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Review article

Do faults preserve a record of seismic slip: A second opinion

Christie D. Rowe [a, *], W. Ashley Griffith [b]

[a] Department of Earth & Planetary Sciences, McGill University, 3450 University St., Montréal, QC H3A 0E8, Canada
[b] Department of Earth and Environmental Sciences, University of Texas at Arlington, Box 19049, Arlington, TX 76019, USA

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ABSTRACT

Exhumed fault zones offer insights into deformation processes associated with earthquakes in unparalleled spatial resolution; however it can be difficult to differentiate seismic slip from slow or aseismic slip based on evidence in the rock record. Fifteen years ago, Cowan (1999) defined the attributes of earthquake slip that might be preserved in the rock record, and he identified pseudotachylyte as the only reliable indicator of past earthquakes found in ancient faults. This assertion was based on models of frictional heat production (Sibson, 1975, 1986) providing evidence for fast slip. Significant progress in fault rock studies has revealed a range of reaction products which can be used to detect frictional heating at peak temperatures less than the melt temperature of the rock. In addition, features formed under extreme transient stress conditions associated with the propagating tip of an earthquake rupture can now be recognized in the rock record, and are also uniquely seismic. Thus, pseudotachylyte is no longer the only indicator of fossilized earthquake ruptures.

We review the criteria for seismic slip defined by Cowan (1999), and we determine that they are too narrow. Fault slip at rates in the range 10^{-4}–10^{1} m/s is almost certainly dynamic. This implies that features reproduced in experiments at rates as low as 10^{-4} m/s may be indicators of seismic slip. We conclude with a summary of the rock record of seismic slip, and lay out the current challenges in the field of earthquake geology.

1. Introduction

The structural record of fault deformation is available everywhere faults are exposed – from surface scarps of active faults to exhumed shear zones extinct for millions of years. However, structural geologists' ability to read and understand the record of past deformation is incomplete. In order to interpret rheology or strain rates of past deformation, we rely on qualitative and quantitative comparisons to observable deformation where material properties and timescales are well-known. These are available from laboratory deformation experiments, where trade-offs between time, scale, temperature and material analogs allow for the formulation of constitutive relationships for material rheology, and the development of microstructures for qualitative comparison to the real world (e.g. Brace and Kohlstedt, 1980; Kirby, 1983; Hirth et al., 2001). Seismic and geodetic studies provide information about slip rates and strain rates in actively deforming faults and shear zones, but do not elucidate deformation mechanisms at the scales which control fault strength in laboratory experiments, or in the lithosphere.

The dominant deformation mechanisms active at seismogenic depths, especially cataclasis, frictional sliding, and solution creep, still want for theoretical underpinnings. Although these have been reproduced in the laboratory, their behavior is highly sensitive to local conditions such as pore pressure, pore fluid chemistry, and stress state – all of which are difficult or impossible to constrain in ancient faults. How can we interpret past brittle deformation in the rock record?

Structural field and micro-scale observations can bridge the gap between the time-constrained models provided by experiments (at the cm-scale) and active deformation (at the 100s–1000s m-scale)(Sibson, 1977, 1989). Cowan (1999) approached this relationship by defining attributes that are characteristic of seismic slip. He defined an earthquake based on seismological constraints as a slip event that radiates seismic waves with periods of 10 s or less, has a seismic moment on order ~10^{9}–10^{21} Nm, slip rates ~0.1–1 m/s, rise time ≤5 s, rupture velocity ~2.5–3 km/s, and rupture durations on order 30 s and scaling with earthquake size. Based on that definition, Cowan (1999) challenged structural geologists to strictly

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* Corresponding author.
E-mail address: christie.rowe@mcgill.ca (C.D. Rowe).

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determine which of these characteristics might contribute to preservation of evidence of earthquakes in the rock record, and he concluded that only the rapid frictional heating which results in the formation of pseudotachylyte could be confidently identified as a ‘fossilized earthquake’.

Significant progress has been made by integrating laboratory friction experiments with field observations in an attempt to recreate structures observed in fault gouge or cataclasite, and then relate these to the specific boundary conditions required to form them in the laboratory (e.g. Boutareaud et al., 2008; French et al., 2014; Rempe et al., 2014). Niemeijer et al. (2012) present a thorough review of this approach. In this contribution, we first revisit Cowan (1999)’s definition of an earthquake and argue for an expansion of the range of slip rates which are recognized as exclusively seismic. We review the progress made in pseudotachylyte research in the last 15 years, and then we summarize advances that have been made in defining other fault rock features which are diagnostic of fast slip, particularly through the identification of signatures of frictional heating. We explore preserved evidence of stress transients associated with dynamic rupture, as potential evidence of seismic slip. We conclude with a summary of current consensus on the evidence for past seismic slip in the rock record, and lay out the current challenges in the field of earthquake geology.

2. Characteristics of earthquakes

Cowan (1999) defined earthquake rupture using a conceptual model based in fracture mechanics, where slip nucleates at one point and propagates along a two-dimensional discontinuity. The rupture velocity is the rate at which the front of the rupture moves along the fault, behind which particles adjacent to the fault accelerate such that the relative particle velocity (slip rate) across the fault increases from zero to a local peak velocity and then decays to zero at the tail end of the rupture (Fig. 1A). As a result, the slip rate varies along the fault as a function of time and spatial position, but the average cumulative slip and slip velocity can be determined seismologically (Fig. 1B). Cowan (1999) defined *aseismic slip* as slip which did not produce elastic waves detectible with short-period seismometers (10 s or less). In practice, “aseismic slip” has come to mean fault slip at rates slower than earthquake slip, down to creep at tectonic plate rates; however, the exact cut-off may vary with detection capabilities.

