On the recurrence of earthquakes: Role of wear in brittle faulting

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[1] The time of occurrence of an earthquake is related to the state of the fault, tectonic loading, and possible triggering mechanisms, and it plays a prominent role in hazard assessment. In this paper we incorporate the effects of wear generation into a seismogenic model. We show that without wear the recurrence time of repeated earthquakes is constant through time and it is controlled by the initial conditions, tectonic loading and constitutive properties, including the presence of pore fluids. Our results indicate that considering the wear development into the fault model dramatically affects the temperature evolution of the fault, the stress release, the developed cosesimic slip and ultimately the duration of the seismic cycle. Moreover, we find that as long as the slipping zone thickness increases, the recurrence time continuously decreases through time. This further complicates the predictability of a subsequent earthquake, even in the simple case of an isolated fault. **Citation:** Bizzarri, A. (2010), On the recurrence of earthquakes: Role of wear in brittle faulting, *Geophys. Res. Lett.*, *37*, L20315, doi:10.1029/2010GL045480.

1. Introduction

[2] The time of occurrence of an earthquake event has a major relevance in the context of the physics of faults and it has clear implications in hazard assessment. In the idealized situation when no other events perturb the state of the considered fault, the basic concept of characteristic earthquakes [e.g., *Reid*, 1910] postulates that a dynamic event occurs in the Earth crust when the tectonic shear stress reaches some critical level, at regular time intervals, determined by the state of the fault and by the tectonic load.

[3] It has been previously shown [e.g., *Mitsui and Hirahara*, 2009] that the inclusion of the thermal pressurization of pore fluids [*Sibson*, 2003], due to frictional heat, can prolong the recurrence time of subsequent slip failures. Here we incorporate into a dynamic model the fault wear that causes a temporal variation of the slipping zone where the deformation is concentrated. Indeed, a large number of geological observations [e.g., *Robertson*, 1983; *Power et al.*, 1988] indicate that the relative slip of two surfaces in contact generates wear material (breccia or gouge) as a consequence of abrasion, fragmentation and pulverization of rocks. Moreover, it has been observed that in many natural systems the thickness of gouge and breccia increases approximately linearly with accumulated fault slip [*Power et al.*, 1988; *Marone*, 1998; *Childs et al.*, 2009].

[4] In this paper we show that the evolution of the slipping zone thickness over time scales typical of repeated slip failures can significantly affect the characteristics of the earthquake events; it will dramatically change *i*) the temperature evolution due to the frictional heat, *ii*) the migration of thermally–pressurized pore fluids and ultimately *iii*) the recurrence interval of the earthquakes on the same fault, even in the simplest case of an isolated fault (i.e., without stress triggering effects).

2. A Simple Fault Analog Model

[5] The modeling of the entire seismic cycle is an extremely challenging task in terms of computer time and memory [e.g., *Lapusta and Liu*, 2009]. The most severe technical problem is the need to physically resolve different characteristic time scales during the whole life of the fault, which experiences sliding velocities that vary over several orders of magnitude (from inter–seismic sliding to seismic instabilities). In the present paper we adopt a simple 1–D spring–slider analog fault model, schematically reported in Figure S1 of the auxiliary material.[1] In such a model a block of mass m per unit surface, subject to an external load (the loading rate of tectonic origin $\dot{\tau}_0 = kv_{load}$), slides on an interface against a frictional resistance τ. The equation of motion for such a system is:

$$m\ddot{u} = k(u_{load} - u) - \tau \qquad (1)$$

where k is the elastic constant of the spring (which mimics the elastic medium surrounding the fault), u_{load} is the displacement of the loading point moving at velocity $v_{load} \equiv \dot{u}_{load}$ and u is the displacement (i.e., the "fault" slip). The first term in equation (1) is the inertia, which is accounted for only when the sliding velocity $v \equiv \dot{u}$ exceeds a critical value v_c; below v_c the quasi–static regime is considered (see *Bizzarri and Belardinelli* [2008] for a further discussion). Above v_c we consider the complete system, in that we do not need to introduce the radiation damping approximation (as in the work of *Mitsui and Hirahara* [2009]) to solve the rupture problem.

