論文内容の要旨

論文題目　Theoretical Study on Thermoporoelastic Effects on Dynamic Earthquake Rupture

（動的地震破壊における熱及び流体の効果に関する理論的研究）

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We theoretically study thermoporoelastic effects on dynamic earthquake rupture and succeed in explaining diversity of dynamic earthquake behavior. We first present the governing equations assuming a thermoporoelastic medium, based largely on the work of *Pride et al.* [1992] and temperature change is taken into account in the constitutive equations. Our study provides a detailed numerical simulation of thermoporoelastic effects on dynamic fault rupture. Our treatment is much more reasonable than earlier studies, which are limited by weaknesses in their assumptions. For example, *Andrews* [2002] made an *a priori* assumption of a specific form for spatiotemporal change in fault slip, such that it is impossible to use his model to investigate changes in fault slip due to thermoporoelastic effects on the model framework.

We then include an effect of inelastic porosity change in the mathematical framework. We find that a single nondimensional parameter controls two types of feedback appearing in the system behavior. We found that the single nondimensional parameter S controls the system behavior in 1D fault model. This parameter is proportional to the ratio of D_c, the characteristic distance appearing in the governing equation of temporal change in fluid pressure, to d_c, the characteristic fault slip for the inelastic porosity evolution. If S satisfies the condition that the fluid pressure decreases monotonically with time ($S > -P_0^*$), the single feedback is found to appear. The feedback suppresses the rate of fluid pressure change and finally the static equilibrium state is attained. We show in this paper that two qualitatively different feedbacks appear in the system behavior when the condition $S < -P_0^*$ is satisfied; the nature of fault slip behavior is dependent on which of the two feedbacks is dominant. We also demonstrate that one of the feedbacks can be transformed into the other because the feedback mechanism is non-linear. This nonlinearity produces a system behavior in our model that differs significantly from predictions based on the Griffith crack model.

When we study dynamic fault slip assuming a one-dimensional (1D) fault model based on the derived system of equations, we observe slip-weakening behavior due to thermoporoelastic effects if the parameter S is small. The slip-weakening behavior and gradual slip onset observed in our study are clearly related to the non-linear feedback. We derived the approximate solution for the slip-weakening distance in a simple form; seismological estimates are consistent with our model predictions. It is also shown that temperature increase is suppressed because of the reduction in the effective normal stress acting on the fault plane. Our simulation shows that the elevated rock temperature during slip remains below the melting temperature of rocks provided that the rate of fluid outflow from the heated fault zone is relatively low; this has previously been documented by *Lachenbruch* [1980] and *Mase and Smith* [1987]. The normal stress acting on a fault surface asymptotically approaches zero with ongoing slip, where the heat source term becomes zero; this acts to suppress the temperature rise.

On the other hand, when $S \sim 1$ or $S > 1$, the slip-hardening behavior appears. The slip ceases spontaneously because of the reduction in the stress drop induced by fluid pressure decrease. The shear stress recovers the initial strength after some slipping when $S > 1$ and the fluid outflow is negligible. The difference in permeability produces difference of the recovered shear stress level, which is consistent with some observational results that the shear stress does not always recover the initial stress. Temperature increase is again suppressed because of reduction in slip velocity due to stress drop decrease induced by fluid pressure decrease. This mechanism of temperature suppression explains again the unexpectedly rare occurrence of pseudotachylyte as a consequence of low permeability within porous fault zones. If permeability increase occurs because of the inelastic porosity increase, temperature increase may be larger; as the normal stress acting on a fault surface remains large in this situation, temperature continues to increase upon the fault plane and in surrounding rock, which may result in localized melting.

In a two-dimensional (2D) antiplane shear fault model, when the parameter is around zero, smaller events tend to have smaller static stress drops. Our simulation predicts fault slip duration that is generally longer than that predicted by the classical Griffith crack model when $S \simeq 0$. We also found that smaller-size ruptures tend to have smaller static stress drops; this is consistent with some seismological observations. These two findings are closely associated with the increase in stress drop that accompanies fluid-pressure build-up and ongoing fault slip. Previous analyses of earthquake fault processes, however, have found that fault slip duration is much smaller than that expected from the Griffith crack [*Heaton,* 1990]. Such a proposal is contradictory to the above findings; however, the slip behavior described by *Heaton* [1990] can be explained by considering the inelastic porosity change. If the rate of fluid flow into microcracks is larger than the rate of fluid build-up on the fault surface, then fluid pressure on the fault plane decreases for a period of time. The fluid pressure decreases in this way, which can explain the observation of *Heaton* [1990] in the framework of our model. Our study revealed that the static stress drop averaged over the fault plane is smaller for smaller earthquakes. This relationship occurs because of fluid pressure increase with increasing fault slip. This observation is consistent with the findings of *Kanamori and Rivera* [2004], given that the rupture velocity can be assumed to be independent of earthquake size.

We then consider the inelastic porosity effect, in which we observe a propagating slip pulse due to the inelastic porosity change and the slip-hardening behavior in some parameter ranges. The stress drop weakly depending on the earthquake size appears, which is consistent with some previous studies. The problem that the radiation efficiency sometimes exceeds unity is solved by considering the inelastic porosity change. This paradox has been attributed to estimation errors of, for example, radiated energy, though some authors suggested the effect of change in a constitutive law [*Venkataraman and Kanamori*, 2004]. It should be emphasized that earthquakes having the radiation efficiency larger than unity in the study of *Venkataraman and Kanamori* [2004] agree well with those showing pulse-like slip, which are concluded to have large S values.

The effects of temperature, fluid pressure, inelastic porosity and slip velocity on earthquake source mechanics have been studied by many authors, while they have frequently studied those effects individually. We suggested that those effects should be treated in a unified way in earthquake source mechanics because they interact and the interaction plays fundamental roles in dynamic earthquake rupture. This ‘unified-way understanding’ of earthquake source mechanics is necessary to the step of earthquake source physics. Our model explains many aspects of dynamic earthquake rupture such as temperature change, slip-strain relationship and slip velocity distribution on fault planes. Dynamic earthquake rupture should not be investigated in separate aspects; non-linear interaction among quantities such as temperature and fluid pressure affects the rupture process, which results in that effects of all quantities should be considered.