# Nonlinear Geophysics

## NG52A MCC: 103 Friday 1330h

### Scaling, Predictability, and Earthquake Fault Models *(joint with G, S, T)*

***Presiding:*** **D L Turcotte,** Cornell University**; V G Kossobokov,** International Institute of Earthquake Prediction Theory**; K F Tiampo,** University of Colorado**; M Glasscoe,** University of California, Davis

#### NG52A-01 1330h INVITED

**Scaling and Correlations in Earthquakes**

Luciano Pietronero[1] (+39-06-49913488; luciano@pil.phys.uniroma1.it)

Luigi Ciofi degli Atti[1]

Vittorio Loreto[1] (loreto@pil.phys.uniroma1.it)

[1]Universita degli Studi di Roma "La Sapienza", P.le A. Moro 5, Roma 00185, Italy

Most of the breakdown phenomena of interest show instabilities at all sizes or scales. In this respect they represent an ideal playground to apply and test the novel concepts of critical and self-organized structures that have been developed mostly in physics. The basic idea is that the application of these new concepts should lead to a broader and deeper understanding of these phenomena. In this way it should be possible to cast the concept of predictability within a scientific framework, leading to a new generation of analysis and prediction methods.

It is with this spirit that we have analyzed space-time correlations in real earthquakes catalogs with the aim to define new statistical parameters for a quantitative description of the seismicity. We introduce in particular a method suitable to identify the spatial extension L(m) and the time duration T(m) of the aftershocks series as a function of the main event's magnitude m. It turns out that L(m) and T(m) are multivalued functions: events of the same magnitude may display significant fluctuations in the spatial extensions and durations of the aftershocks series. This method provides a new framework to define declustered catalogs which represent one of the main ingredient of any statistical analysis of the seismicity.

#### NG52A-02 1345h INVITED

**On the short-term earthquake prediction: renormalization algorithm and observational evidence in S. California, E. Mediterranean, and Japan**

Vladimir Keilis-Borok[1,2,3] (vkb@ess.ucla.edu)

Peter Shebalin[3] (shebalin@mitp.ru)

Ilya Zaliapin[1,3] (zal@ess.ucla.edu)

Olga Novikova[3] (onovikov@mitp.ru)

Andrei Gabrielov[4] (agabriel@math.purdue.edu)

[1]Institute of Geophysics and Planetary Physics, UCLA, Los Angeles, CA 90095, United States

[2]Department of Earth and Space Sciences, UCLA, Los Angeles, CA 90095, United States

[3]International Institute for Earthquake Prediction Theory and Mathematical Geophysics, Warshavskoe sh., 79, korp. 2, Moscow 113556, Russian Federation

[4]Departments of Mathematics and Earth and Atmospheric Sciences, Purdue University, West Lafayette, IN 47907, United States

Our point of departure is provided by premonitory seismicity patterns found in models and observations. They reflect increase of earthquake correlation range and seismic activity within "intermediate" lead-time of years before a strong earthquake. A combination of these patterns, in renormalized definition, precedes within months eight out of nine strong earthquakes in S. California, E. Mediterranean, and Japan. We suggest on that basis a hypothetical short-term prediction algorithm, to be tested by advance prediction. The algorithm is self-adapting and can be transferred without readaptation from earthquake to earthquake and from area to area. If confirmed, it will have a simple, albeit non-unique, qualitative interpretation. The suggested algorithm is designed to provide a short-term approximation to an intermediate-term prediction. It remains not clear, whether it could be used independently.

URL: http://www.igpp.ucla.edu/mcdonnell

#### NG52A-03 1400h INVITED

**Discrete Models of Seismicity: A Case Study in Complexity**

William I. Newman (310 825 3912; win@ucla.edu)

University of California, Dept. Earth and Space Sciences, Los Angeles, CA 90095, United States

Complexity describes the transition from order to chaos, where nonlinear interactions inextricably link space and time, where the whole is greater than the sum of its parts. Complexity may be seen in patterns that can reproduce at different scales embracing a hierarchy of interactions, where fractal structures are often produced, yet preserving a subtle sensitivity in its detail to its starting point. The seismicity observed in the earth is an example of such a complex system. While the equations of mathematical physics are generally given continuum representations, discrete models offer substantial simplification both in simulations and in their mathematical properties without sacrificing the essential physics. By combining discrete models with features derived from the renormalization group, we can learn much about scalings, cascades, and possibly predictability in application to many geophysical phenomena, including seismicity. We begin with percolation models, focusing on the emergence of criticality and relevance to modeling forest fires and earthquake events. Slider-block models are considered as well as their non-inertial equivalents, so-called "sandbox" models. We present fiber bundle models as a description of hierarchical structure, and then progress to colliding-cascades model for seismicity which have been successful recently in describing all observed scalings present in seismicity but have lead as well to the discovery of new scalings.

