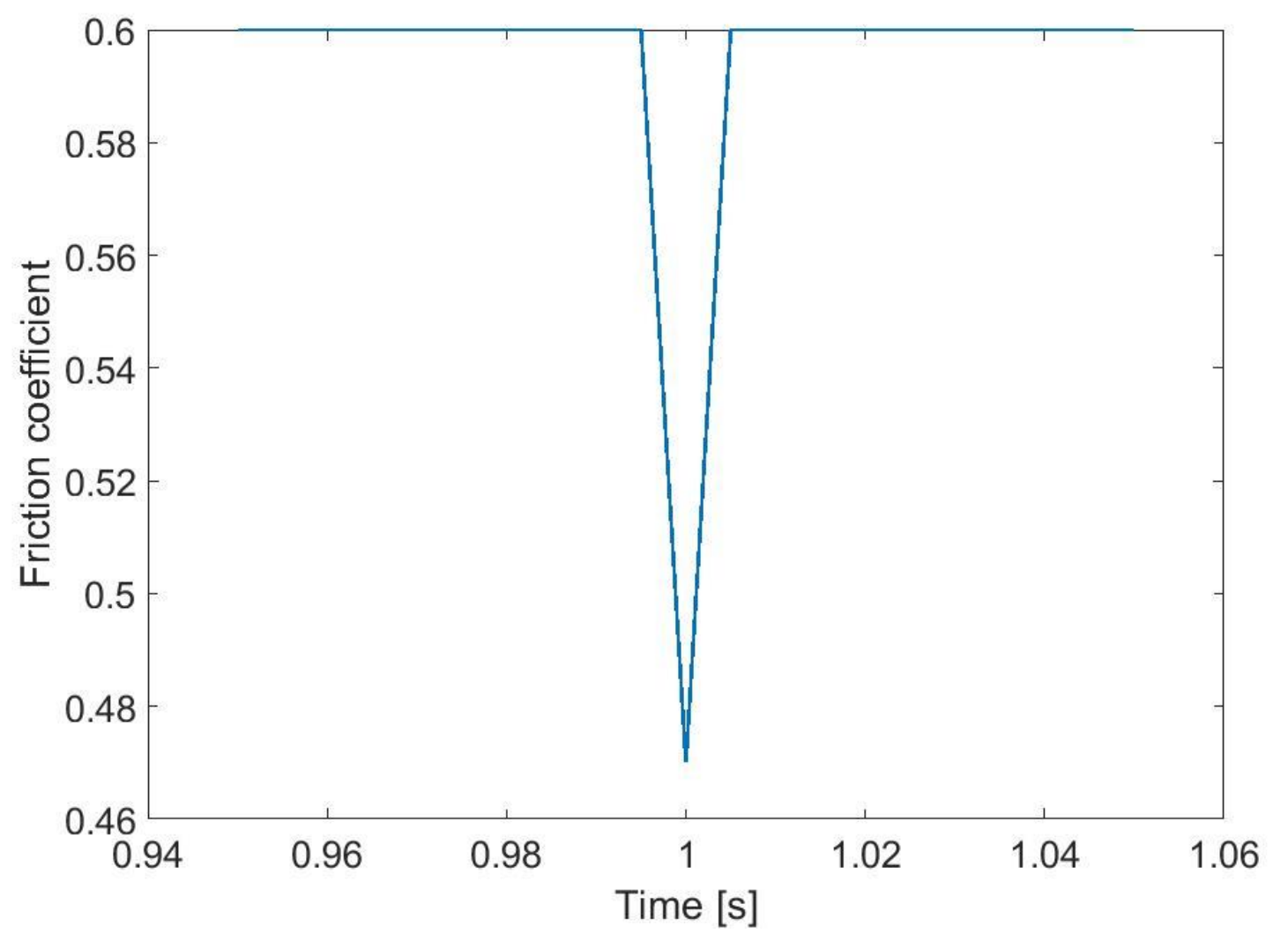

FIGURE 2: friction coefficient function with respect to time.

