Development of Visualization Techniques to Integrate Simulations with Data, and Computational Algorithms for Networked Parallel Computing Environments

for the

Computational Simulation of Earthquake Physics in Southern California

An Investigation in the
General Earthquake Model (GEM) Project

A Proposal to the US Natonal Science Foundation

by

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PROJECT SUMMARY

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A.Proposal Abstract:

This proposal to the National Science Foundation is focused on the development of 1) visualization techniques to integrate geometrically realistic simulations of multiple earthquake fault systems with field and laboratory data in the General Earthquake Model (GEM) project; and 2) computational algorithms that can be used in networked parallel computing environments for the solution of computationally hard nonlinear problems. The GEM project is a multi-institutional, multi-investigator project whose purpose is to provide a focus for developing a greatly enhanced understanding of why and how earthquakes occur in seismically active regions. We are developing large scale, massively parallel numerical simulations of large numbers of nonlinear interacting earthquake fault systems in seismically active areas, focusing at first on Southern California, and making extensive use of Information Wide Area Year technology. We will build upon a large body of recent research that has led to a capability to simulate the dynamics of single faults, as well as of small numbers of interacting faults in elastic and viscoelastic earth models. In addition to these scientific challenges, major computational challenges must also be met. These include the development of computational algorithms to efficiently carry out massively parallel simulations for these nonlinear fault systems in a networked supercomputing environment, and to develop the visualization tools that will allow simulation results to be integrated with geophysical field data. The techniques we develop will also be applicable to other hard nonlinear problems, such as neural computation. A similar program of numerical simulation to understand weather and climate using General Circulation Models (GCM's), and to make near-term weather forecasts, was begun in the 1950's by Von Neumann and Charney, and has permanently changed the manner in which atmospheric science is conducted. Our broad goals are to construct 1) a General Earthquake Model (GEM) methodology to understand the physics of earthquakes, somewhat similar to the GCM's; and 2) a Numerical Earthquake Forecast (NEF) technology, that would allow field observations of current conditions on fault sytems to be projected forward in time for estimating probable times and locations of future events. These simulations will produce temporal and spatial patterns of earthquakes, surface deformation and gravity change, seismicity, stress, as well as, in principle, other variables, including pore fluid and thermal changes, for comparison to field and laboratory data.

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C PROJECT DESCRIPTION

C.1One Page Executive Summary for Reviewers:
(A) GEM Approach (generic statements) and (B) This NSF Proposal

Objective (A): For the fault systems in southern California, build large scale numerical simulations for the physics of earthquakes, with the purpose of:
1) Developing methods to systematically compare field and laboratory data to simulations to evaluate the relative importance of the various physical processes that occur on spatially extended earthquake fault systems over a range of spatial and temporal scales.
2) Developing the numerical and computational algorithms and environment(s) needed to carry out large scale simulations of nonlinear physical processes over a geographically widely distributed, heterogeneous computing network.
3) Developing a testbed for earthquake "forecasting" & "prediction" methodologies.

Method (A): Numerical simulation techniques developed by, among others, Stuart (1986), Rundle (1988) and Ward and Goes (1993) will be used as a starting point to model the physics of earthquake fault systems in southern California. It is now known that these types of models display chaos and intermittancy, resulting from the nonlinearity of the sliding physics, and the coupling across spatial scales. Thus it will be of critical importance to include as many temporal and spatial scales in the simulations as possible.

Scientific and Computational Foci (B): Understanding the nonlinear physics of earthquakes is a necessary prelude to understanding the degree to which earthquakes may be forecast. To answer this question, it will be necessary to develop the capability to carry out large scale simulations of complex, multiple, interacting fault systems. **Thus our research proposed to NSF will focus on:**
1) Developing the computational algorithms necessary to solve computationally difficult nonlinear problems involving ("discontinuous") thresholds and nucleation events in a networked parallel (super) computing environment.
2) Developing the visualization techniques to allow researchers to rapidly integrate simulation data with field and laboratory data (visually and quantitatively). This problem is becoming increasingly acute with the exponential increase in seismic, as well as space-based deformation data.

Significance of Anticipated Results (A): As implemented in the southern California simulations, the GEM approach will allow the physics of large networks of earthquake faults to be analyzed within a general theoretical framework for the first time, in much the same way that the General Circulation Models have changed the way atmospheric science is carried out. At the present time, modeling and observational activities are taking place largely independently of one another. With the GEM approach, observations and theory would take place within a positive feedback loop, where improvements in observations would suggest new theoretical avenues, and advances in models and simulations would encourage specific new observations to test the hypotheses proposed. Finally, we expect that the computational techniques developed by the project will have important applications in many other large, computationally hard problems, such as understanding the physics of learning and cognition in large neural networks.

Investigator Team and Project Organization (A): We have assembled a group of internationally recognized experts in the three areas of 1) observational and theoretical earth science 2) statistical mechanics and complex systems and 3) computer and computational science. Rundle will serve as Principal Investigator. The Investigators will participate in periodic workshops at which 1) results will dicussed; and 2) specific research avenues will be formulated on a regular and timely basis.

C.2General Introduction to the GEM Approach (All GEM Proposals)

Rationale for Simulations. Understanding the physics of earthquakes is complicated by the fact that the large events of greatest interest recurr at a given location along an active fault only on time scales of the order of hundreds of years, over spatial scales of as much as 1000 km (e.g., Richter, 1958; Kanamori, 1983; Pacheco et al., 1992). To acquire an adequate data base of similar large earthquakes therefore requires the use of historical records, which are known to possess considerable uncertainty. Moreover, instrumental coverage of even relatively recent events is often inconsistent, and network coverage and detection levels can change with time (Haberman, 1982). Understanding the details of the rupture process is further complicated by the spatial heterogenity of elastic properties, the vagaries of near field instrumental coverage, and other factors (see for example Heaton, 1990; Kanamori, 1993). We are therefore motivated to use methods that provide insight into details of the rupture process which are complementary to the usual observational techniques (e.g., Kanamori, 1993).

Given these constraints, numerical simulation is a practical means of obtaining experimental information about the behavior of such a nonlinear system over many cycles of activity (Binder, 1979; Binder, 1984; Mouritsen, 1984; Ma, 1985; Yeomans, 1992). If adequate theoretical understanding cannot be developed for the simulations, it is unlikely that the dynamics of real faults can be similarly understood. Numerical simulation has been used extensively to study earthquakes in the recent past (Rundle, 1988, 1989; Rundle & Klein, 1989; Carlson and Langer, 1989; Bak and Tang, 1989; Rundle & Turcotte, 1993; Sahimi et al., 1993). In the case of earthquake faults, complications such as 1) the long time scales involved (comparable to the human lifetime) and 2) the (at present) unpredictable nature of the events, make earthquakes difficult to study systematically in the field. Predictions based on simulations can lead to hypotheses to be tested with specific observational programs or laboratory experiments. In turn, if interesting and unexplained new observations are made, simulations can be carried out with a view towards explaining them.

This General Earthquake Model (GEM) project should be viewed as a "testbed" for HPCC technologies. Over the past decade, an increasing number of research studies have investigated the physics of failure on individual faults (e.g., Rundle and Klein, 1995). The vast majority of this work was done on single computers, either workstations or supercomputers. A level of maturity has now been reached at which the next logical step is to build simulations of systems of faults, and to look at the influences of one upon another in that setting. In order to make this step, simulations on a scale not previously attempted will be necessary, of the order of solving 10^6 to 10^9 simultaneous nonlinear equations. These simulations will demand: 1) significant advances in numerical algorithms in a distributed and shared memory environment; 2) advances in messaging and high speed communication hardware and software for networking supercomputers, both with each other and with other distributed processors; and 3) the development of ideas about how to deal with physical processes on smaller spatial and temporal scales than is practical to include in the simulations.

While the methods to be developed in the proposed work will be generally applicable to all fault systems, the initial modeling focus will be on one of the most well-studied earthquake fault systems in the world, southern California. For that reason, close cooperation and coordination is envisaged with the staff and management of the Southern California Earthquake Center. Coordination will be greatly facilitated since Rundle (PI) is Chair of the Advisory Council of SCEC, Jordan (Co-I) is a member of the Advisory Council, Minster (Co-I) is Vice Chair of the Board of Directors, and Stein (Co-I) is an active member of SCEC.

Construction of Models. As a general principle, we will examine the simplest physical models that can be shown to capture a given observable effect. In complex systems such as earthquake faults, it is often found that a given physical observable may have its origin in a variety of physical processes, some quite unexpected. The first example is the question of whether the Gutenberg-Richter magnitude frequency relation arises from self-organization processes on a single fault with no inherent scale (Model 1: Burridge and Knopoff, 1967; Model 2: Rundle and Jackson, 1977), or from a scale invariant distribution of faults (Rice, 1993). Even for single faults, Models 1 and 2 are very different. The first (BK model) includes inertia, whereas the second, a massless Cellular Automaton (CA) model, does not. For the massive BK models, the dynamics must be obtained by solving a set of coupled nonlinear differential equations. It was shown by Nakanishi (1990) that massless CA's can be constructed that give the same quantitative results as the massive slider block models examined by Carlson and Langer (1989). These results include not only the rupture patterns, but also the scaling statistics. The second example is the decision about whether or not to include seismic radiation. Kanamori and Anderson (1975) estimated that the seismic efficiency η, which measures the fraction of energy in the earthquake lost to seismic radiation, is less than 5%-10%. The absence of inertia does not preclude a time evolution process in the CA, with a separation of loader plate and source time scales, just as in models with inertia and waves. The physical interpretation of the CA time scales is discussed by Gabrielov et al. (1994).

Other decisions revolve around how to include: 1) Interactions between fault segments that might be short range due to screening effects, $1/r^3$ "continuum interactions", or long range of some other variety; 2) Friction arising from any of the variety of models discussed below; 3) Asperities (Lay et al., 1982) and other regions of heterogeneous friction; 4) The influence of unmodeled faults, particularly at small length scales, which might be treated as some kind of "noise" in the model; 5) The effects of pore water, along with the effects associated with variable normal stress on the fault.

