Technical Report

Evolution of frictional shear resistance in response to rapid variations of normal stress

SCEC Award # 19093

Principal Investigator: Ares Rosakis, California Institute of Technology

1. Summary of the results
Friction formulations typically assume shear resistance to be proportional to normal stress. However, when normal stress changes rapidly enough, frictional shear resistance no longer obeys proportionality to the normal stress but rather evolves with slip gradually (Prakash and Clifton, 1993). In this project, we investigate the evolution of shear stress in response to rapid normal stress variations using laboratory experiments of spontaneously propagating dynamic ruptures. Our experiments produce variations in fault-normal stress due to the interaction of dynamic rupture with the free surface, similarly to what occurs in natural thrust events (Gabuchian et al., 2014; 2017).
Our experimental measurements clearly demonstrate the delay between normal stress changes and the corresponding changes in frictional resistance, with important implications for the dynamics of thrust earthquakes near the free surface. The experiments make use of full-field measurements of displacements, strains, and stresses by combining digital image correlation (DIC) technique with ultrahigh-speed photography (Rubino et al., 2016; 2017; 2019; 2020), which thoroughly characterize rupture interaction with the free surface, including the large normal stress reductions. In particular, our results indicate that the delay in shear resistance response to variations in normal stress is associated with an evolution distance that is 2–3 orders of magnitude larger than that of rate-and-state friction. Such delay is important in other earthquake source problems that involve rapid normal stress variations, such as seismic slip on non-planar faults, on bi-material faults, and in the presence of shear-heating-induced pressurization of pore fluids.

1. Project motivation and objective

The delayed in response of frictional shear resistance to variations in normal tractions, and its proper representation in friction formulations, is critically important for investigations of several key earthquake source problems, including (i) slip on locally rough/nonplanar interfaces, a topic of particular interest in SCEC5 (Dieterich and Smith, 2009; Fang et al., 2011; Dunham et al., 2011; Duru and Dunham, 2016); (ii) the dynamics of ruptures on thrust and normal faults near the Earth's surface, which is important for near-fault shaking and tsunami generation, and which contains rapid changes in the fault-normal stress due to the interaction of rupture with the free surface (e.g., Oglesby et al. 1998; Nielsen, 1998; Oglesby et al., 2000; Madariaga, 2003; Duan and Oglesby, 2005; Ma and Beroza, 2008; Kozdon and Dunham, 2014; Gabuchian et al., 2014; 2017), (iii) dynamic rupture on faults separating crustal rocks with different elastic properties, a common case for mature strike-slip faults that have slipped many kilometers, which causes rapid fault-normal stress changes due to coupling between the fault normal stress and slip (e.g., Andrews and Ben-Zion, 1997; Cochard et al., 2000; Rice et al., 2001; Xia et al., 2005; Shi and Ben-Zion, 2006; Rosakis et al., 2007; Bhat et al., 2010; Shlomai and Finberg, 2016), and (iv) shear-heating-induced rapid pressurization of pore fluids during seismic slip, which potentially results in rapid enough effective normal stress changes (e.g., Lachenbruch, 1980; Mase and Smith, 1985; Rice, 2006; Schmitt et al., 2011).
In this project, we use laboratory experiments to investigate the evolution of shear stress in response to rapid normal stress variations in order to achieve the following goals:
• Quantify normal stress variations and the corresponding shear resistance evolution produced by the propagation of spontaneous ruptures near a free surface.
• Use the measurements to test the validity of various friction laws proposed to capture the effects of

rapidly varying normal stresses.
• Investigate the effects of asymmetric geometry and heterogeneous frictional resistance on the ground motion.

2. Relevance of the project goals to the objectives of SCEC

This project addresses the following SCEC5 Research Priorities:

P4.a. Determine the relative roles of fault geometry [and] heterogeneous frictional resistance, […] in controlling and bounding ground motions.

P1.d. Quantify stress heterogeneity on faults at different spatial scales.

P3.g. Assess the importance of the mechanical properties of the near-surface.

