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The geophysics, geology and mechanics of slow fault slip

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ABSTRACT

Modern geodetic and seismologic observations describe the behavior of fault slip over a vast range of spatial and temporal scales. Slip at sub-seismogenic speeds is evident from top to bottom of lithospheric faults and plays an important role throughout the earthquake cycle. Where earthquakes and tremor accompany slow slip, they help illuminate the spatiotemporal evolution of fault slip. Geophysical subsurface imaging and geologic field studies provide information about suitable environments of slow slip. In particular, exhumed fault and shear zones from various depths reveal the importance of multiple deformation processes and fault-zone structures. Most geologic examples feature frictionally weak and velocity-strengthening materials, well-developed mineral fabrics, and abundant veining indicative of near-lithostatic fluid pressure. To produce transient slow slip events and tremor, in addition to the presence of high-pressure fluids a heterogeneous fault-zone structure, composition, and/or metamorphic assemblage may be needed. Laboratory and computational models suggest that velocity-weakening slip patches smaller than a critical dimension needed for earthquake nucleation will also fail in slow slip events. Changes in fluid pressure or slip rate can cause a fault to transition between stable and unstable fault slip behavior. Future interdisciplinary investigations of slow fault slip, directly integrating geophysical, geological and modeling investigations, will further improve our understanding of the dynamics of slow slip and aid in providing more accurate earthquake hazard characterizations.

1. Introduction

Faults represent displacement discontinuities in rocks that accommodate lithospheric deformation by fast (seismic) and slower (aseismic) slip (Fig. 1). While earthquakes involve fault slip velocities ranging from 10^{-4} to 1 m/s and produce high-frequency seismic waves, slow slip, also referred to as fault creep, can be many orders of magnitude slower. However, there is no sharp boundary between the two modes of slip, and slow slip can sometimes involve radiation of long-period seismic energy or secondary small seismic events in the fault zone. The slip behavior on a fault may vary spatially and we refer to a fault that accommodates a fraction of its slip aseismically as partially coupled. The fault creep rate can be steady or vary in time. We refer to distinct episodes of accelerated slip as slow slip events (SSEs), creep events and slow (or silent) earthquakes. Slip duration at a point on a fault during an earthquake is generally less than ∼10 s, while an SSE may endure from tens of seconds to tens of years.

For a fault to slip slowly requires a strengthening mechanism that puts on the brakes and contains fault slip velocities to sub-seismogenic speeds. Independent of the process and physics involved, we refer to an increase of fault strength with rising slip rate as velocity strengthening, preventing fast earthquake rupture and promoting fault creep. Faults that weaken as slip rate increases are velocity weakening and may accelerate into a seismic stick-slip event or may limit themselves to produce an SSE if the elastic load stress decays more rapidly during slip than the strength of the fault. Whether fault offset occurs by a seismic or slow mode of slip appears to depend on the make-up of fault materials, the fault's environmental conditions, and the history and rate of loading. As geophysical observations improve, we find increasing evidence of slow slip in a wide range of tectonic regimes, fault environments and phases of the earthquake cycle of large ruptures. These observations and fault mechanical models also point to substantial complexity in fault behavior, including spatiotemporal transitions between slip modes. This has led to increased efforts in examining the geophysics, geology and mechanics of slow slip, in recent years.

Slow slip plays an important role in the earthquake cycle and associated earthquake hazard. If faults accommodate a substantial portion of their slip budget by slow slip, their seismic hazard is reduced. Observations of precursory SSEs and associated foreshocks suggest that accelerated creep can initiate or trigger some seismic events. While in no way universal, these observations have renewed interest in precursory activity and suggest the possibility

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Table 1
Glossary of terms.

