2019 SYMPOSIUM
ON THE APPLICATION OF
MECHANICS TO GEOPHYSICS

ABSTRACTS
(Talks & Posters)

Long-dormant faults in the sub-surface and their response to nearby fluid injection

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Active crustal faults imprint a characteristic pattern of granulation, damage, and permeability alteration in the adjoining rock. The shear zone itself has typically undergone severe granulation and consequently has very low permeability. But high off-fault stresses, accompanying propagation of slip ruptures in prior earthquakes, have left a fringe of severely cracked rock, thereby of generally much higher permeability (to the extent not obliterated by long-time healing/sealing processes). That high off-fault permeability generally degrades, with increasing distance from the fault, into much lower ambient permeability values, characteristic of unfaulted, or not recently faulted, crustal rock. As we illustrate in various poroelastic simulations, the permeability distribution means that when fluids are injected at high pressure into the crust, in the vicinity of such permeable relic fault-bordering damage zones, those high pore pressures rapidly diffuse along the relic fault. In doing so, the pressurization can, and in many cases does, induce renewed episodes of seismicity along the fault. *[The process is discused in a related recent paper:*Yehya, A., Yang, Z., & Rice, J. R. (2018). Effect of fault architecture and permeability evolution on response to fluid injection. *Journal of Geophysical Research: Solid Earth, 123.* https://doi.org/10.1029/2018JB016550 *(open access)].*

Study of Potential Biases in Seismologically Estimated Stress Drops of Microseismicity using Dynamically Simulated Earthquake Sources

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Stress drop, an averaged difference between the shear stress on the fault before and after an earthquake, is an important source parameter. Estimates of microseismicity stress drops, in particular, are an important window into properties of faults, and much effort is devoted towards calculating the stress drops estimates and asessing their potential variations in space (especially with depth), time, and different tectonic environments. The commonly used spectral fitting approaches are based on a simplified model of the source in which the rupture starts at one point and spreads axisummetrically with constant rupture speed and constant stress drop, before abruptly arresting at the boundary. Realistic microseismicity sources are unlikely to have such behavior since their very existence implies some level of heterogeneity on the fault interface that prevents them from growing into larger events. The microseismic ruptures are likely to propogate more vigorously along more favorably stressed parts of the fault, potentially exhibiting directivity, variable rupture speeds, non-circular rupture shapes, and variable stress changes along the rupture area.

We use numerical simulations of earthquake sequences to investigate the relation between the actual stress drop as computed from the on-fault quantities and its seimologically estimated values on heterogeneous faults. As a first step, we have considered rate-and-state models of asperity-like sources, in which a circular velocity-weakening, potentially seismogenic, patch exhibits variations in normal stress motivated by a flattened asperity. The patch is surrounded by velocity-strengthening fault areas. In such a model, earthquake ruptures start on the boundary of the patch and propagate into it, always exhibiting directivity. Furthermore, for a number of events, the event duration is constant as it is controlled by the patch size but the event magnitude varies, as it is determined by how much of the patch area is ruptured; these synthetic sources reproduce similar behaviors observed for some natural microseismicity clusters. In the model, some ruptures propagate along the patch boundaries, where the stress concentration is highest, creating ring-like sources. The actual stress drops for all the simulated events, as determined from the on-fault stress changes, are magnitude-invariant at ~3 MPa. However, we find that the stress drops estimated by the spectral fitting analyses significantly increase with the event magnitude, ranging from 0.006 to 8 MPa. This significant difference with the actual stress drops is mainly due to the shape of the ruptured area, with the stress drops of ring-like events being significantly underestimated.

We will also report on our current studies on (i) how the location of the network with respect to the sources affects the estimates of the stress drops, potentially introducing artifical systematic variations with depth and (ii) the performance of the second-moment-based techniques for our synthetic sources.

Linking fluid flow and geomechanics to mitigate injection-induced seismicity

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Since 2008, injection-induced seismicity in the U.S. mid-continent has been an increasing problem of both scientific and public concern. A current challenge in the mitigation of injection-induced seismicity is the lack of quantitative physics-based methodologies to aid the process. Here I will discuss a physics-based framework which links fluid flow and geomechanics which can be used to mitigate injection-induced seismicity. I'll present a suite of example simulations to demonstrate the method as well as application of the methodology to a moderate-sized injection-induced event in Oklahoma: the 09/03/16 M5.8 Pawnee, OK earthquake sequence. Utilizing probabilistic geomechanics and geostatistically derived flow properties, the simulation considers a range of possible subsurface hydromechanics. Three injection scenarios are considered after the mainshock earthquake: (1) no change in nearby injection operations, (2) the implemented injection reduction plan (which was qualitative only), and (3) a simulation-based injection reduction plan. Results show how the qualitative response was effective in reducing pore pressure changes in the injection reservoir and crystalline basement faults as compared to if no injection mitigation took place. In addition, the fluid flow-geomechanics simulation shows promise for avoiding critical perturbations of potentially hazardous faults.

