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Key Points:

- Polycarbonate and granite fractures exhibit period-multiplying cycles near the stability transition
- Correlative stress drop, recurrence times, and acoustic energy in slip-predictable cycles
- Laboratory data explain the cycle of period-doubling bursts of low-frequency earthquakes on the San Andreas Fault

Supporting Information:

Supporting Information may be found in the online version of this article.

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Period-Multiplying Cycles at the Transition Between Stick-Slip and Stable Sliding and Implications for the Parkfield Period-Doubling Tremors

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Abstract The recurrence patterns of the Parkfield tremors with period-multiplying slow and fast ruptures provide new insights on the physics of earthquake cycles. However, the mechanisms behind the peculiar recurrence pattern and the coupling between slow-slip events and seismic radiations are still unclear. Here, we conduct direct-shear experiments on polycarbonate and granite fractures under varying stress conditions to investigate the variations of rupture properties near the stability transition. Laboratory slow and fast ruptures sequences produce slip-predictable period-multiplying cycles with correlative acoustic energy release, stress drop, event duration, and recurrence intervals. However, gouge accumulation by damage of the granite fracture provokes changes in stiffness and stress drops ratios over multiple cycles, affecting the recurrence intervals and energy release of consecutive slip events. These findings confirm the link between low-frequency earthquakes and underlying slow-slip events, with period-multiplying cycles naturally occurring near the stability transition.

Plain Language Summary The seismic waves of tiny earthquakes are often used to monitor the activity of faults. In particular, tiny tremors that repeat every 3 and 6 days on the San Andreas Fault indicate recurring sequences of slow and fast ruptures. However, how the seismic radiations reflect the rupture characteristics remains unresolved. We perform laboratory direct-shear experiments on smooth fractures in polycarbonate and granite to explore the spectrum of fracture slip behaviors. We show that as ruptures change from stick-slip to stable sliding under sequential unloading, sequences of slow and fast ruptures occur near the stability transition. The slip transition is related to effective normal stress and fracture surface roughness. Our data indicate correlative stress drop, recurrence time, and energy release during sequences of slow and fast ruptures, which helps us explain the recurrence pattern of low-frequency earthquakes on the San Andreas Fault.

1. Introduction

Shear failure on natural faults includes a wide range of rupture styles with slip velocities ranging from nanometer to meter per second (Beroza & Ide, 2011). Slow-slip events provide new opportunities to study fault mechanics because of their relatively short recurrence time associated with low stress drops (Nanjundiah et al., 2020). Slow-slip events are often accompanied by low-frequency earthquakes and tremors, but the relationship between the long, sluggish rupture of slow-slip events and the rapid seismic radiation of low-frequency earthquakes and tremors remains enigmatic. Concurrent slow-slip and tremors are widely observed at subduction zones (Dragert et al., 2001; Frank et al., 2013; Kim et al., 2011; Kostoglodov et al., 2003; Peng & Rubin, 2016; Rogers & Dragert, 2003; Rousset, Fu, et al., 2019; Shelly et al., 2006; Shiraishi et al., 2020; Todd et al., 2018), and similar observations in a continental setting are growing (Chamberlain et al., 2014; Baratin et al., 2018; Rousset, Bürgmann, et al., 2019; Wech et al., 2012). Slow-slip events may arise by various mechanisms that inhibit unstable rupture expansion, such as restrengthening at high slip speed (Hawthorne & Rubin, 2013; Shibasaki & Iio, 2003), gouge dilatancy (Segall et al., 2010), limited available rupture width (Liu & Rice, 2005), activation of viscoelastic flow (Goswami & Barbot, 2018), and thermal instabilities (Wang & Barbot, 2020). The mechanical coupling between slow-slip events and seismic emissions may be caused by frictional heterogeneities (Luo & Ampuero, 2018; Luo & Liu, 2019; Tsai & Hirth, 2020) or spontaneous instabilities in conditions of near-neutral velocity-weakening with small characteristic nucleation size (Barbot, 2019b). Slow-slip events can be obtained in laboratory experiments (e.g., Kato et al., 1991; Wong

et al., 1992) within a narrow range of stiffness ratios (e.g., Leeman et al., 2016), but are also controlled by the loading rate (Ikari, 2019; Mcllaskey & Yamashita, 2017), evolving fault fabric (Scuderi et al., 2017), and hydrothermal conditions (Mitchell et al., 2015). Slow-slip events are also associated with precursory velocity changes in the host rocks (Kaproth & Marone, 2013; Scuderi et al., 2016; Tinti et al., 2016) and with seismic emissions during slip acceleration (Zigone et al., 2011).

