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Romain Jolivet, W. Frank

AGU100 ADVANCING EARTH AND SPACE SCIENCE

AGU Advances

COMMENTARY
10.1029/2019AV000126

Key Points:
- Slow slip happens at all spatial and temporal scales
- Slow slip is an intrinsically intermittent and clustered process
- There is no observational evidence for different physical mechanisms for slow slip in different tectonic contexts

Supporting Information:
- Original Version of Manuscript
- Peer Review History
- First Revision of Manuscript [Accepted]

Correspondence To:
R. Jolivet,
romain.jolivet@ens.fr

Citation:
Jolivet, R & Frank, W. B. (2020). The transient and intermittent nature of slow slip. *AGU Advances*, *1*, e2019AV000126. https://doi.org/10.1029/2019AV000126

Received 21 NOV 2019
Accepted 15 JAN 2020
Accepted article online 3 MAR 2020

Peer Review The peer review history for this article is available as a PDF in the Supporting Information

The Transient and Intermittent Nature of Slow Slip

R. Jolivet[1,2] and W. B. Frank[3,4]

[1]Laboratoire de Géologie, Département de Géosciences, École Normale Supérieure, CNRS UMR 8538, PSL Université, Paris, France, [2]Institut Universitaire de France, Paris, France, [3]Department of Earth Sciences, University of Southern California, Los Angeles, CA, USA, [4]Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA, USA

Abstract To first order, faults are locked while stress builds up to a devastating earthquake. However, we know that faults also slip slowly. After decades of geophysical observation, slow slip is now recognized as part of a continuum of transient deformation ranging from the dynamic propagation of seismic rupture to aseismic events over a wide range of durations and sizes. A growing body of evidence suggests that large-scale slow slip events can be decomposed into a multitude of smaller, temporally clustered events. Slow slip is more frequent and more dynamic than is suggested by conceptual models of rate-strengthening, stable slip.

Plain Language Summary The relative motion of tectonic plates on Earth leads to the accumulation of elastic energy at plate boundaries. Tectonic faults can release this energy, either suddenly by rapid (m/s) slip that generates seismic shaking (i.e., during earthquakes) or gently by slow (mm/year to m/year) slip. Subseismic slip can release just as much energy as fast slip, implying slow slip plays an important role in the earthquake cycle. Following decades of discoveries fueled by technological improvements in geophysical observation methods, we argue that the main difference between various slow slip phenomena is, for now, semantics. Diving into the details of time series of geodetic and seismological observations suggests slow slip is made up of many subevents that interact with each other, just like the aftershocks that always follow the triggering earthquake mainshock. We thus conclude that slow slip is simply the release of elastic energy by slip along faults, just at much slower rates than regular earthquakes.

1. A Brief History of Slow Slip

A fault releases elastic energy stored in the crust through slip along its interface. Fault slip rates can be rapid enough to radiate seismic waves during earthquakes (i.e., on the order of m/s) or slow enough that only geodetic instruments sensitive to aseismic motion can capture its surface signature (i.e., on the order of cm/year). Such slow slip was first suspected following observations of the behavior of faults at shallow depth. Observations of slow shearing within serpentines was discovered more than 70 years ago in a tunnel crossing the Hayward fault in the eastern San Francisco Bay area (Louderback, 1942). Although there are no reported measurements of slip, the serpentine is described as "flowing under its own weight like a viscous liquid," and it appeared at the time "quite evident that such material cannot offer the resistance to deformation required to build up a marked elastic strain." The first actual measurements of slow slip were derived from the offsets of the walls of a winery near the northern end of the San Andreas fault central section, south of the San Francisco Bay area (Steinbrugge et al., 1960). Creepmeter-like measurements were made by regularly tracking the offset of markers embedded within the moving walls, all the while seismically monitoring the nearby section of the San Andreas fault. Because no significant earthquakes were identified, slip was considered aseismic and proposed as "a second significant mechanism in relieving the secular accumulation of elastic strain across faults," considered to be "an important modification to Reid's theory" of the elastic rebound (Reid, 1911; Steinbrugge et al., 1960). Ten years later, slow slip was then also suspected in Turkey along the North Anatolian fault (Ambraseys, 1970); subsequent observations confirmed slow slip as a major player along this fault system (e.g., Altay & Sav, 1991; Rousset et al., 2016).