The mechanics of Deep Earthquakes: symmetry breaking

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A model is presented for the mechanics of deep earthquakes based on the dynamic Eshelby inclusion problem, which is a self-similarly expanding ellipsoidal region with phase change (change in density and/or change in moduli under prestress). Noether's theorem dictates that the self-similar shape shall be one that extremizes (minimizes for stability) the energy rate required to move the phase boundary of discontinuity (dyn J integral), which allows it to take a planar disk shape (”pancake”) (consistent with observations in nature). Due to the symmetry breaking, 3D change of density propagating planarly induces unequal eigenstrains in the disk that may be misinterpreted as anisotropy in the moment tensor)(Markenscoff, 2019). Moreover, the unequal eigenstrains, due to the change of density squeezed to propagate *planarly,* produce compensated linear vector dipoles (CLVDs), from which follows a second symmetry breaking in an otherwise isotropic medium with change in density, in which the direction of max shear (double couple DC) makes an angle with the direction of the pancake (CLVD) (Markenscoff and Jeanloz, in preparation). It should be noted that following Knopoff and Randall (1970) the DC and CLVD are taken in seismology to coincide in their axes.

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Fundamental aspects of a new micromechanical model of rate and state friction

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The foundations of a new micromechanical model of rate and state friction are established. Based on the assumption that the relative sliding of two material surfaces is accommodated by the viscoplastic deformation of junctions in their entire volume, the model parameters are characterized in terms of loading conditions, geometrical contact characteristics and rheological properties of the bulk material. A relationship is established between the state parameter of the friction law and the mean microscopic normal stress exerted on the real contact area. Original results are obtained for the transition from stable to unstable slip regimes and applications to geological faults are considered.

Reference

Fundamental aspects of a new micromechanical model of rate and state friction, A. Molinari, H Perfettini, J. Mech. Phys. Solids, 124, 63-82, 2019. Doi : 10.1016/j.jmps.2018.10.002

Modulation of fault strength during the seismic cycle by grain-size evolution at contact junctions and implications for fault dynamics

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The evolution of friction on a fault controls the emergence of earthquakes and other frictional instabilities and is associated with modulations of the real area of contact formed by micro-asperities with time, sliding velocity, and normal stress. The empirical framework of rate-and-state friction captures the behavior of rocks from a large body of laboratory experiments and is also useful to explain natural phenomena, including the spectrum of fault slip during the seismic cycle. I formulate a micro-physical model for rate-and-state friction that describes the effect of grain-size, temperature, real area of contact, gouge thickness, and fault roughness. Fundamental to the model is that fault strength is controlled by the area of the interfacial contact junctions that support the shear and normal loads. The curvature of asperities weakly
controls the area of their contact junction and the resulting fault strength. Flattening of the asperity results in fault healing, comminution, in weakening. The model reduces to the classic
formulation of Dieterich (1979) and Ruina (1983) in isothermal conditions and to the formulation of Chester (1994) in non-isothermal conditions. The formulation takes the form of a power-law and thereby differs slightly from the classic additive, logarithmic form. To
explore the implications for fault-dynamics, I identify four non-dimension parameters in the governing equations that control the relative importance of elastic interactions, local evolutionary effects (healing and weakening), fault strength, and radiation damping. I explore these controls on the style of the seismic cycle using numerical simulations. Because of the natural variability of physical parameters and geometry, two non-dimensional parameters form
a useful phase space where a wide range of varied rupture styles emerge in bounded regions of the phase plane. Slow-slip, slow earthquakes, period-two, period-four, period-five cycles,
deterministic chaos are characteristic behaviors on finite faults. Bursts of slow earthquakes within long periods of slow slip, a behavior reminiscent of episodic tremor and slip, are also found. The physical model also predicts a peculiar behavior for weak faults, with long, multi-pulsed ruptures developing when stress drops are commensurate to static strength, particularly relevant for tsunami earthquakes. The physical foundation therefore provides an explanative
context to understand the earthquake phenomenon from the laboratory scale to natural faul

Viscous deformation of fault damage zones and implications for interseismic development of fault stress heterogeneity