Recent seismogeodetic observations have illuminated even more complex fault behaviors involving the succession of slow and fast ruptures on the same asperity. These events include large overlap between slow-slip events and subsequent large ruptures at subduction zones, such as for the 2011 moment magnitude (Mw) 9.0 Tohoku-Oki, Japan (Ito et al., 2013; Kato et al., 2012) and the 2014 Mw 8.2 Iquique, Chile (Meng et al., 2015; Socquet et al., 2017), but a more striking example is the consecutive ruptures of seemingly the same asperity in slow and fast events at the Parkfield section of the San Andreas Fault (Shelly, 2010, 2017). While the San Andreas Fault exhibits a wide distribution of tremor activity (Nadeau & Dolenc, 2005; Nadeau & Guilhem, 2009; Shelly, 2009; Shelly & Johnson, 2011), a particular region displays a quasiperiodic sequence of rapid bursts of low-frequency earthquakes that repeat every two events (i.e., period-two cycles) with approximate doubling and halving of the recurrence times alternating between 3 and 6 days (i.e., period-doubling cycles), only interrupted by stress change and damage from the nearby Mw 6.0 Parkfield earthquake (Shelly, 2010, 2017). This phenomenon can be explained by bifurcations near the stability transition whereby sequences of ruptures with different characteristics follow each other periodically (Barbot, 2019b; Veedu & Barbot, 2016). As mode III cracks are more unstable than mode II cracks, the condition where only mode III cracks are unstable can be found near the stability transition in numerical and laboratory experiments (Veedu et al., 2020). Period-two cycles may also occur spontaneously in elongated asperities associated with different stiffness in the along-strike and downdip directions of finite faults (Veedu & Barbot, 2016), or in the presence of internal heterogeneities (Ma & He, 2001).

Despite these progress, the mechanics of period-two cycles remains poorly understood. In particular, how the coupling between fault slip and seismic emissions of the Parkfield bursts of low-frequency earthquakes is unresolved. Assuming a microphysical model of rate-dependent and state-dependent friction (Barbot, 2019a), the slip dynamics of a single asperity during seismic cycles is controlled by nondimensional parameters that depend on the frictional and other physical properties and the size of the asperity. Among these, the Dieterich-Ruina-Rice number R_u , which is equivalent to a stiffness ratio and represents the effect of frictional properties and the size of velocity-weakening asperity, and the R_b number, which describes the ratio of static to dynamic stress drops, control the emergence of period-multiplying cycles (Barbot, 2019b). The transition between slow and fast ruptures on a single asperity occurs in a narrow range of these controlling parameters. In addition, Poisson's ratio controls the difference in stiffness for mode II and mode III cracks and also affects the emergence of period-two cycles (Barbot, 2019b). However, these considerations only produce aseismic period-two slow-slip cycles and how the triggering of seismic radiation operates is still unclear. Seismogenic slow-slip events can take place on asperities characterized with near-neutral velocity dependence at steady state with a relatively small characteristic nucleation size (Barbot, 2019b), but the relationship with period-two cycles has not been explored.

We conduct a series of direct-shear experiments on smooth fractures under multiple unloading steps to reproduce the transition from stick-slip to stable sliding. The effect of the Dieterich-Ruina-Rice number can be readily explored in the laboratory by varying the normal stress, directly affecting the stiffness ratio. Varying the R_b number is more challenging because it is associated solely with material properties and it cannot easily be changed gradually. We therefore explore the behaviors of polycarbonate and granite fractures, two materials with different bulk and surface properties.

In the next sections, we describe the samples preparation and the experimental setup. We then describe the conditions under which period-multiplying cycles occur and we describe the associated source characteristics, in particular the number and amplitude of acoustic emissions (AE), stress drop, and event duration. Finally, we discuss the implications of these findings for the Parkfield sequence of period-multiplying slow-slip and associated bursts of low-frequency earthquakes.

