Does Stress Drop Positively or Negatively Correlate With Rupture Speed?

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Key Points:

- There are different contexts for discussing rupture speed, stress drop, and their correlation
- Constant fracture energy favors a positive correlation between stress drop and rupture speed
- Variable fracture energy can lead to a negative correlation between stress drop and rupture speed

Abstract

Rupture speed V_r and stress drop $\Delta\tau$ are two key parameters that can characterize earthquake source and the associated potential for ground shaking. Despite their importance, a controversy has emerged in recent years regarding whether there is a positive or negative correlation between $\Delta\tau$ and V_r. Here I attempt to reconcile the controversy by presenting a context-based solution and a physics-based solution. The first solution calls for attention to the specific context under which V_r and $\Delta\tau$ are discussed, as their meanings and estimated values can vary between different studies. It is noted that a negative correlation between $\Delta\tau$ and V_r can result, at least partly, from a tradeoff effect inherent to certain analysis method. For the second solution, it is shown that the specific correlation between $\Delta\tau$ and V_r can depend on the condition of fracture energy G_c. Constant G_c often favors a positive correlation, whereas introducing a variability of G_c can lead to a negative correlation. More efforts are needed to improve the methods for estimating V_r and $\Delta\tau$, and to explore other mechanisms that may explain the correlation between the two parameters.

Plain Language Summary

Rupture speed describes how fast an earthquake rupture propagates, and stress drop dictates how much strain energy stored in the surrounding media is released by an earthquake. From an energy-based point of view, it may be intuitive to anticipate a positive correlation between stress drop and rupture speed, because larger stress drop would imply more energy supply (converted from strain energy) for rupture propagation. Meanwhile, several recent studies also reveal a negative correlation between stress drop and rupture speed. To reconcile the discrepancy, it is necessary to recognize (1) how rupture speed and stress drop are defined and estimated, and (2) the importance of both energy supply and consumption. Especially, it is shown that reducing the energy consumption required for rupture propagation, known as fracture energy, can lead to a negative correlation between stress drop and rupture speed. Therefore, the detailed correlation between stress drop and rupture speed can depend on whether fracture energy remains invariant. Other mechanisms may also produce a positive or negative correlation between stress drop and rupture speed, and deserve to be explored in the future.

1 Introduction

Since the seminal work of Griffith (1921), it is now generally accepted that fracture of brittle materials is described by an energy balance criterion (Broberg, 1999; Freund, 1990). Significant efforts have been made to extend the key concepts in material science focusing on fracture to earthquake science focusing on frictional slip (Andrews, 1976; Ben-Zion, 2001; Burridge, 1973; Das, 2003; Madariaga, 2012; Rice, 1980), after which energy partitioning can be discussed during an earthquake (Kanamori & Rivera, 2006; Rivera & Kanamori, 2005). Recent laboratory experiments, theoretical analyses, and numerical simulations further support the validity of fracture mechanics for describing the behaviors of both slow and fast earthquakes

(Svetlizky & Fineberg, 2014; Kammer et al., 2018; Reches & Fineberg, 2023; Weng & Ampuero, 2022).

One fundamental question in earthquake science is how fast an earthquake rupture can propagate, since this will affect the understanding of earthquake physics and the assessment of seismic hazard. According to fracture mechanics, rupture speed is controlled by the balance between energy release rate and fracture energy (Freund, 1990). The former tells how much available energy is released per unit rupture length, which is a function of stress drop and rupture speed; while the latter describes how much energy must be dissipated in order to advance the rupture front. Following this idea, a variety of rupture phase diagrams have been constructed to connect rupture speed with other source parameters, such as stress drop or a function of it (Andrews, 1976; Liu et al., 2014; Madariaga & Olsen, 2000; Passelègue et al., 2020; Trømborg et al., 2011; Wei et al., 2021; Xu et al., 2015).

