Slow and fast slip events near the stability transition from laboratory experiments and numerical simulations

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Slow and fast slip events near the
stability transition from laboratory
experiments and numerical simulations

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Asian School of the Environment

A thesis submitted to the Nanyang Technological University

in partial fulfilment of the requirement for the degree of

Doctor of Philosophy (Ph. D.)

2019

Candidate Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research, is free of plagiarised materials, and has not been submitted for a higher degree to any other University or Institution. I confirm that the investigations were conducted in accord with the ethics policies and integrity standards of Nanyang Technological University and that the research data are presented honestly and without prejudice.

19 July 2019

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Date

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Supervisor Declaration Statement

I have reviewed the content and presentation style of this thesis and declare it is of sufficient quality and grammatical clarity to be examined. To the best of my knowledge, it is free of plagiarism and the research and writing are those of the candidate except as acknowledged in the Author Attribution Statement. To the best of my knowledge, the investigations were conducted in accord with the ethics policies and integrity standards of Nanyang Technological University and that the research data are presented honestly and without prejudice.

19. July, 2019

Date

Asst. Prof. Shengji Wei

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Authorship Attribution Statement

This thesis contains material from three papers published/under review/in prep. in the following peer-reviewed journal(s)

Paper 1, Veedu, D. M., & Barbot, S. (2016). The Parkfield tremors reveal slow and fast ruptures on the same asperity. *Nature*, 532, 361–365. <https://doi.org/10.1038/nature17190>.
Located in Chapter 2.

Deepa Mele Veedu is the primary author. Deepa Mele Veedu and Sylvain Barbot designed the experiment, analysed the data, and wrote the paper. David. R. Shelly shared his tremor data and J.-P. Avouac provided comments on an earlier version of the manuscript.

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Deepa Mele Veedu is the primary author. Sylvain Barbot suggested a detailed follow up study on the parameter space around the slow and fast ruptures. Deepa Mele Veedu has designed the simulations and analysed the data by incorporating the suggestions. Deepa Mele Veedu wrote the paper and Sylvain Barbot helped in revising the paper.

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Deepa Mele Veedu is the primary author. Deepa Mele Veedu, Cristiano Collettini, Marco Scuderi, Chris Marone and Carolina Giorgetti designed the experiment. Deepa Mele Veedu performed the initial analysis of the laboratory data. Sylvain Barbot helped with further analysis and to finalize the models. Deepa Mele Veedu wrote the paper. The co-authors have helped in revising the paper.

We the undersigned agree with the above stated “proportion of work undertaken” for each of the above published (or submitted) peer-reviewed manuscripts contributing to the thesis:

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Thesis Summary

Theoretical studies establish a stability criterion for the frictional instabilities. However, how the transition from slow to fast ruptures takes place is not fully understood. Here, I investigate the unique fault behaviour around the stability criterion in numerical and laboratory experiments. In the first study, I simulate sequences of alternating slow and fast ruptures on the same patch to explain the unique recurrence pattern of the period-doubling Parkfield tremors along the San Andreas Fault. Second, I systematically investigate the physical parameters that control the inter-event times of the slow-fast ruptures. I extend the criterion for instabilities from a simple threshold to a finite transition zone characterized by slow-slower and slow-fast events. Finally, I study the slow-fast phenomena in the laboratory using granular quartz samples to compare the bifurcation pattern to that predicted numerically. Overall, these findings provide a theoretical framework to understand the physical conditions of plate boundaries that host standalone quasiperiodic slow slip and bimodal slow-fast ruptures.

Introduction

1.1 Background

Certain phenomena in nature occur in Goldilocks zones that provide just the right conditions. One such phenomenon in earthquake science seems to be the occurrence of slow slip preceding dynamic slip. For example, the slow slip before the 2011 Mw=9.0 Tohoku-Oki, Japan (*Ito et al.*, 2013; *Kato et al.*, 2012) and the 2014 Mw=8.2 Iquique, Chile (*Kato et al.*, 2016a; *Meng et al.*, 2015; *Ruiz et al.*, 2014) earthquakes adds to the growing number of such observations (*Graham et al.*, 2014; *Kato et al.*, 2016b; *Radiguet et al.*, 2016; *Ruiz et al.*, 2017). My quest is to understand the physics behind these enigmatic slow transients preceding dynamic events.

In theoretical studies, the mechanism that generates earthquakes is referred to as a stick-slip instability (Brace and Byerlee, 1966). To model these slip instabilities, the rate- and state-dependent friction law (*Dieterich*, 1979; *Ruina*, 1983), is widely used, and explains earthquake, slow slip, and tremor observations (*Barbot et al.*, 2012; *Chen and Lapusta*, 2009; *Jiang and Lapusta*, 2017; *Kaneko et al.*, 2010; *Liu and Rice*, 2005, 2007; *Michel et al.*, 2017; *Noda and Lapusta*, 2013; *Tse and Rice*, 1986; *Veedu and Barbot*, 2016).

Instabilities take place when the frictional strength decreases with increasing velocity. The direct effect a , the evolution effect b , and the characteristic weakening distance L are obtained from velocity-step experiments conducted in laboratory settings (Fig. 1.1), and these parameters can be used to model

slip instabilities with numerical methods such as finite differences (FD) (*Day, 1982; Day et al., 2005*), boundary integral (BI) method (*Ben-Zion and Rice, 1997; Geubelle and Rice, 1995; Lapusta and Rice, 2003; Lapusta et al., 2000*), and boundary integral equation methods (BIEM) (*Chen and Lapusta, 2009; Lapusta and Liu, 2009; Noda and Lapusta, 2013*).

In rock sliding experiments, the friction between rock surfaces increases instantaneously when the velocity of sliding increases (Fig. 1.1). Following this direct effect, the frictional resistance typically weakens (*Dieterich, 1972, 1978, 1979, 1981, 1992*), even though some experiments show additional hardening in some cases (*Blanpied et al., 1998; Carpenter et al., 2015; Sone et al., 2012*). A state evolution of the points of contact follows this direct effect. The net friction at steady-state, after the direct effect and the period of weakening, either reduces (velocity-weakening friction, $b > a$) or increases (velocity-strengthening friction, $b < a$). However, for the weakening to be complete, sufficient slip must occur, which is a result of fault dynamics, and is in part controlled by the size of the velocity-weakening asperity. Velocity-weakening friction ($a - b < 0$) is a necessary condition for a fault to grow frictional instabilities. Stable creep develops in a velocity-strengthening region, while earthquakes nucleate in a velocity-weakening region. The contact points on the rock surface evolve, and the fault weakens over the slip distance D_c . The characteristic weakening distance is a fraction of the total weakening distance D_c (Fig. 1.1). One of the conditions to generate either slow or fast slip is determined by the characteristic weakening distance L .

A range of fault slip behaviors can be obtained by varying the characteristic weakening distance L . The ratio of final slip and characteristic weakening distance s/L can be related to the ratio of the slip-weakening region and the nucleation size W/h^* ,

$$\frac{s}{L} \sim \frac{(b - a) \bar{\sigma} W}{G L} \sim \frac{W}{h^*}, \quad (1.1)$$

where a and b are the friction parameters; $\bar{\sigma}$ is the effective normal stress, and G is the rigidity modulus. If the slip s is negligible compared to the characteristic weakening distance L , i.e., $s \ll L$, the fault creeps; if s is much larger than L , i.e., $s \gg L$, frictional instabilities and earthquakes can emerge. When

Figure 1.1: Velocity-step experiments provide the necessary conditions to produce slip instabilities. Shear stress varies due to a jump in the sliding velocity. The state evolution follows the direct effect, leading to either velocity-weakening (red line) or velocity-strengthening (blue line) behavior. A negative value for $(a - b)$ is necessary to produce slip instabilities. The characteristic weakening distance L (close to one-tenth of the slip distance D_c) determines the conditionally stable behavior of faults with respect to the value of slip s .

slip is of the order of L , i.e., $s \sim L$, slow earthquakes take place, and the system is stable weakening. The magnitude of slip s depends on the size of the velocity-weakening asperity W . If we have a large asperity, more slip can occur. So, s depends on the asperity size W and the parameters in Eqn. 1.1.

Building upon early modeling studies (*Ben-Zion and Rice, 1997; Rice and Ben-Zion, 1996; Tse and Rice, 1986*), *Lapusta et al. (2000)* developed a method that can model earthquake nucleation, aseismic slip, and seismic slip. Frictional instabilities could be unbounded if not for additional processes consuming energy when the rupture reaches seismic speeds, such as the radiation of seismic waves. However, modeling fault friction and wave propagation together is extremely numerically challenging. Studies focusing on a single event (*Day, 1982*) include these effects consistently, however, the initial conditions must be attributed manually and may not well capture the effect of previous dynamics on the fault. Other studies approximate the radiation of seismic waves by a viscous term, the so-called radiation-damping approximation (*Cochard and Madariaga, 1994; Rice et al., 2001*). This method is particularly numerically efficient, allows seismic cycle modeling with the boundary-integral method, but some important aspects of fault dynamics are missed, including the development of pulse-like ruptures, supershear ruptures, and

dynamic triggering in general. *Cochard and Madariaga* (1994, 1996) and *Lapusta et al.* (2000) augmented the integral method to include the radiation of seismic waves. The method is made tractable by the use of fast implementations of the Fourier transform. *Lapusta and Liu* (2009) applied the approach to finite faults embedded in a three-dimensional elastic medium. Their method is appealing to simulate fault dynamics on planar faults. Currently, the radiation-damping approximation is still relevant to model fault dynamics on non-planar or branched faults (*Hori et al.*, 2004; *Li and Liu*, 2016, 2017; *Ong et al.*, 2019), or viscoelastic media (*Barbot; Lambert and Barbot*, 2016). The key development in *Lapusta et al.* (2000) is the inclusion of radiation of seismic waves. However, the model (*Lapusta et al.*, 2000) is two-dimensional (2-D) and considers variations only in the down-dip direction. Comparing the modeled 2-D results to 3-D observations is challenging. Follow-up 3-D modeling considers the fault as a surface embedded in an elastic medium that can include heterogeneities in stress and frictional properties, and better replicates natural systems (*Lapusta and Liu*, 2009).

1.2 Scientific gaps

Slow slip events are a major contributor to the accommodation of plate motion, particularly at subduction zones (*Beroza and Ide*, 2011; *Gomberg et al.*, 2010; *Peng and Gomberg*, 2010; *Rogers and Dragert*, 2003; *Schwartz and Rokosky*, 2007) and are an essential component in understanding the earthquake cycle. However, the dynamics of earthquakes and slow slip events near the stability transition are not fully understood.

A specific observation with complex intervals occurred along the deep San Andreas Fault near Parkfield (*Shelly*, 2010b); these may be the only known natural observation showing period-doubling slip behavior. The Parkfield tremors oscillated between three and six days from mid-2003 for one and half years until the 2004 Mw=6.0 Parkfield earthquake. Following the 2004 earthquake, the recurrence times of the tremor source were disrupted. The physical mechanism that causes the tremor source to undergo this particular pattern is not fully known.

Complex slip events between stable creeping and unstable regimes are observed in rock friction exper-

iments (*Gu and Wong*, 1992, 1994; *Leeman et al.*, 2016; *Mclaskey and Yamashita*, 2017; *Scholz et al.*, 1972; *Scuderi et al.*, 2016; *Weeks and Tullis*, 1985; *Wong et al.*, 1992), and in numerical studies (*Erickson et al.*, 2008; *Huang and Turcotte*, 1990; *Rice*, 1993; *Ruina*, 1983). However, how the stability transition is controlled by physical parameters in laboratory and numerical experiments is not fully understood. Rock friction studies (*Leeman et al.*, 2015, 2016; *Scuderi et al.*, 2016) report separate stability regimes with slow slip, intermediate slow slip, and fast slip behavior. A recent study by *Mclaskey and Yamashita* (2017) shows slow and fast events using a granite sample, however, the results were obtained by changing the loading conditions during the experiment. The precise transition from slow to fast slip in laboratory samples under constant loading has not yet been investigated.

Recognising the above unknowns, I formulate the following scientific questions:

1.3 Specific scientific problems

1. What is the parameter space that enables complex slip behavior? In particular, what happens near the boundary between aseismic slip and seismic slip? Are there any peculiar slip instabilities near the transition?
2. What drove the complex three- and six-day intervals of the Parkfield tremors? How did the 2004 Mw=6.0 earthquake affect the tremor pattern? What is the mechanism behind the divergence in the number of low frequency events?
3. Can we reproduce the sequence of alternating slow and fast slip instabilities in a controlled laboratory setting? Does the alternating behavior in laboratory and numerical experiments exhibit a similar pattern? What is the meaning of such complex events in the context of recently observed aseismic slip transients within the mainshock region?

1.4 Significance

We show that a simple fault system can break in a range of different ways under specific conditions. Such fundamental work utilising a simple system with a combination of numerical simulations and laboratory experiments is critical to translate theoretical understanding of rock mechanics to slip observations on natural faults. In this thesis, I show that a unified view incorporating a variety of slip behaviors including slow earthquakes is essential for understanding earthquake physics.

1.5 Thesis overview

Using laboratory and numerical methods, I aim to address specific scientific questions (section 1.3) on overlapping slow and fast slip systems near the critical stability. Not much is known about the dynamics of faults that undergo dual modes of deformation. Seismological and geodetic observations report evidence of slow and fast slip in the same region; this study is an attempt to reproduce such phenomena in a laboratory sample and in a numerical setup to shed light on a range of enigmatic observations.

In Chapter 2, I simulate alternating slow and fast slip using rate-and state-dependent friction law with a three-dimensional boundary integral method. The slow-fast phenomenon occurs for the following combination of parameters: aspect ratio = 1 (square), asperity size = 3 m, nucleation size = 1.74 m, ratio of friction parameter = 0.7, loading rate = 3 cm/yr, and Poisson's ratio = 0.25. I explore the sensitivity of the system to the frictional parameters a/b , characteristic weakening distance L , and effective normal stress $\bar{\sigma}$. I apply this model of alternating slow and fast ruptures to explain the period-doubling Parkfield tremors. The parts of a fault that are thought to be moving slowly can no longer be viewed as safe; they can still break in a great earthquake. In Chapter 3, I investigate the role of several key parameters related to slow and fast slip instabilities using numerical models. I look into the sensitivity of a fault patch under several conditions to see how the slip instabilities vary in conjugation with small changes in the extrinsic and intrinsic fault parameters. In Chapter 4, I focus on producing slow and fast slip instabilities in granular quartz samples in the laboratory. The slow-fast phenomenon happens at a constant normal stress (23 MPa) and loading rate (10 $\mu\text{m/s}$). I report the effect of stiffness ratio on the slow and fast slip instabilities

entrenched between the entirely slow and fully dynamic regimes. Finally, in Chapter 5, I synthesize these contributions to shed light on the importance of slow and fast slip instabilities on natural observations, and also discuss plans for future endeavors.

My main contributions are in producing overlapping slow and fast slip in numerical simulations, replicating the same phenomena in laboratory samples, and applying this to explain the natural observation of the period-doubling Parkfield tremors. I also discuss two key bifurcations that distinguish standalone quasiperiodic slow slip from bimodal slow-fast ruptures. I hope that the scientific community will encourage similar studies that combine laboratory and numerical experiments with the goal of better understanding the natural observations.

Chapter 2

The Parkfield tremors reveal slow and fast ruptures on the same asperity

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Abstract

The deep extension of the San Andreas Fault is believed to be creeping, but the recent observations of tectonic tremors from these depths indicate a complex deformation style (*Shelly*, 2010a). In particular, an isolated tremor source near Parkfield produces an intriguing sequence of low-frequency earthquakes (LFEs) (*Shelly*, 2010b), indicating an uncommon mechanism of stress accumulation and release. The tremor pattern was regularly oscillating from mid-2003 until it was disrupted by the 2004 Mw=6.0 Parkfield earthquake. After that event, the tremor source ruptured every about three days only, but it gradually returned to its initial alternating recurrence pattern after two years. The mechanism that drives the tremor source to form this peculiar recurrence pattern is unknown. Here, we use physics-based models to show that the same tremor asperity can regularly slip in slow and fast ruptures, naturally resulting in recurrence intervals alternating between three and six days. This unusual slip behavior occurs when the tremor asperity size is close to the critical nucleation size of earthquakes. We also show that changes in pore-pressure following the Parkfield earthquake can explain the sudden change and gradual recovery of the recurrence intervals. Our findings provide a background to understand fault deformation where the same asperity can release tectonic stress through both slow and fast ruptures.

2.1 Introduction

The San Andreas Fault is one of the few strike-slip faults in the world where tectonic tremors are observed, and they emanate from its predominantly creeping depths (Fig. 2.1). Particularly, near Parkfield an isolated tremor source exhibits a striking pattern of recurrence intervals, radiating bursts of LFEs alternately about every three and six days (Fig. 2.2a and b). This doubling of recurrence intervals is technically referred to as period doubling, and it is generally a sign of the nonlinear dynamics of the mechanical system. A single tremor asperity on a fault isolated from other tremors (*Shelly, 2010b, 2015*) producing doubled recurrence intervals under constant loading is a peculiar phenomenon that challenges our basic assumptions about how the deep extension of faults deform to release tectonic stress.

The Parkfield tremors may be the best-observed manifestation of period doubling of seismic events in a tectonic setting (Fig. 2.2a and b). This pattern began in mid-2003 and was sustained for about eighteen months until the nearby 2004 Mw=6.0 Parkfield earthquake disrupted the tremor recurrence intervals. The Parkfield earthquake introduced overall shorter recurrence intervals and the initial alternating recurrence pattern was recovered after two years, indicating a great sensitivity and a long-lasting response of the tremor source to nearby stress perturbations. The source characteristics of the tremors (the number of LFEs per burst and their amplitude (*Shelly, 2010b*)) can be separated into two types of events based on their recurrence intervals throughout the entire sequence, despite the perturbation (Fig. 2.2a and b). Simulating the recurrence times and rupture characteristics of earthquakes is an over-arching goal of earthquake science, which represents a significant challenge. In this study, we focus on explaining the general recurrence patterns of the Parkfield tremors. We then discuss the implications on the possible micro-mechanics of LFE generation.

Tremors are generally understood as the seismic manifestation of underlying slow-slip events promoting the rapid failure of micro-asperities (*Daub et al., 2011; Ghosh et al., 2012; Ito et al., 2007; Schwartz and Rokosky, 2007*), however the specific features of the Parkfield tremors still elude explanations. Slow slip may be an important component of the underlying mechanism, but invoking events with regular slip is insufficient to explain the period-doubling pattern and the systematic changes in source characteristics of the Parkfield tremors. The period-doubling tremor source may represent the closest observation to the natural response of faults at lower-crustal conditions because of its isolation from other tremors. Hints that period doubling can be the natural response of a single patch are found in analogue experiments, where this phenomenon occurs during short-lived transients (*Gu and Wong,*

Figure 2.1: The Parkfield tremors. **(a)** Seismicity map near the Parkfield segment of the San Andreas Fault with tremors from (Shelly and Hardebeck, 2010) (orange circles) and seismicity from the NCEDC catalogue from 2000 to 2004 (gray dots). The red star shows the hypocenter of the 2004 Mw=6.0 Parkfield earthquake. The period-doubling tremor source (red circle) emits bursts of LFEs alternately every about three and six days (inset). **(b)** Fault-parallel cross section of seismicity. The period-doubling tremor source is around 30 km depth, in the creeping zone, below the locked Cholame segment. The slip distribution of the Parkfield earthquake from Barbot *et al.* (2012) is shown with 10 cm contour. The Moho depth is from Tape *et al.* (2012).

