Final Report - DE-FG02-95ER14498
Collaborative Research: Failure of Rock Masses
From Nucleation and Growth of Microscopic Defects and Disorder
Principal Investigator - W. Klein

Abstract

Over the 21 years of funding we have pursued several projects related to earthquakes, damage and nucleation. We developed simple models of earthquake faults which we studied to understand Gutenburg-Richter scaling, foreshocks and aftershocks, the effect of spatial structure of the faults and its interaction with underlying self organization and phase transitions. In addition we studied the formation of amorphous solids via the glass transition. We have also studied nucleation with a particular concentration on transitions in systems with a spatial symmetry change. In addition we investigated the nucleation process in models that mimic rock masses. We obtained the structure of the droplet in both homogeneous and heterogeneous nucleation. We also investigated the effect of defects or asperities on the nucleation of failure in simple models of earthquake faults.

Key words - Homogeneous nucleation, heterogeneous nucleation, fluctuations, defects, asperities, Gutenburg-Richter scaling, Omori's law, aftershocks.

The structure of this report is as follows. I will describe the highlights of the research over the past 21 years describing the main results. This will be an overview stressing the most important aspects of the research. I will describe the research of the last four years of the funding in greater detail. I have listed the publications, graduate students and post docs and where they are employed at present.

Some Statistics

Over the 21 years of funding from the DOE there have been 16 graduate students and 2 post docs that have been fully or partially funded by the DOE grant. There have been 66 articles published in refereed journals(including 13 in Physical Review Letters) and two that have been submitted. There have also been 13 review articles and conference proceedings. There have also been approximately 90 invited talks given by the PI at conferences, universities and national laboratories based on the research funded during this period. The works has also been cited over 3500 times(Science citation index)

Research Overview of the Entire Funding Period

During this funding period we have concentrated on understanding the process of nucleation and the phenomenon of earthquakes and how they are connected. We have, for the most part, used simple models to understand the underlying physics. In our earthquake research we have compared our model results with real data, mostly from California. For nucleation we have compared our theory with experiments where possible and with extensive simulations where experimental data is not available. The models of earthquake faults we used had long range stress transfer to mimic the long range nature of the elastic force. In nucleation we also concentrated on systems with long range interactions since we are interested in nucleation of cracks in rocks as well as nucleation of solid from molten rock. Our primary results are:

I. **Earthquakes**

1) We have found that the driven dissipative models which reach a steady state cannot be described by equilibrium methods for short range stress transfer but can be described by equilibrium methods when the stress transfer range is infinite. For long, but finite range, stress transfer the models are in a state which we refer to a punctuated equilibrium. In this state the system behaves as if it is in equilibrium for a time until a very large event forces the system out of equilibrium. We test whether the system is equilibrium using a metric suggested by Thirumali and Mountain and we find that the system is indeed in a state of punctuated equilibrium. The discussion of these results and original references can be found in reference 3 in the Review Article part of the Bibliography. In addition we have used a similar metric to find that the Southern California fault system is also in a state of punctuated equilibrium. This result can be found in reference 25 in the refereed articles part of the Bibliography.

2) In the models we find that the Gutenburg-Richter(GR) scaling is due to the existence of a spinodal. Using spinodal scaling we get good agreement with the measured value on real fault systems for single faults. However it should be stressed that the scaling usually quoted is for fault systems or even the entire earth. In general this is not the scaling seen on a single fault. We have proposed that this apparent conflict can be resolved by noting that the GR scaling is simply calculated by adding up the number of events of a given magnitude over all of the faults in the system. In real faults the stress dissipation varies from fault to fault. In the model the change of stress dissipation moves the system further from the spinodal. However, there is data collapse so that all data falls on the same master curve if the variables are scaled properly. This allows us to calculate the GR scaling for fault systems from the model giving support to the result that a spinodal is the cause of GR scaling. These results are found in reference 57 in the refereed articles part of the Bibliography.

3) We have developed a forecasting algorithm that allows us to estimate the probability of large events based of the past history of smaller events. The details of this development are complicated but they can be found in references 20, 33, and 40 in the refereed articles part of the Bibliography. There are several other papers that discuss these methods but these three, and the references therein, contain the basic information.

4) We have also used simple models to investigate the role of asperities in determining the statistics of and possible ability to forecast earthquakes. Asperities are strong areas of the fault that can hold a large amount of stress. The simple models we use generally are lattice models that have a failure threshold and a residual stress on each site. We initiate the model by distributing stress at random to each site. We then check a site too see if the stress on the site is greater than the failure threshold. If not we move on to the next site. If the stress is greater than the failure threshold the stress is reduced to the residual stress plus a small random stress, we will refer to as noise, and we dissipate(throw away) a fraction α, less than one. We then distribute the remaining stress to the neighbors. As stated above there will be many neighbors since we deal mainly with long range stress

transfer. We continue this process, visiting each site in turn, until no site has a stress greater than the failure threshold. We then reload the system by finding the site with the largest stress and adding the amount of stress that brings the site to failure. We add the same amount of stress to every site in the system. We then count the number of sites that fail between reloads.
To add asperities we select a small fraction of the sites to make the failure threshold much larger than the threshold of the majority of sites. The sites with the larger failure threshold(asperities) will act as sinks of stress until they fail and release a large amount of stress into the system. The addition of asperities leads to the addition of foreshocks and aftershocks into the system. We can, by manipulating both the number and distribution of the failure threshold size, obtain Omori's law and foreshocks that appear to have a accelerating "moment release" to failure. This study, as well as the ones discussed above, makes clear that the observed distribution of earthquakes is a result of an interaction of the fault structure with an underlying critical point(spinodal). The study of asperities is discussed in references 64 and 66 in the refereed articles part of the Bibliography.

5) The results of the studies on models that we have discussed so far have come from cellular automata(CA). The question then arises as to whether the addition of inertia and friction changes the results. We tested this by examining the Burridge-Knopoff(BK) model which is a block and spring model set on a surface with a velocity weakened friction force. This model is governed by Newtons equations and hence includes inertia. Whether the BK model gives the same results as the CA models depends on the way that the friction force is weakened with velocity. The take away message is that friction and inertia may change results and that the nature of friction on real faults must be accurately determined. These results are found in reference 47 in the refereed articles part of the Bibliography.

