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Do faults preserve a record of seismic slip? A field geologist's opinion

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1. Introduction

When field geologists study natural faults, we commonly use well-established techniques to determine the total displacement, incremental slip, and the sense of slip. What more can we infer, from field observations, about the character of slip or the rheology of fault-zone materials? One example of this line of inquiry starts with the fact that slip on faults in the upper 10–15 km of the Earth's crust causes earthquakes. Geologists logically have asked whether the seismic or aseismic character of slip on a particular ancient or active fault can be judged by examining exposures of the fault in the field. To illustrate the currency of the question, I cite the Tenth Anniversary Issue of this journal, in which Sibson (1989) considered how we might investigate the structural record of earthquake faulting. Five years later, a symposium, entitled "Inferring paleoearthquakes from fault-rock fabrics: experimental and field evidence", was held at the 1993 Annual Meeting of the Geological Society of America.

In this paper, I revisit the question posed in the title. Can we confidently identify the record of seismic slip in exposures of fault zones, cores obtained by drilling, or thin sections of fault rocks? In my opinion, we are no closer to this goal than we were a decade ago. I defend this position on the basis of my understanding of the seismological definition of an earthquake, and of what this definition implies about the physical character of the earthquake source.

2. The view from seismology

2.1. Definitions of seismic and aseismic

If we want to establish criteria for distinguishing the records of *seismic* and *aseismic* slip in outcrops, we first have to agree on definitions for these terms. I propose to begin with a definition from seismology: a natural seismic event—an earthquake—produces elastic waves in the Earth that can be instrumentally recorded by seismometers. The seismic energy radiates from a source, which seismologists model in most cases as either a shear dislocation on a planar surface, or an equivalent system of counteracting body forces acting at a point—the double couple (e.g. Lay and Wallace, 1995). For the question at hand, the model of a propagating shear dislocation is the more geologically relevant (Fig. 1), and I will consider this source to be an analog of slip on an upper crustal fault.

In this paper, I further restrict the definition of seismic slip to include only those events that radiate waves with periods of 10 s or less, which are recorded on short-period seismometers. I believe my definition encompasses almost all of the events, whether small or large, that seismologists would readily identify as earthquakes. Accordingly, aseismic slip is any shear dislocation on a fault that does *not* radiate energy detectable by short-period seismometers.

2.2. Seismic source parameters

For a seismic event, the characteristics of the actual dislocation cannot be directly observed, except where a

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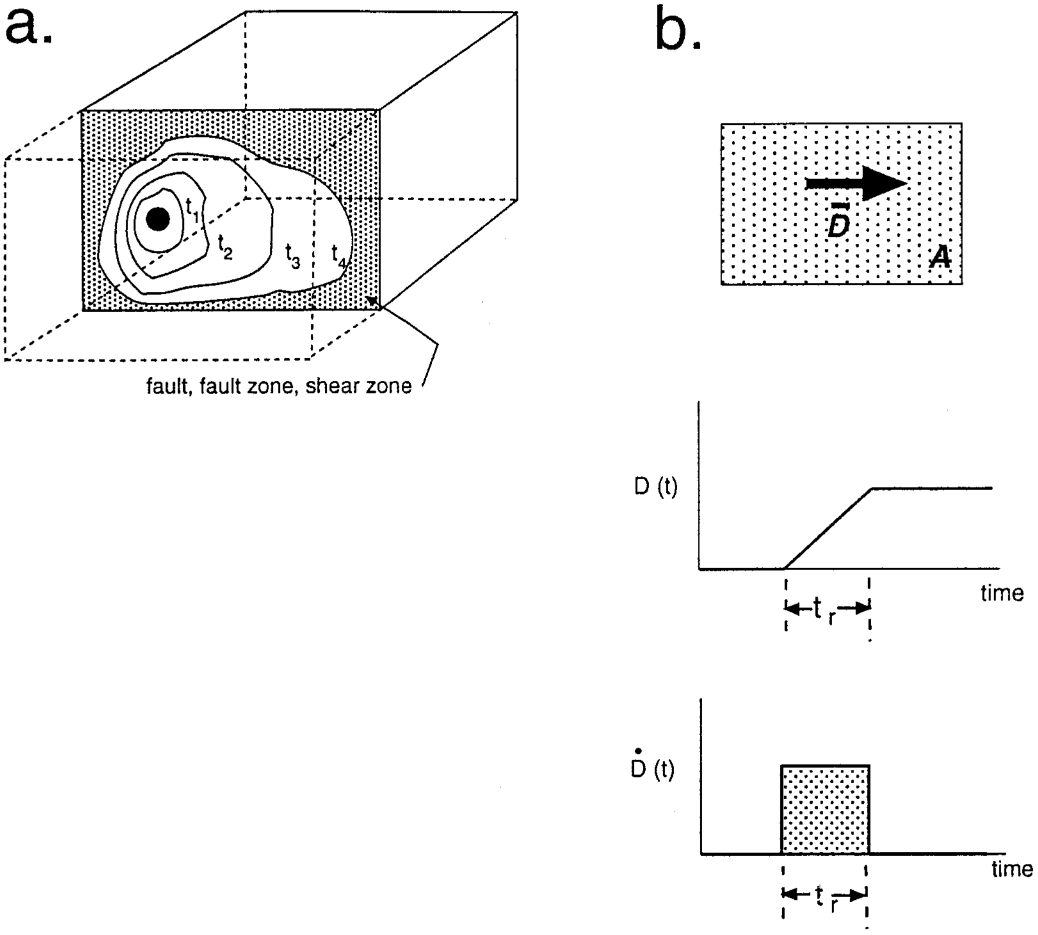