1994). But as of now, no consensus exist regarding the mechanism that can explain the recurrence interval pattern of the Parkfield tremors.

Here, we present a self-consistent numerical model with hundreds of slip cycles in a single simulation to explain the

Figure 2.2: Recurrence pattern and source characteristics of the period-doubling Parkfield tremors and numerical simulations. **(a)** Observed tremor recurrence pattern and number of LFEs per burst, from *Shelly* (2010b). Each tremor burst consists of 1 to 5 LFEs in most cases. Burst preceded by a shorter recurrence interval are associated with more LFEs throughout the sequence (consecutive bursts are connected with a gray line). The regular oscillation of recurrence intervals between about three and six days is from mid-2003 to the onset of the 2004 Parkfield earthquake. The sudden disappearance of the 6-day recurrence intervals coincides with the 2004 Parkfield earthquake. The gradual recovery of recurrence intervals is from the onset of the Parkfield earthquake to the end of 2007, around two years. **(b)** Characterization of the dynamics of the slip events driving the tremors. Most events falling on the equal pre- and post-intervals occur at the onset of the 2004 Parkfield earthquake, when period doubling is momentarily interrupted. **(c)** Numerical simulation of the Parkfield tremor activity incorporating a change in effective confining pressure (red profile) after the Parkfield earthquake. The colored circles denote slip of events. Fast ruptures have larger slip and are preceded by shorter recurrence intervals. **(d)** Characterization of the dynamics of the slip events from numerical simulations. The larger (smaller) slip of the fast (slow) ruptures is preserved after the perturbation of the Parkfield earthquake.

period-doubling of the Parkfield tremors and their change in behavior upon the perturbation by the 2004 Parkfield earthquake. We use a three-dimensional model based on rate- and state-dependent friction, a constitutive law that is adequate to represent frictional resistance at low speed and short seismic slip distance (*Dieterich*, 1979; *Lapusta and Barbot*, 2012; *Scholz*, 1998). The model incorporates all stages of earthquake dynamics, including the nucleation, propagation and termination of slip events, and the radiation of seismic waves in the surrounding rocks (*Barbot et al.*, 2012; *Noda and Lapusta*, 2010). We consider a strike-slip fault segment embedded in an elastic medium, incorporating a homogeneous patch that promotes unstable slip surrounded by a region supporting stable slip, the whole system being driven at a constant plate rate at the boundaries (Fig. S2.1a, 2.2c). The recurrence

pattern of the Parkfield tremors is assumed to be due to the spontaneous response of a single patch, as opposed to the complex interactions of adjacent patches. We model the dynamics of the system assuming that the LFEs emanate from micro-asperities scattered in the source region that are triggered during slip episodes, even though these micro-asperities are not explicitly included (Fig. 2.2c and d).

2.2 The mechanism behind the period-doubling Parkfield tremors before the 2004 Mw=6.0 earthquake

To explain the period-doubling pattern before the 2004 Parkfield earthquake, we use geometrical and frictional parameters that produce slow and fast ruptures on a single asperity. Slow and fast ruptures with less and more slip can emerge spontaneously (Fig. 2.2c, S2.2c) when the asperity size R is close to the theoretical nucleation size h^* , a parameter that depends on friction properties and effective confining stress and that describes the minimum patch size to produce a seismic rupture (*Rubin and Ampuero, 2005*). Specifically, for $R = 3$ m and $h^* = 1.74$ m, the fault patch fully ruptures in a period-doubling sequence every three and six days, before the perturbation brought by the 2004 Parkfield earthquake (Fig. S2.1, 2.2c). This is in contrast with previous studies (*Barbot et al., 2012; Liu and Rice, 2007; Matsuzawa et al., 2010; Noda and Hori, 2014*) where complex interseismic behavior was only observed at the boundary of velocity-weakening regions, leaving the conditions for rupture of the entire asperity with period doubling unidentified. Our model shows less variability in recurrence intervals than in the observations, presumably due to its overly simple design. Among many unknowns, the geometry of the tremor source and the distribution of frictional parameters may be more complex than we assume. Yet, data and model are sufficiently close to demonstrate the likelihood of a fault deformation where the tectonic stress is released in alternating events with less and more slip on the same patch to result in doubling recurrence intervals. If such behavior can be reproduced with a relatively simple setup, it is likely to occur spontaneously in nature.

Our numerical investigations indicate that period doubling can occur on faults of virtually any size (Fig. S2.4). The period doubling occurs on a wider range of parameters on elongated asperities (Fig. S2.5), which may be more frequent than circular or square ones in nature. However, reproducing the three and six days recurrence intervals of the Parkfield tremors requires near-lithostatic pore pressure, in agreement with observations suggesting high sensitivity of tremors to tidal stress and remote triggering (*Ide, 2010; Peng et al., 2008; Rubinstein et al., 2007; Thomas et al., 2009*). We can reproduce the three and six day recurrence pattern only if the effective confining pressure (the difference between lithostatic stress and pore pressure through a coupling coefficient, $\bar{\sigma} = \sigma - \alpha p$) is

lower than 50 MPa. For example, with a confining pressure of 5 MPa the asperity size is $R = 33$ m and the slip events have a moment magnitude close to 1 (Fig. S2.3); for a confining pressure of 50 MPa the asperity size is $R = 3$ m and it produces slip events of moment magnitude below 0 (Fig. 2.2c and d). Currently, there is no direct estimate of the moment magnitude of the Parkfield tremors. Given the advanced and highly tuned techniques used to separate them from seismic noise (Shelly, 2010b, 2015), it is possible that their magnitude is in the range of our models.

2.3 The mechanism behind the postseismic transient

The tremor sequence contains a two-year transient following the 2004 Mw=6.0 Parkfield earthquake that provides an opportunity to test the model with perturbations. The sudden disappearance of the six-day recurrence intervals and period multiplying after the Parkfield earthquake are likely due to changes in normal stress. The effect is two fold: a sudden pore-pressure increase causes a rapid fire of slip events with shorter recurrence intervals (this is the direct, triggering effect); but this change in normal stress places the patch firmly in the sub-critical regime promoting a sequence of slow slip events (Fig. 2.2c and d). The two-year transient can be explained by a decay of the pore-pressure anomaly, during which the fault patch slips in more complex sequences, before returning to a pattern close to the pre-earthquake one after two years (Fig. 2.2c). The amplitude and the time scale of the pore-pressure evolution control the degree of perturbation of the recurrence intervals during the transient and we choose these values by trial and error to best reproduce the observations. The differences between our models and the original observations are likely due to our simplifying assumptions or missing events due to the difficulty of detection, but it is striking that the number of LFEs and modeled slip events are persistent and follow the same pattern before and after the Parkfield perturbation (Fig. 2.2, S2.2).

The postseismic transient of the Parkfield tremors, with the temporary suppression of period doubling, is qualitatively well reproduced assuming the temporal decay of a positive pore pressure perturbation representing about 6% of the background confining pressure (Fig. 2.2c). This denotes either a pore fluid diffusion or the damage and recovery of the solid matrix (the pore pressure is related to the fault normal stress through the effective stress coefficient α of order 1). If the background pore pressure is close to the lithostatic stress (about 1 GPa at 30 km depth), only a few tenths of a percent change in the coefficient of effective stress is sufficient to explain the transient. This is a plausible scenario, as the 2004 Parkfield earthquake did induce a change of shear wave velocity of this order of magnitude in the ambient rocks (Brenguier *et al.*, 2008) (see supplementary material).

2.4 A first order explanation for the generation of low-frequency earthquakes

Equipped with a model that can explain the main features of the Parkfield tremor recurrence patterns, we discuss implications on the mechanics of LFEs at smaller spatial scales than our models can resolve numerically (Fig. 2.3). As slip of fast ruptures is about twice that of slow ruptures (Fig. 2.2, S2.2), the micro-asperities may break more often in this case. But it is unclear whether the observed larger number of LFEs in fast ruptures results from a single micro-asperity rupturing multiple times or from several micro-asperities rupturing sequentially. Every modeled event lasts much shorter than the LFE bursts. And every fast rupture is elasto-dynamic in our simulations and therefore may be detected seismically.

It is possible that LFE generation continues after the underlying slip event and that the fast ruptures represent one of the detected LFEs. Alternatively, the underlying slip event may never reach seismic speed, as would be possible with dilatancy (*Segall et al.*, 2010), or other additions to the rate-and-state friction framework (*Rubin*, 2011) not accounted for in our simulations. A remaining puzzling observation is the lower amplitude of those tremor comprised of many LFEs. If the area of rupture of micro-asperities varies between slow and fast events due to the unusual loading conditions, it may lead to the observed variability in amplitude.

2.5 Conclusions

Our interpretation of the underlying mechanism behind the Parkfield tremors is supported by observations that span hundreds of tremor cycles, an observation window that is not available for great and giant earthquakes. If the mechanism driving sequences of slow and fast ruptures of the same overall patch were behind tremors and earthquakes alike, our results would imply that the occurrence of isolated slow-slip episodes might not necessarily indicate a reduced seismic hazard, as an earthquake could rupture subsequently at the same location.

The 2011 Mw=9.1 Tohoku-Oki and the 2014 Mw=8.1 Iquique earthquakes may have been preceded by slow-slip events with significant overlap with the main rupture (*Ito et al.*, 2013; *Meng et al.*, 2015), contradicting our general expectations about fault behavior. It is possible that, like for the Parkfield tremors, this succession of events is promoted by a particular combination of geometric and frictional properties of the seismogenic zone and its surroundings.

Figure 2.3: The modeled mechanics behind the period-doubling tremors. **(a)** The tremor source slips in successions of slow and fast ruptures resulting in two intrinsic recurrence intervals. Fast ruptures produce large slip and results in many LFEs and are followed by a six-day locked period. Slow ruptures produce less slip and results in a fewer LFEs, and are followed by a three-day locked period. The full cycle repeats every about nine days. **(b)** Slip-deficit evolution with a time-predictable sequence of slip events. **(c)** Phase diagrams of period-doubling cycles with slow and fast ruptures. The slip, frictional resistance, and slip velocity are for the center of the patch.

2.6 Supplementary material

2.6.1 Simulating the Parkfield tremors

The Parkfield tremors, with their unusual recurrence interval pattern, occurred on the San Andreas Fault at around 30 km depth (*Shelly, 2010b*). Here, we describe our methodology to simulate this behavior using a three-dimensional fully dynamic model based on the rate-and state-friction law (*Lapusta and Liu, 2009; Noda and Lapusta, 2010*).

We use the BICycle (Boundary Integral Cycle of Earthquakes) program, a boundary-integral method to simulate fault slip evolution during all stages of the earthquake cycle, including the nucleation, propagation, and termination

of aseismic and seismic events (*Lapusta and Liu, 2009; Noda and Lapusta, 2010*). The method has been under the SCEC/USGS rupture code verification exercise (30). The model has been used to understand the sequence of the Mw=6.0 earthquakes on the Parkfield segment of the San Andreas Fault (*Barbot et al., 2012*), as well as nearby repeating earthquakes (*Chen and Lapusta, 2009*), and to study the segmentation of subduction-zone earthquakes (*Kaneko et al., 2010*).

Figure S2.1: Numerical model of the Parkfield tremors. **(a)** Schematic diagram of the model geometry and frictional properties. A square velocity-weakening patch is embedded in a large velocity-strengthening fault domain. R is the asperity size of the patch. The entire fault domain is driven by a plate rate of $V_L = 3\text{ cm/yr}$. h^* is the minimum size of the velocity-weakening patch to generate elasto-dynamic slip. We use the ratio $R/h^* = 1.72$. The model has $R = 3\text{ m}$, and $L = 5\text{ }\mu\text{m}$ and an effective confining pressure of $\bar{\sigma} = 50\text{ MPa}$, but period-doubling recurrence intervals at three and six days can be obtained for various asperity sizes, as discussed in the text. **(b)** The square patch produces a succession of slow and fast ruptures. Fast ruptures may be detected in seismograms and may coincide with one of the LFEs. The model reproduces the period-doubling recurrence pattern of the Parkfield tremors before the 2004 Parkfield earthquake.

2.6.2 Methods

Our model explains the period doublings and halvings with recurrence intervals of three and six days, and the postseismic transient. Our model has a strike-slip fault segment surrounded by an elastic medium, driven by long-term slip velocity. The model has a single asperity at the center with homogenous frictional property. This model is based on the rate- and state-dependent friction law derived from laboratory experiments (*Dieterich, 1979; Marone, 1998; Rice, 1983; Ruina, 1983*):

$$\tau = \mu \bar{\sigma} = \left[\mu_0 + a \ln \left(\frac{V}{V_0} \right) + b \ln \left(\frac{\theta V_0}{L} \right) \right] \bar{\sigma} \quad (2.1)$$

where μ is the coefficient of friction, $\bar{\sigma} = \sigma - \alpha p$ is the effective confining pressure including the pore pressure through the coefficient of effective stress α , $\bar{\sigma}$ is the lithostatic stress, μ_0 is the steady-state friction parameter at reference slip velocity V_0 , a and b are frictional parameters, L is the characteristic weakening distance, and θ is the

Figure S2.2: Recurrence pattern and source characteristics of the period-doubling Parkfield tremors and numerical simulations. **(a)** Observed tremor recurrence pattern and number of LFEs per burst, modified from Shelly (2010b). Each tremor burst consists of 1 to 5 LFEs in most cases. Burst preceded by a shorter recurrence interval are associated with more LFEs throughout the sequence (consecutive bursts are connected with a gray line). The regular oscillation of recurrence intervals between about three and six days is from mid-2003 to the onset of the 2004 Parkfield earthquake. The sudden disappearance of the 6-day recurrence intervals coincides with the 2004 Parkfield earthquake. The gradual recovery of recurrence intervals is from the onset of the Parkfield earthquake to the end of 2007, around two years. **(b)** Characterization of the dynamics of the slip events driving the tremors. Most events falling on the equal pre- and post-intervals occur at the onset of the 2004 Parkfield earthquake, when period doubling is momentarily interrupted. **(c)** Numerical simulation of the Parkfield tremor activity incorporating a change in effective confining pressure (red profile) after the Parkfield earthquake. The colored circles denote the maximum velocity of the slip events. Fast ruptures are preceded by shorter recurrence intervals. The 2004 Parkfield earthquake results in a rapid occurrence of slip events, followed by a sequence of multiplets with varying period-multiplying factors. **(d)** Characterization of the dynamics of the slip events from numerical simulations. The effective pore-pressure perturbation following the Parkfield earthquake affects the dynamics of the sequence with a momentary interruption of period doubling. The postseismic transient is characterized by an evolution of the recurrence intervals from equal pre- and post-intervals back to period doubling.

state variable representing the breaking and the healing of asperities. The state evolution can be described using the ageing law (Dieterich, 1979):

$$\dot{\theta} = 1 - \frac{V\theta}{L} \quad (2.2)$$

We may write the fault strength at steady state as

$$\tau_{ss} = \left[\mu_0 + (a - b) \ln \left(\frac{V}{V_0} \right) \right] \bar{\sigma}, \quad (2.3)$$

where $(a - b)$ affects the dynamics and style of faulting (*Dieterich, 2007; Marone, 1998; Rice, 1983; Ruina, 1983; Scholz, 1998*). We assign $(a-b) < 0$ in the velocity-weakening asperity, and $(a-b) > 0$ for the rest of the fault region (Fig. S2.1a). The slip dynamics is also controlled by the nucleation size (*Beeler et al., 2013; Chen and Lapusta, 2009; Dieterich, 2007, 1979; Marone and Kilgore, 1993; Marone, 1998; Rice, 1983; Rice and Ben-Zion, 1996; Rice et al., 2001; Ruina, 1983*):

$$h^* = \frac{\pi}{2} \frac{G b L}{(b - a)^2 \bar{\sigma}} \quad (2.4)$$

where G is the rigidity. Depending on the ratio of the nucleation size to the asperity size, creep, slow-slip events, bilateral ruptures and unilateral ruptures can be simulated.

In our model, we use a square asperity with homogenous velocity-weakening property surrounded by a velocity-strengthening region in an elastic space, loaded by a constant plate rate of $V_L = 3$ cm/yr. Other asperity geometries can also reproduce the period-doubling behavior, so the choice of a square asperity is for convenience only.

We assume that the seismic emissions of the tremors are caused by slip on micro-asperities due to slip events on a single, much larger, asperity with homogenous frictional properties (*Daub et al., 2011; Ghosh et al., 2012; Peng et al., 2009; Schwartz and Rokosky, 2007*) (Fig. 2.3). We did not explicitly incorporate the micro-asperities in our model. We assume that the period doubling is caused by a succession of slow and fast ruptures with smaller and larger slip on the same asperity. Here, we assume that any rupture that results in a slip rate greater than a threshold value ($V_{th} = 10^{-4}$ m/s) produces low-frequency earthquakes (LFEs). The threshold velocity is chosen to be lower than the maximum velocity of slow and fast ruptures, yet significantly larger than plate rate.

2.6.3 Model parameters

Here, we present two end-member models with a single square-shaped homogenous velocity-weakening asperity. With a dimensionless ratio $R/h^* = 1.72$ (for an asperity size $R = 3$ m), and R/h^* (for an asperity size, $R = 33$ m), we simulate the sustained cycles of period doublings and halvings of the Parkfield tremors with recurrence intervals of about three and six days (Fig. S2.2c and Fig. S2.3a). In the limit of a relatively large confining pressure of $\bar{\sigma} = 5$ MPa, the parameters of the first end-member model are $R = 3$ m, $L = 5$ μ m, $h^* = 1.74$ m, $a = 10^{-2}$, $b_{vs} = 6 \times 10^{-3}$, $b_{vw} = 14 \times 10^{-3}$, $\mu_0 = 0.65$, and $G = 30$ GPa. The model parameters of the second end member, for a lower effective confining pressure, are $\bar{\sigma} = 5$ MPa, $R = 33$ m, $L = 5$ μ m, $h^* = 17.4$ m, $a = 10^{-2}$, $b_{vs} = 6 \times 10^{-3}$, $b_{vw} = 14 \times 10^{-3}$, $\mu_0 = 0.65$, and $G = 30$ GPa.

Figure S2.3: Simulation of the recurrence intervals of the period-doubling Parkfield tremors in a larger slip patch with $R = 33$ m and $\bar{\sigma} = 5$ MPa. **(a)** Numerical simulation of the Parkfield tremor activity incorporating the change in effective confining pressure (red profile) after the Parkfield earthquake. The colored dots denote the maximum velocity of the slip events. The slip events are flagged when the slip velocity is above the threshold $V_{th} = 10^{-4}$ m/s anywhere along the fault. Fast ruptures are preceded by shorter recurrence intervals. A change of pore pressure of about 300 kPa, representing 6% of the effective confining pressure, is applied at the onset of the Parkfield earthquake, resulting in a rapid occurrence of slip events, followed by a sequence of multiplets with varying period-multiplying factors. The pressure perturbation is chosen by trial and error to create a two-year transient that is similar to the seismic observations. **(b)** Characterization of the dynamics of the slip events. Fast ruptures are preceded by shorter recurrence intervals. The effective pore-pressure perturbation following the Parkfield earthquake affects the dynamics of the sequence with a temporary interruption of period doubling followed by a gradual recovery.

In both cases the effective confining pressure implies pore pressure near lithostatic stress conditions, in agreement with the high sensitivity of tremors to tidal stress and remote triggering (*Ide, 2010; Noda and Lapusta, 2013; Peng et al., 2008; Rubinstein et al., 2007; Shelly et al., 2011; Thomas et al., 2012; Zigone et al., 2012*). For confining pressures lower than 5 MPa, our models produce period doubling, but not at three and six days. For confining pressures greater than 50 MPa, the size of the velocity-weakening patch must be reduced greatly, leading to smaller moment magnitudes of the slip events.