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Fault damage zone rocks are frequently characterized by high crack densities and abundance of clay minerals. The presence of such crack surfaces and ductile clay minerals can make these rocks deform beyond elastic deformation via bulk creep and compaction facilitated by stable sliding along cracks and pore volume loss. There are many field evidences showing that faults “heal”, either mechanically or hydraulically, after earthquakes. For instance, fault zone permeability is temporarily enhanced after earthquakes, but decreases to its pre-seismic level after some time. Sonic logs from Taiwan Chelungpu fault Drilling Project also show progressively faster velocity of the damage zone as the suggested age of the fault becomes older. It is plausible to believe that such healing is facilitated by ductile (viscoplastic) deformation of the damage zone. The importance of such rheological behavior of the damage zone can extend much beyond the healing (re-strengthening) of fault shear strengths. Substantial magnitude of strain is involved in the healing process, which potentially acts to relax some components of stress depending on the form of the constitutive law and boundary conditions.
A finite element model of interseismic loading on a rough fault with viscoelastic damage zones was studied using the PyLith software (Sone and Uchide, 2016). Results shows that shear stress patches associated with fault roughness can dissipate, both in time and space, if damage zone rocks are allowed to deform over time in a Maxwell rheology. The rate of such “stress diffusion” is dependent on the competition between loading and relaxation, thus governed by the effective viscosity of the damage zone, tectonic loading rate, and potentially the wavelength of fault roughness. Although the current model is a crude representation of natural faults due to the use of linear viscoelastic constitutive laws and simple fault geometry, an implication is that fault shear stress and state (e.g. locking degree) can evolve significantly during the interseismic period due to ductile damage zone rheology. Such effect can impact our understanding of how shear stress accumulates on faults and controls statistical properties of seismicity.

Modeling Earthquake Ruptures With High Resolution Fault Zone Physics

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Earthquakes are among the costliest natural hazards on earth. The dynamical instabilities responsible for the onset and ensuing propagation of these events are linked to fundamental physics of granular materials and rocks in the subsurface subjected to extreme geophysical conditions and coupled with long range static and dynamic stress transfer. Over the past few years, advances in computational earthquake dynamics are opening new opportunities in addressing the conundrum of scales in this extreme mechanics and societally relevant problem.

Here, I will focus on a recently developed computational algorithm in my group for modeling earthquake ruptures with high resolution fault zone physics. I will present a hybrid method that combines Finite element method (FEM) and Spectral boundary integral (SBI) equation through the consistent exchange of displacement and traction boundary conditions, thereby benefiting from the flexibility of FEM in handling problems with nonlinearities or small-scale heterogeneities and from the superior performance and accuracy of SBI. We verify the hybrid method using a benchmark problem from the Southern California Earthquake Center's dynamic rupture simulation validation exercises and show that the method enables exact near field truncation of the elastodynamic solution. We further demonstrate the capability and computational efficiency of the hybrid scheme for resolving off-fault complexities using a unique model of a fault zone with explicit representation of small scale secondary faults and branches enabling new insights into earthquake rupture dynamics that may not be realizable in homogenized isotropic plasticity or damage models. Specifically, we show that secondary faults may not only act as energy sinks but they could also be energy sources promoting transient accelerations of rupture propagation speed and slip rate on the main fault. We also show that these secondary features significantly affect the stress state on the main fault and contribute to the enhanced generation of high frequency radiation.

Next, I will discuss the most recent development in extending this method to consistently simulate sequences of seismic and aseismic slip in a fault zone by combining adaptive explicit and implicit integration schemes enabling us to vary the time step over more than seven orders of magnitude. We will present a specific example of modeling earthquake cycles on a 2D anti-plane rate and state fault with low velocity zone (LVFZ). We show that sufficiently compliant LVFZs contribute to the emergence of sub-surface events that fail to penetrate to the free surface and may experience earthquake clusters with nonuniform inter-seismic time. Furthermore, the LVFZ leads to slip rate amplification relative to the homogeneous elastic case. I will close by discussing the potential of this framework to explore the interplay between geometric, rheological, and frictional complexities over short and long time scales as well as future applications in geophysics and engineering mechanics.

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Modeling seismicity induced by fluid injection

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Two distinct methods for modeling induced seismicity that incorporate rate- and state-dependent friction effects have been developed. The first employs the earthquake simulator RSQSim to explicitly model sequences of seismic events arising from time-dependent changes of effective normal stress from fluid pressure changes, together with stress interactions among the simulated events and optional tectonic loading. The second method applies the constitutive formulation for earthquake rates (Dieterich, 1994) to induced earthquakes occurring on fault surfaces subjected to spatially varying pressure changes. With both methods, the space-time patterns of the modeled induced seismicity reproduce a variety of observed effects. One characteristic of the simulations, of possible practical interest, is continuation of induced earthquakes following shut-in even as the local fluid pressure is dropping, which is due to the self-driven, time-dependent character of earthquake nucleation process. Detailed simulations of injection-induced seismicity 2006-20018 observed at the Val d`Agri, Italy oilfield will be presented.