Fig. 1. Modified from Lay and Wallace (1995, fig. 8.9). (a) Schematically illustrates the propagation of a rupture from a hypocenter (filled circle) to positions at successive times t_1–t_4. The non-slipped part of the fault surface is shaded. (b) Idealized average dislocation model. $\bar{D}$ represents average slip during an event, also represented by the vector; A is the area of the model source. The upper graph represents the displacement history at a point, t_r is the rise time. The lower graph, the time function for the slip event, plots the time-derivative of the displacement function in the upper graph against time. The shaded area under the boxcar-curve is proportional to the moment of the event.

rupture on a fault propagates to the Earth's surface. Typically, the seismic source parameters—the source depth, fault orientation, seismic moment, and time function (Lay and Wallace, 1995, p. 402)—are determined by analyzing the waveforms on seismograms using generalized inverse theory. In the case of an exposed fault, two of these parameters, the depth at which slip occurred and the orientation of the fault, can generally be inferred from geological field and petrographic studies. We need to consider whether the other two parameters, the time function and the seismic moment, leave a physical record in the fault.

The scalar seismic moment, M_0, is a widely accepted measure of the size of an earthquake:

$$M_0 = \mu \bar{D} A \tag{1}$$

where μ is the shear modulus or rigidity of the rock mass containing the fault, $\bar{D}$ is the average displacement of a particle on the fault, and A is the ruptured area of the fault. The block diagram in Fig. 1(a) is an idealized representation of how a rupture front propagates outward, at a speed termed the rupture velocity, from a hypocenter and eventually stops after an arbitrary time t_4 has elapsed. An average shear-dislocation model (Fig. 1b) provides a highly generalized but useful way to visualize the seismic moment of an earthquake like the one represented in Fig. 1(a). The model in Fig. 1(b) could represent the entire ruptured fault and therefore convey the total seismic moment, or it might represent a smaller discrete element on the fault surface that is combined with other elements to model the slip. In either case, the area A and average particle displacement $\bar{D}$ might have real physical expressions in a fault: A represents the surface or zone that slipped during an earthquake, and $\bar{D}$ is the total slip along this surface during the seismic event.

Waveform analysis also yields the time function of the seismic source (e.g. Lay and Wallace, 1995, Ch. 9).

Table 1
Time-dependent parameters for recent earthquakes

Earthquake	Average particle velocities	Rise time	Rupture velocities	Rupture duration	References
Japanese	0.42–0.92 m/s				Kanamori (1994)
Landers	0.5–1.5 m/s	maximum of a few s	2.7 km/s	24 s	Wald and Heaton (1994)
Western N. America	average 0.43 m/s; as high as 1.03 m/s	0.3–5 s	2.6–3.0 km/s		Heaton (1990)
Kobe	maximum 0.8 m/s	3–5 s		13 s	Ide and Takeo (1997)

To glimpse the general idea of how this source parameter relates to slip, imagine that the total slip on a fault or within a discrete element on the fault in Fig. 1(b) could be represented by the displacement of a single particle at a point source. The upper graph beneath the diagrammatic fault surface shows the simplest possible displacement history for a sudden-onset earthquake: a ramp function. The duration of particle slip is the rise time. The lower graph plots time against the time-derivative of the displacement. This boxcar-shaped time function is proportional to the rate of moment release, which determines the amplitude spectrum of the seismic waves. The boxcar curve can in principle be retrieved from waveform analysis; the area under the curve is proportional to M_0.

