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# 1 Multiphase rheology as a cause for stick-slip like melt extraction

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## 8 Highlights

- 9 ○ Numerical model of melt extraction
- 10 ○ Sporadic motion of melt and an analogue with dry friction (stick-slip)
- 11 ○ Hysteresis and memory effects during changes in input parameters
- 12 ○ Global expression of the free energy variation, with a term akin to velocity and a  
13 second term to acceleration
- 14 ○ Interactions between strain, chemistry and entropy (order)

15

## 16 **ABSTRACT**

17 When partial melting is parametrized in numerical thermo-mechanical models in a  
18 straightforward manner, it directly relates to variations in temperature. However, melt  
19 extraction is, to our knowledge rarely taken into account in these models, even if melt  
20 extraction and escape have a key influence on the mechanical behavior of the entire system.

21 Here, we propose a first step towards a numerical simulation for melt extraction in partially  
22 molten portions of the continental crust. We use a Lagrangian description, considering a  
23 discrete mineral distribution at sample scale. A cellular automaton mimics the mobile melt  
24 phase moving from cell to cell. An infinite source and sink for the melt and lateral periodic  
25 boundaries avoid melt accumulation. Time is represented by a proxy through successive  
26 iterations. The major controlling factors are the initial bulk melt percentage and a threshold  
27 controlling melt escape. We test pure and simple shear conditions to simulate strain  
28 partitioning between the melt and its matrix. The parameters, provided they do not vary,  
29 determine a regular or steady state amount of melt extraction after a few iterations. In  
30 contrast, for varying parameters during a single run, the quantity of melt extracted at each step  
31 presents alternate variations in amplitude ( $\sigma_\mu$ ) around an average value. Variations are neither  
32 periodic in the sense of a sinusoidal wave, nor of equal amplitude. Melt extraction behaves  
33 similar to a stick-slip motion in dry friction. Since we cannot have access to the prediction of  
34 melt amount, we test the origin of the sporadic motion. We examine variations of the input  
35 parameters (initial melt  $\phi$ , permeability  $\zeta$ , applied stress  $\sigma$  or  $\tau$ ). The transient effects mark by  
36 spikes ( $\Delta\mu$ ) with two contrasted situations. Return to a steady state is exponential, similar to  
37 the discharge of a capacitor. Nevertheless, a first mode occurs when the changes are made on  
38 separate runs, reinitializing the parameters between them. These experiments show a linear  
39 dependence of the variation in amplitude of  $\sigma_\mu$  with the parameters. Alternatively, when the  
40 changes are successive during the same run, then  $\sigma_\mu$  decreases accordingly. The exponential  
41 variation is interpreted as a memory effect or hysteretic behavior of melt extraction. Similarly,  
42 the amplitude of the stiction spikes ( $\Delta\mu$ ) does not show the same behavior when permeability  
43 increases or decreases. By analogy with friction, the change from sticking to slipping is  
44 interpreted as a manifestation of pinning and depinning, leading to an avalanche-like  
45 phenomena. Mechanically they correspond to a change in friction velocity. Physically, it

46 points to the change in the free energy of the system, with a first derivative akin to velocity  
47 and a second derivative akin to acceleration. During melting, the mechanical barriers  
48 correspond to the energy variations due to chemical reactions between melt and crystals.  
49 Depinning corresponds to enhanced melting whereas pinning links with back reactions  
50 leading to garnet growth. The sporadic melt extraction links dry friction to poroelastic flow,  
51 or more generally to a consequence of two-phases rheology. Hence the sporadic motion of the  
52 weak phase originates from interactions with its matrix. Hence the flow (velocity) suffers  
53 modulations due to interactions with chemical potential (back-reaction, melting), entropy  
54 (ordering through dislocation creep), and strain (aperture of porous flow). Such interactions  
55 should be considered when dealing with quantitative mush (melt+ matrix) modeling  
56 (rejuvenation, extrusion).

57

## 58 **Graphical Abstract**

59

60 **Keywords:** stick-slip; melt extraction; friction; hysteresis; pinning/depinning

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## 72     **1.                   Introduction**

73           Temperature rules melt generation in the crust, most often through heat diffusion, or  
74 advection, which are both continuous processes. The extraction of melt out of its matrix is by  
75 contrast discontinuous, initiating from melt pockets that aggregate to form veins to escaping  
76 and feeding isolated plutons (Kisters et al., 1998). According to such field observations, the  
77 paradigm of melt extraction and transport turned from diapirism or dyking to discrete solitary  
78 waves (Connolly and Podladchikov, 2000; Rabinowicz and Vigneresse, 2004) that propagate  
79 from themselves, driven by alternate changes in permeability. Such models of porous flow  
80 also apply to propagating fluids, melt or water within a stressed crust, with applications to  
81 magmatism, geothermic and water circulation into the basement. They form the basis of  
82 poroelasticity (Cheng, 2016). The paradigm switch from a viscous material more mobile into  
83 a viscous matrix to a problem of permeability suggests that hydraulic parameters should rule  
84 crustal fluid transport.

85           Modelling melt extraction thus points to the rheology of multi-phase material, i.e. the  
86 differential response of a mobile fluid circulating into a deforming matrix. The viscosity  
87 contrast between the melt and its matrix i.e. a weak and a strong phase, may be apprehended  
88 from several points of view including estimates of an effective viscosity, intermediate  
89 between the two end-members (Pistone et al., 2016; Agard et al., 2018). Three factors then  
90 add complexity to such a direct approach. The first is the dependence of the viscosity of the  
91 strong phase on the applied strain rate whereas the melt is simply Arrhenian. This makes the  
92 experimental studies hard to be transposed to natural conditions (Pistone et al., 2016) because  
93 the fast strain rate imposed by the duration of experiments. The second factor is strain  
94 partitioning (Vigneresse and Tikoff, 1999) between the weak and the strong phase (Goodwin  
95 and Tikoff, 2002). Their respective abundance determines which phase globally controls the  
96 effective rheology. When the weak phase is abundant, the rheology is governed by the

