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Key Points:
• A power density-dependent friction law can be used to describe the runout of coherent landslides
• Different minerals are associated with different frictional weakening mechanisms, likely determining different landslide dynamics
• The rate of frictional weakening seems sample size dependent: Much faster weakening may occur in landslides than in the laboratory

Supporting Information:
• Supporting Information S1

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Abstract
The evolution of the shear resistance at the base of a coherent landslide body can effectively control its dynamic behavior. High-velocity rotary shear experiments have allowed scientists to explore stress-strain conditions close to those found in large landslides and faults. These experiments have led to two alternative models being proposed, which describe the evolution of the shear resistance through friction laws that depend either on normal stress or on velocity. Here, we discuss an integrated approach, first proposed to study seismic fault behavior, that reconciles these two models under a single parameter—the power density—which we utilize for the first time to investigate landslide dynamics. Using thermodynamic and process-based considerations, different soil and rock types can be related to different weakening mechanisms, which in turn can determine different landslide behaviors.

Plain Language Summary
In coherent landslides, the shape and structure of the unstable soil or rock mass remains intact while it slides down. Large coherent landslides are relatively uncommon, yet they are of great concern because of their destructive power. The friction at the base of the unstable mass is a fundamental parameter that controls the movement of landslides. It can be estimated through laboratory experiments and is often assumed as a constant value. However, this assumption does not always hold, especially for large and fast-moving landslides, where friction changes through time, or according to the velocity and thickness of the sliding mass. The dynamic stresses in large coherent landslides and seismic faults are somewhat similar. Geophysicists have proposed the concept of power density to explain the behavior of faults. Here, for the first time, we apply this concept to landslides. We analyze data from 280 published experiments on soils and rocks, showing how the power density correlates with friction for various minerals. By discussing the mechanical and thermodynamic processes that are involved, we provide a framework to link the behavior of coherent landslides to physicochemical parameters using the power density concept.

1. Introduction
Large long-runout landslides (volume > 1 Mm³) are catastrophic, yet remarkable geological processes. The friction coefficient (μ), defined as the ratio of the shear stress to the effective normal stress, is a key parameter controlling the dynamics and runout of landslides. It can be roughly estimated a posteriori from the H/L ratio (Heim’s ratio)—where H is the fall height and L is the runout distance. Low values of Heim’s ratio are typical of high-mobility landslides. In large landslides, μ scales negatively with volume (Legros, 2002; Lucas et al., 2014), promoting high mobility. Dynamic simulations of landslides suggest that a unique value of μ may be insufficient to describe different stages of landslide runout, whereas slip-, velocity-, or stress level-dependent weakening laws seem more appropriate (Goren & Aharonov, 2007; Liu et al., 2015; Lucas et al., 2014; Wang et al., 2017).

High-velocity rotary shear experiments provide insights into the frictional mechanisms controlling fault dynamics as well as landslide dynamics. By fitting experimental data, Mizoguchi et al. (2007) obtained an exponential-decay equation for the friction coefficient of shear gouge

$$\mu = \mu_{ss} + \left(\mu_p - \mu_{ss}\right)e^{-\frac{d}{D_c}}$$  

(1)

where $\mu_p$ and $\mu_{ss}$ are the peak and steady-state friction coefficients, respectively, $d$ is the shear displacement of the specimen, and $D_c$ is the slip-weakening distance. An exponential decrease of $\mu_{ss}$ with the
The relationship between PD (Sawai et al., 2012) and landslides, as demonstrated through discrete element simulations by Zhao and Crosta (2018). Here, we investigate the relationships between the shear velocity (velocity-dependent law) was observed, yet some experiments also identified a similar dependence on the normal stress (Boneh et al., 2013; Wang et al., 2018). Therefore, \( \mu_{\text{ss}} \) can be generally expressed as

\[
\mu_{\text{ss}} = A + Be^{\xi}
\]

where \( \xi \) represents either the velocity \( v \) or the normal stress and \( A, B, \) and \( C \) are fitting parameters. Experiments also show a power law decrease of \( D_c \) with the normal stress (Hou et al., 2012; Mizoguchi et al., 2007; Togo et al., 2009; Togo et al., 2014; Yao, Ma, et al., 2013), which can be expressed as

\[
D_c = E\xi^F
\]

where \( E \) and \( F \) are fitting parameters.

