

Abstract

The stability of frictional sliding affects the spectrum of fault slip, from slow-slip events to earthquakes. In laboratory experiments, the transition from stable sliding to stick-slip is often explained by the ratio of the stiffness of the loading system to a critical value that depends on effective normal stress and other physical properties. However, theoretical considerations indicate other controls on fault stability that have not been validated experimentally. Here, we exploit the dependence of frictional properties on load-point velocity to explore the dynamics of frictional sliding with gradual variations of frictional properties. We use the period-multiplying and chaotic cycles that appear at the transition between stick-slip and stable sliding as a sensitive indicator of fault stability. In addition to the stiffness ratio, we find that the ratio of the parameters that describe the dependence on velocity and state constitutes another control on the stability of faulting and rupture dynamics.

Multiplicative form of rate- and state-dependent friction

We consider a physics-based constitutive law for fault friction that captures essential attributes of fault healing and weakening and allows seismic cycles (Barbot, 2019a), the multiplicative form of rate- and state-dependent friction in isothermal conditions is described as

$$\tau = \mu_0 \bar{\sigma} \left(\frac{V}{V_0} \right)^{\frac{a}{\mu_0}} \left(\frac{\theta V_0}{L} \right)^{\frac{b}{\mu_0}}$$

where V_0 is a reference velocity, τ is the amplitude of the shear traction, μ_0 is a reference friction coefficient, θ is the state variable representing the age of contact, L is a characteristic weakening distance, and the parameters a and b control the velocity and state dependence of dynamic friction. Seismic cycles are allowed by weakening during contact rejuvenation and healing at stationary contact, which can be captured by the aging law (Dieterich, 1979)

$$\dot{\theta} = 1 - \frac{V\theta}{L}$$

Two equations form a simple constitutive framework for rate-and-state friction that allows us to discuss the stability of faulting and the evolution of effective frictional properties a , b , and L with varying load-point velocity.

The wide spectrum of rupture styles that develop during seismic cycles is controlled by the frictional and geometrical properties of a fault. These parameters can be combined into dominantly two non-dimensional parameters: the Dieterich-Ruina-Rice number R_u and the R_b number (Barbot, 2019b)

$$R_u = \frac{(b-a)\bar{\sigma}}{kL} \equiv \frac{k_c}{k},$$

$$R_b = \frac{b-a}{b}.$$

The R_u number is the inverse of the stiffness ratio commonly used in laboratory experiments to describe stability and rupture style and also comes about in a linear stability analysis of a spring-slider system (Ruina, 1983). Furthermore, the R_u number is associated with a characteristic nucleation size and it controls the complexity of seismic cycles. The R_b number is a ratio of frictional properties that control the dynamic and static stress drops. Varying the load-point velocity and the normal stress allows us to explore the two-dimensional parameter space of the non-dimensional parameters R_u and R_b and to deconvolve their respective effects on seismic cycles.