97 distribution and geometry of rigid blocks (Agard et al., 2018; Ioannidi et al., 2021) as  
98 observed at the interface of subduction zones. In contrast, when the weak phase is in minor  
99 amount, the strong rigid matrix controls the bulk rheology (Vachon and Hyeronimus, 2017).  
100 The two approaches can be considered as a variant of a direct problem, overdetermined, and  
101 always offering a solution. However, they do not tackle the third factor, which is the exchange  
102 of matter between the melt and its matrix, forming feedback loops. Hence melting occurs  
103 when adequate minerals are close together, thus lowering the energy of melting. Conversely  
104 back reactions, especially involving ferro-magnesian minerals, precipitate elements,  
105 consuming energy to form incongruent minerals (Cenki et al., 2002; Nyström and Kriegsman,  
106 2003). The two reactions act in modifying the free Gibbs energy budget of the reactions.  
107 However, their extent, i.e. the amount of material involved that rules the energy budget cannot  
108 be controlled exactly in time and space. It thus lowers the accuracy of a direct modelling.

109 To partly avoid and solve these ambiguities, a cellular automaton has been constructed  
110 and modified (Vigneresse and Burg, 2005; Vigneresse et al., 2020), giving insights to the  
111 mechanisms of two-phase rheology in partially molten rocks (see below).

112 The process of melt fusion and extraction can be directly compared with frictional motion,  
113 that rules displacement of two materials in contact under an applied force (Persson, 1995;  
114 Marone, 1998). Friction characterizes the relative motion, usually between two solid phases  
115 (Byerlee, 1978). It links the tangential ( $\tau$ ) to normal ( $\sigma$ ) forces (Fig. 1). The former controls  
116 motion imposed by an applied force, whereas the second akin to the gravitational force resists  
117 to lateral motion. The static coefficient of friction ( $\mu_0$ ) is a linear function of the applied  
118 forces, and it is constant for most materials (Byerlee, 1978) (Fig. 1a). The irregularities of the  
119 contact make lateral motion sporadic in time. A kinetic coefficient of friction (Dieterich,  
120 1979; Ruina, 1983) quantifies the derivative of the displacement, akin to a velocity.

121 Irregularities, or asperities in the planar surface separating the two bodies resist to motion.  
122 The frictional motion becomes transient owing to the change in the velocity of the motion  
123 (Fig. 1b). Stick-slip is a special case of motion in which a prolonged stagnation (the “stick”  
124 phase) is interrupted by short bursts of movement (the “slip” phase). The motion is not  
125 periodic in the sense that the time interval between the short bursts is not always identical,  
126 depending on the resisting forces (Fig. 1c). The amplitude of the bursts that vary around an  
127 average value are not identical neither. When the initial conditions locally vary, a transient  
128 motion develops with sudden acceleration in motion. Such transient effects are not well  
129 understood, though they represent the responses of the system to the initial parameters  
130 variations

131 While the discontinuous nature of melt extraction could be easily been transposed from  
132 discrete permeability waves, the transient effects are not intuitively transposable to  
133 displacements between viscous bodies or to poroelasticity. Hence, the discontinuous nature of  
134 seismicity for example, yield to the concepts of asperity, small irregularity in the contact  
135 between materials. They represent pinning points restraining motion and the sudden change in  
136 contact area, or depinning leads to sliding. Following this model, frictional motion manifests  
137 by alternate sticking and sliding phases, known as stick-slip motion (Baumberger and Caroli,  
138 2006; Brace and Byerle, 2008).

139 Illustrating and interpreting frictional motion between a fluid, melt or water, and its matrix  
140 represents an example of alternate concepts between rheology and hydraulics applied to  
141 magmatism. The starting point of this study is a numerical simulation of melt extraction using  
142 a cellular automaton (Vigneresse and Burg, 2005). The origin of a sporadic motion is  
143 examined in relation with the initial parameters and internal changes in free energy through  
144 the interactions between its three components (entropy, strain and chemical potential).

145

## 146      2.                      Numerical modelling set up

147            A numerical modelling using a Lagrangian formulation has been built from a cellular  
148 automaton modified from a preceding model (e.g. available code in Vigneresse and Burg,  
149 2005). The initial system consists in discrete cells, organized in a hexagonal pattern with  
150 dimension 64 by 38 cells (Fig. 1). Cells contain indifferently melt and solid in proportion  
151 varying from 0 to 100 (Vigneresse et al., 2021). The solid phase involves quartz and  
152 plagioclase, two micas as muscovite and biotite, and some incongruent or residual  
153 ferromagnesian minerals. The initial mineral and melt proportions are fixed, with a textural  
154 disposition, either random, in layers or small pockets (Vigneresse et al., 2021). A  
155 stoichiometric equation rules dehydration melting (Gardien et al., 2000). Similarly, back  
156 reactions are introduced for the ferromagnesian (Cenki et al., 2002). The melt sink is infinite,  
157 as well the heat source. Those two conditions assume a stationary condition for melt  
158 evolution. The remaining solid phase is replaced by the moving melt from one cell to the next,  
159 according to simple and/or pure shear geometry. Shear strain localization is possible by  
160 moving melt to more than one cell. Periodic lateral boundaries avoid melt accumulation. The  
161 initial melt content can be modulated, or by partial refilling in melt mimicking temperature  
162 burst. Superimposed to the initial conditions and geometric parameters, two rules control melt  
163 motion and extraction (Vigneresse et al., 1996). In addition to a liquid percolation threshold  
164 (LPT) a melt escape threshold (MET) controls extraction. The effect of stress and strain rate is  
165 also examined in both situations of pure ( $\sigma$ ) and simple ( $\tau$ ) shear. However, the adopted 2D  
166 geometry biases the results since melt may escape the system in the third direction. The time  
167 is represented by an iterative process. As in most cellular automata, that are qualitative by  
168 essence, the time aspects are only apprehended through iterations, i.e. without exact  
169 calibration in time.