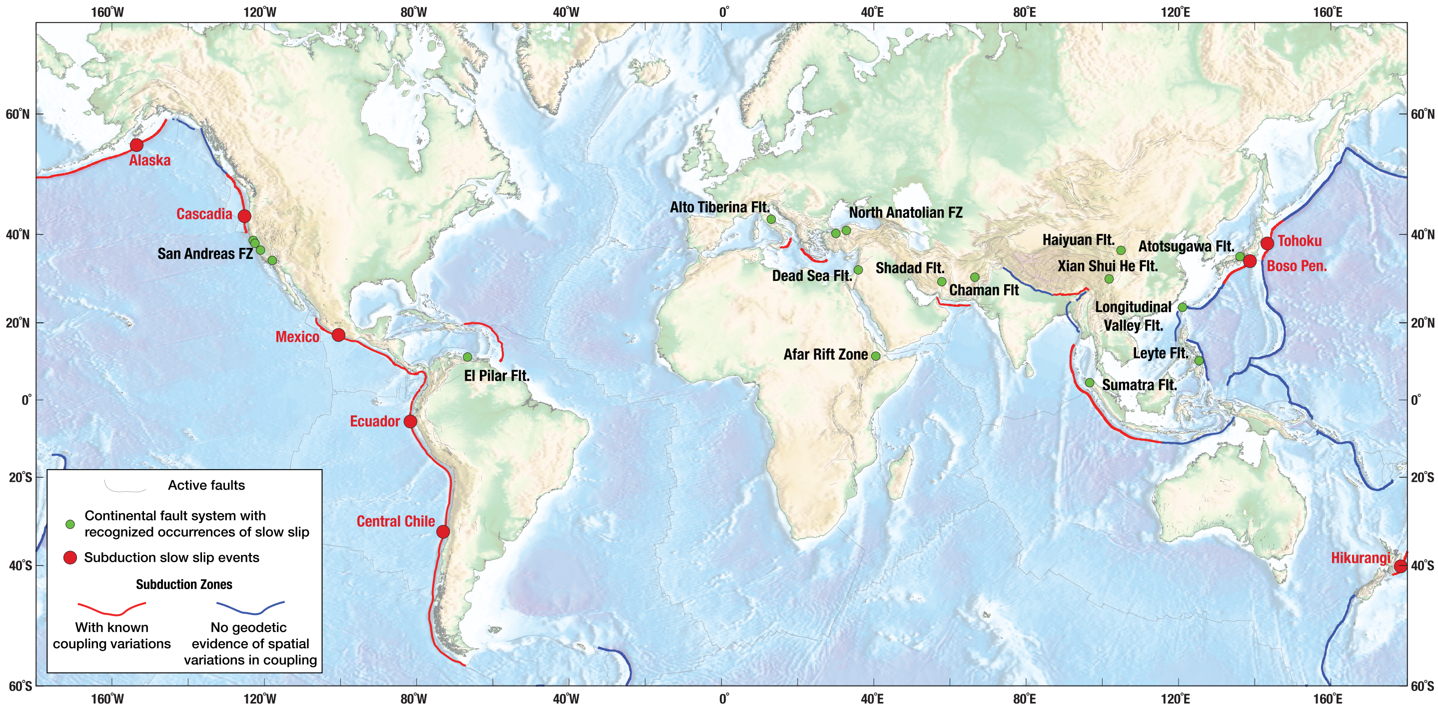

Figure 1. Slow slip happens wherever we look for it. Colored dots highlight where slow slip has been observed; red dots highlight observations at subduction zones; green dots indicate slow slip on continental fault systems. Blue and red lines are subduction zones, with red indicating subduction zones where there is geodetic evidence of spatially heterogeneous coupling. Dark thin lines are active faults from the Global Earthquake Model (http://globalquakemodel.org). Background color is the ETOPO1 global topography (Amante & Eakins, 2009).