If the rupture area and rupture velocity are independently determined or assumed, then the time function allows one to determine the duration and velocity of slip of a particle at the earthquake source. I assume that these source parameters are physically equivalent to the duration and velocity of displacements on an actual fault. I argue below that our ability to judge whether a fault slipped seismically depends overwhelmingly on whether we can use the physical evidence preserved in faults to infer the velocity and duration of slip.

2.3. Scaled time-dependent parameters

Whether a slip event at a source radiates short-period elastic waves depends not only on the size of the event as measured by the seismic moment but also on the rate of moment release, which is proportional to the rate of growth of the rupture area and to the history of particle velocity. Values of time-dependent parameters, such as rupture and particle velocities, have been determined for many recent earthquakes. Representative examples are given in Table 1. Geller (1976) also tabulated data for pre-1974 earthquakes.

These data indicate that most seismic events, as defined in this paper, are characterized by slip velocities on the order of 0.1–1 m/s, and slip durations, at any point on the fault, on the order of 1–10 s. The moment is released over periods of 1–10 s for sudden-onset earthquakes, or over periods of up to about 100 s for slow-rupture earthquakes. Recent literature has highlighted slip events on major upper crustal faults during which moment or elastic strain is released over periods ranging from hours up to a year (e.g. Marone et al., 1991; Linde et al., 1996; Heki et al., 1997). The total moment released during these events, which have been called slow or silent earthquakes, is comparable to the moment released by conventional sudden-rupture earthquakes, but the modeled rise times and slip durations for the former are distinctly longer. According to the definitions I adopt in this paper, slow and silent earthquakes are not seismic events, because they do not produce short-period elastic waves, but the strains that they induce can be detected by either very long-period seismometers (Beroza and Jordan, 1990), near-field strain meters (Linde et al., 1996), or geodetic measurements made with the Global Positioning System (GPS; Heki et al., 1997).

Whatever one chooses to call these slow or silent earthquakes, it is possible that they belong to a continuum based on the duration of slip (DeMets, 1997). At one end of the hypothetical continuum are sudden-onset events with durations on the order of a second. Anchoring the other end is steady-state, very slow slip:

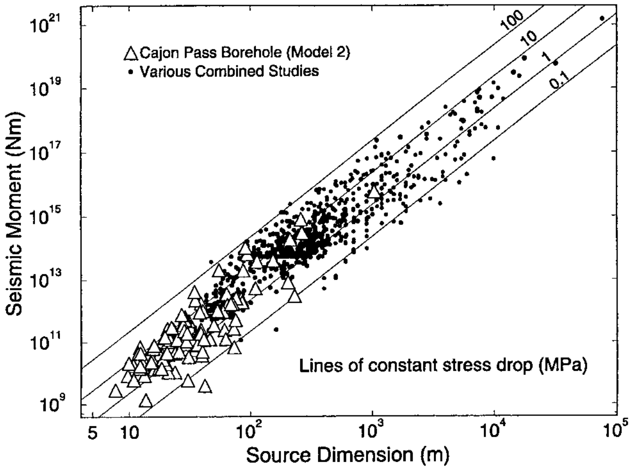

Fig. 2. Reproduced from fig. 11 in Abercrombie, R., Journal of Geophysical Research, 100, 24033, 1995, by permission of the American Geophysical Union. Plots source dimension, expressed as the radius of a circular source, for natural tectonic earthquakes, against scalar seismic moment. The smallest events, measured in a borehole, are plotted as open triangles.

the best known example is occurring on parts of the San Andreas fault in California, which has been creeping at rates of up to 35 mm/y for tens of years (e.g. Scholz, 1990, Ch. 6). This kind of slip is universally regarded as aseismic.