### 171 3. Results concerning melt extraction

172 Results allow to identify the effects on melt extraction of the main parameters: i.e. the  
173 initial amount of melt ( $\phi_0$ ) and the threshold for extraction (MET). The former is supposed to  
174 overcome melt percolation through the system. The latter is equivalent to fluid draining, thus  
175 renamed as  $\zeta$  (Fig. 2d, e). All parameters vary on a scale from 0 to 100. The extreme values of  
176 met ( $> 50$ ), i.e. with more melt than matrix, are not representative of nature, but allow a  
177 control on the evolution of the numerical model.

178 Bulk results show a stationary state when there is no significant change in the input  
179 parameters, but a spike in melt extraction occurs when the  $\zeta$  value changes, and more  
180 commonly when sporadic extraction occurs. The three modes (stationary, spike and sporadic)  
181 show a good analogy with frictional motion, pointing to interpretation with the changes in  
182 friction, i.e. in terms analogue to a frictional law (e.g. Marone, 1998).

#### 183 3.1. Preliminary assessment of the results

184 Melt extraction is scaled in relative quantity of melt extracted versus iterations, i.e. time,  
185 without possibility of more precise scaling (e.g. hours or years) yielding a relative time scale.  
186 Similarly, the energy budget of the process is not quantitatively available.

187 The amount of melt is another parameter used during the computation. The possible  
188 amount of melt in each cell ranges from 0 to 100. Consequently, the extracted melt fraction  
189 ( $\sigma$ ) at each step also ranges from 0 to 100 (Fig. 3). The fraction of extracted melt per step  
190 shows, as expected, a spike at the start of the model, that rapidly converges toward a  
191 stationary value. The spike is positive when the initial melt fraction is high, negative when  
192 melt fraction is low. Curves with different initial melt fractions converge after about 70-80  
193 steps. In a second stage, the percentage of melt extracted ( $\sigma$ ) at each step is normalized to the  
194 initial melt ( $\phi_0$ ) and the dimension of the model ( $N_x * N_y$ ), providing the coefficient of melt

195 extraction ( $\mu$ ) (Fig. 3). After normalization, the value converges after about 150 steps toward  
196 a value ranging 0 to about 1.5 (Fig. 3) increasing with the initial melt ( $\phi_0$ ). In this example, the  
197 linear relation between  $\mu$  and  $\phi_0$  defines a bulk coefficient of melt extraction ( $\mu_0$ ) that equals  
198  $0.17 \pm 0.002$  whatever the initial melt percentage, and using a value of 0.25 for  $\zeta$  assuming a  
199 one order less variation of ( $\mu_0$ ) as a function of  $\zeta$  (Vigneresse and Burg, 2005).

200 A note of caution seems necessary, here, prior to interpreting the results. The coefficient  
201 of melt extraction reaches a value of 1.0 for  $\phi_0$  larger than 50 and values higher correspond to  
202 more melt extracted than produced. It means that the model diverges for high values of initial  
203 melt, i.e. when there is more liquid than solid. Such a situation, mathematically possible, does  
204 not reflect reality. However, it allows examining the results in a larger range of parameters.  
205 We have indicated on the figures 6 to 7 the range of values for melt extraction, as estimated in  
206 nature.

207 The coefficient of melt extraction ( $\mu$ ) shows two behaviours, regular or stationary, and  
208 transient (Fig. 4), depending on whether the other parameters are constant or not during a  
209 single run. Both cases are examined separately. The first case leads to a steady state regime.  
210 Conversely, the transient mode due to varying  $\zeta$ , or strain rate ( $\epsilon^\circ$  and  $\gamma^\circ$ ) induces a spike of  
211 amplitude  $\Delta\mu$ .

212 The return to the steady state values follows a classical damping effect reflecting an  
213 exponential decrease of the sharp increase with a characteristic time ( $D_c$ ) about 70-80 steps  
214 (Fig. 4). The lack of definition in time (i.e. iterations) precludes a more detailed investigation  
215 on the variability of  $D_c$ . The spike is positive or negative, depending on the lack or enhanced  
216 quantity of melt. It thus, like a charge and discharge of a capacitor, requires using a  
217 logarithmic function, with the sharp increase normalized to the initial value. The function

218 takes the form of a  $\ln(\phi/\phi_0)$ . Such functions are applied to changes in  $\zeta$  and strain rate ( $\epsilon^\circ$  and  
219  $\gamma^\circ$ )

### 220 3.2. Towards a law of melt extraction

221 The preceding diagrams allow quantifying the relative variations as a function of the input  
222 parameters. The results can be summarized as follow and interpreted by a simplified law of  
223 melt extraction that takes into account the linear and non-linear effects, associated to the  
224 potential barriers of melt extraction mimicking a frictional law (Vigneresse and Burg, 2005):

$$225 \mu = \mu_0 + a (\phi/\phi_0) + b (\zeta/\zeta_0) + c (\sigma/\sigma_0) + d \ln (\delta\phi/\phi_0) + e \ln (\delta\sigma^\circ/\sigma^\circ_0)$$

226 with the numerical values  $\mu_0 = .022$ ,  $a = .0018$ ,  $b = -.0015$ , and  $c = .016$  (simple shear)  
227 or  $= .066$  (pure shear) (Vigneresse and Burg, 2005). The two functions in  $\delta\phi$  and stress rate  
228 ( $\delta\sigma^\circ$ ) variations are non-linear and could not be determined quantitatively. Globally, the  
229 effective production of melt ranges from 15 % to a maximum of 40 % depending on protolith  
230 composition (Vigneresse et al., 2021). The potential barriers represent variations one order of  
231 magnitude less than the coefficient of melt extraction  $\mu_0$ .