II. **Nucleation, Glass Transition, Unstable State Evolution**

1) We are interested in nucleation in systems with long range interactions. This means that the nucleation will generally take place near the spinodal. In the first project we are interested in how the spinodal appears in systems with long, but finite range, interactions. The reason is that spinodals only exist in systems with infinite range interactions. We determined that the spinodal has an associated Lee-Yang theorem. That is, in Ising models, there are zeros of the partition function in the complex temperature and complex magnetic field space that move toward the real temperature - magnetic field plane as the range of interaction diverges. As with the Lee-yang theorem this allows us to understand how the "spinodal" (which we will refer to as a pseudo-spinodal(ps) for long but finite range interactions) affects the system. That is the ps acts like a true spinodal unless one gets too close. The details of this study can be found in reference 26 in the refereed articles part of the Bibliography.

2) We studied the structure of fluctuations near the spinodal. To do this we used a mapping we developed to express the thermal spinodal critical point as a percolation problem. We found that fluctuations near the spinodal are related to the nucleation droplet in an unusual way. That is, nucleation is a process of a coalescence of clusters rather than the adding of one particle at a time as postulated in the classical Becker-Doering theory. Unlike the classical theory where the interior of the nucleation droplet is compact and has the same

structure as the stable phase the nucleation droplet near the spinodal is ramified. That is it has a fractal structure and the density difference between the center of the droplet and the metastable state goes to zero as the spinodal is approached. The details can be found in reference 12 in the refereed articles part of the Bibliography.

3) In most studies of nucleation we assume that the metastable state can be treated as if it were an equilibrium state. This is a good approximation if the metastable state is long lived. However if the system is quenched deeply enough into the metastable state then the nucleation barrier is low enough so that nucleation occurs on a time scale too short for the system to come into a metastable equilibrium. The first question we approached is how does a system come into equilibrium. To test this we used the mapping of the thermal problem onto a cluster or percolation problem. We then asked what was the time scale associated with clusters of a size s to come to equilibrium. We found that the time $\tau \sim s^x$ where x varied with the dimension of space. The details can be found in reference 46 in the refereed articles part of the Bibliography.

4) We studied the nucleation process near the spinodal of a fluid metastable with respect to the solid. Here the theory predicts that the structure of the nucleation droplet is modified by the proximity of the spinodal. Rather than the classical droplet which will have an interior structure identical to that of the stable phase the droplet near the spinodal can only have one of a few structures specified by a symmetry condition. These structures are bcc, stacked planes with an in plane hexagonal structure and what we refer to as an onion structure droplet. The onion structure is rotationally symmetric but the density has a damped oscillation as one moves out from the droplet center. The actual structure of the droplet depends on the details of the potential.

We have found these structures in Lennard-Jones systems(bcc), a modified embedded atom potential for nickel(stacked planes) and a simple model for an austenite to martensite transition(possible onion structure). The details can be found in references 12, 15, 17, 27, 30, 42 and 49 in the refereed articles part of the Bibliography.

5) We also studied the process of transient nucleation near the spinodal and found that the droplet was more compact than what one finds in spinodal nucleation when the equilibrium approximation is valid. The details can be found in reference 41 in the refereed articles part of the Bibliography.

6) We studied the evolution of the system when quenched into the unstable region of the phase diagram. In Ising models we found that the spatial structure evolved by the evolution of localized clusters. This predicts that the linear, or Cahn, Hilliard, Cook theory breaks down at small length scales first. For the fluid unstable with respect to the solid we find the unusual case that the initial evolution is non-linear and there is a crossover to linear behavior at a somewhat later time and finally a late stage non linear behavior.The details can be found in references 48 and 49 in the refereed articles part of the Bibliography.

7) We studied the glass transition in a two component Lennard-Jones Fluid. We found that the glass transition was caused by the formation of long lived structures near the spinodal of the supercooled liquid. The clusters scale in the same way clusters scale near the spinodal in supercooled Ising models. The details can be found in reference 7 in the refereed articles part of the Bibliography.

Research of the Past Four Years

During the funding period we investigated the nature of the nucleation process in simple models that contained the physics expected in rock masses. In particular this included long range interactions that are associated with elasticity and defects that will act as nucleation sites. We investigated both homogeneous nucleation (the process by which the droplet that initiates the decay of the metastable state arises via spontaneous fluctuations) and heterogeneous nucleation (where the droplet that initiates the decay of the metastable state is initiated on a defect or surface). We obtained the following results.

1. Many driven threshold systems display a spectrum of nucleation event sizes, often characterized by power-law scaling. An important problem is to compute probabilities of the largest events. We develop a data-driven approach to the problem by transforming to the event index frame, and relating this to Shannon information. For earthquakes nucleation, we find the 12-month probability for magnitude m¿6 earthquakes in California increases from about 30% after the last event, to 40%50% prior to the next one[1].

2. Natural earthquake fault systems are highly nonhomogeneous. The inhomogeneities occur because the earth is made of a variety of materials which hold and dissipate stress differently. In this work, we study scaling of nucleation events in earthquake fault models which are variations of the Olami-Feder-Christensen and Rundle-Jackson-Brown models. We use the scaling to explore the effect of spatial inhomogeneities due to damage and inhomogeneous stress dissipation in the earthquake-fault-like systems when the stress transfer range is long, but not necessarily longer than the length scale associated with the inhomogeneities of the system. We find that the scaling depends not only on the amount of damage, but also on the spatial distribution of that damage[2].

3. Nucleation of cracks is influenced by noise as is all other variations of the nucleation problem. With cracks however the noise would involve the dissipation of stress which can be influenced by the size of the crack opening. In this case the noise would be multiplicative rather than additive. However, the influence of multiplicative noise on ensemble averages is not understood when the noise is multiplicative. We studied the effect of ensemble averaging on multiplicative noise using geometric Brownian motion. Geometric Brownian motion (GBM) is a model for systems as varied as financial instruments and populations. The statistical properties of GBM are complicated by nonergodicity, which can lead to ensemble averages exhibiting exponential growth while any individual trajectory collapses according to its time average. We find that time averages get closer to ensemble averages the larger the number of systems averaged over in the ensemble[3].