2.4. Scaled moments and lengths for earthquakes

Probably the best known and most widely published graphs of source parameters plot seismic moment against a length scale—area, length, width, or radius—of the source (e.g. Scholz, 1990, Ch. 4; Lay and Wallace, 1995, Ch. 9). The graph in Fig. 2 shows the characteristically linear relationship on a log–log plot. This particular graph is interesting because it includes natural events recorded by a seismometer placed 2.5 km deep in a borehole (Abercrombie, 1995). The smallest events have moments of about 10^9–10^{12} N m, well below the moments, which range upwards from ca. 10^{18} N m, of well-known large earthquakes (Hanks, 1977). The source dimensions of these small events, expressed as the radius of a circular source, are on the order of 10 m; the slip increments are sub-millimetric.

Some workers (e.g. King, 1978; Scholz et al., 1986; Sibson, 1989; Lay and Wallace, 1995) have cited another relationship, which scales the average particle displacement, $\bar{D}$, during a seismic event against the length, L, of the ruptured fault. For large earthquakes with seismic moments of about 10^{20}–10^{23} N m, $\bar{D}/L$ is approximately 10^{-4}–10^{-5}. The predicted average displacements on faults ranging in length from a few km to 100 km are on the order of a few tenths of a meter to 10 m. If this proportionality applies to the smallest events in Fig. 2, then the average displacements predicted on these surfaces would be about a millimeter.

The graph in Fig. 2 takes no account of time or the rate of moment release. If slower, aseismic events on faults are distributed along a continuum comparable to that shown in Fig. 2, then I infer that particle displacements during either aseismic or seismic slip are comparable and range over at least four orders of magnitude, from ca. 10^{-3} to 10^1 m. Therefore, even if a geologist *could* measure the net slip that accrued during a shear dislocation—an outcome rarely achieved except for faults that slipped during historic earthquakes—this information alone cannot be used to determine the speed or duration of slip.

3. Geological evidence in faults

3.1. The question rephrased

From my review above, I conclude the following. During seismic events, as they are defined here, particles along a fault slip relative to one another at velocities on the order of 0.1–1 m/s, for durations of about 1–10 s. During aseismic slip and creep, particles slip at average velocities slower than 0.1 m/s for periods that are generally much longer than 1000 s. Seismic and aseismic displacements differ in velocity, not in the length dimensions of either the slip or the fault surface. Therefore, if geologists want to address the question of *seismic vs aseismic slip*, we need empirical criteria for differentiating faster from slower rates of slip, and shorter from longer durations of slip—per event.

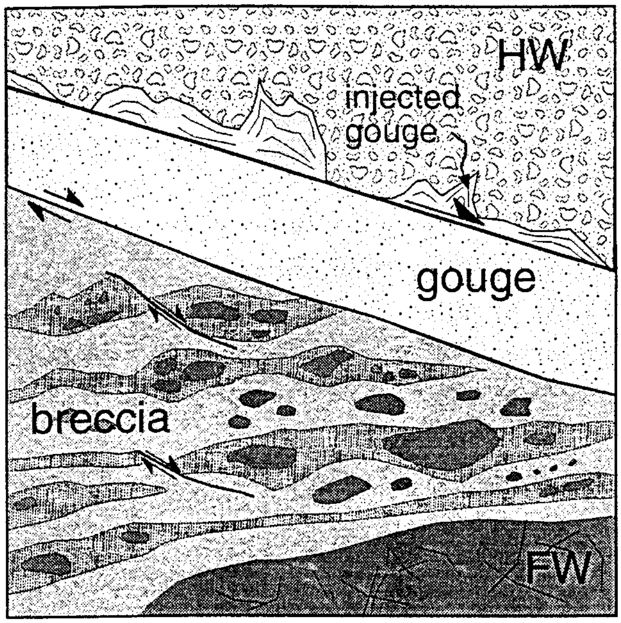

Fig. 3. A highly idealized, approximately two-meter high cross-section of a late Cenozoic low-angle normal fault in Death Valley, California, showing the major components of an upper crustal brittle shear zone. Fault rocks include gouge and foliated cataclastic breccia. Principal slip surfaces are parallel to boundaries of the shear zone, or oblique to it (R-surfaces). Injected gouge intruded the hanging wall (HW). FW = footwall.

Even if the values cited above for the duration and rates of seismic events are too short or fast by an order of magnitude, I can simplify the argument and pose the following questions to geologists: Can we confidently identify features in fault zones that formed on the order of seconds and which involved particle velocities of the order of 0.1–1 m/s? Can we differentiate these features from those that developed over time periods longer than, say, 1000 s?

