

# **Weak phases production and heat generation controls fault friction during seismic slip**

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**The triggering and magnitude of earthquakes is determined by the friction evolution along faults. Experimental results have revealed a drastic decrease of the friction coefficient for velocities close to the maximum seismic one, independently of the material studied<sup>1,2</sup>. Due to the extreme loading conditions during seismic slip, many competing physical phenomena are occurring (like mineral decomposition<sup>3</sup>, nanoparticle lubrication<sup>1</sup>, melting<sup>4</sup> among others) that are typically thermal in origin<sup>5</sup> and are changing the nature of the material.**

**Here we show that a large set of experimental data for different rocks can be described by such thermally-activated mechanisms<sup>6</sup>, combined with the production of weak phases. By taking under account the energy balance of all processes during fault movement, we present a framework that reconciles the data, and is capable of explaining the frictional behavior of faults, across the full range of slip velocities ( $10^{-9} - 10$  m/s).**

**The similarity of microstructures observed in nature and in experiments suggests that energetic frameworks like the one presented could quantitatively link observations across the scales and provide deep, physics-based insight on the physical mechanisms driving seismic slip.**

The knowledge of the friction (shear strength) evolution along a pre-existing fault is of major

21 importance, as it allows extracting many characteristics and features of seismic slip. In particular,  
22 the decrease of the friction with increasing velocity or displacement (a process called frictional  
23 weakening) determines the possible nucleation of earthquakes. If the weakening rate is larger than  
24 a critical value, this leads to the triggering of a dynamic slip at the origin of earthquakes<sup>7</sup>. In  
25 addition to nucleation, the evolution of the friction coefficient- and thus of the fault's shearing  
26 resistance- determines the arrest of the fault slip and governs the form and budget of energy dissi-  
27 pation during seismic slip<sup>8</sup>. The latter is essential as it determines the amount of energy produced  
28 at the fault, which is radiated on the surface through seismic waves and tremors.

29         During the last 20 years, a large set of experimental works has been devoted to reproducing  
30 the extreme conditions of a seismic slip. The development of high velocity shear apparatus al-  
31 lowed the research community to perform experiments at the maximum velocity reached during an  
32 earthquake event (1 – 10 m/s) and, thus, characterize the behaviour of a fault over the full range of  
33 possible slip rates<sup>9</sup>. A drastic decrease of the friction has been observed in most cases for veloc-  
34 ities closed to the maximum slip velocity independently of the material considered<sup>1</sup>, however the  
35 physical mechanisms accompanying this rapid weakening being different for each rock type. Fol-  
36 lowing microstructural observations and measurements in the sheared samples, several thermally  
37 and mechanically activated weakening mechanisms were proposed to understand the experimental  
38 results at seismic slip rates<sup>6</sup>. The common feature of all these weakening mechanisms is phase  
39 transformation -like mineral decomposition<sup>3</sup>, nanoparticle lubrication<sup>1</sup>, melting<sup>4</sup>- during which a  
40 change in the nature of the material takes place.

41 To describe the effect of such a weak phase on the frictional behaviour of a mixture of a  
42 strong/weak phase and constrain the influence of phase change on the mechanical behaviour, we  
43 consider first experiments looking at the effect of a weak phase on the frictional response of fault  
44 zones. The weak phases used for the tests are talc or saturated clay materials sheared at low  
45 velocities (lower than  $10^{-5}$  m/s), so that the mechanisms described above are not triggered. The  
46 results are shown in Figure 1, where we may observe that the friction coefficient  $\mu$  decreases as  
47 the weak phase fraction increases. This effect of the weak phase fraction can be captured using  
48 an exponential law  $\mu = \mu_0 + \Delta\mu e^{-\alpha w}$ , where  $\mu_0$  is the friction coefficient of the weak phase,  
49  $\Delta\mu = \mu_s - \mu_0$  is the difference of the friction coefficient of the strong and weak phases,  $w$  is  
50 the weak phase fraction and  $\alpha$  a weakening coefficient ranging from 0.1 to 15 (see supplementary  
51 information). Note that such nonlinear weakening laws are also used in geomechanical engineering  
52 to describe the weathering of calcarenite<sup>10,11</sup>.