4. As stated above we are studying systems with long range interactions consistent with the elastic force present in rock masses. In such systems there is a spinodal that affects the structure of he critical or nucleation droplet. How this structure is modified in the freezing transition in which crystalline rock forms from the molten structure is not completely understood. We studied homogeneous nucleation from a deeply quenched metastable liquid to a spatially modulated phase. We found, for a general class of density functional theories,

that the universally favored nucleating droplet in dimensions d ? 3 is spherically symmetric with radial modulations resembling the layers of an onion. The existence of this droplet has important implications for systems with long-range interactions, and in addition to nucleation in rock it potentially also applies to polymers, plasmas, and metals[4].

5. We expect the nucleation of earthquakes to be heterogeneous so that it will depend on the fault structure. We studied the effect of various arrangements of asperities on the statistics of earthquake nucleation. We found that a distribution of both asperity strengths and spatial locations resulted in foreshocks as well as aftershocks. The aftershocks appear tot obey Omori's law[5].

6. As stated above the long range interaction results in the existence of a spinodal that influences the nucleation process. The properties of the droplet are affected by scaling properties and critical exponents in the vicinity of the spinodal. We investigate these properties in the fully connected Ising model. Although the fully connected Ising model does not have a length scale, we showed that the critical exponents for thermodynamic quantities such as the mean magnetization and the susceptibility can be obtained using finite size scaling with the scaling variable equal to N, the number of spins. Surprisingly, the mean value and the most probable value of the magnetization are found to scale differently with N at the critical temperature of the infinite system, and the magnetization probability distribution is not a Gaussian, even for large N. Similar results inconsistent with the usual understanding of mean-field theory were found at the spinodal. We related these results to the breakdown of hyperscaling and show that hyperscaling can be restored by increasing N while holding the Ginzburg parameter rather than the temperature fixed, or by doing finite size scaling at the pseudocritical temperature where the susceptibility is a maximum for a given value of N. We conclude that finite size scaling for the fully connected Ising model yields different results depending on how the mean-field limit is approached.

7. Many models of earthquake faults have been introduced that connect Gutenberg-Richter (GR) scaling to triggering or nucleation processes. However, natural earthquake fault systems are composed of a variety of different geometries and materials and the associated heterogeneity in physical properties can cause a variety of spatial and temporal behaviors. This raises the question of how the nucleation process and the structure interact to produce the observed phenomena. We investigated a simple earthquake fault model based on the Olami-Feder-Christensen and Rundle-Jackson-Brown cellular automata models with long-range inter- actions that incorporates a fixed percentage of stronger sites, or asperity cells, into the lattice. These asperity cells are significantly stronger than the surrounding lattice sites but eventually rupture when the applied stress reaches their higher threshold stress. The introduction of these spatial heterogeneities results in temporal clustering in the model that mimics that seen in natural fault systems along with GR scaling. In addition, we observed sequences of activity that start with a gradually accelerating number of larger events (foreshocks) prior to a main shock that is followed by a tail of decreasing activity (aftershocks). This work provides further evidence that the spatial and temporal patterns observed in natural seismicity are strongly influenced by the underlying physical

properties and are not solely the result of a simple cascade mechanism. Although the paper was published in 2015 most of the work was done during the funding period.

8. Since the systems we study have defects we need to understand the effect of defects on the spinodal. This study was done on Ising models where we introduced vacancies and studied there effect on the properties of the spinodal. One conclusion is that defects move the location of the spinodal further from the coexistence curve but the exponents at the spinodal remain the same as the model without dilution. In addition we examined the nucleation droplet in the spinodal region and found a similar structure to the pure system without dilution[8].

9. We have done a study of the effect of different shapes of impurities on the shape and probability of the nucleation droplet near the spinodal. This was performed on the Ising model where we placed the system in a metastable state with the majority of the spins are in the up direction. We then fixed groups of spins in the down direction(the direction of the stable state) in different configurations and sizes of groups. We found that near the spinodal the extended or ramified structures were more efficient in that ramified, or fractal like, structures would decrease the metastable state lifetime by a larger amount than compact structures of the same size9.

Papers Referenced in the Description of Research in Last Four Funding Years

1. J. B. Rundle, J. R. Holliday, W. R. Graves, D. L. Turcotte, K. F. Tiampo and W. Klein, "Probabilities for Large Events in Driven Threshold Systems" Physical Review E **86**, 021106 (2012

2. R. Dominguez, K. F. Tiampo, C.Serino and W. Klein, "Scaling of Earthquake Models with Inhomogeneous Stress Dissipation" Physical Review E**87**, 022809 (2013)

3. O.Peters and W. Klein, "Ergodicity Breaking in Geometric Brownian Motion" Physical Review Letters, **110**, 100603 (2013)

4. K. Barros and W. Klein, "Liquid to Solid Nucleation via Onion Structure Droplets" Journal of Chemical Physics **139**, 174505 (2013)

5. J. Kazemian, R. Dominguez, K. Tiampo and W. Klein, "Spatial Heterogeneity in Earthquake Fault-Like Systems", Pure and Applied Geophysics DOI 10.1007/s00024-014-0843-6, (2014)

6. L. Colonna-Romano, H. Gould and W. Klein, "Anomalous Mean-Field Behavior of the Fully Connected Ising Model", Physical Review E, **90**, 042111 (2014)

7. J. Kazemian, K. F. Tiampo, W. Klein and R. Dominguez, "Foreshocks and Aftershocks in Simple Earthquake Models" Physical Review Letters **114**, 088501(2015)

8. K. Liu, W. Klein and C. A. Serino, "The Effect of Disorder on Metastable States" Physical Review E (in preparation)

9.N. Gulbahce, W. Klein and H. Gould, "Heterogeneity in Classical and Non-Classical Nucleation" Physical Review E. (submitted for publication)con- mat. 0407304

Graduate and Post Docs Students Funded Fully or Partially During the Funding Period

GRADUATE STUDENTS, Thesis Titles and Current Position

Charles Ferguson, Ph.D. 1996, "Theoretical and Numerical Studies of Models of Earthquake Faults", President of the Federation of American Scientists

Cyril Muratov, Ph.D. 1997 "Structure in Systems with Long Range Interactions of the Coulombic Type", Professor New Jersey Institute of Technology

Aaron Schweiger Ph.D. 2007 "Phase Transition Kinetics in Driven Dissipative Systems", Quantatative Research, Trade Informatics LLC

Aaron Santos Ph.D. 2007 "Nucleation and Instabilities in Biological Molecules" Professor Simpson College

Kipton Barros Ph. D. 2009 "Phase Transitions in Systems with Long-Range Interactions", Technical Staff Member, Los Alamos National Laboratory.