2.2. Equations:

- Coupled equation between **structural** and **thermal** modules.

$$\begin{bmatrix} [M] & [0] \\ [0] & [0] \end{bmatrix} \begin{Bmatrix} \{\ddot{u}\} \\ \{\ddot{T}\} \end{Bmatrix} + \begin{bmatrix} [C] & [0] \\ [C^{tu}] & [C^{t}] \end{bmatrix} \begin{Bmatrix} \{\dot{u}\} \\ \{\dot{T}\} \end{Bmatrix} + \begin{bmatrix} [K] & [K^{ut}] \\ [0] & [K^{t}] \end{bmatrix} \begin{Bmatrix} \{u\} \\ \{T\} \end{Bmatrix} = \begin{Bmatrix} \{F\} \\ \{Q\} \end{Bmatrix} \tag{2}$$

The key coupling factor is **the thermoelastic stiffness** $[K^{ut}]$ and its inverse $[C^{tu}]$ which are both related to the **thermal expansion** and the **elastic stiffnes**s of the material.

$$[K^{ut}] = -\int_{vol} [B]^T \{\beta\} \{N\}^T d(vol) \tag{3}$$

where $\{\beta\}$ is the thermo-elastic coefficient represented as

$$\{\beta\} = [D]\alpha \tag{4}$$

with $\boldsymbol{\alpha}$ being the coefficients of thermal expansion.

- Heat generation due to friction

$$Q_f = \sigma_f DS \tag{5}$$

- Temperature increase

$$\Delta T = \frac{\sigma_f 10^{1.5M_w+9.1}}{C\mu S\rho w} \tag{6}$$

- Moment of magnitude (Mw)

$$\text{Seismic moment:} \quad M_o = \mu DS \tag{7}$$

$$\log(M_o) = 1.5M_w + 9.1 \tag{8}$$

The results show that the **displacement** (D), **frictional stress** (σ_f) and **fault area** (S) play a key roll on the heat generation (Kanamori & Heaton, 2000).

3. Results & Discussion

3.1. Validation test

- Aubry's results:

To test our model, we **simulated the temperature** increase at 180[MPa] of confining pressure following the model proposed by (Aubry et al., 2018)