Eqs. 1-3 are useful not only in fault mechanics, but also for investigating the dynamics of coherent landslides. In these landslides, the entire mass slides as a nearly rigid body, with little internal energy dissipation. As a consequence, their behavior is essentially controlled by the frictional resistance in a thin basal layer (often just a few millimeters or centimeters thick), or even on the landslide-bedrock interface. Both can be well characterized in terms of overburden stresses, strain or slip rates, and energy metrics. Partially coherent landslides also occur, in which partial coherence can be identified either spatially (part of the mass remains intact) or temporally (the mass remains intact initially, then disaggregates). The frictional mechanisms in partially coherent landslides are more complex but occur at comparatively lower energy levels as internal dissipation is more significant than in coherent landslides. Extensive fragmentation may also occur in most large landslides, as demonstrated through discrete-element simulations by Zhao and Crosta (2018).

Shear-weakening mechanisms in the basal layer of coherent landslides and, more limitedly, in partially coherent landslides may be studied through high-velocity shear experiments, which can reproduce the stress states occurring during landslide runout. Energy dissipation in high-velocity shear experiments can arise from grain crushing (Hu, Yin, et al., 2018; Zhang et al., 2018) and heat generation. Some energy can also be consumed in endothermic reactions, namely thermal decomposition, and dehydration. Grain crushing can only account for the dissipation of a small fraction (<6%) of the energy budget at laboratory scale (Brantut et al., 2008), whereas most of it is dissipated as heat. In landslides experiencing heavy fragmentation, plastic deformation, and/or basal erosion during runout, quantifying the energy dissipation in the basal layer is difficult. Conversely, the condition of coherent landslides is more similar to that occurring in laboratory experiments, as internal deformation is small, and energy dissipation largely occurs within a “thin” basal shear zone (1–10 \( \mu \) thick in laboratory experiments; more variable, from millimeter to meter scale in landslides) (Brantut et al., 2008; Iverson, 2005).

Researchers often consider landslide bodies as rigid or relatively coherent while investigating thermal weakening mechanisms, such as thermal softening (Cecinato et al., 2008), thermal pressurization (Vardoulakis, 2002; Veveakis et al., 2007), thermal decomposition (Hu, Huang, et al., 2018; Hu et al., 2019; Mitchell et al., 2015; Goren et al., 2010), or frictional melting (De Blasio & Medici, 2017). Under this hypothesis, the key parameter controlling thermal weakening (Di Toro et al., 2011) is the mechanical work rate per unit area, or power density: \( PD = \tau_v \nu_v \). Here, the equivalent shear stress \( \tau_v \) is computed as \( \tau_v = \tau_{\text{ss}} + 0.538(\tau_p - \tau_{\text{ss}}) \), where 0.538 = \( \frac{\sqrt{\pi \text{Erfi}(1)}}{2\pi} \) and \( \text{Erfi}(1) \) is the imaginary error function evaluated at 1, and \( \nu_v \) is the equivalent velocity for cylindrical samples from the center to the edge. Information about normal stress and \( v \) can be incorporated in \( PD \) through equations 2 and 3. \( PD \) controls the temperature during fault slip (Di Toro et al., 2011) and is negatively correlated with the specific surface area of the sheared mineral (Sawai et al., 2012).

The relationship between \( PD \) and \( \mu_{\text{ss}} \) or \( D_c \) has been explored in faults (Di Toro et al., 2011; Reches et al., 2019), but not in landslides. Moreover, past works focused on relatively low \( PD \) regimes and did not address possible ways to extrapolate the results to the higher \( PD \) regimes that may occur in landslides. Here, we investigate the relationships between \( \mu_{\text{ss}}, D_c, \) and \( PD \) using published experimental data from high-velocity shear experiments on various gouge materials, including nonreactive, hydrous, and carbonate gouges, and we discuss the implications of our findings to the understanding of the mobility of coherent landslides.
2. Materials and Methods

We gathered published data from 280 high-velocity rotary shear experiments, available in the supporting information (SI) file, conducted on nonreactive gouges (quartz, feldspar, and plagioclase, which can be assumed inert during shearing), hydrous gouges (containing hydrous minerals, such as kaolinite, smectite, and gypsum, which can release H2O), and carbonate gouges (such as limestone, which can release CO2 and/or produce nanoparticles during shearing at high temperature). The latter group was further classified into carbonate-bearing gouges (with calcite and dolomite accounting for <80% of the mass), and pure carbonate gouges (with calcite and/or dolomite being the sole components). Rock-to-rock experiments on marble were also considered, for comparison (Figure S1, SI file). All the experiments were performed in "dry" condition (room humidity) to rule out preexisting pore water pressures.