Rachele Dominguez Ph. D 2009 "Early Evolution of Symmetry Breaking Phase Transitions" , Professor, Randolph Macon College

Christopher Serino Ph.D 2012 "Statistical Properties of Systems with Damage and Defects" Scientist, MIT Lincoln Laboratory

Kang Liu Ph.D 2013 "The Effect of Damage on Nucleation" Post Doc Brandeis University (Michael Hagen Advisor)

Tyler Xuan Gu 2016 "Modified Earthquake Olami, Feder, Christensen Model with Low Noise, Asperities and Inhibitions"

James Silva 2016 " The Role of Heterogeniety in Long-Range Interacting Systems: From Nucleation To Earthquake Fault Systems" Scientist, SAS

Nick Lubbers 2016 "Statistical Mechanical Model of Economics" Post Doc, Los Alamos National Laboratory

Rashi Verma(current student) TBA

Patrick Greene(current student) TBA

CO - DIRECTED STUDENTS

Greg. Johnson, Ph.D. 2002 (Advisor - H. Gould, Clark University) "Near Mean-Field Effects in Fragile Glass Formers" , Scientist, Google

Natali. Gulbahce, Ph.D. 2005 (Advisor - H. Gould, Clark University) "Phase Transitions in Systems with Long-Range Interactions", Scientist, Genomic Health Inc.

Jun. Xia, Ph.D. 2006, (Advisor H. Gould, Clark University) "Computer Simulations of Statistical Models of Earthquakes", Research Scientist, Carnegie Mellon

Hui Wang Ph.D. 2007 (Advisor H. Gould, Clark University) "Nucleation in Ising Models, Lennard-Jones Liquids and the FPU Problem", Analyst Goldman Sachs

Ranjit Chacko(Advisor H. Gould, Clark University) (TBA)

POST-DOCTORAL FELLOWS

Frank J. Alexander, Oct. 1996-Sept. 1998, Technical Staff Member, Los Alamos National Laboratory.

Marian Anghel, Sept. 1998 - Sept. 2000, Technical Staff Member, Los Alamos National Laboratory.

Bibliography

Papers Published During Total Funding Period

[1] J. B. Rundle, W. Klein and S. Gross, " Dynamics of a Traveling Density Wave Model for Earthquakes" *Phys. Rev. Lett.* **76**, 4285 (1996)

[2] J. B. Rundle, S. Gross, W. Klein, C. Ferguson and D. L. Turcotte, "The Statistical Mechanics of Earthquakes" *Tectono Physics* **277**, 147 (1997)

[3] J. B. Rundle, W. Klein, S. Gross and D. L. Turcotte, "Reply to "Non-Boltzmann Fluctuations in Numerical Simulations of Nonequilibrium Lattice Threshold Systems", *Phys. Rev. Lett* **78**, 3798 (1997)

[4] W. Klein, J. B. Rundle and C. D. Ferguson, "Critical Phenomena and Metastability in Models of Earthquake Faults" *Phys. Rev. Lett.* **78**, 3793 (1997)

[5] J. B. Rundle, W. Klein, S. Gross and C. D. Ferguson "Stochastic and Traveling Density Wave Models for Earthquakes and Sliding Friction: Physical Realizations of Driven Threshold Systems" *Phys. Rev. E* **56**, 293 (1997)

[6] N. Gross, W. Klein and K. Ludwig, "Clusters and Failure of the Cahn-Hilliard-Cook Theory" Phys. Rev. E **56**, 5160-5173 (1997)

[7] G. Johnson, A. Mel'cuk, H. Gould, W. Klein and R. Mountain "Molecular Dynamics Study of Long-Lived Structures in a Fragile Glass Forming Liquid" *Phys. Rev. E*, **57** 5707 (1998)

[8] J. B. Rundle, E. Preston, S. McGinnis and W. Klein, "Why Earthquakes Stop: Growth and Arrest in Stochastic Fields" *Phys. Rev. Lett.*, **80**, 5698 (1998)

[9] C. F. Ferguson, W. Klein and J. R. Rundle "Spinodals, Scaling and Ergodicity in a Model of a Threshold Model with Long-Range Stress Transfer" *Phys. Rev. E* **60**, 1359 (1999)

[10] J. R. Rundle, W. Klein and S. Gross "Physical Basis for Complex Patterns in Complex Earthquake Populations: Models Predictions and Tests" *Journal of Pure and Applied Geophysics* **155**, 575 (1999)

[11] J. B. Rundle, W. Klein, K. Tiampo and S. Gross, "Linear Pattern Dynamics in Nonlinear Threshold Systems" *Phys. Rev. E* **61**, 2418 (2000)

[12] W. Klein, H. Gould, J. Tobochnik, F. J. Alexander, M. Anghel and G. Johnson "Clusters and Fluctuations at Mean-Field Critical Points and Spinodals" *Phys. Rev. Lett.* **85**, 1270 (2000)

[13] J. B. Rundle, W. Klein, D. L. Turcotte and B. D. Malmud, "Precursory Seismic Activation and Critical-Point Phenomena" *Pure and Applied Geophysics* **157**, 2165 (2000)

[14] E. Preston, J. Sa Martins, J. B. Rundle, M. Anghel and W. Klein "Models of Earthquake Faults with Long Range Stress Transfer" *Computers in Science and Engineering* **2**, 34 (2000)