C.3 Scientific Framework for the GEM Approach (All GEM Models)

The basic problem to be solved in the GEM project can be simply stated (e.g., Rundle 1988a). Given some network of faults embedded in an earth with a given rheology, subject to loading by distant stresses, the state of slip $\mathbf{s}(\mathbf{x},t)$ on a fault at $(\mathbf{x},t)$ is determined from the equilibrium of stresses according to Newton's Laws. This can be written schematically as:

$$\sigma_{int}[\mathbf{x},t;\ \mathbf{s}(\mathbf{x}',t');\ \mathbf{p}] = \sigma_f(\mathbf{x},t;\ \mathbf{s}(\mathbf{x},t)) \quad (1)$$

where 1) σ_{int} is the interaction stress provided by transmission of stress through the earth's crust due to background tractions **p** applied to the earth's crust, as well as stresses arising from slip on other faults at other sites **x**' at times t'; and 2) σ_f is the cohesive fault frictional (f) stress at the site (**x**,t) due to processes arising from the state of slip **s**(**x**,t). The transmission of stress through the earth's crust involves both dynamic effects arising from the transient propagation of seismic waves, as well as static effects that remain after wave motion has ceased. For the GEM project, it will suffice to assume that, exterior to the fault zones, the earth's crust has a rheology (deformation constitutive relation) that is linear elastic, linear viscoelastic, or linear poroelastic.

There are a few other model techniques that are being used to simulate faults, the primary example being the molecular dynamics simulations of Mora and Place (1994). At the moment, these seem to be primarily useful for simulating dynamics of individual faults, so these will not be considered further.

Friction Models: At the present time, there are six basic friction laws that have been proposed for faults. Our goal in this proposal is to develop computational methods to allow systematic comparison of the predictions of these friction models in the context of models with multiple, interacting fault systems similar to those found in southern California.

1) Cellular Automaton (CA) models: These are the simplest ("freshman physics") models to implement on the computer, and for that reason have been widely used (e.g., Rundle and Jackson, 1977; Nakanishi, 1991; Brown et al., 1991; Rundle and Brown, 1991; Rundle and Klein, 1992). A static failure threshold, or equivalently a coefficient of static friction μ_S is prescribed, along with a residual strength, or equivalently a dynamic coefficient of friction μ_D.

2) Slip Weakening model: This friction law (Rabinowicz, 1965; Stuart, 1988; Li, 1987; Rice, 1993; Stuart and Tullis, 1995) assumes that the frictional stress at a site on the fault $\sigma_f = \sigma_f[\mathbf{s}(\mathbf{x},t)]$ is a functional of the state of slip. The state of slip at a site on a fault in elastic medium, for example, is then obtained by solving the quasistatic equation $\sigma_{int}[\phi(\mathbf{x},t)] = \sigma_f[s(\mathbf{x},t)]$ at every instant of time.

3) Velocity Weakening model: This model (Burridge and Knopoff, 1967; Carlson and Langer, 1989) is based on the observation that frictional strength diminshes as sliding proceeds. In the implementation of this model, a differential equation is written expressing the balance of forces to be solved.

4) Rate and State Dependent Friction Laws: These friction laws are based on certain kinds of laboratory sliding experiments in which two frictional surfaces are slid over each other at varying velocities, without ever experiencing arrest (Dieterich, 1972; 1978; 1981; Ruina, 1983; Rice and Ruina, 1983; Dieterich and Linker, 1992; Rice, 1993). More recent work by Beeler et al. (1994) and Beeler and Tullis (1996) demonstrates that sliding surfaces do experience arrest, and this substantially modifies the friction law and the associated results.

5) Traveling Density Wave Model: This new model (e.g., Rundle et al., 1996; Gross et al., 1996) is based on the same experiments that led to the formulation of the slip weakening model. The equation of motion $\sigma_e[\phi] = \sigma_f[s] = \sigma_f[\phi + Vt]$ indicates that the slip state is located at the intersection of the curve $\sigma_e[\phi]$ and a leftward moving wave $\sigma_f[\phi + Vt]$. This equation is regarded as the Euler-Lagrange equation derived from a Lyapunov functional $U[\phi]$, which in turn leads to a rate kinetic equation. Temporal changes in the friction law

itself, related to wearing of the frictional contact surfaces is then modeled by random changes in the friction parameters, such as the energy of cohesion.
6) Hierarchical Statistical Models: Classes of hierachical, statistical models have been developed recently. Examples of these are the models by Allegre et al. (1982); Smalley et al. (1985); Blanter et al. (1996); Allegre and Le Mouel (1994); Allegre et al. (1996); Heimpel (1996); Newman et al. (1996); and Gross (1996). These are probabilistic models in which hierarchies of blocks or asperity sites are assigned probabilities for failure.

The remaining parts of the framework for the GEM modeling approach is discussed briefly in the following:

Quasistatic Interactions: Because of the linearity property, the fundamental problem is reduced to that of calculating the stress and deformation Green's function for the rheology of interest. For materials that are homogenous in composition within horizontal layers, numerical methods to compute these Green's functions for layered media have been developed (e.g., Okada, 1985, 1992; Rundle, 1982a,b, 1988; Rice and Cleary, 1976; Cleary, 1977; Burridge and Varga, 1979; Maruyama, 1994). The problem of heterogeneous media, especially media with a distribution of cracks too small and numerous to model individually is often solved by using effective medium assumptions or self-consistency assumptions (Hill, 1965; Berryman and Milton, 1985; Ivins, 1995a,b.). While the computational problems present certain challenges, the methods are straightforward because the problems are linear.

Elastic Wave Interactions: Stresses are initially transmitted in the earth by means of elastic waves (e.g., Aki and Richards, 1980; Zheng et al., 1995; Kanamori, 1993; Beroza, 1995; Jordan, 1991; Imhle et al., 1993), and during an earthquake, these will affect the details of the temporal development of sliding during the event. Since the time scales over which earthquakes occur are short relative to relaxation times for viscous and porous effects, the effects of waves need only be calculated in linear elastic, attenuating, dispersive media (Perrin and Rice, 1994; Geubelle and Rice, 1995). However, all of the friction equations have been derived on the basis of experiments that are sensitive only to mean field conditions, implying that only the longest wavelength, or largest spatial scale effects are important. This computational plan is consistent with our philosophical approach to the problem of spatial scales (see below).

Heirarchy of Spatial and Temporal Scales: The presence of heirarchies of spatial and temporal scales is a recurring theme in simulations of this type. It is known, for example, that fault and crack systems within the earth are distributed in a scale invariant (fractal) manner over a wide range of scales. Time intervals between characteristic earthquakes on this fractal system is known to form scale invarient set (Allegre et al., 1982, 1994 1996; Smalley et al., 1985; 1987). We will begin by focusing on the largest scale effects first, working down toward shorter scales as algorithms and numerical techniques improve. Moreover, our practical interest is limited primarily to the largest faults in a region, and to the largest earthquakes that may occur. Therefore, focussing on quasistatic interactions and long wavelenth and long period elastic wave interactions is the most logical approach. We plan to include smaller faults and events as a background "noise" in the simulations.

Renormalization Group Analysis: This topic is closely connected to the previous discussion of spatial and temporal scales. Many of the models that have been proposed (see e.g., the review by Rundle and Klein, 1995); Rundle et al. (1996); Klein et al. (1996); Ma (1976), Newman and Gabrielov (1991); Newman et al. (1994); Newman et al (1996); Stauffer and Aharony (1994); Turcotte (1994); are at some level amenable to analysis by Renormalization Group techniques. At the very least, an RG analysis be used to identify and analyze fixed points and scaling exponents, as well as to identify any applicable universality classes.

C.4Data

The types of data from real fault systems to which we shall compare our simulations include all the same data that characterize natural fault systems (see, e.g., Kanamori, 1993). This includes, for example, 1) earthquake histories obtained from paleoseismic investigations, other geological data and historical records; 2) fault creep data obtained from creepmeters and strain meters; 3) the temporal development of slip on faults as determined by local, regional, and teleseismic data, including strong motion instruments; 4) spatial and temporal seismicity patterns, together with scaling statistics such as Gutenberg-Richter distributions, Omori laws, and foreshock and aftershock statistics; 5) surface deformation data obtained from historical geodetic techniques, land-based methods such as multiwavelength trilateration, and newer space-based methods such as Global Positioning System technology and Synthetic Aperature Radar Interferometry; 6) in situ data such as stress and dilatometer measurements, pore fluid pressure, and radon emission rates; and 7) earthquake source mechanism compilations.

A detailed example of the approach described above, comparing simulations with real data can be found in Rundle (1988). That simulation of the San Andreas fault system used 80 fault segments embedded in an elastic lithosphere overlying a viscoelastic half space. The simulations clearly show that field data can be simulated to as realistic an extent as is desired for comparison with natural, observed data.

Examples of other kinds of important data include the following.

1. Evidence for Long Distance Correlations: In the June 28, 1992 Landers event (Sieh et al., 1993), observed effects (Hill et al., 1993) indicated that microearthquake activity in geothermal areas as remote as 1000 km epicentral distance (Cascades, Yellowstone) were triggered by the sudden onset of stress increments associated with the Landers event. These data may imply very long correlation lengths for fault systems, of the order of a thousand km or more. Along with other data

2. Space-Time Clustering vs Periodic Characteristic Events : The missing Parkfield, California, M ~ 6 earthquake, which was originally forecast to occur by January, 1993 (Bakun and Lindh, 1984), has cast doubt on the hypothesis that characteristic earthquakes are perodic in time. Retrospective studies have concluded that the pattern of occurrence of the the historic Parkfield events is consistent with considerable variation in event interoccurrence time (Savage, 1991; 1993). This theme was echoed in work on the validity of the

seismic gap hypothesis by Kagan and Jackson (1992), who concluded that the dominating effect is the tendency of earthquakes to cluster in time. Space-time clustering of events is an important signature of a nonlinear complex system (Stauffer and Aharony, 1994; Ma, 1985). The tendency for earthquakes to cluster in time is supported also by paleoseismic observations of Grant and Sieh (1994).

3. Rupture Mode, Kostrov Slip, Heaton Pulse, Slow Earthquakes: The Kostrov distribution arises when no healing takes place until progression of the rupture front stops. By contrast, the "Heaton pulse" model (Heaton, 1990) allows healing just behind the rupture front, and in fact, there is no a priori reason to exclude other more general modes of rupture as well (Rundle and Klein, 1994). Evidence for rupture pulses and non uniform healing behind rupture fronts is now accumulating (Wald et al., 1991; Beroza, 1991; Mendoza et al., 1994). Observations indicate that "slow" earthquakes precursory to mainshock events may be an important component of the rupture process (Kanamori and Cipar, 1974; Jordan, 1991; Ihmle et al., 1993; Kanamori and Hauksson, 1993; Kanamori and Kikuchi, 1993; Kikuchi et al., 1993; Wallace et al., 1991).

