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IS THE DEPENDENCE ON THE TEMPERATURE OF THE FRICTION IMPORTANT IN STRESS TRIGGERING PHENOMENA? THE CASE OF THE 2000 ICELAND SEISMIC SEQUENCE

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Introduction

We perform numerical experiments by using a mass–spring fault model subject to an external coseismic stress perturbation due to a remote seismic event happening on another fault, the causative fault. In particular, the aim of this study is to investigate the instantaneous fault interaction and possible triggering that happens when a fault perturbed by a stress change fails before the so–called unperturbed instability. As a realistic example we focus our attention on the instantaneous dynamic triggering phenomena occurred during the 17 June 2000 south Iceland seismic sequence in the South Iceland Seismic Zone (SISZ, Reykjanes Peninsula). The main event (M_s 6.6) was followed by three large events within a few tens of seconds (8, 26 and 30 s, respectively) located in a neighborhood of several tens of km. Among them the 26 s event was the best constrained (Bizzarri and Belardinelli, 2008).

In the present study, conditions to simulate the instantaneous dynamic triggering connected to the former three events, have been investigated using the simple 1–D spring–slider analogue model representing a fault governed by the rate– and state–dependent friction laws. In previous studies suitable constitutive parameters of the modeled fault which allow the instantaneous triggering of the three events, have been found (Antonioli et al., 2006) and, furthermore, it was also shown how the dynamics of the 26 s event strongly depends on the assumed constitutive law and stress conditions (Bizzarri and Belardinelli, 2008) by considering the Dieterich–Ruina (DR henceforth) and the Ruina–Dieterich (RD henceforth) governing laws. In this context take place the present study original contribution that is to better understand if the conditions of instantaneous dynamic triggering (focusing on the case of the 26 s triggered event) provide any significant differences if modeled with a different rate– and state–dependent governing equation, the Chester and Higgs law (CH henceforth; see Chester and Higgs, 1992; Bizzarri, 2010b; Bizzarri, 2010c) which accounts for the thermal effect for frictional heating which may occur during seismic sliding.

1. State of the art

Instantaneous fault triggering is not a well understood phenomenon, probably because it has not been so widely observed, since the detection of events before the end of the shake caused by a remote earthquake is difficult, especially in the near field conditions (Bizzarri and Belardinelli, 2008). In the present study we focus on the remote triggering and on the instantaneous fault interaction, a kind of dynamic triggering phenomenon which may happen when a fault perturbed by a stress change fails before the end of the transient stress perturbation, hence within its duration. Remote dynamic triggering, which can happen within a time interval of few seconds, is a case of dynamic triggering because it occurs at distances larger than the dimensions of the causative fault (e.g., Antonioli et al., 2006).

Previous studies on earthquake nucleation conducted with a rate– and state–dependent rheology suggested that the instantaneous triggering is the most convincing interaction effect because of purely transient stress changes (Gomberg et al., 1998; Belardinelli et al., 2003; Antonioli et al., 2006), provided that the amplitude of such changes is large enough compared to the direct effect of the friction. The rate– and state–dependent rheology has been widely adopted in nucleation studies in order to explain the temporal distribution of aftershocks sequences.

The present study focuses on the event of the 17 June 2000 seismic sequence in the SISZ (Figure 1), with hypocenter located at the absolute coordinates of 63.973°N, 20.367°W, 6.3 km of depth, which can be treated as an interesting example of remote and instantaneous dynamic fault triggering. As previously mentioned, the sequence of interest was followed by at least three events monitored in the first minute after the 17 June quake within 80 km from its epicenter (Vogfjord, 2003). The origin time of these events (after 8, 26 and 30 s, respectively) is comparable with the arrival time of seismic waves generated by the main shock, suggesting a causative link between them (Antonioli et al., 2006).

Previous studies (Antonioli et al. 2006; Bizzarri and Belardinelli, 2008) investigated this possibility through the performance of numerical models assuming a rate– and state–dependent fault rheology which allowed to estimate model constrains for instantaneous triggering to occur, to reproduce the failure time t_p of the three triggered events and to compute the normal stress acting at the three hypocenters. In particular of these three events, the 26 s event was the best constrained from seismological observations: therefore in the following of this report we will focus on this aftershock whose absolute coordinates are 63.951°N, 21.689°W, 7.6 km.

Indeed, the study of Antonioli et al. (2006) suggested that, except for very close to failure initial conditions of the fault, in order to have instantaneous triggering, rate- and state-dependent friction laws require the additional condition regarding a relatively low value of the initial effective normal stress. In addition Bizzarri and Belardinelli (2008), through the comparison between two formulations (DR and RD) of the rate– and state–dependent governing models, confirmed previous results (e.g., Belardinelli et al., 2003) showing that, in the case of Iceland, the RD law is more unstable than the DR law; in particular the RD model is shown to provide the closer to reality perturbed failure time. The 26 s aftershock model parameters constrained through numerical analyses conducted in previous studies are reported in Table 1.

In this context take place our contribution to the just mentioned studies: because to investigate the instantaneous triggering phenomena of Iceland only two constitutive laws have been used so far (those of DR and RD), we want to better understand if the instantaneous dynamic triggering can be somehow affected by considering also the temperature evolution in the fault rheology. In particular the main goal of this paper is to reproduce the dynamics of the 26 s event through the 1–D mass–spring model using both the RD (already performed in Bizzarri and Belardinelli, 2008) and CH constitutive relations in order to figure out any dependences of the response of the triggered fault from the temperature. The numerical simulations conducted with the CH and RD governing laws are reported in the next sections.