[15] W. Klein, "The Instability of Alexander-McTague Crystals and its Implication for Nucleation" *Phys. Rev. E*, **64**, 056110 (2001)

[16] P. B. Rundle, J. B. Rundle, K. F. Tiampo, J. de sa Martins, S. McGinnis and W. Klein, "Non-Linear Network Dynamics on Earthquake Fault Systems" *Phys. Rev. Lett.* **87** 148501(article number) (2001)

[17] W. Klein, T. Lookman, A. Saxena and D. Hatch, "Nucleation in Systems with Elastic Forces" *Phys. Rev. Lett.* **88**, 085701 (2002)

[18] J. B. Rundle, P. B. Rundle, W. Klein, J. de sa Martins, K. F. Tiampo, A. Donnellan and L. H. Kellog, " GEM Plate Boundary Simulations for the Plate Boundary Observatory: A Program for Understanding the Physics of Earthquakes on Complex Fault Networks via Observations, Theory and Numerical Simulation" *Pure and Applied Geophysics* **159**, 2357-2381 (2002)

[19] J. sa Martins, J. B. Rundle, M. Anghel and W. Klein, "Precursory Dynamics in Threshold Systems" *Physical Review E* Rapid Communications **65**, 056117 (2002)

[20] K. F. Tiampo, J. B. Rundle, S. A. McGinnis and W. Klein, "Pattern Dynamics and Forecast Methods in Seismically Active Regions" *Pure and Applied Geophysics* **159**, 2429-2467 (2002)

[21] K. F. Tiampo, J. B. Rundle, S. McGinnis, S. J. Gross, and W. Klein, "Meanfield Threshold Systems and Earthqakes; An Application to Earthquake Fault Systems" *Euro Physics Letters* **60**, 481-487 (2002)

[22] K. F. Tiampo, J. B. Rundle, S. McGinnis, S. J. Gross and W. Klein, "Eigenpatterns in Southern California Seismicity" *J. Geophys. Res.* 10.129 (2002)

[23] J. B. Rundle, K. F. Tiampo, W. Klein, M. Anghel and J. de sa Martins, "Self-Organization in Leaky Threshold Systems; The Influence of Near-Meanfield Dynamics and its Implications for Earthquakes, Neurobiology and Forecasting" *Proceedings of the National Academy of Sciences* **99**, 2514-2521 (2002)

[24] J. B. Rundle, D. L. Turcotte, R. Shcherbakov, W. Klein, and C. Sammis, "Statistical Physics Approach to Understanding the Multi-scale Dynamics of Earthquake Fault Systems" Reviews of Geophysics **41**, 1019 (2003)

[25] K. F. Tiampo, J. B. Rundle, W. Klein, J. sa Martins and C. D. Ferguson, "Ergodic Dynamics in a Natural Threshold System" Phys. Rev. Letters, **91**, 238501 (2003)

[26] N. Gulbahce, H. Gould and W. Klein, "Zeros of the Partition Function and Pseudospinodals in Long-Range Ising Models" *Phys. Rev. E* **69**, 036119 (2004)

[27] F. J. Cherne, M. I. Baskes, R. B. Schwarz, S. G. Srinivasan, and W. Klein "Non-classical Nucleation in Supercooled Nickel" Modelling and Simulation in Material Science and Engineering **12** 1063-1068 (2004)

[28] K. F.Tiampo, J. B. Rundle, W. Klein, Y. Ben Zion, and S. McGinnis, Pure and Applied Geophysics, "Using Eigen-Patterns to Constrain Seasonal Signals in Southern California" **161**, 1991-2003 (2004)

[29] K. F. Tiampo, J. B. Rundle, J.S.S. Martins, W. Klein and S. McGinnis,"Methods for Evaluation of Geodetic Data and Seismicity Developed with Numerical Simulations: Review and Applications" Pure and Applied Geophysics, **161**, 1489-1507 (2004)

[30] C. Gagne, W. Klein, T. Lookman, A. Saxena and H. Gould, "Simulation of Nucleation in Systems with Elastic Interactions" Phys. Rev. Lett. **95**, 095701 (2005)

[31] J. Xia, H. Gould, W. Klein and J. Rundle, "Simulation of the Burridge Knopoff Model of Earthquake Faults with Variable Stress Transfer" Phys. Rev. Lett. **95**, 248501 (2005)

[32] J. B. Rundle, P. B. Rundle, A. Donnellan, D. L. Turcotte, R. Shcherbakov, P. Li, B. D. Malamud, L. B. Grant, G. C. Fox, D. McLeod, G. Yakovlev, J. Parker, W. Klein and K. F. Tiampo "A Simulation-Based Approach to Forecasting the Next Great San Francisco Earthquake" Proceedings of the National Academy of Science, **102**, 15363-15367(2005)

[33] J. R. Holliday, J. B. Rundle, K. F. Tiampo, W. Klein and A. Donnellan "Modification of the Pattern Infomatics Method for Forecasting Large Earthquake Events Using Complex Eigenfactors, Tectonophysics, **413**, 87-91(2006),

[34] J. B. Rundle, P. B. Rundle, A. Donnellan, P. Li, W. Klein, G. Morein, D. L. Turcotte and L. Grant, "Stress Transfer in Earthquakes, Hazard Estimation and Ensemble Forecasting: Inferences from Numerical Simulations" Tectonophysics **413**, 109 - 125- (2006)

[35] K. F. Tiampo, J. B. Rundle and W. Klein, Premonitory Seismicity Changes Prior to the Parkfield and Coalinga Earthquakes in Southern California" Tectonophysics **413**, 77-86 (2006)

[36] J. R. Holliday, J. B. Rundle, D. L. Turcotte, W. Klein and K. F. Tiampo, "Space Time Clustering and Correlations of Major Earthquakes" Phys. Rev. Lett. **97**, 238501 (2006) (cond. mat. 0605008)

[37] K. F. Tiampo, J. B. Rundle, W. Klein and J. R. Holliday "Forecasting Rupture Dimension using the Pattern Informatics Technique" Tectonophysics, **424**, 367-376 (2006)