4. Fault Interactions, Self-Organization, and Scaling: Recent observational work continues to confirm the importance of fault interactions (Bilham and Bodin, 1992; Hill et al., 1993; Sanders, 1993), which also exist between patches on the same fault. These interactions cause slip on the fault to self-organize, so that slip occurs in earthquakes obeying the Gutenberg-Richter relation, and not as random events (the existence of power law behavior is incompatible with truly random dynamics). Other work indicates that the existence of scaling implies that small earthquakes are as important as large events in redistributing stress (Hanks, 1992).

C.5Computational & Numerical Challenges (All GEM Proposals)

C.5.1 Introduction

We envision the GEM system as an efficient problem-solving environment in which geophysicists and earthquake modelers can rapidly test new theories by quickly developing and experimenting with specific models. The GEM system must provide a flexible modeling environment which incorporates: (1) multiple representations and tools for the construction of fault
geometries, (2) powerful parallel and distributed algorithms for simulating earthquake physics, (3) simulation distribution and management services, (4) comprehensive and flexible visualization tools, (5) extensive data management facilities, and (6) WWW Internet access. The work proposed here will focus on the development of (1), (3) and (6). Funding for (2), (4), (5) will be sought in a complementary proposal to the National Science Foundation.

The design and implementation of a large software system is a complex task and the difficulty of our task is exacerbated by the additional requirement that GEM provide national/international access through the World Wide Web (WWW). Developing a good initial design which can evolve in a flexible manner is of paramount importance. Thus, it is clear that we will have to develop an object-oriented design in which components can be updated in a transparent fashion. In the last few years we have seen a significant change in the kinds of tools available for software design and development for workstations, high performance systems and the Internet. Many of these tools were initially developed at national, regional and local Supercomputer Centers such as NCSA, NPAC, SDSC, CTC, ANL and BU-CCS as well as several commercial vendors. HPF, PVM, MPI, WWW, HTML, MOSAIC, NETSCAPE, JAVA, HOTJAVA, VRML and WEBMAGIC are just a few of the better known tools which can be utilized in the development of the GEM system. Although these tools aid in the software development process, a coherent design must first be established. The GEM project is a mixture of scientific research, computer science and computational science research, software design and software engineering. Scalability is a critical component in our development. Professors Fox, Giles and York all have substantial experience in developing parallel and distributed scientific applications. Below we discuss the major components of the GEM system from the computational/computer science perspective.

Representation of Fault Geometries: In somewhat simplistic terms the geometric modeling of a system of earthquake faults involves describing a portion of the earth (say, southern California) as a collection of interconnected volumes of irregular shape, each bounded by a mesh of surface patches. A fault is a fracture in the earth's surface which penetrates downward into the earth for some distance (up to 35km). Along the fault there is a physical separation of the adjacent volumes of earth; thus, a fault may be represented by the two cross- -sectional surfaces on either side of the fracture. In the simplest case, one can represent a collection of volumes by a 3D lattice and a fault by a piecewise planar cross section. A fault system is just an interconnected collection of faults within a geographical area. The physical state of this object is captured by a state vector consisting of position, slip state and stress defined at each point of the lattice. Thus, an earthquake can be viewed as an event that transforms the system from one state to another based upon a set of rules governing patch interaction dynamics.

As discussed above, the presence of hierarchies of spatial and temporal scales is an important characteristic of the proposed simulations. We plan to develop data structures for fault geometries which allow representations at multiple scales to interact. In the normal case (as stated above) we assume a rheology for the earth's crust which is linear elastic, linear viscoelastic or linear poroelastic. Our challenge is to integrate these fine-grained, local, nonlinear friction models with more coarse-grained, linear interaction models involving elastic transmission of stress between fault locations. We plan to meet this challenge by exploring a variety of techniques for combining the geometric configuration of fault surfaces, the models for representing the earth's rheology, and the advanced numerical techniques needed for simulating nonlinear dynamical processes of frictional sliding. Ideas such as matched asymptotic expansions, treatment of smaller spatial and temporal scales as noise terms, and dynamical acceleration algorithms will be explored. Of course, these kinds of advanced fault surface models typically address only the issue of multiple spatial resolutions. GEM must also have facilities for handling multiple temporal resolutions.

York (1990) implemented SIMD codes on an 8K-processor (256 FPUs) Connection Machine CM2 with 64MB of memory for a neural network which solved seven, coupled, nonlinear, first-order differential equations on a 2D 512x512 grid. Typical runs of this system achieved a processing rate of 66 MFlops while the peak rate for this machine was about 300

MFlops. 20% of peak was fairly common on this type of architecture and some hand optimized codes could achieve 50% of peak. Typically, the best performance that could be achieved on the CM5 (the CM2's successor) was 62% of peak for a highly optimized FFT code. In 1996 shared-memory symmetric multiprocessor machines (SMPs) have become very popular high performance systems, because they offer both high performance and ease of programming. The Center for Computational Science at Boston University currently runs an 18-processor SGI Power Challenge Array (PCA). This machine has a peak performance of approximately 7 Gflops and a total memory of 2 GB. It is anticpated that within the next 18 months this machine will be enhanced to the level of 65 Gflops and 9GB of main memory. It is very likely that for this type of architecture (SMP) a higher percentage of peak performance will be obtainable for most codes. If we assume a conservative rate of 40% of peak, then our earthquake simulations should execute at the 25 Gflops rate in a memory that is at least a factor of 32 larger than that available for previous simulations.

Rundle (1988) was able to simulate an 80-fault system in southern California. In this model Rundle used a matrix of rectangular patches embedded in an elastic layer in welded contact with a Maxwell viscoelastic half-space. The time-dependent interaction matrix coefficients are computed by use of the approximate analytic Green's function (Rundle and Jackson, 1977b) for vertical, strike-slip faults removing the necessity to deal with singularities at the patch edges. Therefore, the additional integrations associated with the stress Green's functions over the patches can be easily computed. Rundle determined that the time complexity of his algorithm was quadratic in the number of patches. A typical simulation would run for 10 hours on a VAX 8600 to compute a 2000 year slip-history (increment equals 1 year). Only a few years later, Mora and Place (1994) and Place and Mora (1995) were able to simulate an earthquake model using a molecular dynamics approach. The earlier model Mora and Place (1994) was a single fault having 256 x 256 system of particles, and ran on a 64-node CM5 with 2 GB of memory. The later simulations of Place and Mora (1995) run on a 5.7 Gflop, 16 node SGI Power Challenge Array computer, and use 1024 x 1024 particles. These simulations require 256 Mb of memory and take one day to simulate 1,000,000 time steps.

Recently York and his students ported Rundle's 1988 model to the SGI PCA at Boston University. Running on a single R8000 processor a typical 2000 year simulation completes in about 10 minutes. We expect to achieve near linear speedup through straightforward parallelization due to the relative independence of patch computations in this model. We suspect that we can achieve a performance degradation of no more than a factor of two to four as a result of more sophisticated fault geometries.

C.5.2 Other Issues

Distribution of Large Scale Simulations over a heterogeneous collection of geographically dispersed computers: As we gain more insight into the simulation process, we will want to simulate larger systems in increasing levels of detail. In order to handle the storage and computational requirements, we must understand how to distribute the computation over a (possibly) heterogeneous collection of networked high performance computers. These issues are largely in the domain of algorithms and software engineering. From the latter standpoint we need to develop technology which handles the distribution of model components mostly automatically. Geoffrey Fox, as the director of NPAC, has special experience in the development of distributed algorithms and with large scale distributed computation; as an example, NPAC initiated the computation to crack RSA129 in 1994. In order to achieve the goal of automated distribution to a heterogeneous network of machines, we will carefully study the current simulation algorithms, develop appropriate distributed algorithms, develop cost functions associated with various distributions, build in fault tolerance, and develop the WWW GEM interface.

Development of Visualization Techniques and Software: Scientific visualization is a reasonably well developed field; however, we are still at the stage where, for each new application, techniques must be specialized in order for the visualizations to be of use to domain scientists. Earthquake modeling can benefit from almost all of the modern visualization techniques -- e.g. contour, isosurface and particle gradient displays, mesh deformation animations, 2D and 3D scalar and vector fields, tensor mappings, graphic interaction and possibly virtual reality techniques. We plan to develop software which allows the earthquake modeler to synthesize the desired visualization from among a number of standard methods. By using an object-oriented approach to the design of the GEM system, we can bring a mix-and-match, plug-and-play style to the development of specific earthquake models that has been entirely lacking heretofore.

Of particular interest are visualization techniques that will allow projected three dimensional displays of seismicity, temporal development of clusters of seismic events, imaginative methods for the superposition of synthetic and real data, interactive point and click data retrieval, high fidelity topographic and geologic map displays with superposed data, differencing capability to display similarities and divergence between synthetic and real data in both space and time domains, and so forth. We note that Fox, Giles and York have all developed individual visualization techniques in the past and have substantial experience with current visualization tools. The idea is to make it possible for data comparisons and new hypotheses to be framed on an intuitive basis.

Earthquake data management: Primary responsibility for earthquake data management lies with the Southern California Earthquake Center (SCEC) at the University of Southern California. They obtain field data through a number of mechanisms such as trilateration, satellite laser ranging, VLBI, and GPS. These field data are used to update the fault geometry models developed under the GEM project. In addition, SCEC maintains fault slip histories which can be used to validate various earthquake models developed under GEM.

C.6 Proposed Work:

Physics of Simulations: Our simulations will be constructed in a series of levels, each increasingly more realistic, more involved, and with smaller spatial scale details than the prior simulations. We will work in this manner so that simpler models can be completely understood, evaluated, and discussed before proceeding to more detailed models. Our starting point for the southern California model will be the simulations of Rundle (1988), as indicated in figures 1 and 2. The exact physics to be included in a given program of simulations will be decided by the investigator group, or large subsets of the investigators. Throughout this work, close coordination with be pursued with the Southern California Earthquake Center, which Rundle currently advises as Chair of the Advisory Council of SCEC.

C.7.1 Basic Model (All GEM Proposals)

<u>Level 0 simulations will be built upon the following assumptions:</u>

1) Realistic geometries for the major faults. Fault geometry will
at least initially not be allowed to evolve in time.
2) Linear isothermal elastic and viscoelastic rheologies for the
upper crust of the earth.
3) "Simple" friction involving a Cellular Automaton-type jump rule
Note that this will still allow a moment release function
to be computed for simulated earthquakes.
4) Neglect of inertia in the sliding process.
5) Neglect of faults below a given spatial scale

Note that these are basically the same assumptions that were used in the 80-fault segment simulations carried out by Rundle (1988).