2. Experimental Setup and Material Properties

We perform a series of direct-shear experiments on smooth fractures in Makrolon polycarbonate and Grisal granite. The sketch of the direct-shear setup is shown in Figure 1a. The bulk density, shear modulus, and Poisson's ratio of the polycarbonate are 1,190 kg/m³, 0.9 GPa, and 0.38, respectively. Those of granite are 2,650 kg/m³, 26.3 GPa, and 0.25, respectively. The driving and fixed plates are cut by a waterjet machine with 120 grit abrasive sand and the interface between the plates is used to simulate a preexisting fracture. The normal and shear loads are applied on the fracture via servo-controlled hydraulic rams and measured by load cells with an accuracy of ± 0.02 kN. The load point displacement and slip distance are measured by linear variable displacement transformers (LVDTs) installed on the vertical hydraulic ram and driving plate top, with an accuracy of ± 0.1 μ m. The loads and displacement are monitored at a sampling rate of 10 kHz using a National Instrument data acquisition system.

We explore the stability transition of the polycarbonate and granite fractures by conducting sequential unloading steps. We first apply an initial normal stress of 2.0 MPa, and shear the fracture at a constant load point velocity of 180 μ m/s. We then decrease the normal stress in multiple steps each with 0.2 MPa normal stress reduction and 3 mm load point displacement until the fracture slides stably. We measure the normal and shear stresses, load point displacement and shear distance, and AE signal during the experiment. AE signal is recorded at a sampling rate of 1 MHz using a SAMOS AE monitoring system with four piezoelectric sensors attached on the driving plate along the fracture. The fracture surface topographies of the driving plate are imaged at a resolution of 0.5 μ m using a Keyence 3D scanner before and after each experiment, and the thickness of sheared-off layers is determined by subtracting the elevation of fracture surface after the experiment by that before the experiment.

To better understand the controls on the stability transition, we first conduct a series of stepped-velocity friction experiments using the direct-shear setup to obtain the frictional properties of the polycarbonate and granite fractures. We measure the friction coefficient when the load point velocity drops from 50 to 1 μ m/s under 0.5 MPa normal stress and identify the rate-dependent and state-dependent friction parameters a , b , and L for individual velocity steps (e.g., Ruina, 1983) and how they evolve with cumulative slip (Figure 1b). The parameters a and b control the rate and state dependencies, respectively, and L is the characteristic weakening distance. For $(b - a) > 0$, the fracture is velocity-weakening and has the potential for earthquake nucleation. Under a constant normal stress σ_n , laboratory fractures exhibit unstable weakening when the stiffness ratio $K = k / k_c$ is less than unity (Gu et al., 1984; Leeman et al., 2016), where k is the loading stiffness and k_c is the critical stiffness

$$k_c = \frac{(b - a)\sigma_n}{L}. \quad (1)$$

The loading stiffness is estimated as the slope of the prepeak portion of the shear stress versus load point displacement curve in a stick-slip cycle (Figure S1) and shows much consistency for both fractures. The variation of individual kinematic parameters vary as a function of point load displacement (Figures 1c, 1d, and 1f). For the polycarbonate fracture, the variations of a , b , and L somehow compensate and give rise to relatively constant ratios of $(b - a) / L$ and $(b - a) / b$, which play an important role for stability and rupture dynamics. For the granite sample, the latter two combined parameters show more variability. For the purpose of comparing the experimental results for polycarbonate and granite fractures, we consider the average quantities. For the polycarbonate fracture, we find average frictional properties of $a = 0.059$, $b = 0.086$, and $L = 22.22$ μ m and a loading stiffness of $k = 1140 \pm 43$ MPa/m (Figures 1 and S1). For the granite fracture, we find the average frictional properties of $a = 0.016$, $b = 0.030$, and $L = 3.46$ μ m with a loading stiffness of $k = 1735 \pm 149$ MPa/m.

