Final Report
US Department of Energy Grant
DE-FG02-04ER15568 YR7

September 29, 2015

Project Title: Collaborative Research: Damage and Burst Dynamics in Failure of Complex Geomaterials: A Statistical Physics Approach to Understanding the Complex Emergent Dynamics in Near Mean-Field Geological Materials

Project Participants:

John B. Rundle (Project Director and PI), Department of Physics, University of California, Davis

Wlliam Klein (CoI), Department of Physics, Boston University

Project Objectives:

- Determine the dynamics of failure in complex geomaterials, specifically focusing on the role of defects, damage and asperities in the catastrophic failure processes (now popularly termed "Black Swan events").
- Examine fracture branching and flow processes using models for *invasion percolation*, focusing particularly on the dynamics of *bursts* in the branching process.
- Understand the fundamental dynamics of *nucleation* in complex geomaterials, specifically in the presence of inhomogeneous structures.

Project Description and Methods: In this project, we used numerical simulations and theory, together with new classes of models, to obtain answers to our project objectives described above. Modeling these types of processes requires consideration of fully interacting fields of dislocations, defects, damage, and other material disorder. Observations of rock masses over a range of spatial scales indicate that the failure modes of these systems, such as fracture and other forms of catastrophic failure demonstrate scale invariant deformation, or power law behavior. These are observed in both laboratory settings in acoustic emission experiments, as well as in large scale field settings associated with tectonic faults. In much of the previous work over the last decades on these types of systems, disorder fields were assumed to be non-interacting or dilute, allowing classical solid-solid mixture theories to be employed. With the development of new high performance computing algorithms, however, together with new theoretical methods based on statistical field theories, we can now model a wide variety of fully interacting disordered systems. An important new topic we will consider in detail in this current period of research will be models of the *invasion percolation* ("IP") type. The model has been previously researched for applications of extracting oil and gas from reservoirs, and also in the context of the computation of scaling exponents. Notable among the physical processes of IP is the concept of *bursts*, defined as rapid changes in the configuration of the percolation lattice. Understanding the dynamics of bursts is critical to illuminating the metastable (nucleation) processes by which natural fracture networks evolve and grow, and from which catastrophic failure originates.

Benefits and Outcomes: In this research we developed significantly improved understanding of fracture networks, catastrophic failure, and transport in complex geomaterials (rocks) that is critical to energy extraction via drilling and hydrofracturing, the safety of nuclear reactors and nuclear waste repositories, and for proposed carbon sequestration processes. It has been of particular important to understand the processes involved in hydrofracture, which is both an old and a new technology with significant implications for global energy supplies and US economic competitiveness.

Research Under this Grant

Published:

J.Q. Norris, D.L. Turcotte and J.B. Rundle, Loopless nontrapping invasion-percolation model for fracking, *Phys. Rev. E.*, **89**, 022119 (2014).

D.L. Turcotte, E.M. Moores and J.B. Rundle, Super Fracking, *Phys. Today*, **67**, 34-39 (2014).

J.Q. Norris, D.L. Turcotte and J.B. Rundle , Anisotropy in Fracking: A percolation model for observed microseismicity, *Pure Appl. Geophys.*, **172**, 7-21 (2015) DOI: 10.1007/s00024-014-0921-9

In Press:

J.Q. Norris, D.L. Turcotte, E.M. Moores, E.E. Brodsky and J.B. Rundle, Fracking: What is it, what does it accomplish, and what are its consequences?, *Ann. Reviews of Earth Planet Sci.*, in press (2015)

Summary:

Fracking is a popular term referring to hydraulic fracturing when it is used to extract hydrocarbons. It is important to distinguish between low volume traditional fracking and the high volume "super" fracking used to extract large volumes of hydrocarbons from shales. Shales are fine grained rocks with low granular permeabilities and a platy fabric caused by abundant clay minerals. The formation of oil and gas gen- erates large fluid pressures. These pressures result in natural fracking which allows oil and gas to escape, thereby reducing the fluid pressures. Subsequent fracture sealing by depositional processes can result in so- called "tight" shale formations. The objective of super fracking is to reopen these fractures and/or create new fractures on a wide range of scales. Serious environmental objections to super fracking discussed in this review include the requirement for very large water volumes, for- mation and disposal of toxically contaminated water, possible ground- water and atmospheric contamination, induced earthquakes, and the volatility and explosiveness of the oil produced.

PhD Students Graduated Under Funding from This Grant

Dr. J. Quinn Norris, PhD, University of California, Davis, CA 2015.