Our experiments featuring spontaneously propagating ruptures reaching the free surface, performed under a range of experimental parameters, will contribute to determine the relative roles of fault geometry and frictional resistance in controlling and bounding ground motion, and thus address **P4.a**. Our measurements of shear stress in the near-surface region will also contribute to **P1.d** and **P3.g**.

3. Results

Understanding friction response to rapid normal stress variations is key to analyzing a number of problems in earthquake source science, as discussed in section 1. We study this problem in a highly instrumented experimental setup that produces variations in fault-normal stress due to the interaction of dynamic rupture with the free surface. The lab earthquake setup features a dynamic rupture along an inclined, frictional interface formed by two compressed quadrilateral sections of Homalite (Figure 1, Top panel). The full-field imaging technique that we have developed enables to image the motions and stress changes within a field of view (FOV) close to the free surface. It allows us to both obtain the dynamic details of the phenomenon as well as image the evolution of fault-normal stress, fault-parallel shear stress, and hence friction along the interface close to the free surface, and hence to study how friction evolves under the conditions of rapid normal stress variations and to distinguish between different proposed formulations. We have already been successful to characterize dynamic friction evolution in the bulk and used friction laws to describe its behavior (Rubino et al., 2017).

The full-field imaging technique that we have developed is perfectly suited to image the motions and stress changes within a field of view (FOV) close to the free surface. Accurate measurements of stresses near the interface are very important when digital image correlation (DIC) is applied to study the dynamics of laboratory frictional rupture. However, DIC algorithms involve small errors that can lead to non-physical discontinuities in the stress field across the interface. Using the previous SCEC award, we have developed an algorithm to locally adjust the displacements computed by DIC near frictional interfaces, such that local stress fields satisfy the continuity of traction across the interface (Tal et al., 2019).

To study normal stress variations and modulate their intensities in our experimental setup, we have started by considering geometry and loading conditions similar to those employed by Gabuchian et al., (2014; 2017), with interfaces inclined at α = 29° and two levels of applied vertical loading P = 10 MPa and 15MPa. Initial experimental results show that the method is capable of providing very coherent full-field measurements of fault-parallel velocity, shear stress, and fault-normal stress. An example of a test conducted with α = 29° and P = 15 MPa is given in Figures 1 and 2, where snapshots are shown of the particle velocity and stress maps of a supershear crack-like rupture, as it breaks the free surface, followed by the trailing Rayleigh disturbance. This loading configuration corresponds to a resolved normal prestress of $\sigma_0 = 11.6$ MPa. Significant reductions of normal stress are observed close to the free surface (Figure 2f). The resolved friction coefficient near the free surface (black circles in Figure 3a) initially increases to $\tau/\sigma \approx 0.6$ and then decreases with slip to $\tau/\sigma \approx 0.35$ at slip of about 25 μm. At larger levels of slip, when the impinging rupture is reflected at the free surface, σ decreases and because of a delayed response of the frictional shear resistance the ratio τ/σ increases. The rate-and-state formulation, supplemented with flash heating, which does not account for this delay (blue curve in Figure 3), cannot match the observed response.

The rate-and-state formulation enhanced with flash heating and combined with the Prakash-Clifton formulation results in a much better fit of the measured evolution of effective friction (Figure 3, purple curves). However, the model is consistently below the measured curve. Further, using the parameters constrained with this test with another experimental configuration (e.g. $\sigma_0 = 7.6$ MPa), reveals that the combined formulation predicts a significantly lower friction coefficient. This evidence suggest that in addition to the delayed response, the value of f_w in these tests is slightly larger than that estimated in Rubino et al., 2017. We posit that accounting for the dependence of friction parameters f_w and V_w upon normal stress may significantly reduce the discrepancies.

Publications

Tal, Y., Rubino, V., A. J. Rosakis, and N. Lapusta (2019) Enhanced Digital Image Correlation Analysis of Ruptures with Enforced Traction Continuity Conditions Across Interfaces. *Applied Sciences*, 9 (8). Art. No. 1625. ISSN 2076-3417. http://resolver.caltech.edu/CaltechAUTHORS:20190418-111823081

Tal, Y., Rubino, V., A. J. Rosakis, and N. Lapusta (2020) Illuminating the physics of dynamic friction through laboratory earthquakes on thrust faults, *Proceedings of the National Academy of Sciences*, under review.