[38] K. F. Tiampo, J. B. Rundle, and W. Klein, "Stress Shadows Determined from a Phase Dynamical Measure of Historic Seismicity" PAGEOPH **10.107**/s00024-006-0134-y(2006)

[39] J. R. Holliday, J. B. Rundle, K. F. Tiampo, W. Klein and A. Donnellan, "Systematic Procedural and Sensitivity Analysis of the Pattern Informatics Method for Forecasting Large (M¿5) Earthquake Events in Southern California" Pure and Applied Geophysics, **163**, 2433-2454 (2006)

[40] J. B. Rundle, D. L. Turcotte, P. B. Rundle, R. Shcherbakov, G. Yakovlev, A. Donnelian and W. Klein, "Pattern Dynamics, Pattern Hierarchies and Forecasting in Complex Multi-Scale Earth Systems" Hydrology and Earth Systems, **10**, 789 - 796 (2006)

[41] A. O. Schweiger, K. Barros and W. Klein, "Transient Nucleation near the Mean-Field Spinodal" Phys. Rev. E, **75**, 031102 (2007)

[42] W. Klein, H. Gould, N. Gulbahce, J. B. Rundle and K. F. Tiampo, "The Structure of Fluctuations near Mean-Field Critical Points and Spinodals and its Implication for Physical Processes" Phys. Rev. E **75**, 031114 (2007) cond. mat. 0607066

[43] J. B. Rundle, K. F. Tiampo and W. Klein "Pattern Infomatics and Cellular Seismology: A Comparison of Methods" EOS **88** Number 24 (2007)

[44] K.F. Tiampo, J. B. Rundle, W. Klein, J. R. Holliday, J. S. Sa Martins, and C. D. Ferguson, "Ergodicity in Natural Earthquake Networks" Phys. Rev. E **75**, 066107 (2007) cond.-mat. 0604053

[45] H. Wang, H. Gould and W. Klein, "Homogeneous and Heterogeneous Nucleation of Lennard-Jones Liquids" Phys. Rev. E **76** 031604 (2007) con-mat 0706.0328

[46] H. Wang, K. Barros, H. Gould and W. Klein, "Approaching Metastable Equilibrium"' Phys. Rev. E **76**, 041116 (2007) con-mat 0704.0938

[47] J. Xia, H. Gould, W. Klein and J. B. Rundle "Simulation of the Burridge-Knopoff Model of Earthquakes with Variable Range Stress transfer" Phys. Rev. E, 031132 (2008) con-mat 0601679

[48] R. Dominguez, K. Barros and W. Klein "Early Time Kinetics of Systems with Spatial Symmetry Breaking" Phys. Rev. E **79**, 041121 (2009)

[49] K. Barros, R. Dominguez and W. Klein, "Beyond Cahn-Hilliard-Cook: Early Time Behavior of Symmetry Breaking Phase Transition Kinetics"" Phys. Rev. E. **79**, 042104 (2009) con-mat 0810.3949

[50] W. Klein, J. Xia, C. D. Ferguson, H. Gould, K. F. Tiampo and J. B. Rundle, "Models of Earthquake Faults: Ergodicity and Forecasting" International Journal of Modern Physics B, **23**, 5553-5564 (2009)

[51] C. Serino, W. Klein and J. B. Rundle, "A Cellular Automaton Model of Damage" Physical Review E **81**, 016105 (2010)

[52] K. F. Tiampo, W. Klein, H. C. Li, A. Mignan, Y. Toya, S. Z. L. Kohen-Kadosh, J. B. Rundle and C. C. Chen, "Ergodicity and Earthquake Catalogs: Forecast Testing and Resulting Implications" Pure and Applied Geophysics **167**, 763-782 (2010)

[53] N. F. Cho, K. F. Tiampo, S. McKinnon, J. Vallejos, W. Klein and R. Dominguez, "A Simple Metric to Quantify Seismicity" Nonlinear Processes in Geophysics **17**, 293-302 (2010)

[54] Y. Toya, K. F. Tiampo, J. B. Rundle, C. C. Chen, H. C. Li and W. Klein,"Pattern Informatics Approach to Earthquake Forecasting in 3D" Concurrency and Computation-Practice and Experience **22**, 1569-1592 (2010)

[55] G. Yakolev, J. Gran, J. Holliday, J. B. Rundle, D. Turcotte and W. Klein, "A Damage Mechanics Model for Fracture Nucleation and Propagation " Theoretical and Applied Fracture Mechanics **53**,180-184(2010)

[56] J. D. Gran, J. B. Rundle, D. L. Turcotte, J. R. Holliday and W. Klein, "A damage Model based on Failure Threshold Weakening" Physica A **390**, 1269-1278 (2011)

[57] C. Serino, K. F. Tiampo and W. Klein, " A New Approach to Gutenburg-Richter Scaling" Physical Review Letters **106**, 108501 (2011)

[58] John B. Rundle, James R. Holliday,Mark Yoder,Michael K. Sachs, Andrea Donnellan, Donald L. Turcotte, Kristy F. Tiampo, William Klein and Louise H. Kellogg: "Earthquake precursors: activation of quiescence?" Geophys J. Int. (2011) 187, 225-236.

[59] J. B. Rundle, J. R. Holliday, W. R. Graves, D. L. Turcotte, K. F. Tiampo and W. Klein, "Probabilities for Large Events in Driven Threshold Systems" Physical Review E **86**, 021106 (2012)

[60] R. Dominguez, K. F. Tiampo, C.Serino and W. Klein, "Scaling of Earthquake Models with Inhomogeneous Stress Dissipation" Physical Review E**87**, 022809 (2013)

[61] O.Peters and W. Klein, "Ergodicity Breaking in Geometric Brownian Motion" Physical Review Letters, **110**, 100603 (2013)

[62] A. Santos and W. Klein, "Kinetics of the Melting Transition in DNA" Journal of Physics A: Math. Theor. **46**, 415002 (2013)[1]

[63] K. Barros and W. Klein, "Liquid to Solid Nucleation via Onion Structure Droplets" Journal of Chemical Physics **139**, 174505 (2013)[3]