2. Slow Slip Is Ubiquitous

We now know that slow slip is an important part of the slip budget at active faults. New geophysical instrumentation has been necessary to identify and characterize worldwide occurrences of slow slip. The first time-dependent measurements were made possible with the deployment of continuous strain meters and creepmeters along active faults (e.g., Bilham, 1989; King et al., 1975; Lienkaemper et al., 2012). Networks of continuously operating Global Positioning System (GPS) stations and suites of Interferometric Synthetic Aperture Radar (InSAR) images now capture the spatiotemporal evolution of slow slip at high resolution (e.g., Doubre & Peltzer, 2007; Khoshmanesh & Shirzaei, 2018; Michel et al., 2019; Rousset et al., 2016, 2017, 2019). At depth, slow slip was first thought to only affect the first "few miles" of the crust (Louderback, 1942), while earthquakes would control the slip budget at greater depth. We now know that some faults are locked up to the surface while others slip aseismically down to seismogenic depth (e.g., Cetin et al., 2014; Jolivet et al., 2015). Finally, growing evidence suggests the nucleation, propagation, and arrest of seismic rupture are mediated by slow slip, which in turn directly affects the seismic hazard in tectonically active regions (e.g., Avouac, 2015; Bürgmann, 2018; Obara & Kato, 2016).

Along any fault network where regional-scale, dense, and continuous geodetic data sets have been gathered, we have been able to observe slow slip (Figure 1). The advent of continuously operating GPS networks and high-resolution InSAR time series provoked a series of slow slip discoveries across multiple subduction zones and major continental fault networks (e.g., Cavalié et al., 2008; Duquesnoy et al., 1994; Pousse Beltran et al., 2016; Wallace et al., 2016). We have observed slow slip to exhibit a range of temporal behaviors, including periodic oscillations or episodic transients, along all kinds of plate boundaries, whether convergent, divergent, or transform and even within volcanic contexts (Cervelli et al., 2002; Doubre & Peltzer, 2007; Jolivet et al., 2012; Rogers & Dragert, 2003). This implies that there is no fundamental difference between these tectonic contexts with regards to the mechanics of slow slip. We thus suggest that slow slip is a general tectonic process to transiently release built-up stress along faults, similar to earthquakes. With the development of seafloor geodesy and ocean bottom seismic networks, we should be able to extend our coverage into zones of oceanic-oceanic plate convergence, ocean transform faults, and eventually mid-ocean ridges.

This exciting time of discovery after discovery has, however, created a dense lexicon of aseismic slip, whose litany of acronyms is impenetrable to the uninitiated. Both networks of permanent GPS stations and time series of InSAR data capture aseismic slip with an apparent constant rate (e.g., Harris, 2017; Jolivet et al., 2015; Loveless & Meade, 2011; Metois et al., 2012), postseismic afterslip (e.g., Lin et al., 2013; Perfettini et al., 2010), or episodic slow slip events (e.g., Radiguet et al., 2012; Rogers & Dragert, 2003), sometimes even with qualifiers like “long term” or “short term” that refer to different time scales that vary from region to region. We can also include low fault coupling at subduction zones (e.g., Metois et al., 2016) or continental faults (e.g., Jolivet et al., 2015) as another form of slow slip with yet another name. Seismology has also contributed to the confusion with its own jargon of indirect manifestations of slow slip, including sequences of repeating earthquakes (i.e., seismic ruptures embedded in a predominantly aseismic fault segment; e.g., Nadeau & McEvilly, 1999; Uchida et al., 2016), or the unique seismic signals that accompany slow slip, whether it be emergent tectonic tremors (e.g., Obara, 2002; Rogers & Dragert, 2003), impulsive low-frequency earthquakes (Shelly et al., 2007), or even very low frequency earthquakes (Ito et al., 2007).