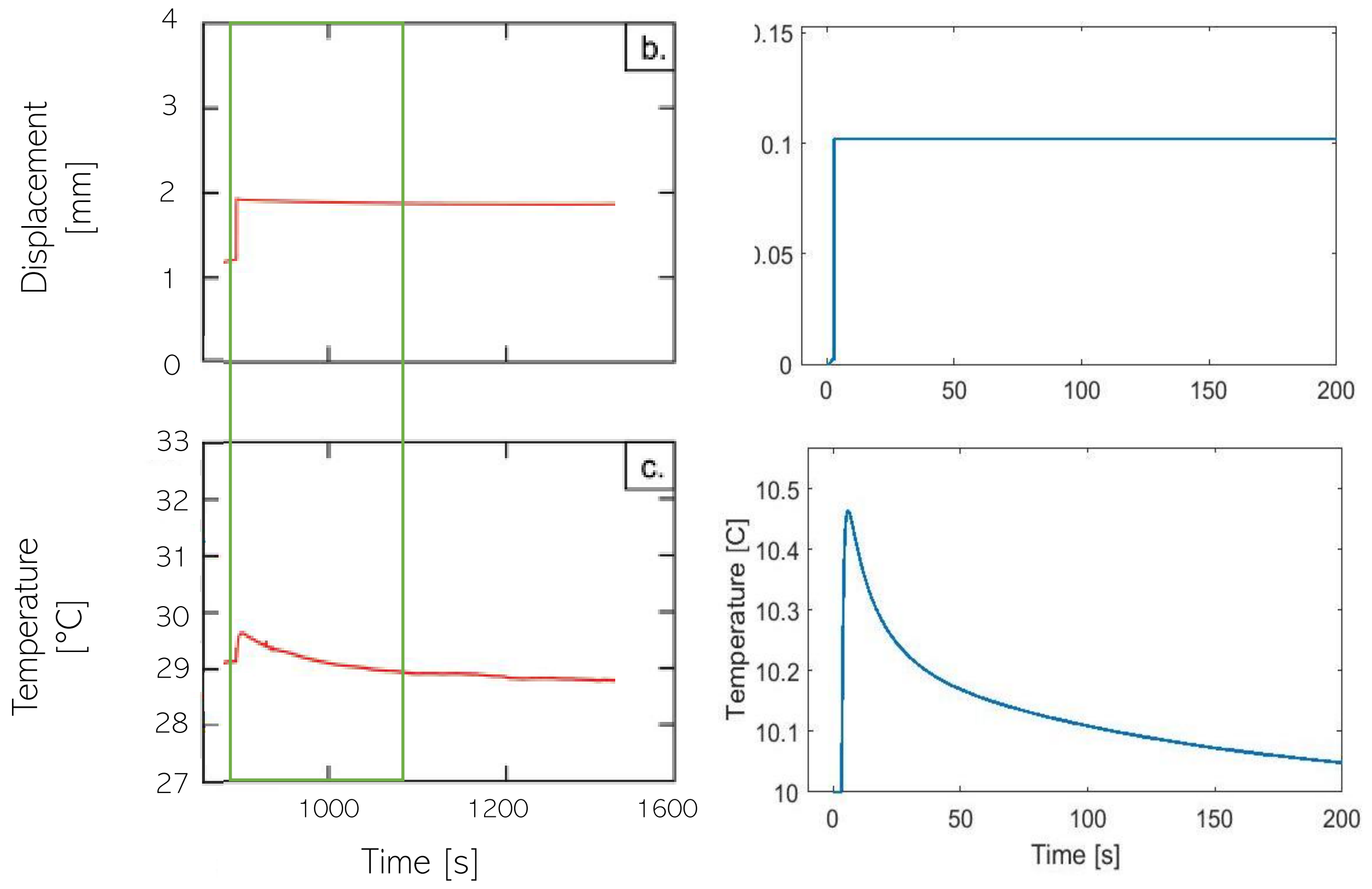

FIGURE 3: (left column) Aubry's model. The green lines are showing the temporal window that was selected for comparison purposes. (right column) Our model results in the selected temporal window

As can be observed in **Figure 3** we got the same temperature increase as Aubry's model, around 0.45 [°C]. However, these results considers a displacement that differs considerably from the original research. This could be explained considering the minimum friction coefficient that we are using.
Smaller coefficients would lead to bigger displacement

- Kanamori's equation:

As we keep testing our model, we tried to fit our temperature results with the Kanamori's equation **(equation 6)**, To accomplish that, we modified the confining pressure from 10 to 180[MPa], keeping the other parameters constant.