3. Multiplying-Cycles Near the Stability Transition

We first consider the unloading sequence on the polycarbonate fracture (Figure 2a). The stick-slip cycles first occur under 2.0, 1.8, and 1.6 MPa normal stresses. In these steps, the average shear stress drops are 0.50, 0.35, and 0.31 MPa, and the average recurrence intervals (i.e., time since previous event) are 2.1, 1.3, and

Figure 1. Experimental setup and constitutive properties for smooth polycarbonate and granite fractures. (a) Sketch of the direct-shear setup. (b) Schematic of the rate-dependent and state-dependent friction law parameter estimation during a change of load point velocity. (c) Evolution of velocity-dependence parameter a as a function of load point displacement. (d) Same for the state-dependence parameter b , (e) the steady state velocity-dependence parameter $b - a$, and (f) the characteristic weakening distance L . (g) Evolution of the combination of parameter $(b - a) / L$ that, once combined with normal stress and stiffness, controls the stiffness ratio of the fracture. (h) Evolution of the R_b number $(b - a) / b$ as a function of load point displacement. The material and surface parameters $(b - a) / L$ and $(b - a) / b$, or combinations thereof, are thought to control the rupture style.

1.1 s, respectively, exhibiting much regularity. The period-multiplying cycles then occur under 1.4, 1.2, and 1.0 MPa normal stresses, from period-two cycles to period-three cycles, to deterministic chaos, where period- n cycles refer to sequences of ruptures that repeat periodically every n different events and deterministic chaos indicates a sequence of ruptures with no identifiable repeatability in terms of size and recurrence time. The shear stress drops and recurrence intervals in a period- n cycle change in repeating sequences of n events. For instance, under 1.4 MPa normal stress, the average shear stress drops during the period-two sequence of slow and fast ruptures are 0.20 and 0.27 MPa, respectively, with average recurrence intervals of 0.7 and 1.0 s, respectively. The association of lower stress drops with lower peak load-point velocity and of larger stress drops with higher load-point velocity during period-doubling cycles is shown in Figure S3. Last, the fracture slides stably under 0.8 MPa normal stress.

The granite fracture exhibits a similar transition from quasiperiodic fast ruptures to stable sliding from 2.0 to 0.8 MPa normal stress, but with notable differences (Figure 3). Stick-slip cycles occur under 1.8 and 1.0 MPa normal stresses, also with great regularity, but period- n cycles and deterministic chaos take place under 0.8 and 0.6 MPa normal stresses. The successive changes of shear stress drops and recurrence intervals on the granite fracture are less regular than those on the polycarbonate fracture.

We estimate a representative stiffness ratio for the polycarbonate and granite fractures across the stability transition using the average frictional parameters and the varying normal stress (Figures 2b and 3b). We find regular stick-slip cycles for low stiffness ratios and a transition to stable sliding occurs across $K = 1$ for both polycarbonate and granite fractures, as expected. However, the range of normal stress and associated stiffness ratio for period- n cycles varies for these two materials, with $0.71 < K < 1$ for the polycarbonate fracture and $0.51 < K < 1$ for the granite fracture. We attribute the difference in range of parameters by the different Poisson's ratios, frictional properties, and physical dimensions of the whole samples.

4. Source Characteristics During Period-Multiplying Cycles

We now focus on the source characteristics of slip events during period- n cycles for polycarbonate (Figures 2c and 2d) and granite fractures (Figures 3c and 3d), with a particular focus on the relation between rupture properties (slip distance, stress drop) and seismic properties (AE energy, duration, and count). The shear stress drop and AE energy release are nearly identical from one event to the next during the stick-slip cycles, which appear quasiperiodic for both types of fractures. In contrast, the regular fluctuation of source characteristics between consecutive events during period- n cycles indicates the successive occurrence of slow and fast ruptures (Figure S2). The cycles appear slip-predictable for all cases considered for both polycarbonate and granite fractures.

There are systematic differences of source characteristics between stick-slip and period- n cycles, the former releasing much higher AE energy with longer AE duration and larger AE count than the latter. In the period- n cycles, the slow rupture releases lower AE energy than the fast rupture and the AE duration and count from the slow rupture are vanishingly small. The shear stress drop of the granite fracture is similar to that of the polycarbonate fracture in the stick-slip cycles but smaller in the period- n cycles. The AE energy released from the granite fracture is lower than that from the polycarbonate fracture as the AE duration is much smaller and the AE count is slightly larger. The slow and fast ruptures appear more frequently due to the brittle failure of asperity contacts on the granite fracture and the AE duration and count decrease markedly after the asperities are significantly sheared off. The fast rupture releases more strain energy after a longer recurrence interval than the slow rupture. These results indicate a strong relationship between the source and seismic emissions characteristics, with a correlative stress drop, AE count, duration, and energy during stick-slip and period- n cycles.