We used the least squares method to fit empirical laws in the form of equations 2 and 3 to the experimental data. Even though we are aware that this fitting method is not optimal for power law distributions, as it does not guarantee that the data actually follow such distribution (Clauset et al., 2009), it has been used extensively in past works with reasonable results (Crosta et al., 2018; Lin et al., 2015; Mizoguchi et al., 2007). Nonetheless, we discuss the issue in the SI file and propose an alternative fitting that yields similar results (Chen & Rempel, 2014).

3. Results and Discussion

3.1. A Power Density-Weakening Law

Figure 1a shows trends of $\mu_{ss}$ for three kinds of gouges. Despite the scatter, similar trends with respect to $PD$ are evident. We identify two regimes for $\mu_{ss}$ for samples with 25-mm diameter: (1) for $PD < 0.95$ MW m$^{-2}$, $\mu_{ss}$ decreases exponentially from a maximum around 0.7–0.9; (2) for $PD > 0.95$ MW m$^{-2}$, $\mu_{ss}$ remains nearly
constant at ~0.15. For samples with 40-mm diameter, a threshold between the regimes is found at $PD = 0.4$ MW m$^{-2}$.

In nonreactive gouges, the onset of weakening may be related to flash heating of asperities (Chen & Rempel, 2014; Rice, 2006). Some studies of landslide dynamics have recognized the role of thermal-induced weakening (Cecinato et al., 2008; Vardoulakis, 2002). In hydrous gouges, weakening can be attributed to flash heating-related thermal pressurization (Goren & Aharonov, 2009) and moisture fluidization (Mizoguchi et al., 2006). Elevated temperature leads to the release of absorbed water, or even to dehydration reactions. This water—detected as humidity in the test chamber—may produce excess pore pressure in the shear zone, decreasing the shear resistance (Brantut et al., 2011). However, the results in Figure 1a do not show significant difference between hydrous and nonreactive gouges, suggesting that the relatively low $PD$ may be insufficient to trigger thermal pressurization or moisture fluidization or that these mechanisms are not obvious at the experimental scale.

The least squares method was used to fit the data in Figure 1 based on equations 2 and 3. The meaning of the factor $\xi$ is listed case by case. The fitting parameters and coefficient of determination ($R^2$) are given in Table S4 (SI file). $R^2$ is higher for the $PD\mu_{ss}$ relationship than for the velocity-dependent friction law for nonreactive gouges, while it is lower for carbonate-bearing gouges, and is nearly equal for hydrous gouges. Although, statistically, there is little difference between the two models, the correlation with $PD$ in Figure 1a seems to describe the general trend better than that in Figure 1b, especially for nonreactive gouges and hydrous gouges. This suggests a way to extrapolate $\mu_{ss}$ from the experimental scale (0–2 MW m$^{-2}$ for gouges, and 0–10 MW m$^{-2}$ for rock-to-rock friction) to the natural landslide scale (0–20 MW m$^{-2}$), whereas more data are needed to constrain this upscaling through the velocity-dependent friction law. In Figures 1c and 1d, the trends of $D_c$ for the three kinds of gouges are consistent, all of them showing a power law decrease with $PD$ increasing. The $PD$-dependent and normal stress-dependent laws show similar trends, with a slightly higher $R^2$ in the former.