Given the complexity of rate-and-state friction faults and the large number of physical parameters, it is possible that period doubling can be obtained for other combinations of frictional parameters and fault geometry. So our proposed range of model parameters is simply to illustrate the non-uniqueness of the model.

Our slow ruptures do not exceed 10^{-3} m/s. The fast ruptures, however, reach up to 0.6 m/s for a short duration (Fig. S2.1b). Elasto-dynamic events occur when the slip velocities exceed the critical slip rate, in which the direct effect becomes negligible in comparison to the inertial effect (*Noda and Hori, 2014*):

$$V_{\text{dyn}} = 2V_s \frac{a\bar{\sigma}}{G}, \quad (2.5)$$

where V_s is the shear-wave speed (3000 m/s). Fast ruptures are elasto-dynamic and may be detected in seismograms as one of the LFEs.

2.6.4 Effect of geometry and friction properties on slip stability

We simulate period-doubling sequences of slow and fast ruptures along at least eight orders of moment magnitude. We increase the size of a square asperity as well as the fault dimension accordingly, and keep the dimensionless ratio $R/h^* = 1.72$ the same in all simulations. We obtain period-doubling sequences in asperities of different sizes, such as 6 m, 60 m, 600 m and 6 km, indicating that the period-doubling phenomenon is self-similar and scale independent (Fig. S2.4). We obtain pairs of slow and fast ruptures with equivalent geodetic moments of $M_w = -1.9$ and $M_w = -0.5$, respectively, for a square asperity with $R = 3$ m and $L = 5$ μm (Fig. S2.4a). The magnitudes are $M_w = 0.07$ and $M_w = 1.4$ for $R = 30$ m and $L = 0.05$ mm (Fig. S2.4b). For $R = 300$ m and $L = 0.5$ mm, we obtain magnitudes of $M_w = 2.1$ and $M_w = 3.5$ (Fig. S2.4c). Finally, we get $M_w = 3.9$ and $M_w = 5.4$ for $R = 3$ km and $L = 5$ mm (Fig. S2.4d). We assume the same rheological parameters of $\bar{\sigma} = 50$ MPa, $a = 10^{-2}$, the velocity-weakening regions with $(a - b) = -4 \times 10^{-3}$ and the velocity-strengthening region with $(a - b) = +4 \times 10^{-3}$, except for the characteristic length L , which is used to adjust the ratio $R/h^* = 1.72$ within

Figure S2.4: Simulations of period-doubling sequences of slow and fast ruptures along eight orders of magnitude. All simulations assume the same rheological parameters except for the characteristic weakening distance L , which is used to adjust the ratio R/h^* to with in the period-doubling range. **(a)** With $R = 3$ m and $L = 5$ μ m, we obtained slow and fast ruptures with an equivalent geodetic moment of $M_w = -1.9$ and $M_w = -0.5$, **(b)** With $R = 30$ m and $L = 0.05$ mm, the range is $M_w = 0.07$ and $M_w = 1.4$, **(c)** For $R = 300$ m and $L = 0.5$ mm, the range is $M_w = 2.1$ and $M_w = 3.5$ and **(d)** For $R = 3$ km and $L = 5$ mm, the range is $M_w = 3.9$ and $M_w = 5.4$. Square patches of velocity-weakening friction with different sizes may exhibit period doubling virtually at all magnitudes. The blue lines are aseismic and the red lines are seismic.

the period-doubling range in all simulations. These explorations suggest that velocity-weakening friction assigned in a square asperity with different sizes may exhibit period doubling virtually at all magnitudes.

Non-circular asperities have more potential in producing sequences of period doubling slow and fast ruptures (Fig. S2.5). Velocity-weakening asperities with elliptical shapes promote period-doubling events compared to a circular

asperity, indicating that the geometry of the velocity-weakening asperity is important in enabling period-doubling events. In these experiments, we keep the nucleation size h^* constant, and change the shape of the asperity. The parameters considered here are: $\bar{\sigma} = 50$ MPa, $a = 10^{-2}$, $L = 5$ μm . The velocity-weakening regions and the velocity-strengthening regions are characterized by $(a - b) = -4 \times 10^{-3}$ and $(a - b) = +4 \times 10^{-3}$ respectively. We assume the same frictional parameters and confining pressure in all simulations. With this choice of parameters, the non-circular asperities produce period-doubling events while the circular patch does not.

Figure S2.5: Potential of non-circular shaped asperities to produce complex sequences of slow and fast ruptures with period doubling. The left figures (a and c) show velocity-weakening (VW) patches with two different shapes. The right figures (b and d) show the corresponding history of the period separating each event. For both simulations, we assume the same frictional parameters and confining pressure. Elliptical (and potentially other non-circular) patches can produce period doubling in a wider range of parameters than for a circular asperity. With the parameters considered, the non-circular asperities produce period doubling of recurrence time, but the circular patch does not. The parameters considered are 50 MPa, $a = 10^{-2}$, $L = 5$ μm , and the velocity-weakening regions are characterized by $(a - b) = -4 \times 10^{-3}$, while the velocity-strengthening regions have $(a - b) = +4 \times 10^{-3}$. Slip events (seismic and aseismic) are singled out when the slip velocity threshold reaches the value $V_{\text{th}} = 10^{-4}$ m/s.

2.6.5 Modeling pore-pressure changes following the 2004 Mw=6.0 Parkfield earthquake

We model the effect of pore pressure evolution numerically using a diffusion model. We use the approach of (Noda and Lapusta, 2010, 2013) to model thermal pressurization. We ignore the shear heating effects and only allow

diffusion of external pore pressure perturbations applied at prescribed times. The pore-pressure perturbation Δp follows the diffusion equation:

$$\dot{\Delta p} = \alpha_{\text{hy}} \nabla^2 \Delta p, \quad t > t^{\text{eq}}, \quad (2.6)$$

where α_{hy} is the hydraulic diffusivity, with the conditions $\Delta p(t < t^{\text{eq}}) = 0$ and $\Delta p(t^{\text{eq}})$ given. The amplitude of the pore pressure perturbation and the hydraulic diffusivity affect the dynamics of the transient and they are chosen by trial and error to best reproduce the seismic observations. We use a pore pressure perturbation of $\Delta p(t^{\text{eq}}) = 3 \text{ MPa}$ for the model with $R = 3 \text{ m}$ and $\bar{\sigma} = 50 \text{ MPa}$, and $\Delta p(t^{\text{eq}}) = 300 \text{ kPa}$ for the model with $R = 33 \text{ m}$ and $\bar{\sigma} = 5 \text{ MPa}$. In both cases, the pore pressure perturbation represents about 6% of the background effective confining pressure. The change in effective confining pressure and its temporal decay can explain the postseismic transient following the 2004 Mw=6.0 Parkfield earthquake (Fig. 2.2c and d, Fig. S2.2c and d). The effective confining pressure influences the critical nucleation size (Eq. 2.4). Changes in the critical nucleation size can move the asperity to different stability regimes leading to different dynamics: An increase in pore pressure in the period-multiplying asperity fosters conditional stability and the occurrence of slow-slip events (shorter recurrence intervals); and a decrease in pore pressure promotes conditional instability and the occurrence of bilateral ruptures (longer recurrence intervals). The sudden termination of period doubling after the Parkfield earthquake can therefore be understood as a change of dynamics with a succession of slow-slip events. As the pore pressure perturbation decays, the stability regime converges towards the pre-earthquake conditions and period doubling with slow and fast ruptures is obtained again after a two-year transient.

The origin of the perturbation can be due to damage caused by the nearby earthquake or a direct pore-pressure change from the same. Our numerical simulations should be taken to describe a combined effect of damage evolution and pore pressure diffusion. The effective background confining pressure $\bar{\sigma} = \sigma - \alpha p$ depends on the pore pressure through the coefficient of effective stress α (dimensionless parameter of order 1), so both changes in pore pressure and in the effective coupling coefficient can affect the effective confining pressure. If a nearby earthquake compresses the solid matrix around the tremor source, it gives rise to a pore pressure change:

$$\Delta p = -\frac{B}{3} \Delta \sigma_{kk}, \quad (2.7)$$

where $\Delta \sigma_{kk}$ is the change in isotropic stress and B is the Skempton's coefficient. If damage is introduced and alters the mechanical coupling between the solid matrix and the pore fluids, the effective coupling coefficient is perturbed

by $\Delta\alpha$. Then, the new effective confining pressure becomes:

$$\bar{\sigma} = \sigma - (\alpha p + \alpha \Delta p + \Delta\alpha p + \Delta\alpha \Delta p) . \quad (2.8)$$

The higher-order term $\Delta\alpha \Delta p$ can be neglected. The other terms can be evaluated to establish the likely source mechanism of the perturbation.

First, we evaluate the change in pore pressure induced by the 2004 Mw=6.0 Parkfield earthquake using the coseismic slip distribution (*Barbot et al.*, 2012) and setting $B = 0.5$ for the Skempton's coefficient. We use the Relax program (*Barbot and Fialko*, 2010) to evaluate the coseismic isotropic stress in the bulk. We find that the 2004 Mw=6.0 Parkfield earthquake produced a direct change of pore pressure of the order of $\Delta p = 0.7$ kPa near the tremor source, a value much smaller than inferred from our model.

We then evaluate the contribution of damage as follows. At 30 km depth, over-pressurized fluids (pressure greater than hydrostatic equilibrium) are required to maintain a low effective confining pressure. Assuming $\bar{\sigma} = 50$ MPa and $\alpha = 1$, we get a pore pressure of the order of 800 MPa. In this context, perturbations of the coefficient of effective stress of a few tenth of a percent incur a change in effective confining pressure of the order of $\Delta\alpha p = 1$ MPa, a value in the middle range of our estimates ranging from 300 kPa to 3 MPa.

Given that the Parkfield earthquake was found to induce a shear velocity reduction in the ambient rocks of the order of 0.1% (*Brenguier et al.*, 2008), the effect of damage evolution may be more prevalent than the direct pore pressure change.

2.6.6 Implications for the physics of low-frequency emissions

The seismic observations show that most events preceded by a short recurrence interval contain more LFEs per burst (Fig. 2.2a). But the same events have overall less amplitude (*Shelly*, 2010b). The two characteristics are not straightforward to reconcile.

Our physics-based modeling suggests that the unique recurrence pattern of the LFEs at Parkfield may be due to forcing from underlying slip events. In this conception, the LFEs recurrence pattern mimics the behavior of the surrounding asperity. But the details of the mechanics of tremor emission are still poorly understood. Because of the difficulty of deciphering tremors from noise (*Shelly*, 2010a,b, 2015; *Shelly and Hardebeck*, 2010), some source characteristics such as cumulative moment, moment rate, or stress drop are still unavailable, leaving some aspects of the physical model unconstrained. In particular, it is unknown whether multiple LFEs in a single

tremor burst represent multiple emissions from a single micro-asperity or if the source consists of multiple micro-asperities breaking sequentially. The intrinsic response time of the micro-asperity under rapid loading is also poorly characterized, so it is unknown whether slip on micro-asperities is simultaneous to, or comes after the slip on the underlying patch.

Despite these difficulties, our model makes certain predictions that can be compared to the seismic record. First and foremost, the period-doubling model creates two types of events, i.e. the slow and fast ruptures, which are associated with different recurrence intervals. Similarly, the available tremors characteristics (number of LFEs per burst, and amplitude) also show two types of events, which can be separated based on the pre or post recurrence intervals (*Shelly, 2010b*). The modeled slip events cannot be the direct representation of the tremor generation process, but it still implies that LFEs are sensitive to the loading rate of the underlying patch.

Physical controls on the emergence of slow and fast slip sequences near the stability transition

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Abstract

The conditions for the nucleation and propagation of earthquakes have been studied extensively. Yet, how and why faults would rupture with a complex sequence of slow and fast ruptures has received relatively little attention. Here, we explore the physical conditions for a single asperity to develop sequences of slow and fast ruptures that break the entire velocity-weakening region. Using numerical simulations that resolve all phases of the seismic cycle, we explore key factors that promote this behavior, including the patch geometry (size, aspect ratio, and area), normalized slip-weakening region W/h^* , the ratio of frictional parameters a/b , the Poisson's ratio ν , and the loading rate V_L . For a Poisson's solid, slow and fast ruptures on a square or circular asperity can follow each other for a narrow range of $2.95 < W/h^* < 3.55$, assuming a fixed $a/b = 0.4$. For a fixed $W/h^* \sim 3.28$, period-doubling oscillations can be obtained for $0.35 < a/b < 0.5$. This parameter range corresponds to a bifurcation in phase space between periodic slow and periodic fast ruptures. Two different stability criteria occur for mode II and mode III ruptures, due to their different stiffness, modulated by

Poisson's ratio ν . We find that period-doubling cycles prevail for $\nu \geq 0.135$, but only single-periodic cycles occur for $\nu = 0$, for which the conditions for nucleation are identical for mode II and mode III. Period-doubling cycles may also result from large geometrical aspect ratios in the spatial distribution of frictional properties in the velocity-weakening region. However, the shape of the region alters other characteristics of the cycles, with elliptical or rectangle asperities producing period-doubling cycles of slow or fast ruptures with longer inter-event times as opposed to their symmetric counterparts. The recurrence time ratio within the bifurcation is a strong function of a/b and W/h^* , but is typically bounded between 1 and 2.6, the maximum recurrence time ratio across the bifurcation itself being a function of the loading velocity.

3.1 Introduction

Stick-slip instability is considered as a mechanism that generates earthquakes on faults (Brace and Byerlee, 1966). A zone of oscillating instabilities was first identified in friction experiments around four decades ago (Scholz, 1998; Scholz *et al.*, 1972) (Fig. 3.1b). Following that finding, a similar complex phenomenon has been observed in laboratory experiments (Gu and Wong, 1992, 1994; Ruina, 1980; Weeks and Tullis, 1985) and numerical simulations (Abe and Kato, 2013, 2014; Becker, 2000; Erickson *et al.*, 2008; Gu *et al.*, 1984; Gu and Wong, 1992, 1994; He *et al.*, 1998; Huang and Turcotte, 1990; Kato, 2003; Ma and He, 2001; Rice, 1993; Ruina, 1983; Veedu and Barbot, 2016). The zone demarks a transition between stable sliding (Fig. 3.1a) and unstable behavior (Fig. 3.1c). In the stability transition, the events occur with varying slip, slip rates, stress drops, and inter-event times. However, the extent of this stability transition is poorly known.

Slow slip events occurring around the point of critical stability were recorded in a series of laboratory experiments (Ikari *et al.*, 2013; Leeman *et al.*, 2015, 2016; Scuderi *et al.*, 2016). Numerical modeling studies (Liu and Rice, 2005, 2007; Segall *et al.*, 2010) also report slow slip transients. Yet, the nature and the variability of slip behaviors around the stability condition have not been characterized. The behavior of the system across the stability boundary can be explored numerically to inform further work in the laboratory and to extrapolate the parameters to natural faults.

The only known natural fault observations in which the style of rupture alternates persistently between 3 and 6 days (Shelly, 2010b) and 2 and 4 days (Shelly, 2017) are the Parkfield tremors along the San Andreas Fault. The Parkfield tremors may be just one type of oscillation within the theoretically identified stability transition, and

Figure 3.1: The stability transition is sandwiched between stable sliding and earthquake behavior. **(a)** Stable sliding with no slip events. Stable creep is the tendency of a fault to move extremely slow at the rate of tectonic plate velocity (a few cm/yr) without producing any slip events. **(b)** Periodic transients (self-sustaining oscillatory events) occur in between stable and unstable regimes (Scholz, 1998; Scholz *et al.*, 1972). **(c)** A series of stick-slip events (earthquakes) in a theoretical model. ‘Stick’ represents the quiet time between two earthquakes, and ‘slip’ means the movement of a fault during an earthquake.

there could be new types of behaviors within the transition. Numerical studies of brittle and ductile frictional strengths (Daub *et al.*, 2011) and slow and fast ruptures (Veedu and Barbot, 2016) explain the Parkfield tremor oscillations. Independent studies model slow and fast ruptures using multiple fault patches (Mitsui, 2018; Romanet *et al.*, 2018), focusing on the source processes, but not on the range of parameters that can affect the alternating events. A study by Kato (2003) explores the role of the normalized asperity radius on the repeating slip events using a circular asperity. However, the role of the ratio of frictional parameters a/b is not well documented.

Although there is ample evidence of oscillatory events in modeling studies and friction experiments, so why is it rare to make similar observations in a natural tectonic setting? The Parkfield tremors show the effect of the Mw=6.0 2004 earthquake on a fault patch, which disrupted the tremor intervals (Shelly, 2010b), pointing to the sensitivity of faults to external conditions. Apart from external conditions, like pore-fluid fluctuations, it is possible that a change in intrinsic factors (material properties a/b) could also move the fault patch in or out of the stability transition. The less frequent observations from natural faults make us hypothesize if particular conditions are required to produce such oscillations. We also assume that such behavior may be vulnerable to small changes in internal and external parameters.

As faults are prone to stress interactions and other external fluctuations simultaneously, it is necessary to study how a fault patch responds to several parameters using controlled experiments. Controlled experiments allow the testing of one parameter at a time to systematically understand what induces oscillations and also to pin down the exact parameters that can allow the fault patch to transit through the transition zone.

Changes in geometry and frictional parameters are known to affect fault dynamics (*Barbot et al.*, 2012; *Kaneko et al.*, 2010; *Lapusta and Liu*, 2009; *Noda and Hori*, 2014; *Noda and Lapusta*, 2010), however, their role in the stability transition or in the slow and fast slip instabilities is not thoroughly understood. Achieving uniform results in laboratory experiments is often challenging due to differences in materials, machines, and limited manpower, and there are constraints in a laboratory setup that restrict changing the patch geometry and applying a wide range of loading conditions. To circumvent these issues, we investigate the problem with numerical simulations. Since the stability transition includes fast events that in some cases generate seismic waves, we adopt a numerical method that includes wave-mediated stress transfer (*Lapusta and Liu*, 2009). Indeed, quasi-dynamic and full dynamic approaches are known to generate qualitatively similar slip patterns on faults with standard rate-and-state friction, but with quantitative differences, such as smaller stress drops, slower slip velocities, and slower rupture speeds during earthquakes (*Lapusta and Rice*, 2003; *Lapusta et al.*, 2000; *Thomas et al.*, 2010).

The main goal of this study is to understand the effects of several key parameters on slow and fast slip instabilities near the stability transition, by investigating the roles of geometric, frictional, and mechanical properties and the loading conditions on slip events. It is important to note that the term stability transition, used in this study, does not mean the spatial transition between a seismogenic zone and stably creeping zone. Moreover, the role of frictional heterogeneities within the asperity is not considered. In this study, we investigate: 1) the parameters that promote or inhibit oscillatory slip behavior, 2) the parameters that affect the peak recurrence time ratio, and 3) the factors that control the extent of the transition in parameter space, for example, the change in normal stress that is required to shift the fault patch from the stable to the unstable regime. Essentially, we aim to develop a better understanding of the factors that affect the oscillatory behavior of fault, which might reveal the processes that are intrinsic to natural faults.