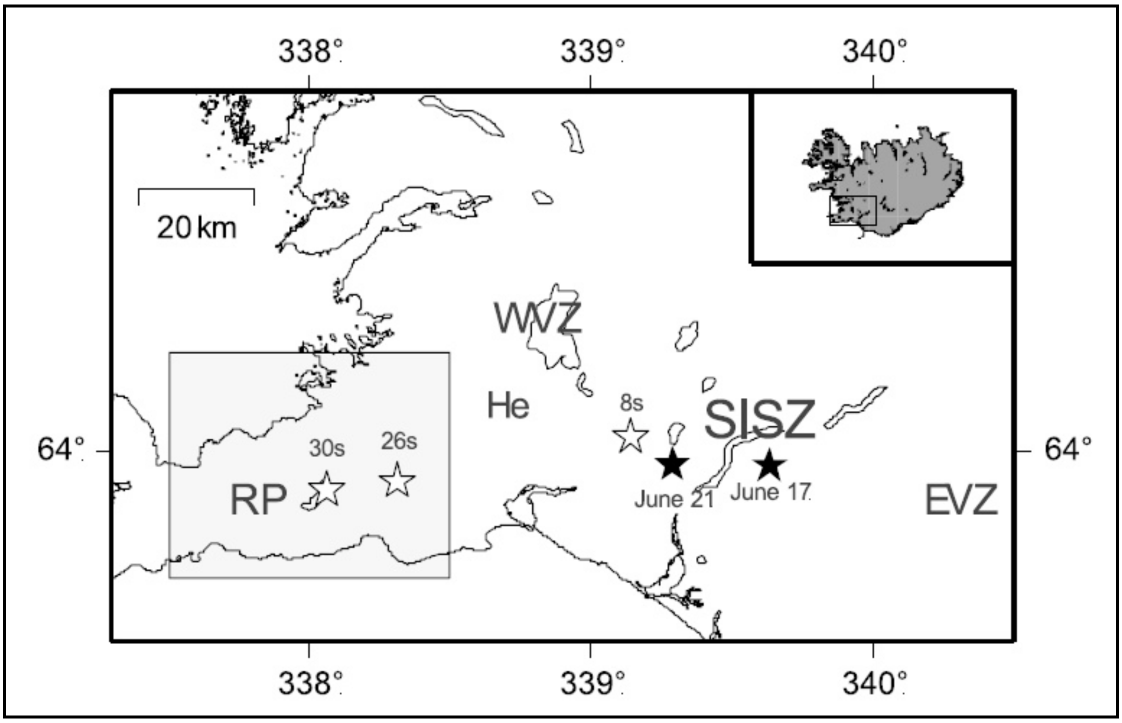

Figure 1. The South Iceland the South Iceland Seismic Zone (SISZ) and the Reykjanes Peninsula (RP). The epicenter locations of the two largest events of the June 2000 sequence (17 and 21 June) are shown by the solid stars, and the three largest aftershocks occurring in the first minute after the 17 June main shock are shown by open stars, with their origin times (expressed in s) relative to the main shock (from Antonioli et al., 2006).

Parameter	Value		
Model Parameters			
Tectonic loading rate, $\dot{\tau}_0 = kv_{load}$	1.902×10^{-9} MPa/s (= 3 bar/yr)		
Machine stiffness, k	3 MPa/m		
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		
Fault Constitutive Parameters			
Initial effective normal stress, σ_n^{eff}	2.85 MPa		
Logarithmic direct effect parameter, a	0.003		
Evolution effect parameter, b	0.010		
Characteristic scale length, L	1×10^{-3} m		
Reference value of the friction coefficient, μ_*	0.70		
Reference value of the sliding velocity, v_*	6.34×10^{-10} m/s		
Initial slip velocity, v_0	6.34×10^{-10} m/s		
Initial shear stress, τ_0	1.995 MPa (= $\mu_* \sigma_n^{eff}$)		
Initial temperature, T_0	100 °C	500 °C	1200 °C
Heat capacity for unit volume of the bulk composite, c	2.6×10^6 J/(m^3 °C)		
Thermal diffusivity, χ	1×10^{-6} m^2/s		

Table 1. Parameters adopted in the present study. Initial values refer to the time $t = 0$. The values of temperature will be useful in order to carry out a wide set of CH simulations.

2. Is the temperature evolution important in instantaneous dynamic triggering?

Instantaneous triggering represents a particular case of fault interaction that can't be investigated only through a simple analysis of static stress changes, but it requires Modelling of the complete dynamic stress perturbation caused by an earthquake on neighboring faults (Antonioli et al., 2006). For this reason Antonioli et al. (2006) computed and estimated the stress field variations as a function of the time by using the discrete wave number and reflectivity code developed by Cotton and Coutant (1997), in order to evaluate the dynamic stress changes caused by the main shock. In this study we adopt the shear traction perturbation at the 26 s aftershock hypocenter as obtained by Bizzarri and Belardinelli (2008); these stress variation are reported in Figure 2.

In particular, in the present study we will extend such a study by modelling the perturbed fault rheology through the CH constitutive law (see next section 2.2), in order to evaluate the importance of the thermal evolution during triggering nucleation.

The spring–slider model (Figure 3) here considered is the same as that one introduced in many previous works dealing with fault dynamics, and it will be shortly described for completeness.