<u>Level I and higher level simulations will include the following to varying degrees:</u>

1) Evolving fault geometries
2) Different and more realistic frictional physics
3) Inclusion of the exponentially increasing number of smaller fault
systems as a kind of "noise" in the simulations
4) Inclusion of inertia and elastic waves
5) Inclusion of other rheologic effects, including pore fluids,
60 Thermal effects, and possibly chemical processes, particularly as related
to stress corrosion

C.7.2 Proposed Major Tasks and Research Foci by Year (This NSF Proposal)

Note that these standalone tasks are complementary to, but do not duplicate, the tasks in the GEM proposal to US Department of Energy.

Major Category I Tasks: Visualization/Integration of Simulations with Data

Year 1

- Port static visualization codes of Rundle (1988) to variety of networked environments, including PVM, NPAC archictectures, and BU SGI Power Challenge Array.

- Recode simulation algorithms from Rundle (1988) for PVM environment.
- Explore existing data/map overlay techniques, including color 3D mesh and projected 3D rendering

Year 2

- Systematically explore excitatory/inhibitory interactions between simulated faults and use field seismicity and deformation data for comparison with simulation data.
- Develop correlation analysis techniques for spatial and temporal seismic data streams, and integrate these into visualization environment.
- Compile representative catalogs of synthetic simulation data, and carry out parametric studies, for systematic comparison to natural seismicity catalogs. Investigate "scenario earthquakes" that arise in the synthetic data set that may be similar to past or hypothesized future events in southern California.

Year 3

- Assemble data on slow earthquakes and other precursory seismicity patterns, and develop space-time rendering capability to quantitatively compare these with results from simulations.
- Develop space-time cluster analysis techniques using Coniglio-Klein bond probabilities for real and simulation data, together with visualization in 2D and 3D. Explore the nature of the "seismicity backbone" of real and simulated fault networks using alternative cluster definitions.
- Carry out simulations and investigate optimal methods to display space time patterns of stress and other in situ data.

Year 4

- Apply computational mechanics formulation of Crutchfield to explore new observables for earthquake dynamics. In particular, adapt and apply statistical complexity measures, and explore appropriate 2D and 3D projected formats for enhancing information transmission. Compare with phase space attractor structure as obtained from independent analysis (Shkoller and Minster, 1996)
- Construct/adapt M8-type and active zone (Carlson, 1996) pattern recognition techniques to simulation data to evaluate effectiveness of these methods.

Year 5

- Summarize methods developed during the preceeding four years, in particular, integrate software and help files into a package(s) and install on the GEM web site develeped under the proposal to DOE. Make all computational methodologies available to the external user community.
- Assess next-generation visualization and data analysis needs, in particular, investigate data base and archiving needs for simulation and natural data. Construct data archiving

and display methods for simulation data complementary to those currently used and contemplated for natural events.

Category II Tasks: Computational Algorithms for Networked Parallel Computing Environments

Year 1

Year 2

Year 3

Year 4

Year 5

C.7.3Individual Work Statements

John B. Rundle, University of Colorado, Boulder, CO:

Claude Allegre, Institute de Physique du Globe, Paris, France: Allegre, an unfunded collaborator, will advise and work with us on developing and analyzing hierarchical statistical models for fault failure. He will also continue his current collaboration with Turcotte on the applicability of Renormalization Group techniques to failure on faults.

James Crutchfield, Santa Fe Institute, Santa Fe, NM: Crutchfield will investigate how new perspectives can elucidate the underlying mechanics particular to the GEM model. Crutchfield's new approach to computation in dynamical systems --- computational mechanics (Crutchfield, 1994; Crutchfield and Young, 1989) --- suggests a new observable for earthquake dynamics. To date work has focused on statistics such as fractal dimension, metric entropy, and related scaling properties. Crutchfield recently introduced a new observable that is complementary to fractal dimension and metric entropy measures. The statistical complexity, which is a measure of the amount of memory used by a process to produce its behavior, will be very helpful in characterizing new aspects of earthquake dynamics, possibly leading to predictive methods.

Geoffrey Fox, NPAC, Syracuse University, Syracuse, NY: The Syracuse activity will focus on the algorithms and software support for GEM in a portable fashion that spans traditional MPP's (distributed, shared and distributed shared memory) as well as the more loosely coupled network of workstations or their limit, the World Wide Web. Today we understand well, good algorithms for tightly coupled MPP's and their software typified by MPI and HPF for message and data parallel programming models. The growing interest in clustered computing or NOW's/COW's as well distributed shared memory architectures is changing the situation with new capabilities and new issues. We expect that over the next year, new available technologies will include JAVA and Compute enhanced Web Server support for HPCC applications on the World Wide Web. Further commercial distributed shared memory computers should be available from many vendors. We should also even see quality HPF compilers finally delivered. Syracuse through its collaborations with Boston University (WebWork) and CRPC(The Center for Parallel Computation -- MPI,HPF and its more glamorous followon HPJAVA) will help the GEM collaboration evaluate the trade offs between these different programming models. We will also implement the necessary runtime support and key algorithms needed to support the different bandwidth and latency trade-offs exhibited by the various architectures for high performance computing. This work will be performed in the context of the Web based GEM Problem Solving Environment developed as part of a proposal to DOE. (See (http://www.npac.syr.edu/techreports/hypertext/sccs-748/index.html and http://www.npac.syr.edu/users/gcf/sccs750/index.html for more details)

Roscoe Giles, Boston University, Boston, MA:

Thomas H. Jordan, Massachusetts Institute of Technology, Cambridge, MA: J

Hiroo Kanamori, California Institute of Technology, Pasadena, CA:

Bill Klein, Boston University, Boston, MA:

J. Bernard Minster, University of California, San Diego, CA:

Ross Stein, United States Geological Survey, Menlo Park, CA:

Donald Turcotte, Cornell University, Ithaca, NY: Turcotte is principal investigator of an NSF Grant that employs eight senior scientists at the International Institute for Earthquake Prediction and Theoretical Geophysics in Moscow. This group includes the international leaders in applying statistical techniques to recognizing patterns in global seismicity. Turcotte and students will test these techniques on simulation data, with the objective of understanding similar patterns in natural data.

Bryant York, Northeastern University, Boston, MA:

D.LETTER OF SUPPORT FROM DAVID JACKSON, SCIENCE DIRECTOR FOR THE SOUTHERN CALIFORNIA EARTHQUAKE CENTER

E. BIBLIOGRAPHY

Aki, K. and P.G. Richards, *Quantitative Seismology, Theory and Methods*, vols I and II, W.H. Freeman, San Francisco, 1980.

Aki, K., Magnitude-frequency relations for small earthquakes: A clue to the origin of f_{max} of large earthquakes, *J. Geophys. Res*., **92**, 1349-1355, 1987.

Allegre, C., J.L. Le Mouel and A. Provost, Scaling rules in rock fracture and possible implications for earthquake prediction, *Nature*, **297**, 47-49, 1982.

Allegre, C.J. and J.L. Le Mouel, Introduction of scaling techniques in brittle fracture of rocks, *Phys. Earth Planet Int.*, **87**, 85-93, 1994.

Allegre, C.J., J.L. Le Mouel, H.D. Chau and C. Narteau, Scaling organization of fracture tectonics and earthquake mechanism, *Phys. Earth Planet Int.*, in press, 1996.

Allen, M.P. and D.J. Tildsley, *Computer Simulations of Liquids*, Clarendon Press, Oxford, 1987.

Amit, D.J., *Field Theory, the Renormalization Group, and Critical Phenomena*, World Scientific, Philadelphia, 1984.

Arrowsmith, D.K. and C.M. Place, *An Introduction to Dynamical Systems*, Cambridge University Press, Cambridge, U.K., 1991.

Bak, P. and C. Tang, Earthquakes as a self-organized critical phenomenon, *J. Geophys. Res.*, **94**, 15635-15638, 1989.

Bakun, W. and T.V. McEvilly, Recurrence models and Parkfield, California, earthquakes, *J. Geophys. Res.*, **89**, 3051-3058, 1984

Bakun, W.H. and A.G. Lindh, The Parkfield, California prediction experiment, *Earthquake Pred. Res., 3,* 285-304, 1985.

Beck, S.L. and D.H. Christensen, Ruture process of the February 4, 1965, Rat Islands earthquake, *J. Geophys. Res.*, **96**, 2205-2221, 1991.

Beck, S.L. and L.J. Ruff, The rupture process of the 1976 Mindanao earthquake, *J. Geophys. Res.*, **90**, 6773-6782, 1985.

Beck, S.L. and L.J. Ruff, The rupture process of the great 1979 Colombia earthquake: Evidence for the asperity model, *J. Geophys. Res.*, **89**, 9281-9291, 1984.

Beeler, N., TE Tullis and JD Weeks, The roles of time and displacement in the evolution effect in rock friction, *Geophys. Res. Lett.*, **21**, 1987-1990, 1994.

Beeler, N. and TE Tullis, Self healing slip pulses in dynamic rupture models due to velocity dependent strength, *Bull. Seism. Soc*, in press, 1996.

Ben-Zion, Y. and J.R. Rice, Earthquake failure sequences along a cellular fault zone in a 3D elastic solid containing asperity and non-asperity regions, *J. Geophys. Res.*, **98**, 14109-14131, 1993.

Ben-Zion, Y. and J.R. Rice, Earthquake failure sequences along a cellular fault zone in a three-dimensional elastic solid containing asperity and non asperity regions, *J. Geophys. Res., 98,* B8, 14109-14131, 1993.

Ben-Zion, Y., J.R. Rice, and R. Dmowska, Interaction of the San Andreas Fault creeping segment with adjacent great rupture zones and earthquake recurrence at Parkfield, *J. Geophys. Res., 98,* 2135-2144, 1993.

Beroza, G.C., Near Source modeling of the Loma Prieta earthquake; evidence for heterogeneous slip and implications for earthquake hazard, *Bull. Seismol. Soc. Amer., 81,* 1603-1621, 1991.

Beroza, G.C., Seismic source modeling, *US National Rept. to IUGG 1991-1994*, Amer Geophys. Un., 1995., pp. 299-308.