[6] The quantity τ in (1) expresses the constitutive friction law. Among the different possibilities proposed in the literature [*Bizzarri and Cocco*, 2006c; *Bizzarri*, 2009] we adopt here the following formulation of the rate– and state–dependent friction [*Linker and Dieterich*, 1992; *Boettcher and Marone*, 2004]:

$$\begin{aligned} \tau &= \left[\mu_* + a\ln\left(\frac{v}{v_*}\right) + b\ln\left(\frac{\Psi v_*}{D_c}\right)\right]\sigma_n^{eff} \\ \frac{\mathrm{d}}{\mathrm{d}t}\Psi &= 1 - \frac{\Psi v}{D_c} - \left(\frac{\alpha_{LD}\Psi}{b\sigma_n^{eff}}\right)\frac{\mathrm{d}}{\mathrm{d}t}\sigma_n^{eff} \end{aligned} \qquad (2)$$

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[7] This model accounts (via the parameter α_{LD}) for the coupling between pore fluid pressure p_{fluid} and the state variable Ψ, which physically represents the average lifetime of the micro–asperity contacts and therefore accounts for the memory of previous failures. In equation (2) a, b and D_c are the constitutive parameters, μ_* and v_* are reference parameters for the frictional coefficient and sliding velocity, respectively, and σ_n^{eff} is the effective normal stress (expressed as the difference between lithostatic load σ_n and p_{fluid}). As in the work of *Bizzarri and Cocco* [2005], equation (2) is considered in the whole range of variability of v.

[8] The system of equations, which is solved by adopting the Runge–Kutta integration scheme with adaptive step–size control [*Press et al.*, 1992], is closed by considering the temporal evolution of temperature due to frictional heat

$$T(t) = T_0 + \frac{1}{2c}\int_0^t \mathrm{d}t' \mathrm{erf}\left(\frac{w(t')}{2\sqrt{\chi(t-t')}}\right)\frac{\tau(t')v(t')}{w(t')} \quad (3)$$

and the evolution of pore fluid pressure (see *Bizzarri and Cocco* [2006a, 2006b] for analytical details):

$$p_{fluid}(t) = p_{fluid_0} + \frac{\gamma}{2}\int_0^t \mathrm{d}t'\left\{-\frac{\chi}{\omega-\chi}\mathrm{erf}\left(\frac{w(t')}{2\sqrt{\chi(t-t')}}\right) + \frac{\omega}{\omega-\chi}\mathrm{erf}\left(\frac{w(t')}{2\sqrt{\omega(t-t')}}\right)\right\}\frac{\tau(t')v(t')}{w(t')} \quad (4)$$

where c is the heat capacity for unit volume, χ and ω are thermal and hydraulic diffusivities, respectively, erf(.) is the error function, γ is a dimensionless constant and w is the half–thickness of the slipping zone that we consider in this study as the characteristic length of the fault wear.

3. Prominent Role of Wear

[9] The slipping zone thickness has received much recent attention in the literature. Some geological evidence suggests that $2w$ can be spatially variable even within the same fault structure [e.g., *Rathbun and Marone*, 2010]. Moreover, there are indications from faults in mines, at outcrops and in laboratory specimens that wear processes occurring during brittle faulting cause the slipping zone to enlarge [*Hull*, 1988; *Marrett and Allmendinger*, 1990].

[10] In this paper we consider the positive correlation between the slipping zone thickness and the displacement (cumulative slip) expressed by the following evolution law, inferred by *Power et al.* [1988]:

$$w(t) = Ku(t) \quad (5)$$

K being a dimensionless constant [see also *Robertson*, 1983]. Physically, this widening model assumes that the slipping zone thickness of natural faults depends on the accumulated slip because the micro–asperities that must be broken during sliding also depend on u. Since the displacement is controlled by the fault rheology (i.e., by the analytical expression of the constitutive law), w also depends on the rheological properties of the sliding interface.