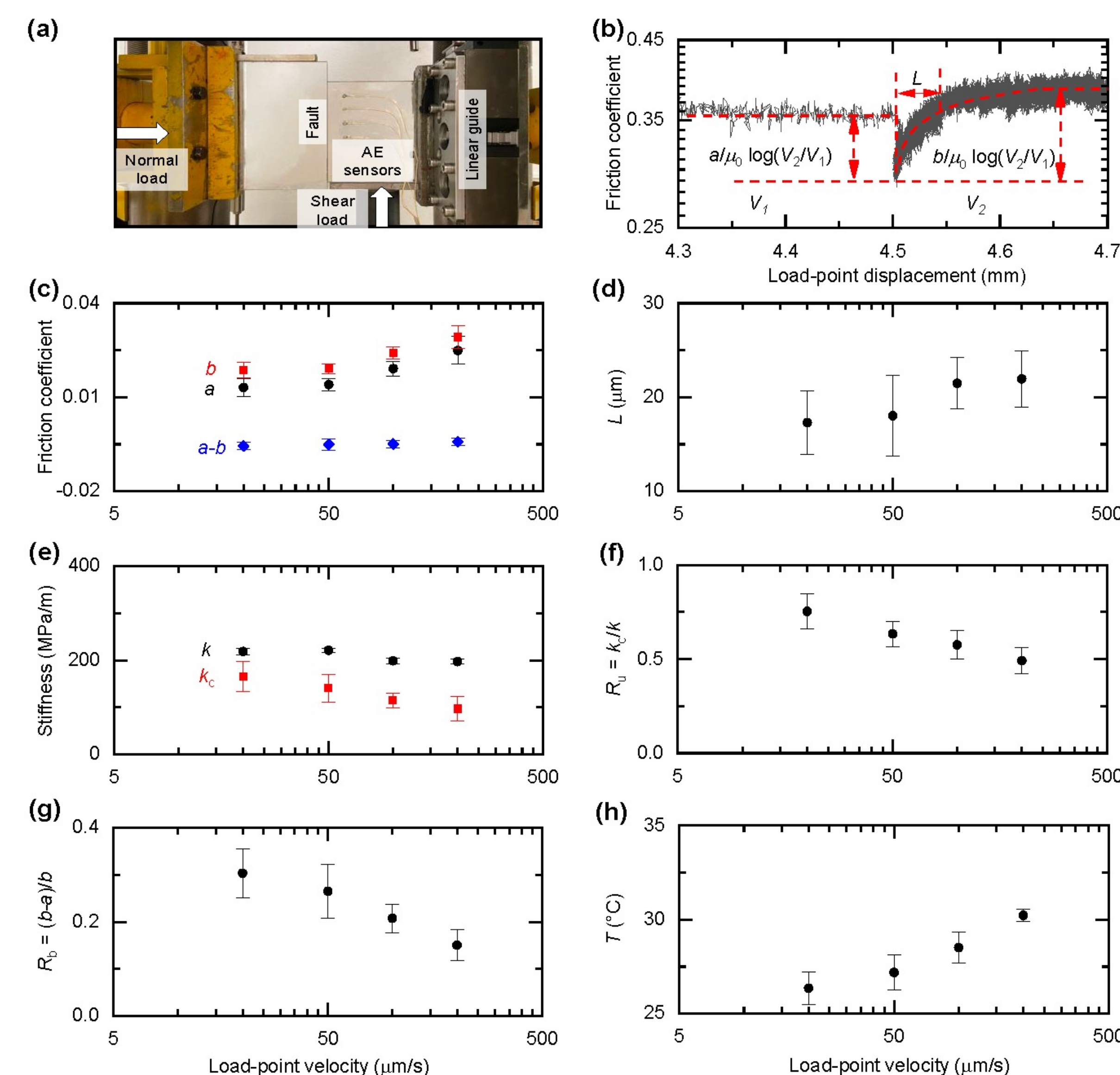


Fig. 1. Effect of load-point velocity on effective frictional properties. a) Direct-shear setup with a polycarbonate fault. The lengths of the fixed (left) and driving (right) plates are 180 and 150 mm, respectively. The width and thickness of two plates are 100 and 9.3 mm, respectively. The shear modulus and Poisson's ratio of polycarbonate are 0.9 GPa and 0.38, respectively. b) Estimation of friction constitutive parameters with load-point velocity changing from V_1 to V_2 . c) Mean values and standard deviation of constitutive parameters a , b , and $a-b$. d) Same for the characteristic weakening distance L . e) Stiffness of loading system k , and critical stiffness of fault k_c . f) Dieterich-Ruina-Rice number R_u as a function of load-point velocity. g) The R_b number. h) Theoretical estimates of temperature on the fault. The error bars represent the standard deviation of measured data for multiple events.

Experimental evidence for multiple controls on fault dynamics

We conduct a series of direct-shear experiments on a smooth fault in Makrolon polycarbonate. As a preliminary step, in velocity-step experiments, we assess representative values of the frictional constitutive parameters a , b , and L as well as the stiffness of the loading system as a function of load-point velocity under a constant normal stress of 0.5 MPa (Fig. 1). Variations of characteristic weakening distance and stiffness of the loading system introduce some modest change of the R_u number from 0.75 to 0.49 (Figs. 1d-1f). However, most critically, the load-point velocity greatly affects the R_b number (Figs. 1g), showing systematic variations from 0.30 to 0.15.

