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Fault activation by induced aseismic slip

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Summary

For natural faults systems, slow (aseismic) slip is increasingly recognized as a fundamental component of earthquake processes. Unlike dynamic rupture processes that occur on a timescale of seconds to minutes and generate normal earthquakes, aseismic slip may occur over a timespan of hours or days. Aseismic slip is the expected behaviour for fault systems characterized by velocity-strengthening frictional rheology, including cases where faults contain certain clay minerals and organic carbon that commonly occur in unconventional petroleum systems. In the last few years, direct and indirect observations have revealed aseismic slip processes during hydraulic-fracturing operations. Documented cases include precursory aseismic slip accompanied by microseismicity prior to a moment magnitude (M_W) 4.1 event; inferred progressive slow-slip fault activation with arrested rupture; and a M_W 5.0 slow-slip event that resulted in casing deformation. Several of these cases harness emerging technology to complement traditional seismological observations, such as Distributed Acoustic Sensing (DAS) and satellite Interferometric Synthetic Aperture Radar (InSAR). This paper reviews recently published case studies and provides a framework for future research to better understand how these processes may contribute to risk, including induced earthquakes and casing deformation.

Introduction

In the past several decades, there has been increasing scientific recognition that the temporal slip behaviour of natural fault systems forms a spectrum, ranging from near-instantaneous stick-slip motion (dynamic rupture), which produces regular earthquakes, to steady-state fault creep (Peng and Gomberg, 2010). Between these endmembers lies a range of fault-slip behaviour that includes tremor, low-frequency earthquakes (LFEs), and episodic slip transients. Detecting and characterizing seismic and aseismic signals generally require different types of instrumentation; regular earthquakes and tremor are well suited to observation using broadband seismometers, whereas slow earthquake processes are best observed using geodetic methods such as Global Navigation Satellite System (GNSS) or Interferometric Synthetic Aperture Radar (InSAR). In general, slip processes that are too slow to produce radiated seismic wave energy that is detectable using broadband seismometer are described as “aseismic”. There is growing evidence that distributed acoustic sensing (DAS) could provide broadband frequency sensitivity that spans both regular earthquakes and slow-slip parts of the spectrum.

Figure 1 is a schematic illustration showing the generalized distribution of seismic and aseismic slip regions for two different types of natural fault systems. For subduction zones (Figure 1a), the simplest model contains two transitions between stick-slip (seismic) and aseismic behavior (Schwartz and Rokosky, 2007). The updip and downdip limits of the seismic region, which remains locked throughout most of the seismic cycle, is governed by the frictional behaviour of the fault. As discussed below, dynamic earthquake rupture occurs along regions of the interface that are characterized by velocity weakening, whereas aseismic slip occurs in regions that are conditionally stable or characterized by velocity strengthening. Figure 1b illustrates the distribution of seismic and aseismic slip behaviour for a section of the San Andreas Fault near Parkfield, California (Bürgmann, 2018). In the upper crust above the brittle-ductile transition (BDT), at about 15 km depth, a south-north lateral transition occurs from seismic to aseismic slip behaviour. Within the aseismic regime, fault creep, slow slip events (SSEs) and small repeating earthquakes are observed. In the lower crust below the BDT, fault slip behaviour is dominated by aseismic processes that include continuous creep and episodic tremor.