53 The derived exponential decrease of the mechanical strength from the experimental data of  
54 Figure 1 is then included into a thermo-chemo mechanical model that accounts for the coupled  
55 mechanisms activated at higher velocity conditions (see Methods for the mathematical description  
56 of the model). In this model, the degradation or creation of a weak phase is induced by the energy  
57 input to the system and it is not present before shearing. This unifying approach aims at reconcil-  
58 ing observations across a wide spectrum of materials and velocities. The extensive experimental  
59 data set used for the comparison corresponds to shear tests performed with rotary shear apparatus  
60 that allows to reach high displacements and therefore the steady state (see Figure 2). These exper-  
61 iments are realized on either gouge granular samples (usually 1mm thick<sup>17</sup>) sandwiched between

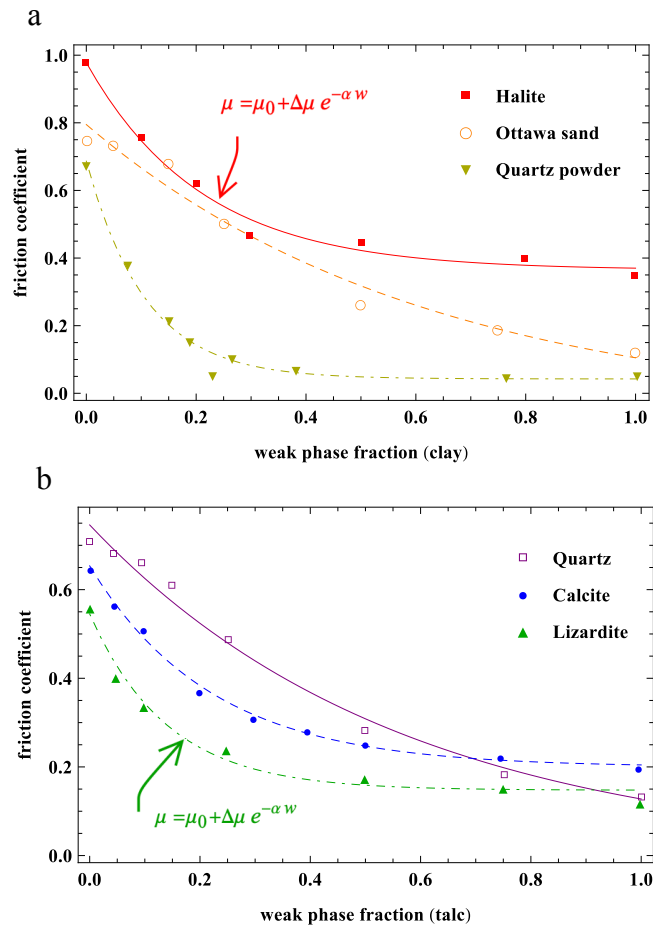


Figure 1: **Effect of the weak phase content on the steady state friction coefficient.** The friction of weak/strong phase binary mixtures is represented as function of the weak phase content in experiments carried out at subseismic sliding velocities and at constant normal stress using triaxial saw cut, double and simple direct shear and rotary shear configurations. **a**, results for clay as weak phase: red corresponds to a muscovite/halite mixture <sup>12</sup>, orange to a crushed Ottawa sand/montmorillonite mixture <sup>13</sup>, dark yellow to a quartz powder/bentonite mixture <sup>14</sup>. **b**, results for talc as weak phase: purple corresponds to quartz as strong phase <sup>14</sup>, blue to calcite <sup>16</sup>, green to Lizardite <sup>15</sup>. In **a-b**, the points represent the experimental data and the solid or dashed lines represent the interpolation using this exponential function.

62 two blocks or on bare rock samples<sup>18</sup>. In the latter, a gouge material is formed after only a few  
63 millimetres of displacement<sup>2</sup> with a thickness of 100 to 300  $\mu\text{m}$ . The data are gathered based on  
64 the nature of the material sheared and the physical mechanisms that are inferred to operate during  
65 the experiments<sup>1,19</sup>.

66 The constitutive law for the mechanical behaviour is applied to the gouge material, which ac-  
67 commodates all the deformation and is affected by the temperature, the weak phase fraction and the  
68 state of stress. The weak phase creation is modelled as an endothermic first order chemical trans-  
69 formation affecting the energy balance equation and respecting the mass balance. The geometry  
70 of the model chosen is larger of one or two orders of magnitude than the gouge in order to impose  
71 far field boundary conditions for the temperature and the extend of the phase transformation (see  
72 Figure 2). The steady states of this model can be determined using a continuation algorithm (see  
73 Methods), to test the hypothesis that the combination of thermally activated weakening and the  
74 creation of a weak phase may account for the observed steady state frictional response over many  
75 orders of magnitude of shear velocity.