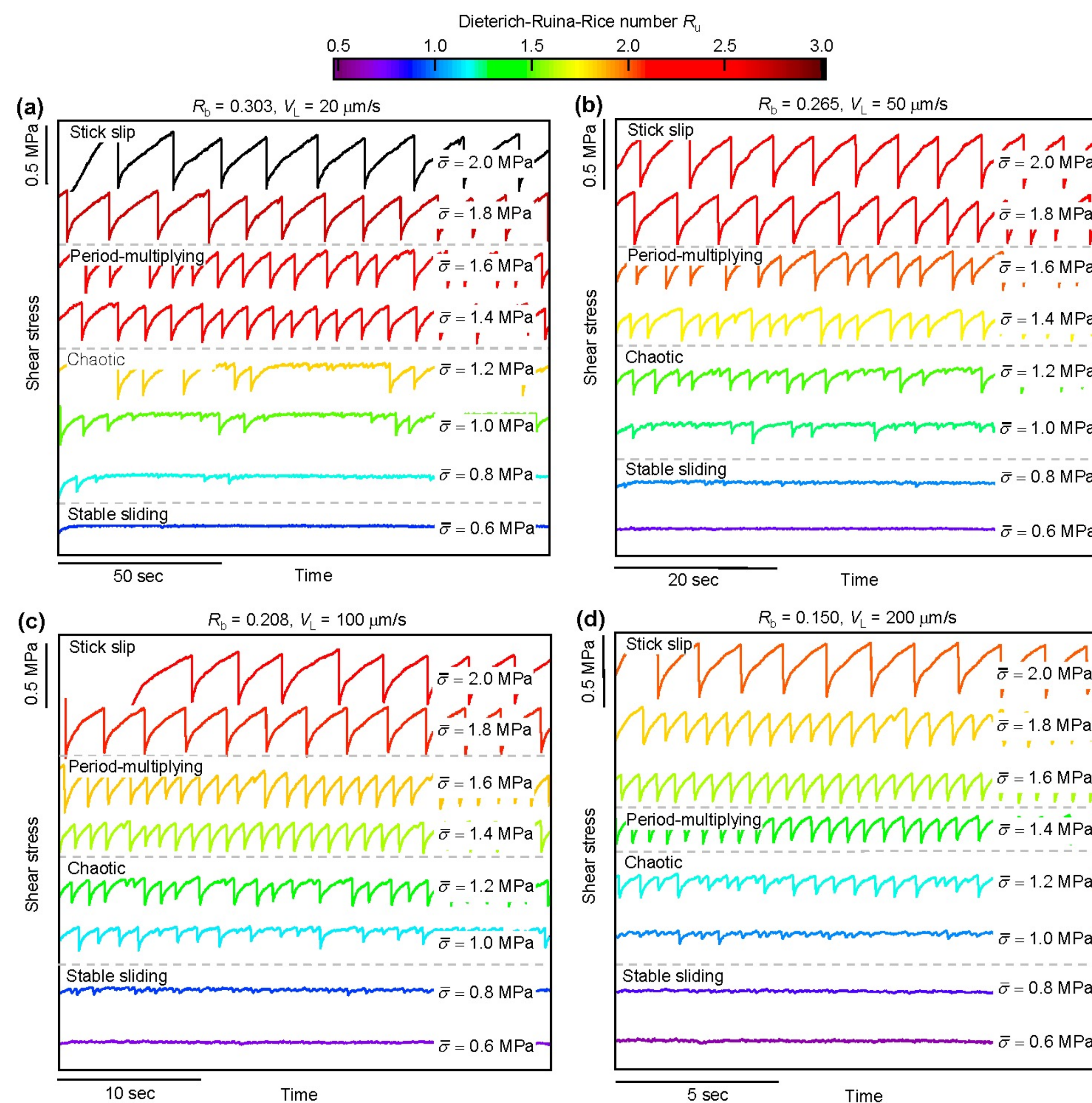


Fig. 2. Fault responses, including stick-slip, period-multiplying cycles, chaotic cycles, and stable sliding as a function of normal stress and load-point velocity under multi-step normal stress reduction. The corresponding R_u and R_b numbers are calculated using the properties measured in Fig. 1. a) Load-point velocity of 20 $\mu\text{m/s}$ giving rise to $R_b = 0.303$. b) Load-point velocity of 50 $\mu\text{m/s}$ corresponding to $R_b = 0.265$. c) Load-point velocity of 100 $\mu\text{m/s}$ leading to $R_b = 0.208$. d) Load-point velocities of 200 $\mu\text{m/s}$, corresponding to $R_b = 0.150$. In each case, variations of normal stress affect the R_u number from about 2.5 to 0.5, traversing the stability transition.