Earthquake Nucleation, Seismic Wave Radiation, and Termination of Dynamic Rupture in a 3 m Rock Experiment

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I describe sequences of laboratory earthquakes generated on a 3-meter laboratory rock experiment that provide insights into how earthquakes initiate, radiate seismic waves, and terminate. The granite sample was loaded to 2-12 MPa stress levels and then sheared, while local shear stress, and fault slip were measured at 16 locations along the sample length L = 3 m. If the initial along-fault stress distribution was sufficiently heterogeneous, continued loading produced sequences of smaller, **M** -2.5 earthquakes that repeatedly ruptured the same subsection of the fault, with successive events increasing in rupture length and stress drop. These contained events initiate on fault sections with conditions favorable to rupture—of length p—but do not rupture the sample ends, since p < L. In our experiments, rupture most often terminates within the sample because it runs into unfavorable stress conditions (low strain energy release rate) rather than reaching a barrier with high fracture energy. We also study the stress drop and radiated energy of the contained events since they are less influenced by the machine stiffness and are more representative of natural earthquakes than standard complete-rupture stick-slip events. We observe a spectrum of slow to fast events depending on the ratio p/h* , where h* is a critical nucleation length scale. Slow events, with 0.5 mm/s slip rates and 50 kPa stress drops, are produced from p/h* < 1. These events radiate tremor-like signals and have w^{-1} spectral falloff, consistent with slow events observed in nature. Fast events occur if p/h* >5. They have 100 m/s slip speeds, 0.4 MPa stress drop, and source spectra consistent with a Brune model. Most of these laboratory earthquakes exhibit a meter-sized zone of slow slip (nucleation zone) that expands and accelerates until reaching seismic slip speeds (>0.1 m/s), therefore h* ~ 1 m. However, we find that loading rate and strength heterogeneity cause large variation in h*, which has implications for how natural earthquakes initiate, and the interpretation of foreshocks.

Scale Effects in Friction at Broad Scales: Roughness Scaling Experiment

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Rock friction is typically characterized by low-pressure (up to $0.2\ \mathrm{GPa}$), high-pressure (between 0.2 and $2\ \mathrm{GPa}$) frictions, for dry friction, due to asperity (including gouge and breccia) characteristics of surface roughness. Here, we present experimental studies of roughness scaling for relatively low-pressure friction, and fragmentation of asperities including gouge micro-fragmentation and breccia crushing for high pressure friction. For the low-pressure scaling, renormalizations of uncorrelated and correlate multi-asperity slips will be discussed with the results of roughness- and instability-scaling experiments. The renormalization scheme helps understand various frictional weakening and strengthening mico-mechanisms. For the correlated multi-asperity slip experiments, a novel experimental technique of time-space interferometry with streak imaging is introduced. For the high-pressure friction, roles of the breccia crushing and asperity micro-fragmentation in frictional processes will be discussed.

A machine-learning meta-modeling game for generating traction-separation law for frictional interfaces across length scale

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We introduce a meta-modeling game based on concepts from multi-graph theory to find the optimal way to generate data and write models for blind predictions of cohesive-frictional responses of an interface. We consider an idealized situation in which the modeling process of history-dependent process can be represented by a sequence of decision making where modelers make choices to formulate a sequence of actions to generate models. Our goal is to seek the best option that represents the hierarchy of material responses, i.e. the knowledge represented by a directed graph. As such, we introduce a new concept where all the modeling options can be recast as a directed multi-graph and each instant/configuration of the model can be understood as a path that links the source of the directed graph (e.g. relative displacement) to the sink (e.g. traction). This treatment enables us to further conceptualize the hybrid modeling process as a selection of the optimal choices in a decision tree search via deep reinforcement learning. By using sub-scale simulations to generate database to train material models, an offline homogenization procedure is used to replace the up-scaling procedure to generate cohesive laws for localized physical discontinuities at both grain and specimen scales. Due to the usage of bridging-scale technique, the proposed model may provide multiple opportunities to incorporate different types of simulations and experimental data across different length scales for machine learning. Numerical issues will also be discussed.

Mechanisms of unsteady shallow creep on active faults in Southern California (and elsewhere)