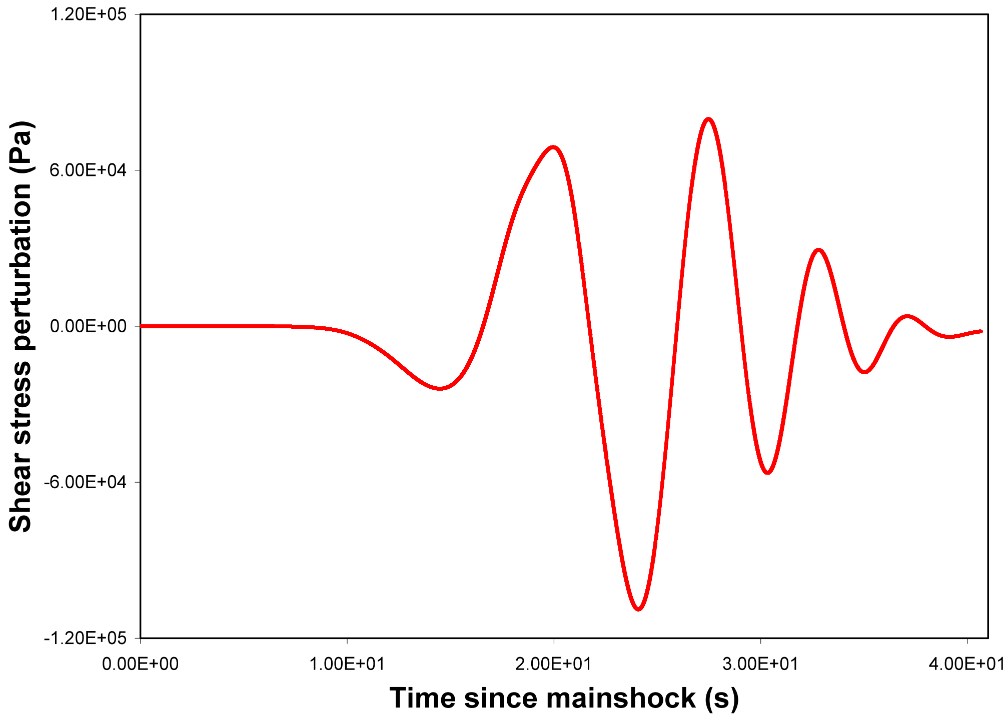

Figure 2. The variations of the shear stress ($\Delta\tau(t)$) as function of time in the location of the hypocenter of the 26 s aftershock resulting from the truly 3–D spontaneous modelling of Bizzarri and Belardinelli (2008).

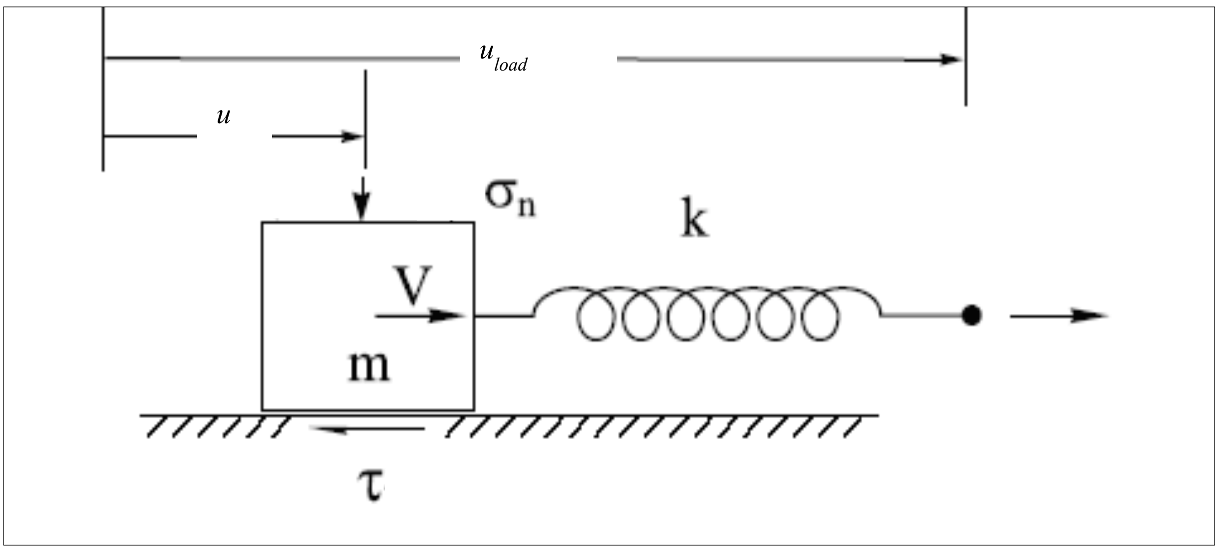

Figure 3. Schematic representation of a spring–slider dashpot system.

The equation of motion (1) of a spring–slider dynamic system, including the inertial term, is expressed as follows:

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

As well known, the spring–slider model is composed by a rigid block, a spring and a support base: the interface between the base of the block and the underlying floor represents the fault plane, and the spring mimics the elastic medium surrounding the fault. Focusing on Figure 3, u is the slip, m is the mass per unit of area, τ is the frictional resistance, u_{load} is the load point displacement, k is the elastic spring constant and V is the sliding velocity.

In numerical simulations when the slider velocity reaches very large values compared to the loading point velocity, a seismic instability may occur. In particular, a seismic slip event occurs when the slip velocity becomes transiently larger than an assumed threshold velocity $v_l = 0.1$ m/s (Belardinelli et al., 2003; Bizzarri and Belardinelli, 2008).

In the present study the equation of motion and the rate– and state–dependent friction laws (RD or CH) governing the spring–slider model are solved numerically, accounting also for the stress variations of Figure 2.

2.1. Modelling with the Ruina-Dieterich constitutive law

In this section we reproduce the numerical simulations already performed by Bizzarri and Belardinelli (2008), namely the direct modeling of the temporal response of the fault perturbed by the stress variations shown in Figure 2 by assuming a RD rate– and state–dependent constitutive law. The aim of these simulations is to evaluate model parameters that allow to obtain a modeled failure time as closer as possible to the observed aftershock time (26 s), in order to evaluate the importance of the computed stress variations.