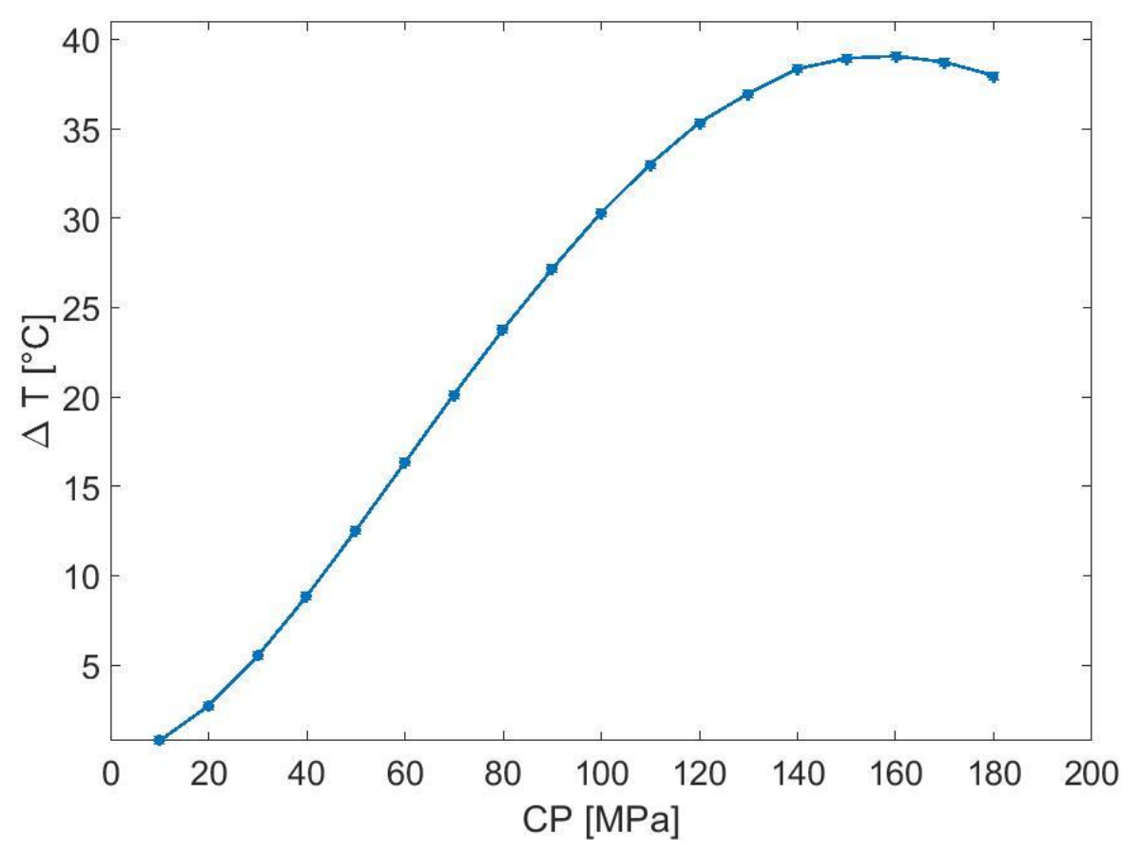

FIGURE 4

The maximum increase of temperature reached in the seismic zone for the diferent confining pressures is displaced to the left. **Figure 5** shows the displacement and the frictional stress obtained for the different confining pressures.