232 It should be compared to the suggested frictional laws (Dieterich 1972), with the modification  
233 about displacement (Ruina 1983).

$$234 \mu = \mu_0 + a \ln(V/V_0) + b \ln(V_0 \theta / D_c) \text{ and } d\theta/dt = 1 - V\theta/D_c$$

235 Nevertheless, because of the poor access to time, the problems of strength recovery (healing)  
236 interpreted from the state variable  $\theta$ , without more specification (Ruina, 1983), have not been  
237 considered in the actual study. The analogy points to the effect of velocity, either as the  
238 velocity of traction during dry friction, or melt flux under strain partitioning on the viscous  
239 melt, eventually enhanced by acting stress. In addition, a second term related to imposed  
240 strain is present in the equations, that may have an influence on the sporadic motion during

241 friction or melt extraction. In a first approach, this term is a derivative of the motion, akin to  
242 acceleration. It suggests that melt motion is represented by the relative value of melt volume  
243 ( $\phi/\phi_0$ ), whereas the remaining other parameters ( $\zeta$ , strain) act as enhancing/damping the flow.

244

#### 245 **4. Sporadic melt extraction**

246 One difficulty in interpreting the irregular sporadic melt extraction patterns mostly links  
247 with the poor determination related to temporal calibration. It includes difficulties in a true  
248 scaling in time units, but also difficulty in interpreting a discontinuous diagram of irregular  
249 amount of extracted quantity of melt. It manifests during friction by a stick-slip motion (Fig.  
250 2c), as a second order manifestation, interpreted by the hysteretic nature of friction. Hence,  
251 friction is a dissipative function of energy, that needs additional energy to recover the initial  
252 state. We provisionally adopt the term stick-slip behaviour for describing melt extraction.

##### 253 4.1. Variations in stick-slip amplitude ( $\sigma_\mu$ )

254 Stick-slip manifests during friction by alternate periods of no or restricted motion, or  
255 stick phase, followed by slip at constant velocity (Fig. 2c). Similarly, the amplitude of melt  
256 extraction, varies with iterations, but remains constrained between two values defining a  
257 dynamic and static extraction modes (Fig. 2f). The difference is referred to as  $\sigma_\mu$ . This value  
258 is examined as a function of the other parameters. The amplitude of  $\sigma_\mu$  varies linearly  
259 between 0.0015 and 0.013 for an initial melt content varying from 5 to 85 %, though the last  
260 value is unrealistic in nature, but brackets the range of variables. It slightly varies by about  
261 0.003 for a variation of 50 in the initial melt content ( $\phi_0$ ), i.e. from dry to saturated melt. The  
262 values increase with  $\zeta$  by about 0.035 for a change of 20 in  $\zeta$  (Fig. 5). Thus, the effect is more

263 pronounced depending on  $\zeta$  rather than on  $\phi_0$ . The linear effect also excludes artifacts such as  
264 errors or noise. It correlates with a non-strictly periodic effect in amplitude.

265 The very moderate decrease, about one order less than the coefficient of melt  
266 extraction with the initial melt content points to an enhanced melt extraction with the total  
267 melt content (Fig. 5), suggesting a possible lubrication of the interface between melt and its  
268 matrix. Nevertheless, this effect remains weak compared to the effect of  $\zeta$ . It also points to  
269 enhanced/damping effects occurring during transient changes compared to the variations  
270 induced by varying the initial parameters.

271

#### 272 4.2. Variation of amplitude depending on the system history

273 The amplitude increase of the sporadic melt extraction has been tested against the other  
274 parameters evidenced in the melt extraction law ( $\phi$ ,  $\zeta$ ,  $\varepsilon^\circ$ ) (Vigneresse and Burg, 2005). This  
275 has been realized under two modes. In a first set of runs, these parameters remain fixed along  
276 the whole run. The separate runs (previous sections) show moderate variations in  $\sigma_\mu$ , with a  
277 bulk increasing linear trend whatever the change in all parameters (Fig. 6).

278 Alternatively, a second set of runs, that are successive, allows abrupt changes in the  
279 parameters during iterations, indicated by enhanced melt extraction spikes before a  
280 progressive return to the previous extraction mode. Those spikes, with amplitude  $\Delta\mu$ , are  
281 positive or negative depending on charge or discharge of melt. By contrast, the amplitude of  
282 melt extraction ( $\sigma_\mu$ ) shows a pronounced decrease, for all parameters ( $\phi$ ,  $\zeta$ ,  $\varepsilon^\circ$ ), when one of  
283 them is kept constant (Fig. 6). The decrease in amplitude is significant (0.12 to 0.0), since  $\sigma_\mu$   
284 tends to zero when the changes in input parameters modify the coefficient of melt extraction  
285 by a factor 2 or 3. In addition the variation in amplitude for separate runs largely overcomes

286 the variation for separate runs (Fig. 6). To further explore the situation, their amplitudes have  
287 been plotted during successive variations of the inputs (Fig. 7a). The amplitudes decrease with  
288 iteration (i.e. time) according to a law proportional to  $\zeta^{-1} \ln(\zeta/\zeta_0)$  with a coefficient  $\alpha$  and  $\zeta_0$   
289 the initial permeability (Fig. 7b). It points to a memory effect acting on the stick-slip  
290 amplitude, and decreasing with the system memory. Nevertheless, as stated before, the poor  
291 variability in the amplitude of Dc, i.e. some quantification of the time constant of the  
292 relaxation, precludes insights to the energetical aspects of melt extraction. An interpretation  
293 would be an enhanced permeability due to healing. Once porosity is enlarged, it should keep  
294 its high value, leading to enhanced melt extraction.

295

#### 296 4.3. Return on the spike amplitudes

297 The fact that  $\sigma_\mu$  decrease with the melt extraction has an impact on the amplitude of the  
298 enhanced melt extraction spikes ( $\Delta\mu$ ), but no real trend could be estimated from the spike  
299 amplitudes. Taking into account a possible memory effect allows to reconsider differently the  
300 spikes. From the various runs, the spikes amplitudes have been plotted as a function of  $\zeta$   
301 variations, distinguishing the positive from the negative variations. These plot shows a weak  
302 coherence, adopting a double curve, not symmetric to each other, but mimicking some kind of  
303 hysteresis cycle as a function of the quantity of melt refilling or escaping. It corroborates the  
304 asymmetric plot of  $\Delta\mu$  versus  $\phi$  variations (Fig. 4).