While the importance of rupture speed and stress drop has been recognized, how the two parameters correlate with one another is still a subject of debate. Some studies show a positive correlation based on experimental observations (Chen et al., 2021; Passelègue et al., 2013; Svetlizky et al., 2017; Xu et al., 2018), whereas others report a negative correlation based on source inversion of natural earthquakes (e.g., Chounet et al., 2018). In this commentary, I present two solutions for reconciling the discrepancy. The first solution calls for attention to the context under which rupture speed and stress drop are discussed, as their meanings can vary between different studies. The second solution is more physics based and will invoke fracture energy to tune the correlation between stress drop and rupture speed.

2 Different contexts for discussing rupture speed and stress drop

While the definitions of rupture speed and stress drop are clear in the literature (Bizzarri, 2011; Kanamori & Rivera, 2006; Noda et al., 2013), to estimate their values from actual observations requires experience and sometimes can be challenging.

In the laboratory, rupture speed V_r is usually estimated by two approaches: (1) counting the travel time of rupture front over some propagation distance, and (2) matching the near-field waveform against a V_r-dependent reference solution. Although the two approaches can often yield similar results, some issues deserve to be mentioned. First, the approach of waveform matching has a low and high sensitivity to V_r when V_r is slow and fast, respectively, owing to the pronounced Lorentz effect only when V_r approaches the limiting speed (Svetlizky & Fineberg, 2014; Svetlizky et al., 2020). Consequently, one study recommends combining rupture front trajectory and detailed waveform pattern for a robust estimation of rupture properties (Xu et al., 2019a). Second, when rupture process is not smooth (Xu et al., 2023) or when rupture evolution has not become spontaneous, e.g., during rupture nucleation (Guérin-Marthe et al., 2019), then the two approaches may not converge. The estimation of stress drop $\Delta\tau$ in the laboratory also requires experience and caution. Here I don't consider the cases equipped with only macroscopic observations (Baumberger & Caroli, 2006; Leeman et al., 2016; Nielsen et al., 2016), because rupture propagation is not explicitly involved. For other cases where rupture propagation can be resolved, $\Delta\tau$ is typically estimated during the passage of rupture front (Bayart et al., 2018; Xu et al., 2018), known as dynamic stress drop. The purpose is to minimize undesired effects, such as fault re-rupturing, healing, reflected waves from sample boundaries, and interaction with external apparatus. That said, caution must be taken to study the static stress drop finalized after rupture termination (Ke et al., 2018; Passelègue et al., 2016) or the long-tailed slip-weakening process (Brener & Bouchbinder, 2021; Paglialunga et al., 2022), since undesired effects can be involved if the selected time window is long. Moreover, spatial heterogeneity (Bayart et al., 2018), off-fault measurement (Xu et al., 2019a), and intermittent rupture process (Rubino et al., 2022; Xu et al., 2023) can also complicate the estimation of stress drop or slip-weakening curve.

Despite the aforementioned various issues, as long as careful calibrations are made, rupture speed and stress drop can be estimated directly and accurately in the laboratory, whose values are sometimes cross-validated by fracture mechanics (Bayart et al., 2018; Kammer et al., 2018; Svetlizky et al., 2017; Xu et al., 2019a).