### 3.2. Thermochemical Pressurization and Nanoparticles Lubrication in Carbonate Gouges

Thermal pressurization is the prevailing weakening mechanism (with some remarkable exceptions; cf. Hu et al., 2017) in water-saturated shear zones in coherent landslides under high-velocity shearing (Goren & Aharonov, 2007; Vardoulakis, 2002). First, unequivocal evidence of thermal pressurization in noncohesive rocks has been documented by Violay et al. (2015). However, pore pressure is speculated to arise also in dry friction experiments (De Paola et al., 2011; Han et al., 2010), but with a likely onset at higher temperatures, related to mineral decomposition with gas release. In fact, microstructure observations showed evidence of thermal decomposition of carbonate samples (CaO) after high-velocity shearing in the laboratory experiments (Han et al., 2010; Hu, Huang, et al., 2018). Release of pore fluids (H$_2$O and CO$_2$) was also monitored. Calcite and dolomite decompose at high temperature, releasing CO$_2$ that may promote excess pore pressure ($\Delta p$) generation. This may decrease the available shear strength to $\tau = \mu(\delta - \Delta p)$, where $\delta$ is the pre-existing effective normal stress, coinciding with the total normal stress in absence of pore pressures.

Pure carbonate gouges and marble show consistent evolutions of $\mu_{ss}$ (Figure 2a), and both materials yield higher $\mu_{ss}$ than carbonate-bearing gouges for $PD < 1.5$ MW m$^{-2}$, while the opposite holds true for $PD > 1.5$ MW m$^{-2}$. However, more experiments are needed to better constrain this phenomenon, which could be explained by thermal decomposition, whereby the ejected CO$_2$ may enhance pore pressures, and calcium and magnesium oxides may cause powder lubrication.

Decarbonization of carbonate minerals has been observed in experiments by monitoring the CO$_2$ content, conducting X-ray diffraction analyses to identify mineral change, and recording microstructure changes. CO$_2$ release is a direct evidence of carbonate decomposition. In a series of experiments (Han et al., 2010), calcite and predecomposed gouges were tested under equal normal stress and velocity, in drained condition. Similar trends of friction coefficient were observed, suggesting that CO$_2$ release from thermal decomposition had little effect on the shear resistance at the experimental scale in unconfined condition. However, if a Teflon sleeve was used to ensure lateral confinement, frictional weakening by CO$_2$ production was observed (Han et al., 2010), suggesting that, in unconfined condition, the rate of CO$_2$ production was simply smaller than its rate of diffusion, and the weakening mechanism was not activated. This is consistent with what
shown in Figure 1a, where carbonate-bearing gouges and nonreactive gouges are associated with similar friction coefficients.

Thermochemical pressurization is not the prevailing weakening mechanism in unconfined experiments at room humidity (Figures 1 and 2). Whether this mechanism is significant in landslides is still debated. It is reasonable to hypothesize that the thermodynamic condition of the basal shear zone in large landslides is approximately adiabatic and undrained during fast motion. This hypothesis can be verified by thermo-hydro-mechanical modeling (Cecinato et al., 2008; Pinyol et al., 2017). In this condition, excess pore pressure can build up, resulting in significant thermochemical pressurization, which, in turn, may control the landslide runout (Han et al., 2007; Hu et al., 2019). On the other hand, powder lubrication may control the thermal weakening at high PD due to the low μss of pure carbonate gouges and marble (Figure 2a). Lubrication by nanocrystalline grains (CaO and MgO) has also been speculated to occur, as nanometer-scale grains roll on the slip surface during shearing rather than sliding, decreasing the frictional resistance (Han et al., 2010; Han et al., 2007).

The slip-weakening distance for marble is the largest among the tested materials at a given PD. DC is associated with grain size reduction, particle rearrangement, and wear rate for rock. A higher fracture energy is needed for marble to deteriorate and thermally induced cracks to propagate compared to the other tested materials (Sawai et al., 2012), which translates into a longer slip distance required to attain the steady-state friction.

**3.3. Implications for the Mobility of Coherent Landslides**

A PD-dependent law has the advantage of having physical meaning, as it can be related to the rate of temperature changing (Di Toro et al., 2011), and to the frictional wearing of shear plane roughness (Boneh et al., 2013). It also solves the apparent contradictions between velocity-dependent and normal stress-dependent friction laws, and it better correlates (has a higher R^2) with experimental observations compared to velocity- and normal stress-dependent friction laws (cf. Table S4, SI file).