Berryman, J.G. and G.W. Milton, Normalization constraint for variational bounds on fluid permeability, *J. Chem. Phys.*, **83**, 754-760, 1985.

Bilham, R. and P. Bodin, Influence of fault zone connectivity on segment slip rate: Boundary element estimates for the San Francisco Bay area, *Science, 258,* 281-284, 1992.

Binder, K., *Applications of the Monte Carlo Method in Statistical Mechanics*, vol. 36 of *Topics in Current Physics*, Springer-Verlag, Berlin, 1987.

Binder, K., *Monte Carlo Methods in Statistical Physics*, vol. 7 of *Topics in Current Physics*, Springer-Verlag, Berlin, 1986.

Blanter, EM, MG Schnirman, JL Le Mouel and C.J. Allegre, Scaling laws in block dynamics and dynamic self-organized criticality, *Phys. Earth. Planet. Int.*, in press, 1996.

Brown, S. and G. Gruner, Charge and spin density waves, *Sci. Amer., 270,* 50-57, 1994.

Brown, S.R, C.J. Scholz and J.B. Rundle, A simplified spring-block model of earthquakes, *Geophys. Res. Lett.*, *18*, 2, 215-218, 1991.

Brune, J.N., S. Brown, and P.A. Johnson, Rupture mechanism and interface separation in foam rubber models of earthquakes; a possible solution to the heat flow paradox and the paradox of large overthrusts, *Tectonophys., 218,* 59-67, 1993.

Burridge, R. and C.A. Varga, The fundamental solution in dynamic poroelasticity, *Geophys. J. Roy. astr. Soc.*, **58**, 61-90, 1979.

Carlson, J.M., Prediction studies of earthquake fault models and applications to seismic catalogs, pp. 273-292 in JB Rundle, D. Turcotte and W. Klein, eds., *Reduction and Predictability of Natural Disasters,* vol XXV in the Santa Fe Inst. series on the Sciences of Complexity, Addison Wesley, 1996.

Carlson, J.M and J.S. Langer, Properties of earthquakes generated by fault dynamics, *Phys. Rev. Lett.*, **62**, 2632-2635, 1989.

Carlson, J.M., J.S. Langer, B.E. Shaw and C. Tang, Intrinsic properties of a Burridge-Knopoff model of an earthquake fault, *Phys. Rev. A*, *44,* 2, 884-897, 1991.

Carlson, J.M., Time intervals between characteristic earthquakes and correlations with smaller events; an analysis based on a mechanical model of a fault, *J. Geophys. Res., 96,* 4255-4267, 1991.

Constantin, P., "Integral and Inertial Manifolds for Dissipative Partial Differential Equations", Springer-Verlag, 1989.

Chen, G. and H. Spetzler, Complexities of rock fracture and rock friction from deformation of Westerly granite, *PAGEOPH, 140,* 95-119, 1993a.

Chen, G. and H. Spetzler, Topographic characteristics of laboratory induced shear fractures, *PAGEOPH, 140,* 123-135, 1993b.

Cleary, M.P., Fundamental solutions for a fluid-saturated porous solid, *Int. J. Solids Str.*, **13**,785-806,1977.

Coniglio, A. and W. Klein, J. Phys. A, **12**, 2775, 1980.

Cornell, C.A., S.-C. Wu, S.R. Winterstein, J.H. Dieterich, and R.W. Simpson, Seismic hazard induced by mechanically interactive fault segments, *Bull. Seism. Soc.Am., 83,* 436-449, 1993

Crutchfield, JP, The calculi of emergence: Computation, dynamics, and induction, *Physica D*, **75**, 11-54, 1994.

Crutchfield, JP and K Young, Inferring statistical complexity, *Phys. Rev. Lett.*, **63**, 105-

108, 1989.

Crutchfield, JP, Subbasins, portals and mazes: Transients in high dimensions, *J. Nucl. Phys. B.*, **5A**, 287, 1988.

Crutchfield, JP and K. Kaneko, Are attractors relevant to turbulence?, *Phys. Rev. Lett.*, **60**, 2715, 1988.

Crutchfield, JP and BS McNamara, Equations of motion from a data series, *Complex Systems*, **1**, 417-452, 1987.

Crutchfield, JP and JE Hanson, Turbulent Pattern Bases for Cellular Automata, *Physica D*, **69**, 279 - 301, 1993.

de Sousa Vieria, M., G.L. Vasconcelos and S.R. Nagel, Dynamics of spring-block models: Tuning to criticality, *Phys. Rev. E*, *47*, 4, R2221-2224, 1993.

Dieterich, J.H. and M.F. Linker, Fault stability under conditions of variable normal stress, *Geophys. Res. Lett., 19*, 16, 1691-1694, 1992

Dieterich, J.H., A constitutive law for rate of earthquake production and its application to earthquake clustering, *J. Geophys. Res., 99,* 2601-2618, 1994.

Dieterich, J.H., Constitutive properties of rock with simulated gouge, In *Mechanical Behavior of Crustal Rocks. AGU Geophys. Monograph 24*, Washington, DC, American Geophysical Union, 103-120, 1981.

Dieterich, J.H., Time dependent friction and the mechanics of stick slip, *Pure Appl. Geophys.*, **116**, 790-806, 1978.

Dieterich, J.H., Time dependent friction in rocks, *J. Geophys. Res.*, **77**, 3690-3697, 1972

Ding, E.J. and Y.N. Lu, Analytical treatment for a spring-block model, *Phys. Rev. Lett., 70,* 3627-3630, 1993.

Dmowska, R. and L. Lovison, Influence of asperities along subduction interfaces on the stressing and seismicity of adjacent areas, *Tectonophysics*, **211**, 23-41, 1992.

Dowla, F.U., T.F. Hauk, J.B. Rundle and J.J.Hopfield, Earthquake forecasting using neural networks (abstr.), *Seism. Res. Lett., 63,* 21, 1992.

Eberhart-Phillips, D. and A.J. Michael, Three-dimensional velocity structure, seismicity, and fault structure in the Parkfield region, central California, *J. Geophys. Res., 98*, B9, 15737-15758, 1993.

Engdahl, E.R., S. Billington, and C. Kisslinger, Teleseismically recorded seismicity before and after the May 7, 1986 Andreanof Islands, Alaska, earthquake, *J. Geophys. Res.*, **94**, 15481-15498, 1989.

Feynman, R.P. and A.R. Hibbs, *Quantum Mechanics and Path Integrals,* McGraw-Hill, New York, 1965.

Fortuin, C.M. and P.W. Kasteleyn, *Physica*, (Utrecht), **57**, 536, 1972.

Gabrielov, A., W. Newman and L. Knopoff, Lattice models of failure: Sensitivity to the local dynamics, *Phys. Rev. E*, **50**, 188-197, 1994.

Geubelle, P. and J.R. Rice, A spectral method for 3D elastodynamic fracture problems, *J. Mech. Phys. Sol.*, in press, 1995.

Grant, L. and A. Donnellan, 1855 and 1991 surveys of the San Andreas fault: Implications for fault mechanics, *Bull. Seism. Soc. Am., 84,* 241-246, 1994.

Grant, L. and K. Sieh, Paleoseismic evidence of clustered earthquakes on the San Andreas fault in the Carrizo Plain, *J. Geophys. Res., 99,* 6819-6842, 1994.

Gross, S., On the scaling of average slip with rupture dimensions of earthquakes, pp.157-166 in JB Rundle, D. Turcotte and W. Klein, eds., *Reduction and Predictability of*

Natural Disasters, vol XXV in the Santa Fe Inst. series on the Sciences of Complexity, Addison Wesley, 1996.

Gross, S., J.B. Rundle and W. Klein, Simulations of the Traveling Density Wave model for earthquakes and comparison to observations, preprint, 1996

Haberman, R.E., Consistency of teleseismic reporting since 1963, *Bull. Seism. Soc. Am.*, **72**, 93-111, 1982.

Hanks, T.C., Small earthquakes, tectonic forces, *Science, 256,* 1430-1432, 1992.

Harris, R.A., and R.W. Simpson, Changes in static stress on Southern California faults after the 1992 Landers earthquake, *Nature (London), 360,* 251-254, 1992.

Heaton, T., Evidence for and implications of self-healing pulses of slip in earthquake rupture, *Phys. Earth and Planet. Int.*, **64**, 1-20, 1990.

Heaton, T.H., Evidence for and implications for self-healing pulses of slip in earthquake rupture, *Phys. Earth Planet. Int., 64,* 1-20, 1990.

Heimpel, M., Earthquake size-frequency relations from an analytical stochastic rupture model, *J. Geophys. Res.*, in press, 1996.

Herz, A.V.M. and J.J. Hopfield, Rapid phase locking in coupled integrate-and-fire neurons, preprint, 1995.

Hill, R. A self consisten mechanics of composite materials, *J. Mech.. Phys. Sol.*, **13**, 213-222, 1965.

Hill, D.P., and others, Seismicity remotely triggered by the magnitude 7.3 Landers, California, earthquake, *Science* , *260*, 1617-1623, 1993.

Hopfield, J.J., Neurons, dynamics and computation, *Physics Today*, **47**, 40-46, 1994.

Huang, J. and D.L. Turcotte, Chaotic seismic faulting with a mass-spring model and velocity weakening friction, *PAGEOPH, 138,* 570-589, 1992.

Huang, J., G. Narkounskaia and D.L. Turcotte, A cellular-automata, slider-block model for earthquakes, II. Demonstration of self-organized criticality for a 2- -D system, *Geophys. J. Int., 111*, 2, 259-269, 1992.

Ihmle, P.F., P. Harabaglia and T.J. Jordan, Teleseismic detection of a slow precursor to the great 1989 Macquarie Ridge earthquake, *Science*, *261*, 5118, 177-183, 1993.

Ivins, E.R., *Composite Constitutive Theory for a Solid Earth of Strong Lateral Viscosity Contrast*, Ph.D. Dissertation, Univ. Southern Calif., 1995a.

Ivins, E.R. and C.G. Sammis, On lateral viscosity contrast in the mantle and the rheology of low frequency geodynamics, *Geophys. J. Int*, in press, 1995b.

Jackson, D.D. and others, Seismic hazards in southern California: Probable earthquakes, 1994 to 2024, *Bull. Seism. Soc. Am.*, *85*, 379-439, 1995.

Jaume, S.C., and L.R. Sykes, changes in state of stress on the southern San Andreas Fault resulting from the California earthquake sequence of April to June 1992, *Science, 258,* 1325-1328, 1992.