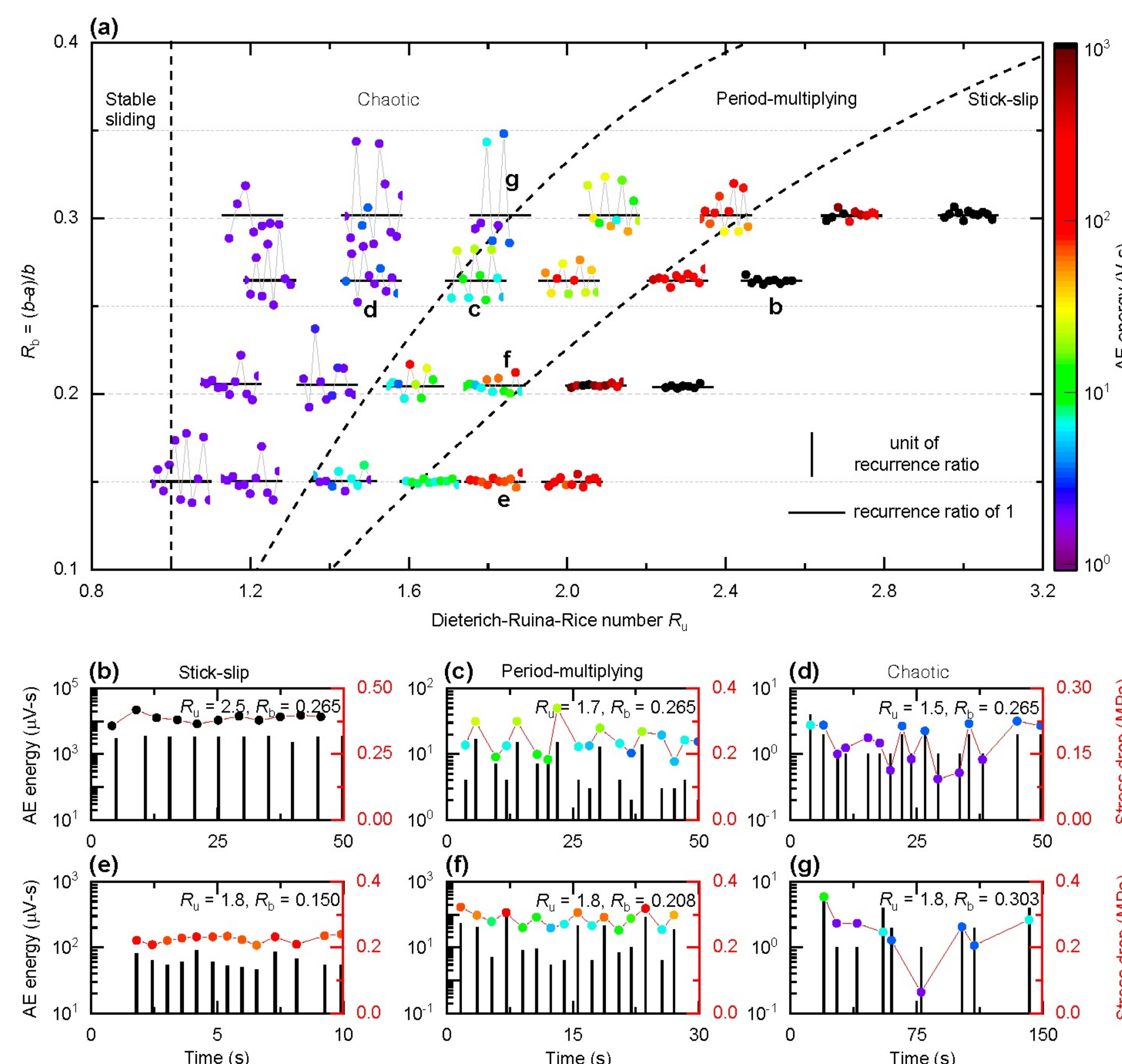


Fig. 3. (a) A wide spectrum of rupture styles under variable R_u and R_b , including stick-slip cycle, period-multiplying cycle, chaotic cycle, and stable sliding. The symbol-curves show the recurrence time ratio of fast to slow ruptures for ten successive events associated with AE energy. Examples of b) stick-slip cycles, c) period-multiplying cycles, and d) chaotic cycles characterized by AE energy and shear stress drop from high R_u to low R_u , and examples of e) stick-slip cycles, f) period-multiplying cycles, and g) chaotic cycles from low R_b to high R_b .

We now explore the two-dimensional space of R_u and R_b numbers across the stability transition using the normal stress and the load-point velocity as controlling parameters (Fig. 2). To understand the influence of frictional properties on the stability transition, we carry out four separate experiments using the constant load-point velocities of 20, 50, 100, and 200 $\mu\text{m/s}$, same as in the velocity-step experiments. Formally, these experiments document the spontaneous pattern of rupture cycles for the two-dimensional parameter space of normal stress and load-point velocity. As we decrease the normal stress at a constant load-point velocity, the fault transitions from stick-slip to stable sliding, going through a stability transition that features period-multiplying cycles of slow and fast ruptures and a distinct phase of chaotic cycles of events.