305

### 306 5. Implications and discussion

307 The large variability observed in the modelled melt extraction has some direct  
308 consequences.

309

## 310 5.1. Hysteresis

311 Hysteresis is the dynamic time lag between input and output of the system, reflecting its  
312 dependence on its previous history. It is associated with the need to consume or deliver  
313 additional energy for the return to initial conditions. Examples of hysteresis in geological  
314 systems include remanent magnetism, plastic deformation, phase change during melting and  
315 crystallization, or surface tension (Persson, 1995; Hill, 1998). A simplistic representative  
316 example is a drop of water on a glass. In case of a porous medium, with a two-phase flow (air  
317 and water) the curve of capillary pressure versus the wetting phase saturation also describes a  
318 hysteretic cycle, with a wetting stage, and return along drying curve. Due to the solubility of  
319 the gaseous phase, the hysteretic curve shrinks with successive cycles of drying and wetting.

320

## 321 5.2. Pinning and depinning

322 The sporadic melt extraction, with alternate bursts, links to variations in the melt  
323 velocity, i.e. de-/acceleration. As stated in friction, it relates to a state variable  $\theta$  (Ruina,  
324 1983), essentially defined by its derivative with time ( $d\theta/dt$ ). It is characterized by alternate  
325 episodes of lock (stick) and motion (slip). The frictional interpretation commonly relates to  
326 those stages to surface conditions. Indeed, they present asperities, or small stronger areas of  
327 relief, arresting the motion. If the interpretation is correct, the alternate stages of  
328 enhanced/reduced melt extraction should also be controlled by such points of resistance, i.e.  
329 pinning and depinning, and their equivalent in terms of chemical thermodynamics is  
330 consuming/releasing Gibbs free energy.

331 Experimental studies on stick-slip, using small transducers and fast camera recording  
332 allow a better understanding of the phenomena traduces in a force vs time diagram during dry

333 friction (Fig. 8a). The equivalent diagram in displacement vs time indicates periods of no  
334 motion corresponding to the stick stage followed by a sudden jump in velocity (Fig. 8a).  
335 However, more sensible experiments from the group of Jay Fineberg (Hebrew University,  
336 Jerusalem) tackled the fine motion during the sticking stage in a bi-phase material interface.  
337 They record high-speed measurements of the real contact area, whereas the strain field is  
338 measured in the region surrounding propagating rupture tips (Svetlizky and Fineberg, 2014).  
339 They observe highly localized slip pulses accompanied by a large local reduction of the  
340 normal stress near the rupture tip. The pulses propagate along the direction of motion of the  
341 softer material at a maximal velocity, evolving while propagating. When the rupture front  
342 velocity overcomes the seismic S-waves velocity, it determines a supershear front (Rosakis et  
343 al., 1999) that propagates in the opposite direction, suggesting crack-like rupture. Such results  
344 corroborate the ideas of dislocations steadily propagating along a material interface. In  
345 parallel, the transition from static to dynamic friction is quantitatively described by classical  
346 singular solutions for the motion of a rapid shear crack (Rubinstein et al., 2004). They  
347 observed propagations at sub-Rayleigh velocity, the sound speed along a free surface, but also  
348 a slower front that could be the trace of healing at contact area, before slip arrest. This is  
349 similar to ageing that immediately commences as contact area increases. Its characteristic  
350 timescale is determined by the local memory of the system, according to its effective contact  
351 time before slip arrest (Ben-David et al., 2010).

352         Such evolution at the microscale of dislocations has been surveyed in detail on a single  
353 LiF crystal since it allows simultaneous observation of evolution of the dislocation structures  
354 through the Bauschinger effect, a piling-up of dislocations at grain boundaries. Indeed, the  
355 microscopic distribution of stress alters the stress/strain characteristics of the material (Harea  
356 et al., 2013). This property is used to trace the dislocation pattern during deformation  
357 (Perfilyev et al., 2014). Observations show that the indenter velocity increases nonlinearly

358 during the transition from stick to slip. in the mid-part of the slip phase, the indenter reaches  
359 its maximum velocity, while the friction force decreases abruptly (Fig. 8b). The average  
360 velocity of the indenter in the stick phase drops by about 300 times than the maximum  
361 velocity in the slip phase. It drastically affects the behaviour of the dislocation regime. Three  
362 stages of creep are evidenced between two slip events (Perfilyev et al., 2014). First, a primary  
363 creep links with the formation of bonds (pinning effect). Their number increases during the  
364 second long-time steady state. In contrast, the tertiary creep is characterized by the rupture of  
365 bonds (depinning effect).

366 The link between pinning/depinning and dislocations (Anderson et al., 2017) brings  
367 some highlights on the asperity model since it marks by acoustic emission that may be  
368 recorded during the stick-slip motion. Known as the Barkhausen noise in ferro-magnetism  
369 (Santa-Aho et al., 2019) it results from the rapid size variations of magnetic domains, with  
370 their magnetic spins equally oriented. The produced noise is recorded and is currently in use  
371 to detect defects in the alloys.

372

### 373 5.3. Implications on melt extraction processes

374 The preceding section provides mechanical examples involving the role of  
375 dislocations in pinning/depinning effects during frictional stick-slip motion (Fig. 9a).  
376 Dislocations creep correspond to a change in the ordering of a crystal, i.e. a change in  
377 entropy. It may apply to solid-solid contacts but fails when a viscous material is present  
378 (Marone, 1998). Another model of stick-slip behaviour derived from poroelasticity (Cheng,  
379 2016) takes into account the surface tension and the solubility between the components, solid,  
380 liquid and air (Fig. 9c). It corresponds to an interaction between strain of the flow and strain  
381 imposed by the matrix. In both cases a locking effect, or barrier, retards motion while an

382 acceleration occurs when additional energy overcomes the resisting forces. In both cases, the  
383 processes are the sum of a static equivalent to the free energy of the system plus a term  
384 function of the its first derivative, equivalent to velocity, and a second derivative, equivalent  
385 to acceleration. The energy barrier linked to dislocations has a fixed amplitude, also linked to  
386 a progressive increase in pinning, thus favouring a limit to a dynamic friction coefficient.