The RD law, also known as the slip evolution law, is expressed as it follows:

$$\begin{cases} \tau = \left[\mu_* + a \ln\left(\dfrac{v}{v_*}\right) + b \ln\left(\dfrac{\Psi\, v_*}{L}\right) \right] \sigma_n^{eff} \\ \dfrac{\mathrm{d}}{\mathrm{d}t}\Psi = -\dfrac{\Psi\, v}{L} \ln\left(\dfrac{\Psi\, v}{L}\right) \end{cases} \tag{2}$$

In the above equation τ is the frictional strength of a sliding surface, μ_* is a constant frictional coefficient considered at a reference slip rate, v_* in a reference slip velocity and the empirical parameters a and b describe the direct dependence of friction on the slip rate and the evolution effect that the velocity exerts on the frictional strength respectively. Furthermore τ depends on the characteristic distance L of sliding which especially controls the evolution of the state variable ψ, which accounts for the slip history and for the contact sliding surfaces properties. Eventually v is the slip velocity and σ_n^{eff} is the effective normal stress.

On the basis of numerical results, for experimental values of the rheological parameter a (direct effect that the slip rate exerts on the friction), relatively small values on the initial effective normal stress can provide instantaneous triggering of the three early events (in particular the 26 s one), if a rate– and state–dependent friction law is assumed to characterize the considered fault system (Antonioli et al., 2006; Bizzarri and Belardinelli, 2008). The value of the initial normal stress and the other model parameters are reported in Table 1.

Therefore after imposing at the spring–slider fault system the stress perturbation $\Delta\tau(t)$ computed in

Figure 2, the first time instant of failure t_p was evaluated in perturbed conditions (Figure 4). For σ_n^{eff} = 2.85 MPa, in Figure 4 is shown the evolution of the perturbed fault in terms of slip rate: the computed failure instant t_p = 23.93 s results in general agreement with the observation, being slightly smaller than the observed origin time (25.9 ± 0.1 sec, Antonioli et al., 2006). Hence we have well reproduced the triggering conditions already carried out from the numerical simulations of Antonioli et al. (2006) and Bizzarri and Belardinelli (2008).

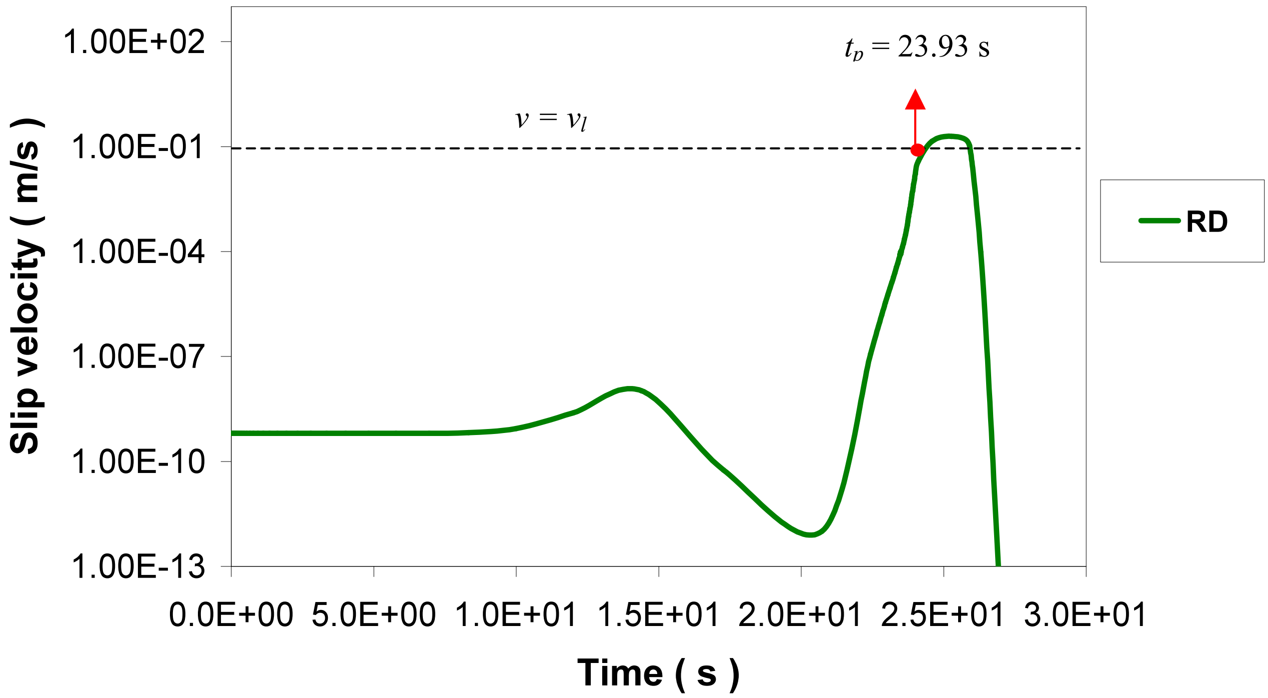

Figure 4. Evolution of the sliding velocity of the spring–slider system governed by the RD law following the stress perturbation $\Delta\tau(t)$ of Figure 2 obtained in the 26 s aftershock hypocenter. It is clear that the system goes to the instability because the slip velocity exceeds the limit velocity v_L = 0.1 m/s (dashed line).

2.2. Modelling with the Chester and Higgs constitutive law

Our original contribution to the dynamic instantaneous triggering widely described so far, was that one to extend the work of Antonioli et al. (2006) and Bizzarri and Belardinelli (2008) to the case of a fault in which are considered the variations of temperature for frictional heating. In particular, we wanted to investigate if there could be any differences between RD and CH modelling because of considering the temperature as further weakening parameter of the fault system. For example as Antonioli et al. (2006) and Bizzarri and Belardinelli (2008) stated that a very small value of the effective normal stress is required at the hypocentral depth of the triggered event (the 26 s event) in order to activate it, we wondered whether a smaller value of σ_n^{eff} is still needed, using a CH rheology on the spring–slider fault system.