Presentations

Tal, Y., Rubino, V., A. J. Rosakis, and N. Lapusta, The dynamics of laboratory thrust earthquakes near the free surface, *AGU Fall Meeting*, San Francisco, CA, December 9-13, 2019.

Patent

Provisional patent application: CIT File No,: CIT-8201-P2. “Enhanced Digital Image Correlation Analysis With Enforced Traction Continuity Conditions Across Interfaces”.

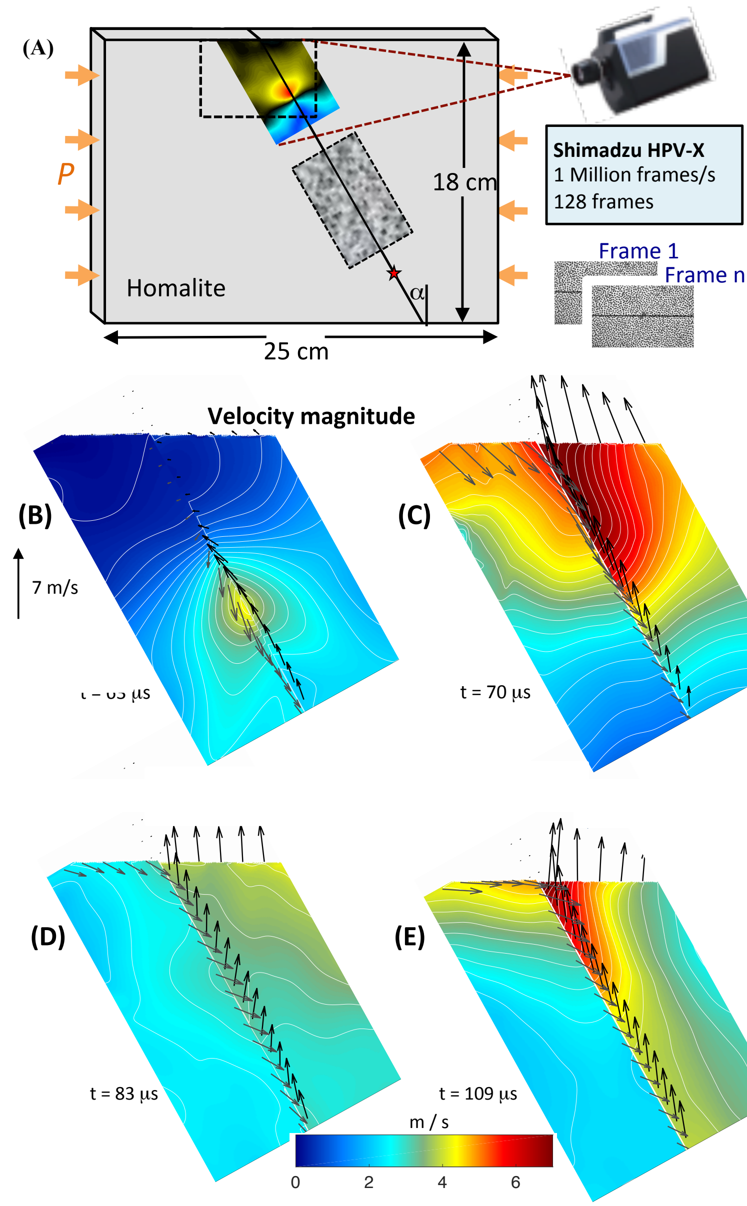

Figure 1. Full-field measurements of an up-dip thrust rupture during interaction with the free surface. (A) Experimental setup: Dynamic shear ruptures evolve spontaneously along a frictional interface with inclination angle α between two Homalite plates under a compressional load *P*. An ultrahigh-speed camera is used to take a sequence of images of a region near the free surface. (B-E) Snapshots of the particle velocity magnitude obtained using a field of view (FOV) of 19 x 12 mm^2, with overlaid vector plot showing the direction of motion near the interface and at the free surface, as a supershear crack-like rupture interacts with the free surface during a test conducted with a fault at α = 29° and initial fault-normal stress of σ_0 = 11.6 MPa. The rupture propagates upward, crosses the center of the FOV at t = 63 *s* (B), and arrives to the free surface at *t* = 70 μs (C). Sliding continues after the rupture is reflected (d). At *t* = 109 *s*, a trailing Rayleigh rupture arrives to the free surface (E).