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Observations of shallow fault creep reveal increasingly complex time-dependent slip histories that include quasi-steady creep and triggered as well as spontaneous accelerated slip events. I will review existing observations and present new data documenting a recent slow slip event on the southern San Andreas fault (SSAF). The timing of the slow slip event suggests that it was triggered by the 2017 M8.2 Chiapas (Mexico) earthquake that occurred 3000 km away. Geodetic and geologic observations indicate that surface slip on the order of 10 mm occurred on a 40-km-long section of the SSAF between the Mecca Hills and Bombay Beach, starting minutes after the Chiapas earthquake and continuing for more than a year. Both the magnitude and the depth extent of creep vary along strike. We derived a high-resolution map of surface displacements by combining Sentinel-1 Interferometric Synthetic Aperture Radar (InSAR) acquisitions from different lines of sight. InSAR-derived displacements are in good agreement with the creepmeter data and field mapping of surface offsets. Geodetic data suggest that the width of the surface shear zone associated with surface creep is greater than 100 m at some locations along the fault. At other locations, a good agreement between low-aperture creepmeter and geological measurements, on the one hand, and InSAR data sampled at distances of tens to hundreds of meters away from the fault indicates that most of the deformation is localized on a fault interface, in some places possibly as narrow as a few millimeters. We performed 2-D simulations of shallow creep on a strike-slip fault obeying rate-and-state friction to constrain frictional properties of the top few kilometers of the upper crust. Models assuming monotonic variations in the velocity-dependence parameter (a-b) are able to reproduce a number of features in the observed slip histories. However, more complicated models including e.g. stochastic variations in the rate and state parameters, and rate-dependent hardening mechanisms such as dilatancy, may be required to fit all of the available data.

The Mechanics of Episodic Caldera Collapse as Revealed by the 2018 Kilauea, Hawaii Eruption

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The 2018 eruption of Kilauea volcano, Hawaii resulted in by far the best monitored caldera collapse in history. In 2.5 months, the caldera floor dropped up to 500 meters and its volume increased by ~0.8km^3. Collapse was both driven by, and facilitated, lava effusion at rates up to 200 m^3/s. Over 700 homes were destroyed before the eruption abruptly ended in early August 2018.

Collapse occurred in over 60 discrete events in which the caldera dropped from several to nearly 10 meters, accompanied by M_W 5.2 to 5.4 Very Long Period earthquakes. Volcano-tectonic (VT) seismic activity increased steadily prior to collapse events and then decreased dramatically immediately afterward. Caldera collapses were accompanied by remarkable *inflationary* deformation transients with radially outward GPS displacements of up to 0.17 m, and outward tilts in excess of 80 micro-radians. The inflationary steps were followed by decelerating *deflations*. Similar transients have been recorded during other basaltic caldera collapses.

Two ideas have been proposed to explain co-collapse inflation: down-dropping of caldera blocks rapidly pressurizing the magma chamber, and elastic rebound on the caldera bounding faults. Here, I compute the expected deformation due to slip on faults that bottom adjacent to a fluid filled magma reservoir. Collapse occurs on time scales of 5 to 10 seconds, during which the mass of magma within the chamber is constant. This leads to inflationary deformation for either vertical or inward dipping faults, but not for outward dips. For inward dipping faults elastic distortion (rebound) contributes to uplift, however only nearly vertical faults are consistent with the observations.

The time dependence of the collapse is explored with a lumped parameter model in which the weight of the caldera block is balanced by magma pressure at its base and rate-and-state dependent friction on its sides. Flow is driven by the pressure difference between the chamber outlet and the eruption site. Under appropriate conditions the model system exhibits sequences of stick-slip events. As magma chamber pressure decreases due to outflow, shear stress increases potentially triggering a stick slip event. Predicted magma chamber pressure histories mimic observed deformations and the rate of stress increase between stick-slip events mirrors observed changes in seismicity. If the pressure difference between the chamber outlet and the eruption site falls below a threshold the pressure monotonically decays, and stick slip does not occur, consistent with the 2018 eruption site being at low elevation.

POSTER ABSTRACTS

Slip Patterns on Heterogeneous Fault Interfaces Governed by Rate and State Friction Model

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Observations in the Parkfield section of San Andreas fault show that the both seismic and aseismic phenomena display significant variability in their moment and recurrence time. Similarly, the creeping segment may be accumulating its slip unsteadily, as suggested by surface creep meters and inversions of GPS data. Such behavior may be pointing to the heterogeneity of fault properties within the seismogenic velocity-weakening (VW) patches and/or the surrounding velocity-strengthening (VS) matrix. Such complexities motivate us to explore the consequences of heterogeneity in the VW/VS property distribution in terms of the resulting slip patterns. We focus on rate-and-state interfaces that mix VW and VS patches. Both slow and rapid slip events could occur in such surfaces, depending on the fractional area, connectivity, strength contrast of VW patches with respect to the surrounding VS region and the size of the VW patches with respect to the nucleation size. Overall, we aim to understand how local heterogeneities in friction properties translate into larger-scale behaviors, both in terms of stability and slip patterns.

To that end, we numerically study the slip patterns on fault interfaces with fractal-like distributions of frictional properties, using 3D simulations of a 2D interface embedded in a homogeneous elastodynamic space, with an efficient and rigorous numerical procedure. With incorporating more complex heterogeneity into the model and matching the observations, we could potentially start to constrain the level of heterogeneity on natural faults. The important questions we aim to address are: 1) How important is smaller-scale heterogeneity of the friction properties to the large-scale response? 2) Is there a physically motivated upscaling of the effect of smaller- scale heterogeneity on larger scales that allows to maintain the statistics of the slip events?