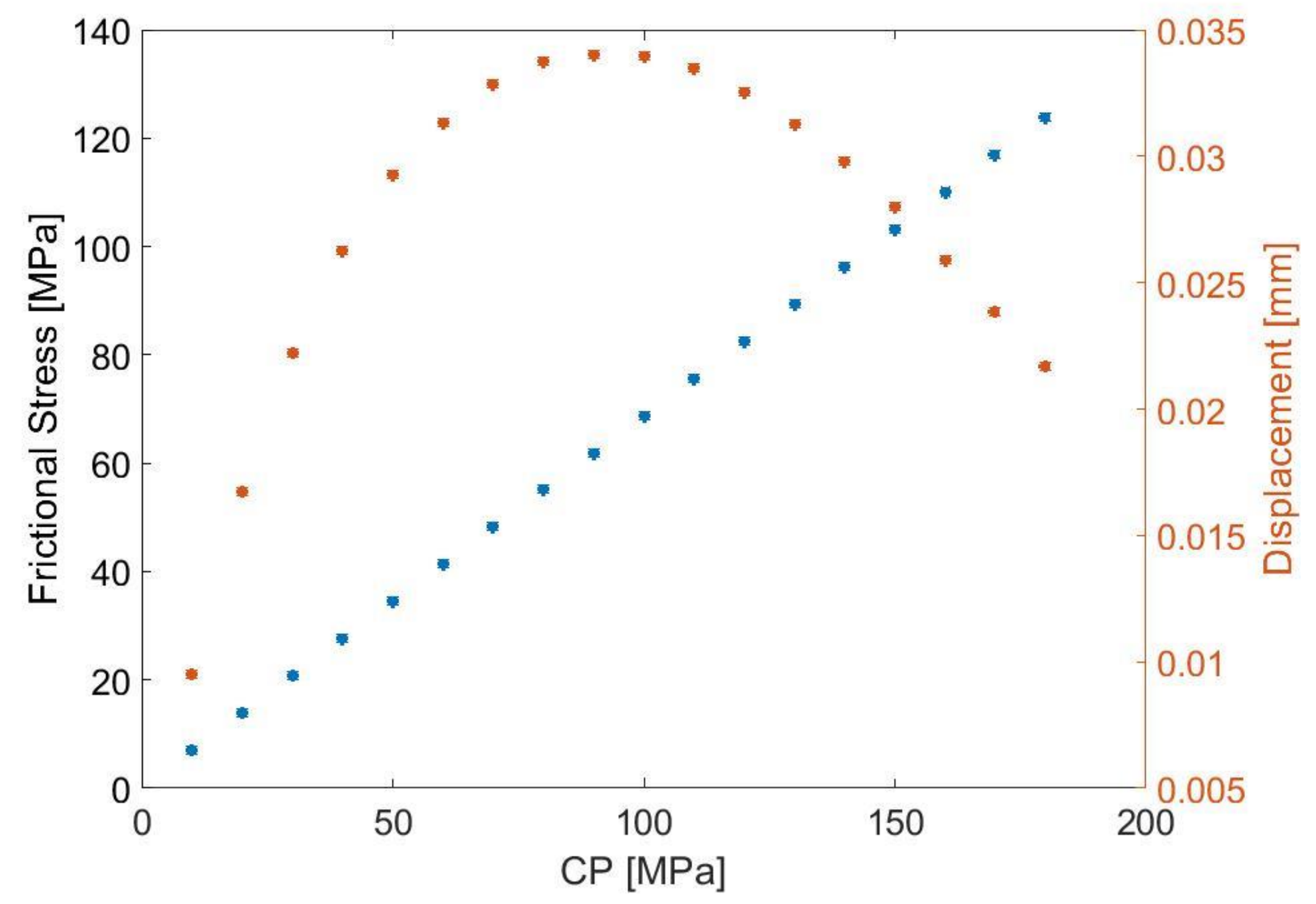

FIGURE 5

The increase in temperature is related to the heat generated by friction, according to **equation 3**, In our case, the displacement reached a maximum at a confining pressure of 90 [MPa]. Consequently, according to **equation 2** the temperature would reach its maximum at around 160 [MPa], when the product between the frictional stress and displacement reach a maximum,.
With the displacement data of **figure 5**, we calculate the moment of magnitude (M_w). Results are shown in the **table 1**.

CP	10	20	30	40	50	60	70	80	90
M_w	0.54	0.92	1.11	1.22	1.29	1.34	1.37	1.39	1.40
CP	100	110	120	130	140	150	160	170	180
M_w	1.39	1.38	1.37	1.34	1.31	1.26	1.21	1.16	1.10

Table 1: Confining pressure vs moment magnitude considering the abovementioned parameters.