Our experimental results highlight multiple controls on fault stability and rupture dynamics that we summarize in a two-dimensional phase diagram formed by the non-dimensional parameters R_u and R_b (Fig. 3). To capture the recurrence patterns that take place at various coordinates in this space, we consider the ratio of previous to subsequent inter-event times in a sequence of 10 events. Although the different rupture styles can be observed at all load-point velocities, the domain boundaries vary load-point velocity. Stick-slip cycles of fast ruptures take place for R_b numbers greater than 1.6, 1.9, 2.2, and 2.5 for R_u number of 0.150, 0.208, 0.265, and 0.303, respectively. Similarly, the transition between period-multiplying and chaotic cycles occurs for R_u number around 1.3, 1.5, 1.7, and 1.9 for the same range of R_b number. In contrast, the transition to stable sliding seems independent of the R_b number, occurring systematically around $R_u = 1.0$.

In our experimental setting, the conditions leading to period-multiplying cycles at the lowest R_u number occur for a constant normal stress of 1.4 MPa, irrespective of load-point velocity (Fig. 4). As the latter is increased from 20 to 200 $\mu\text{m/s}$, the R_b number decreases from 0.303 to 0.150 and the recurrence pattern evolves from period-multiplying cycles of seismically energetic events with recurrence ratios of two-to-one to an almost periodic cycle of weakly energetic ruptures.