Johnson, P.A., M. Antolik, W.A. Peppin, W. Foxall, and T.V. McEvilly, Structure and rupture processes of the fault zone at Parkfield from the spectra of microearthquakes, *Seism. Res. Lett., 63,* 75, 1992.

Jordan, T.H., Far-field detection of slow precursors to fast seismic ruptures, *Geophys. Res. Lett., 18,* 11,2019-2022, 1991.

Kagan, Y.Y., and D.D. Jackson, Seismic gap hypothesis; ten years after, *J. Geophys. Res., 96,* 21419-21431, 1991.

Kanamori, H, Global seismicity, pp. 596-608 in *Earthquakes: Observation, Theory and In-*

terpretation, Course LXXXV, Proc. Intl. School of Physics "Enrico Fermi", the Italian Physical Society, North Holland, Amsterdam, 1983.

Kanamori, H. and D.L. Anderson, Theoretical basis for some empirical relations in seismology, *Bull. Seism. Soc. Am.*, **65**, 1073-1095, 1975.

Kanamori, H. and M. Kikuchi, The 1992 Nicaragua earthquake: A slow tsunami earthquake associated with subducted sediments, *Nature*, *361*, 6414, 714-716, 1993.

Kanamori, H., E. Hauksson, A slow earthquake in the Santa Maria Basin, California, *Bull. Seismol. Soc. Amer., 85,* 2087-2096, 1992.

Kanamori, H., Mechanics of Earthquakes, *Ann. Rev. Earth Planet. Sci.*, **21**, 1993.

Karageorgi, E., R. Clymer and T.V. McEvilly, Seismological studies at Parkfield, II. Search for temporal variations in wave propagation using Vibroseis, *Bull. Seism. Soc. Amer.*, *82*, 3, 1388-1415, 1992.

Kikuchi, M., H. Kanamori and K. Satake, Source complexity of the 1988 Armenian earthquake: Evidence for a slow after-slip event, *J. Geophys. Res.*, *98,* B9, 15797-15808, 1993.

King, G.C.P. and J. Nabelek, Role of fault bends in the initiation and termination of earthquake rupture*Science*, **228,** 984-987, 1985.

King, G. C. P., R. S. Stein, and J. Lin, Static stress changes and the triggering of earthquakes, *Bull. Seismol. Soc. Amer.*, **84**, 935-953, 1994.

Kisslinger, C., The stretched exponential function as an alternative model for aftershock decay rate, *J. Geophys. Res.*, *98*, 1913-1921, 1993.

Klein, W. and F. Leyvraz, Crystalline nucleation in deeply quenched systems, *Phys. Rev. Lett., 57,* 2845-2848, 1986.

Knopoff, L., J.A. Landoni, and M.S. Abinante, Dynamical model of an earthquake fault with localization, *Phys. Rev. A467*, 7445-7449, 1992.

Kostrov, BV, Self similar problems of propagation of shear cracks, *J. Appl. Mech.*, **28**, 1077-1087, 1964.

Lay, T., H. Kanamori, and L. Ruff, The asperity model and the nature of large subduction zone earthquakes, *Earthquake Prediction Research*, **1**, 3-71, 1982.

Lees, J.M., and C. Nicholson, Three-dimensional tomography of the 1992 southern California earthquake sequence: constraints on dynamic earthquake rupture?, *Geology*, *21,* 387-390, 1993.

Li, V.C., Mechanics of shear rupture applied to earthquake zones, in *Fracture Mechanics of Rock*, ed. B.K. Atkinson, Academic Press, London, 1987, pp. 351-428.

Linde, A.T., M.T. Gladwin, and J.J.S. Johnston, The Loma Prieta earthquake, 1989 and earth strain tidal amplitudes; an unsuccessful search for associated changes, *Geophys. Res. Letts., 19,* 317-320, 1992.

Lomnitz-Adler, J., Automaton models of seismic fracture: constraints imposed by the magnitude-frequency relation, *J. Geophys. Res.*, *98,* 17745-17756, 1993.

Ma, S.-K., *Modern Theory of Critical Phenomena*, Benjamin-Cummings, Reading MA, 1976.

Ma, S.-K., *Statistical Mechanics*, World Scientific, Philadelphia, PA, 1985.

Marone, C.J., C.H. Scholz, and R. Bilham, On the mechanics of earthquake afterslip, *J. Geophys. Res., 96,* 8441-8452, 1991.

Maruyama, T., Fluid pressure responses of a water-saturated porous elastic multilayered half space to water pumping and atmospheric loading, *J. Phys. Earth*, **42**, 331-375, 1994.

McNally, K.C., Plate subduction and prediction of earthquakes along the Middle America Trench, in *Earthquake Prediction, An International Review*, AGU monograph 4, American Geophysical Union, Washington, DC, 1981.

Mendoza, C., Hartzell, S. and T. Monfret, Wide-band analysis of the 3 March, 1985 Central Chile earthquake: Overall source process and rupture history, *Bull. Seism. Soc. Am., 84,* 269-283, 1994.

Monette, L. and W. Klein, Spinodal nucleation as a coalescence process, *Phys. Rev. Lett.*, **68**, 2336-2339, 1992.

Mora, P. and D. Place, Simulation of the frictional stick slip instabilty, *Pure Appl. Geophys.*, **143**, 61-87, 1994.

Mouritsen, O.G., in *Computer Studies of Phase Transitions and Critical Phenomena*, Springer-Verlag, Berlin, 1984.

Nadeau, R., M. Antolik, P.A. Johnson, W. Foxall and T.V. McEvilly, Seismological studies at Parkfield III: Microearthquake clusters of fault zone dynamics, *Bull. Seism. Soc. Am., 84,* 247-263, 1994.

Nakanishi, H., Cellular automaton model of earthquakes with deterministic dynamics, *Phys. Rev. A,* **43**, 6613-6621, 1990.

Narkounskaia, G., and D.L. Turcotte, A cellular-automata, slider-block model for earthquakes; I, Demonstration of chaotic behaviour for a low order system, *Geophys. J. Internat., 11,* 250-258, 1992.

Narkounskaia, G., J. Huang and D.L. Turcotte, Chaotic and self-organized critical behavior of a generalized slider block model, *J. Stat. Phys.*, **67**, 1151-1183, 1992.

Narkounskaia, G., J. Huang and D.L. Turcotte, Chaotic and self-organized critical behavior of a generalized slider block model, *J. Stat. Phys.*, **67**, 1151-1183, 1992.

Nishenko, S.P., L.R. Sykes, D.D. Jackson, and Y.Y. Kagan, Seismic gap hypothesis; ten years after [discussion and reply], *J. Geophys. Res., 908,* 9909-9920, 1993.

Newman, W.I. and A.M. Gabrielov, Failure of hierarchical distributions of fiber bundles, *Int. J. Fracture*, **50**, 1-14, 1991.

Newman, W.I., AM Gabrielov, TA Durand, SL Phoenix and D.L. Turcotte, An exact renormalization model for earthquakes and material failure. Statics and dynamamics, *Physica*, **D77**, 200-216, 1994.

Newman, W.I., D.L. Turcotte and A. Gabrielov, A hierarchical model for precursory seismic activation, pp. 243-260, in J.B. Rundle, D.L. Turcotte and W. Klein, *Reduction and Predictability of Natural Disasters*, vol. XXV in the Santa Fe Institute series on complexity, Addison Wesley, 1996.

Okada, Y., Internal deformation due to shear and tensile faults in a half-space, *Bull. Seism. Soc. Am.*, **82**, 1018-1040, 1992.

Okada, Y., Surface deformation duei to shear and tensile faults in a half-space, *Bull. Seism. Soc. Am.*, **75**, 1135-1154, 1985.

Olami, Z., H.J.S. Feder, and K. Christensen, Self-organized criticality in a continuous, nonconservative cellular automaton modeling earthquakes, *Phys. Rev. Lett., 68,* 1244-1247, 1992 (Comment by W. Klein and J. Rundle, *Phys. Rev. Lett., 71,* 1288, 1993, with reply by Christensen, *Phys. Rev. Lett., 71,* 1289, 1993)

Pacheco, J.F., C.H. Scholz, and L.R. Sykes, Changes in frequency-size relationship from small to large earthquakes, *Nature (London), 355,* I 71-73, 1992.

Pepke, S.L., J.M. Carlson and B.E. Shaw, Prediction of large events on a dynamical model of a fault, *J. Geophys. Res., 99,* 6769-6788, 1994.

Perrin, G. and J.R. Rice, Disordering of a dynamic planar crack front in a model elastic medium of randomly variable toughness, *J. Geophys. Mech. Sol.*, *42*, 1047-1064, 1994.

Place, D and P. Mora, Large scale simulations of the physics of earthquakes, *Trans. Am. Geophys. Un. EOS*, v. 76 Suppl., F424, 1995.

Rabinowicz, E., *Friction and Wear of Materials*, John Wiley, New York, 1965.

Reid, HF, in A.C. Lawson, *The California Earthquake of April 18, 1906, Report of the State Earthquake Investigation Commission,* Vol I (Carnegie Institution of Washington, Washington, DC, 1908).

Rice, J.R. and M.Cleary, Some basic stress diffusion solutions for fluid saturated elastic porous media with compressible constituents, *Rev. Geophys. Space Phys.*, **14**, 227-241, 1976.

Rice, J.R. and A.L. Ruina, Stability of steady frictional slipping, *J. Appl. Mech.*, **105**, 343-349, 1983.

Rice, J.R., Spatio-temporal complexity of slip on a fault, *J. Geophys. Res.*, *98*, 9885-907, 1993.

Richter, C.F., *Elementary Seismology*, W.H. Freeman, San Francisco, 1958.

Romanowicz, B. and J. B. Rundle, On scaling relations for large earthquakes, *Bull.Seism. Soc. Am., 83*, 1294-1297, 1993.

Romanowicz, B., Strike-slip earthquakes on quasi-vertical transcurrent faults: Inferences for general scaling relations, *Geophys. Res. Lett., 19,* 481-484, 1992.

Rudnicki, J.W., J. Yin, and E.A. Roeloffs, Analysis of water level changes induced by fault creep at Parkfield, California, *J. Geophys. Res.*, *98*, 8143-8152, 1993.

Ruff, L.J., Asperity distributions and large earthquake occurrence in subduction zones, *Tectonophys., 211,* 61-83, 1992.