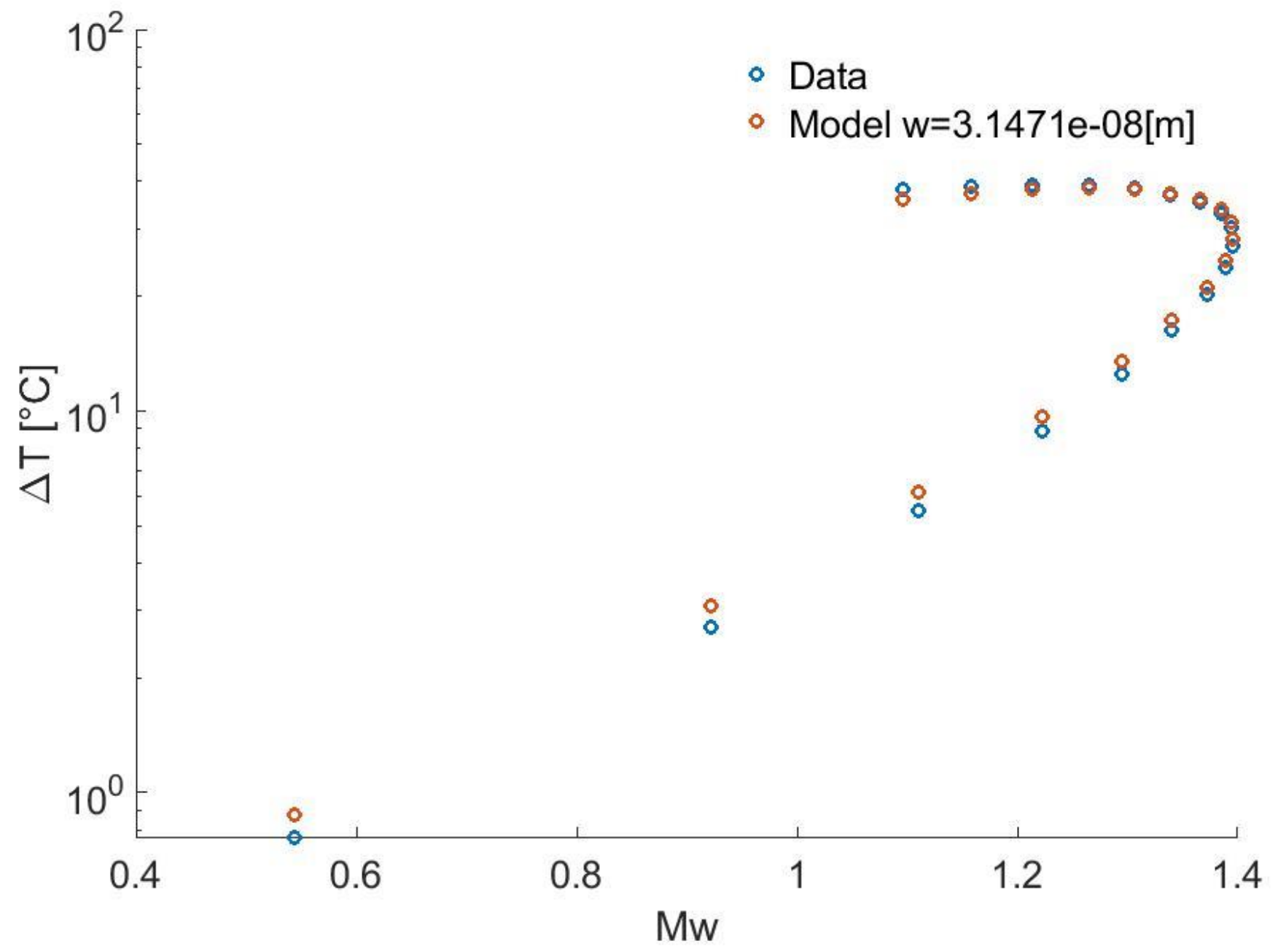

FIGURE 6: model fitting our results and Kanamori's model.

To fit our data to **equation 3** we vary the **width, w**. All other parameters are constants or simulated results. Using the minimum square difference method, we reached a value for w of 3.0518e-8[m]. The model fit can be seen in **figure 6**

Kanamori's equation considers an ideal fault zone, Our model has temperature boundary conditions and gradient of stresses along the fault; therefore we have different temperatures in the fault zone.
This more realistic behavior may be the cause of the defective model fitting.

3.2. Fault length change

We changed the fault length from 80 [mm] to 120 [mm] to understand how it affects the behavior of the simulated microearthquake.
To increase the fault length, we must increase the whole probe, which means that we are having more material to displace under the same conditions. Finally the displacement decays for bigger probes as shown in **figure 7**.