[64] J. Kazemian, R. Dominguez, K. Tiampo and W. Klein, "Spatial Heterogeniety in Earthquake Fault-Like Systems", Pure and Applied Geophysics DOI 10.1007/s00024-014-0843-6, (2014)

[65] L. Colonna-Romano, H. Gould and W. Klein, "Anomalous Mean-Field Behavior of the Fully Connected Ising Model", Physical Review E, **90**, 042111 (2014)

[66] J. Kazemian, K. F. Tiampo, W. Klein and R. Dominguez, "Foreshocks and Aftershocks in Simple Earthquake Models" Physical Review Letters **114**, 088501(2015)

[67] K. Liu, N. Lubbers, W. Klein, J. Tobochnik, B. Boghosian and H. Gould, "The Effect of Growth on Equality in Models of the Economy" Physical Review Letters (submitted for publication)

[68 K. Liu, W. Klein and C. A. Serino, "The Effect of Disorder on Metastable States" Physical Review Letters (submitted for publication)

[69] N. Gulbahce, W. Klein and H. Gould, "Heterogeniety in Classical and Non-Classical Nucleation" Phys. Rev. Lett. (submitted for publication)con- mat. 0407304

Review Articles and Conference Proceedings

[1] C. D. Ferguson, W. Klein and J. B. Rundle, "Long Range Earthquake Fault Models" Computers in Physics, **12**, 34 (1998)

[2] J. R. Rundle and W. Klein, "Coarse Grained Models and Simulations for Nucleation, Growth and Arrest of Earthquakes" to be published in Earthquake Thermodynamics, R. Teisseyre and E. Majewski (Cambridge University Press)

3] W. Klein, M. Anghel, C. D. Ferguson, J. B. Rundle and J. S. Sa' Martins "Statistical Analysis of a Model for Earthquake Faults with Long Range Stress Transfer" in *GeoComplexity and the Physics of Earthquakes* J. B. Rundle, D. Turcotte and W. Klein eds. (American Geophysical Union, Washington D.C. 2000)

[4] J. B. Rundle, W. Klein, K. F. Tiampo and S. J. Gross,"Dynamics of Seismicity Patterns in Systems of Earthquake Faults" in *GeoComplexity and the Physics of Earthquakes* J. B. Rundle, D. Turcotte and W. Klein eds. (American Geophysical Union, Washington D. C.)

[5] K. F. Tiampo, J. B. Rundle, S. McGinnis, S. J. Gross and W. Klein "Observation of Systematic Variations in Non-Local Seismicity Patterns from Southern California" in *GeoComplexity and the Physics of Earthquakes* J. B. Rundle, D. Turcotte and W. Klein eds. (American Geophysical Union, Washington D. C. 2000)

[6] J. B. Rundle, W. Klein, D. Turcotte, B. D. Malamud, "Precursory Seismic Activation and Critical Point Phenomena" First Workshop of APEC Cooperation for Earthquake Simulation, Brisbane Australia, (2000)

[7] K. F. Tiampo, J. B. Rundle, S. McGinnis, and W. Klein, "Pattern Dynamics and Forecast Methods in Seismically Active Regions" Proceedings of the Second ACES Workshop,

Tokyo, Japan pp 471-476 eds. M. Matsu'ura, K. Nakajima, and P. Mora, University of Queensland Press, Brisbane AU (2001)

[8] J. B. Rundle, A. Donnellan, G. Fox, W. Klein, P. Rundle and K. Tiampo, "General Earthquake Models: Progress and Prospects" Proceedings 2nd ACES Workshop, ed M. Matsu'ura, K. Nakajima and P. Mora, University of Queensland Press, Brisbane AU (2001)

[9] K. F. Tiampo, J. B. Rundle, S. McGinnis, S. J. Gross and W. Klein, "Systematic Variations in Non-local Seismicity Patterns in Southern California" in *Seismotectonics in Convergent Plate Boundaries* eds. Y. Fujinawa and A. Toshida, Terra Scientific Publishing, Tokyo, Japan (2002)

[10] "J. B. Rundle, W. Klein, K. Tiampo, A. Donnellan and G. Fox, "Strategies for the Detection and Analysis of Space - Time Patterns of Earthquakes on Complex Fault Systems" *Computational Science* **2659** 827-836 (2003)

[11] W. Klein, J. Xia, C. D. Ferguson, H. Gould, K. F. Tiampo and J. B. Rundle, "Models of Earthquake Faults:Ergodicity and Forecasting" Journal of Modern Physics B, **23**, 5553-5569 (2009)

[12] R. Dominguez, K. F. Tiampo, C. A. Serino and W. Klein, "Characterizing Large Events and Scaling in Earthquake Models with Inhomogeneous Damage," Extreme Events and Natural Hazards: The Complexity Perspective, Geophysical Monograph Series, v. 196, Sharma, A. S., Bunde, A., Dimri, V.P. and Baker, D.N., Eds. (AGU, Washington, D. C., 371 pp) doi:10.1029/GM196, 2012.

[13] W. Klein, H. Gould, K. F. Tiampo, J. B. Silva, T. Gu, J. Kazemian, C. Serino, and J. B. Rundle, "Statistical Mechanics Perspective on Earthquakes" Need book title

INVITED TALKS

Colloquium, Leheigh University, March 1996
Department Lecturer, Earth Sciences Department, MIT, March 1996
Seminar, Harvard University, April 1996
Invited Talk, Mathematical Geophysics Meeting, Santa Fe, NM, June 1996
Colloquium, CNLS, Los Alamos, June 1996
Colloquium, Boston College, November 1996
Seminar, Chemistry Department, Boston University, February 1997
Invited Speaker, Special Topics in Statistical Mechanics, NIST April, 1997
Invited Speaker, Workshop on Topics in Nucleation, Boulder Colorado, June 1997
Invited Speaker, DOE workshop on "Nonlinearity in the Earth Sciences" Albuquerque, New Mexico, August 1997
Seminar, ITP Santa Barbara, CA Sept. 1997
Invited Speaker, Workshop on "Jamming and Rheology" ITP, Santa Barbara, October, 1997
Speaker, Session on the Physics of Earthquakes, American Geophysical Union, San Francisco, December 1997
Seminar, Geology Department, University of Southern California, March 1998
Invited speaker, Rutgers Meeting, May 1998
Invited speaker, Southern California Earthquake Center Workshop, June 1998