76 The resulting steady state response of the model, in terms of friction and velocity, is depicted  
77 in Fig. 2. We can identify five distinct regimes of the system response to loading velocity: (I)  
78 **Static**. At low velocities, the material remains at static friction. Negligible temperature increase  
79 or weak phase production is observed. (II) **Thermo-mechanical weakening**. The temperature  
80 increase leads the friction coefficient to drop, in the absence of any weak phase production. (III)  
81 **Thermo-chemical stabilization**. With increasing velocity and temperature, small fractions of the

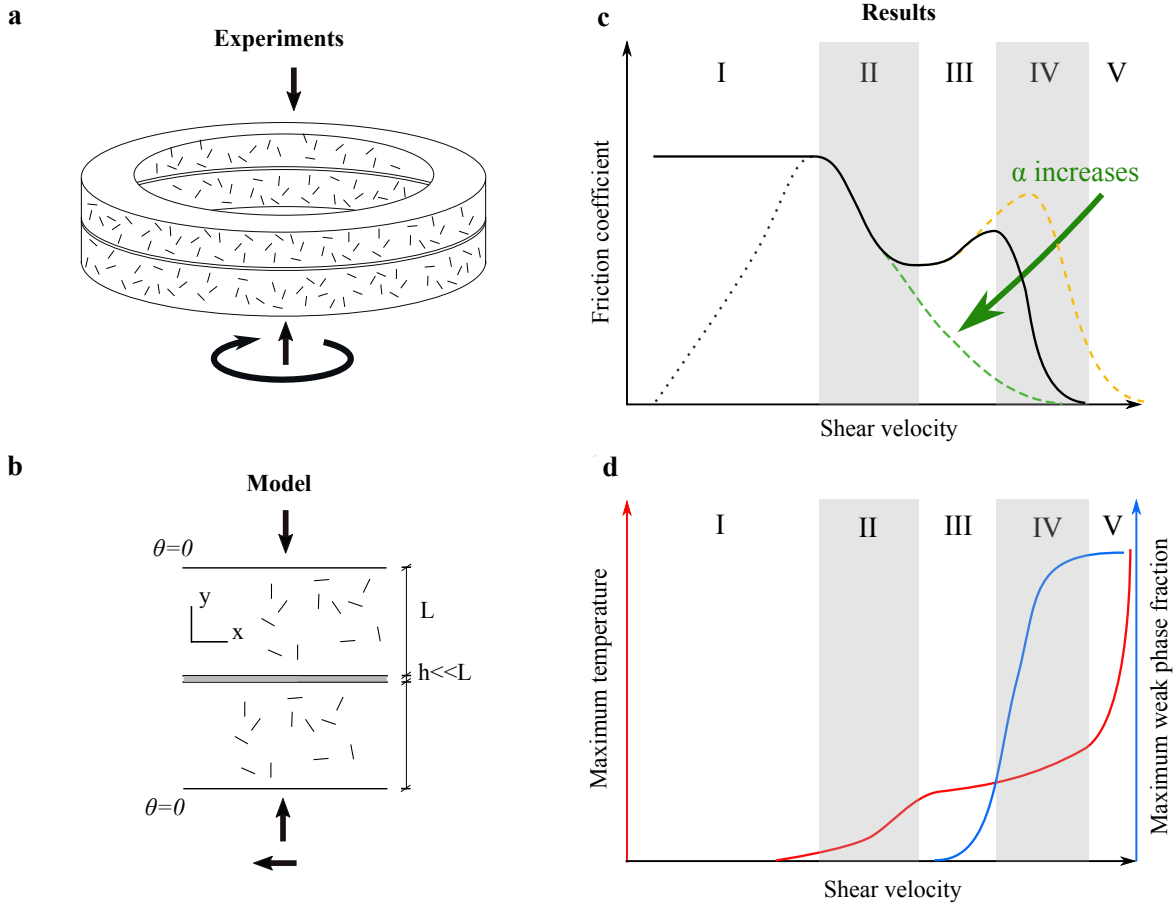
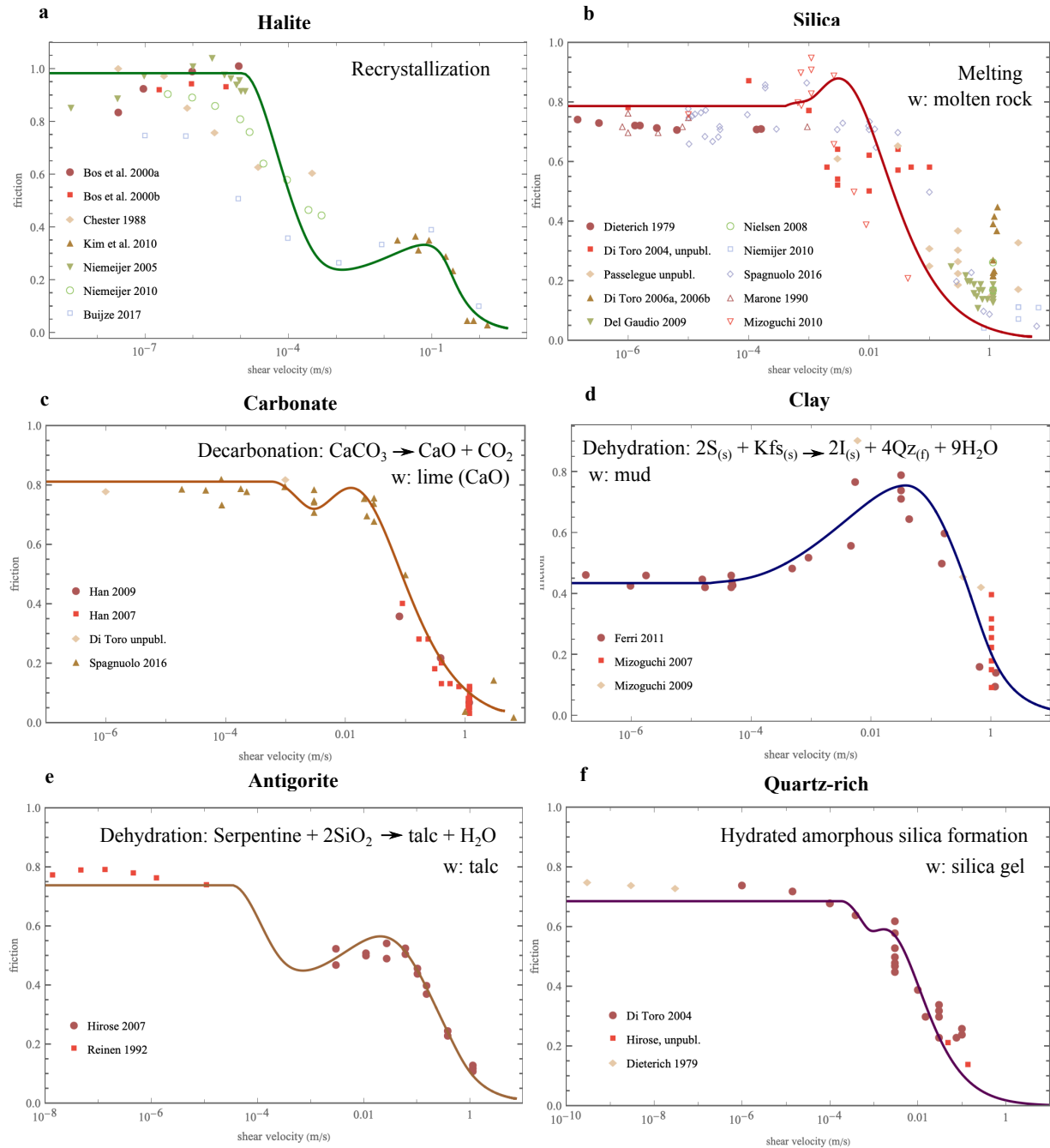