These results thereby confirm the strong connection between the seismic radiation and the underlying slow-slip event. The stick-slip cycles occur presumably with tighter asperity contacts and more severe asperity damage. Period-two cycles are more clearly identified for polycarbonate than for granite fractures. To further explain these findings, we consider the evolution of controlling parameters on the dynamics of seismic cycles. Theoretical considerations supported by experimental data (Barbot, 2019b; Veedu & Barbot, 2016;

Figure 2. a) Results of direct-shear experiments on polycarbonate fracture. (b) Zoomed-in shear stress under each normal stress and corresponding stiffness ratio K . Shear stress drop, AE signal and slip deficit during (c) stick-slip and (d) period-multiplying cycles under 1.6 and 1.4 MPa normal stresses, respectively.

Figure 3. a) Results of direct-shear experiments on granite fracture. (b) Zoomed-in shear stress under each normal stress and corresponding stiffness ratio K . Shear stress drop, AE signal and slip deficit during (c) stick-slip and (d) period-multiplying cycles under 1.4 and 0.8 MPa normal stresses, respectively.

Veedu et al., 2020) indicate that the emergence of period- n cycles is controlled by the stiffness ratio K and by the nondimensional number

$$R_b = \frac{b - a}{b}. \quad (2)$$

Therefore, the constancy of these controlling parameters with accumulating slip distance affects the repeatability of the period- n sequences. The stepped-velocity friction experiments indicate evolving frictional properties a , b , and L (Figure 1). In contrast, the machine stiffness appears relatively uniform during the experiments (Figure S1). However, the combination $(b - a) / L$, which once combined with the normal stress and the loading stiffness controls the stiffness ratio K , and the R_b number are more constant for the polycarbonate than for the granite fracture. As these controlling parameters evolve markedly with slip accumulation for the granite fracture, the sequences randomly drift from period-two, to period-three, to deterministic chaos. Examination of fracture surface topography before and after the unloading experiments (Figure 4) indicates that the granite fracture experiences more abrasion, with a sheared-off thickness of $29 \mu\text{m}$, almost thrice the $11 \mu\text{m}$ for the polycarbonate fracture. The root mean square roughness also suggests a more severe change in surface topography on the granite fracture. The sheared-off particles accumulate as a gouge layer with distinct frictional properties. A more heterogeneous distribution of sheared-off particles results in a more irregular pattern of fracture slip. We therefore attribute the variability of slip sequences in the granite fracture to the change of texture of the shear layer during the experiments.

5. Recurrence Time and Seismic Patterns Across the Stability Transition

The recurrence time and seismic patterns of stick-slip and period- n cycles mirror the evolution of the source characteristics across the stability transition (Figure 5). The interevent time for the polycarbonate fracture under a normal stress of 1.4 MPa and a stiffness ratio of 0.71 shows quasiperiodic period-two cycles where the velocity amplitude of seismic emissions correlate with the time since previous event. The granite fracture under a normal stress of 0.8 MPa and a stiffness ratio of 0.51 exhibits more variability, as previously discussed, but features similar correlation between velocity amplitude and time since previous event. The recurrence patterns formed by consecutive events can be displayed in a phase diagram of time since previous event versus time to next event to characterize the period-multiplying factor of consecutive events. Recurrence ratios close to one indicate characteristic periodicity and alternating recurrence ratios different than one indicate period-multiplying cycles. The unloading sequence on the polycarbonate and granite fractures features characteristic events that fall on the diagonal line, corresponding to stick-slip cycles (Figure S4). However, their period- n cycles are clearly visible, with many events falling within the doubling and halving interval lines. In general, the events following a longer quiescent period generate more energetic AE and larger stress drops (Figure S4), confirming a correlation between source characteristics, seismic emissions properties, and recurrence times.