We believe that a PD-dependent law can offer superior performance compared to other approaches describing landslide dynamics. For instance, Lucas et al. (2014) illustrated that the H/L ratio is not an appropriate way to quantify the effective friction coefficient, as it does not have a physical meaning in terms of actual stress and strain histories in the landslide body. The H/L ratio is affected by the level of fragmentation during runout, the final spreading of the landslide deposit, and the basal topography. For instance, the H/L ratio of the Tsaoiling and Jiuengershan landslides, having the same lithology, were 0.22 (Togo et al., 2014) and 0.29 (Chang et al., 2005), respectively, whereas high-velocity rotary shear experiments yielded μss = 0.17 under a normal stress of 3 MPa and velocity > 0.65 m/s (Togo et al., 2014). The angle of reach, a similar concept proposed by Corominas (1996), also depends on topography. Estimations for the 2017 Pusa landslide predicted a wide range of μreach (friction coefficient corresponding to the angle of reach), 0.294–0.388, while the actual event had μreach = 0.34 (Fan et al., 2019). Lucas et al. (2014) concluded that a velocity-weakening law would
be more suitable than constant H/L (or \( \mu_{\text{reach}} \) or \( \mu_{\text{ss}} \) values to describe the dynamics of large landslides (cf. Scaringi, Hu, et al., 2018). This has also been demonstrated in experiments (Hou et al., 2012; Yao, Ma, et al., 2013), yet a pure velocity-dependent approach still neglects the variability of the normal stress. For example, the thickness of the failed mass in the Jiweishan landslide varied spatially from 50 to 80 m (Hu, Yin, et al., 2018). This may have affected its runout behavior as different evolutions of the friction coefficient may be associated with different thicknesses. Experiments have indeed demonstrated the control of normal stress on the friction coefficient as well as on the velocity-dependent behavior in a wide range of stress and velocity (Boneh et al., 2013; Scaringi & Di Maio, 2016; Wang et al., 2018). Using a single parameter, a PD-dependent law can incorporate both the velocity-dependent and normal stress-dependent behaviors while tracking the evolution of the landslide movement through time. For instance, a PD-based reanalysis of the 2008 Daguangbao landslide (He et al., 2019)) or the 2017 Xinmo landslide (Scaringi, Fan, et al., 2018) could suggest values increasing from 0 to many megawatts per square meter in a matter of seconds during runout, and then decreasing in the deposition phase.

A detailed and possibly thermodynamically consistent model should be developed to track the various forms of energy transfer, accounting for internal deformation and fragmentation. In such a model, the PD concept could play a primary role. In fact, while PD alone cannot provide an answer regarding the type of weakening mechanism that will be activated during landslide runout, it can serve as a comprehensive energy metric that, together with information on initial conditions (e.g., depth and water content of the shear zone or landslide-bedrock interface) and mineralogy, can help identifying/predicting the weakening mechanism. The advantage we see in this approach is essentially that we shift our attention from multiple mechanical variables (slip distance, velocity, and stresses) to a unique energetic parameter. This may simplify models of landslide behavior significantly.

A PD-based approach seems also suitable for extrapolating the results of laboratory experiments to the scale of natural landslides. We compare values of normal stress, velocity, and PD of natural landslides with those in the experiments. Representative normal stresses applied to the gouges in the experiments were in the range of 0.4–3.6 MPa (cf. SI file), which is consistent with effective normal stresses at the base of large landslides (thickness > 20–40 m, generally typical of landslides with surface area > 0.5–2.5 km\(^2\) and volume > 5–45 Mm\(^3\); cf. Larsen et al., 2010, for thickness-area-volume relationships). However, the equivalent velocity in the experiments (cf. the SI file) was in the range of 0.1–2.6 m/s (Di Toro et al., 2011), significantly lower than those observed in high-velocity large landslides, which can reach 30–70 m/s (Chang & Taboada, 2009; Scaringi, Hu, et al., 2018; Togo et al., 2014). Values of PD that can be explored in laboratory experiments with current technologies are limited to 0–2 MW m\(^{-2}\) for gouges, insufficient to capture the PD values in both faults and large fast-moving landslides directly. Nonetheless, the trend exhibited by \( \mu_{\text{ss}} \) with respect to PD in Figure 1a is clear enough to attempt an extrapolation to higher PD values. Yet, being this an extrapolation, the applicability of the results requires additional research and discussion.