Lava lake sloshing excited by rockfalls at the summit of Kilauea Volcano during the 2018 May eruption

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Semi-permanent lava lakes provide valuable opportunities for studying basaltic volcanism. During first 10 days of the 2018 May Kilauea eruption, multiple very long period (VLP) oscillatory modes are excited by rockfalls into the summit lava lake. The longest period mode (VLP mode) (~ 30-40 s) persists during the lava lake drainage, indicating its primary association with the underlying conduit-reservoir system. Modes with periods of 10-20 s are due to lava lake sloshing and diminish as magma is drained. The surface displacements of two longest sloshing modes are well explained by a horizontal force along the axes of the crater, resulted from the imbalance of pressure perturbation on the crater walls, and a volume change in a reservoir located at the VLP mode source centroid. Both sloshing modes are in the "deep-water" limit where disturbances are confined near the free surface. Combining magma sloshing dynamics in the crater and a conduit-reservoir oscillation model, we constrain the compliance of the shallow magma reservoir to be greater than 0.4 m^3/Pa, probably indicating the presence more compliant magma bodies (than a spherical chamber), such as sills or dikes. Our work demonstrates the clear signature of lava lake sloshing modes in the broadband seismic data and the vast potential of these modes in unraveling the physical properties of the shallow magmatic system.

Influence of fluid-assisted healing on fault permeability structure

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Micro-cracks in fault damage zones can heal through diffusive mass transfer controlled by temperature and pressure. The diffusion of pore fluid pressure in fault damage zones accelerates mass diffusion and assists healing processes. In this work, we use fluid flow model coupled with heat transfer and crack healing to investigate, through different scenarios, the role of subsurface warm fluid migration, along damage zones, in enhancing healing and re-shaping the fault permeability structure. Our results show that if the flow communication exists between the bed and only one side of the damage zone and not the other side, it leads to an asymmetric permeability structure caused by healing in the side circulated by fluids (ex: Dombjerg fault, Greenland). Another scenario is when the damage zone adjacent to the fault core is not the interval with the highest permeability, as conventionally expected, which is the case of the Alpine Fault, New Zealand. As shown by our simulations, this can be due to healing by diffusive mass transfer, favored by the localized high geothermal gradients and the upward fluid migration through the fault relay structure.
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Poroelastic effects destabilize mildly rate-strengthening friction to generate stable slow slip pulses

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Slow slip events represent a broad class of sliding instabilities that never accelerate to inertially limited ruptures or earthquakes. While observations of slow slip events continue to mount, a plausible mechanism that permits instability while simultaneously limiting slip speed remains elusive. Rate-and-state friction has been successful in describing most aspects of rock friction, faulting, and earthquakes, but current explanations of slow slip events appeal to rate-weakening friction to induce instabilities, which are then stalled by additional stabilizing processes like dilatancy or a transition to rate-strengthening friction at high slip rates. However, the temperatures and/or clay-rich compositions at slow slip locations are almost ubiquitously associated with rate-strengthening friction. We propose a fundamentally different instability mechanism that may reconcile this contradiction and provide added coherence between theory and experiments. We demonstrate how slow slip events can spontanously nucleate at steady state sliding with mildly rate-strengthening friction using both linearized stability analysis and numerical simulations. We identify two destabilizing mechanisms, both reducing frictional shear strength through reductions in effective normal stress, that counteract the stabilizing effects of rate-strengthening friction. We focus on a poroelastic mechanism where changes in volumetric stress induce changes in effective normal stress at the slip surface. Linearized analysis reveals that there is a perturbation wavelength of maximum growth rate with stability at both larger and smaller wavelengths. Simulations demonstrate that these instabilities develop into slow slip pulses. We quantify parameter controls on pulse length, propagation speed, and other characteristics, and demonstrate broad consistency with observations of tectonic slow slip events as well as laboratory tribology experiments.

Numerical Modeling of Fluid-Induced Slip on a Rate-and-State Fault Motivated by a Field Experiment

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Numerous activities in the geo-energy industry (e.g., hydraulic fracking, wastewater disposal, CO_2 sequestration and enhanced geothermal systems) involve fluid injections into the shallow crust (~1 to 5 km depth). That these fluid injections can induce fault slip (either seismic or aseismic) is now well recognized from surface and borehole observations. When injected directly into a fault system, fluids decrease fault strength by increasing pore pressure. This strength drop may in turn result in seismic or aseismic slip. However, what conditions promote stable versus unstable failure, and the exact physical mechanisms at play are still poorly understood. For example, the fluid-injection field experiment described by Guglielmi et al. (2015) resulted in aseismic slip first, followed by a sequence of 80 seismic events (i.e. microearthquakes), with the initial aseismic slip attributed to velocity-strengthening rate-and-state properties based on a spring-slider model.