We suggest here that whether it be called slow slip, low coupling, episodic tremor and slip (an imprecise term that conflates seismic and aseismic slip together), silent earthquakes, precursory aseismic slip, active fault or surface creep, transient aseismic slip, or even afterslip, these are all different names for one phenomenon constrained by comparable observations: the slow, transient release of stress by aseismic slip along a fault. The obvious parallel is earthquakes: They come in many different flavors, but earthquakes are always called earthquakes. The differences in naming conventions likely originate from the different communities that have explored different geological contexts in parallel series of discoveries and advances.

It is tempting to appeal to different physical mechanisms for slow slip in different tectonic contexts, but, so far, our geophysical evidence of all of these phenomena is quite comparable. For instance, observations of time-varying megathrust coupling in subduction zones (e.g., Materna et al., 2019) are in fact not so different from the major slow slip events that regularly occur in Cascadia or Japan. A recent study (Frank, 2016) found that the collection of slow slip cycles in one subduction segment could explain nearly 100% of the geodetically inferred lack of slip deficit (i.e., coupling). It has also been proposed that to explain the geodetic measurements in Cascadia, the downdip end of the coupled portion of the megathrust migrates toward shallower depth with time (Bruhat & Segall, 2017). These different geodetic observations could all be interpreted either as spatiotemporal variations of plate coupling or occurrences of slow slip, because there is no observational difference between the two possibilities aside from the methodological approach. In short, one might wonder whether there is a significant mechanistic difference between a month-long slow slip event and a year-long variation in fault coupling.

We thus posit that the differences in observational contexts are, for now, semantics. All observations point to a transient release of elastic energy through aseismic slip, and no observational evidence to argue differently has yet been made. We thus argue here that our community must simplify our jargon, in an effort to foster collaborations with allied disciplines like physics and solid mechanics and to ease the entrance of new scientists into our field of study.

3. Spatial and Temporal Complexity of Slow Slip

One characteristic feature that emerges from our collection of geodetic observations is that slow slip appears to be made up of smaller subevents. The characteristic temporal and spatial scales of the smallest detectable events continue to decrease as the resolution of our observations becomes finer. Observing the spatial and temporal complexity of slow slip using slip inversions is still limited, as we must consider issues of resolution and regularization of the inversion procedure. Although new approaches aim to solve such kind of issues (e.g., Dettmer et al., 2014; Minson et al., 2013; Michel et al., 2019; Rousset et al., 2017), the fine scale of aseismic slip is most evident when exploring the details of our direct observations: the time series of surface displacements (e.g., Michel et al., 2019; Rousset et al., 2019).

Although GPS time series of displacement have been used extensively to explore the temporal evolution of slow slip, seismological data have been key recently to guide the eyes of experts in extracting more detailed information from the geodetic record. In Mexico, Cascadia, and Japan, dense networks of seismic stations, often colocated with GPS, have recorded new seismic signals such as tectonic tremors and low-frequency earthquakes that accompany slow slip (Kostoglodov et al., 2010; Obara, 2002; Rogers & Dragert, 2003; Shelly