Afterslip	Post-earthquake slow slip on nearby fault sections relieving static coseismic stress change and decaying (∼logarithmically) with time.
Cataclasite	Fault rock sheared by brittle fracturing and comminution of mineral grains.
Earthquake swarm	Burst of earthquakes that does not exhibit clear mainshock–aftershock pattern.
Fault coupling	The degree to which slip on a fault is accommodated by seismic vs. aseismic slip. Average coupling during an observation period can be expressed as a ratio ranging from <0 (accelerated creep), 0 (creep at long-term slip rate), 1 (fully locked), and >1 (creep opposite to long-term slip direction) (Wang and Dixon, 2004).
Fault gouge	Fine-grained, highly sheared fault zone material made of cataclasite that may also be chemically altered.
Low-frequency earthquake (LFE)	Small ($M_W \ll 3$) and short (<1 s) seismic events contained in more enduring tremor signal indicative of shear slip (Beroza and Ide, 2011).
Magnetotellurics (MT)	Geophysical imaging of lithospheric electrical conductivity structure using natural electromagnetic field variations as sources.
Mélange shear zone	Fault zone structure with heterogeneous mechanical properties comprising blocks of variable composition in sheared sedimentary matrix.
Mylonite	Foliated fault zone rock sheared by crystal plastic deformation mechanisms at high temperatures.
Rate and state friction	Empirical expressions describing the experimentally observed (logarithmic) dependence of frictional strength on slip velocity (rate) and an evolving time-dependent effect (state) (Marone, 1998).
Receiver function analysis	Characterization of body-wave scattering from teleseismic events to obtain a point measurement of crustal seismic velocity structure beneath a seismic station.
Repeating earthquakes	Earthquakes with nearly identical seismic waveforms, locations and mechanisms inferred to re-slip the same rupture surface, often driven by surrounding slow slip.
Slow slip (also aseismic slip and fault creep)	Fault slip that is slow enough to not produce seismic energy associated with earthquakes.
Slow slip event (SSE) (also creep event and slow/silent earthquake)	Aseismic slip transient on a fault patch over durations ranging from minutes to decades. Some slow earthquakes generate low-frequency seismic energy.
Tectonic tremor	Enduring low-frequency seismic signals generally interpreted as being associated with otherwise slow slip.
Triggered SSE	Slow slip episode following an earthquake due to static or dynamic stress changes that is not afterslip.
Very-low-frequency earthquake (VLFE)	Similar to LFEs but longer (10–200 s) and larger (M 3–4) seismic events generally associated with tremor (Beroza and Ide, 2011).

of raising hazard warning levels at times of accelerated slow slip. Transient slow slip relieving stress increases from recent earthquake ruptures on nearby fault sections is called afterslip. Static stress changes or dynamic shaking from earthquakes may also lead to triggered SSEs of any size, both near and very far from a mainshock. Postseismic slow slip of either kind helps expand the reach of stress interactions from an earthquake and may play an important role in the generation of aftershocks and extended sequences of hazardous earthquakes.

There are many excellent recent review papers on various aspects of slow slip. Schwartz and Rokosky (2007), Rubinstein et al. (2010), and Beroza and Ide (2011) focus on geophysical observations and the setting, properties and mechanics of episodic tremor and slip events below the base of the seismogenic zone. Peng and Gomberg (2010) and Schwartz (2015) highlight the wide spectrum of episodic slow slip characteristics. Obara and Kato (2016) relate slow earthquakes to large seismic ruptures, consider their similarities and differences, and emphasize the role that SSEs can have in the initiation of some great earthquakes. Wang and Bilek (2014) consider the role of seafloor morphology and other factors in the coupling of subduction thrusts around the world. Audet and Kim (2016) review insights gained from seismic imaging of deep-seated slow slip zones on subduction thrusts, while Saffer and Wallace (2015) examine the nature and environment of very shallow subduction slip episodes. Avouac (2015) puts slow slip in the context of the earthquake cycle, considering kinematic and dynamic models of the release of elastic strain energy by seismic and aseismic slip on mechanically heterogeneous faults. While many of these reviews were especially focused on subduction zones, Harris (2017) addresses the role of aseismic fault creep on shallow continental faults and examines to what degree slow slip changes the character of large earthquakes on partially coupled faults. Rowe and Griffith (2015) provide a geologic perspective focused on recognizing seismic fault slip from a range of observables in exhumed fault zones.

Here, I present an overview of geodetic and seismological observations of slow slip, consider results from geophysical imaging of creeping faults, assess geologic studies of faults that may represent exhumed examples of slow slip and its environment, and finally discuss recent laboratory and theoretical studies that try to explain the mechanics and dynamics of slow slip. A glossary of terms (Table 1) and summary of the tools of slow slip research (Table 2) are provided. The emphasis is on providing a balanced and interdisciplinary overview of recent advances in slow slip research and highlighting some outstanding questions for future investigations.

2. The geophysics of slow slip

While the initial discovery of fault creep came from observations of damage to manmade structures straddling faults, the quantification of slow slip in space and time requires geophysical observations. Geodetic measurements of surface deformation along faults allow for mapping out the kinematics of slow slip below the Earth's surface. There are also certain types of seismic signals (e.g., repeating earthquakes, earthquake swarms, and tremors) that help illuminate slow slip at depth. Geophysical imaging (e.g., seismic tomography, receiver functions and electrical resistivity) provides valuable insights into the structure and environment of slow slip deep in the crust, including information about the width, compo-