387 In between those two end-members, melt extraction results from a viscous-viscous  
388 interface. There is no dislocation, by lack of a true crystalline network, and there is no non-  
389 percolating third phase as air bubbles. Hence the matrix is a crystalline rock undergoing  
390 melting, but with a heterogeneous amount of solid phases either products or unreacted  
391 inherited minerals. The melt is a mixture of silicate polymers and ions in a supercritical state.  
392 Metamorphic reactions between the melt and its matrix may be considered as a cause of for  
393 pinning/depinning effects (Fig. 9b). Retrograde, melt-consuming reactions, producing solid  
394 phase are the counterpart of prograde melting and may produce new minerals phases acting as  
395 asperities causing stick-slip or sporadic melt extraction. Both type of reactions are commonly  
396 observed in migmatites, rocks that have undergone partial melting (Stüwe, 1997; Kriegsman,  
397 2001).

398 Dehydration of hydrous minerals occurs during prograde melting, mainly muscovite  
399 above 730 °C and the biotite around 800°C (Clemens, 1990). Hence the leucocratic portions  
400 of migmatites, or leucosomes, are mostly composed of quartz, feldspars and rare micas. These  
401 are interpreted as crystallized melt usually of granitic composition. The darker  
402 ferromagnesian minerals form the melanosome and may segregate aside the leucosomes by  
403 flow differentiation or reactive transport (Kriegsman, 2001). The minerals from the  
404 melanosome can either be relics of reactants, products of melt consuming reactions or newly  
405 formed incongruent mineral phases.

406           During muscovite breakdown with temperature increase, mineral phases disappear  
407 whereas melt-consuming reactions may form new solid phase upon cooling (Kriegsman,  
408 2001). Those may be quartz, plagioclase and muscovite (Nyman et al., 1995; Konn et al.,  
409 1997) followed by biotite, sillimanite, quartz and plagioclase (Cenki et al., 2002). In contrast  
410 garnet and cordierite may grow as incongruent porphyroblasts (Nyström and Kriegsman,  
411 2003). During growth, they may incorporate large quartz rounded inclusions indicating  
412 surface tension and immiscibility. Upon cooling, retrograde phases may form coronas around  
413 these porphyroblasts, surrounding by the leucosome, illustrating back reactions between the  
414 restitic phases and the melt. Ti-rich biotites also grow at the expense of ferro-magnesian  
415 incongruent phases (Cesare et al., 2008). Melt consuming reactions include mica growth, fine-  
416 grained intergrowths in micas, breakdown of incongruent mineral phases and coronas  
417 formation (Cenki et al., 2002; Cesare et al., 2008). The amount of melt production, or  
418 consumption, depends on the ability of elements to enter such reactions. It thus has no  
419 bounding values, making the amplitude of stick slip non periodic.

420           Interestingly, the formation of garnet coronas through a process of diffusion is slow.  
421 Thus, depending on the heat flow variations, a so-called tectonic “hysteresis” in the melt  
422 extraction may result (Loomis, 1977). The retrograde reactions, added to changes in the pore  
423 size, determine zones of pinning and depinning (Fig. 9b).

424           The sporadic mode of melt extraction corroborates with the observation of segregated  
425 melt from its matrix in discrete pockets (Kisters et al., 1998). Such discrete pockets  
426 commonly form shrinking patterns with subvertical pipe-like bodies. They further connect  
427 together to evacuate a felsic melt into veins following the regional foliation planes. Discrete  
428 melt batches also corroborate numerical models of porosity waves (Connolly and  
429 Podladchikov, 2000; Rabinowicz and Vigneresse, 2004).

430 Another conclusion from such competition between melting and solidification (back-  
431 reactions) during melt extraction may have implications on the interpretation of field samples.  
432 Hence, magma crystallization is commonly coeval with fluids release, due to space shrinking,  
433 rapidly reaching fluid saturation (e.g. second boiling, Candela, 1997). The additional presence  
434 of a compressible fluid phase within the competing enhanced melting and crystallization (i.e.  
435 external pressures variations on the system) is coherent with an variation in the extraction rate  
436 during solidification with sudden pressure changes (Pistone et al., 2020). The stick-slip like  
437 melt motion thus adds a supplementary positive feedback loop to the process. Conversely,  
438 during initial melting, the freed fluid from hydrous minerals does not develop in a separate  
439 phase since it immediately enters the melt because of its solubility. In addition, the poor  
440 volume change due to biotite dehydration (Rushmer, 2001) does not alter the bulk volume of  
441 the system, thus avoiding pressure related loops.

442 Hysteresis and differences in melt motion increase the symmetry breaking between  
443 melting and solidification. In particular, the order of minerals crystallization, commonly  
444 accepted from ferro-magnesian, plagioclase and quartz, i.e. following a decrease in chemical  
445 potential, is perturbed when fluids (water-dominated) enter the process. It has implications  
446 on the segregation or not of incompatible elements that do not follow a similar trend  
447 compared to congruent minerals. The second important difference between melting and  
448 crystallization relates to the fate of water, inducing a large scale more or less independent  
449 hydrothermal activity during magma crystallization, whereas the processes of dry or hydrous  
450 melting imply changes in the melt final composition. However, developing such ideas is out  
451 of the scope of the present paper.

452 5.4. Analogy between dry friction and melt extraction

453 The dry friction coefficient ( $\mu_d$ ) characterises the relationship between a force (F) applied to a  
454 mass (m) pulled by a spring. The usual relation between the force applied on a mass and its  
455 acceleration applies. The force is proportional to the first derivative of the motion (dx/dt)  
456 through the coefficient of friction ( $\mu_d$ ). Thus

$$457 \quad m \delta^2 x / \delta t^2 = - \mu_d \delta x / \delta t$$

458 The solution to this differential equation is given by

$$459 \quad \delta x(t) / \delta t = \delta x(0) / \delta t \exp [-(\mu_d / m) t]$$

460 It relates the mass-force relationship to the stress-strain relationship. It also points the double  
461 effect of the velocity and its variations (i.e. acceleration), thus providing an explanation to the  
462 “state variable” ( $\theta$ ) introduced in dry friction (Ruina, 1983). In terms of melt extraction, it  
463 corresponds to variation in the melt flow, either due to enhanced motion under applied stress  
464 or enhanced/retarded melting.