Figure 2: **a-b**, Schematic view of the geometry of the high velocity rotary shear experiments and the model. **c-d**, Steady state of the thermo-chemo mechanical model. Response of the mathematical system of equations (Eqs. 5-6 in Methods) at steady state. **c**, the steady state friction coefficient as a function of velocity, for varying weak phase sensitivity coefficient  $\alpha$ . **d**, the steady-state temperature and weak phase content dependency on the velocity, plotted for the black line of **c**. The five regimes (I - V) that can be observed in the response of the friction coefficient are correlated with the temperature and weak phase production processes, as explained in the main text.

82 weak phase are produced, absorbing the excess temperature and reducing the thermal softening  
83 effect on the friction coefficient. Depending on the value of the weakening coefficient, the friction  
84 coefficient can experience an intermediate increase. (IV) **Chemo-mechanical weakening.** Even-  
85 tually, weak phase content will be produced until it reaches a critical value that will dominate the  
86 friction coefficient and lead the material to unconstrained weakening. (V) **Runaway instability.**  
87 Once the reactants are depleted ( $w = 1$ ), the temperature is increasing uncontrollably and the  
88 friction coefficient drops towards zero.

89       After identifying the regimes of the steady frictional response of faults, the model is applied  
90 to experimental data. Figure 3 summarizes the results of the model for the steady state friction  
91 coefficient as a function of the velocity for six sets of materials<sup>1,9,18-21</sup>. The experimental data  
92 are a collection of several independent studies at different experimental conditions. As shown in  
93 the supplementary information, the normal stress shows no clear effect on the value of the friction  
94 coefficient reported here and for this reason it is not further investigated in this study. One of  
95 the interesting features of the model is the reproduction of strengthening observed experimentally  
96 at intermediate velocities (regime III in Figure 2) without supposing any additional hardening  
97 mechanism. For each material, the inferred phase transformation and the resulting weak product  
98 are highlighted. The model enables to capture accurately the observations and uses as input the  
99 material parameters listed in the supplementary information. Moreover, it enables us to retrieve  
100 information for the parameters of the different processes such as the activation energies, together  
101 with an assessment of the temperature evolution. This can be used as a basis to compare with  
102 the microstructural observations of the samples after the experiments. Indeed, in Figure 4 we



**Figure 3: Results of the model for different types of materials.** Application of the mathematical model (solid lines) to literature data (dots) of the friction coefficient as a function of the velocity. See the Methods for the mathematical description, Fig. 2 for the qualitative steady-state response and the supplementary information for the references of the experimental data. For each material, the phase transformation and the associated weak phase are indicated. **a**, for halite rocks. The model reproduces the experimental behaviour with  $\alpha = 0$ . **b**, for silicate rocks ( $\alpha = 7.5$ ). **c**, for carbonate rocks ( $\alpha = 5.3$ ). **d**, for clay-rich rocks ( $\alpha = 2$ ). **e**, for antigorite ( $\alpha = 1.5$ ). **f**, for quartz-rich rocks ( $\alpha = 14$ ).



103 are summarizing the evolution of the Temperature and weak phase ratio  $w$  required to obtain the  
104 friction coefficient results of Figure 3. Based on these two figures, we can compile the processes  
105 underpinning the macroscopic response of the frictional resistance of the different materials.

106 The temperature predicted by the model when the weak phase begins to appear can be  
107 compared to the theoretical activation temperature of the phase transformation (decarbonation<sup>22</sup>,  
108 melting<sup>23</sup>, dehydration<sup>24</sup> or clay type transition<sup>9</sup>), when available. In all cases, the temperature of  
109 the model is lower than the theoretical one (e.g. 530° C against 720° C for carbonates) imply-  
110 ing that the phase transition is triggered locally at the contact of the grains where the temperature  
111 can be higher than the bulk temperature. Moreover, these local phase changes are hard to detect  
112 even though essential for the mechanical behaviour. This also explains why the evidences of the  
113 phase transformations from specific sensors or microstructural observations (recrystallized halite  
114 grains<sup>17</sup>, increase of CO<sub>2</sub><sup>22</sup> or humidity next to the tested sample<sup>18</sup>, melted asperities<sup>25</sup> and white  
115 flakes due to silica gel<sup>20</sup>) are retrieved for higher velocities in experiments than predicted by the  
116 model. A notable case is halite, for which the weakening factor is  $\alpha = 0$  implying that any weak  
117 phase generated during shear does not affect the friction coefficient. As the material undergoes  
118 recrystallisation<sup>17</sup> during shearing which is a phase transformation that produces the same mineral  
119 with different grain sizes. Despite not producing a weak phase directly though, recrystallisation af-  
120 fects the energy budget and, thus the temperature produced (Figure 4) and therefore the mechanical  
121 behaviour of the gouge.