Except for some cases equipped with near-field stations (Fukuyama & Mikumo, 2007; Fukuyama & Suzuki, 2016), the source properties of natural earthquakes usually cannot be directly measured; instead, they are inferred from remote observations in the context of certain models, and thus are subject to attenuation and model dependence. Although dynamic inversion has been applied to a few cases (Madariaga & Ruiz, 2016), common practice still assumes a kinematic model with prescribed rupture process to invert for earthquake source properties. For large earthquakes, finite fault inversion can be performed to discretize the source region into several patches. Depending on data quality and model parameterization, either a constant (Hartzell & Heaton, 1983; Kikuchi & Kanamori, 1991; Ye et al., 2016) or a variable rupture speed (Ji et al., 2002; Minson et al., 2013) can be inverted. With the inverted slip history, a dislocation model can be further applied to obtain the evolution of stress (Bouchon, 1997; Ide & Takeo, 1997; Tinti et al., 2005) and the final static stress drop (Okada, 1992), either on each patch or over the entire region (Noda et al., 2013; Shao et al., 2012). For small-to-moderate earthquakes, simple models such as the circular crack or rectangular fault models are preferred (Brune, 1970; Haskell, 1964; Kaneko & Shearer, 2015; Madariaga, 1976; Sato & Hirasawa, 1973), although only some of them explicitly consider rupture propagation (Udías et al., 2014). Another useful approach is to analyze the second moment tensor (McGuire, 2004; Meng et al., 2020). Several studies have already applied simple models to global (Allmann & Shearer, 2009; Chounet et al., 2018) or regional earthquakes (Abercrombie & Rice, 2005; Abercrombie et al., 2017; Yoshida & Kanamori, 2023). In these studies, rupture speed is either assumed or inferred from pre-defined misfit functions, while stress drop is estimated from the corner frequency of source spectrum and the scaling relation related to seismic moment.

Three issues deserve to be mentioned for the kinematic inversion of natural earthquakes. First, the inverted rupture speed does not necessarily reflect the true rupture speed, because there is no cross-validation against fracture mechanics. Second, for most cases, the estimated stress drop depends on the entire rupture process, including fault rupturing, re-rupturing and healing, and thus can deviate from the dynamic stress drop solely produced by one rupture front (Madariaga, 1976; Kaneko & Shearer, 2015; Ke et al., 2022; Song & Dalguer, 2017). Third, there is a tradeoff between stress drop $\Delta\tau$ and rupture speed V_r through the scaling relation $\Delta\tau \cdot (V_r)^3 \propto M_0$, where M_0 denotes seismic moment (Kanamori & Rivera, 2004). This can easily render a negative correlation between $\Delta\tau$ and V_r (Ye et al., 2016).

In summary, the context for discussing rupture speed and stress drop can vary between laboratory and natural earthquakes (Table 1), or between studies on the same earthquake but with different models. Consequently, it is quite possible that the derived correlation between stress drop and rupture speed can also vary. To avoid apple vs. orange comparison, it is better to stick to the same context, and mind the assumptions and limitations of the employed model.

Table 1 Different contexts for estimating rupture speed V_r and stress drop $\Delta\tau$

	Laboratory earthquakes (with rupture propagation)	Natural earthquakes (kinematic inversion)
Near-field observation	yes	sometimes yes but mostly no
V_r	directly measured or inferred	inferred or assumed; constant or variable
$\Delta\tau$	directly measured; mostly dynamic stress drop	indirectly estimated; mostly static stress drop
Independent estimations of V_r and $\Delta\tau$	yes	usually no
V_r and $\Delta\tau$ cross-validated by fracture mechanics	sometimes yes	no

3 Physical mechanisms explaining the correlation between stress drop and rupture speed

In this section, I focus on the same context(s) where rupture speed and stress drop can be estimated in a consistent way. Although tradeoff effect and estimation error may still exist, the main purpose here is to seek physical mechanisms for understanding the correlation between stress drop and rupture speed.

In the laboratory, several studies have revealed a positive correlation between stress drop $\Delta\tau$ and rupture speed V_r (Chen et al., 2021; Okubo & Dieterich, 1984; Passelègue et al., 2013, 2016; Svetlizky et al., 2017; Xu et al., 2018). This can be understood by the balance between dynamic energy release rate $G_d(V_r, \Delta\tau) = g(V_r) \cdot G_s(\Delta\tau)$ and fracture energy G_c (Freund, 1990). Here, $g(V_r)$ is a monotonically decreasing function of V_r, while $G_s(\Delta\tau)$ is a functional of $\Delta\tau$ and known as static energy release rate. Assuming G_c is constant, larger $\Delta\tau$ in general would indicate larger $G_s(\Delta\tau)$. To still hold a balance between $G_d(V_r, \Delta\tau)$ and G_c, the function $g(V_r)$ must decrease, which then implies an increase in V_r. While fracture energy G_c does appear constant in some cases once the conditions for loading and fault interface are set (Bayart et al., 2016), there is no particular reason to believe that G_c must always remain constant. Indeed, G_c can vary by a factor of two during the same sequence of earthquakes (Xu et al., 2019a), or by two orders of magnitude between the primary and secondary rupture fronts (Kammer & McLaskey, 2019).