[11] In Figure 1 we compare the results obtained for a reference, "dry" fault (with both σ_n^{eff} and $2w$ temporally constant; black lines) with those considering a fluid–saturated fault with both constant and variable length, $2w$ (red and blue curves, respectively). The parameters adopted in the present study are tabulated in Table 1. As already pointed out by coseismic studies [e.g., *Bizzarri and Cocco*, 2006b], the thermal pressurization enhances the fault instability, causing larger coseismic slips (Figure 1a) and larger stress releases (Figure 1d). Our results also confirm the findings by *Mitsui and Hirahara* [2009] that the pore fluid migration increases the recurrence interval of the instability events (Figure 1b); for the parameters adopted here the inter–event time T_{cycle} (i.e., the time which separates two subsequent instabilities, defined when slip velocity exceeds a threshold value v_l) increases by nearly 120% (from 138 yr to 165 yr, see also Figure 2d). This is basically due to the fact that thermal pressurization also enhances the healing and the decelerating phases subsequent to an instability event, causing the system to reach a state having both the residual stress and the slip velocity lower than in the reference case (Figure 1c). This ultimately implies that the slider has to endure a longer recovery phase (the inter–seismic fault restrengthening) before it undergoes the next slip failure.

[12] More interestingly, we can notice that while without wearing effects T_{cycle} is constant through time, when $2w$ varies the system does not converge asymptotically to the limiting cycle (Figure 1c) and the recurrence interval continuously changes. Indeed, from Figure 1b we can see that, as long as the slipping zone evolves, the minimum value of v (that reached after a dynamic instability) progressively increases. Moreover, the dynamic stress drop ($\Delta\tau_d = \tau_0 - \tau_{res}$, where τ_{res} is the residual stress attained after an instability) decreases through time (Figure 1d). Physically, this implies that, as $2w$ increases, the duration of the fault restrengthening phase decreases; in other words, the fault takes less time to recover (through the constant loading rate) the fault strength necessary to fail to a subsequent instability. Consequently, T_{cycle} decreases, as we will discuss in more detail in the next section.

4. Wear and Recurrence Interval

[13] In this section we will explore the effects of different values of the constant K controlling the temporal evolution of $2w$ (see equation (5)). We have considered values within the range of observations and inferences [e.g., *Power et al.*, 1988; *Robertson*, 1983]. The resulting time evolutions of the slipping zone are plotted in Figure 2a and the corresponding solutions are reported in Figures 2b and 2c.

[14] First of all, we want to emphasize that in absence of thermal pressurization, a variation in $2w$ is expected to cause only variations in the developed temperature. Contrarily, when fluid migration is considered in the model, the fluid pressure will also change through time. In turn, this influences the value of the effective normal stress.

[15] Indeed, from Figure 2b it is clear that, as long as $2w$ increases, the variations in σ_n^{eff} during the coseismic slip failures continuously decrease, as predicted by equation (4). With thermal pressurization and constant $2w$ (red lines in Figure 2b) the coseismic variations of σ_n^{eff} are roughly equal to 12 MPa (40% of ${\sigma_n^{eff}}_0$), while for varying $2w$ with $K = 0.05$, after 1380 yr we have $\Delta\sigma_n^{eff} \sim 4$ MPa (13% of ${\sigma_n^{eff}}_0$). In accordance with this observations, the temperature changes $\Delta T = T - T_0$ are strongly affected by the wear process (Figure 2c); when $2w$ is constant (black line) ΔT remains