122 These results suggest that a thermally activated creep and the transformation of the material

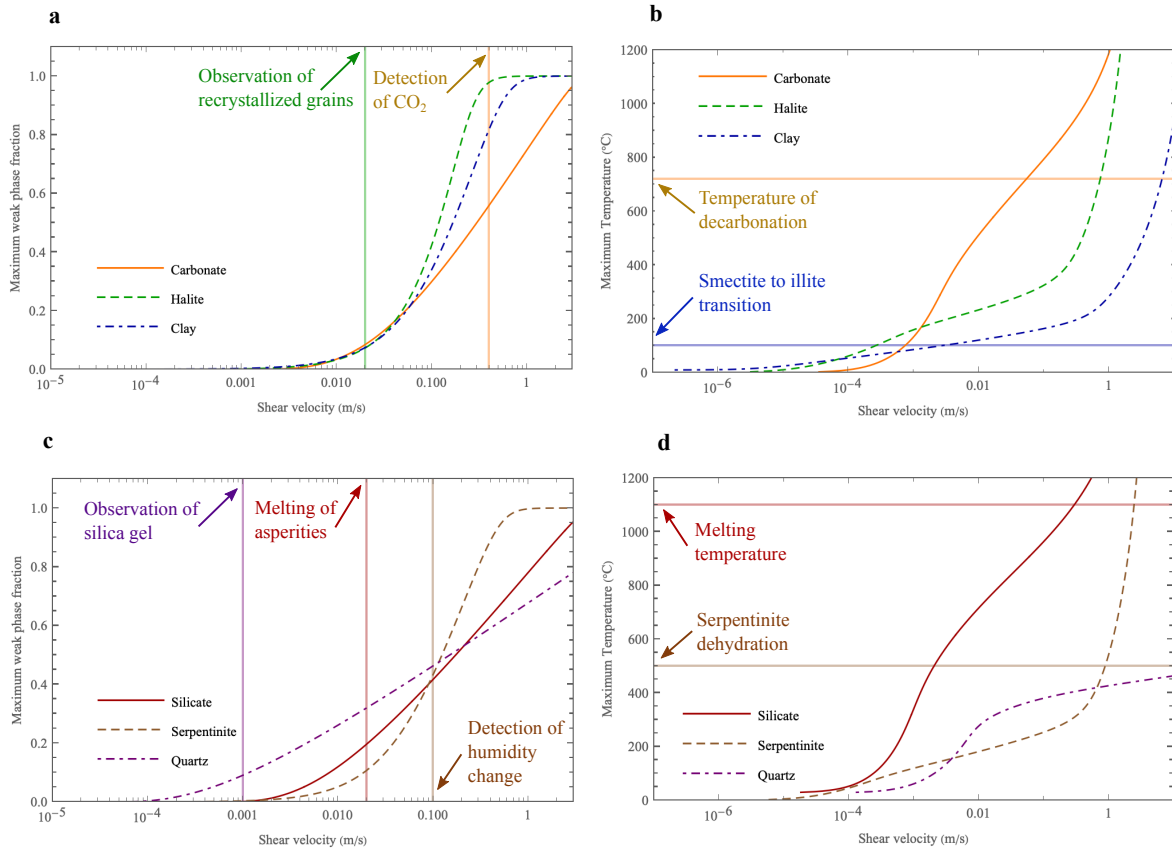


Figure 4: **Temperature and weak phase fraction evolution with the velocity for the experiments of Fig. 3.** **a** and **c**, weak phase fraction in the middle of the sample. Note that weak phase production has been approached as a first order chemical reaction, thus reaching its maximum value of one (100% weak phase present) when the reaction is depleted. **b** and **d**, maximum temperature in the middle of the sample.

123 inside the fault zone may be the dominant mechanisms during seismic slip of dry rocks. In the case  
124 where pressurized fluids are present -a scenario difficult to study experimentally- the static friction  
125 response<sup>9</sup> and the transient behaviour through thermal pressurization<sup>26,27</sup> are likely to be affected.  
126 In that case a detailed comparison between phase transition and thermal pressurization needs to be  
127 carried, to assess the dominant mechanism of slip <sup>28</sup>.

## 128 **Methods**

129 **Description of the Mathematical Model.** When the shear velocity applied to a rock or a granular  
130 sample is increased, thermal effects tend to dominate the frictional response<sup>5,20,29,30</sup>. A critical  
131 velocity is required to activate this mechanism that is related to the processes at asperities or grain  
132 contacts<sup>5</sup>. In this paper, we focus on the response of the material for intermediate and high veloc-  
133 ities where the thermal and chemical effect are important (other models have been developed for  
134 lower velocities and the nucleation of earthquakes<sup>29,31</sup>). Therefore, we consider here that for low  
135 velocities experiments the strength of the material is determined by the static friction of the ma-  
136 terials in contact or the internal static friction of the granular assembly. For velocities larger than  
137 the critical one, the shear stress of the system is calculated by solving a thermo-chemo-mechanical  
138 model inside the deforming zone. The critical velocity is retrieved as a result from this model  
139 and can be approximated by an analytical solution (see supplementary information). Physically, it  
140 corresponds to the critical velocity for which thermal weakening becomes significant.