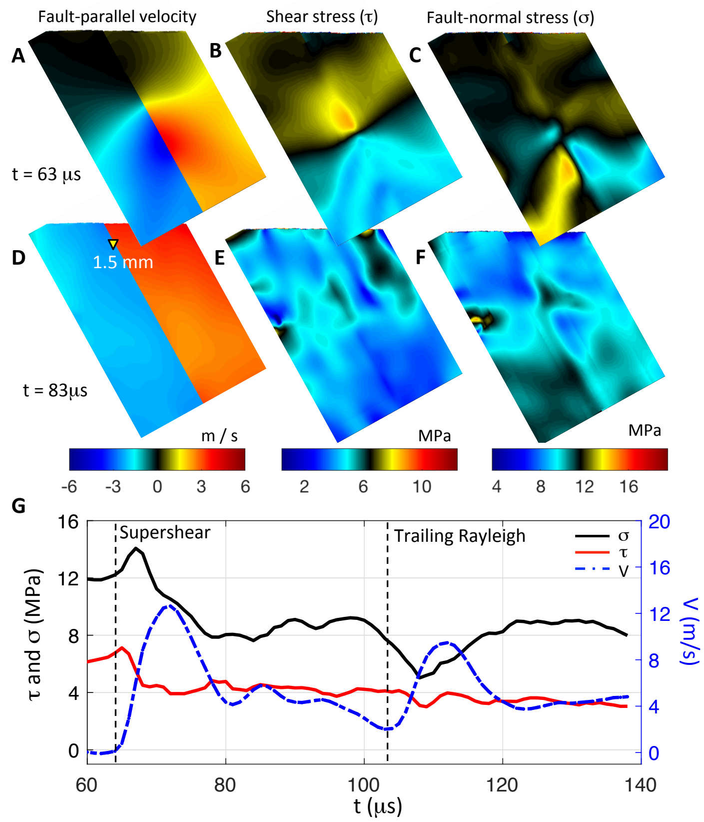

Figure 2. Experimental measurements of normal stress reduction, shear stress response, and fault-parallel velocity as the rupture interacts with the free surface. (A to F) Full-field images of fault-parallel velocity [(A) and (D)], shear stress [(B) and (E)], and fault-normal stress [(C) and (F)] during Exp. #1, corresponding to the propagation of the rupture upward through the field of view ($t = 63$ μs) and to steady sliding after reflection and decrease in fault-normal stress ($t = 83$ μs). (G) Local time histories of τ (red), σ (black), and V (blue) at a point on the fault 1.5 mm from the free surface [see location in (D)]. The curves are generated using a temporal moving average, with a width of three data points, on the local data for each quantity.