It is a common assertion that the characteristic earthquake slip rate is on the order of 1 m/s (e.g. Sibson, 1986). Although initially estimated by Brune (1976), this number is often attributed to Heaton (1990) who showed that the average slip rates on several large earthquakes was ~0.8 m/s and peak slip velocity at the rupture front could be ~10–20 m/s. However, slip must persist at rates below 1 m/s for significant periods of time after initial peak slip rate (e.g. Dunham et al., 2011; Harris et al., 2011). Slip rate can also vary spatially along a fault, even during a single earthquake rupture (Beroza and Mikumo, 1996). Therefore, some areas of a rupture surface experience much higher or much lower average slip rates, and declining slip rate must follow peak slip rate at a point.

The traditional end-member models of seismic (~1 m/s) vs. plate rate, aseismic (~10^{-10} m/s) slip have been challenged by the recent discoveries of slip events at intermediate slip velocities (Rogers and Dragert, 2003; Obara et al., 2004; Wallace and Beavan, 2006; Ito and Obara, 2006; Gomberg et al., 2008). These intermediate ‘slow slip events’ (SSE) are characterized by durations of days to months, and quasi-static slip which may be fast enough to emit low frequency seismic waves (c. 10^{-7}–10^{-8} m/s, Schwartz and Rokosky, 2007). Recent studies in Cascadia have shown that rupture propagation rate, not only slip rate, may be most important in controlling the generation of seismic tremor during slow slip events (Wech and Bartlow,

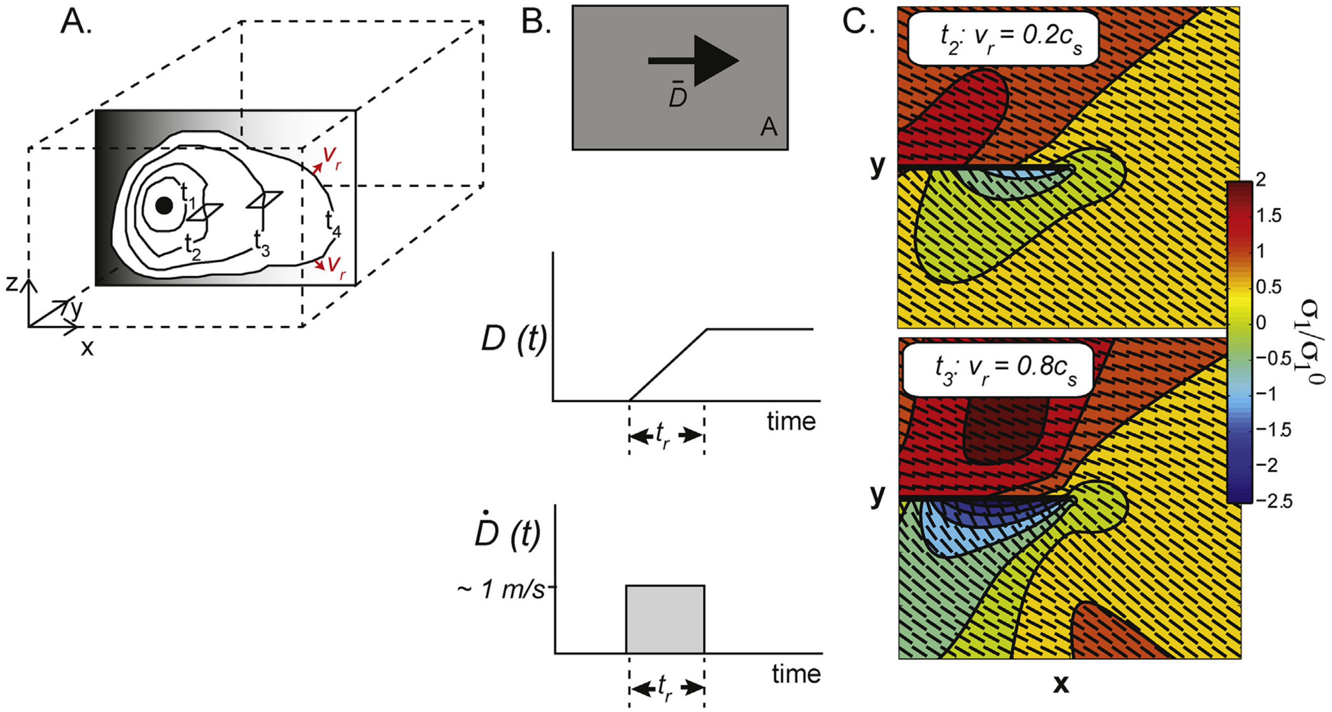

Fig. 1. (a) Schematic illustration of a rupture propagating from hypocenter (filled circle) along a pre-existing fault contained within x-z plane. Rupture front shown at successive times t_1, t_2, t_3, t_4, and boxes drawn at t_2 and t_3 rupture tip lines in x-y plane show locations of plots in c. Modified from Lay and Wallace (1995); Cowan (1999). (b) Idealized average dislocation model, where vector $\overline{D}$ is the average slip and A is the area of the rupture. The plot of $D(t)$ is the slip history at a point, and t_r is the rise time. The plot of $D(t)$ is the slip rate, the time derivative of $\dot{D}(t)$. The shaded area under the boxcar curve is proportional to the seismic moment. Modified from Lay and Wallace (1995); Cowan (1999). (c) Schematic σ_1 fields (normalized by the static far field principal stress σ_1^0) at the tips of the rupture at times t_2 and t_3, respectively. Dashes show the directions of σ_1. The only difference between the two plots is the rupture velocity, v_r shown as a function of the shear wave speed, c_s. Modified from Di Toro et al. (2005).