3.2. Potential geological criteria for rates and durations of slip

In previous sections, faults have been treated largely in a seismological sense as surfaces in average dislocation models. Actual 'surfaces' as we see them in the field include (e.g. van der Pluijm and Marshak, 1997, table 6.1) single faults, fault zones, and brittle shear zones. These structures include three kinds of features that could preserve a record of slip at seismic rates: fault rocks, principal slip surfaces, and injected masses of fault-related materials (Fig. 3). Below, I briefly but critically review some of the natural features that other workers have suggested are indicative of seismic slip.

3.2.1. Fault rocks

A consensus holds that one type of fault rock, pseudotachylite consisting of a "fragment-laden, melt-supported suspension" (Spray, 1995, p. 1121), is evidence of localized slip at seismogenic velocities on the order of 1 m/s (e.g. Sibson, 1975; Spray, 1997). Because of the transient high temperatures necessary for local melting, pseudotachylite cannot form at the strain rates and particle velocities attending aseismic slip. Moreover, certain types of breccias are envisioned to have formed when wall rocks imploded into the meter- or kilometer-scale voids created at dilational jogs or releasing bends on faults (Sibson, 1986a). The generation of an implosion breccia is inferred to result from local fluid-pressure imbalance accompanying rapid transfer of slip across dilational irregularities in fault surfaces. I ask, however, whether we can rule out the possibility that breccias that are devoid of pseudotachylite melts and which instead contain hydrothermal vein fillings (e.g. Pavlis et al., 1993) could not have formed over time periods longer than a few seconds? For example, Blenkinsop and Sibson (1992) presented petrographic evidence from cataclastically deformed rocks supporting their interpretation that extension fracturing and vein filling proceeded contemporaneously at slower-than-seismic strain rates.

Other types of fault rocks, including matrix-rich, very fine-grained gouge and fragment-rich, coarser grained breccia (Fig. 3) are ubiquitous in brittle shear zones and common in fault zones. The microscale deformation mechanisms that accommodated mesoscopic penetrative strain in these materials include cataclastic and particulate flow. Sibson (1986b) noted that these mechanisms, as well as rate-dependent mechanisms involving dislocations and diffusion, could in principle allow aseismic 'shearing flow', which according to my definition is characterized by slower-than-seismogenic particle velocities. The idea that foliated gouge and breccia, like those shown in Fig. 3, owe their origin to aseismic flow is one that I find intuitively appealing. Sibson (1986b, 1989), however, pointed out that we lack not only constitutive laws for cataclastic flow, but also reliable observational criteria for distinguishing 'fast' cataclastic deformation from 'slow'. For example, is there an empirical basis for ruling out the possibility that slip at seismogenic velocities on the bounding fault in Fig. 3 drove distributed flow at seismogenic strain rates in the gouge beneath?

3.2.2. Principal slip surfaces

Many upper crustal fault and shear zones contain sub-planar surfaces upon which relative slip has been strongly localized. In this category, I include discrete singular faults, networks of sub-parallel, anastomosing faults, and arrays of mesoscopic R- and P-shear fractures oriented obliquely to the boundaries of tabular shear zones (Fig. 3). In mature fault zones, cumulative displacements range from millimeters on individual R- and P-fractures to perhaps kilometers on discrete faults. Some principal slip surfaces feature smooth, shiny slickensides, which may be decorated with striations and tool marks.

Some workers (e.g. Power and Tullis, 1989; Doblas et al., 1997), who conducted field and petrographic studies of natural faults, favored the interpretation that slickensides might owe their origin in part to seismic slip. In support of this hypothesis, one could cite the slickensides that are exposed on some fault scarps resulting from earthquakes. Moreover, Spray (1989) showed that striated slickensides, developed on partly melted gouge, can be artificially generated during sliding at seismogenic velocities. Means (1993) concluded, however, that only the presence of a former melt on a sliding surface is unambiguous evidence that slickensides formed at seismogenic rates. In the absence of any new empirical data to the contrary, I apply his conclusion to principal slip surfaces in general.

