Strategies for the Detection and Analysis of Space-Time Patterns of Earthquakes on Complex Fault Systems

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Abstract: Our research focuses on computational techniques to understand the dynamics of space-time patterns in driven threshold systems, particularly on earthquake fault systems. We discuss the scientific and computational formulation of strategies for understanding such space-time patterns, leading optimistically to earthquake forecasting and prediction. In particular, we describe pattern dynamics techniques that can be used to relate the observable processes on earthquake fault systems to the fundamentally unobservable dynamical processes. To illustrate our results, we study the emergent modes of the earthquake fault system in southern California, both with models (*Virtual California*) and with data.

1 Earthquakes

Earthquake faults occur in topologically complex, multi-scale networks that are driven to failure by external forces arising from plate tectonic motions. Such networks are prominent examples of driven threshold systems, other instances of which are the human brain, convective circulations in the atmosphere, one-dimensional electron waves in solids, driven foams, and magnetic de-pinning transitions in high temperature superconductors. The basic problem in this class of systems is that the true (force-displacement or current-voltage) dynamics is usually *unobservable*. Since to define the dynamics, one needs to know values of the variables in which the dynamics is formulated, lack of such knowledge precludes a deterministic approach to forecasting the future evolution of the system. With respect to earthquakes, the space time patterns associated with the time, location, and magnitude of the sudden events (earthquakes) from the force threshold are *observable*. Our scientific focus is therefore on understanding the *observable space-time earthquake patterns* that arise from fundamentally *unobservable dynamics*, using new data-mining, pattern recognition, and ensemble forecasting techniques appropriate for these multi-scale systems.

2 Earthquakes

Earthquakes are a complex nonlinear dynamical system, so that techniques appropriate for the study of linear systems have not been of much utility. For example, earthquake forecasting based on linear fits to historic data have not been successful [1,2]. Moreover, the nonlinear dynamics, combined with our lack of microscopic knowledge about the system means that earthquake forecasting and predictability cannot be understood using deterministic dynamical methods, but must instead be approached as a stochastic problem. In addition, as Edward Lorenz showed [3], for nonlinear dynamical systems such as weather and earthquakes, *the past is not necessarily the key to the future*. Therefore, one must be extremely wary of simply extrapolating past behavior into the future, as the Parkfield prediction experience has shown [1,2].

2.1 Numerical Simulations

As elaborated below, there are two serious drawbacks to a purely observational approach to the problem of earthquake forecasting: 1) *Inaccessible* and *unobservable* stress-strain dynamics, and 2) *Multiscale dynamics* that cover a vast range of space and time scales. Because of these fundamental problems, the use of numerical simulations, together with theory and analysis, is mandatory if we are to discover answers to the questions above. Correspondingly, all types of earthquake-related data, including seismic, geodetic, paleoseismic, and laboratory rock mechanics experiments must be employed. The data are used both to determine physical properties of the models we simulate, a process of data assimilation, as well as to critically test the results of our simulation-derived hypotheses, so that future hypotheses can be developed. Moreover, as the computational complexity of the simulation process increases, we are necessarily led to the adoption of modern Information Technology (IT) approaches, that allow rapid prototyping of candidate models within a flexible, web-based computing framework. While advances in IT are thus an integral part of a systematic approach to numerical simulation of complex dynamical systems, our work is focused primarily on the use of simulations to advance scientific understanding of the fault system problem.

2.2 Unobservable Dynamics

Earthquake faults occur in topologically complex, multi-scale networks that are driven to failure by external forces arising from plate tectonic motions [4-7]. The basic problem in this class of systems is that the true stress-strain dynamics is *inaccessible* to direct observations, or *unobservable*. For example, the best current compendium of stress magnitudes and directions in the earth's crust is the World Stress Map [8], entries on which represent point static time-averaged estimates of maximum and minimum principal stresses in space. Since to define the fault dynamics, one needs dynamic stresses and strains for all space and time, the WSM data will not be sufficient for this purpose. Conversely, the space time patterns associated with the time, location, and magnitude of the earthquakes are easily *observable*. Our scientific focus is therefore on understanding how the *observable space-time earthquake patterns* are related to the fundamentally *inaccessible* and *unobservable dynamics*, thus we are developing new data-mining, pattern recognition, theoretical analysis and ensemble forecasting techniques. In view of the lack of direct observational data, any new techniques that use space-time patterns of earthquakes to interpret underlying dynamics and forecast future activity must be developed via knowledge acquisition and knowledge reasoning techniques derived from the integration of diverse and indirect observations, combined with a spectrum of increasingly detailed and realistic numerical simulations of candidate models.