3.2 Modeling fault slip

We model earthquakes and slow slip using the laboratory-derived rate-and state-dependent friction law (*Dieterich*, 1979; *Ruina*, 1983), Eqn.3.2, that has been used extensively to explain earthquake observations (*Barbot et al.*, 2012; *Tse and Rice*, 1986). In particular, rate-and-state friction has been useful to model the slow-slip phenomenon (*Liu and Rice*, 2005) and fast ruptures (*Jiang and Lapusta*, 2017). In an earthquake, a fault segment releases accumulated strain energy efficiently by slipping several meters per second. A slow slip event, on the other hand, is a fault movement that does not reach the fast slip regime. Instead of radiating significant energy, slow slip events exhibit

prolonged movement on fault segments for days, months, years, making it invisible to seismometers, but still detectable with geodetic instruments (*Hirose et al.*, 1999; *Ohta et al.*, 2006).

We use a three-dimensional fully dynamic boundary integral method (*Lapusta and Liu*, 2009) that implements the rate- and state-dependent friction law (*Dieterich*, 1979; *Ruina*, 1983) to simulate the long-term history of seismic and aseismic slip cycles. Rate- and state-dependent friction describes the velocity dependence and weakening and healing phases of friction evolution. The shear stress, τ , depends on the effective normal stress, $\bar{\sigma}$, through the consistency equation,

$$\tau = \mu \bar{\sigma} = \mu(\sigma - p), \quad (3.1)$$

where μ is the friction.

The rate- and state-dependent friction law assumes that frictional resistance depends not only just on the velocity of fault slip but also on the slip history. The state variable θ represents the evolution of the fault surface at the microscale (*Barbot*, 2019a). In the context of rate- and state- dependent friction, the friction coefficient μ varies with the logarithm of velocity of the fault slip and the logarithm of a state variable, θ , as:

$$\mu = \mu_0 + a \ln \left(\frac{V}{V_0} \right) + b \ln \left(\frac{V_0 \theta}{L} \right). \quad (3.2)$$

The state variable θ follows the ageing,

$$\dot{\theta} = 1 - \frac{V\theta}{L}. \quad (3.3)$$

The fault segment is embedded in an elastic medium, driven by long-term slip velocity, and has a single asperity with homogenous frictional properties. The model is capable of producing multiple stages of an earthquake cycle, from nucleation to rapid dynamic propagation, to postseismic slip, including aseismic transients. In all simulations, we ignore the first 10 events to get a representative behavior of the fault patch. The method may help us to explore the extents of the stability transition as well as to discover other slip behaviors. The numerical method facilitates the testing of several input parameters and helps to measure the output behavior of the system consistently, which may, in turn, help us to identify potentially new slip behaviors.

3.3 Defining the slow-fast slip phenomena (SFP)

We consider a reference slow-fast rupture sequence to compare with other slip behaviors that might occur within the stability transition (Fig. 3.2 and Fig. 3.3). We design a numerical experiment with the parameters shown in Fig. 3.2. We model a section of a fault plane with dimensions $24 \times 24 \text{ m}^2$. A circular region of radius $R = 3 \text{ m}$ is assigned

velocity-weakening properties with $a = 0.01$, $b = 0.025$, $\bar{\sigma} = 50$ MPa, $L = 45.8 \mu\text{m}$. The fault is loaded at the rate of $V_L = 10^{-9}$ m/s. The slip rate oscillates above and below the threshold velocity (0.1 m/s). We define this style of slip as the slow-fast slip phenomenon. The modeled slow and fast slip events have inter-event times of 22 and 8.5 days, with a recurrence time ratio (the ratio between time since previous event and time to the next event) of 2.6.

Theoretical studies indicate that the stability of such a system is controlled by several intrinsic length scales such as h_a^* , h_b^* , h_c^* , and h_d^* (Eqn. 3.4, 3.6, 3.7, and 3.8). For example, linear stability analysis (*Rice, 1993; Rice and Ruina, 1983; Ruina, 1983*) reports a critical wavelength, interpreted as nucleation size h_a^* , which includes the effect of the characteristic weakening distance L , the difference of friction parameters $(a - b)$, and the effective normal stress $\bar{\sigma}$:

$$h_a^* = \frac{2}{\pi} \frac{G^* L}{(b - a) \bar{\sigma}} \quad (3.4)$$

where G^* is the effective rigidity. Note that $G^* = G$ for mode III and

$$G^* = \frac{G}{1 - \nu} \quad (3.5)$$

for mode II, where G is the shear modulus and ν is the Poisson's ratio.

The size of the nucleation zone defined by *Dieterich (1994, 1992)* is:

$$h_b^* = \frac{G^* L}{b \bar{\sigma}} \quad (3.6)$$

Utilizing the energy balance for a quasi-statically extending crack, *Rubin and Ampuero (2005)* defines the size of the nucleation zone on finite faults for values of $a/b > 0.5$:

$$h_c^* = \frac{2}{\pi} \frac{G^* b L}{(b - a)^2 \bar{\sigma}} \quad (3.7)$$

Note that h_c^* is for two-dimensional problems. To consider the three-dimensional estimates, *Chen and Lapusta (2009)* uses a factor of $\pi^2/4$ with h_c^* and introduces the nucleation size as below :

$$h_d^* = \frac{\pi}{2} \frac{G^* b L}{(b - a)^2 \bar{\sigma}} \quad (3.8)$$

Given their important roles for stability, we expect that these length scales also control some aspects of the stability transition, however, in this study, we restrict the scope to the dependence of h^* (Section 3.4.2, Fig. 3.10) at a fixed slip-weakening region W .

$$h^* = \frac{GL}{(b - a) \bar{\sigma}} \quad (3.9)$$

Figure 3.2: The characteristics of the reference slow and fast slip instabilities. **(a)** Model geometry with reference parameters. **(b)** The cumulative slip along the strike direction of the fault shows slow and fast ruptures with magnitudes 0.39 and 0.55, respectively. **(c)** The slip rate of the slow and fast slip events from the center of the patch. **(d)** The evolution of shear stress of the slow-fast ruptures from the center of the patch. The model parameters of the reference slow-fast behavior are in the legend.

We also discuss the effect of geometry on the development of cycles with slow and fast ruptures, in particular, the asperity size, its aspect ratio, and the overall area. As the recurrence time of any instability is controlled at first order by the fault loading rate, we also investigate the effect of this parameter. Finally, we investigate the causative origin of period-doubling cycles, noting the different stability criteria for mode II and mode III ruptures modulated by Poisson's ratio. Overall, this constitutes a comprehensive set of parameters, which represents a substantial space to explore numerically. In the next section, we study the factors that promote or inhibit similar oscillatory ruptures, and then we investigate the role of nine key parameters on the extent of the stability transition that exhibits slow-fast ruptures.

Figure 3.3: Snapshots of slip rate distribution of a pair of consecutive slow and fast slip cycles. **(a)** The locked patch just before the initiation of the slow slip. **(b)** The slow slip starts, grows, and terminates. **(c)** The locked patch before the fast slip initiation. **(f)** Long nucleation phase before the fast rupture. **(g)** and **(h)** The fast rupture grows and terminates. The black color indicates a locked patch as the slip rate is below 10^{-12} m/s. The blue color shows slower rupture processes. The threshold slip velocity is 0.1 m/s for the fast events.

3.4 Factors promoting multiple rupture styles

3.4.1 The role of patch geometry (patch size, aspect ratio, and patch area) on the slow and fast alternating cycles

We first explore the effect of patch size, all other parameters being the same. Fault stability is controlled by the ratio of patch size to nucleation size, therefore, systematically enlarging the patch is an effective way to traverse the stability transition (Fig. 3.4a, c and e). At radius, $R = 2.5$ m, we find slow slip events with a recurrence interval of 7 days. Slow-slower oscillations with recurrence times of 8.5 and 12 days occur when $R = 2.8$ m. The patch slips slow and fast at $R = 3$ m with inter-event times of 8.5 and 22 days. The fast events cross the threshold slip velocity of 0.1 m/s whereas the slow events slip at a rate close to 10^{-6} m/s. This is an observation of the slow-fast slip phenomena. The recurrence times of slow and fast events alternate between two fixed intervals, e.g., 8.5 and 22 days, thus they are period-doubling cycles, but with slightly longer recurrence times than that of the slow-slower events.

The recurrence times of the events increase with the patch size, $R = W/2$, for circular patch (where, s is slip and W is the slip-weakening region):

$$T = \frac{s}{V_L} = \frac{(b-a)\bar{\sigma}}{G V_L} W \quad (3.10)$$

We then explore the role of asymmetry in the velocity-weakening asperity (Fig. 3.5a, c and e) in generating alternating events similar to Fig. 3.4d and f. With elliptical patches, we produce slow slip at $R_1 = 2.5$ m and $R_2 = 3$ m with an interval of 7 days; slow-slower oscillations at $R_1 = 2.5$ m and $R_2 = 3.136$ m with intervals of 8 and 15 days; slow-fast ruptures at $R_1 = 2.5$ m and $R_2 = 3.6$ m with intervals of 23 and 8 days. The slip styles and recurrence times are sensitive to the longest dimension.

Now, we focus on understanding how the peak recurrence time ratio of the reference slow-fast behavior varies upon changes in nine parameters: (i) slip-weakening region W , (ii) aspect ratio R_2/R_1 , (iii) patch area A , rate- and state-dependent parameters such as (iv) characteristic slip distance L , and friction parameters a and b in terms of (v) $(a-b)$ and (vi) a/b , (vii) effective normal stress $\bar{\sigma}$, (viii) the Poisson's ratio ν , and (ix) loading rate V_L . We explore if a small change in a input parameter results in a higher recurrence time ratio than the reference behavior. We use the slow and fast slip instabilities as the reference point (the model parameters are in the legend). Our immediate goal is to check the conditions for which the oscillatory expression deviates from the reference phenomena.

Figure 3.4: Inducing slow-fast events by increasing the patch size symmetrically (a) Model geometry with 2.5 m patch size. (b) A circular patch with radius $R = 2.5\text{ m}$ and area $A = 19.63\text{ m}^2$ produces slow-slip events with 7 days recurrence time. (c) Model geometry with 2.8 m patch size. (d) A circular patch with $R = 2.8\text{ m}$ and area $A = 24.62\text{ m}^2$ produces slow-slower events with 8.5 and 12 days recurrence time. (e) Model geometry with 3 m patch size. (f) A circular patch with radius $R = 3\text{ m}$ and area $A = 28.26\text{ m}^2$ produces slow and fast slip instabilities with 22 and 8.5 days recurrence time.

Figure 3.5: Generating slow-fast events by extending the patch size asymmetrically **(a)** Model geometry with $R_1 = R_2 = 2.5$ m and $R_2/R_1 = 1$. **(b)** A circular patch with radius $R_1 = R_2 = 2.5$ m, aspect ratio $R_2/R_1 = 1$, and area $A = 19.63$ m² produces slow-slip events with seven days recurrence time. **(c)** Model geometry with $R_1 = 2.5$ m, $R_2 = 3.136$ m, and $R_2/R_1 = 1.25$. **(d)** An elliptical patch with radius $R_1 = 2.5$ m, $R_2 = 3.136$ m, aspect ratio $R_2/R_1 = 1.25$, and area $A = 24.63$ m² produces slow-slower events with 8 and 15 days. **(e)** Model geometry with $R_1 = 2.5$ m, $R_2 = 3.6$ m, and $R_2/R_1 = 1.44$. **(f)** An elliptical patch with radius $R_1 = 2.5$ m, $R_2 = 3.6$ m, aspect ratio $R_2/R_1 = 1.44$, and area $A = 28.26$ m² produces slow and fast slip instabilities with 9 and 23 days. The recurrence time depends on the longer radius R_2 , and the aspect ratio R_2/R_1 . E.g., for a given area $A = 28.26$ m², the elliptical patch with $R_2 = 3.6$ m and aspect ratio $R_2/R_1 = 1.44$ has longer recurrence times (9 and 23 days) whereas a circular patch with $R_2 = 3$ m and $R_2/R_1 = 1$ has slightly shorter recurrence times (8.5 and 22 days).

Figure 3.6: Transition between periodic slow slip and periodic fast slip as a function of the aspect ratio of an elliptical asperity. The recurrence time ratio ($T_{\text{prev}}/T_{\text{next}}$) tracks the stability transition. Any given event has time before and time after that event, which can be plotted as (a) time since the previous event (b) and time to the next event with respect to the input parameter under study (e.g., the aspect ratio of an elliptical patch). (c) The two recurrence times (T_{prev} and T_{next}) when plotted against each other give a clear pattern that diverges from slow slip and converges to fast slip. (d) The ratio of recurrence times ($T_{\text{prev}}/T_{\text{next}}$) as a function of the input parameter (e.g., the aspect ratio) helps to study the changes in the oscillatory behavior of the fault. Using the recurrence time ratio throughout the study helps to maintain the consistency for comparison.

We increase the aspect ratio of the patch to check what happens beyond slow-fast rupture (Fig. 3.6a and b). Overall, the events diverge from periodic slow slip, become period-doubling slow-fast ruptures with peak recurrence time ratios of 2.6, and converge to periodic fast slip. The higher the recurrence time ratio, the larger the distinction between consecutive slow and fast events. Events that are dissimilar from previous events in a time series are difficult to forecast in the short term. Knowing what contributes to the dissimilarity between succeeding events may be useful for short-term forecasting.

Overall, the patch produces five slip behaviors - stable sliding, slow slip, slow-slower, slow-fast, and fast slip - as we change the aspect ratio, $R_2/R_1 = 0.52$ to 1 to 2.56 (ellipse to circle to ellipse) (Fig. 3.7). If the slip rate is below 2×10^{-8} m/s (i.e., 20 times the plate rate), the slip behavior is considered as stable sliding. The slip velocity of the periodic slow slip events ranges between 2×10^{-8} m/s and 0.1 m/s. The same range applies to the slow-slower events, but the events oscillate. None of the slip events within the slow-slower regime crosses the threshold velocity of 0.1 m/s, whereas the fast events within the slow-fast regime crosses the threshold slip velocity. The circular patch also produces five slip behaviors, similar to an ellipse (Fig. 3.8a and b). The results depend on the patch area irrespective of the aspect ratio. For example, the circular and elliptical patches with the same area of 28.26 m^2 produce slow-fast ruptures, which indicates that the phenomenon is independent of the aspect ratio for a given patch area. This conclusion may not be generally true as previous studies (*Lapusta and Liu, 2009*) show that smaller dimension of the patch affects slip dynamics for a fixed nucleation size.

To confirm if the patch area is the controlling factor for oscillatory behavior, we use a rectangular patch in addition to the circular and elliptical patches of the same area, 28.26 m^2 (Fig. 3.9). We find that patches of these shapes produce slow-fast slip events similar to our other geometries. We also find that the emergence of slow and fast slip instabilities is dependent on the patch area, 28.26 m^2 . However, the behavior is independent of the aspect ratio and the patch shape.

For patches of various shapes, we find that the largest radius R_2 , or the aspect ratio R_2/R_1 controls the recurrence times. For instance, a rectangular patch with $R_2 = 2.83 \text{ m}$ produces 21 and 8 day recurrence times, whereas an elliptical patch with $R_2 = 3.6 \text{ m}$ produces slightly longer inter-event times, 23 and 9 days, although their areas are the same (28.26 m^2). A square patch with $R_2 = 3 \text{ m}$ and an area of 36 m^2 (Fig. 3.9c and d, 36 m^2) produces fast slip events with the longest recurrence time of 26 days.

Our results show that variations in the patch geometry can affect the alternating slip events. Similar to the symmetric enlargement of the patch, an asymmetric extension of the patch also produces slow and fast slip events. Although the overall behavior of the fault depends on the patch area, the recurrence times tend to depend on the longest radius R_2 , or the aspect ratio R_2/R_1 .

Figure 3.7: The aspect ratio of the patch (ellipse to circle) affects the fault slip behavior. **(a)** Patch size $R_1 = 2.5 \text{ m}$; $R_2 = 1.3 \text{ m}$, 2.5 m , 3.1 m , 3.6 m , 6.4 m . **(b) to (f)** The cumulative slip and Moment magnitude. **(g) to (k)** The slip rate and **(l) to (p)** the shear stress from the center of the patch. Aseismic lines are plotted in grey, and seismic lines are plotted in red. The aspect ratio of 0.52, 1, 1.25, 1.44 and 2.56 produces creep, slow slip, slow-slower, slow-fast and fast events, respectively.

Figure 3.8: Elliptical and circular patches with the same area produce qualitatively similar behavior irrespective of the aspect ratio. (a) and (b) Elliptical patches of radius $R_1 = 2.5$ m, $R_2 = 2.5$ m to $R_2 = 6.4$ m, $R_2/R_1 = 0.5$ to 2.6 , and area of $A = 10.2 \text{ m}^2$ to 50.2 m^2 produce creep, slow-slip, slow-slower, slow and fast slip, and fast events similar to that of (c) and (d) circular patches of radius $R = 2.32$ m to 4 m, $R_2/R_1 = 1$ (circle), $A = 10.2 \text{ m}^2$ to 50.2 m^2 . Specifically, the circular and elliptical patches with the same area (28.26 m^2) produces the slow and fast slip instabilities, which indicates that the phenomena are independent of the aspect ratio for a given patch area. The same applies to other slip behaviors. However, their recurrence times depend on the longer radius R_2 or the aspect ratio (R_2/R_1).

Figure 3.9: Patches of any shape (or aspect ratio) may exhibit slow and fast slip instabilities for a given patch area. (a) and (b) A circular patch with $R_1 = 3\text{ m}$ (diameter = 6 m), $R_2 = 3\text{ m}$ (diameter = 6 m), $R_2/R_1 = 1$, area $A = 28.26\text{ m}^2$ produces slow-fast events. (c) and (d) A square patch with $R_1 = 3\text{ m}$ (side = 6 m), $R_2 = 3\text{ m}$ (side = 6 m), $R_2/R_1 = 1$, area $A = 36\text{ m}^2$, produces periodic fast events. (e) and (f) An elliptical patch $R_1 = 2.5\text{ m}$ (width = 5 m), $R_2 = 3.6\text{ m}$ (length = 7.2 m), $R_2/R_1 = 1$, area $A = 28.26\text{ m}^2$, and (g) and (h) a rectangular patch with $R_1 = 2.5\text{ m}$ (width = 5 m), $R_2 = 2.8\text{ m}$ (length = 5.7 m), $R_2/R_1 = 1.1$, area, $A = 28.26\text{ m}^2$ produces slow and fast slip instabilities, indicating that the oscillating behavior is dependent on the patch area with respect to the nucleation size h^* , and it is independent of the aspect ratio for a given patch area. However, the higher aspect ratio with large R_2 produces longer recurrence times (e.g. 21 and 8 days for the rectangular patch compared to 23 and 9 days for the elliptical patch).

3.4.2 The role of nucleation size on the oscillating slow and fast events through (1) normal stress, (2) characteristic slip distance, and (3) difference in frictional parameters at a constant asperity size $R = 3\text{m}$ and $a/b = 0.4$

In Section 3.3, we defined four length scales (*Chen and Lapusta, 2009; Dieterich, 1994, 1992; Rice, 1993; Rice and Ruina, 1983; Rubin and Ampuero, 2005; Ruina, 1983*). Here, we use h_a^* without the factor of $2/\pi$, and naming it as h^* for simplicity (Eqn. 3.9). To focus on the effect of this nucleation zone on the oscillating events, we choose a circular patch with a fixed slip-weakening region (twice the asperity radius), $W = 2R = 6\text{ m}$, and normalize it with nucleation size h^* as W/h^* (namely, the normalized slip-weakening region). The nucleation size, h^* , is the minimum size required to produce an earthquake.