465

#### 466 5.5. Notes of caution

467 The ideas presented here are derived from the numerical model that examines the motion  
468 of melt in migmatites. As such, it should be considered as a model, i.e. either representing  
469 the effects of the identified parameters, or in contrast, as a way to bracket the values of the  
470 parameters to better fit field observations. This requires a note of caution on the way the  
471 results are interpreted. In its actual shape, all parameters have been varied in a full range.  
472 For instance, the initial amount of melt ranges 0 to 100, though such high values are  
473 obviously not observed in partially molten rocks. However, the extreme values are  
474 considered as providing the numerical trends that rule the underlying process. Similarly, the  
475 coefficient of melt extraction presents values greater than 1. It corresponds to the effect of an

476 infinite source and sink for the melt. They are not realistic. Such large values correspond to  
477 an initial melt larger than 50. Such notes of caution being stated, what are the main results of  
478 the model.

479 First, the model illustrates the role of sharp variations in the ability of melt to be  
480 extracted and move ( $\zeta$ ), formerly assimilated to a melt escape threshold (Vigneresse and  
481 Burg, 2005). These variations show a transient behaviour. It implies that the definition of the  
482 melt escape threshold as a purely geometric threshold corresponding to percolation is  
483 incorrect since it is essentially static. Hence, the  $\zeta$  parameter is dynamic, determining  
484 stiction spikes ( $\Delta\mu$ ) and the amplitude of the stick-slip motion ( $\sigma_\mu$ ). It corresponds to a  
485 variation of the flux, i.e. an acceleration, positive or negative, of the flux.

486 Secondly, chemical reactions develop between the matrix and the melt as prograde  
487 reactions, but also between the melt and its matrix, as retrograde reactions. They consume or  
488 produce melt, thus modifying the melt flow velocity. Such reactions of chemical exchange  
489 are important when considering the free energy balance of the system. the corresponding  
490 interactions between strain (flow velocity) and chemical potential (melting and back-  
491 reactions) modify the bulk energy of the system, inducing sporadic variations. Because they  
492 were not considered in other forward models (Ioannidi et al., 2021), they resulted in a  
493 stationary motion, that certainly does not fully consider the exact nature of two-phase  
494 rheology. Similarly, variations due to the energy required to overcome dislocations induces  
495 instabilities due to strain (flow) and entropy due to ordering modification (dislocation creep)  
496 as in dry friction (Fig. 9a). In poroelastic flow, the interactions develop between strain  
497 (flow) and changes in the pore aperture (external strain) determine sporadic motion (Fig.  
498 9c). The specific case of melt extraction implies chemical exchanges (melting and back  
499 reactions) between the melt and its matrix (Fig. 9b).

500 Thirdly, the transient character of the flow presents some memory effects, due to the  
501 irreversibility of the reactions and the thermodynamic metastability of some minerals  
502 phases. However, such memory effects should not be confused with a time-related effect. In  
503 particular, it does not implicitly to point any re-use of veins.

504 At last, because of the model is constructed from a cellular automata, the model cannot  
505 be scaled in time, but uses a proxy through iterations. It is therefore not aimed to prediction,  
506 e.g. for quantitative mush (crystal-melt) interaction, as described for magma chamber  
507 rejuvenation or in magma eruptability. Similarly, a purely chemical approach is no more  
508 predictive, and a dry friction modelling does not inform on the next earthquake to occur. In  
509 contrast, and we focus on the message here delivered, any modeling of a multi-phase  
510 material should incorporate the interactions between the three components of energy, i.e. the  
511 external variables such as entropy, strain and chemical potential.

512

## 513 **6. Conclusions**

514 The present model examines the transient flow of melt extraction depending on variations  
515 of the controlling parameters, mostly the changes in flux velocity (amount of melt). The  
516 occurrence of spikes reflecting sporadic melt extraction with a progressive return to a  
517 stationary state is remarkable. We interpret these results with an analogy to the stick-slip  
518 behaviour in mechanics that might develop resulting in an irregular, non-periodic amount of  
519 melt extracted. This effect shows hysteresis, essentially due to the presence of phases  
520 consumed during prograde (melting) or retrograde (garnet and sillimatite growth)  
521 metamorphic reactions. The interactions between strain, chemical potential and entropy  
522 modify the free energy of the system. They act as pinning and depinning during dry friction  
523 and other flows of a weaker phase within a stronger matrix. The model highlights a dynamic  
524 concept of melting and places melt extraction between dry friction and poroelasticity.

525

526

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531 motion of the melt. In particular, we focused on the transient behaviours, yielding an analogue  
532 to stick-slip motion, pointing to pinning/depinning processes that illustrate discontinuous  
533 motion. The analogies with dry friction and poroelasticity should bring insights on irregular  
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538 paper, i.e. interactions between the energy components.

539

540

541       **References**

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662

663

664 **Figure captions**

665 Figure 1. Model of melt extraction using a cellular automata (c) with minerals  
666 distributed in cells. A melting equation (e) implies muscovite, biotite, plagioclase and quartz,  
667 resulting in melt, Kfeldspar and garnet (undifferentiated ferro-magnesian). All minerals are  
668 plotted according to a given colour. Melt production depends on the textural distribution, random  
669 (r) or layered (l) and according to the chemical equation (e) of dehydration. Melting (m) occurs when  
670 adequate minerals are adequately and proportionally distributed. Two thresholds (t) control liquid  
671 percolation (LPT), i.e. melt motion, and melt extraction (MET). Particles motion may move under  
672 pure shear (PS) or simple shear (SS) modifying the disposition of cells. Values with melt larger than  
673 50, i.e. more melt than the matrix, are not considered.