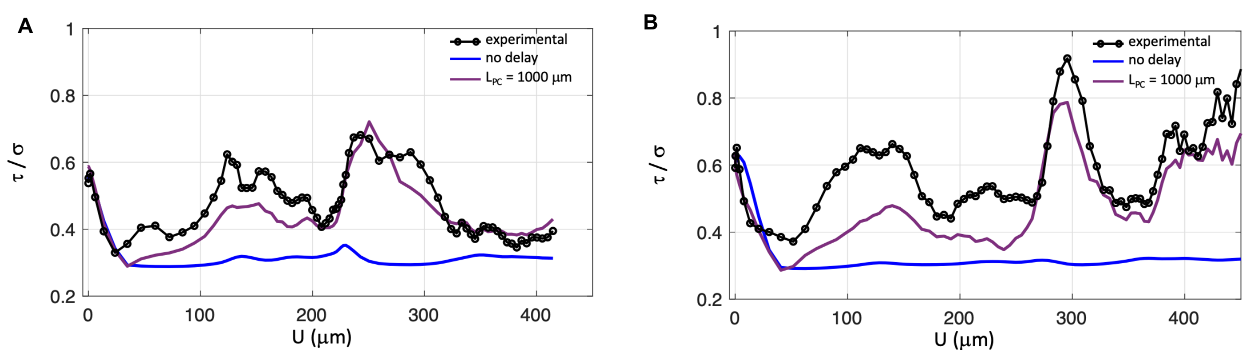

Figure 3. Experimental evidence of pronounced delay in shear resistance response to rapid normal stress variations (Tal et al., 2020, PNAS, under review). Evolutions of experimental (black circles) and modeled (solid curves) effective friction with slip near the free surface for experiments conducted with two levels of normal stress: (A) Exp #1, at $\sigma_0 =$ 11.6 MPa and (B) Exp #2, at $\sigma_0 = 7.6$ MPa. Two formulations are shown for each test: (1) Enhanced-weakening RS friction without accounting for a delayed response to variations in σ (blue); (2) Enhanced-weakening RS friction together with a Prakash-Clifton formulation (purple). The curves for both experiments were estimated using the model parameters constrained with the data of Exp #1. While the modeled curve works fairly well for Exp #1, there are some important discrepancies for Exp #2, conducted at a lower level of normal stress and we expect even larger discrepancies for tests to be conducted at lower normal stress levels. We postulate that accounting for the dependence of friction parameters f_w and V_w upon normal stress may significantly reduce the discrepancies.

References

Andrews, D. J., Y. Ben-Zion, Wrinkle-like slip pulse on a fault between different materials, *J. Geophys. Res. Solid Ea*. **102** (B1), 553-571, 1997.

Bhat, H. S., R. L. Biegel, A. J. Rosakis, C. G. Sammis, The effect of asymmetric damage on dynamic shear rupture propagation II. With misatch in bulk elasticity, *Tectonophysics* **493**, 263-271, 2010.

Cochard, A. and J. R. Rice, Fault rupture between dissimilar materials. Ill-posedness, regularization, and slip-pulse response, *J. Geophys. Res.* **105** (B11), 25891-25907, 2000.

Dieterich J.H., and D.E. Smith, Nonplanar faults: Mechanics of slip and off-fault damage, **166**(1799-1815), 2009.

Duan, B. and D. D. Oglesby, Multicycle dynamics of nonplanar strike-slip faults, *J. Geophys. Res.* **110** (B3), 1-16, 2005.

Duru, K. and E. M. Dunham, Dynamic earthquake rupture simulations on nonplanar faults embedded in 3D geometrically complex, heterogeneous elastic solids, *J. Comput. Phys.* **110** (B3), 1-16, 2005.

Dunham, E. M., D. Belanger, L. Cong, and J. E. Kozdon, Earthquake ruptures with strongly rate-weakening friction and off-fault plasticity, 2: Nonplanar faults, *Bulletin of the Seismological Society of America*, **101**(5), 2308-2322, 2011.

Fang, Z., J.H. Dieterich, K.B. Richards-Dinger, and G. Xu, Earthquake nucleation on faults with nonconstant normal stress, **116**(B09307), 2011.

Gabuchian, V., A. J. Rosakis, N. Lapusta, and D. Oglesby, Experimental investigation of strong ground motion due to thrust fault earthquakes, *J. Geophys. Res.* **119** (2), 1316-1336, 2014.

Gabuchian, V., Rosakis, A. J., Bhat, H., Madariaga, R. and Lapusta, N., Experimental evidence that thrust earthquake ruptures might open faults, *Nature* **545,** 336-340, 2017.

Kozdon, J. E. and E. M. Dunham, Constraining shallow slip and tsunami excitation in megathrust ruptures using seismic and ocean acoustic waves recorded on ocean-bottom sensor networks, *Earth and Planetary Science Letters*, **396**, 56-65, 2014

Ma, S., G. C. Beroza, Rupture dynamics on a bimaterial interface for dipping faults, *Bull. Seismol. Soc. Am.* **98** (4), 1642-1658, 2008.

Madariaga, R., Radiation from a Finite Reverse Fault in a Half Space, *Pure Appl. Geophys.* **160**, 555-577, 2003.