141 The mathematical model consists of solving the momentum, mass and energy balance equa-  
142 tion at steady state, for an infinite sheared layer. The equations are briefly summarized here for  
143 easiness in reproducibility of the results<sup>3</sup>.

144 The momentum balance equations are considered and we neglect the inertia terms<sup>32</sup>:

$$\sigma_{ij,j} = 0 \quad (1)$$

145 where  $\sigma_{ij}$  is the stress tensor. These equations lead in the case of one dimensional shear zone to a  
146 constant normal and shear stress in space inside the layer.

147 The constitutive law for the mechanical behaviour is a rigid elastic-viscoplastic law with  
 148 the most generic form: an Arrhenius-power law dependency<sup>3,33</sup>. This law is only considered in  
 149 a layer of thickness  $h$ , much smaller than the total thickness of the layer  $L$  (see Figure 2). This  
 150 enables to describe the fact that after only a few millimetres of slip during the shear experiments  
 151 on bare rocks, a thin layer of gouge materials forms. This layer composed of crushed grains from  
 152 the initially rough surfaces has generally a thickness of 100-300  $\mu\text{m}^2$  and accommodates all the  
 153 deformation. However, as the boundary conditions for the weak phase and the temperature are  
 154 not well defined for this gouge layer, a domain of 1 cm is considered in order to apply Dirichlet  
 155 boundary conditions for these fields.

$$\dot{\epsilon}^{vp} = \dot{\epsilon}^0 \left( \frac{\tau}{\tau_y} \right)^m e^{-Q/RT} \quad (2)$$

156 where  $\dot{\epsilon}^0$  is a reference strain rate,  $m$  is the exponent of the power law,  $\tau$  is the shear stress,  $\tau_y$  is  
 157 the yield stress,  $Q$  is an activation enthalpy for the microscopic mechanism inducing a nonlinear  
 158 behaviour,  $R$  is the perfect gas constant and  $T$  is the temperature. This law allows to include more  
 159 physics into the hardening evolution as in the theory of plasticity for metals<sup>33</sup>. The Arrhenius  
 160 dependency of the flow law enables to introduce multi-physical couplings such as the effect of  
 161 heat generation on the frictional strength or more generally interface phenomena between the solid  
 162 skeleton and the pores<sup>34,35</sup>.

163 The effect of the non-mechanical state variables on the mechanical behaviour of the system  
 164 can be expressed as a single scalar function called the weathering index<sup>11</sup>,  $X_d$ . The strength of the  
 165 material depends on both the plastic strain and this weathering index. It is assumed that the two

166 effects are uncoupled<sup>10,11</sup> and a multiplicative structure of the yield stress is postulated:

$$\tau_y = T_y(\epsilon^p)T_y(X_d) \quad (3)$$

167 In our case, we do not consider any purely mechanical hardening law, so that the function  $T_y(\epsilon^p)$  is  
 168 constant. Moreover,  $X_d$  is considered to be a weak phase volume fraction. As shown in Figure 1,  
 169 the presence of a weak phase induces an exponential decrease of the frictional strength along with  
 170 the weak phase fraction. Assuming negligible shear strength for the weak phase, the final form of  
 171 the constitutive law is therefore:

$$\dot{\epsilon}^{vp} = \dot{\epsilon}^0 \left( \frac{\tau}{\tau_0} \right)^m e^{-Q/RT} e^{\alpha m w} \quad (4)$$

172 where  $\tau_0$  is the yield strength of the strong phase and  $\alpha$  is the weak phase sensitivity coefficient.

173 For a material consisting of two species: a weak and a strong phase, occupying volumes  $V_w$   
 174 and  $V_s$  respectively, we may define the volume ratio  $w = \frac{V_w}{V_w + V_s}$ . Inside a one dimensional shear  
 175 zone yield a system of two equations<sup>3,36</sup> obtained from the mass balance of the weak phase fraction  
 176 and the energy balance equations:

$$\frac{\partial T}{\partial t} = c_{th} \frac{\partial^2 T}{\partial y^2} + F(y) \frac{\tau \dot{\epsilon}^{vp}}{\rho C} - \frac{\Delta H r_F}{\rho C} \quad (5)$$

$$\frac{\partial \rho_1}{\partial t} + \frac{\partial J_w}{\partial y} = r_F \quad (6)$$