The RD law has been extended by the CH model to incorporate the temperature effects along the fault for frictional heating. Indeed Chester and Higgs (1992) found in their experiments that the temperature does affect the frictional strength as it follows:

$$
\begin{cases}
\tau = \left[\mu_* + a \ln\left(\dfrac{v}{v_*} \right) + \dfrac{a\, Q_a}{R} \left(\dfrac{1}{T^f} - \dfrac{1}{T_*} \right) + b \ln\left(\dfrac{\Psi\, v_*}{L} \right) \right] \sigma_n^{eff} \\
\dfrac{\mathrm{d}}{\mathrm{d}t} \Psi = -\dfrac{\Psi\, v}{L} \left[\ln\left(\dfrac{\Psi\, v}{L} \right) + \dfrac{Q_b}{R} \left(\dfrac{1}{T^f} - \dfrac{1}{T_*} \right) \right]
\end{cases}
\tag{3}
$$

where the symbols are the same as those already mentioned after the equation (2), with the exception of Q_a and Q_b which are activation energies, R which is the universal gas constant, T_* which is a reference temperature and T^f which is the temperature developed by frictional heating. Indeed, T^f represents the solution of the 1–D Fourier's heat conduction equation. Its discrete equivalent can be written as follows (see Bizzarri, 2010b; his equation (5)):

$$
T^{(m)} = T_{ini} + \frac{1}{c\sqrt{\pi\,\chi}} \sum_{n=1}^{m} \left(\sqrt{(m-n+1)\Delta t} - \sqrt{(m-n)\Delta t} \right) v^{(n-1)}\, \tau^{(n-1)} \tag{4}
$$

where m denotes the time level ($t^{(m)} = t$), $t^{(0)} = 0$ and $v^{(0)} = \tau^{(0)} = 0$. Equation (4) was originally formulated by Kato (2001) by considering an infinitesimal thickness fault governed by uniform slip, slip rate (v) and shear stress (τ), and furthermore evaluates the thermal evolution of a fault plane in response to the frictional heating. In particular, T_{ini} is the initial uniform temperature at $t = 0$, c is the heat capacity for unit volume of the bulk composite and χ is the thermal diffusivity of the surrounding medium.

We performed three tests at different initial temperatures (from very low to very high, see Table 1) by means of one degree of freedom spring–slider analog model governed by the CH constitutive law, and representative results are reported in Figure 5. The model parameters are the same used for the RD simulations and reported in Table 1.

The Figure 5 clearly shows that there are not any significant differences between the two models, at least if we consider the first 30 seconds of simulations, because this is the proper window of time for the instantaneous dynamic triggering here investigated. Therefore in this time interval the shear stress variations seems to be the prevalent perturbing factor, even stronger than the temperature variations. This is a plausible conclusion as all the slip velocity curves extrapolated at different temperatures (100 °C, 500 °C and 1200 °C) overlap almost perfectly (Figure 5). Furthermore referring to Figure 6, considering the temperature variations as function of time, we can easily appreciate that in the first 30 seconds the temperature varies approximately in the same way in all the four simulations considered, that is of about 70–80°C. This means that the temperature effect is practically irrelevant at least in the early stages of the triggering nucleation: this is an acceptable conclusion as the triggered fault here considered (the 26 s aftershock) is activated from very low slip velocities comparable to those associated at the loading rate reported in Table 1 (1.902×10^{-9} MPa/s) which influences the initial stages of the temperature evolution.

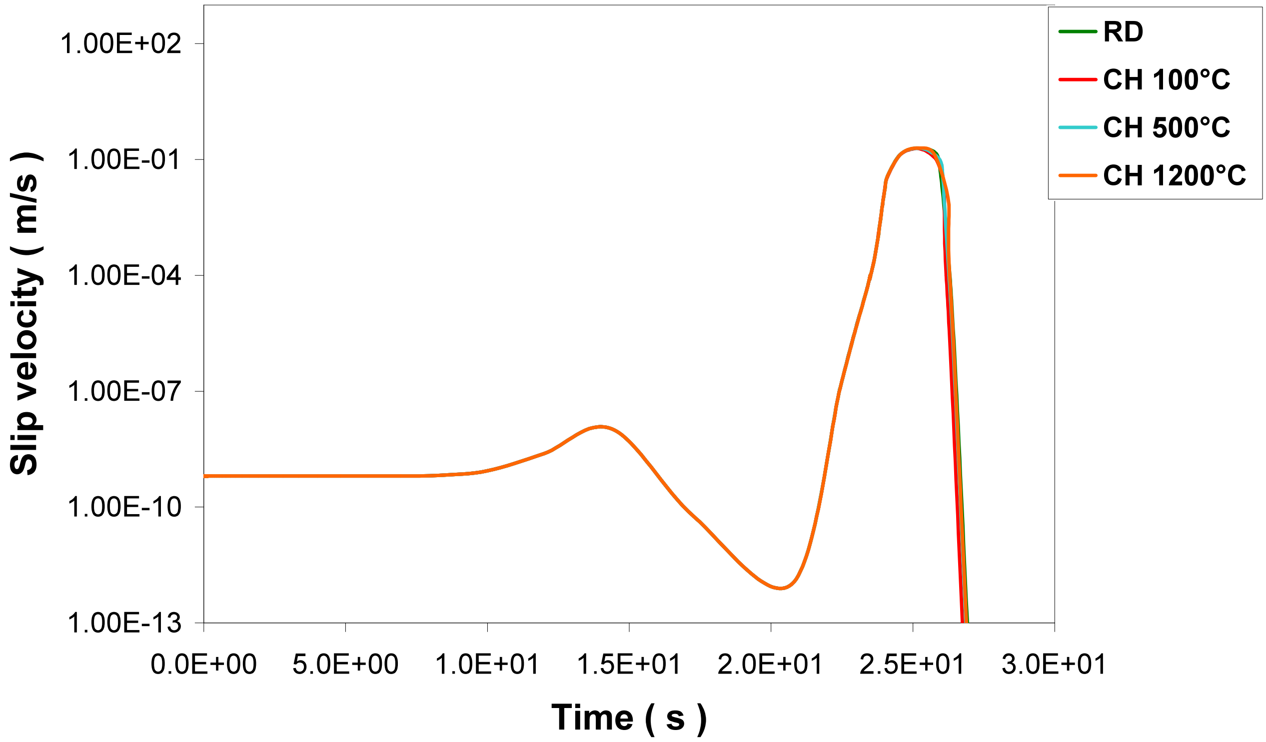

Figure 5. The same as Figure 4 but with the additional case of the CH simulations performed at different starting temperatures that is 100 °C, 500 °C and 1200 °C.

