

## Learning to read fault-slip behavior from fault-zone structure

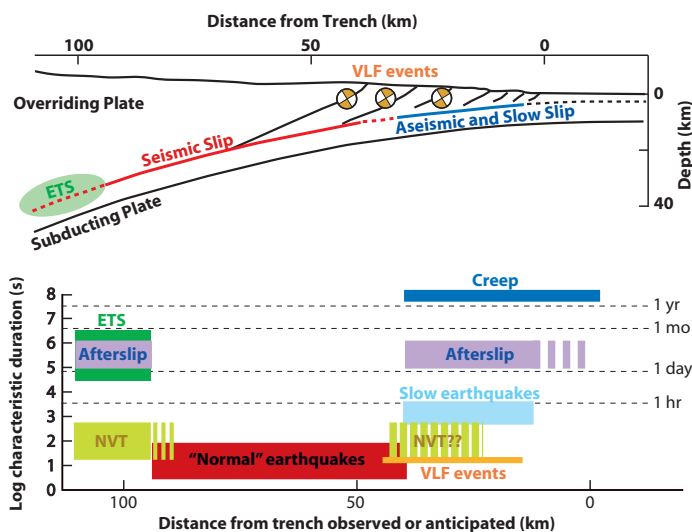
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The connection between fault-zone architecture and seismic behavior is central to studies of the physics of earthquakes and faulting. Earthquakes represent one end-member of slip behavior; frictional melting and pseudotachylites provide field evidence for highly localized slip during dynamic rupture (e.g., Sibson, 1977; Cowan, 1999; Cashman et al., 2007). Aseismic slip represents the other end-member, in which creep deformation is associated with pervasive shearing within fault zones. However, recent work shows that this view is oversimplified. Tectonic faults, in fact, fail in a continuous spectrum of modes including creep events and strain transients, slow and silent earthquakes, low frequency earthquakes, tectonic fault tremor, and post-earthquake afterslip (Fig. 1).

Complex modes of fault slip, involving transient acceleration with or without seismic radiation, have been known for some time (e.g., Tocher, 1960; Beroza and Jordan, 1990; Linde et al., 1996). However, failure modes such as tectonic fault tremor were unknown as recently as ten years ago (e.g., Obara, 2002; Rogers and Dragert, 2003), and recent studies indicate strong interest in slip behaviors that fall between the traditional end-members of seismic and aseismic slip (Amoruso and Crescentini, 2009; Brown et al., 2009; Johnson et al., 2009; Lambert et al., 2009; La Rocca et al., 2009; Liu et al., 2009; Nadeau and Guilhem, 2009; Peng et al., 2009; Rubinstein et al., 2009; Shelly, 2010; Smith and Gomberg, 2009; Thomas et al., 2009; Uchide et al., 2009; Wdowinski, 2009).

Figure 1 highlights the distinct time constants for various modes of fault slip, ranging from a few seconds (for dynamic earthquake rupture) to a few days (for migrating tremor) to a year or more (for postseismic



**Figure 1.** Upper panel shows a range of fault slip behaviors illustrated in a subduction zone setting. Episodic tremor and slip (ETS) are often observed at the downdip end of the seismogenic zone. Earthquakes that are deficient in high frequency energy, so-called low- (or very low) frequency earthquakes (VLF) occur in a variety of settings and possibly in association with slow earthquakes or aseismic transients. Lower panel shows the corresponding range of characteristic durations for the different slip behaviors, including non-volcanic tremor (NVT) (From Saffer et al., 2009.).

afterslip and aseismic creep). This model retains the basic idea of a seismogenic zone with aseismic slip above and below it (e.g., Scholz, 1988) and it suggests that transient modes of slip, including tremor and earthquakes with enhanced low frequency spectral content (very low frequency, VLF) occur primarily in the transition zones at the updip and downdip limits of the seismogenic zone. This view is consistent with current observations but may need to be revised as transient slip location techniques improve. The known range of slip behaviors necessitates a more sophisticated view of the correlation between fault-zone structure and fault-slip behavior and raises important questions, including: (1) How are the physics of slow fault slip related to the physics of earthquakes, (2) do tremor and other forms of quasi-dynamic failure occur on the same sections of the fault that host dynamic rupture, (3) what controls the migration velocity of slow slip, (4) do these transient modes of slip impart (or arise from) distinct structural styles in the fault zones on which they occur, and (5) can we distinguish among fault-zone structures formed during dynamic rupture, during aseismic creep, and during the other forms of faulting across the spectrum?

Fagereng and Sibson (2010, p. 751 in this issue of *Geology*) provide new insights on this problem. They show that fault slip recorded at a given location within a subduction-zone mélange reflects partitioning between both seismic and aseismic modes of slip. Departing from the traditionally held view that earthquakes and tremor (or creep events) are confined to different segments of the fault, they posit that fault-zone heterogeneity causes spatial variations in rheology and strain rate, resulting in a variety of failure modes. The heterogeneity may arise from competency contrasts (Fagereng and Sibson, 2010) or variations in friction constitutive behavior (Marone et al. 2009). One expects that more competent blocks within the fault zone and more indurated zones of shear localization would have lower fracture toughness and behave in a more brittle fashion than clay-rich regions or zones of less competent material. This could create natural segmentation of the fault zone with implications for earthquake nucleation and seismic productivity (e.g., Wesnousky, 1988). Therefore, transient modes of fault slip may be more common early in a fault's seismic cycle when localized shear bands are less developed.

The issue of mixed-mode fault slip behavior highlights the complexity of defining the seismogenic zone. Traditional definitions of the seismogenic zone relied solely on hypocenter locations and thereby provided a view based on earthquake nucleation. As techniques for resolving the spatial distribution of slip improved, an alternate definition of the seismogenic zone became: the region that slips coseismically during earthquakes. This region can exceed the nucleation zone because a dynamic rupture can propagate through the conditionally stable region at both the updip and downdip limits of the earthquake nucleation zone. The complex, mixed-mode fault slip behavior such as envisioned by Fagereng and Sibson, (2010) may therefore occur in this conditionally stable transition region.

Another explanation for mixed-mode fault slip behavior at a given fault location involves the effect of shear localization on friction stability. A broad range of laboratory studies show an increased tendency for instability as shear becomes more localized (e.g., Collettini et al., 2009). Recent studies show that fault zone fabric and clay coatings on foliation surfaces may play a key role in determining fault strength and the relationship

between frictional rheology and shear localization (e.g., Schleicher et al., 2010; Collettini et al., 2009). Knowing the role of shear fabric and microstructures in fault zones should inform our attempts to read the mode of fault slip from observations of fault zone structure.

In the context of the friction laws and stability models that were in use during the 1970's and early 1980's, the observed range of fault slip behaviors is unexpected. However, modern friction constitutive laws are capable of describing the full spectrum of fault slip behaviors (e.g., Marone, 1998; Scholz, 1998; Rubin, 2008). Earthquake simulations that incorporate rate and state friction laws are capable of describing slip nucleation, dynamic rupture propagation, transient earthquake afterslip, and creep. However these friction laws remain largely empirical and the underlying processes are poorly understood. Key constitutive parameters are not well constrained by laboratory data nor by modeling of field observations. To arrive at a better understanding of the spatio-temporal interactions between the complex multi-mode faulting behaviors now ubiquitously observed, friction constitutive laws, instrumental observations, and fault zone field studies must be synthesized. The work of Fagereng and Sibson represents a critical new direction in doing so.

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