2.3 Multiscale Dynamics

The second problem, equally serious, is that earthquake dynamics is strongly coupled across a vast range of space and time scales that are both much smaller and much larger than "human" dimensions [9-13]. The important spatial scales span the range from the *grain scale*, of 1 nm to 1 cm; the *fault zone scale*, at 1 cm to 100 m; the *fault segment scale*, at 100 m to 10 km; the *fault system or network scale*, at 10 km to 1000 km; finally to the *Tectonic plate boundary scale* in excess of 1000 km. Important time scales span the range from the *source process time scale* of fractions of seconds to seconds; to the *stress transfer scale* of seconds to years; to *event recurrence time scales* of years to many thousands of years; finally to the *fault topology evolution scale*, in excess of many thousands of years up to millions of years. There is considerable evidence that many/most/all of these spatial and temporal scales are strongly coupled by the dynamics. Consider, as evidence, the Gutenberg-Richter relation, which is a power law for frequency of events in terms of cumulative event sizes. Power laws are a fundamental property of scale-invariant, self-organizing systems [14,15] whose dynamics and structures are strongly coupled and correlated across many scales in space and time. If the dynamics were were instead unconnected or random, one would expect to see Gaussian or Poisson statistics.

Simulations can help us to understand how processes operating on time scales of seconds and spatial scales of meters, such as source process times in fault zones, influence processes that are observed to occur over time scales of hundreds of years and spatial scales of hundreds of kilometers, such as recurrence of great earthquakes. Numerical simulations also allow us to connect observable surface data to underlying unobservable stress-strain dynamics, so we can determine how these are related. Thus we conclude that numerical simulations are mandatory if we are to understand the physics of earthquake fault systems. However, simulations of such complex systems are, at present, impossible to understand without some parallel theoretical investigation which gives us a framework to both interpret the vast amount of data generated and to ask the proper questions.

3 The Virtual California Model

Although all scales are important, we place more emphasis on the *fault system* or *fault network* scale, since this is the scale of most current and planned observational data networks. It is also the scale upon which the data we are interested in understanding, large and great earthquakes, occur. Furthermore, since it is not possible to uniquely determine the stress distribution on the southern California fault system, and since the friction laws and elastic stress transfer moduli are not known, it makes little sense to pursue a deterministic computation to model the space-time evolution of stress on the fault system. We therefore coarse-grain over times shorter than the source process time, which means we either neglect wave-mediated stress transfer, or we represent it in simple ways.

The Virtual_California model [5,6] is a stochastic, cellular automata instantiation of an earthquake *backslip model*, in that loading of each fault segment occurs via the accumulation of slip deficit S(t)-Vt, where S(t) is slip, V is long term slip rate, and t is time. At the present time, faults used in the model are exclusively vertical strike slip faults, the most active faults in California, and upon which most of the seismic moment release is localized. Thrust earthquakes, such as the 1994 Northridge and 1971 San Fernando faults, are certainly damaging, but they occur infrequently and are therefore regarded as perturbations on the primary strike slip fault structures. The Virtual_California model also has the following additional characteristics:

1. Surfaces of discontinuity (faults) across which slip is discontinuous at the time of an earthquake, and which are subject to frictional resistance. Surfaces analyzed in current models range from infinitely long, vertically dipping faults to topologically complex systems of vertically dipping faults mirroring the complexity found on natural fault networks.
2. Persistent increase of stresses on the fault surfaces arising from plate tectonic forcing parameterized via the backslip method.
3. Linear elastic stress transfer or interactions between fault surfaces. In some model implementations, elastic waves and inertial effects may be included in simple ways. In other implementations, details of the rupture and stress transfer process are absorbed into stochastic terms in the dynamical equations, and quasistatic stress Green’s functions are used. Other types of linear stress transfer are also possible, including linear viscoelastic and linear poroelastic physics [16].
4. Parameters for friction laws and fault topology that are determined by assimilating seismic, paleoseismic, geodetic, and other geophysical data from events occurring over the last ~200 years in California.
5. Frictional resistance laws that range from the simplest Amontons-Coulomb stick-slip friction [17], to heuristic laws such as slip- or velocity-weakening laws

[4,17,18], to laws based on recent laboratory friction experiments including rate-and-state [19-28] and leaky threshold laws [18,25,26,28], to other types of rupture and healing laws characterized by inner- and outer- physical scales [7].