In this study, we seek to determine the range of frictional regimes consistent with these experimental observations through numerical simulations of slip on a fault in a continuum medium. Specifically, we simulate slip on a rate-and-state fault embedded in a homogeneous elastic medium and subjected to increasing pore pressure at the injection site, with the fault and pore pressure parameters informed by the Guglielmi et al.'s study. We use an elastodynamic boundary-integral code supplemented with fluid pressure diffusion along the fault. We find that attempted but arrested nucleation events might be the cause of the episodes of (aseismic) slip acceleration observed during the experiment. Explaining the slip observations measured at a single point with rate-and-state friction is thus a non-unique problem. Constraining the frictional parameters further would require additional experimental studies with simultaneous measurements of fluid pressure, fault-normal and fault-parallel displacements and seismicity, both at the injection site and its surroundings.

By extending the simulations to a longer injection schedule, we can also investigate whether injecting fluids in this particular setting could eventually induce significant seismicity. Holding the injection pressure constant at its maximum value for an additional hour after the initial half-hour injection, we find that the model can produce continued aseismic slip, contained seismic event(s) and/or a runaway rupture depending on the frictional parameters prescribed. For example, faults that are closer to failure in their initial state are more prone to seismic instabilities later on. These fully-dynamic simulations could be a helpful tool to assist in the design and planning of future injection experiments (e.g., SEISMS) which could provide invaluable insight into the physics of both induced and natural earthq

Comparing seismic, mechanical, and geometrical asperities observed in a laboratory granite fault undergoing stick-slip cycles.

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We conducted triaxial deformation experiments with stick-slip sequences along rough faults created in granite samples, while passively recording acoustic emissions (AEs), accompanying the cracking and actively acquiring tomographic p-wave velocity structures along the fault, in order to investigate the correspondence between rough fault geometries and various indicators of seismic asperities along the fault. The objective is to give direct physical validation to the notion that b-value distributions highlight regions of faults where shear stress has accumulated and therefore prone to slip in an imminent earthquake event. In each experiment, granite samples of 4 cm diameter and 10 cm height were first failed at 75 MPa confining pressure, then locked by raising the pressure to 150 MPa to promote stick-slip behavior. Over 700,000 AE events were located per experiment from the 16 AE sensors distributed around the sample, which allowed us to map the distribution of b-value, AE rate, and moment release rate along the fault. Periodic acquisition of p-wave velocities between 12 AE sensors distributed around the fault plane also allowed us to obtain p-wave velocity structures along the fault plane every 10 seconds via tomographic analysis. We focus on the velocity structure as rock velocities are sensitive to stress magnitudes and could serve as potential proxies for stress. Slip events were observed to nucleate within or at the edge of low b-value regions consistent with past studies (e.g., Goebel et al., 2012). Slip events also appear to nucleate along the edge of topographic high regions along the fault plane as identified by X-ray CT tomography and white-light profilometry. The distribution of the velocity determined by the p-wave tomography also delineates boundaries between high and low velocity regions which also has loose correlations with the edges of the topographic highs. However, current observations do not suggest a clear correlation between the b-value distributions and the velocity structure, thus it is unclear whether b-values along faults actually have causal relationships with fault shear stress.

A machine-learning meta-modeling game for generating traction-separation law for frictional interfaces across length scale

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We introduce a meta-modeling game based on concepts from multi-graph theory to find the optimal way to generate data and write models for blind predictions of cohesive-frictional responses of an interface. We consider an idealized situation in which the modeling process of history-dependent process can be represented by a sequence of decision making where modelers make choices to formulate a sequence of actions to generate models. Our goal is to seek the best option that represents the hierarchy of material responses, i.e. the knowledge represented by a directed graph. As such, we introduce a new concept where all the modeling options can be recast as a directed multi-graph and each instant/configuration of the model can be understood as a path that links the source of the directed graph (e.g. relative displacement) to the sink (e.g. traction). This treatment enables us to further conceptualize the hybrid modeling process as a selection of the optimal choices in a decision tree search via deep reinforcement learning. By using sub-scale simulations to generate database to train material models, an offline homogenization procedure is used to replace the up-scaling procedure to generate cohesive laws for localized physical discontinuities at both grain and specimen scales. Due to the usage of bridging-scale technique, the proposed model may provide multiple opportunities to incorporate different types of simulations and experimental data across different length scales for machine learning. Numerical issues will also be discussed.