We choose a simple form of h^* (Eqn. 3.9) to investigate how the normal stress (Fig. 3.10a and b) and the rate- and state-dependent parameters (L and $(a - b)$, Fig. 3.11c to f) influence oscillating slow-fast ruptures. We apply normal stress from 38 to 55 MPa to study the behavior and find that the stability transition ranges from 45 to 54 MPa (Fig. 3.10a). A change of 9 MPa is required to shift the slow slip regime to fast slip regime, which corresponds to a change in W/h^* of 0.59 (Fig. 3.10b). Likewise, we test the role of characteristic slip distance from 40 to 52 μm and found that the stability transition occurs within 42 to 51 μm (Fig. 3.10c) with a range of 8 μm , equivalent to a difference in W/h^* of 0.63 (Fig. 3.10d). When testing the friction parameters $(a - b)$, the values of a and b are varied simultaneously to keep the ratio $a/b = 0.4$ a constant (Fig. 3.10e and f). Slip events oscillate when $(a - b)$ ranges from -0.0135 to -0.016. A change in $(a - b)$ of 0.0025 (Fig. 3.10e) gives rise to a change in W/h^* of 0.54 (Fig. 3.10f). Within the stability transition, the slow-fast phenomenon with a peak recurrence time ratio of 2.6 emerges only when the combination is $W/h^* = 3.28$ and $a/b = 0.4$, indicating that the peak events are bounded by W/h^* and a/b with no regards to the way we change the nucleation size (Fig. 3.10g).

The estimates for the recurrence interval are given below:

For slow-slip events, we assume that the fault slip is bounded by a small multiple of the characteristic weakening distance. Indeed, if the slip were larger in comparison to the characteristic weakening distance, the instability would grow. Here, the magnitude of the slip scales with the slip-weakening region W . Accordingly, we write

$$T^{\text{slow}} = \frac{L}{V_L} . \quad (3.11)$$

Figure 3.10: Irrespective of the way we change the normalized slip-weakening region W/h^* , the stability transition occurs when W/h^* is in between ~ 2.95 and ~ 3.55 . The slow fast phenomenon with peak recurrence time ratio 2.6 emerges when $W/h^* = 3.28$ and $a/b = 0.4$. The nucleation size h^* is changed by varying (a) and (b) the normal stress $\bar{\sigma} = 38$ to 55 MPa (c) and (d) the characteristic slip distance $L = 40\text{ }\mu\text{m}$ to $52\text{ }\mu\text{m}$, and (e) and (f) the difference in friction ratios ($a - b$) $= -0.012$ to -0.017 . (g) The effect of W/h^* on the fault behavior is consistent in all the three cases. The slow-fast phenomenon with peak recurrence time ratio of 2.6 is bound to a combination of $W/h^* = 3.28$ and $a/b = 0.4$.

For fast ruptures, we assume that the slip is controlled by the stress drop $(b - a)\bar{\sigma}$, and the corresponding potency density is $(b - a)\bar{\sigma}/G$, up to a multiplicative constant. We obtain

$$T^{\text{fast}} = \frac{(b - a)\bar{\sigma}}{G} \frac{W}{V_L} . \quad (3.12)$$

The recurrence time ratio of a slow-slip event, from Eqn. 3.11 and 3.12, can be written as:

$$\frac{T_{\text{prev}}}{T_{\text{next}}} = \frac{T^{\text{fast}}}{T^{\text{slow}}} = \frac{s}{L} = \frac{W}{h^*} . \quad (3.13)$$

It appears that the peak recurrence time ratio depends on the normalized slip-weakening region W/h^* , for a given loading rate.

3.4.3 The role of the ratio of frictional parameters a/b on the slow and fast slip instabilities for a constant normalized slip-weakening region W/h^*

Within a range of a/b from 0.1 to 1, we test three cases of W/h^* (3.28, 4.00 and 8.75) by using $(a - b)$ values of -0.015, -0.0183, and -0.04 in each set (Fig. 3.11a to f). At $(a - b) = -0.015$ and $W/h^* = 3.28$, the stability transition appears between a/b : 0.35 and 0.5 (Fig. 3.11a and b). The zone starts to diminish as we increase W/h^* from 3.28 to 4 by decreasing $(a - b)$ from -0.015 to -0.0183 (Fig. 3.11c and d). The stability transition fully closes at $W/h^* = 8.75$ with $(a - b) = -0.04$ by slipping only at fast slip rates (Fig. 3.11e and f). The difference in friction parameter is kept as a constant in each set, but a and b are varied simultaneously to change a/b from 0.1 to 1. Slip event does not emerge when a/b values are greater than 0.8 and 0.7 (Fig. 3.12c and Fig. 3.12e, respectively). Overall, no oscillatory events occur when W/h^* is less than three or more than four, given $a/b = 0.4$ (Fig. 3.11).

The findings in Sections 3.4.2 and 3.4.3 show that alternating events can be obtained with a subtle variation in the nucleation size by changing the normal stress $\bar{\sigma}$ (Fig. 3.10a and b) or in the characteristic slip distance (Fig. 3.10c and d) or in the difference in the friction parameters $(a - b)$ (Fig. 3.10e and f) as long as the ratio of the slip-weakening region W and nucleation zone size h^* falls within the respective slip regimes implied in Fig. 3.8 and Fig. 3.9. The findings so far show that a combination of W/h^* and friction parameters a/b may control the occurrence of oscillating events. In the next section, we explore the effect of the Poisson's ratio, a mechanical property, on the bifurcation pattern.

Figure 3.11: The stability transition with slow and fast slip instabilities shrinks when W/h^* is smaller than three or larger than four. (a) and (b) The zone exists between $a/b = 0.35$ and 0.5 when $(a - b) = -0.015$ and $W/h^* = 3.28$. The slow and fast slip instabilities with peak recurrence time ratio of 2.6 occur at $a/b = 0.4$ and $W/h^* = 3.28$. (c) and (d) The recurrence time ratio reduces and the zone diminishes as we increase W/h^* from 3.28 to 4 by decreasing $(a - b)$ from -0.015 to -0.0183 . (e) and (f) The stability transition fully disappears at $W/h^* = 8.75$ with $(a - b) = -0.04$ by producing only fast ruptures. In the three cases, a and b are varied simultaneously to change a/b from 0.1 to 1 , but a constant $(a - b)$ is kept for each set. No slip event emerges for a/b values greater than 0.8 and 0.7 in (c) and (e) respectively. No values of a/b can produce oscillating events when W/h^* is equal to or greater than 4.

3.4.4 The role of Poisson's ratio on the oscillating slip events

In two-dimensional finite faults embedded in a three-dimensional continuum, mode II and mode III ruptures occur simultaneously. Therefore, two distinct stability conditions control fault slip. As mode III is more unstable than mode II for positive Poisson's ratios, the stability condition may be met for none, one, or two conditions across the stability transition. When none of the stability conditions for mode II or mode III are met, the cycle may be single periodic with slow slip events. When only one condition is met, for mode III but not mode II, this may lead to the conditions enabling period-doubling cycles. When both conditions are met, the cycle may be single periodic again, but with fast ruptures. The slip distributions of slow and fast ruptures (Fig. 3.3) allude to this phenomenon. The dominance of mode III and mode II ruptures can be inferred from the slip distribution. Pure mode III is found when the rupture is infinitely long in the loading direction, whereas pure mode II occurs when the rupture is infinitely long in the direction perpendicular to loading. Figure 3.4 shows that the fast ruptures are more elongated in the direction of loading than the slow ruptures, indicating a predominance of the more unstable mode III. The slow ruptures are more axisymmetric, signifying a smaller dominance of mode III and more stability. To test this hypothesis, we conduct numerical simulations with the parameters of the reference model, except that we vary Poisson's ratio (Fig. 3.12).

For Poisson's ratios smaller than 0.135, the oscillations disappear. The Poisson's ratios from 0.135 to 0.30 allow distinct stability conditions for mode II and mode III ruptures, as shown in equations 3.4 and 3.5. As the ν becomes zero, $(1-\nu)$ becomes 1; G becomes G^* for both mode II and mode III cracks, and there are no longer two simultaneous stability conditions and in turn no period-doubling cycles. Two stability conditions may coexisting to produce period-doubling behavior when ν is more than 0.135 (Fig. 3.12). When the Poisson's ratio is in between 0 and 0.135, only fast ruptures occur. A Poisson's ratio of 0.25 results in a peak recurrence time ratio of 2.6.

3.4.5 The effect of loading rate on the characteristics of the stability transition

To understand how a sudden increase in the local loading velocity V_L influences the oscillations, we test a wide range of rates from one cm/yr to ~ 3 m/s. We show that V_L (Fig. 3.13) affects the oscillatory behavior strongly, especially the recurrence time ratio. No oscillations occur for slip rates faster than 10,000 cm/yr.

To explain the importance of the critical nucleation size and the loading rate, we assume a time-predicable model where the time of quiescence following any event is proportional to the amount of slip that occurred during the event and a (generally small) nucleation time that is independent of the loading rate.

Figure 3.12: The alternating events disappear for small values of the Poisson's ratio. **(a)** and **(b)** Fast events thrive when the Poisson's ratio is in between 0 and 0.13. The values of the Poisson's ratios at which the slow and fast slip instabilities emerges is ≥ 0.135 .

The recurrence time ratio T_R is defined as the ratio of time since previous event and time to the next event. For a given slow slip event, the recurrence time ratio can be written as:

$$T_R = \frac{T^{\text{fast}}}{T^{\text{slow}}} \quad (3.14)$$

If we account for the duration of nucleation $T^{\text{nucleation}}$, the recurrence time ratio in Eqn. 3.14 becomes

$$T_R = \frac{T^{\text{fast}} + T^{\text{nucleation}}}{T^{\text{slow}} + T^{\text{nucleation}}} \quad (3.15)$$

The Eqn.s 3.11 and 3.12 show the inter-event times for slow slip and fast slip. The interval of slow-slip event (Eqn. 3.11) can be approximated such that

$$T^{\text{slow}} = \frac{L}{V_L} + T^{\text{nucleation}} \quad (3.16)$$

where $T^{\text{nucleation}}$ is the short time required for instabilities to nucleate, L is the characteristic slip distance, and V_L is the loading rate. The interval of fast rupture (Eqn. 3.12) can be assumed as

$$T^{\text{fast}} = \frac{(b-a)\bar{\sigma} W}{G V_L} + T^{\text{nucleation}} \quad (3.17)$$

where $(b-a)\bar{\sigma}$ is the assumed stress drop, up to a constant, $(b-a)\bar{\sigma}/G$ is the eigenstrain, and $(b-a)\bar{\sigma}W/G$ is the approximated cumulative slip, again up to a constant.

Substituting Eqn. 3.16 and 3.17 in Eqn. 3.14, we get

$$T_R = \frac{\frac{(b-a)\bar{\sigma}W}{G} + V_L T^{\text{nucleation}}}{L + V_L T^{\text{nucleation}}}, \quad (3.18)$$

For a small enough loading rate, this can be approximated by

$$T_R = \frac{\frac{(b-a)\bar{\sigma}W}{G}}{L} = \frac{W}{h^*}, \quad (3.19)$$

same as equation (3.13), clearly showing how the ratio of slip-weakening region to nucleation size controls the recurrence time ratio. However, for increasing loading velocity, the time to nucleation becomes dominant, until the period-doubling cycle disappears altogether.

When $V_L T^{\text{nucleation}}$ is large in Eqn. 3.18, we get

$$T_R = \frac{V_L T^{\text{nucleation}}}{V_L T^{\text{nucleation}}} = 1. \quad (3.20)$$

This explains the convergence towards equal inter-event times at high loading rates.

If we account for the phenomena that have a duration that only scales weakly with the loading rate, for example, nucleation or afterslip, we can write,

$$T^{\text{nucleation}} = \frac{C}{V_L^\alpha} \quad (3.21)$$

where C is an unknown constant and $\alpha \ll 1$.

Substituting $T^{\text{nucleation}}$ with $\frac{C}{V_L^\alpha}$ in Eqn. 3.18, we get,

$$T_R = \frac{\frac{(b-a)\bar{\sigma}W}{G} + C V_L^{1-\alpha}}{L + C V_L^{1-\alpha}} \quad (3.22)$$

Section 4 shows the factors that promote or inhibit the slow and fast slip instabilities within the stability transition. It also shows the parameters that control the peak recurrence time ratio. We observe that both the Poisson's ratio and the loading rate can switch on and off the slow and fast slip instabilities. The W/h^* and a/b are bound to produce oscillatory events when the Poisson's ratio is between 0.135 and 0.30 and the loading rate V_L , is between one and 10,000 cm/yr. Although the loading rate can induce alternating rupture styles across a wide range, the range of Poisson's ratio for the same is narrow. The emergence and disappearance of the oscillatory behavior of the fault patch depends on the normalized slip-weakening region W/h^* , the ratio of friction parameters a/b , the Poisson's ratio, ν , and the loading rate V_L . The findings indicate that a specific set of values are required to produce a wide stability transition in parameter space, and certain values of parameters can make the oscillations completely disappear. For a Poisson's ratio $\nu = 0.25$ and loading rate of 3 cm/yr, a combination of $W/h^* = 3.28$ and $a/b = 0.4$ gives the maximum recurrence time ratio of 2.6. This happens with any arrangement of normal stress, characteristic slip distance, and difference in friction parameters. A change in either Poisson's ratio or the loading rate drastically shifts this peak recurrence time ratio.

Figure 3.13: The oscillating events vanish when the loading rate increases. (a) and (b) The oscillations have the highest recurrence time ratio when the loading rate is 1 cm/yr. The recurrence times decrease with an increase in the loading rate. The slow-fast ruptures have peak recurrence time of 2.6 at $V_L = 3$ cm/yr, and it decreases to 1.65 when the loading rate is 167 times faster (500 cm/yr). The value of the loading rate at which the oscillations vanish is 10,000 cm/yr.

3.5 Tracking the extent of the stability transition

In this section, we investigate the effect of several key parameters on the extent - height and width - of the stability transition (i.e., the bifurcation pattern). Here, the height refers to the peak recurrence time ratio, and the width refers to the magnitude of the change in normal stress required to shift the regime from periodic slow slip to periodic fast slip. The effect of these variations are shown in Fig. 3.15a, Fig. 3.16a, Fig. 3.17a, and Fig. 3.18a, compared to a reference pattern.

Bifurcation patterns for circular, elliptical, square, and rectangular patches The asperity shape and the aspect ratio do not affect the peak recurrence time ratio. In these cases, the peak recurrence time ratio is between 2.5 and 2.6 (Fig. 3.14). Similarly, the change in normal stress required to flip from the slow to fast slip regime is around 9 MPa for all patch shapes. As we change the patch shape from a circle to square to ellipse and finally to a rectangle, the normal stress corresponding to the peak recurrence time ratio decreases from 50 to 38 MPa.

The bifurcation patterns at different characteristic slip distances and Poisson's ratios Similar to the asperity shape, neither the characteristic slip distance nor the Poisson's ratio strongly affects the height or width of the stability transition. In all the cases shown in Fig. 3.15, the peak recurrence time ratio is between 2.6 and 2.7; the width is between 9 and 11 MPa.

Figure 3.14: The extent of the stability transition is consistent for circular, square, elliptical, and rectangular patches. (a) A circular patch with radius $R_1 = 3 \text{ m}$ and $R_2 = 3 \text{ m}$, aspect ratio $R_2/R_1 = 1$, (b) a square patch with dimensions $R_1 = 3 \text{ m}$ and $R_2 = 3 \text{ m}$, aspect ratio $R_2/R_1 = 1$, (c) an elliptical patch with dimensions $R_1 = 3 \text{ m}$ and $R_2 = 4 \text{ m}$, aspect ratio $R_2/R_1 = 1.3$, and (d) a rectangular patch with dimensions $R_1 = 3 \text{ m}$ and $R_2 = 4 \text{ m}$, aspect ratio $R_2/R_1 = 1.3$ produce stability transitions with a width of around 9 MPa. The normal stress corresponding to the peak recurrence time ratio (~ 2.5) decreases as we change the patch shape from a circle (50 MPa) to square (45 MPa) to ellipse (42 MPa), and finally to a rectangle (38 MPa).

Figure 3.15: The stability transition is less affected by small changes in the characteristic slip distance or the Poisson's ratio. **(a)** The reference pattern with characteristic slip distance $L = 45.8\text{ }\mu\text{m}$ has a peak recurrence time ratio of 2.6, and the width of the zone is 9 MPa. **(b)** A decrease in the characteristic slip distance L from $45.8\text{ }\mu\text{m}$ to $42.4\text{ }\mu\text{m}$ does not induce a significant change in the pattern. **(c)** A decrease in the Poisson's ratio from 0.25 to 0.135 also does not result in much change in the stability transition. In the three cases, the width is between 9 and 11 MPa and the peak recurrence time ratio is from 2.6 to 2.7.

Figure 3.16: The height of the stability transition decreases with an increase in the loading rate. **(a)** and **(b)** The peak recurrence time ratio is 2.6 at $V_L = 3\text{ cm/yr}$. **(c)** and **(d)** The peak recurrence time ratio is 1.8 at $V_L = 500\text{ cm/yr}$. When the loading rate is 167 times faster, the peak recurrence time ratio becomes 1.4 times smaller. The change in normal stress in both cases is in between 8 and 9 MPa, showing that the loading rate has a negligible effect on the range of normal stress, but strongly affects the overall range of recurrence ratios. The intervals for $V_L = 500\text{ cm/yr}$ are very small as compared to that of the $V_L = 3\text{ cm/yr}$.

The dependence of the bifurcation pattern on the loading rate The loading rate does not affect the zone width to a great extent (9 MPa compared to the reference pattern with 8 MPa). However, the peak recurrence ratio dramatically reduces from 2.6 to 1.8 (Fig. 3.16a and c) when the loading rate is about 167 times faster than that of the reference model (Fig. 3.16a).

Figure 3.17: The width of the stability transition increases with an increase in the ratio of friction parameters a/b . **(a)** and **(b)** The width of the zone is 9 MPa at $a/b = 0.4$. **(c)** and **(d)** The width of the zone is 23 MPa at $a/b = 0.5$. The bifurcation pattern, with ($a/b = 0.5$), widens about twice the original pattern with a small change in a/b . The peak recurrence times in both the cases is close to 2.6, showing that the friction ratio has a negligible effect on the height of the zone, but strongly affects the width of the zone, as opposed to the effect of the loading rate on the zone (Fig. 3.16).

The dependence of the bifurcation pattern on the ratio of friction parameters Although the ratio of friction parameters does not change the height (i.e., the peak recurrence ratio) (2.6 at both $a/b = 0.4$ and 0.5), the zone widens from 9 MPa to 23 MPa with just a 0.1 difference in a/b (Fig. 3.17). The ratio of friction parameters has an opposite effect on the width of the zone in comparison to that of the loading rate on the height of the zone.

3.6 Summary

To have a physical understanding of the transition zone and its bifurcation pattern, we investigated the boundaries of stable creeping (no slip events) and fully dynamic events (earthquakes) by a methodical and meticulous exploration of a representative range of the geometric, frictional, and mechanical properties, and loading conditions. In particular, we investigated the factors that control stress drop, inter-event time, and the recurrence time ratio.