Colloquium, Clark University, September 1998
Colloquium, Florida State University, Tallahasse FL, November 1998
Seminar, LANL, Los Alamos, NM, January 1999
Invited Speaker APS Meeting, Atlanta, GA March 1999
Invited Speaker SIAM Meeting, San Antonio, TX March 1999
Invited Speaker to meeting on General Earthquake Models, Syracuse University, June 1999
Invited Speaker, Unifying Concepts in Glass Physics, Trieste Italy September 1999
Invited Speaker, GEM/AGU Meeting, San Francisco, December, 1999
Seminar, Sandia National Laboratory, Alburquerque, New Mexico, February 2000
Colloquium, CNLS-Los Alamos National Laboratory, February 2000
Invited Speaker, Complexity in the Earth Sciences, SCEC Meeting Maui, March, 2000
Invited Speaker, International Workshop on Scaling and Disordered Systems, Paris, April 2000
Invited Speaker, Rutgers Meeting, Rutgers University, May 2000
Invited Speaker, ACES International Workshop, Tokyo, Oct. 2000
Invited Speaker, Rutgers Meeting, Rutgers University, May 2001
Invited Speaker, American Geophysical Union Meeting, Boston, May 2001
Invited Speaker, SIAM Meeting, Boulder CO, June 2001
Colloquium, University of Queensland, Brisbane Australia, Aug. 2001
Seminar, University of Queensland, Brisbane Australia, Aug. 2001
Lecture Series on "Fundemantals of the Kinetics of Phase Transitions" Los Alamos National Laboratory February - March 2003
Colloquium, University of California at Davis, April 2003
Seminar, Seminar, Center for Computational Science and Engineering, University of Calofornia at Davis, August, 2003
Seminar, Los Alamos National Laboratory, November 2003
Invited Speaker, American Geophysical Union Meeting, December 2003
Invited Speaker, DELFS Meeting, Santa Fe New Mexico, March 2004
Speaker at Central High School in Philadelphia "What is it Like to be a Physicist" April 2004
Seminar, University of California at Davis, June 2004
Invited Speaker, Fourth ACES Meeting, Beijing, China, July 2004
Seminar, Boston University Quantum Condensed Matter Theory Group, October 2004
Seminar, Condensed Matter, U. C. Davis November 2004
Invited Speaker, American Geophysical Union, San Francisco December 2004 (Talk 1)
Invited Speaker, American Geophysical Union, San Francisco, December 2004 (Talk 2)
Seminar, Lujan Center LANCE, Los Alamos National Laboratory, March 2005
Invited Speaker, Next Generation Neutron Source Workshop, San Diego CA, June 2005
Colloquium, U. Mass. Lowell, December 2005
Seminar, Los Alamos National Laboratory, December 2005
Seminar, Center for Computational Science, Boston University, January 2006
Invited Speaker, 5th ACES International Workshop, Maui, Hawaii, April 2006
Invited Speaker, Meeting for M. Zuckermann's 70th Birthday, Vancouver, Canada, August 2006

Colloquium, University of Missouri at Columbia, October 2006
Colloquium, University of California at Riverside, October 2006
Colloquium, University of Western Ontario, Canada, November 2006
Invited Speaker, Application of Statistical Mechanics to the Earth Sciences, Erice, Italy, May 2008
Invited Speaker, 6th ACES International Workshop, Palm Cove, Australia, May 2008
Seminar, Center for Non-Linear Studies, Los Alamos National Laboratory, August 2008
Colloquium, University of Missouri at Rolla, September 2008
Invited Speaker, Novel Phase Transition Behavior in Systems with Long Range Interactions, Tokyo, Japan, October 2008
Invited Speaker, American Geophysical Union meeting, Toronto, Canada, May 2009
Colloquium, Los Alamos National Laboratory, August 2009
Invited Speaker, AOGS Meeting Singapore, August 2009
Colloquium, Virginia Tech, October 2009
Colloquium, Boston University Material Science, November 2009
Invited Speaker, Geophysics and Subsurface Fluid Flow, Gaithersburg Maryland March 2010
Invited Speaker, Simulation Models for Climate Modeling, IPAM, UCLA May 2010
Invited Speaker, Problems and Perspectives in Charged Particle Systems, UC Berkeley 2010
Seminar, Boston College, June 2010
Invited Speaker, Non-Linear Geophysics, AGU December 2010
Seminar, Boston University Earth Science Department, March 2011
Seminar, Complexity Center, Imperial College London, England, March 2011
Invited Speaker, SPS New England Regional Meeting, April 2011
Invited Speaker, Workshop Advances in Simulations of Multi-hazards, Maui, May 2011
Invited Speaker, Statsei7, Santorini, Greece, May 2011
Invited Speaker, Perspectives and Challenges for Statistical Physics in the Next Decade, Natal Brazil, November 2011.
Invited Speaker, Frontiers in Statistical Physics and Complex Systems, Catania, Sicily, June 2012
Invited Speaker, Assimilation of Remotely Sensed Observations to Advance Multihazards Simulation Maui, Hawaii, October, 2012
Seminar for Undergraduates(PY 482), Boston University, March 2013
Colloquium, CNLS Los Alamos National Laboratory, June 2013
Invited Speaker, Workshop - Energy Landscapes: Structure, Dynamics and Exploration Algorithms. Telluride Colorado, 2013
Seminar for graduate students in course in Econophysics, Boston University, Boston, May, 2014
Invited Speaker, "Novel Applications of Statistical Mechanics" Boston, May 2014
Seminar, University of Massachusetts Amherst, October, 2014
Invited Speaker, "Avalanches in Functional Materials and Geophysics" Cambridge England, December 2014

Delivered Graduation Address, Temple University College of Science and Technology, December 2014
Seminar for graduate students in course in Econophysics, Boston University, Boston, May, 2016
Invited Speaker, "Sixty-Fifth Birthday Celebration for John Machta", Santa Fe New Mexico, June 2016