It should be noted again that the power density concept was initially proposed to investigate the frictional behavior of faults. While it is true that the normal stress along active faults can reach hundreds of megapascals, and rarely falls below tens of megapascals, their slip velocity is in the range of 0.1–1 m/s (Di Toro et al., 2011). Therefore, PD in faults is rarely <1 MW m\(^{-2}\) and can reach many tens of megawatts per square meter. On the other hand, as aforementioned, large coherent landslides (with normal stresses of 0.1–3 MPa) can reach velocities of 30–70 m/s, and thus maximum PD values of 1–20 MW m\(^{-2}\), if not higher. It is therefore apparent that, in terms of PD, the seismic slip of faults and the basal slip in large coherent landslides are comparable. The same cannot be said for incoherent landslides, for which important energy dissipation occurs within the landslide body, leaving little PD at basal slip, and hence little room for thermally activated slip-weakening processes. Conversely, evidence of high temperature at the base of large coherent landslides during high-velocity runout has been demonstrated in several cases (De Blasio & Medici, 2017; Hu, Yin, et al., 2018; Mitchell et al., 2015).

A further aspect deserving attention is the scale effect observed in experiments. Yamashita et al. (2015) found that the frictional properties of Indian metababbro were dependent on the sample diameter. The friction coefficient in rotary shear experiments (inner and outer diameters of 17 and 40 mm, respectively) decreased when PD reached 0.1 MW m\(^{-2}\), while meter-sized rock samples exhibited a decrease already at 0.008 MW m\(^{-2}\). The phenomenon was attributed to spatial stress heterogeneity and localized high work.
rate. Following this concept, we collected experimental data for various rocks and soils from natural landslides, obtained on samples of different diameter (25 or 40 mm), and plotted them in Figure 3a. The steady-state friction coefficient decreases from ~0.05 MW m$^{-2}$ on samples with 25-mm diameter, while samples with 40-mm diameter exhibit a decrease from ~0.01–0.05 MW m$^{-2}$. The behavior with respect to $D_c$ (Figure 3b) is consistent with that observed on $\mu_{ss}$. The behavior of meter-sized rock samples (Yamashita et al., 2015), also plotted in Figure 3a, is consistent with the observed trend, supporting the hypothesis that frictional weakening occurs at increasing levels of PD as the sample size decreases (cf. also Figure 2a). This may signify that the friction coefficient in landslides decreases faster (i.e., at shorter slip distances) than in laboratory-scale experiments.

Further experiments are needed to better explore the frictional behavior at high PD and different scales. Possible implications of a PD-dependent friction law in partially coherent landslides also should be discussed. Extension of the framework to partially coherent landslides could be carried out using the concept of conversion efficiency from mechanical to thermal energy, which has been explored in a recent study (De Blasio & Medici, 2017). However, this concept is still poorly constrained across various types of landslides and deserves a dedicated study.

4. Conclusion

Results of high-velocity rotary shear experiments on nonreactive gouges, hydrous minerals gouges, and carbonate-bearing gouges have been collated in this study and analyzed to investigate the control of power density on the frictional behavior. The main results are summarized as follows:

1. The experimental data are well fitted by a power density-dependent friction law, which captures the experimentally observed frictional weakening better than conventional velocity-dependent and normal stress-dependent friction laws.
2. Thermal pressurization does not seem significant at the experimental scale, at room humidity, and in unconfined condition (Figure 1). However, it might become the dominant frictional weakening process at landslide scale.
3. The steady-state friction coefficient of carbonate-bearing gouges is smaller than that of intact marble when the power density is larger than 1.5 MW m$^{-2}$, possibly because a high power density induces a rapid rise in temperature, and calcium and magnesium oxides generated by thermal decomposition produce powder lubrication on the slip surface.
4. By comparing experimental data obtained from specimens with different diameter, a significant scale effect was observed (Figure 3a). Larger diameters are associated with the onset of frictional weakening at smaller power densities. This is consistent with experimental results on meter-sized rock samples. This scale effect might be the key for the correct upscaling of laboratory-scale results to interpret the behavior of natural landslides.
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