In general, any of the friction laws described in bullet 5 can be written in either of the following representative, equivalent forms on an element of fault surface:

$$\frac{\partial\sigma(t)}{\partial t} = K_L V - f[\sigma(t),V(t)] \quad \text{or} \quad K_L \frac{dS(t)}{dt} = f[\sigma(t),V(t)] \qquad (1)$$

Here σ is the shear stress, and K_L is the self-interaction or "stress drop stiffness" and $f[\sigma,V]$ is the *stress dissipation function* [29]. For example, the "Amontons" or Coulomb friction law, having a sharp failure threshold, can be written in the form (1) using a Dirac delta function [28].

4 Software Technology

Virtual California simulates fault interaction to determine correlated patterns in the nonlinear complex system of an entire plate boundary region. The evolution of these patterns enables forecasts of future large events. Capturing the nonlinear pattern dy-

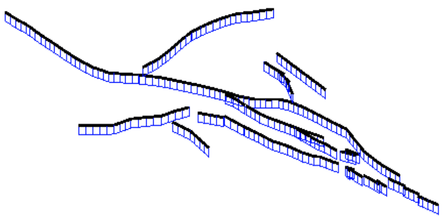

Figure 1. Model fault segment network for southern California.

namics of the fault system along a plate boundary implies the realization of a digital laboratory, which allows understanding of the mechanisms behind the observations and patterns. Our software technology development is based on the principle of scalabilityj. When it is fully deployed, researchers will be able to create and verify pat-

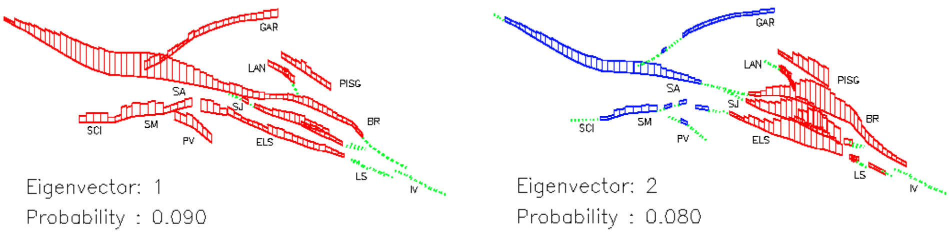

Figure 2. First two correlation eigenpatterns for model fault network shown in figure 1.

terns down to ever smaller spatial scales, which will enable cross-scale parameterization and validations, thus in turn enabling plate-boundary system analysis. The possibility of forecasting large earthquakes will therefore be greatly enhanced.

Pattern analysis methods are another type of recently developed tool. One method bins many decades of seismic activity on a gridded representation of California. Eigensystem analysis reveals clusters of correlated space and time activity. These eigenpatterns can be used to develop forecast methods [28]. When these methods attain parallel speedup we will produce better forecasts and enable speedy tests of earthquake correlations and predictions. This will be due to the ability to use much smaller geographic cell sizes and so forecast the frequent magnitude 4 earthquakes, not just the rare magnitude 6 events.

Examples of recent results using Virtual California simulations are shown in figures

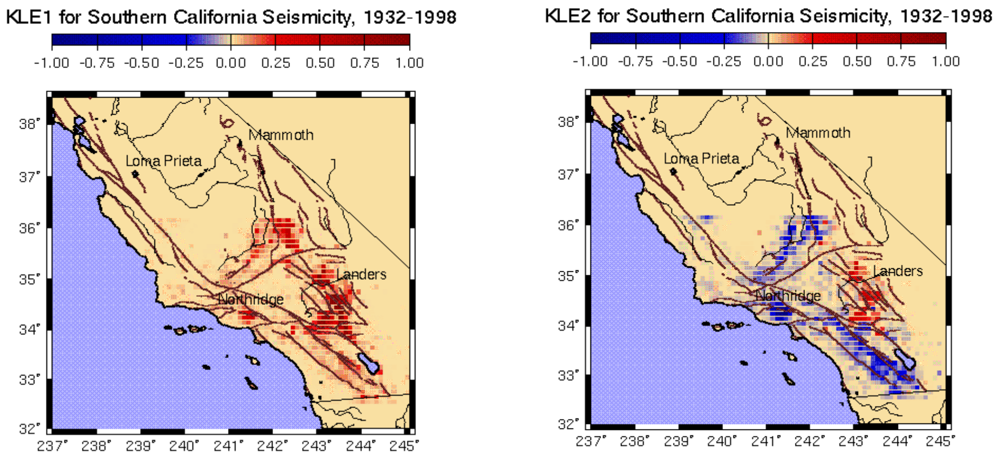

Figure 3. First two correlation eigenpatterns for the actual earthquake data in southern California since 1932.