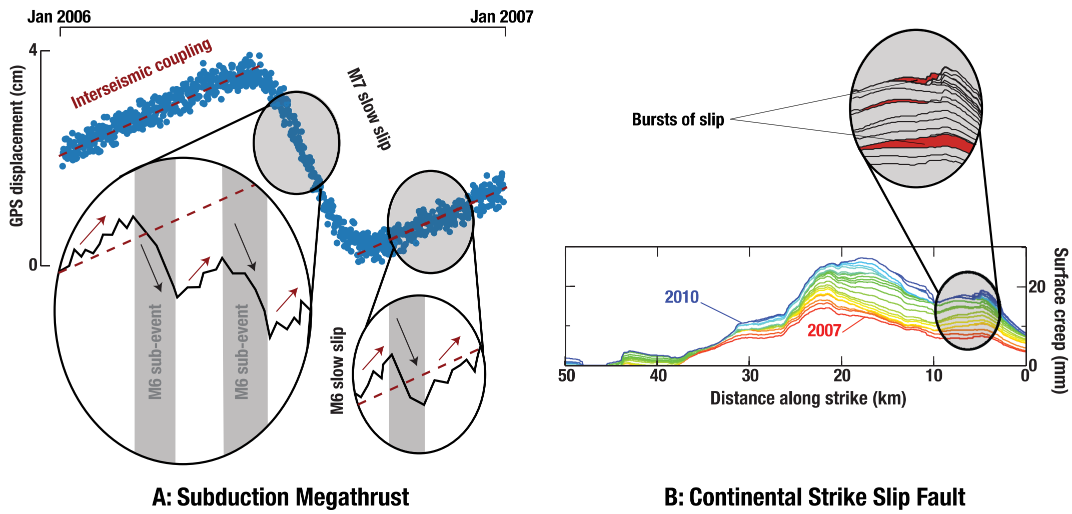

Figure 2. Schematic observations of the temporal intermittence of slow slip. (Left) A synthetic GPS time series of slow slip. The slow slip event is clearly identified by the reversal of surface motion in the time series. A closer look at the time series reveals that the macroscale slow slip is a complex sequence of aseismic subevents, each accompanied by a burst of microseismicity (e.g., Frank et al., 2018; Rousset et al., 2019). Intermittent slow slip is also prevalent during the interim period between major slow slip events, implying that long-term tectonic coupling underestimates the actual coupling over short time scales (Frank, 2016). (Right) Temporal evolution of aseismic slip as a function of distance along strike measured by InSAR along the Haiyuan transform fault. Color indicates time with first line in early 2007 and last line in 2010. Slip is made of bursts of different amplitudes and along strike length. Figure modified from Jolivet et al. (2015).

et al., 2007; Wech & Bartlow, 2014). These phenomena are now considered the seismic signature of slow slip, but they only represent a small fraction of the total moment of slow slip captured by geodesy (e.g., Frank & Brodsky, 2019; Kao et al., 2010; Kostoglodov et al., 2010). The consensus physical interpretation is that tremor and low-frequency earthquakes are the rupture of small brittle asperities driven to failure by the surrounding slow slip (Bartlow et al., 2011). Testing the limits of this interpretation, finer details emerge when using the seismic information to analyze the GPS time series.

Figure 2 schematically shows that noisy daily variations of surface displacements in the GPS record are in fact well correlated with low-frequency earthquake activity. This indicates that slow slip transiently occurs on the same time scales as tremor and low-frequency earthquakes (Frank & Brodsky, 2019; Hawthorne & Rubin, 2013), that is, time scales of seconds to minutes, far shorter than the typical daily sampling of GPS time series. A geodetic signal of slow slip can then be extracted by summing the daily surface displacements during episodes of seismicity, coherent with the release of elastic energy (Frank, 2016; Frank et al., 2018). Recent work has confirmed this observation of intermittent slow slip in many subduction zones (Frank, 2016; Frank et al., 2018; Fujita et al., 2019; Rousset et al., 2019). Conversely, summing surface displacements when no tremors or low-frequency earthquakes are recorded shows (as expected) motion compatible with increasing elastic strain, or convergent locking of the plate interface.

Complementing this observed temporal complexity of slow slip, the spatial complexity of slow slip becomes evident with InSAR observations of aseismic slip along continental faults (Figure 2). Along the Haiyuan fault and the San Andreas Fault, the along-strike evolution of aseismic slip suggests creep is not steady in time and rather occurs in bursts with potency distributed following a power law distribution (Jolivet et al., 2015; Khoshmanesh & Shirzaei, 2018). The probability distribution of slip rates during the events peaks near the plate rate (i.e., the loading rate) and shows an excess of fast events that can be interpreted as the signature of interaction between events. Frank et al. (2016) also found that the occurrence of low-frequency earthquakes during slow slip are clustered: swarms of low-frequency earthquakes individually correlate in time with one another, and their occurrence is best represented by a power law distribution. Such clustered behavior of low-frequency earthquakes has been established over multiple plate boundaries (Lengliné et al., 2017) and resembles the well-known Gutenberg-Richter law for earthquakes (i.e., small slow slip episodes are more frequent than large ones). An analysis of the timing of slow slip transients reveals the same statistical signature of clustering (Frank et al., 2018). Such pervasive clustered behavior might be indicative of an underlying process that drives and controls aseismic slip or of a cascade of interacting events, like earthquakes do (Frank et al., 2018; Jolivet et al., 2015).