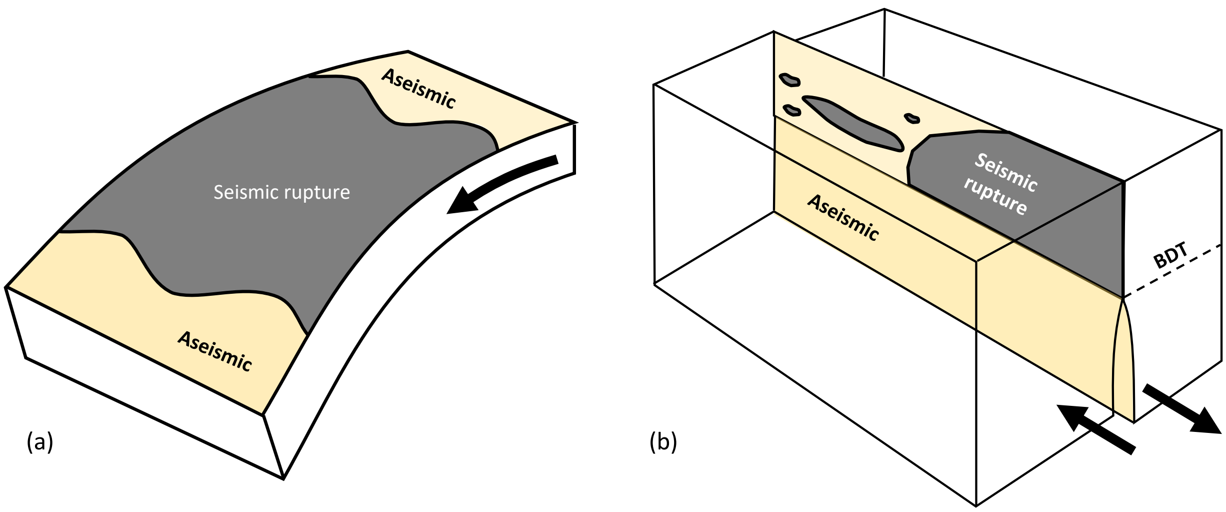

Figure 1. Schematic illustration of the distribution of seismic rupture and aseismic slip for (a) a simple subduction zone model (modified from Schwartz and Rokosky, 2007) and (b) a section of the San Andreas Fault near Parkfield, California (modified from Bürgmann, 2018). In both cases, partitioning of the fault into seismic and aseismic regimes is governed by the frictional behaviour of the slip interface. BDT denotes brittle-ductile transition, which is at a depth of ~15 km.

Aseismic slip has also been documented for fluid-induced seismicity. Guglielmi et al. (2015) directly measured fault-slip processes induced by fluid injection into a natural fault. Using a specialized probe that enabled pressure isolation of a natural fault, coupled with precise measurement of the strain tensor, they showed that induced microseismicity was preceded by aseismic tensile fault opening and shear. In the case of a hydraulic-fracturing induced earthquake, Eyre et al. (2019) presented indirect evidence from precursory microseismicity, 3D seismic data and numerical simulation based on log-derived geomechanical properties to support a model for fault triggering from aseismic creep. In their model, hydraulic fracturing caused aseismic slip on the fault within the reservoir (Duvernay) zone, which progressively loaded an unstable, shallower fault segment. This model is consistent with documented cases of aseismic slip as a triggering mechanism for dynamic rupture elsewhere on natural faults (Peng and Gomberg, 2010) as well as experimental data (Bhattacharya and Viesca, 2019) showing that aseismic slip can outpace subsurface fluid diffusion. Recently, Eyre et al. (2022) showed direct evidence based on InSAR and casing deformation for several slow-slip earthquakes in northeast BC, triggered by hydraulic fracturing.

Rate-state friction

In general, partitioning of a fault into seismic and aseismic regions is governed by frictional properties of the fault. Based on extensive experimental studies of rock friction, the best available constitutive relationship for fault friction is a nonlinear model known as rate-state friction, so named because it involves both slip rate (*V*) and a 'state variable' (θ) that depends on the past slip history (Scholz, 1998). The Dieterich-Ruina form of rate-state friction (Dieterich, 1978; Ruina 1983) can be written as

$$\mu = \mu_0 + a \cdot ln(V/V_0) + b \cdot ln(V_0 \cdot \theta/d_c) \ , \qquad (1)$$

where μ is the coefficient of friction, μ_0 is a reference friction value for a reference slip velocity V_0, and *a*, *b* and d_c are model parameters. The last model parameter, d_c , represents a critical slip distance, while the state variable θ satisfies