Mase, C. W. and L. Smith, Pore–fluid pressures and frictional heating on a fault surface, *Pure Appl. Geophys*. **122**, 583–607, 1985.

Nielsen, S. B., Free surface effects on the propagation of dynamic rupture, *Geophys. Res. Lett.* **25** (1), 125-128, 1998.

Oglesby, D. D., R. J. Archuleta, and S. B. Nielsen, Earthquakes on Dipping Faults. The Effect of Bronken Symmetry, *Science* **280** (5366), 1055-1059, 1998.

Oglesby, D. D., R. J. Archuleta, and S. B. Nielsen, The Three-Dimensional Dynamics of Dipping Faults, *Bull. Seimol. Soc. Am.* **90** (3), 616-628, 2000.

Prakash, V., and R. J. Clifton, Time resolved dynamic friction measurements in pressure-shear, *Experimental Techniques in the Dynamics of Deformable Solids*, Applied Mechanics Div. Vol. 165 (AMD-Vol. 165). American Society of Mechanical Engineers, New York, pp. 33-48, 1993.

Rice, J. R., N. Lapusta, K. Ranjith, Rate and state dependent friction and the stability of sliding between elastically deformable solids, *J. Mech. Phys. Solids* **49** (9), 1865-1898, 2001.

Rice, J. R., Heating and weakening of faults during earthquake slip, *J. Geophys. Res*., **111** (B5), 1-29, 2006.

Rosakis, A. J., K. Xia, G. Lykotrafitis and H. Kanamori, Dynamic Shear Rupture in Frictional Interfaces. Speeds, Directionality and Modes, *Treatise Geophys.* **4**, 153-192, 2007.

Rubino, V., A. J. Rosakis, and N. Lapusta, Dynamic visualization of supershear ruptures, *XXIV ICTAM*, Montreal, Canada, August 21-26, 2016.

Rubino, V., A. J. Rosakis, and N. Lapusta, Understanding dynamic friction through spontaneously evolving laboratory earthquakes, *Nature Communications*, 8:15991, 2017.

Rubino, V.; Rosakis, A.J.; Lapusta, N. Full-field ultrahigh-speed quantification of dynamic shear ruptures using digital image correlation. *Exp. Mech*, 59(5), 551-582, 2019.

Rubino, V., A.J. Rosakis and N. Lapusta, Spatiotemporal properties of sub-Rayleigh and supershear ruptures inferred from full-field dynamic imaging of laboratory experiments, *Journal of Geophysical Research: Solid Earth,* 125, e2019JB01892, 2020.

Saffer, D. M. & Marone, C. Comparison of smectite-and illite-rich gouge frictional properties: application to the updip limit of the seismogenic zone along subduction megathrusts. *Earth Planet. Sci. Lett.* **215,** 219–235, 2003.

Schmitt, S.V., P. Segall, T. Matsuzawa, Shear heating-induced thermal pressurization during earthgquake nucleation, *J. Geophys. Res*. **116**, B06308, 2011.

Shi, Z., Y. Ben-Zion, A. Needleman, Properties of dynamic rupture and energy partition in a solid with a frictional interface, *J. Mech. Phys. Solids* **56** (1), 5-24, 2008.

Shlomai, H. and J. Fineberg, The structure of slip-pulses and supershear ruptures driving slip in bimaterial friction, *Nature Communications* **7** (11787), 2016.

Tal, Y., Rubino, V., A. J. Rosakis, and N. Lapusta (2019) Enhanced Digital Image Correlation Analysis of Ruptures with Enforced Traction Continuity Conditions Across Interfaces. *Applied Sciences*, 9 (8). Art. No. 1625. ISSN 2076-3417.

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Tal, Y., Rubino, V., A. J. Rosakis, and N. Lapusta, Studying the shear resistance response to rapid normal-stress variations near the free surface on experimental thrust faults, *SSA meeting*, Miami, Florida, USA, May 14-17, 2018.

Xia, K., A. J. Rosakis, H. Kanamory, and J. R. Rice, Laboratory Earthquakes Along Inhomogeneus Faults. Directionality and Supershear, *Science* **308** (5722), 681-684, 2005.