Clustering is not inconsistent when considering geodetic observations of slow slip in other tectonic contexts. Small-scale variations are observed during year-long postseismic sequences, during which the rate of afterslip decays exponentially with time, slowly diffusing the stress changes imposed by a large earthquake (Avouac, 2015). While slow slip was considered to follow such exponential decay since the last large M_w 7 earthquake along the North Anatolian Fault creeping section in 1947, InSAR and recent creepmeter measurements highlight the transient-like behavior of slow slip there (Bilham et al., 2016; Rousset et al., 2016). Close examination of creepmeter data recording the postseismic aseismic transient slip following the 1973, M_w7.6, and 1981, M_w6.9, earthquakes along the Xianshuihe fault along the eastern boundary of the Tibetan plateau suggests slip is also made of transient events (Zhang et al., 2018). Such burst-like behavior was even evidenced much earlier on along the San Andreas fault system following the 1966 M_w6 Parkfield or 1987 M_w6+ Superstition Hills earthquakes (Bilham, 1989; Smith & Wyss, 1968). Similarly to episodic slow slip events and persistent slow slip, postseismic afterslip might also be made of the collection of small events, although this remains to be carefully examined for afterslip at depth.

It is important to note that this fine temporal behavior of slow slip was already present within early geodetic data sets. In the first report of aseismic slip along the famous San Andreas Fault creeping section, Steinbrugge et al. (1960) showed the time series of slow slip measured at markers installed on the walls of the Taylor winery to argue that “creep [is] concentrated in spasms of duration on the order of a week”. Additionally, early creepmeter measurements across the North Anatolian fault suggest slow slip occurs in several day-long events with slip ranging from a few millimeters to a few centimeters (Altay & Sav, 1991). The transient nature of aseismic slip we argue for was readily visible and recognized in early data.

We suggest that a defining feature of slow slip in all its forms is that it is made up of constituent aseismic transients or subevents, whose interevent interaction aggregates disparate events into the macroscale slow slip that is typically observed in GPS and InSAR observations. Observed power law clustering suggests that events of all sizes and all durations should be occurring. The size distribution of these events likely also follows a power law distribution, and, similarly, a continuous distribution of slip rates could be established. This is consistent with a composite moment rate power spectrum of slow slip, which shows a roughly decaying amplitude as a function of frequency (Hawthorne & Bartlow, 2018). Such a decaying spectrum suggests energy is released at all temporal scales, confirming the transient nature of slow events.

Ide et al. (2007) and Peng and Gomberg (2010) initiated the debate on the nature of scaling laws of earthquakes compared to slow slip. Recently, macroscale slow slip events in Cascadia have been suggested to be earthquakes in slow motion, obeying the same scaling as expected for fast earthquakes (Michel et al., 2019). Another recent study focused instead on the intermittent slow rupture process, ignoring the loading or “off” time in between transients, to demonstrate that the isolated slow rupture process scales just like earthquake rupture (Frank & Brodsky, 2019). We note that these observations are not necessarily consistent with one another, as the two studies are intrinsically not measuring the same thing: Michel et al. (2019) analyze the macroscale slow slip while Frank and Brodsky (2019) constrain the collection of subevents. These two observations are consistent only if the intermittence, or the ratio of the slip time to the “off” time, of the cluster of subevents scales with the macroscale slow rupture. We speculate that scaling laws for large slow events might be irrelevant, as the scaling of such events strongly depends on the ability to detect the beginning and end of events. If slow slip is a continuous, burst-like process, what is the meaning of the scaling of such “events”?