$$\frac{d\theta}{dt} = 1 - \frac{\theta \cdot V}{d_c} \ . \qquad (2)$$

Based on this model, the generalized frictional behaviour in response to a boxcar-like velocity jump (i.e. a step increase from the reference slip velocity, followed by a step-like decrease to the original slip state) is shown schematically in Figure 2. In essence, a sudden increase in slip velocity is accompanied by an abrupt increase in friction followed by a period of relaxation. Essentially the reverse pattern occurs when the slip velocity is restored to its original reference level. The temporal behaviour of the frictional relaxation is controlled by d_c , while the asymptotic values are controlled by the *a* and *b* parameters. In particular, the rate-state *a* parameter determines the value of the initial increase in friction, while the rate-state *b* parameter determines the long-term asymptotic value of friction, μ. Importantly, if the difference $a - b < 0$, the fault has so-called velocity-weakening characteristics. In this case, once slip initiates the frictional rheology leads to runaway behaviour that produces dynamic rupture (a regular earthquake). Conversely, if $a - b > 0$ then the fault has velocity-strengthening characteristics. In this case, the slip velocity is regulated by the frictional increase such that creep-like slip occurs.

Seismic moment

Regardless of slip velocity, the scalar seismic moment (M_0) is given by (Eaton, 2018)

$$M_0 = G\bar{d}A \ , \qquad (3)$$

where *G* is the shear modulus, *A* is the total area of the rupture zone, and $\bar{d}$ is the spatially averaged net displacement within *A*. SI units of seismic moment are N-m. The moment magnitude (M_W) can be calculated using the formula (Hanks and Kanamori, 1979)

$$M_w = 2/3\, log(M_0) - 6.033 \ , \qquad (4)$$

where M_0 is specified in SI units.

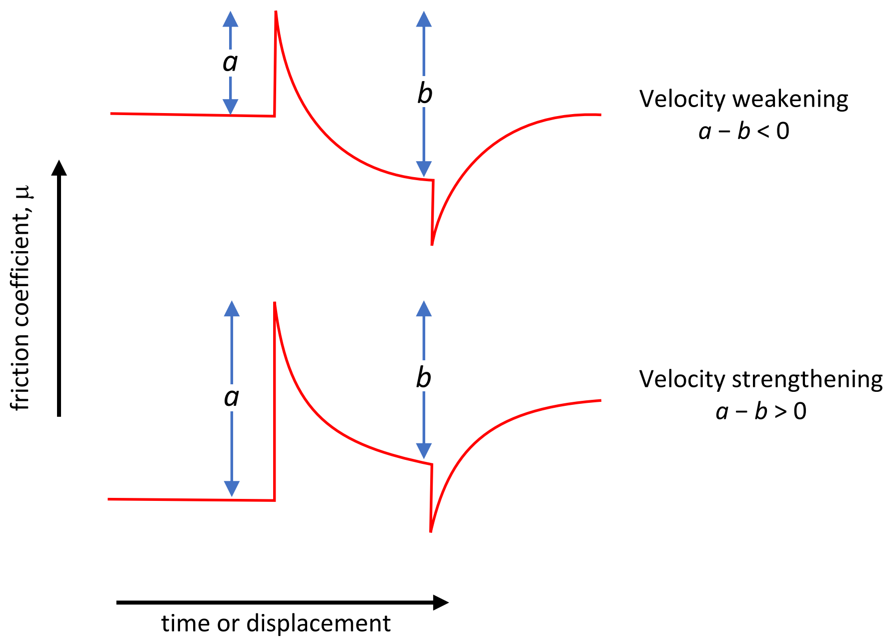

Figure 2. Schematic diagram showing the change in friction (μ) for a boxcar-like step in slip velocity, *V*. Whether the system is velocity-weakening or velocity strengthening depends on the difference between rate-state parameters, *a* and *b*. Modified from Kang et al. (2019).

Conclusions and Outlook

This paper provides a concise summary and description of aseismic slip processes within a spectrum of slip behaviour of fault systems. Growing evidence points to the potentially important role of aseismic slip as a factor that influences induced seismicity. Aseismic slip does not radiate elastic waves that can produce damaging ground motion. Therefore, inasmuch as aseismic slip releases stored stress on a fault, understanding aseismic slip behaviour is important for risk analysis. In addition, there is evidence for both natural and induced seismicity that aseismic slip may trigger a subsequent regular earthquake by increasing stress on other parts of a fault system. In general, the slip behaviour is controlled by fault rheology. More work is needed to better characterize rate-state parameters of subsurface faults in areas prone to induced seismicity.

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