Ruff, L.J., Fault asperities inferred from seismic body waves, pp. 251-276, in *Earthquakes: Observation, Theory and Interpretation*, Course LXXXV, Proc. Intl. School of Physics "Enrico Fermi", the Italian Physical Society, North Holland, Amsterdam, 1983.

Rundle, J.B. and D.D. Jackson, Numerical simulation of earthquake sequences, *Bull. Seism. Soc. Am.*, 67, 1363 - 1378, 1977.

Rundle, J.B. and S.R. Brown, Origin of rate dependence in frictional sliding, *J. Stat. Phys.*, 65, 403-412, 1991.

Rundle, J.B. and D.L. Turcotte, New directions in theretical studies of tectonic deformation: A survey of recent progress, in *Contributions of Space Geodesy to Geodynamics: Crustal Dynamics*, ed. D.E. Smith and D.L. Turcotte, Geodynamics Ser. Vol. 23, AGU, Washington, DC, 1993.

Rundle, J.B. and W. Klein, Implications of a "toy" slider block model for the rupture mechanics of earthquakes, *J. Geophys. Res.,* submitted, 1994 *(also Trans. Am. Geophys. Un. EOS Fall meeting suppl. abstr.,* 405, 1993)

Rundle, J.B. and W. Klein, New ideas about the physics of earthquakes, *AGU Quadrennial report to the IUGG and Rev. Geophys. Space Phys.*, in press, 1994.

Rundle, J.B. and W. Klein, Nonclassical nucleation and growth of cohesive tensile cracks, *Phys. Rev. Lett.*, **63**, 171-174, 1989.

Rundle, J.B. and W. Klein, Nonlinear dynamical models for earthquakes and frictional sliding: An overview, *Proc. 33rd Symposium Rock Mech.*, A.A. Balkema, Rotterdam, 1992.

Rundle, J.B. and W. Klein, Scaling and critical phenomena in a class of slider block cellular automaton models for earthquakes, *J. Stat. Phys., 72,* 405-412, 1993.

Rundle, J.B., A physical model for earthquakes: 1, Fluctuations and interactions, *J. Geophys. Res.*, **93**, 6237-6254, 1988.

Rundle, J.B., A physical model for earthquakes, 2, Application to southern California, J. Geophys. Res., 93, 6255-6274, 1988.

Rundle, J.B., A physical model for earthquakes: 3, Thermodynamical approach and its relation to nonclassical theories of nucleation, *J. Geophys. Res.*, **94**, 2839-2855, 1989.

Rundle, J.B., and W. Klein, Scaling and critical phenomena in a cellular automaton slider-block model for earthquakes, *J. Statist. Phys.*, *72*, 405-412, 1993.

Rundle, J.B., Derivation of the complete Gutenberg-Richter magnitude-frequency relation using the principle of scale invariance, *J. Geophys. Res., 94,* 12337-12342, 1989.

Rundle, J.B., J. Ross, G. Narkounskaia, and W. Klein, Earthquakes, self-organization, and critical phenomena, *J. Stat. Phys.*, submitted, 1995a.

Rundle, J.B., Magnitude frequency relations for earthquakes using a statistical mechanical approach, *J. Geophys. Res.,* **98**, 21943-21949, 1993.

Rundle, J.B., Viscoelastic crustal deformation from a rectangular fault in a layered earth, *J. Geophys. Res*., **87**, 7787-7796, 1982a.

Rundle, J.B., Some solutions for static and pseudo-static deformation in layered nonisothermal media, *J. Phys. Earth*, **30**, 421-440, 1982b.

Rundle, J.B., W. Klein and S. Gross, Dynamics of a Traveling Density Wave model for earthquakes, *Phys. Rev. Lett.*, submitted, 1996.

Rundle, J.B., W. Klein, S. Gross and D.L. Turcotte, Boltzmann fluctuations in numerical simulations of nonequilibrium lattice threshold systems, *Phys. Rev. Lett*., **75**, 1658-1661,1995b.

Sahimi, M., M.C. Robertson and C.G. Sammis, Fractal distribution of earthquake hypocenters and its relation to fault patterns and percolation, *Phys. Rev. Lett., 70,* 2186-2189, 1993.

Sammis, C.G., D.Sornette and H. Saleur, Complexity and earthquake forecasting, pp. 143-156, in JB Rundle, DL Turcotte, W. Klein, eds., *Reduction and Predictability of Natural Disasters*, vol. XXV in Santa Fe Institute series in Sciences of Complexity, Addison Wesley, 1996.

Sanders, C.O., Interaction of the San Jacinto and San Andreas fault zones, southern California: Triggered earthquake migration and coupled recurrence intervals, *Science, 260,* 973-975, 1993.

Savage, J.C., W.H. Prescott, and G. Gu, Strain accumulation in southern California, 1973-1984, *J. Geophys. Res.*, **91**, 7455-7473, 1986.

Savage, J.C., Criticism of some forecasts of the National Earthquake Prediction Evaluation Council, *Bull. Seismol. Soc. Amer., 81,* 862-881, 1991.

Savage, J.C., The Parkfield prediction fallacy, *Bull. Seismol. Soc. Amer., 83,* 1-6, 1993.

Scholz, C.H., A reappraisal of large earthquake scaling, *Bull. Seism. Soc. Am., 84,* 215-218, 1994.

Scholz, C.H., *The Mechanics of Earthquakes and Faulting*, Cambridge University Press,

Cambridge, U.K., 1990.
Schulman, L.S., *Techniques and Applications of Path Integration,* John Wiley, New York, 1981.
Schwartz, D.P. and K.J. Coppersmith, Fault behavior and characteristic earthquakes: Examples from the Wasatch and San Andreas faults, *J. Geophys. Res.*, **89**, 5681-5698, 1984.
Schwartz, S.Y. and L.J. Ruff, Asperity distribution and earthquake occurrence in the southern Kurile Islands arc, *Phys. Earth Planet. Int.*, **49**, 54-77, 1987.
Schwartz, S.Y. and L.J. Ruff, The 1968 Tokachi-Oki and the 1969 Kurile Islands earthquakes: Variability in the rupture process, *J. Geophys. Res.*, **90**, 8613-8626, 1985.
Schwartz, S.Y., J.W. Dewey and T. Lay, Influence of fault plane heterogeneity on the seismic behavior in the southern Kurile Islands arc, *J. Geophys. Res.*, **94**, 5637-5649, 1989.
Senatorski, P., *Fault Zone Dynamics Evolution Patterns*, Ph.D. Dissertation, Geophysical Institute of the Polish Academy of Sciences (Polska Akademia Nauk, Instytut Geofizyki), Warsaw, 1993.
Shaw, B.E., J.M. Carlson, and J.S. Langer, Patterns of seismic activity preceding large earthquakes, *J. Geophys. Res., 97,* 479-488, 1992.
Shkoller, S. and Minster, J.B., "Chaos in a Burridge-Knopoff Model with state and rate dependent friction law", submitted to Nonlinear Processes in Geophysics, 1996.
Sibson, R.H., Implications of fault-valve behaviour for rupture nucleation and recurrence, *Tectonophys. 211,* 283-293, 1992.
Sieh, K.E. and R.H. Jahns, Holocene activity of the San Andreas at Wallace Creek, California, *Geol. Soc. Bull.*, **95**, 883-896, 1984.
Sieh, K.E. and others, Near field investigations of the Landers earthquake sequence, April to July, 1992, *Science, 260,* 171-176, 1993.
Smale, S., Differentiable dynamical systems, *Bull. Amer. Math. Soc.*, **73**, 747-817, 1967.
Smalley, R.F., D.L. Turcotte and S.A. Solla, A renormalization group approach to the stick slip behavior of faults, *J. Geophys. Res.*, **90**, 1884-1900, 1985.
Smalley, R.F., J.L. Chatelain, D.L. Turcotte, and R. Prevot, A fractal approach to the clustering of earthquakes: Applications to the seismicity of the New Hebrides, *Bull. Seism. Soc. Am.*, **77**, 1368-1381, 1987.
Sornette, D. and J. Virieux, Linking short-timescale deformation to long-timescale tectonics, *Nature, 357,* 401-404, 1992.
Sornette, D., A. Johansen, A. Arneodo, JF Muzy and H. Saleur, Complex fractal dimensions describe the hierarchical structure of Diffusion-Limited-Aggregation clusters, *Phys. Rev. Lett.* , **76**, 251-254, 1996.
Stauffer, D. and A. Aharony, *Introduction to Percolation Theory*, Taylor and Francis, London, 1992.
Stein, R.S., G.C.P. King and J lin, Changes in failure stress on the southern San Andreas fault system caused by the 1992 magnitude = 7.4 Landers earthquake, *Science, 258,* 1328-1332, 1992.
Stein, R. S., A. A. Barka, and J. H. Dieterich, Progressive earthquake failure on the North Anatolian fault since 1939 by stress triggering, *Geophys. J. Int.*, submitted, 1996.
Stein, R. S., G. C. P. King, and J. Lin, Stress triggering of the 1994 M=6.7 Northridge, California, earthquake by its predecessors, *Science*, **265**, 1432-1435, 1994.

Stuart, W., Strain softening prior to two dimensional strike slip earthquakes, *J. Geophys. Res.*, **84**, 2153-2160, 1979.

Stuart, W.D., Instability model for recurring large and great earthquakes in southern California, *Pure Appl. Geophys.*, **122**, 793-811, 1985.

Stuart, W.D., Forecast model for recurring large and great earthquakes in southern California, J. Geophys. Res., **91**, 13771-13786, 1986.

Stuart, W.D. and T.E. Tullis, Fault model for preseismic deformation at Parkfield, California, *J. Geophys. Res.*, **100**, 24079-24101, 1995.

Turcotte, D.L., Earthquake prediction, *Ann. Rev. Earth Planet. Sci., 19, 181-194,* 263-281, 1991.

Turcotte, DL, *Fractals and Chaos in Geology and Geophysics*, Cambridge, 1992.

Vasconcelos, G.L., M. de Sousa Vieira, and S.R. Nagel, Implications of a conservation law for the distribution of earthquake sizes, *Phys. Rev. A., 44*, R7869-R7872, 1991.

Wald, D.J., D.V. Helmberger, and T.H. Heaton, Rupture model of the 1989 Loma Prieta earthquake from the inversion of strong-motion and broadband teleseismic data, *Bull. Seismol. Soc. Amer., 81,* 1540-1572, 1991.

