摩擦の不安定性に関するエネルギー的評価と剪断に伴う組織発達の定量的評価
Energetic Assessment of Frictional Instability and Quantitative Evaluation of Microstructural Development with Shear

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1. Introduction
Frictional instability has been evaluated empirically by using a frictional parameter (velocity dependence) on the basis of the rate and state dependent friction law (Dieterich, 1979; Ruina, 1983). In addition, shear development in a gouge layer influences frictional instability (e.g., Byerlee et al., 1978; Logan et al., 1979; Ikari et al., 2011; Onuma et al., 2011). Ikari et al. (2011) pointed out a possibility that velocity dependence of friction changes with shear. However, it is difficult to accurately observe shear structures developed in recovered gouge samples and deal with shear zone development in gouge statistically. Therefore, the underlying theoretical relation between frictional instability and shear development has not been clear yet. In the present study, we aim to clarify (1) relation between frictional instability and shear development by energetic analysis, and (2) process of shear development toward frictional instability of gouge through theoretical and experimental analysis.
2. The energetic criterion for frictional instability
Deformation of particles progresses in an energetically efficient way (Rowe, 1962). Thus, both energy ratio defined as a ratio of input mechanical energy to output energy, and hence dissipation energy of particles become minimum. Stability of a mechanical system is influenced by energy. If a frictional system represented by a spring-slider model experiences frictional damping, the stored energy in the system decreases leading to stable slip. In contrast, if the system experiences negative frictional damping, the stored energy increases leading to unstable slip. Negative frictional damping indicates that friction force works to the direction of motion and might be related to shear development. Because the stored energy coincides with the difference in energy during deformation, the stored energy can be represented by the energy ratio between input energy to output energy through deformation. Thus, the energetic criterion for frictional instability is obtained from the relation between the stored energy and mechanical behavior of the frictional system.
3. The friction experiments
We analyzed data of friction experiments using simulated fault gouge (Hirata et al., 2014) to obtain energy ratio of gouge during friction experiments in gas apparatus. The cylindrical samples with dry quartz powder as gouge were loaded under 140, 160, and 180 MPa of confining pressures. Data about stress and strain in major and minor principal axes were recorded through strain gauges placed onto samples. The values of energy ratios of gouge were obtained based on these values.
4. Results and discussion
We clarified that the output energy has a linear relationship with input mechanical energy, but energy ratios changed slightly with shear. Change in the energy ratio which is a function of internal friction angles implies shear development. R1-shear angles from major principal stress axis can be estimated using internal friction angles (Morgenstern and Tchalenko, 1967). Thus, the energy ratio controlled by the internal friction angle closely related to shear development. R1-shear angles we estimated show that R1-shears becomes more parallel to a rock-gouge boundary

before the occurrence of unstable slip. At 140 MPa of confining pressure, R1-shear was inferred to be developed almost parallel to the boundary (3 degrees to the boundary) at the top of a sample as deformation proceeds. The reduction of shear angles with respect to shear zone boundary with progressive shear is consistent with previous works (e.g., Gu and Wong, 1994).

5. Summary

We investigated relation between frictional instability and shear development energetically. Our results revealed that (1) the energetic background for their relation; (2) the efficacy of the energetic criterion for frictional instability; and (3) shear development in gouge in situ.

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