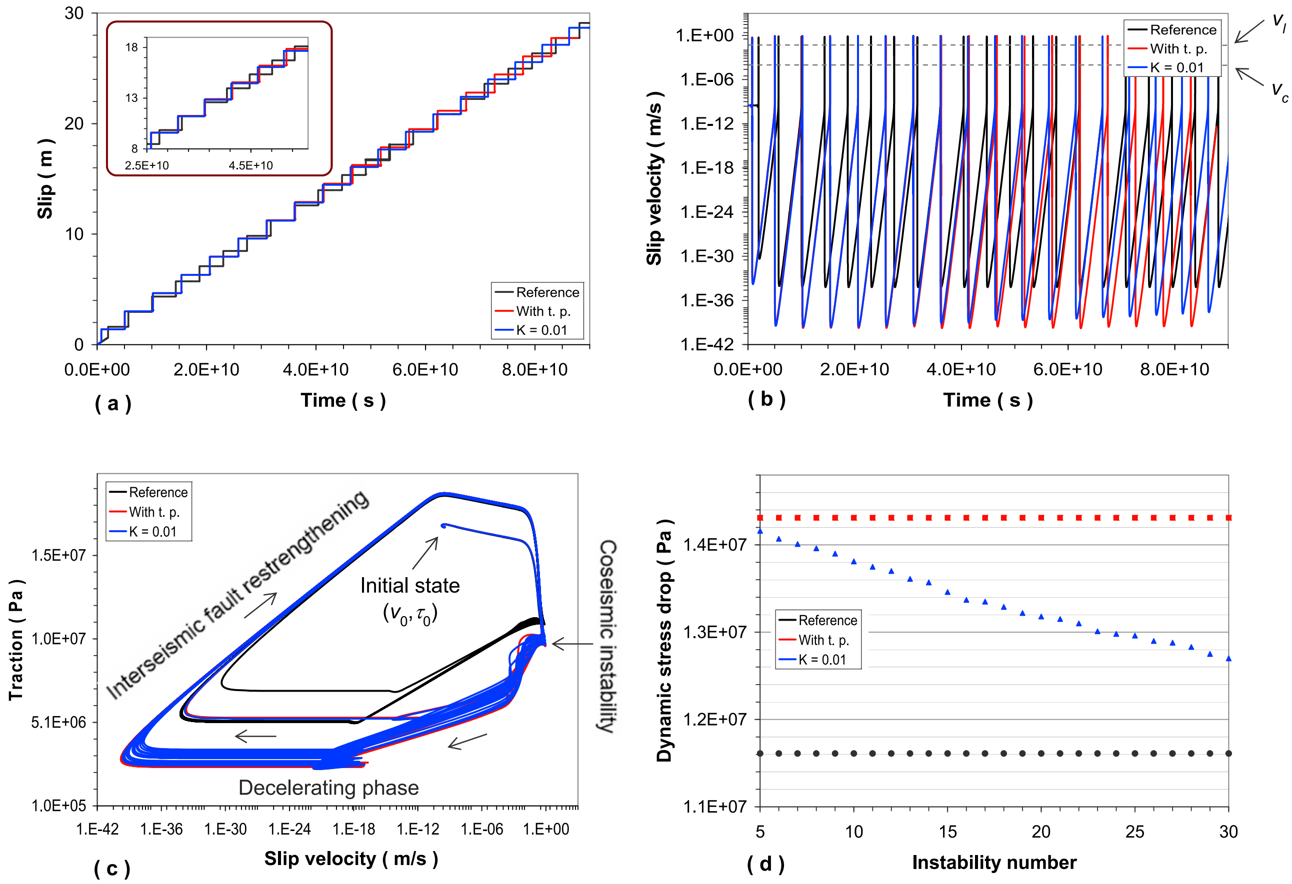

Figure 1. Comparison of solutions for a reference, "dry" fault (with σ_n^{eff} and $2w$ constant; black curves) and fluid–saturated faults without ($K = 0$ in equation (5)) and with ($K \neq 0$) the effects of wear (read and blue curves, respectively). The evolution of σ_n^{eff} is given by equation (4), while that of $2w$ is given by equation (5). (a) Time evolutions of cumulative slip from the initial state (with inset displaying a zoom of a shorter time window), clearly showing the stick–slip behavior. (b) Time history of the slip velocity. Velocities v_c and v_l define when the quasi–static phase terminates and when the system undergoes a dynamic instability, respectively. (c) Trajectories of the system during the life of the fault in the phase portrait. (d) Dynamic stress drops ($\Delta\tau_d$) as a function of the number of instability; $\Delta\tau_d$ is calculated after the 5th dynamic instability in order to avoid the possible effects of the transient phase affected by the initial conditions of the system. The adopted parameters are listed in Table 1.

roughly constant and around 1000 °C (1000% of T_0), while when wear is considered for K = 0.05, after 1380 yr ΔT is nearly 150% of T_0 (note also that when wear is considered ΔT continuously decreases through time). This result has important consequences, since the temperature evolution can directly affect the dynamic behavior of an earthquake rupture [*Bizzarri*, 2010].

[16] More interestingly for the present matter, we can see that the evolution of the slipping zone significantly changes the duration of the seismic cycle. To quantify this, we report in Figure 2d the estimated values of T_{cycle} for the different values of K as a function of subsequent instability events. Cases of a "dry" fault (black circles) and fluid–saturated fault, but with constant $2w$ (red squares) exhibit constant recurrence times, in that the system enters the limiting cycle. This is also the case when $K \leq 0.001$, i.e., when wear processes are negligible (Figure 2a). On the contrary, when wear is significant we observe from Figure 2d a continuous change in T_{cycle} because the limiting reference cycle is not reached by the system in these cases. We emphasize that as long as $2w$ increases the pore fluid pressure variation is smaller and correspondently T_{cycle} decreases.