Wallace, T.C., A. Velasco, J. Zhang, and T. Lay, A broadband seismological investigation of the 1989 Loma Prieta, California, earthquake; evidence for deep slow slip?, *Bull. Seismol. Soc. Amer., 81,* 1622-1646, 1991.

Ward, S,N, and S.D.B. Goes, How regularly do earthquakes recur? A synthetic seismicity model for the San Andreas fault, *Geophys. Res. Lett., 20,* 2131-2134, 1993.

Ward, S.N., An application of synthetic seismicity in earthquake statistics: the Middle America trench, *J. Geophys. Res.*, *97*, 6675-6682, 1992.

Ward, S.N. and S. Goes, How regularly do earthquakes recur? A synthetic seismicity model for the San Andreas fault, Geophys. Res. Lett., 20, 2131-2134, 1993.

Ward, S.N., Synthetic earthquake models for long-term prediction, *Geotimes, 37,* 18-20, 1992.

Wuethrich, B., California quake assessed, *Trans. Am Geophys. Un. EOS., 75,* 41, 1994.

Yeomans, J.M., *Statistical Mechanics of Phase Transitions*, Clarendon Press, Oxford, 1992.

Zheng, G., Y. Ben-Zion, J.R. Rice and J. Morrissey, A new method for calculating elastodynamic response over long stressing histories containing rapid rupture episodes, *Trans. Am. Geophys. Un. EOS (Suppl.)*, **76**, F405, 1995.

F.PROJECT PERSONNEL

F.1Summary of Past and Present Collaborations

The challenges posed by the GEM project are at least equal to those found by atmospheric scientists working on GCM models, because the physical processes are less susceptible to direct observation. We have therefore brought together an extremely high quality team of some of the best theoretical and observational(experimental) geophysicists, condensed matter physicists and computational scientists in the country. These scientists have all collaborated in the past in various subsets.

Rundle and Klein have collaborated since 1987 on a series of papers whose subject is the physics of earthquakes, and the relation between slip events and nucleation phenomena. The most recent of these papers was published in Phys. Rev. Lett., 75, 1658-1661, 1995. Rundle has also collaborated with Turcotte, Kanamori, Minster, and Stein at various times, and has published with all of them on the subject of stress redistribution in earthquakes; source processes of earthquakes; and geodetic tests of earthquake models. Crutchfield and Rundle are currently developing pattern recognition algorithms for seismicity distributions. Jordan and Minster have a long history of collaboration on plate tectonic and other research dating back 25 years to the time they were graduate students together at Caltech. Turcotte and Allegre are long time collaborators in reseach dealing with mantle convection and the applicability of Renormalization Group techniques to scaling problems in the earth sciences.

Fox has worked in many interdisciplinary projects during his years at Caltech, including neural network activities with Hopfield (unfunded collaborator with Rundle), as well as several other data analysis and simulation projects with geophysicists within the Seismological Laboratory. These are described in a recent book "Parallel Computing Works!" Fox is also collaborating with Marina Chen, head of the computer science department at Boston University. Fox has successfully integrated HPCC technologies into many applications. The book Parallel Computing Works describes some 50 examples from his time at Caltech where he collaborated with the Geophysics group there on seismic (Clayton) and mantle (Hager before he left) simulations on parallel computers.

York, Klein and Giles have all collaborated together in the past in carrying large scale supercomputer simulations of nonlinear problems. York and his students have are curently collaborating with Rundle to port Rundle's 1988 model to the SGI PCA in Fortran 77. In addition, they are implementing primitive surface patch models for use in developing sophisticated fault geometries.

F.2 Investigator Vitae

G. INSTITUTIONAL QUALIFICATIONS AND BUDGET JUSTIFICATION: COMPUTATIONAL FACILITIES

Simulations will be carried out in a variety of computational environments. These are described below.

MARINER:

The MARINER (Metacenter-Affiliated Resource in the New England Region) project (established at Boston University in October 1995) provides a focal point for HPCC/NII related activities in New England. As a Metacenter Regional Affiliate, its goal is to act as a catalyst for wide diffusion of technologies and as a channel to the Metacenter. MARINER will draw on the University's advanced computing and communications facilities and build on its broad experience in computational science, scalable parallel computing and wide area networking in order to provide education and training to a wider audience as well as to facilitate computational science research and education.

Computational facilities that will be available for this project are the supercomputing facilities associated with the Center for Computational Science at Boston University. At present these facilities include a 38 processor SGI POWER CHALLENGEarray with a peak performance of 13 Gflops, high performance networks and associated visualization peripherals, and a laboratory of networked SGI graphics workstations. The POWER CHALLENGE array represents the first phase equipment of Boston University's third generation supercomputing facility. The equipment for the second phase will consist of SGI's next-generation, highly-scalable supercomputing system with about 25 Gflops of peak performance. The first phase systems will continue in operation, so that our total computational power will increase to about 38 Gflops at that time. About 12 months later, the third and final phase will consist of an upgrade to the second phase system, bringing it to a peak power of about 65 Gflops, or a total of more than 75 Gflops including the first phase systems. The computing environment also includes numerous high performance workstations, HiPPI and FDDI high performance networks in addition to universal Ethernet connectivity and a 10Mb per second connection to the NSF backbone. In the near future we plan to provide ATM connectivity by routing through the SGI Power Challenge machine to a Fore Systems ATM switch. ATM will also be brought to several Indigo-2 workstations serving scientific computing at the University.

Cornell Theory Center:

The Cornell Theory Center (CTC) provides a world-class supercomputing environment that features scalable parallel systems. CTC supports a 512- processor IBM RISC System/6000 Scalable POWERparallel System (SP2). The SP2 is capable of 136 peak Gigaflops and has unprecedented memory capabilities for a scalable parallel machine. The SP2 has 48 wide nodes and 464 thin nodes. The wide nodes have between 256 MBytes and 2 GBytes of memory. The thin nodes each have 128 or 256 MBytes. Large amounts of disk space accessible to user applications -- 1.8 GBytes on each wide node and over 650 MBytes on each thin node -- are another notable feature of this architecture.

CTC has been a leading user of AFS from Transarc (based on the Andrew File System developed at Carnegie-Mellon University) and runs the largest production cell among the NSF centers. CTC runs the National Storage Laboratory (NSL) version of UniTree, which has the unique ability to perform high-speed transfers directly between a network (HiPPI) attached RAID disk cache and a HiPPI-equipped SP2 node. The capacity of this mass storage system, measured in terabytes, is virtually unlimited. Visualization resources include a Visual Insight Zone (VIZ), Silicon Graphics Workstations, and a 32-processor Power Visualization Server (PVS). CTC is a national center of expertise for the visual programming interface Data Explorer (DX).

San Diego Supercomputer Center:

The San Diego Supercomputer Center (SDSC) supports two supercomputers used by the research community, a CRAY C90 vector supercomputer and an Intel Paragon parallel supercomputer. These systems are available for use through a peer-review system to academic researchers and students in the US. They are also available to commercial and government researchers in the US and abroad under special cost sharing arrangements. Currently, more than 4,850 researchers are using these platforms for research.

The CRAY, the main production platform at SDSC, supports more than 125 applications packages. This machine has 8 processors and a peak aggregate speed of 7.7Gflops. It features 1 Gbyte of main memory, 4 Gbytes of Solid-State Storage Device (auxiliary memory), and 189 Gbytes of local high-speed disk storage. The Paragon has 400 processors (nodes) and has a peak aggregate speed of 40 Gflops in 32 bit arithmetic. Memory is allocated per node: 256 nodes have 32 Mbytes of memory each, and the rest have 16 Mbytes of memory each, giving the machine an aggregate memory of 10.25 Gbytes. The Paragon also has 48 Gbytes of local disk storage. The SDSC also supports an 8,096 node CM- -2, which is attached to a Sun 4/260 front-end processor with 64 Mbytes of memory and has access to disk through SDSC's Auspex file server. This machine is being used to study heterogeneous computing applications in an environment where the resources must be shared among researchers.

Northeast Parallel Architectures Center (NPAC):

The Northeast Parallel Architectures Center (NPAC) is a research and development center focusing on high performance computing and communications. Established at Syracuse University in 1987, the center is directed by Geoffrey C. Fox, a pioneer in the development and application of parallel computers, who assumed NPAC leadership in 1990. NPAC has a strong emphasis on computational science applications where one seeks to obtain "real solutions to real problems." NPAC's InfoMall technology transfer program puts high-performance computing and communications (HPCC) to work in industry. Other major projects include research and development in the areas of parallel languages and parallel compilers, including work on High Performance Fortran (HPF) -- a standardized parallel version of Fortran; distributed computing; parallel database technology; integration of relational databases with the NII; parallel algorithms; distributed and cluster computing; and networked digital multimedia applications providing Information, Video, Imagery, and Simulation on demand.

NPAC's role in this collaboration will focus on appropriate use of the best HPCC technologies both the Southern California models, as well as in GEM, such as MPI and HPF. This will naturally use the expertise of the NSF Science and Technology center CRPC -- - the Center for Research in Parallel Computation -- led by Kennedy at Rice where Fox is a founding member. The Southern Calfornia model and GEM are both natural projects in which to exploit World Wide Web technology where NPAC is a pioneer for expoiting both databases (http://asknpac.npac.syr.edu) and distributed computing (http://www.npac.syr.edu/factoring.html). The Web naturally links the data and simulation aspects of GEM and this integration is at the heart of a joint MARINER-NPAC project WebWork where Fox is collaborating with Marina Chen -- the head of the computer science department at Boston University.

H. **BUDGET**

1.Direct funding to John Rundle, <u>University of Colorado</u> with subcontract attachments:

a) Subcontract to James Crutchfield, Santa Fe Institute

b) Subcontract to Tom Jordan, MIT

c) Subcontract to Hiroo Kanamori, California Institute of Technology

d) Subcontract to Ross Stein, US Geological Survey

e) Subcontract to Don Turcotte, Cornell

2.Direct funding to Geoffrey Fox, **Syracuse University**

3.Direct funding to William Klein and Roscoe Giles, **Boston University**

4.Direct funding to J.-Bernard Minster, **Scripps Inst. Oceanography UCSD**

5.**Direct funding to Bryant York, Northeastern University**

I. **CURRENT AND PENDING SUPPORT:**

1.John B. Rundle, University of Colorado

2.**Geoffrey C. Fox, Syracuse University**

3.William Klein and Roscoe Giles, Boston University

4.J.-Bernard Minster, Scripps Inst. Oceanography, UCSD

5.Bryant York, Northeastern University