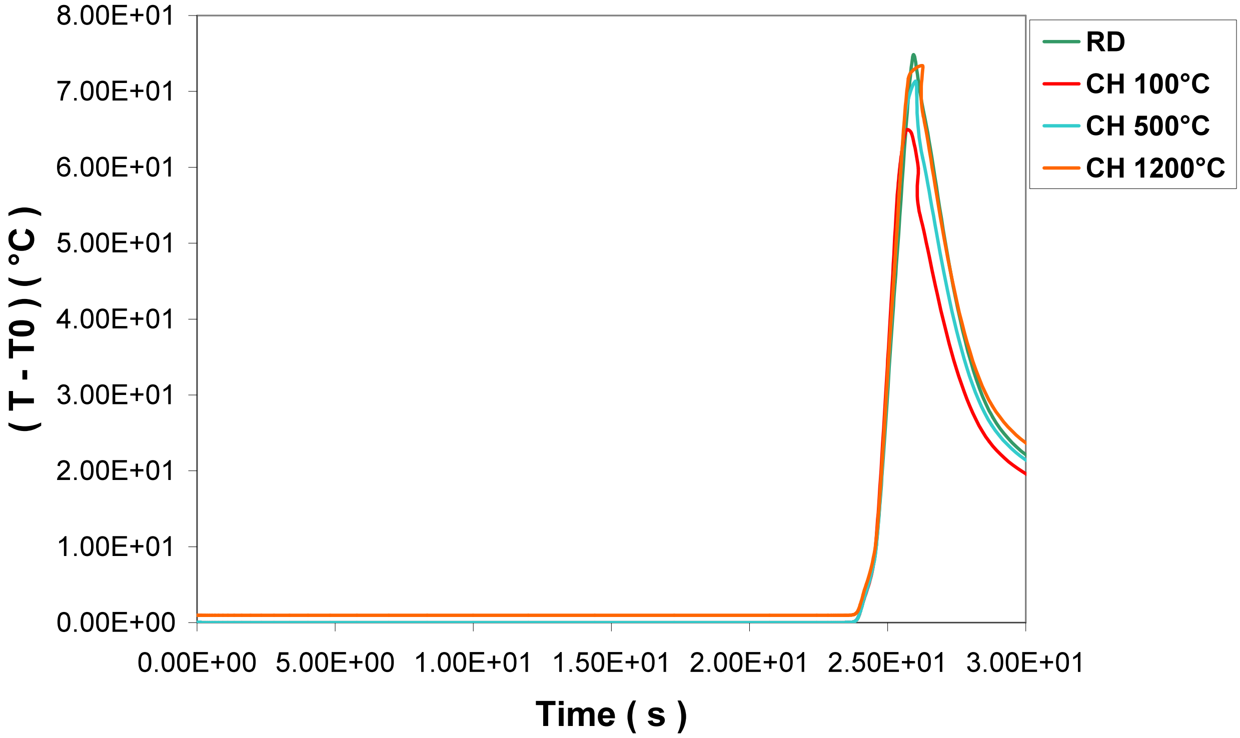

Figure 6. Temperature change considered in the early stages of the earthquake nucleation. In all the four simulations considered the temperature varies approximately in the same way leading the two governing law considered (CH and RD) very similar to each other, at least in the first 30 s time window.

On the contrary, if we account for further instabilities considered in the middle of the full seismic cycle we can appreciate that the role of the temperature is very important as already stated in our previous studies (Bizzarri et al., 2011). In Figures 7, 8 and 9 only the RD and CH simulations conducted at 500 °C have been considered in order to show the temperature influence on the recurrence of seismic instabilities and within the seismic cycle, through simple but concise comparisons. In particular in Figure 7 we can appreciate how the seismic instabilities produced through the CH governing law clearly anticipate those produced by the RD law and, consequently, this means that the temperature represents a further weakening effect on the faulting process which promotes the earthquake occurrence.

In Figure 8 the phase diagram for the two constitutive models considered in the present study is showed: in particular here is evident that the seismic cycle referred to the CH law (light blue line), which shows a lower stress drop, is shorter than that one associated to the RU law (green line).

Furthermore referring to Figure 9 the seismic cycle associated to the CH simulations (about 13.5 yr) is lower than the RD cycle (about 14.2 yr), corroborating the previous observations stated for the Figure 7 and Figure 8.