[17] In all previous numerical simulations the characteristic length D_c, over which the state variable evolves, has been considered constant through time. Although D_c has generally been interpreted in terms of the mechanics of micro–asperity contacts on surfaces free of gouge (bare rock interfaces), laboratory experiments by Marone and Kilgore indicate that D_c linearly increases with enlarging slipping zone thickness. Therefore we have considered that D_c in constitutive model (2) linearly increases with $2w$ with a rate of 8 μm/mm (a representative value from *Marone and Kilgore* [1993]). The results are reported in Figures 2e and 2f. An increase of D_c will cause a reduction of the ratio k_{cr}/k, which is known to quantify the degree of instability of the system ($k_{cr} \equiv (b - a)\sigma_n^{eff}/D_c$) [*Gu et al.*, 1984]. This is confirmed by the numerical results; as $2w$ increases, the stress release decreases (Figure 2f) and the local minima in velocity (after an instability) progressively increases (Figure 2e). As observed above, this causes the fault restrengthening phase to be shorter and consequently T_{cycle} to decrease. This can be clearly seen in Figure 2d (open symbols). Finally, we emphasize that the reduction of T_{cycle} due to the variation of D_c are even more severe than those caused by the variation

Table 1. Reference Constitutive Parameters Adopted in This Study

Parameter	Value
Model Parameters	
Tectonic loading rate, $\dot{\tau}_0 = kv_{load}$	3.17×10^{-3} Pa/s (= 1 bar/yr)
Machine stiffness, k	10 MPa/m[a]
Period of the analog freely slipping system, $T_{a.f.} = 2\pi\sqrt{m/k}$	5 s
Critical value of the sliding velocity above which the dynamic regime is considered, v_c	0.1 mm/s
Threshold value of the sliding velocity defining the occurrence of an instability, v_l	0.1 m/s[b]
Fault Constitutive Parameters	
Initial effective normal stress, $\sigma_n^{eff}{}_0 = \sigma_n - p_{fluid_0}$	30 MPa
Logarithmic direct effect parameter, a	0.007
Evolution effect parameter, b	0.016
Characteristic scale length, D_c	1×10^{-2} m
Coupling between pore fluid pressure and state variable, α_{LD}	0.53
Reference value of the friction coefficient, μ_*	0.56
Reference value of the sliding velocity, v_*	3.17×10^{-10} m/s
Initial slip velocity, v_0	3.17×10^{-10} m/s
Initial shear stress, τ_0	16.8 MPa (= $\mu_* \sigma_n^{eff}{}_0$)
Initial temperature, T_0	100 °C
Heat capacity for unit volume of the bulk composite, c	3×10^6 J/(m^3 °C)
Thermal diffusivity, χ	1×10^{-6} m^2/s
Hydraulic diffusivity, ω	0.4 m^2/s
Dimensionless parameter γ	0.5
Slipping zone thickness, $2w$	1.4 mm

[a]With the adopted constitutive parameters this corresponds to an unstable regime, in that $k < k_{cr} \equiv (b - a)\sigma_n^{eff}/D_c = 27$ MPa/m [*Gu et al.*, 1984].
[b]In agreement with *Bizzarri and Belardinelli* [2008] and references cited therein.

of $2w$ alone in thermal pressurized faults and that the limiting cycle is not reached in these cases (T_{cycle} continuously decreases). This is not surprising, in that it might happen that, depending on the rate of increase in $2w$, the critical stiffness k_{cr} becomes lower than k, tending to inhibit a dynamic rupture.

5. Concluding Remarks

[18] In this paper we mainly focus on the recurrence interval of repeated earthquakes on the same seismogenic fault. The fault is modeled through a single degree of freedom spring–slider system [e.g., *Gu et al.*, 1984], accounting for inertial effects and obeying the *Linker and Dieterich* [1992] formulation of rate– and state–dependent friction over the whole range of sliding velocities. Classical models of earthquake recurrence [e.g., *Shimazaki and Nakata*, 1980] assume that the time of occurrence of a next earthquake can be predicted a priori, given the critical level of stress (strictly periodic or time–predictable models) or the stress drop that occurred during the previous event (slip–predictable models).