We find that both the symmetric enlargement and the asymmetric extension of the patch cause oscillatory slip events. The transition from creep to fast slip occurs through three different slow slip regimes - slow slip, slow-slower, and slow-fast ruptures. Circular and elliptical patches with the same area produce similar fault behaviors irrespective

of the aspect ratio. Patches of any shape (or aspect ratio) may exhibit slow and fast slip instabilities at a given patch area. However, the longest radius R_2 , and the aspect ratio R_2/R_1 control the recurrence interval of the events. Irrespective of the way we change the nucleation size h^* , the peak slow-fast phenomenon emerges when $W/h^* = 3.28$ and $a/b = 0.4$. The slow and fast slip instabilities cease to exist at $a/b = 0.4$ when the value of W/h^* is less than three or more than four. The slow-fast phenomenon is strongly influenced by both the Poisson's ratio and the loading rate. The bifurcation pattern is consistent for circular, elliptical, square and rectangular patches and is less affected by a small change in the characteristic slip distance or the Poisson's ratio. The peak recurrence time ratio decreases with an increase in the loading rate V_L whereas the width of the bifurcation pattern increases with an increase in the ratio of friction parameters a/b . Conclusively, nine parameters affect slow and fast slip instabilities: (i) slip-weakening region W , (ii) aspect ratio R_2/R_1 , (iii) patch area A , rate-and state-dependent parameters such as (iv) characteristic slip distance L , and friction parameters a and b in terms of (v) $(a - b)$ and (vi) a/b , (vii) effective normal stress $\bar{\sigma}$, (viii) the Poisson's ratio ν , and the (ix) loading rate V_L . Among the nine parameters, the slip-weakening region W , characteristic slip distance L , difference in friction parameters $(a-b)$, ratio of friction parameters (a/b) , effective normal stress $\bar{\sigma}$, and Poisson's ratio ν can be grouped and represented by the non-dimensional W/h^* , which affects the slip dynamics, whereas the loading rate affects mainly the inter-event times.

The stability transition occurs when W/h^* is in between 3 and 4 (specifically, from 2.95 to 3.55) for a given $a/b = 0.4$. Normal stress ranging from 45 to 54 MPa, characteristic slip distance from 40 to 52 μm , and a difference in friction ratio from -0.0135 to -0.016 allow the oscillatory behavior. The maximum distinction between consecutive events within a stability transition occurs when their recurrence time ratio is 2.6, which happens when W/h^* is 3.28 and $a/b = 0.4$. The parameters used in this study are summarized in Table 3.6.1.

Table 3.6.1: The range of values corresponding to the model parameters

Parameter	Symbol	Value
<i>Fault geometry</i>		
Fault dimensions	λ_x and λ_z	24 x 24 m ²
Fault depth	$\lambda_z/2$	12 m
<i>Velocity-weakening patch</i>		
Circle	R	2.3 to 4 m
Ellipse	R1	1.3 to 6.4 m
	R2	2.5 and 3 m
Square	R	3 m
Rectangle	R1	2.83 and 4 m
	R2	2.5 and 3 m
<i>Rate- and state- dependent parameters</i>		
Direct effect	a_{vw}	0.002 to 0.36
	a_{vs}	0.01
Evolution effect	b_{vw}	0.02 to 0.4
	b_{vs}	0.006
Difference in friction parameters	$(a-b)_{vw}$	-0.01 to -0.04
	$(a-b)_{vs}$	0.004
Ratio of friction parameters	$(a/b)_{vw}$	0.1 to 0.8
Characteristic slip distance	L	40 to 52 μ m
Reference friction	μ_0	0.65
Reference velocity	V_0	10 ⁻⁶ m/s
<i>Elastodynamic parameters</i>		
Poisson's ratio	ν	0 to 0.25
Shear modulus	G	30 GPa
Shear wave speed	C_s	3 km/s
<i>Loading conditions</i>		
Normal stress	σ	32 to 110 MPa
Loading velocity	V_L	1 to 10 ⁶ cm/yr

Note: vw: velocity-weakening; vs: velocity-strengthening.

3.7 Discussion and conclusion

To produce a bifurcation pattern, first of all, the fault patch must have a negative value for the difference in friction parameters ($a - b$). In other words, the patch has to be velocity-weakening to produce any instabilities inclusive of oscillatory events. So, the shallow and deep portions of the crust, if the material has a positive value for the friction parameters, will not host a stability transition. Given that the material is velocity weakening, if the geometric, frictional and normal stress conditions are such that the value of W/h^* is less than 2.95 or greater than 3.55, the patch will still not induce oscillatory events. Moreover, loading rates faster than 10,000 cm/yr, and Poisson's ratios smaller than 0.135 also inhibit oscillatory events.

We observe that the loading rate V_L mainly controls the peak recurrence time i.e., the height of the stability transition, and a/b controls the width of the zone. The loading rate determines the distinction between consecutive events because, among all nine parameters, loading rate has the most effect on the peak recurrence time ratio (Section 4, Fig. 3.14). The fault patch is more sensitive to the material properties a and b , especially the ratio of friction parameters, a/b , which allows the patch to either stay within or move out of the stability transition. We find that V_L and a/b are the major factors controlling the normal stress change that is needed for the flip between two non-oscillatory regimes. All of the key findings from Section 5 indicate that although parameters like the characteristic slip distance and the Poisson's ratio do not produce massive difference in the width of the zone, a 0.1 difference in a/b can widen the stability transition to 2.55 times the original size, and specific values of the Poisson's ratio (less than 0.135) and loading rate (faster than 10,000 cm/yr) can impede the oscillations.

The effect of W/h^* (Liu and Rice, 2007; Segall et al., 2010), a/b (Noda and Hori, 2014; Viesca, 2016), and velocity perturbations (Gu and Wong, 1994; Leeman et al., 2018; McLaskey and Yamashita, 2017; Scholz et al., 1972; Wong et al., 1992) on fault slip are well-documented. Note that some of the similar slip patterns are described using rate and state fault models (Chen and Lapusta, 2019). We complement these studies by incorporating possible parameters that are testable in a numerical setup. The transition from entirely slow slip to fully fast slip is not through a sudden jump. Instead, the fault goes through a transitory regime before it produces fast slip, as hinted in early studies (Gu and Wong, 1994). Changes in the loading rate due to fault interactions may also make the fault shift through the zone. If the loading rate decreases or increases due to local fluctuations, that can affect the nearby faults and their recurrence times.

As hypothesized, our findings show that alternating rupture styles happen under particular conditions and are

susceptible to changes in several parameters. Our results suggest that prolonged cycles made of different rupture styles are only possible when two conditions are met: 1. A narrow range of physical parameters and 2. A few perturbations; Therefore, probably an isolated system. As an example, the Parkfield tremor family (*Shelly, 2010b*) is the only one reported observation of period-doubling tectonic tremor. We claim that persistent oscillations like the Parkfield tremors are less frequent may be because the range of parameters needed to produce such pattern with unusual recurrence times is specific. Even if some fault patches enter into the stability transition, inter-event times can be quite different, depending on the fault properties, and the susceptibility of those zones to local loading conditions and other parameters would not allow the patch to oscillate for a prolonged period. If the conditions for the oscillations were less strict or if the patches are free from external perturbations, we would observe many more cleaner period-doubling observations from tectonic faults.

Based on extensive numerical simulations, we provide a systematic understanding of the critical parameters that influence the slow and fast slip instabilities within the stability transition and their inter-event times, a result that is not easily achieved via laboratory experiments due to the difficulties in maintaining uniform conditions. The identified range of values from our numerical modeling may help to inform future laboratory studies. By understanding the independent effects of several key parameters on the slow-fast ruptures, we can better understand the parameter space that promotes or inhibits these phenomena in a natural environment. Identifying the factors that control the height of the bifurcation pattern may shed light on the parameters that cause the peak recurrence time ratio, which would then inform us about the variability in recurrence times.

Because the physical conditions strongly affect the dimensions of the stability transition, the possibility of finding such phenomena in natural systems depends on a methodical understanding of the fault behavior from controlled experiments and also on the availability of instrumentation. The results presented here provide an explanatory context to understand seismological observations at the laboratory and the natural scales. Informed by these theoretical predictions, specifically designed laboratory experiments may capture the dynamics of fault slip with increasing resolution.

Emergence of period-doubling slow and fast ruptures in laboratory friction experiments

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Abstract

Slow slip events and earthquakes are often spatially separated along plate boundaries (*Gao and Wang, 2017*), but in increasingly well-documented instances, the same fault segments fail in both slow and fast ruptures within a short period, e.g., before the 2011 Mw=9.0 Tohoku-Oki, Japan (*Ito et al., 2013; Kato et al., 2012*) and 2014 Mw=8.2 Iquique, Chile (*Meng et al., 2015; Socquet et al., 2017*) earthquakes. Why slow slip alternates with fast slip in certain regions, but is more pervasive and quasi-periodic in others, for example, along Cascadia (*Gomberg et al., 2010*), Middle America (*Radiguet et al., 2012*), and Nankai subduction zones (*Gardonio et al., 2018*), is not well understood. Here, we integrate double direct shear experiments and numerical simulations to investigate the physical conditions leading to period-doubling cycles where two distinct events are repeated. We show that a bifurcation takes place near the stability transition (*Leeman et al., 2015, 2016; Scuderi et al., 2016*), where period-doubling slow-slower and slow-fast rupture sequences spontaneously occur under steady

loading. We reproduce this behavior in numerical simulations, but only in models that adequately capture the fault dynamics in three dimensions. Direct application of these findings to natural faults is complicated by the presence of additional morphological and rheological heterogeneities, but the range of frictional instabilities and slip cycles identified in our integrated study represent important end-members to understand the interaction of slow and fast slip.

4.1 Introduction

Decades of seismologic and geodetic monitoring along active faults have illuminated distinct slip behaviors, for example, fault creep, slow slip events, and slow and fast earthquakes, each developing in separate fault regions (Fig. 4.1a), compatible with the notion that specific physical conditions can be associated with a unique rupture style (*Obara and Kato*, 2016). However, this simple view is now challenged by a compelling set of observations revealing the intrusion of aseismic transients in otherwise seismogenic regions, e.g., the aseismic transients before the 2011 Mw=9.0 Tohoku-Oki, Japan (*Ito et al.*, 2013) (Fig. 4.1b), 2012 Mw=7.6 Costa Rica (*Voss et al.*, 2018), 2012 Mw=7.4 Ometepec, Mexico (*Graham et al.*, 2014), 2014 Mw=8.2 Iquique, Chile (*Meng et al.*, 2015; *Socquet et al.*, 2017) (Fig. 4.1c), 2014 Mw=7.3 Papanao, Mexico (*Radiguet et al.*, 2016), 2015 Mw=8.4 Illapel, Chile (*Huang and Meng*, 2018), 2016 Mw=7.0 Kumamoto, Japan (*Kato et al.*, 2016b), and 2017 Mw=6.9 Valparaíso, Chile (*Ruiz et al.*, 2017) earthquakes; period-doubling tremors with slow and fast slip along the San Andreas Fault (*Shelly*, 2010b) (Fig. 4.1d); and mixed aseismic-seismic slip in the Andean subduction zone (*Villegas-Lanza et al.*, 2015). Although rock friction experiments have revealed the conditions for a wide spectrum of fault slip (*Gu and Wong*, 1994; *Leeman et al.*, 2016; *Mcllaskey and Yamashita*, 2017; *Scholz et al.*, 1972; *Scuderi et al.*, 2016; *Wong et al.*, 1992; *Zhuo et al.*, 2018), the range of conditions leading to persistent period-doubling cycles where two distinct events alternate with slow and fast slip is not thoroughly understood.

4.2 Laboratory experiments

Here, we conduct friction experiments on synthetic gouge to investigate the conditions under which the same fault region may slip in repeated sequences of slow and fast ruptures. We use the Brittle Rock Deformation Versatile Apparatus (BRAVA), a servo-controlled biaxial shearing apparatus (Fig. S4.1), to study the effect of normal stress and in turn the effect of the stiffness ratio on fault dynamics. We use a double direct shear setup (Fig. 4.2a) where granular quartz layers sandwiched between three steel side blocks are clamped at a constant horizontal normal stress and are slid with a constant vertical loading velocity 10 $\mu\text{m/s}$ (*Giorgetti et al.*, 2016; *Scuderi et al.*, 2016) (Ref.

Figure 4.1: A landscape of fault failure modes. (a) Distribution of creeping faults (Harris, 2017), slow slip, tremors (Obara and Kato, 2016), and earthquakes (USGS). Majority of the slip behaviors arise from separate fault segments. (b) Mw=7.0 slow slip preceding the 2011 Mw=9.0 Tohoku-Oki earthquake (Ito et al., 2013), Japan. (c) Occurrence of aseismic slip before the 2014 Mw=8.2 Iquique earthquake (Meng et al., 2015), Chile. Red patch is the coseismic slip area and blue patch is the aseismic slip area. (d) Period-doubling tremors along the San Andreas fault (Shelly, 2010b). (e) Slow slip events along the northern Cascadia subduction zone with inter-event times close to 14.5 months (Rogers and Dragert, 2003).

Supp.). In laboratory experiments, the stiffness ratio k/k_c controls the fault slip behavior, where k is the system stiffness and k_c is the critical stiffness of the gouge layer derived from velocity step experiments (Ref. Supp.). If the stiffness ratio is larger than one, faults produce stable creep. If the ratio is close to one, faults generate slow slip, and if it is less than one, fast ruptures occur. As the variations in normal stress modulate the stiffness ratio (Ref. Eqn. 4.1, Supp.), we explore the incremental change in normal stress to look for consecutive slow and fast ruptures. We explore the parameter space around the stable/unstable transition in small increments of the normal stress. To overcome the bounds in cumulative slip imposed by the apparatus that limit the number of slip cycles, we conduct 14 independent experiments, each based on a fresh gouge sample. The applied normal stress from 13.6 to 25 MPa reflects a stiffness ratio slightly above 1 to a value close to 0.6. We use stress drop (Fig. 4.2c) and slip rate (Fig.

Figure 4.2: The fault zone in a laboratory setting deforms in various ways to release the shear stress accumulated during inter-event times. **(a)** A double direct shear setup to study gouge deformation. **(b)** Peak shear stress progressively increases with applied normal stress. **(c)** Stress drop, the difference between maximum and minimum shear stress, is used to categorize slip events. Inter-event time, the difference of the times corresponding to the maximum shear stresses of consecutive events, is used to determine the periodicity or regularity of the events. **(d)** Regular single-peak shear stresses are observed from 15 to 17 MPa, and double-peak shear stresses are detected at 18, 20, 22 and 23 MPa. At 25 MPa, the events have larger magnitude single-peak shear stresses.

S4.2) to categorize the rupture styles, as the peak shear stress and slip rate increase systematically with the applied normal stress (Fig. 4.2d and Fig. S4.2). Under relatively low (15 MPa) and relatively high (25 MPa) normal stresses (Fig. 4.2d), the gouge slips quasi-periodically with a single failure style, with single-peak shear stresses, after a transient period of textural maturation, similar to previous findings (*Scuderi et al.*, 2016). However, at intermediate stresses, between 16.4 and 23 MPa, the frictional interface slips in consecutive events with different stress drops and peak velocities. After a few initial events, the cycle repeats virtually identically, up to nine times in a row. To characterize periodicity in the inter-event times, we use the ratio of the time since the previous event to the time to the next event (Fig. 4.2c), also called the pre-event to post-event time ratio (Fig. 4.3), or recurrence ratio. Stable creep (slip rate close to 10 $\mu\text{m/s}$) occurs at 13.6 MPa, where k/k_c is above 1. Slow slip events (slip rate $\sim 100 \mu\text{m/s}$ and stress drop $< 0.4 \text{ MPa}$) originate around 15 MPa (Fig. 4.3a and b), where the stiffness ratio is close to 0.9. The gouge exhibits complex cycles at intermediate stresses (17-23 MPa, Fig. 4.3c to h) with stiffness ratios between 0.87 and 0.64. Fast slip (slip rate $> 1.5 \text{ mm/s}$ and stress drop $> 1 \text{ MPa}$) takes place at 25 MPa normal stress (Fig. 4.3i and j), where the stiffness ratio is 0.6. At 17 MPa ($k/k_c = 0.87$), we resolve a new slip mode with a sequence of slow and slower slip events where the slip rate alternates above and below 0.5 mm/s and stress drop fluctuates between 0.4 MPa and $< 1 \text{ MPa}$ (Fig. 4.3c and d, Fig. S4.2b). At 23 MPa ($k/k_c = 0.64$), the fault zone switches from slow to fast slip, where the slip rate oscillates above and below a threshold slip rate of 1.5 mm/s and stress drop fluctuates between 0.4 MPa and $> 1 \text{ MPa}$ (Fig. 4.3g and h, Fig. S4.2c).

We assemble 14 laboratory experiments, each at a constant normal stress, to highlight five distinct transitions: 1) Stable sliding (lower end-member) at 13.6 MPa, 2) Slow slip from 14 to 15.4 MPa, 3) Period-doubling slow-slower slip from 16.4 to 22 MPa, 4) Period-doubling slow-fast slip at 22 and 23 MPa and 5) Fast slip (upper end-member) at 24 and 25 MPa (Fig. 4.4a and b). The separate regimes of slow and fast slip are comparable to previous laboratory studies (*Leeman et al.*, 2016; *Scuderi et al.*, 2016). However, we discovered two new regimes where different modes of slip alternate: slow-slower and slow-fast slip cycles (Fig. 4.4b). Overall, the pre-event to post-event time ratio transits through a bifurcating pattern of recurrence ratios by diverging from 1 to ~ 1.7 at intermediate normal stresses and converging back to 1 at high normal stresses (Fig. 4.4b). The range of normal stress in which period-doubling cycles occur is large, covering about 9 MPa, with slow slip at $\sigma_n = 15.4 \text{ MPa}$ and quasi-periodic fast slip at $\sigma_n = 24 \text{ MPa}$. The slow-fast mode switching with complex intervals is observed close to the upper stability boundary ($\sigma_n = 23/24 \text{ MPa}$). The slip events at intermediate normal stress tend to become more dynamic as the normal stress approaches the upper stability boundary. The consecutive time intervals become increasingly equal,

Figure 4.3: Emergence of complex sequences of slow and fast ruptures around the stability condition. (a) and (b) Slow events are observed near the lower stability boundary. (c) to (h) Consecutive slow-slower and alternating slow-fast modes with aperiodic time intervals emerge at intermediate normal stresses (17 to 23 MPa). (i) and (j) Fully dynamic events slip periodically and are observed near the upper stability boundary. The events are categorized based on the direct measurement of stress drop and time derivative of displacement during the event. The changes in the stress drop (Fig. 4.2c) and slip rate (Fig. S4.2) show the transitions in failure modes. The pre-event to post-event time ratio, a ratio between time since previous event and time to the next event, is used to characterize periodicity in the inter-event times. If the time intervals are equal, this ratio becomes one, and the events are periodic. If the intervals are different, the ratio deviates from one, and the events are aperiodic. Deviations in this ratio show the variability in the consecutive time intervals, with in turn the complexity of the system.

and the ratio converges to one, leading to single-periodic fast slip. The laboratory data reveal a clear bifurcating pattern between slow slip events and fast ruptures with period-doubling cycles (Fig. 4.3, 4.4b), but the underlying mechanisms for this transition remain unclear.

Figure 4.4: Stability-tuned fault system in laboratory and numerical experiments unwrap a panoramic view of slow to fast, periodic to aperiodic failure modes. **(a)** and **(c)** Increment in normal stress. The normal stress is kept constant during each laboratory and numerical experiment and incremented with respect to the experiment number. **(b)** Laboratory experiments show five distinct slip modes - stable creep, slow slip, aperiodic slow-slower slip, aperiodic slow-fast slip, and fast earthquakes. No slip events emerge during stable sliding. The lower stability boundary distinguishes between stable creeping and slow slip. The upper stability boundary demarcates aperiodic slow-fast mode and fast mode. The phenomenon of alternating slow-fast slip emerges before the fully dynamic regime. The pre-event to post-event time ratio diverges from a value close to 1, increases up to 1.7 and decreases back to a value close to 1 as a function of the applied normal stress. Laboratory data show transitory phases within 16.4 to 23 MPa (~ 7 MPa change in normal stress). **(d)** Numerical simulations show five distinct slip modes similar to the laboratory data with lower and upper stability boundaries. The pre-event to post-event time ratio bifurcates from 1, increases up to 1.8 and decreases back to 1 as a function of applied normal stress. The numerical data show transitory phases within 45 to 51 MPa (6 MPa change in normal stress) similar to the laboratory data. In both laboratory experiments and numerical simulations, aperiodic slow-slower events emerge when the pre-event to post-event time ratio diverges from 1. Aperiodic slow-fast events terminate when the pre-event to post-event time ratio converges to 1. The stability condition corresponding to the peak ratio could be the dividing boundary between slow-slower and slow-fast modes. The first ten events are excluded to make sure the subsequent events are similar.