674

675 Figure 2. Schematic representation of frictional law and its analogue for melt  
676 extraction. a) Stationary friction of a block submitted to a force F. A coefficient of friction ( $\mu$ )  
677 is defined as the ratio of normal ( $\sigma$ ) to tangential ( $\tau$ ) stress components. b) Dynamic friction.  
678 The applied force varies from a velocity  $V_0$  to  $V$ . The coefficient of friction presents a spike  
679 ( $\Delta\mu$ ) function of the relative change in velocity, with a return to stationary conditions after a  
680 delay  $D_c$ . The new coefficient of friction may be higher or lower than the initial  $\mu_0$ . c) The  
681 basal contact of the block is no more homogenous, with either two phases or asperities. An  
682 irregular motion, with successive sticking and sliding states is observed, with amplitude ( $\sigma_\mu$ ).  
683 A stiction spike is also observed, as well as return to stick-slip when the velocity varies. d)  
684 Melt extraction coefficient ( $\mu$ ) defined as the ratio of initial melt to permeability (z) taken as a  
685 melt escape threshold. e) Similar to friction, the initial melt ( $\phi$ ) varies, as well as the  
686 permeability ( $\zeta$ ) and added stress ( $\tau$ ). A spike is observed before return to a stationary state. f)

687 irregular amount of melt is extracted mimicking stick-slip behaviour when the melt flow  
688 presents reactions damping its amount and velocity.

689

690 Figure 3. Results of the numerical simulation for different values in the initial amount  
691 of melt. a) The amount of melt extracted by step ( $\sigma$ ) presents a stick-slip behaviour that  
692 attenuates with the quantity of initial melt ( $\phi_0$ ). Stiction spike appears when this quantity is  
693 suddenly changed. b) normalizing the amount of melt produced at each step by the initial  
694 permeability ( $\zeta$ ) and dimension of the system results in curves converging toward a  
695 coefficient of melt extraction ( $\mu$ ).

696

697 Figure 4. Two regimes, regular or stationary and transient, are observed depending on  
698 whether the initial conditions vary during runs. Changing the melt proportion ( $\phi_0$ ) induces  
699 spikes ( $\Delta\mu$ ) and stick-slip motion with amplitude  $\sigma_\mu$ . Spikes ( $\Delta\mu$ ) in melt extraction with  
700 iterations taken as a proxy for time ( $Dc$ ), when the acceleration ( $\zeta$ ) is suddenly varied.  
701 Changes are made at different iteration intervals, and shown with three initial melt percentage  
702 ( $\phi_0$ ).

703

704 Figure 5. Variation of the amplitude of the stick-slip effects ( $\sigma_\mu$ ) as a function of the  
705 initial melt ( $\phi_0$ ) when the permeability ( $\zeta$ ) varies. A weak linear variation shows the poor  
706 effect of the initial melt content. Also indicated the range of values for melt (m) escape (in  
707 pale grey) as estimated in nature.

708

709 Figure 6. a) Variation of the amplitude of the stick-slip effects ( $\sigma_\mu$ ) in function of the  
710 melt extraction coefficient in two different situations, when the changes operate in separate  
711 runs, or in succession during a single run. The changes concern the initial melt ( $\phi_0$ ), the  
712 permeability ( $\zeta$ ) or the strain rate ( $\varepsilon^\circ$ ). The linear relationship indicates the dependence of  $\sigma_\mu$   
713 on the coefficient of melt extraction ( $\mu$ ). It corroborates all variations with the equivalent  
714 velocity parameters ( $\phi_0$ ,  $\zeta$ ,  $\varepsilon^\circ$ ). The range of melt amount in nature ( $m$ ) is indicated in light  
715 grey. Conversely, the transient effects illustrate a neat decrease of  $\sigma_\mu$  during the successive  
716 variations of the equivalent velocity parameters, pointing to some memory effect. b)  
717 Amplitudes of  $\sigma_\mu$  plotted for individual values of  $\zeta$ , show an exponential decrease with the  
718 iteration numbers, taken as a proxy for time. It reinforces the memory effects, damping with  
719 time.

720

721 Figure 7. Amplitude of the spikes ( $\Delta\mu$ ) when the permeability value varies along a  
722 single run. The successive changes are positive or negative, yielding similar changes in  $\Delta\mu$ .  
723 The curves have been separated for increasing and decreasing permeability changes.

724

725 Figure 8. Experiments on stick slip on a single crystal of LiF, redrawn from Perfilyev et  
726 al. (2014). a) The displacement (mm) as a function of time (s) shows the stick-slip behaviour,  
727 following increases and sudden drop in frictional force (mN). Each episode occurs in about  
728 180 s with a displacement of about 7 mm, implying a strain rate of about  $5.5 \cdot 10^{-3} \text{ s}^{-1}$ . b) The  
729 corresponding velocity of the indenter varies by a factor about 300 in less than 1 s (note the  
730 change in time scale between a and b). It is interpreted as depinning and pinning effect  
731 corresponding to dislocation creep.

732

733       Figure 9.           Cartoon illustrating the analogies between (a) frictional law, (b) melt  
734 extraction and (c) poroelasticity. Friction implies solid-solid contact, i.e. crystalline networks  
735 in a polycrystal material, with inherent dislocations (inverted tau) that act as pinning points  
736 for motion. At the other end, poroelasticity describes a liquid flow, percolating through the  
737 system, but with discrete air bubbles, non-percolating. The different surface energy values  
738 between air, liquid and solid make the system hysteretic. They also rule pinning and  
739 depinning when the local porosity changes due to the pore size. In between, melt extraction  
740 consists in a polymerized silicate melt (tetrahedra) and undifferentiated ions (circles) flowing  
741 in between crystallized matrix ongoing melting reactions. Minerals consist in quartz,  
742 plagioclase, biotite and muscovite (white to black, with pale and dark grey), with incongruent  
743 mineral (coloured hexagons), among which garnet (red) and sillimanite (stripes). Dehydration  
744 melting occurs when the four quoted minerals are in contact (plain circle), feeding the melt  
745 layer. They act as depinning points. In contrast, retrograde reactions manifest by garnet  
746 coronas (dashed circles), consuming elements of the melt. They act as pinning points.

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