3.2.3. Injected materials

Several workers have described outcrop-scale features, in and adjacent to faults, that resulted from the intrusion or injection of mobile materials into shear fractures, extension fractures, or irregular spaces (Fig. 3). Where fractures contain pseudotachylite (Sibson, 1975; Grocott, 1981), the injections very probably occurred at seismogenic rates; otherwise, the friction-generated melt would have frozen in situ. In my opinion, it is still an open question whether morphologically similar injections of non-melted materials, such as granular or very fine-grained, matrix-rich gouges solely derived by cataclasis (Brock and Engelder, 1977; Lin, 1995) required seismogenic slip on associated principal slip surfaces. Even though processes such as 'fluidization' and 'hydraulic fracturing' have been invoked to explain the injections observed in outcrops and thin sections, is there an empirical basis for ruling out the possibility that most of these features were generated at aseismic rates?

3.3. The earthquake or stress cycle

Seismic events recur episodically. From this observation, it is deduced that shear stresses resolved on faults vary cyclically, as do slip velocities. Several workers have described evidence from natural faults that is fully consistent with the model of the earthquake cycle. For example, Chester et al. (1993) interpreted certain features in fault rocks as a record of coseismically dilatant fractures that were charged with fluids and post-seismically filled with vein minerals, which were repeatedly comminuted by subsequent events of seismogenic slip. Power and Tullis (1989) proposed that the behavior of quartz in certain slickensides cyclically alternated between continuous, diffusion-controlled deformation at low, interseismic strain rates, and cataclasis during slip at seismogenic rates. Sibson (1986a, 1986b), Sleep and Blanpied (1992), and others have hypothesized that cyclically changing fluid pressures very likely promote the recurrence of earthquakes.

I believe most field geologists would agree that many faults preserve an outcrop-scale or microstructural record of cyclic phenomena. In my view, most of this observational evidence can be explained by episodic changes in more than one physical parameter; many of these parameters in some way influence or are influenced by the physical or chemical activity of fluids. The rate and duration of slip are two parameters among several, which include fluid or pore pressure, effective normal stress, shear stress resolved on the fault, and the rate- or state-dependent frictional stability of the fault surface or fault rocks. Fluids could also contribute to the subcritical growth of microfractures (Atkinson, 1982), structures which would otherwise be interpreted as having propagated at seismic rupture velocities.

Even if the features in an exposed fault could be explained by cyclic changes in rates of slip, I am not aware of any criteria with which one can eliminate the possibility that both 'faster' and 'slower' parts of the cycle were aseismic. In fact, geodetic evidence from creeping parts of the San Andreas fault (Wesson, 1987; Linde et al., 1996) shows that aseismic slip is apparently episodic; days or months of steady creep are punctuated by transient episodes of faster slip.

4. Conclusions

I restate the question at hand as follows. Can we identify features in exposures of fault zones that formed in a period of a few seconds and which involved particle velocities on the order of 0.1–1 m/s? Can we confidently differentiate such features from those that developed over periods longer than, say, one minute? Except for the small percentage of faults containing pseudotachylite, I conclude that the answer to these questions is no.

This conclusion follows from the logic underlying the scientific method. Imagine that a couple of geologists are examining the striated slickensides on a fault surface. One geologist hypothesizes that these features were produced by fast, seismogenic slip; the other thinks they record slower aseismic slip. These two hypotheses are perfect examples of mutually contradictory models; both cannot be true, even if one is. In order to choose the better hypothesis, these geologists need to find evidence that is predicted by one model but which is incompatible with or prohibited by the alternative. I follow Means (1993) and argue that the empirical predictions needed for crucial tests of these particular hypotheses will have to come from experiments, not from intuitive guesses based on theory or observations at an outcrop.

So far, it seems as though we lack experiment-based criteria that enable field geologists to distinguish the records of seismic and aseismic slip as I define them here. Given the apparent intractability of the problem, I shall temporarily adopt the philosophical position of Krauskopf (1968) and wonder if distinguishing criteria other than pseudotachylite really do exist in faults and fault rocks? If not, then the question, 'Was slip on this fault seismic or aseismic?' is meaningless, and no amount of 'further research' will lead to a solution.

If this is the case, then field geologists could more profitably formulate and address questions that have a better chance of being answered using direct observation. For example, were the displacements along a fault accommodated by strongly localized slip on discrete surfaces, or by penetrative flow in fault rocks? Did slip become more strongly localized with time? Answers to these questions will be of interest to the experimentalists proposing criteria for differentiating velocity-strengthening from velocity-weakening, and by inference, stable from unstable, slip (Beeler et al., 1996; Marone, 1998; Scholz, 1998).

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