Taken to the extreme, one study shows that some secondary slip fronts, corresponding to one type of interface waves, can propagate rapidly with zero G_c and zero $\Delta\tau$ (Xu et al., 2019b). Apparently, if one relaxes the assumption of constant G_c, then there will be room for a negative correlation between $\Delta\tau$ and V_r. This is further demonstrated by a recent experimental work showing that a smooth fault tends to produce subshear ruptures with larger $\Delta\tau$ and longer recurrence interval, whereas a rough fault can host supershear ruptures with smaller $\Delta\tau$ and shorter recurrence interval (Xu et al., 2023). It is conceived that G_c, which scales with recurrence interval, is smaller on the rough fault.

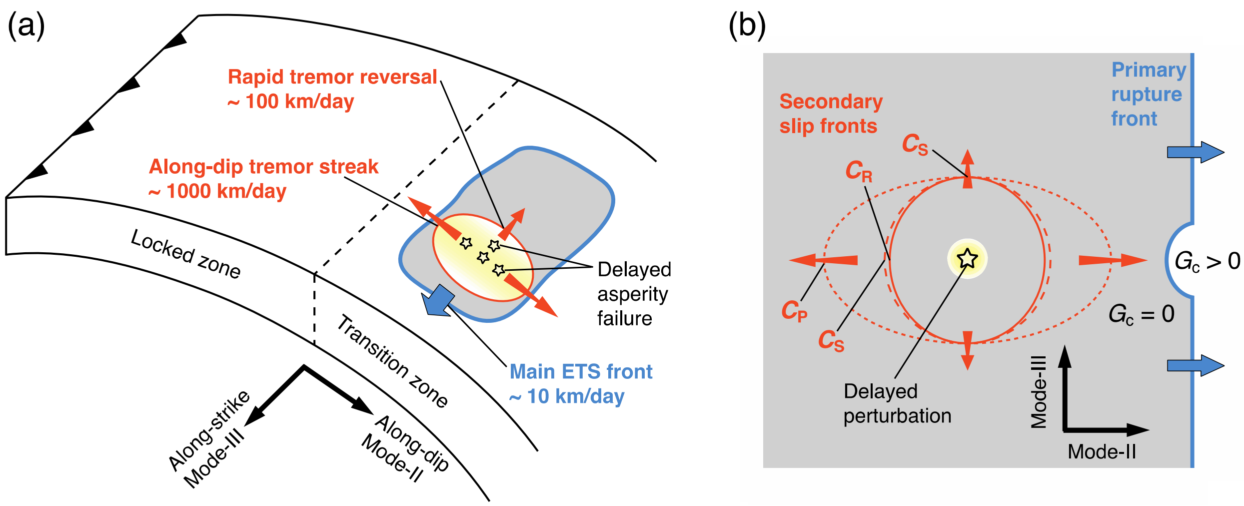

Figure 1. Schematic diagrams showing secondary slip fronts in a region that has already been ruptured by a main slip front. (a) In the transition zone of a subducting plate, along-strike tremor reversal and along-dip tremor streak can emerge in the wake of a main ETS front. Figure drawn based on figures 3 and 6 in Luo & Ampuero (2017). (b) Under the condition of constant friction (implying zero fracture energy G_c) behind a primary rupture front, secondary slip fronts can propagate at the Rayleigh, S, or P wave speed (denoted by C_{R}, C_{S}, and C_{P}, respectively). Figure drawn based on figure 1 in Dunham et al. (2003).