4.3 Numerical simulations

We seek a deeper understanding of slow-fast transition from physics-based modeling of the seismic cycle, expanding on previous work that identified consecutive slow and fast slip on a single asperity (Veedu and Barbot, 2016). To

explore the continuity in the slip mode transitions and to leverage the existing modeling infrastructure (*Barbot et al.*, 2012; *Lapusta and Liu*, 2009), we consider a finite planar fault with homogenous friction embedded in an infinite elastic space. A circular velocity-weakening patch is placed within the surrounding velocity-strengthening region (Fig. S4.4). The model geometry is therefore slightly different from the laboratory setting. We model the seismic cycle using the boundary integral method, and different types of events originate depending on the nucleation size, h^* relative to the asperity size, R (Ref. Supp.). We broaden this picture by exploring the model parameter space around the stability transition to shed light on how the progression from slow to fast ruptures operates.

The numerical simulations reveal a wide range of rupture styles. The slip rate from the center of the patch (Fig. S4.4) transits through stable creep, periodic slow slip events, period-doubling slow and slower slip events, period-doubling slow and fast ruptures, and periodic fast ruptures, depending on the normal stress (Fig. S4.4c and d). These types of cycles are similar to our laboratory findings (Fig. S4.2), despite the difference in geometry. We have also explored the parameter space for semi-infinite faults in a two-dimensional approximation and have not found a similar transition with period-doubling cycles. We conclude that this behavior is relatively insensitive to the details of the patch geometry and is a hallmark of fault dynamics near the stability transition for finite faults.

4.4 Explanation for the period-doubling slow and fast ruptures and the decrease in the recurrence time ratio

We understand period-doubling slow and fast ruptures as a spontaneous phenomenon originating in three dimensions on finite faults from two coexisting stability conditions for Mode II and Mode III ruptures, which may differ based on Poisson's ratio (*Andrews*, 1976a,b). This is confirmed by exploring the effect of Poisson's ratio on the pre-event to post-event time ratio (Fig. S4.7). For relatively small Poisson's ratio ($0 \leq \nu \leq 0.13$), the stiffness of Mode II and Mode III cracks are similar and the period-doubling cycles are suppressed. Poisson's ratios from 0.135 to 0.30 allow more distinct stability conditions for Mode II and III ruptures, resulting in period-doubling cycles throughout the stability transition. We further explore the dependence of the maximum pre-event to post-event time ratio on the normal stress, characteristic weakening distance, asperity size, asperity shape, the ratio of friction parameters a and b , and the loading rate (Ref. Supp.). Among these parameters, we find that the loading rate has a strong influence on reducing the peak ratio that occurs across the stability transition (Fig. 10a). At 3 cm/yr, the pre-event to post-event time ratio rises from 1 at 45 MPa to 2.65 at 50 MPa. It then decreases to 1 at 54 MPa (Fig. 10b), resulting in a peak ratio of 2.65 (Fig. 10b), which is 1.6 times much larger than in the laboratory events (~ 1.7 , Fig. 4.4b). At

500 cm/yr, the pre-event to post-event time ratio rises from 1 at 45 MPa to 1.8 at 48 MPa, then, and then decreases to 1 at 52 MPa (Fig. 10c). The ratio reveals a bifurcating pattern (diverges from 1 to 1.8 and converges back to 1, Fig. 4.4d) similar to the laboratory findings (Fig. 4.4b, Fig. S4.5). However, the model does not capture the maturation of the laboratory sample during the initial stage of shearing. For the peak ratio to depend on the loading rate, the duration of some processes must be independent of loading rate, such as the nucleation of frictional instabilities, and early afterslip.

The parameters used to obtain the bifurcation pattern in the laboratory experiments and in the numerical simulations are markedly different. In the laboratory experiments, we use a square sample of 25x25 cm² area that is fully velocity-weakening, whereas the geometry used in the numerical simulations has a circular velocity-weakening patch of radius 3 m surrounded by velocity-strengthening region of 24x24 m² area. The loading rate (10 μ m/s) used in the laboratory experiments is extremely small in comparison to the loading rate (3 cm/s) used in the modeling. The range of normal stress applied in the laboratory experiments is from 13.4 to 25 MPa, whereas the normal stress range is 35 to 54 MPa. Even with these differences, the two approaches are able to produce a similar bifurcation due to the overall dependence of slip behavior on the stiffness ratio k_c/k in laboratory experiments and on the length scale ratio R/h^* in the numerical simulations.

The rich slip patterns in the laboratory experiments (Fig. 4.3) might be caused by irreversible changes in the internal configuration of the gouge layer that accrues over multiple slip cycles (Fig. S4.3, Ref. Supp.). The modeled slip events show less variability in stress drops and inter-event times as compared to the laboratory events. One of the reasons for the differences could be due the use of double direct shear setup in the laboratory experiments as opposed to a finite fault in three-dimensional modeling. Moreover, the shear experiments incorporate gouge layers that thin with slip distance. Such processes that includes an increase in shear strain with slip distance is not incorporated in the numerical model.

4.5 Conclusions

Our laboratory and numerical experiments show that a particular range of fault loading conditions may spontaneously create complex sequences of slip events with different slip velocities and stress drops. These different slip cycles form a bifurcating pattern near the stability transition. Although the geometry and the loading conditions on natural faults may differ widely, our study suggests that alternating slow and fast slip may be a feature of the seismic cycle that emerges spontaneously from the nonlinear dynamics, absent of any external perturbations. If our simple

fault analog already exhibits a plethora of slip modes with complex inter-event times, natural faults (being rough, heterogenous, anisotropic, nonplanar and interconnected) may have the potential of generating far more complex slip behaviors than a characteristic rupture model can predict.

4.6 Supplementary material

To gain a fundamental understanding of the slip mode switches, we combine laboratory experiments and numerical simulations of fault failures. We explain the laboratory setup and procedures, followed by the modeling technique and approaches.

4.6.1 Reproducing fault failures in a laboratory setting

We aim to map possible transitions between stable creeping (no slip events) and fully dynamic events (earthquakes) in a laboratory setup. The criterion for the stick-slip instability in a one-dimensional system depends on the critical stiffness,

$$k_c = \frac{(b - a) \bar{\sigma}_n}{D_c}, \quad (4.1)$$

where a and b are friction parameters, and D_c is the critical weakening distance (Marone et al., 1998). If $a < b$, the fault zone exhibits velocity-weakening, and if $a > b$, it displays velocity-strengthening. The velocity-weakening region is a necessary condition for nucleating instabilities. With this prerequisite, if the system stiffness is $k < k_c$, unstable stick-slip events emerge, and if $k > k_c$, the system will develop stable creeping. For $k \sim k_c$, oscillatory behavior occurs.

Individual modes of aseismic and seismic slip were reproduced by modulating the critical stiffness k_c with respect to the overall system stiffness k (Leeman et al., 2015, 2016; Scuderi et al., 2016). To further explore the values of k_c , we apply fine increments in normal stress (in the order of ~ 0.5 MPa) with respect to the experiment number. Our focus is to track the transitions in slip modes and in inter-event times by studying the variations in stress drop, slip velocity, and inter-event times.

4.6.2 Experimental setup

To apply a constant normal stress in each experiment, we use a servo-controlled biaxial shearing apparatus (Fig. S4.1). A double direct shear configuration (Fig. S4.1a) is used in a biaxial setup (Fig. S4.1b). In double direct shear, two gouge layers, made of fine (median diameter 10.3 microns) powdered silica (from US Silica) are sandwiched between three steel blocks (Fig. S4.1a). The initial thickness of the gouge layer is 3mm. We apply a normal stress

perpendicular to the gouge surface, and we shear it with a constant load rate of 10 $\mu\text{m/s}$ during the experiment. The gouge deforms under shear displacement and layer thinning occurs (Fig. S4.1d). We step up the normal stress with respect to each experiment number, starting from 13.6 to 25 MPa normal stress, resulting in fourteen experiments in total.

Figure S4.1: A typical rock friction experiment setup after Scuderi et al. (2017). (a) A double direct shear configuration. Granular gouge layers are sandwiched between steel blocks and are slid with a constant loading velocity. Normal stress is applied to the blocks horizontally. (b) Biaxial apparatus with normal stress and shearing rate. (c) The rock deformation apparatus, Brittle Rock deformation Versatile Apparatus (BRAVA). (d) A sketch to show thinning of the gouge layer during an experiment.

4.6.3 Laboratory data analysis

Mode switching is identified based on the average slip velocity as well as the stress drop (Fig. S4.2, Fig. 4.2 and 4.3). We obtain the displacement of each event from the onboard Linear Variable Differential Transformers (LVDTs) instrument. The time derivative of the displacement of each slip event provides the slip rate. To distinguish various slip events based on the average slip velocities, it is necessary to fix a threshold slip velocity for the fast stick-slip events ($\sim 1.5 \text{ mm/s}$). The prominent behavior observed at the respective normal stresses are given in Table 4.6.1.

Figure S4.2: Average slip rates of the fault zone under different normal stresses in a laboratory setting. **(a)** The events at 14 MPa, with slip velocities far below 0.5 mm/s are considered as slow slip events. **(b)** Those events at 17 MPa, with slip rates fluctuating above and below 0.5 mm/s are recognized as the consecutive slow-slower slip. **(c)** Similarly, those events at 23 MPa, with slip rates oscillating below and above 1.5 mm/s are identified as the consecutive slow and fast slip. **(d)** At 24 MPa normal stress, the slip rate of the events go beyond 1.5 mm/s and are considered as fast stick-slip events. Slip rate is a quantity used to identify the mode switches.

Table 4.6.1: The predominant slip behavior of the fault gouge under different normal stresses

Sl. No.	Experiment No.	Normal stress (MPa)	Slip behaviors
1	b724	13.6	Stable creep
2	b722	14	Slow slip
3	b696	14.4	Slow slip
4	b726	15	Slow slip
5	b694	15.4	Slow slip
6	b697	16.4	Aperiodic slow-slower slip
7	b693	17	Aperiodic slow-slower slip
8	b698	17.4	Aperiodic slow-slower slip
9	b695	18	Aperiodic slow-slower slip
10	b728	20	Aperiodic slow-slower slip
11	b721	22	Aperiodic slow-slower, and aperiodic slow-fast slip
12	b725	23	Aperiodic slow-fast slip
13	b727	24	Fast slip
14	i417	25	Fast slip

4.6.4 Estimating the stiffness ratios in the laboratory

We used the stiffness ratios from *Scuderi et al.* (2016), and interpolated at newly tested normal stresses (15.4, 17, 23, 24 MPa). The critical stiffness k_c can be calculated using equation (4.1). The shear-loading stiffness k , is the sum of the stiffnesses of the loading blocks and the apparatus. The rate- and state-dependent parameters a and b and the critical weakening distance D_c were estimated in the previous study (*Scuderi et al.*, 2016), where each velocity step was modeled using an iterative singular value decomposition technique. The estimated and interpolated values of k_c/k are shown in Table 4.6.2.

Table 4.6.2: Estimated and interpolated ratios of k_c/k

Normal stress (MPa)	Estimated ratios of k/k_c & k_c/k , (<i>Scuderi et al.</i> , 2016)	
14.5	1	1
20	0.7	1.43
25	0.6	1.67
Normal stress (MPa)	Interpolated ratios of k/k_c & k_c/k , used this study	
15.4	0.95	1.05
17	0.87	1.15
23	0.64	1.56
24	0.62	1.61

We found that the fault zone deforms in two different ways - slow and fast ruptures consecutively - in a single experiment at a constant normal stress (Fig. S4.2c, Fig. S4.3c, Fig. 4.3g), when the stiffness ratio is close to 1.56 (Table 4.6.2). The stiffness ratio of the slow-slower slip mode is close to 1.15 (Fig. S4.2b, Fig. 4.3c). Our methodology with constant loading conditions mimics natural faults under constant far-field loading, which is more

realistic as compared to laboratory findings of slow and fast ruptures under varying loading conditions (Mclasky and Yamashita, 2017).

Figure S4.3: Multiple transitions in a single experiment under a constant normal stress of 23 MPa. The gouge is driven at a fixed loading rate, 10 $\mu\text{m/s}$. **(a)** The mode of slip varies with shear displacement or experimental time. The magnitude of peak shear stress increases with shearing displacement. The slip events transition through aperiodic slow-slower slip, aperiodic slow-fast slip, and fast slip. Accumulation and release of shear stress in **(b)** slow-slower mode and **(c)** slow-fast mode. **(d)** Fast slip mode has larger stress drop values as compared to the other modes.

The stability of the fault zone is tuned through the fixed normal stress in each experiment according to equation (4.1), where k , the system stiffness, is a constant. For a drastic shift from slow slip at 15.4 MPa to fast slip at 24 MPa (Fig. 4.4b), the fault system requires around 9 MPa normal stress. Such a huge change in normal stress makes the stability condition to shift from $k \sim k_c$ to $k < k_c$. Though a fixed normal stress was applied during each experiment, the stability of the fault, k_c can be influenced by the changes in a, b and D_c due to the gouge deformation under shearing (Scuderi *et al.*, 2017). The variability in stress drop of the events at the intermediate stress, 23 MPa (Fig. S4.3), can be explained by this reason.

4.6.5 Challenges and limitations of the laboratory experiments

One of the challenges in laboratory experiments is to have a firm control on the application of a constant normal stress during the test. The conditions that promote aperiodic slow-fast mode are narrow (between 22 and 23 MPa). If we use large increments in the normal stress, we might not observe the transitions. For example, if we test the gouge only at 15 and 20 MPa, the transitory modes in between those stresses might go undetected. The key here is to apply small increments in normal stress with respect to the experiment number, and to maintain strong control of the machine to produce sequences of aperiodic events exhibiting mode switches.

The current setup provides an average slip rate, not the peak slip rate on the frictional interface. During a slipping phase, the slip velocities of some of the zones are likely to be higher. With the current laboratory facility, we are unable to monitor the peak slip velocity within different portions of the slipping zone.

4.6.6 Numerical modeling of fault failures

To model multiple transitional behaviors in between stable creeping and earthquakes, we use the BICycle (Boundary Integral Cycle of Earthquakes) code. The three-dimensional boundary-integral method simulates fault slip evolution during different stages of an earthquake cycle, including nucleation, propagation, and termination (*Lapusta and Liu, 2009; Noda and Lapusta, 2010*). The code has been used for separate studies of individual slip behaviors, e.g., slow slip events (*Liu and Rice, 2005*), repeating earthquakes (*Chen and Lapusta, 2009*), and the period-doubling Parkfield tremors (*Veedu and Barbot, 2016*) on the San Andreas Fault. In this study, we model all these slip behaviors and more by using a simple model geometry, but incrementing the normal stress in different independent experiments. Even though the boundary conditions assumed in the numerical simulation do not closely conform to the laboratory setup, these simulations help us to understand the switches in slip modes and transitions in the inter-event times and to provide an explanatory context to our laboratory findings (Fig. 4.4 b and d).

4.6.7 Modeling approach, model geometry and assumptions

We use the laboratory-derived rate- and state-dependent friction law (*Dieterich, 1979; Ruina, 1983*) to model fault slip. The fault plane has a single circular asperity at the center, with homogenous frictional properties (Fig. S4.4). The fault is embedded in an elastic medium and is loaded at a constant rate.

The shear strength in the model evolves as:

$$\tau = \mu \bar{\sigma} = \left[\mu_0 + a \ln \left(\frac{V}{V_0} \right) + b \ln \left(\frac{\theta V_0}{L} \right) \right] \bar{\sigma}, \quad (4.2)$$

where $\bar{\sigma}$ is the effective normal stress, μ is the coefficient of friction, μ_0 is the steady-state friction parameter at reference slip velocity, V_0 , a and b are frictional parameters, θ is the state variable, and L is the characteristic weakening distance. The ageing law describes the state evolution (*Dieterich, 1979*):

$$\dot{\theta} = 1 - \frac{V\theta}{L}. \quad (4.3)$$

The fault strength at steady state is:

$$\tau_{ss} = \left[\mu_0 + (a - b) \ln \frac{V}{V_0} \right] \bar{\sigma}. \quad (4.4)$$

Figure S4.4: Slip rate of the fault system under different normal stresses in a numerical modeling setup. **(a)** Model geometry with a velocity weakening patch surrounded by a velocity-strengthening region driven at a constant loading rate of 3 cm/yr. **(b)** At 40 MPa normal stress, regular events slip with velocities close to 0.1 $\mu\text{m/s}$ and are considered as slow slip. **(c)** Events at 46 MPa, alternating between 0.1 $\mu\text{m/s}$ and 0.1 m/s, are identified as slow-slower slip. None of the events are elastodynamic in this regime. **(d)** The events at 50 MPa, oscillating above and below 0.1 m/s (the threshold slip rate for elastodynamic events) are recognized as slow-fast slip. **(e)** Regular events that cross the threshold velocity are fast slip. Slip velocities are measured from the center of the fault patch.

The velocity-strengthening region of the fault interface has $a > b$ and the velocity-weakening asperity has $a < b$ (Rice and Ruina, 1983; Ruina, 1983; Scholz, 1998).

Friction parameters, a and b and nucleation size, h^* control the occurrence of individual slip behavior (Dieterich, 1979; Rice and Ruina, 1983; Ruina, 1983). G is the rigidity modulus in the equation for nucleation size:

$$h^* = \frac{\pi}{2} \frac{GbL}{(b-a)^2\bar{\sigma}}. \quad (4.5)$$

Separate slip behaviors such as stable creep, slow slip events, and earthquakes can be simulated by changing the nucleation size, which can be done by varying any of the parameters in equation (4.5). If the nucleation size is much larger than the asperity size, the fault creeps; if it is negligible compared to the asperity size, frictional instabilities (or earthquakes) emerge. When the nucleation size is of the order of the asperity size, slow transients originate. We keep the asperity size R constant in all of the simulations. Similar to the stiffness ratio k_c/k , in the laboratory experiments, the stability criteria in the numerical modeling explain three distinct slip behaviors, but not all the transitional behaviors. Hence, we apply a small increment in normal stress with respect to the simulation number (Fig. 4.4c and d), in order to tune the stability of the fault system. The resulting slip events are identified based on the slip rate from the center of the patch (threshold slip rate for the elastodynamic model is $\sim 0.1\text{m/s}$, Ext. Fig. 4.4), and the stress drop during each event (Fig. S4.5 and S4.6).

Figure S4.5: Comparing the pattern of inter-event times of the modeled and laboratory events. **(a)** The pattern corresponds to model with a loading rate of 3 cm/yr. **(b)** Laboratory slip events. The slow slip, aperiodic slow-slower, aperiodic slow-fast, and fast slip constitute a continuum of slip modes.

The normal stress is kept constant in each simulation, and the evolution of a , b and L during each simulation are not incorporated in order to produce continuous transitions in slip modes. For the transition from periodic slow slip at 44 MPa to periodic fast slip at 52 MPa (Fig. 4.4d), the fault system requires around 8 MPa normal stress. This change in normal stress makes the stability condition shift from $h^* \sim R$ to $h^* < R$, hence the drastic change in behavior.