4. Modeling the Complexity of Slow Slip: No Steady State?

Such a hypothesis has considerable implications in terms of our understanding of the physics behind slow slip. Geodetic observations led us to consider that fault segments hosting apparent constant slow slip rates (or low fault coupling) are governed by a strengthening behavior (e.g., Avouac, 2015). However, if slow slip is made up of a sum of spontaneous events, then this rheology is only an effective one, and the physical underlying mechanism should allow for spontaneous weakening. If there is spontaneous weakening of the fault plane, then some mechanism must keep the rupture slow, such as dilatant strengthening (Segall et al., 2010) or a large nucleation size (Veedu & Barbot, 2016). But if the dynamics of the underlying subevents is different than the total macroscale event, the physics proposed to govern slow slip might only be an effective one. The underlying rupture physics at finer scales should be our target for future physical models.

In general, three factors could be considered for such behavior: (i) the role of fluids, (ii) heterogeneities in fault constitutive properties, and (iii) potential stress interactions. Fluids are known to circulate along fault zones, and pore pressure increase leads to a reduction in normal stress, which promote slip, and an increase in fracture energy and apparent nucleation size (Bayart et al., 2016). A heterogeneous distribution of frictional properties could be responsible for the episodic behavior of fault slip (e.g., Wei et al., 2013). Finally, stress interactions related to fault geometry can lead to the emergence of all kinds of slow and fast events (Romanet et al., 2018). Faults are known to be rough at various scales, and these scales manifest themselves in the distribution of slow slip along active faults (Candela et al., 2012; Jolivet et al., 2015). Reality is likely a combination of all three factors: Fluids could be the underlying forcing that clusters slow slip together, while heterogeneities and stress interactions control the resulting cascading behavior. Of course, deciphering these mechanisms is not easy as rheological variability along the fault plane might directly mediate dynamic stress interactions. As any mechanism that modulates the rate at which energy is released via slip on a fault could explain slow slip dynamics over a range of time and spatial scales, additional mechanisms might of course be involved. One important exercise will be to show how the averaging of all contributions can lead to the effective behavior that has been described and modeled at the scale of the earthquake cycle.

In general, fault slip is governed by a set of dynamical equations relating slip rate and stress through constitutive properties. Without considering the form of these equations, constitutive properties should remain somehow stationary over the geodetic (long time scale) observational period. Slip or slip rate is what we infer from surface observations, and the observed fluctuations are related either to stress changes or changes in constitutive properties. Given observations of slow slip across the world in many different tectonic contexts, this would imply that the evolution of slow slip is controlled mainly by stress perturbations, with a wide range of constitutive fault properties capable of hosting aseismic rupture (we speculate there is little reason to suspect we can characterize all faults with a narrow range of constitutive fault properties). Potential perturbations to the state of stress in the vicinity of a fault, including ocean tides, solid Earth tides, nearby fault slip, hydrology, ice loads variations, erosion, landslides, and many others, cover a wide range of amplitudes and time scales. It is therefore quite unlikely that slip rate would remain constant anywhere. Because perturbations are happening at all times and at all scales, fault slip should show fluctuations at all times and at all scales, and given the nonlinearity of the response, these fluctuations need not to mimic the imposed perturbations; some recent stochastic models with continuously fluctuating slip rates have successfully reproduced some common slow slip observables (Ben-Zion, 2012; Ide & Yabe, 2019). The jury is still out on which mechanical processes control slow slip, but we conclude a synthesis of observational constraints from different tectonic contexts will be key in paving our way toward a greater understanding of slow slip dynamics.

Acknowledgments

This project has received funding from the European Research Council (ERC) under the European Unions Horizon 2020 research and innovation program (Grant Agreement 758210, Geo4D project). This article complies with the FAIR data standard as it does not present new data. The authors would like to thank H. S. Bhat, E. E. Brodsky, O. Oncken, A. Hooper, and S. Barbot for invaluable discussions on the topic and R. Bürgmann and M. Shirzaei for their insightful reviews.

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