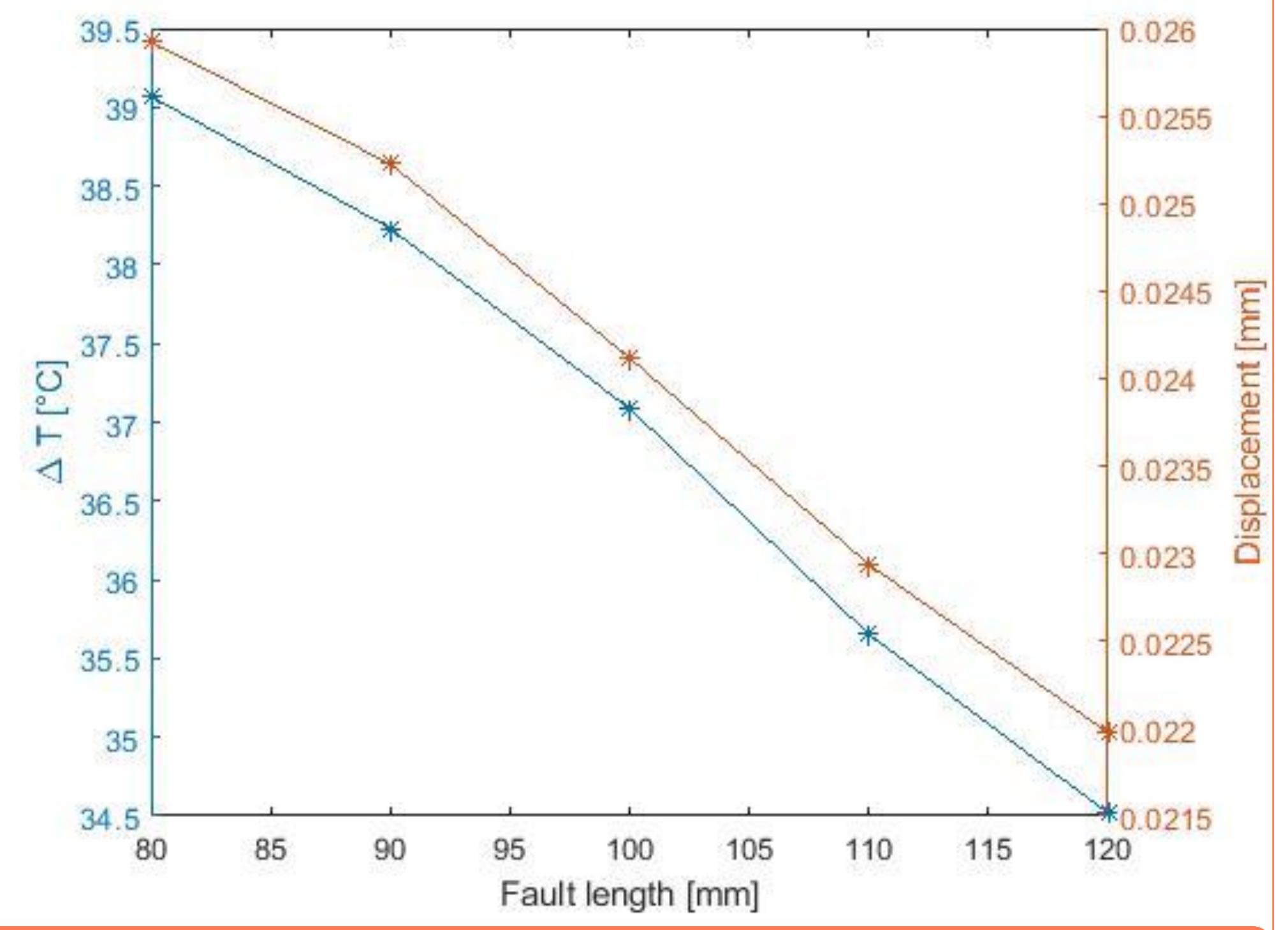

FIGURE 7

Conclusions

The chosen friction coefficient model (Fig. 2) defines accurately the temperature behavior for microearthquakes but differs for the displacement reported (Fig.3)
Changing various model parameters like fault length, confining pressure, axial pressure, friction coefficient drop and others, allows us to analyze the impact on heat generation during seismic slip.
Using the model we should be able to predict temperature increase during micro-earthquakes, e.g. from induced seismicity. This temperature increase could lead to potential changes of underground material properties, increasing the chances for nucleating seismicity.

Acknowledgements

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References

- Aubry, J., Passelègue, F. X., Deldicque, D., & Girault, F. (2018, June). Frictional heating processes and energy budget during laboratory earthquakes. *Geophysical Research Letters, 45,* 12,274-12,282
- Ansys® Academic Research Mechanical. (2020). *Release 19.0, ANSYS, Inc.*
- Kanamori, H., & Heaton, T. H. (2000). Microscopic and Macroscopic Physics of Earthquakes. *Geocomplexity and the Physics of Earthquakes, 120,* 147-163.
- MATLAB. (2020). *version 9.7.0 (R2019b)*. Natick, Massachusetts: The MathWorks Inc.
- Passelègue, F. X., Nielsen, S., Bhat, H. S., Deldicque, D., Schubnel, A., & Madariaga, R. (2016, June). Dynamic rupture processes inferred from laboratory. *Journal of Geophysical Research: Solid Earth, 121,* 4343-4365

Softwares