177 where  $T$  is the temperature,  $c_{th}$  the thermal diffusivity,  $\rho C$  the heat capacity of the mixture con-  
 178 sidered constant here,  $J_w$  the diffusion flux of the weak phase,  $\Delta H$  the enthalpy of the phase  
 179 change reaction considered endothermic,  $r_F$  the reaction rate and  $\rho_1 = \rho_w w$ .  $F(y)$  is a function  
 180 which value is 1 for  $y \in [-h/2, h/2]$  and 0 otherwise. The reaction rate is expressed as first order

181 chemical reaction with an Arrhenius law.

$$r_F = (1 - w) \frac{\rho_s}{M_s} k_F e^{-Q_c/RT} \quad (7)$$

182 where  $\rho_s$  and  $M_s$  are the density and molar mass of the strong phase.  $k_F$  and  $Q_c$  are the preexpo-  
 183 nential factor and activation energy of the chemical reaction. Using Equations 4, 7, considering a  
 184 Fick's law for the diffusion flux (defining a diffusivity  $c_w$ ) and the steady state of Equations 5 and  
 185 6, we obtain a system of two differential equations in space. This system is written in a dimension-  
 186 less form for the purpose of reducing the number of parameters to study and to enable a clearer  
 187 understanding of the main features of the system:

$$\frac{\partial^2 \theta}{\partial \bar{y}^2} + F(\bar{y}) Gr e^{\frac{Ar \theta}{1+\theta}} e^{\alpha m w} - Da(1 - w) e^{\frac{Arc \theta}{1+\theta}} = 0 \quad (8)$$

$$\frac{\partial w}{\partial \bar{y}^2} + \mu Da(1 - w) e^{\frac{Arc \theta}{1+\theta}} = 0 \quad (9)$$

188 where,  $\theta$  is the dimensionless temperature.  $Gr$ ,  $Da$ ,  $Ar$  and  $Arc$  are called the Gruntfest, Damköhler,  
 189 Arrhenius and chemical Arrhenius numbers respectively. They are defined by:

$$Ar = \frac{Q}{R T_0}, \quad Arc = \frac{Q_c}{R T_0} \quad (10)$$

$$Gr = \frac{\tau_0 \dot{\epsilon}_0 L^2}{\rho C c_{th} T_0} \left(\frac{\tau}{\tau_0}\right)^{m+1} e^{-Ar} \quad (11)$$

$$Da = \frac{\Delta H k_F \rho_s L^2}{\rho C M_s c_{th} T_0} e^{-Arc} \quad (12)$$

$$\mu = \frac{\rho C c_{th} T_0 M_w}{\Delta H \rho_w c_w} \quad (13)$$

190 **Numerical Bifurcation of the Steady State friction coefficient.** The solutions of this nonlinear  
 191 system of differential equations are approximated numerically using pseudospectral methods. The  
 192 temperature and weak phase fraction fields are interpolated in space using Chebyshev polynomials

193 of the first kind:

$$\theta(\bar{y}) = \sum_{i=1}^N a_i (\phi_{2i}(\bar{y}) - 1) \quad (14)$$

$$w(\bar{y}) = \sum_{i=1}^N b_i (\phi_{2i}(\bar{y}) - 1) \quad (15)$$

194 where  $\phi_{2i}$  are the Chebyshev polynomials of degree  $2i$ . Note that only the even degree Chebyshev  
195 polynomials are kept here as the solution is symmetric about the origin. Moreover, a basis recom-  
196 bination is used by considering interpolation functions of the form  $\psi_{2i}(y) = \phi_{2i}(y) - 1$ , allowing  
197 to enforce a zero Dirichlet boundary conditions implicitly<sup>38</sup>.  $N$  is the number of polynomials used  
198 to simulate the solutions. A convergence analysis has been conducted in each case to verify that  $N$   
199 is high enough to have a negligible error on the solution.  $a_i$  and  $b_i$  are the interpolation coefficients  
200 for the temperature and the weak phase fraction respectively. The interpolation points used for the  
201 resolution are the Gauss-Lobato points defined by:

$$x_j = \cos\left(\frac{(2j-1)\pi}{4N}\right), \quad j = 1, \dots, N \quad (16)$$

202 The nonlinear system of algebraic equations obtained is solved using the Newton-Raphson method.  
203 In order to capture all the steady state solutions of the system for the different values of the stress, a  
204 continuation pseudo-arclength algorithm is used. The continuation parameter chosen is the Grunt-  
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