6. Implications for the Parkfield Bursts of Low-Frequency Earthquakes

Our experimental results for the polycarbonate and granite fractures provide new insights on the physics controlling the period-doubling cycles of bursts of low-frequency earthquakes at the Parkfield section of the San Andreas Fault (Shelly, 2010). Period-doubling cycles spontaneously emerge near the stability transition, which is controlled by the stiffness ratio in a laboratory setting, but more generally by the Dieterich-Ruina-Rice number (Barbot, 2019b). The range of parameters producing period- n cycles varies for polycarbonate and granite fractures, but is nevertheless narrow, explaining the scarcity of similar observations in nature. The granite fracture is a better proxy of crustal conditions and it exhibits more variability due to the accumulation of gouge during sliding, making the period- n sequence less consistent over multiple cycles. The accumulation of gouge and the associated change of frictional parameters over time may explain the variability of recurrence times at Parkfield and the high sensitivity of the tremor cycle to outside perturbations, such as the one from the 2004 Mw 6.0 Parkfield earthquake that abruptly terminated the period-doubling sequence.

Figure 4. Surface topography and asperity elevation of (a) polycarbonate fracture and (b) granite fracture before and after direct-shear experiments as well as sheared-off layers during these experiments.

The experimental findings reveal a systematic correlation between source characteristics (slip distance and stress drops), recurrence times, and AE properties (duration, count, and energy). This indicates that the bursts of low-frequency earthquakes recorded at the surface represent a good proxy for the rupture properties of the underlying slow-slip events that trigger seismic radiations. This is confirmed by the similarities between the recurrence patterns and AE properties of the unloading experiments with the recurrence patterns of velocity amplitude of the Parkfield tremors (Figure 5). This successful comparison reveals that the occurrence of period- n cycles is related to the evolution of normal stress, which can be caused either by applied stress change, as in our study, or by effective pore pressure variation, as in the Parkfield case (Veedu & Barbot, 2016). However, our findings differ from the physics-based simulation of Veedu and Barbot (2016), whereby the slow and fast ruptures occur in a time-predictable sequence, as our study shows alternating slow and fast ruptures following a slip-predictable cycle, making the AE energy release proportional to the previous recurrence interval. Our laboratory results therefore better explain the amplitude variation of the Parkfield tremors.

Figure 5. Recurrence pattern and AE energy of period-multiplying slow-slip events on (a) polycarbonate fracture and (c) granite fracture, and (e) recurrence pattern and normalized velocity amplitude of Parkfield tremors. Recurrence intervals and normalized velocity amplitude of the period-two slow-slip events on (b) polycarbonate fracture, (d) granite fracture and (f) Parkfield fault patch. The amplitude (maximum ground velocity or fracture slip velocity) of each slip event is normalized to the 1% amplitude of all slip events. Symbols in different shapes and colors represent the slip events with varying stiffness ratios (numbers in the figure) and source characteristics (color on the bar), respectively.

7. Conclusions

We carry out a series of direct-shear experiments on velocity-weakening polycarbonate and granite fractures to better characterize the relationship between source characteristics and seismic radiations near the stability transition. Period-multiplying cycles emerge as the stiffness ratio converges to unity, before the transition to stable sliding. The range of parameters leading to period- n cycles differs for polycarbonate and granite fractures, presumably due to their different bulk elastic properties, sample dimensions, and ratios of average rate- and state-controlling parameters a and b .

Despite these notable differences, we found correlative source characteristics and seismic radiation properties for both fractures for all loading conditions, whether during stick-slip or period- n cycles. These results explain many aspects of the decadal sequence of period-doubling bursts of low-frequency earthquakes at the Parkfield segment of the San Andreas Fault, providing direct experimental support for a mechanical link between the energy, count, and velocity amplitude of seismic emissions and the stress drop and recurrence time of underlying slip events during period-two cycles. The study thus reveals the physics controlling of the period-doubling cycles of the Parkfield bursts, such as the accumulation of sheared-off gouge and the associated change in frictional parameters. The evolution of period- n cycles is related to normal stress and fracture heterogeneity, following a slip-predictable sequence.

As the recurrence patterns and rupture styles of faults may be involving slow and fast slip, periodic and aperiodic sequences, depending on boundary conditions and the regime of frictional parameters, a useful classification is to estimate the nondimensional parameters that govern the dynamics of the frictional contact.

Data Availability Statement

Our data are available at <https://figshare.com/projects/GRL11212020/93053>.

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