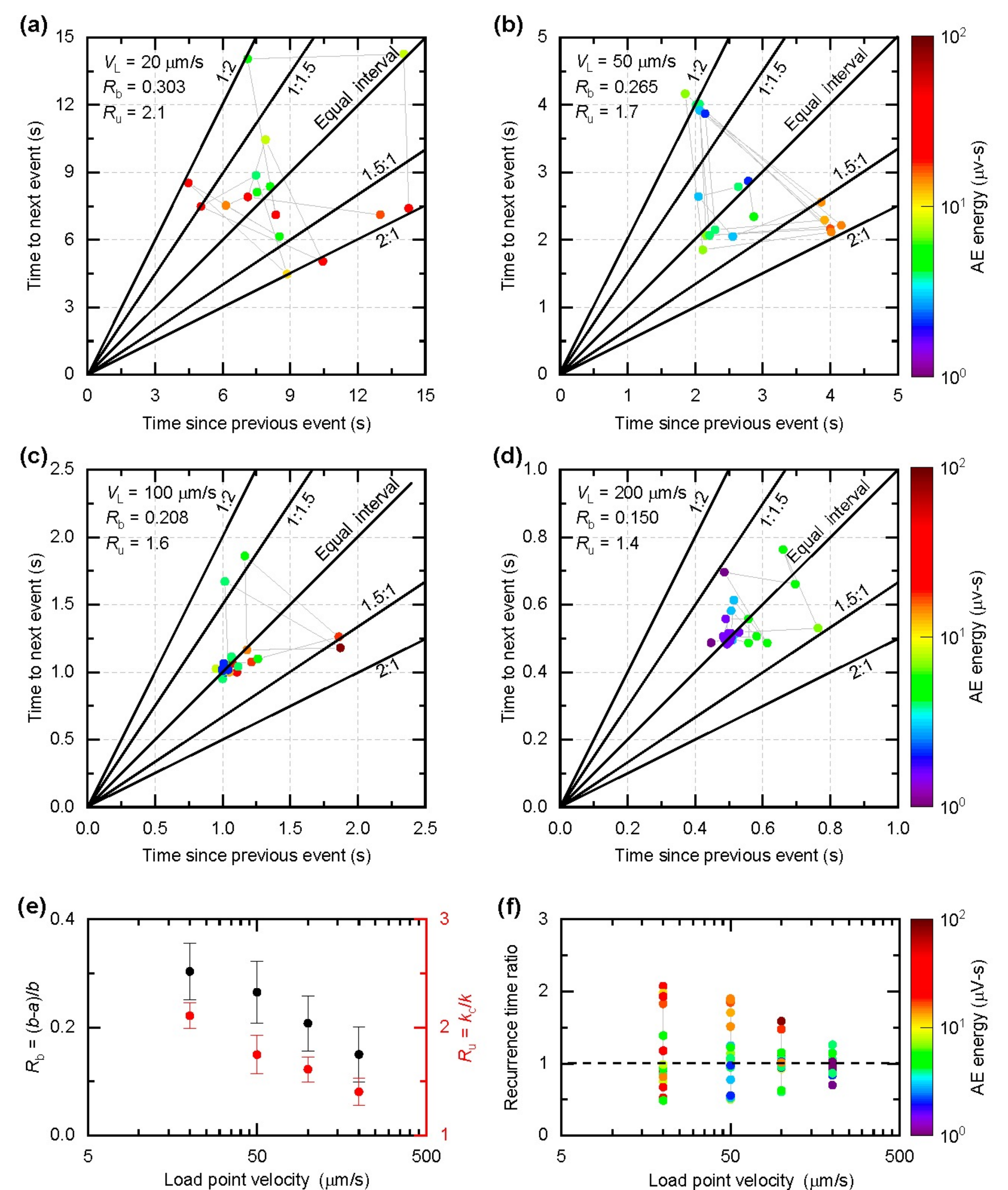


Fig. 4. Recurrence patterns of slip events on the fault under 1.4 MPa normal stress at load-point velocities of a) 20 $\mu\text{m/s}$, b) 50 $\mu\text{m/s}$, c) 100 $\mu\text{m/s}$, and d) 200 $\mu\text{m/s}$. e) Dieterich-Ruina-Rice number R_u and R_b under 1.4 MPa normal stress and f) recurrence time ratio of fast to slow ruptures obtained from direct-shear experiments as a function of load-point velocity.

References

- Barbot, S. (2019a). Modulation of fault strength during the seismic cycle by grain-size evolution around contact junctions. *Tectonophysics*, 765, 129–145.
- Barbot, S. (2019b). Slow-slip, slow earthquakes, period-two cycles, full and partial ruptures, and deterministic chaos in a single asperity fault. *Tectonophysics*, 228171.
- Dieterich, J. H. (1979). Modeling of rock friction: 1. experimental results and constitutive equations. *J. Geophys. Res.*, 84 (B5), 2161–2168.
- Ruina, A. (1983). Slip instability and state variable friction laws. *J. Geophys. Res.*, 516 88 (B12), 10359–10370.