[19] A large number of physical and chemical processes are responsible for (large) variations of the frictional resistance on a fault [e.g., *Bizzarri*, 2009], ultimately leading to temporal variations of frictional stress and thus contesting the previous idealized models.

[20] Here we have shown that in the case of constant model's parameters and in the absence of external perturbations (triggering mechanisms), after the completion of a transient phase, related to the initial state of the fault, the system enters the limiting reference cycle and it exhibits constant recurrence times. We also confirm here (as previously shown by *Mitsui and Hirahara* [2009]) that the thermal pressurization of pore fluids significantly increases the cycle time (T_{cycle}).

[21] We have incorporated the effects of wear in the model, parameterized in agreement with the inferences by *Power et al.* [1988], predicting a progressive enlargement of the thickness of the slipping zone ($2w$) [see also *Marone*, 1998]. This growth of the fault zone thickness — which comprises fault gouge, breccia or cataclasite and where most of the displacement is accommodated — with cumulative displacement leads to a model of fault evolution in which the zone of deformation progressively widens through time [*Shipton and Cowie*, 2003].

[22] The effect of wear is twofold; it affects the pore pressure changes in a fluid–saturated fault (equation (4)) and it changes the value of the characteristic distance D_c controlling the state variable evolution [*Marone and Kilgore*, 1993]. The growth of $2w$ affects the developed temperature changes (Figure 2c), the coseismic stress releases (Figure 1d) and the coseismic fault slip (and therefore the magnitude of each event; Figure 1a). More interestingly, the temporal evolution of $2w$ causes continuous variations in the pore fluid pressure change due to thermal pressurization (Figure 2b). In turn, these variations substantially affect the value of the frictional strength in the inter–seismic period preceding a subsequent failure event and they finally cause different durations of the restrengthening phase. This increase of friction with log of stationary contact time is one manifestation of the state variable evolution in the framework of the rate– and state–dependent friction laws. Notably, when wear is significant ($K > 0.001$) the system does not reach the limiting cycle (Figure 1d) and T_{cycle} exhibits a clear time–dependency (Figure 2d). In particular, our results indicate that as long as $2w$ enlarges, T_{cycle} continuously decreases, even over very large time windows (38 centuries). This is particularly true when we consider a linear increase of D_c with wear (Figure 2d).

[23] The results presented here are pervasively affected by the simplification of the fault model; in fact, with a single spring–slider system we neglect the possible effects of spatial heterogeneities in the constitutive parameters. In particular, we consider that the value of $2w$ at given time is represen-