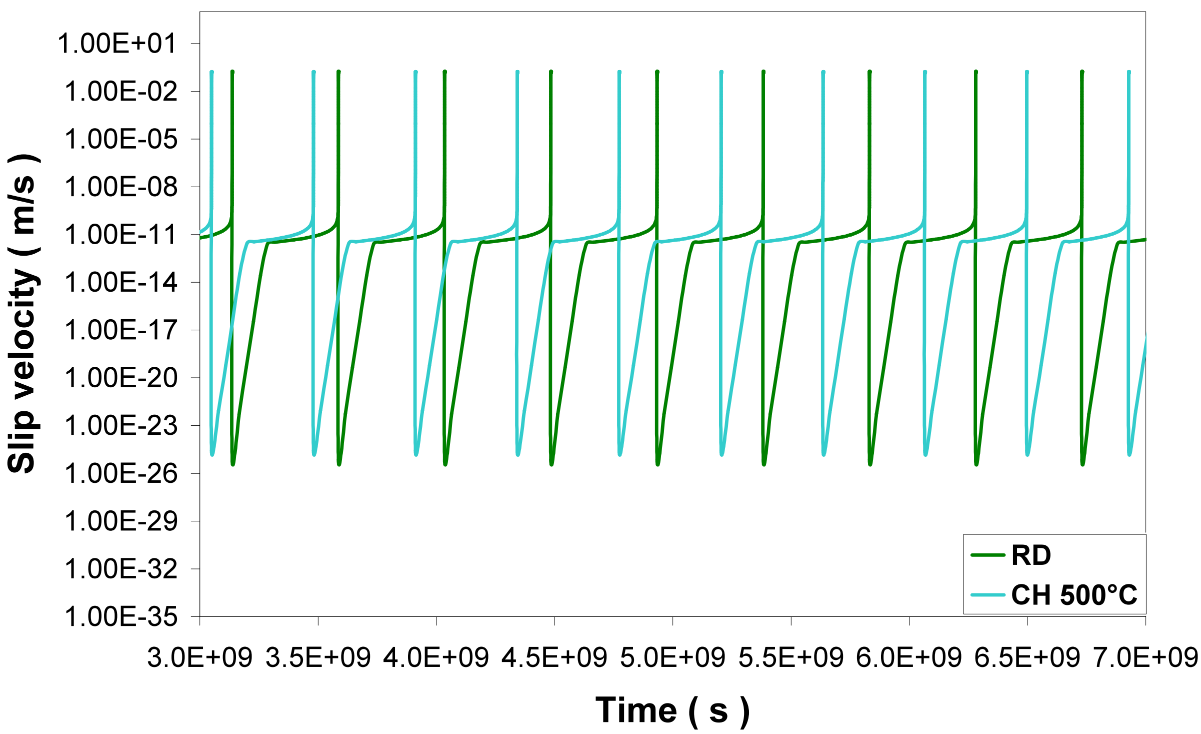

Figure 7. Seismic instabilities considered in the middle of the seismic cycle. It can be appreciated that the earthquakes associated to the CH simulations, carried out at the initial temperature of 500 °C, clearly anticipate the RD instabilities which do not include the explicit time dependence on the temperature.

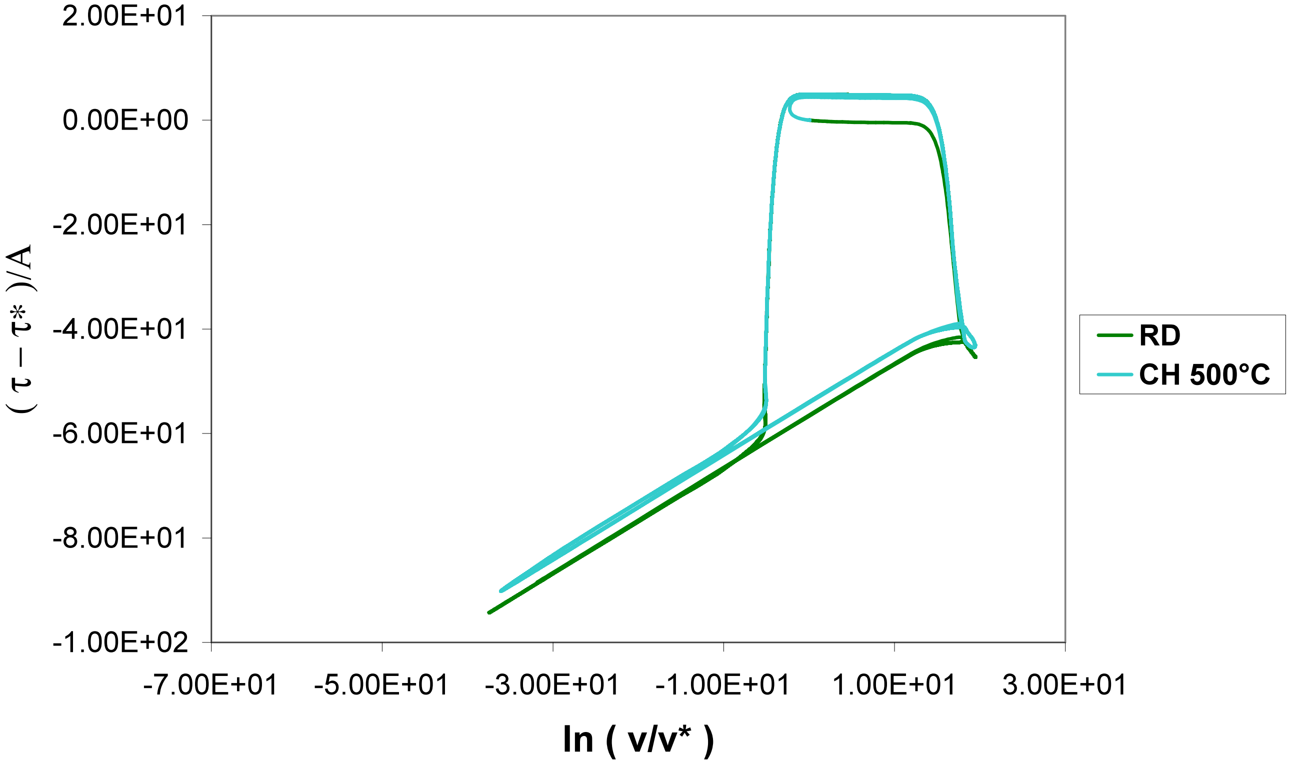

Figure 8. Phase diagram for the two constitutive models considered in this study. Both the RU and CH governing laws reach quite soon the limit cycle.