1-2, while results from observed data in southern California are shown in Figure 3. In Figure 1 we have defined a network of fault segments based upon the actual network of faults in southern California. Figure 2 shows two of the eigenpatterns produced by activity in the model fault system. Red segments are positively correlated with red segments, negatively correlated with blue segments, and uncorrelated with other segments. Figure 3 shows similar eigenpatterns for the actual earthquake data in southern California.

4 Community Grid

As part of our work, we are also leveraging the Grid-based Community Modeling Environment (CME) under development by the Southern California Earthquake Center (SCEC) to produce an emergent computational framework for a broad class of *stress-evolution simulations* (SES) for the dynamics of *earthquake fault systems*. The purpose of SES models is to enhance basic understanding of the phenomena of earthquakes, as well as to build the computational and scientific foundations that will be needed to forecast large and damaging events. The scientific and information technology requirements for this class of physics-based simulations demand that our emergent Grid-computational framework address the following requirements of modern IT systems:

1. Space-time pattern analysis using both simulation-based approaches to computational forecasts of catastrophic and damaging earthquakes.
2. Prototyping computational methods to separate stochastic and nonlinear dynamical factors in earthquake fault networks.
3. Multi-scale analysis and modeling of the physical processes and patterns.
4. Knowledge discovery, visualization and interpretation of highly heterogeneous simulation data sets.
5. Integration of data into the simulations arising from multiple sources including surface deformation, historic and recent seismic activity, geological field investigations, and laboratory-derived friction data.
6. Integrating advanced methods for information storage and retrieval to enhance the interoperability and linkage of fixed and streaming data from observations and simulations.

We term the international collection of scientists and Grid [30-38] or web resources in a particular field as a Community Grid. Our IT research is oriented at enabling and enhancing the interaction of *all* components of the Community Semantic Grid for Earthquake Science (CSGES) for the SES effort, leading to an emergent multi-scale Grid. We are using the ideas and artifacts produced by other relevant activities from both the computer science and earth science areas, including [42-52]:

1. The major SCEC/CME-led effort to build Grid resources for the earthquake field and an information system to describe them.
2. Ontologies and XML data structures being built by SCEC, ACES (with GEM) and related fields as illustrated by OpenGIS and XMML for the mining community.
3. Parallel simulation codes with a portal interface (Gateway) [39-41] developed by GEM as part of a NASA HPCC project. The Gateway Grid Computational Environment will be a key part of the initial CSGES deployment.
4. International ACES capabilities such as the GeoFEM software and Earth Simulator hardware from Japan and the Australian ACcESS simulation software.
5. Basic collaboration capabilities among some participants including audio/video conferencing (Access Grid) and the ability for simple sharing of web pages and other documents as implemented in our system Garnet.
6. Initial designs of use of Web service technologies (WSDL, UDDI) to provide a component model for some relevant web resources.

7. Development of new dynamic models for collaborative environments coming from use of JXTA and other Peer-to-Peer technologies, integrating these with existing event-based collaborative environments.
8. Server or peer-to-peer discovery mechanisms (as in UDDI and JXTA) combining with a component model (WSDL) to lay the groundwork for emergent information systems. Note all components (objects) in the system will have in the spirit of the semantic web, meta-data defined for them which will enable the linkage of components in our proposed Semantic Grid.

5 Final Remarks

The results of our research are critical prerequisites for the analysis and understanding of space-time patterns of earthquakes on arbitrary complex earthquake fault systems. In turn, such understanding is mandatory if earthquake forecasting and prediction is to become a reality. The instantiation of any and all simulations of the dynamics of complex earthquake fault networks must allow use of the full range of methods, attributes, and parameters represented in the current physics-based earthquake simulation literature. Our work is complementary to, but does not duplicate research underway within the SCEC/ITR effort, which is focused primarily on integrating conventional and elastic-wave- based seismic hazard analysis within an emergent Grid-computational environment. Our methods emphasize the process of *optimizing, executing, integrating* and *analyzing* SES. Indeed, we argue that it is precisely the *lack* of an adequate multi-scale computational framework allowing rapid prototyping and analysis of candidate SES models that has seriously retarded the development of these types of simulations.

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