The role of fracture energy may also explain the behaviors of natural earthquakes. Episodic Tremor and Slip (ETS), one form of slow earthquakes (Peng & Gomberg, 2010), has been observed to advance slowly at a speed of ~ 10 km/day, along the strike of the subducting plate in Cascadia (Houston et al., 2011) and southwest Japan (Obara et al., 2012). Occasionally, secondary slip fronts can propagate backward along the strike at a speed of ~ 100 km/day, or back and forth along the dip at a speed of ~ 1000 km/day (Figure 1a) (Ghosh et al., 2010; Houston et al., 2011; Luo & Ampuero, 2017; Nakamoto et al., 2021; Obara et al., 2012).

Theoretical analyses suggest that, for a secondary slip front to attain a faster propagation speed V_r than the main one, either slip rate v_{slip} needs to be increased or peak-to-residual strength drop $\Delta\tau_{p-r}$ needs to be reduced, according to the scaling relation: $V_r = \alpha \cdot v_{\mathrm{slip}} \cdot \frac{\mu}{\Delta\tau_{p-r}}$, where α is a geometric factor of order 1 and μ is the shear modulus (Ampuero & Rubin, 2008; Rubin & Armbruster, 2013). One possibility for achieving higher v_{slip} and/or lower $\Delta\tau_{p-r}$ is to reduce fracture energy G_c (Hawthorne et al., 2016). This is mechanically feasible, because G_c must be weakened by the main slip front and can only be partially recovered for a short elapse time. Similar feature has also been reported for numerically simulated fast earthquakes, where polarized secondary slip fronts can propagate at around the Rayleigh or body wave speed (~ 3-6 km/s for typical crustal rocks) behind a main slip front (Figure 1b) (Dunham et al., 2003; Dunham, 2005). In this case, G_c remains zero after the passage of the main slip front, so that those secondary slip fronts are accompanied with zero stress drop and zero strength drop, despite their fast propagation speeds.

Last but not the least, there is another way for explaining a negative correlation between stress drop $\Delta\tau$ and rupture speed V_r. To do so, one needs to extrapolate the classical concept of fracture energy to any dissipative processes (e.g., off-fault damage) that can effectively damp the acceleration of the rupture front (Andrews, 2005; Ben-Zion & Dresen, 2022; Cocco et al., 2023; Gabriel et al., 2013; Nielsen, 2017; Templeton, 2009). Let's consider a scenario where the entire on- and off-fault region is on the verge of failure and then a dynamic rupture is activated along the fault. On one hand, larger (or smaller) $\Delta\tau$ tends to favor faster (or slower) V_r, as already explained earlier. On the other hand, larger (or smaller) $\Delta\tau$ also tends to induce more (or less) extensive off-fault damage, which in turn can quench (or promote) the further acceleration of the rupture front. A delicate balance between the two competing effects could cause a negative correlation between $\Delta\tau$ and V_r. This is the physical mechanism invoked by Chounet et al. (2018) for understanding their inferred results on global earthquakes. Similarly, a non-monotonic friction law, characterized by rate-weakening at low slip rate but rate-strengthening at high slip rate (Bar-Sinai et al., 2014; Reches & Lockner, 2010; Rubin, 2011; Shibazaki & Iio, 2003), may also cause a negative correlation between $\Delta\tau$ and V_r.

4 Conclusions

Contrasting views on the correlation between stress drop $\Delta\tau$ and rupture speed V_r have been reported in recent years. Two solutions are presented to reconcile the discrepancy: (1) different contexts for discussing V_r and $\Delta\tau$, and (2) some physical mechanisms. In (1), V_r and $\Delta\tau$ can have different meanings in different studies, which may hinder a direct comparison on the derived correlations. Moreover, a negative correlation may reflect a tradeoff effect inherent to the analysis method. In (2), the specific correlation between $\Delta\tau$ and V_r can depend on fracture energy G_c. Constant G_c often favors a positive correlation, whereas variable G_c can lead to a negative correlation. It is hoped that this commentary can help clarify the estimations of V_r and $\Delta\tau$ under different contexts, and can stimulate future studies to investigate the correlation between the two parameters.

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Data Availability Statement

No data were used in this study.

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