The Shape of Slip Profiles in Contained Laboratory-Generated Earthquakes

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Earthquakes are commonly modeled as shear cracks, where the distribution of slip distance on a fault is an accumulated result from all the processes during an earthquake: quasi-static nucleation, dynamic propagation, and abrupt arrest. The simplest linear elastic crack model predicts elliptical slip profiles for constant stress drop within the earthquake rupture. However, it casts stress singularity ahead of the crack tips, which is unrealistic because real materials or frictional interfaces have finite strength. In order to keep stresses finite, the slip distance must gradually taper near the crack tips. Studies have shown that the slip gradients near the tips of earthquake ruptures are approximately linear instead of ellipse-like, *e.g.*, Dawers *et al.* (1983), Manighetti, *et al.* (2001), and Scholz & Lawler (2004). Previous studies approached this problem by assuming the fault's end zones undergo plastic deformation and reach constant shear strength, which results in bell-shaped slip profiles (Cowie & Scholz, 1992; Bürgmann *et al.*, 1994). Our measurements of slip profiles from laboratory earthquakes suggest that the shape of a real earthquake rupture should be something in between those idealized models.

We present results from recent large-scale laboratory experiments where all the rupture processes are completely confined in a 3-meter long saw-cut granite fault (Ke *et al.*, 2018). We measure local slip and local shear strain at 16 locations on the sample and find that the shape of the slip profiles is similar to earthquake ruptures on natural faults, *e.g.*, Dawers *et al.* (1993) and Manighetti *et al.*, (2001). Based on the constitutive relationship between slip and shear stress change of a mode II crack (Bilby & Eshelby, 1968), we derived a simple parametric model to faithfully represent slip profiles and shear stress change of laboratory earthquake ruptures we measured. With both measurements of local slip and shear stress, we can potentially better constrain the features of frictional earthquake rupture process and discuss the mechanics of earthquakes on preexisting faults at depth. Upon inspection, there was no sign of inelastic deformation or damages on the surrounding material, implying that inelasticity near the tips was solely frictional. Consequently, those elastic-plastic crack models with idealized stress conditions are not applicable to friction-dominated earthquake ruptures, and a crack model that is versatile yet numerically stable for fitting both slip profile and distribution of stress change is essential to uncover the complex behavior of friction on rock.

STRESS STATE HETEROGENEITY OBSERVED ALONG THE TCDP WELLS AND ITS RELATION TO LITHOLOGICAL VARIATIONS

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In-situ stress is an important parameter to characterize when studying the driving forces of earthquakes. Previous geomechanical studies have characterized the in-situ state of stress in the Chelungpu fault system based on image logs, extended leak off tests, and rock strength measurements from the Taiwan Chelungpu fault Drilling Project (TCDP). However, results are not necessarily consistent with each other, suggesting faulting environments ranging from normal to reverse faulting environments depending on the study. We revisit previous literature, reanalyze image logs and conduct experiments on cores collected from TCDP to deduce that the stress state in the region fluctuates due to the variation in lithology encountered along the well.

Hydraulic fracturing stress measurements carried out in Hole-B also suggests that the minimum horizontal stress (Shmin) gradient varies with lithology. In test carried out in siltstone/shale layers, Shmin values (24 MPa) were observed to be only slightly less than the vertical stress (Sv=27 MPa); whereas in a sandstone layer, Shmin (16 MPa) was much smaller than the Sv at that depth (25 MPa). Higher Shmin in the siltstone layers can be the result of stress relaxation that occurs in clay-rich siltstone layers. Rocks with higher clay content are known to exhibit ductile properties which helps to relax stress anisotropy and increase the Shmin magnitude over time.

Observation of wellbore failures show that their occurrence varies with lithology. Drilling-induced tensile fractures (DITF) are observed in sandstone layers. We also observe that breakouts are ubiquitous features along the well, although in sandstone layers, their average width is smaller at 27° compared to 31° in siltstone layers. The DITF observations can be explained by the lower tensile strength of sandstone cores (0.5 MPa) compared to the siltstone cores (8 MPa) found from laboratory measurements and the lower Shmin for sandstone compared to siltstone layers, found from hydraulic fracturing. The uniaxial compressive strength (UCS) of siltstone cores (79 MPa) is also higher than that of sandstone cores (10 MPa), i.e. sandstone would require less compressive stress to fail. However, the narrower breakouts in the sandstone layer cannot be explained by the lower UCS of the sandstones, therefore suggests that the maximum horizontal stress (SHmax) magnitude is lower in the sandstone layers. Such lowered SHmax magnitude may potentially be explained by the lower elastic moduli of the higher-porosity sandstones. If formations experience uniform horizontal compression due to tectonic loading, stress accumulation in compliant layers would be less than in stiff layers.
It is important to carefully acknowledge these stress heterogeneities when discussing the relation between in-situ stress and earthquake faulting.

Keywords: in-situ stress, wellbore failures, hydraulic fracturing, lithological variation