It is important to note that deterministic chaos was not observed in any of the simulations reported here with the fully dynamic model, unlike the models that produced deterministic chaos with the radiation damping approximation (Kato, 2014). This implies that deterministic chaos is a feature of the radiation damping approximation. It is not possible to say if the laboratory data contain deterministic chaos because of the noise.

4.6.8 The role of loading rate on the recurrence time ratio

We assume a time-predictable model to explain the effect of the critical nucleation size and the loading rate on the recurrence time ratio. The quiescent time following any event is proportional to the slip of the event and a generally small nucleation time independent of the loading rate.

In the case of a slow slip event, the slip can be approximated by the characteristic slip distance as

$$T^{\text{slow}} = T^{\text{nucleation}} + \frac{L}{V_L} \quad (4.6)$$

where $T^{\text{nucleation}}$ is the short nucleation time of the instabilities, L is the characteristic slip distance, and V_L is the loading velocity.

In the case of fast ruptures, we approximate as

$$T^{\text{fast}} = T^{\text{nucleation}} + \frac{(b-a)\bar{\sigma}}{G} \frac{W}{V_L}, \quad (4.7)$$

where $(b-a)\bar{\sigma}$ is the stress drop, assumed to be a constant, $(b-a)\bar{\sigma}/G$ is the eigenstrain, and $(b-a)\bar{\sigma}W/G$ is the cumulative slip, approximated to be constant.

The recurrence time ratio can be written as

$$\frac{T^{\text{fast}}}{T^{\text{slow}}} = \frac{T^{\text{nucleation}}V_L + \frac{(b-a)\bar{\sigma}W}{G}}{T^{\text{nucleation}}V_L + L} \quad (4.8)$$

For a small enough loading rate, this can be approximated by

$$\frac{T^{\text{fast}}}{T^{\text{slow}}} = \frac{(b-a)\bar{\sigma}}{G} \frac{W}{L} = \frac{W}{h^*}, \quad (4.9)$$

indicating that the normalized slip-weakening region controls the recurrence ratio. For increased loading rate, the nucleation time becomes strong, until the disappearance of the period-doubling cycles.

4.6.9 The effect of the Poisson's ratio on the recurrence time ratio

The nucleation zone size, L_c (Rubin and Ampuero, 2005), can be written as:

$$L_c = \frac{\pi}{2} \frac{G^* bL}{(b-a)^2 \bar{\sigma}} \quad (4.10)$$

for mode II,

$$G^* = \frac{G}{(1-\nu)}, \quad (4.11)$$

and for mode III, $G^* = G$, where, G is the rigidity modulus, and ν is the Poisson's ratio.

For mode II and mode III ruptures, two different stability conditions exist due to the difference in stiffness, which is modulated by Poisson's ratio ν . Only single-periodic cycles occur for $\nu = 0$, for which the conditions for nucleation are identical for mode II and mode III. The period-doubling cycles occur for $\nu > 0.135$.

Overall, we find that the slow-fast ruptures are strongly influenced by both the Poisson's ratio and the loading rate. The occurrence of period-doubling cycles are determined by the simultaneous stability conditions, which occur for values of ν larger than 0.135. The peak recurrence time ratio decreases with an increase in the loading rate, V_L .

4.6.10 Implications for the transitional regimes

Our physics-based modeling suggests irrespective of the individual parameters (L or σ as in equation 4.5), the value of the normalized slip-weakening region controls the mode switches and transitions in inter-event times. Despite the scaling differences between laboratory and numerical experiments, aspects of the conclusions can still be compared. First, the fault gouge sample and circular fault patch at constant loading conditions produce period-doubling slow-slower and slow-fast ruptures. Second, the normal stress required to completely shift from slow slip to fast slip is 7-9 MPa. Third, the stiffness ratio (kc/k , Table 2) and the nucleation size ratio (R/h^*) for the period-doubling slow and fast rupture are comparable (~ 1.6) when h^* is $GL(b-a)/\bar{\sigma}$.

With this interdisciplinary approach involving friction experiments and numerical modeling, we suggest that a small change in the stability condition of a fault system can force it to undergo multi-mode transitions. We suggest that the occurrence of standalone quasiperiodic slow slip in regions like northern Cascadia and Nankai subduction zones, and slow slip preceded by earthquakes in Japan, Chile, and Central American subduction zones may be controlled by two distinct bifurcations in fault stability. The pivotal bifurcations revealed in our laboratory and numerical experiments distinguish single-mode slow slip from complex sequences of bimodal rupture cycles with varying slip velocities and stress drops. In general, the absence of the dynamic-slip bifurcation may be the key in differentiating fault segments that exhibit quasiperiodic slow slip from the segments that generate bimodal slow-fast behavior. Understanding the emergence of slow-fast ruptures in the context of single-mode quasiperiodic slow slip and single-mode fast ruptures may help us to fathom the propensity of faults for seismic hazards.

Figure S4.6: Simulated slip events with pre-event to post-event time ratio close to that of the laboratory slip events. **(a)** The pre-event to post-event time ratio decreases with increasing loading rate. At 3 cm/yr, the ratio is 2.65, and at 500 cm/yr, the ratio is 1.65. **(b)** The pattern of pre-event to post-event time ratio as a function of normal stress at a fixed loading rate of 3 cm/yr. The ratio rises from 1 at 45 MPa to 2.65 at 50 MPa. Following that, the ratio decreases to 1 at 54 MPa. **(c)** The pattern of pre-event to post-event time ratio as a function of normal stress at a fixed loading rate of 500 cm/yr. The ratio rises from 1 at 45 MPa to 1.8 at 48 MPa. Following that, the ratio reduces to 1 at 52 MPa. The ratio is 1.65 at 50 MPa under 500 cm/yr loading rate.

Figure S4.7: The dependence of pre-event to post-event time ratio on the Poisson's ratio. The pre-event to post-event time ratio increases with an increase in Poisson's ratio. Poisson's ratios from 0 to 0.13 induce fast rupture, by eliminating Mode III rupture. Poisson's ratio from 0.135 to 0.30 cause consecutive slow and fast ruptures. The stability conditions for mode II and mode III are similar in this range.

Conclusion

5.1 Thesis synthesis

Seismologic and geodetic monitoring along active faults have revealed distinct slip behaviors such as fault creep, slow-slip events, and earthquakes, establishing a concept that a single fault segment produces a single type of slip behavior. To change this view, we present findings from numerical simulations and laboratory experiments and show that the same segment can rupture in multitude of ways. This is achieved by interlacing three studies that are well-aligned in exploring the phenomenon of alternating slip patterns.

First, we study one of the most fascinating tremors in the world, the Parkfield tremors, that oscillate between ~ 3 and ~ 6 days (Chapter 2). With a fault patch that slips in slow and fast, we explain the peculiar doubling intervals of the Parkfield tremors. We also show that the poroelastic effects (a change in the effective normal stress and the pore-pressure diffusion) can explain the disruption of the tremor pattern by the 2004 Mw=6 Parkfield earthquake. We suggest that the divergence in the number of low frequency waves in a tremor event may be due to the difference in the slip velocity of the underlying events that drive the tremors.

Second, we investigate another aspect of the Parkfield tremors: The rarity of the period-doubling pattern. The Parkfield tremors are the only known observations that show doubling intervals on tectonic faults. To understand the rarity of such observations, we design the second study (Chapter 3). In particular, we attempt to pin down the range of conditions that causes the alternating slip behavior. Using numerical simulations, we incorporate a systematic report on the conditions that allow complex styles of fault slip on fault asperities, including not only fast ruptures (earthquakes) and slow slip, but the complex instabilities that occur between these different regimes. Once we decide a set of model parameters for the slow-fast phenomenon as a reference, we meticulously test how variations in physical parameters affect the details of the rupture behavior. These deviations include geometry of the

patch (size, shape, and area), rate-and state-dependent parameters (direct friction parameter, evolution parameter, characteristic slip distance), Poisson's ratio, normal stress, and loading rate. We show that the transition is not abrupt rather exhibits a bifurcation, where intermediate parameter values produce period-doubling cycles with combinations of slow and fast ruptures. Thus, we extend the understanding of a stability condition to a stability transition zone with slow-slower and slow-fast ruptures.

In particular to the behavior of slow-fast ruptures, we find that, the patch area has more control on this phenomenon than the aspect ratio, for a given nucleation size. To induce slow-fast ruptures, the patch area has to be 28.26 m^2 for a nucleation size of 1.83 m , however, this may not be generally true as previous studies (Lapusta and Liu, 2009) show that the smaller dimension of the patch affects slip dynamics for a fixed nucleation size. The transition with the slow-fast phenomenon happens when the normalized slip-weakening region W/h^* is in between 2.95 and 3.55, for $a/b = 0.4$. The Poisson's ratio of the fault patch has to be between 0.14 and 0.30 in order to exhibit the slow-fast phenomenon. The loading rate V_L , affects the peak recurrence time ratio of the slip patterns strongly, resulting in the most distinct slip events within the transition. The fault patch is sensitive to the material properties a and b , especially the ratio of friction parameters a/b , that controls the width of the transition zone.

In the third study (Chapter 4), we explore beyond the observation of the Parkfield tremors to understand the physical conditions that distinguish single-mode slow slip from bimodal slow-fast ruptures. We present experimental findings of the appearance of alternating slip patterns from laboratory samples (granular quartz) under conditions close to instability nucleation. Validating the modeling results of alternating slow-fast ruptures using laboratory friction experiments is one of the highlights of the Chapter 4. As the normal stress is increased in the laboratory setup in a series of experiments, the sample interface first experiences periodic slow slip, followed by alternating slip patterns, and finally fully dynamic slip. We find three key features that are strikingly common in both laboratory experiments and numerical simulations. First, the system undergoes a dramatic transition with slow-slower and slow-fast ruptures, before it shifts into the fully dynamic regime. Second, the peak recurrence time ratio is close 1.8 in both the cases. Third, both the approaches show two distinct bifurcations that sets apart single-mode slow slip from bimodal slow-fast ruptures. The difference in the nucleation size in the mode II and III direction is identified as the main reason for such alternating patterns, as confirmed by simulations that vary Poisson's ratio and hence the resulting patterns. This work enables us to combine laboratory experiments and numerical simulations to show a broad range of frictional instabilities around the stability transition, which can provide insights into the complex slip observations on natural faults.

5.2 Implications of slow slip and earthquake ruptures

Several studies show the observations of slow slip along the Pacific rim (*Obara and Kato, 2016; Peng and Gomberg, 2010; Schwartz and Rokosky, 2007*), suggesting that slow slip behavior may be ubiquitous on faults. However, there are plate boundaries that lack ample evidence of slow-slip and tremors as compared to the subduction zones such as Japan and Chile. For, eg., the first and the only reported observation of tectonic tremor in Sunda Arc, as far as we know, is by *Sianipar and Subakti (2017)*.

Our second study (Chapter 3) using numerical simulations show that slow slip behavior (standalone slow slip as well as alternating slip patterns) occur within a narrow range of conditions, however, the reasons for the rarity of the observable slow slip events along the Sunda trench is most probably due to the unavailability of high-resolution instruments close to the subduction zone. In such instances, paleogeodetic studies are found to be very helpful to uncover the existence of slow-slip events. For example, a study by *Tsang et al. (2015)* has shown the longest ever recorded slow earthquake in Banyak islands of Sumatra by utilizing the coral records.

Whether a fault segment would slip slow in solo repeatedly or would it slip slow prior to an earthquake is an important question when assessing seismic hazard of a region. Increasingly well-documented instances show that the same fault segment fails in both slow and fast ruptures within a short period, e.g., before the 2011 Mw=9.0 Tohoku-Oki, Japan and 2014 Mw=8.2 Iquique, Chile earthquakes. However, why slow slip alternates with potentially devastating earthquakes in certain regions, but appears separately in others, for example, along the northern Cascadia and Nankai subduction zones, is not well understood.

The pivotal bifurcations revealed in our laboratory and numerical experiments (Study 3/Chapter 4) demarcate single-mode slow slip from complex sequences of bimodal rupture cycles with varying slip velocities and stress drops. We suggest that the occurrence of standalone quasiperiodic slow-slip along northern Cascadia and Nankai subduction zones and slow slip preceded by earthquakes in other cases (Japan, Central America, and Chile subduction zones) may be controlled by these two bifurcations in fault stability. In general, the absence of the dynamic-slip bifurcation may be the key in differentiating fault segments that exhibit standalone quasiperiodic slow slip from the segments that generate bimodal slow-fast behavior. Understanding the emergence of slow-fast ruptures in the context of single-mode ruptures may help us to fathom the propensity of faults for seismic hazards.

Among all the disciplines in earthquake science, the geodetic and seismologic observations contributed to the majority of our current knowledge of slow slip and earthquakes. A growing number of evidence for slow earthquakes

have been made using geodetic instruments (*Hirose et al.*, 1999; *Ohta et al.*, 2006). The related phenomena - tectonic tremors - usually referred to as a manifestation of underlying slow earthquakes, can be observed by seismometers, and in most cases, they inform the existence of the underlying slow earthquakes (*Han et al.*, 2014).

Although the direct identification of slow-slip in a geologic setting is found to be difficult, several structural geologic studies show evidences of exhumed fault zones with characteristics that can be connected to slow-slip events (*Fagereng and den Hartog*, 2017; *Fagereng and Harris*, 2014). An exhumed subduction complex in outcrops that has the features of slow-slip and tremor is reported by *Behr et al.* (2018). Geological evidence of slow slip near the brittle-ductile transition is documented, especially on the high temperatures and pressures at the base of the seismogenic zone that promote ductile deformation processes in some minerals, providing conditions for aseismic shear (*M.R. Handy*, 2007; *S. Angiboust*, 2015).

Occurrences of single-mode slow slip or dynamic slip can be inferred from geological settings, however, recognizing alternating slow-fast patterns may be extremely difficult, mainly due to the possible overprinting of the evidence of slow-slip behavior by that of a dynamic slip. We note that paleoseismologic and structural geologic studies on the occurrence of bimodal slip behavior is yet to be fully explored at the moment, hence it opens up the opportunity to investigate such phenomena in geological settings. Essentially, to understand the true potential of the tectonic faults-the full range of slip behaviors- it is crucial to integrate several scientific disciplines in earthquake science such as seismologic, geodetic, palaeogeodetic, geologic, structural geologic, earthquake cycle modeling, and laboratory friction experiments.

5.3 Future projects

5.3.1 Preslip, nucleation jump, and creep break leading to complex ruptures

Collaborators: Deepa Mele Veedu and Sylvain Barbot

In this project, we propose a unified view of fault dynamics - a phase diagram (Fig. 5.1) that predicts the characteristics of the slip cycles based on physical properties and geometry. We already published one of the key results from this study, the dynamic slip breaking into the surrounding strengthening region, to explain the overlap of coseismic and afterslip areas of the 2008 Mw=7.2 North Pagai earthquake sequences off the west coast of Sumatra (*Salman et al., 2017*).

Figure 5.1: A comprehensive phase diagram from a circular asperity using three-dimensional fully dynamic modeling (*Lapusta and Liu, 2009*). Among the main slip regimes, stable sliding, slow slip, slow-slower, slow-fast, bilateral, and unilateral, the end-member regime reveals a trail of events leading to complex ruptures. We identify eleven different slip behaviors progressively becoming complex towards larger $(b - a)/b$ values.

5.3.2 Investigating the effect of grain size and layer thickness on the slow-fast ruptures using the Biax machine at the Penn State University

Collaborators: Deepa Mele Veedu, Srisharan Shreedharan, David Chas Bolton, and Chris Marone.

To understand the role of grain size and layer thickness on slip behaviors, we conducted 16 experiments using the Biax machine at the Penn State University. For the tests, we use the parameters in Table 5.2.1 as a reference and deviate from it as shown in Table 5.2.2. We found that the slip events from the Biax machine are 6 -16 times faster

than the preceding slow slip event (Fig. 5.2) as compared to the events from the Brittle Rock Versatile Deformation apparatus at the National Institute of Geophysics & Volcanology (Fig.5.3).

Figure 5.2: Slip rate and stress curves of slow-fast ruptures from powdered quartz using the Biax machine at the Penn State University. Slip rate of the slow slip is of the order of a few hundred $\mu\text{m/s}$ whereas that of the fast events are a few mm/s .

Figure 5.3: Slip rate of slow-fast ruptures from powdered quartz using the Brittle Rock Versatile Deformation apparatus at the National Institute of Geophysics & Volcanology (INGV). Slow events slip close to $500 \mu\text{m/s}$. The fast events cross the threshold slip rate of 1.5 mm/s .

Table 5.3.1: The parameters used at the National Institute of Geophysics & Volcanology

Loading rate ($\mu\text{m/s}$)	Grain size (μm)	Layer thickness (mm)	Normal stress (MPa)
10	10.5 (minusil-40)	3	13.4 to 25

Table 5.3.2: The effect of grain size and layer thickness on the stability transition (at Penn State)

Date	Expt. No.	Grain size (μm)	Humidity	dcdtOB	σ (MPa)	Behavior	Aim
15 Oct'18, M	p5163	min-40 (10.5)	N	N	18-35	Slow slip	L boundary
16 Oct'18, T	p5164	min-40 (10.5)	N	N	35-39	Slow slip	U boundary
16 Oct'18, T	p5166	min-40 (10.5)	Y	N	35-38	PDoubling	Humidity
17 Oct'18, W	p5168	min-40 (10.5)	Y	N	32-35	PDoubling	U boundary
18 Oct'18, T	p5169	min-40 (10.5)	Y	N	33	PDoubling	Baseline
19 Oct'18, F	p5170	min-5 (1.7)	Y	N	33	PDoubling	Grain size
19 Oct'18, F	p5171	sil-125	Y	N	33	VS	Grain size
20 Oct'18, S	p5172	min-15 (4.4)	Y	Y	33	PDoubling	Grain size
21 Oct'18, S	p5173	sil-90	Y	Y	33	PDoubling	Grain size
22 Oct'18, M	p5174	sil-106	Y	Y	33	VS	Grain size
23 Oct'18, T	p5177	min-30 (8.5)	Y	Y	33	PDoubling	Grain size
24 Oct'18, W	p5179	min-10 (3.8)	Y	Y	33	PDoubling	Grain size
25 Oct'18, T	p5180	min-5 (1.7)	Y	Y	33	PDoubling	Repeated
25 Oct'18, T	p5181	min-40 (10.5)	Y	Y	33	PDoubling	Gouge at PD
26 Oct'18, F	p5182	min-40, 2 mm	Y	Y	33	PDoubling	Layer thickness
27 Oct'18, S	p5183	min-40, 7 mm	Y	Y	33	PDoubling	Layer thickness

5.3.3 Imaging the slow nucleation before fast ruptures in Poly(Methyl Meth-Acrylate) (PMMA) at the California Institute of Technology

Collaborators: Deepa Mele Veedu, Vito Rubino, Shengji Wei, and Ares Rosakis

We plan to investigate the effect of fluid pressure on inducing slow slip events followed by a fast rupture using the below setup. Seismic sensors, velocity meters, and strain gauges will be incorporated to the 3D PMMA block in 2020.

Figure 5.4: Three-dimensional block of Poly(Methyl Meth-Acrylate) (PMMA) with a narrow conduit to inject fluid (water/gas) to create spontaneous rupture of slow-slip events.

5.3.4 Concluding thoughts

Here, I place my thesis as a humble effort towards understanding the slow-fast phenomena around the stability transition. I look forward to work on other possible behaviors, especially to uncover chaotic slip events and their relation to the instabilities that we identified so far.

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