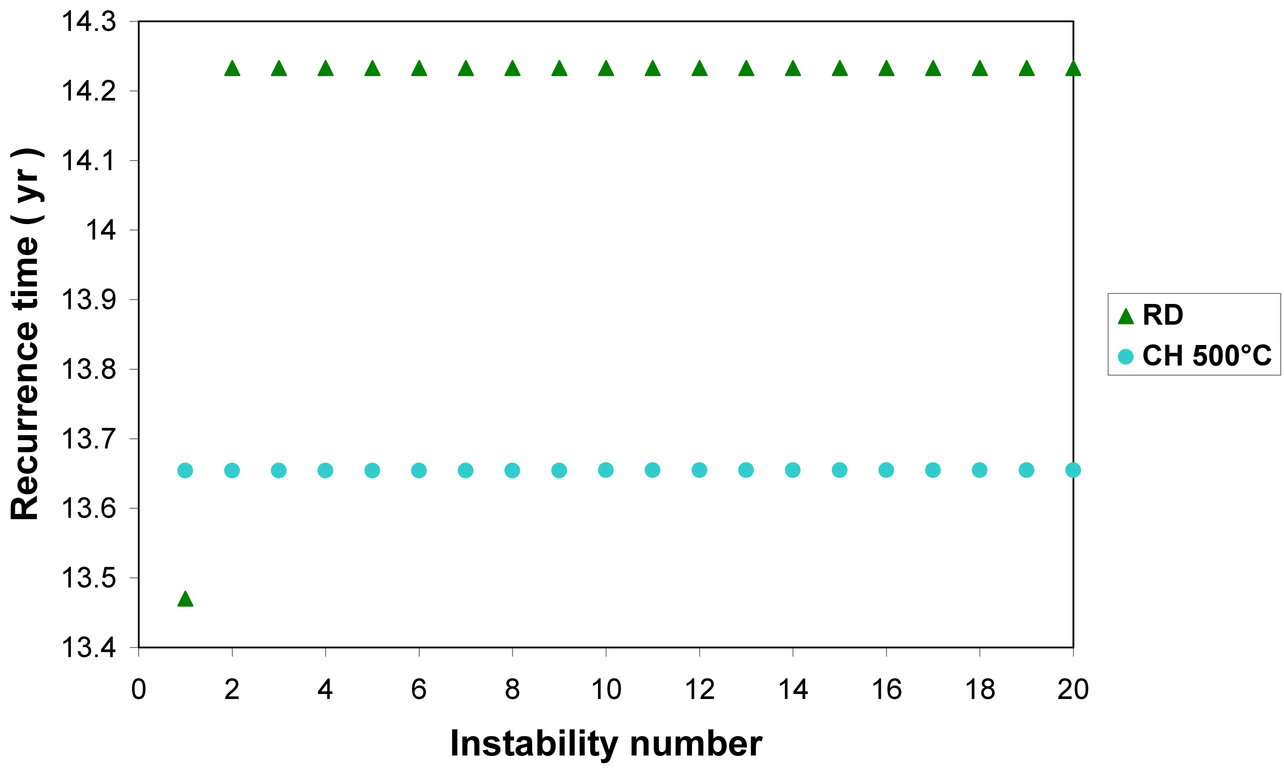

Figure 9. Recurrence time (T_{cycle}) resulting from the two governing models adopted in the present study. The CH seismic events show shorter seismic cycle (roughly 13.5 yr) with respect to the RD simulations (roughly 14.2 yr).

In conclusion we want to highlight that in our numerical results, if we consider the first 30 seconds time window of simulation, the effect of the temperature is negligible and does not produce any important variations on the earthquake triggering phenomenon governed by different constitutive laws. On the contrary in we consider a wider time window of simulation, the role of the temperature can be largely appreciated as it produces evident time advances on the seismic instabilities occurrence.

3. Summary and conclusions

In this study we present the results of numerical simulations conducted through the use of the spring–slider analogue fault where the external perturbations to the fault traction due to a remote earthquake are taken into account. Moreover, different constitutive laws (RD and CH) are considered here to characterize the rheology of the fault surface (see sections 2.1 and 2.2). We focus our attention on the instantaneous dynamic triggering and in particular we analyze one of the three major early events (the 26 s aftershock) occurred in the first minute after the main shock of 17 June 2000 in Southern Iceland.

In particular, Antonioli et al. (2006) and Bizzarri and Belardinelli (2008) already constrained the most suitable set of model parameters in order to reproduce the instantaneous dynamic triggering observed in Iceland on June 2000. Moreover, through their simulations conducted with the “classical” formulation of the rate– and state–dependent constitutive laws, they showed that it is possible to reproduce the failure time t_p in a good agreement with the field and instrumental observations.

In the present study we perform new numerical simulations by adopting the CH constitutive law in order to highlight any differences with respect to the models presented in Antonioli at al. (2006) and in Bizzarri and Belardinelli (2008).

We can conclude that we didn’t find any significant differences between the response of the system predicted by the two different governing formulations (RD and CH), at least in the first 30 seconds time window. This means that the same initial parameters provide approximately the same triggering failure time (26 s) for both the constitutive rheologies analyzed in the present study.

On the other hand, if we consider the whole life of the fault, we confirm here that the temperature returns to be an important contribution to the predicted seismicity rate. Indeed, the CH simulations show a clear time advance with respect the RD instabilities just because they consider a further weakening effect of the sliding system: the temperature.

As an overall conclusion we have found here is that the effect pf the temperature is probably not strong enough during the early nucleation phase of the fault, when the instantaneous dynamic triggering occurs. This makes sense and it is physically reasonable, in that the sliding velocity is relatively small during the early evolutionary phases of the rupture, and therefore the heat input term (τ v in equation (4)) does not change significantly the conditions of the system in that stages.

Another prominent conclusion of the present paper is that the requirement of a low values of the effective normal stress (to have in turn an overall weak fault) is confirmed to be essential to reproduce the instantaneous dynamic triggering of the Icelandic aftershock in the framework of the rate– and state–dependent constitutive laws.

Acknowledgements

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