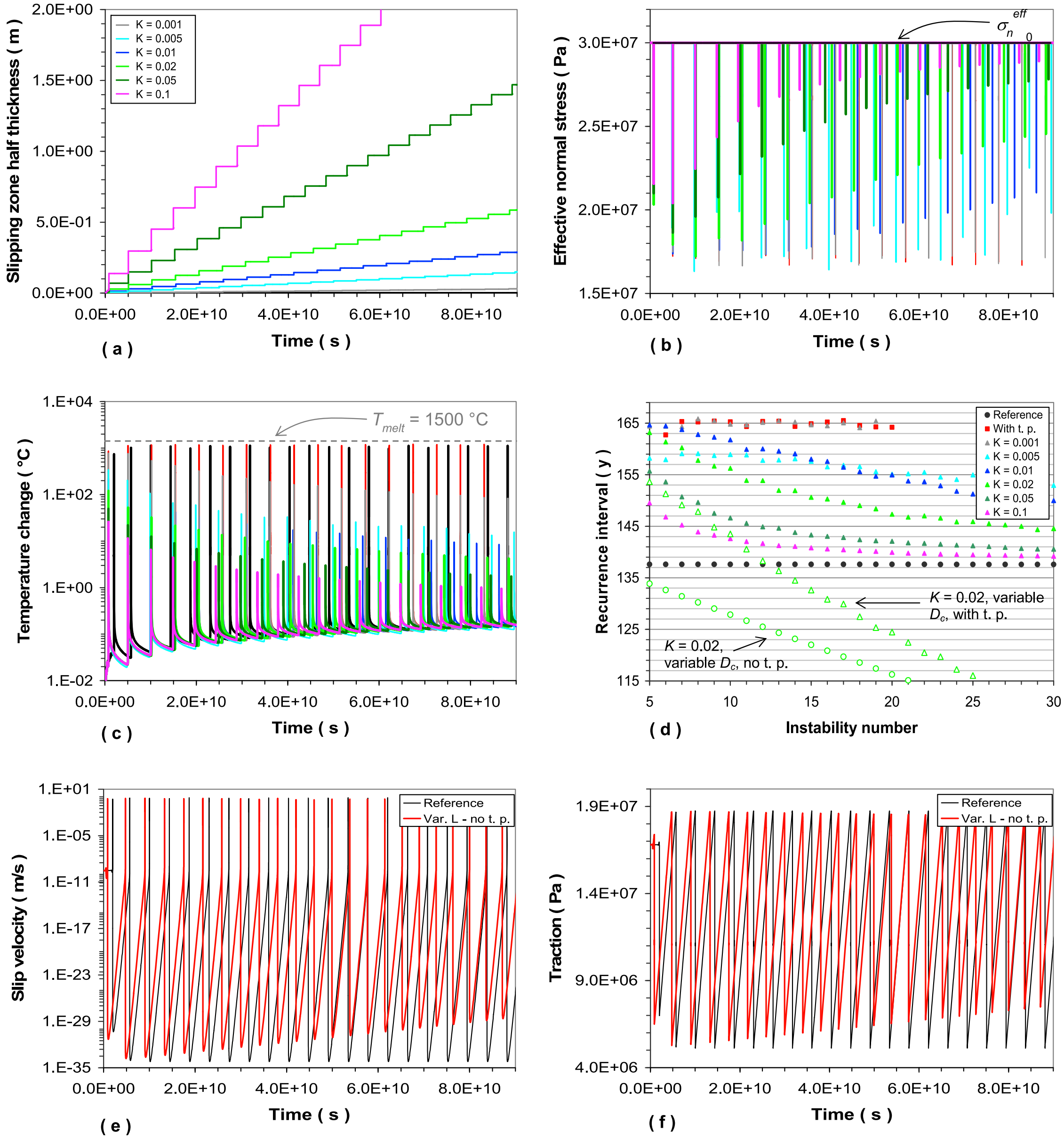

Figure 2. Results for different evolution histories of the slipping zone thickness. (a) Behavior of $2w$ for different values of the constant K in equation (5), which parameterizes the wear processes. (b) Effective normal stress $\sigma_n^{eff} = \sigma_n - p_{fluid}$. (c) Time histories of the temperature change ($\Delta T = T - T_0$, with T given by equation (3)). Note that melting does not occur in all cases. (d) Recurrence intervals (T_{cycle}). (e and f) Comparison between the reference case and a "dry" fault with wear evolving with $K = 0.02$ and with D_c of equation (2) linearly increasing with wear.

tative (in an average sense) of the whole fault surface (in other words, we neglect the surface roughness and the geometrical irregularities). However, we notice that it is likely that repeated slip episodes occurring on the same fault structure continuously modify fault the properties as well as the grain size of gouge materials [*Power and Tullis*, 1991]; we may then expect that the cumulative slip tends to smooth the fault surface, as documented by *Stirling et al.* [1996]. Moreover, the point–like nature of our fault model gives an underestimate of the peaks of the slip velocity and consequently of the temperature change.

[24] Given these limitations, we have shown here that the wear processes can significantly alter the inter–event times, further complicating the predictability of a subsequent earthquake, even in the idealized case of an isolated seismogenic fault.

[25] Additional mechanisms that in principle can affect the earthquake recurrence are the time–dependency of the permeability and frictional parameters (for instance that of a as suggested by *Nakatani* [2001]) and the time–dependency of porosity (leading to dilatancy or compaction). Moreover, also non–linear (i.e., plastic) or viscous effects associated with the formation of micro–cracks and creeping phenomena can potentially affect the accommodation of fault zone deformation during the seismic cycle of a natural fault. Unfortunately, we do not have a comprehensive theory able to include them in the whole seismic cycle modeling, in that additional laboratory and theoretical efforts have to be accomplished.

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