#### NG52A-04 1415h INVITED

**The Fractal Approach to Estimation of the Physical Parameters of Seismicity**

Vladimir Smirnov (7-095-9393848; smirnov@phys.msu.su)

Earth Physics Dept., Physics Faculty, Lomonosov Moscow State University, Leninskie Gory, Moscow, RUS 119992, Russian Federation

Modern physical theory of the failure is based on the fault mechanics and the kinetics of the multi-scale defects in the stress field. This theory contains a series of key parameters which define the character of the failure process. That are first of all such parameters, as the durability of a material in the kinetic concept of strength (known in seismology as a period of seismic cycle or earthquake recurrence time) and the critical concentration of cracks in a crack mechanics. The first one represents the intensity of the failure process; second one reflects the degree of crack interaction. Usual information for estimation of these physical parameters for the seismosphere of the Earth is statistics of earthquakes. However, the problem of quantitative comparison of the results of seismic statistics with the deductions of the physical theory lies in the discordance of corresponding spatial sizes. The typical size of the failure physics is the size of area of failure earthquake source size for seismology. Statistical estimates relate to areas containing a set of earthquakes and having, therefore, the size much more then t?? earthquake source. Hence, the transference of statistical estimates in theoretical field is their extrapolation in the space scales. Such extrapolation is correct only under the adequate account of character of the spatial structure of seismicity.

The combination of the fractal approach to the geometry of seismicity and Gutenberg- Richter relation (known as generalized GR relation) allows us to obtain correct estimates of the physical parameters of seismicity. The technique and results of such estimates, their dependence on the earthquake magnitude are discussed for different regions of the World.

This work is carried out under financial support of the Russian Foundation for Basic Research, grant # 02-05-64268.

#### NG52A-05 1450h INVITED

**Elastodynamic Simulation of Fault System Dynamics**

Peter Mora[1,2] (+61 7 33652128; mora@quakes.uq.edu.au)

Dion Weatherley[1,2] (+61 7 33654853; dion@quakes.uq.edu.au)

[1]QUAKES, The University of Queensland, Brisbane, Qld 4072, Australia

[2]Australian Computational Earth Systems Simulator, The University of Queensland, Brisbane, Qld 4072, Australia

Previous simulations of granular systems subjected to shear with the lattice solid model have exhibited evolution of the stress correlation function in the leadup to large events. While these results provide evidence for a Critical Point-like mechanism in elasto-dynamic systems and the possibility of earthquake forecasting, it remains unclear whether such a mechanism will occur in more realistic models of interacting fault systems or in the real earth. Furthermore, CA simulations suggest that both Self-Organised Critical and Critical Point behaviours are possible depending on the values of tuning parameters. This suggests that even if the the crust does exhibit CP-like behaviour, a given fault system may not depending on the tuning parameters such as fault density, the statistics of fault friction, and dissipation. To progress towards resolving this issue, we develop a 2D fully elasto-dynamic model of parallel interacting faults. Either slip or velocity weakening friction can be defined along faults. Slip weakening friction and a power law distribution of static and dynamic friction coefficients is specified. Numerical shear experiments are conducted in a model with ten parallel interacting faults and fault friction power law exponents of 0.6 and 1.6. The results exhibit a complex evolution of the stress field and a number of interesting features including activity switching between faults and fault segments in the model. The event size distributions are essentially a power law with a slight overabundence of large events. Based upon comparisons with CA simulation results, this suggests the system is in the SOC part of phase space although further analysis is required to confirm this hypothesis. Numerical expriments are now in progress using different fault densities, fault friction statistics and slip weakening distance to study whether or not the model exhibits both critical point and SOC behaviour like the CA models. The model provides a crucial link between CA maps of phase space (e.g. that show regimes of CP or SOC behaviour) and the behaviour of more realistic elasto-dynamic interacting fault system models, and thus, a means to improve understanding of the complex system behaviour of real fault systems and progress towards the goal of a scientific underpinning for earthquake forecasting

#### NG52A-06 1505h INVITED

**Problems and Challenges in Earthquake Simulations**

John B Rundle (530-752-1500; rundle@physics.ucdavis.edu)

Department of Physics University of California, Davis, One Shields Ave., Davis, CA 95616

We describe problems and challenges in constructing topologically realistic simulations of active earthquake fault systems, focusing on 1) Rationales for incorporating successive hierarchies of physical processes and layers of detail; 2) Computational issues associated with performance, efficiency, and optimization of codes; and 3) Knowledge acquisition, related to data mining, visualization, and comparison with theory. Numerical simulations of physical systems are particularly useful for investigating the relationship between observable multi-scale space-time patterns in data and the fundamentally unobservable, underlying multi-scale dynamics that produce them. In general, simulations are designed to provide physical understanding of fault system processes and their influence on factors such as: 1) Seismic activity through time; 2) Surface displacements observable by GPS, strainmeters and InSAR; 3) Relative importance of fault network topology and frictional processes in determining dynamical behavior; and 4) Partitioning of slip and seismic activity among active strike slip faults in California. As an example of how simulations can provide substantial insight into the collection, processing, and interpretation of observational data, we discuss a new result suggesting that surface observations from NASA space geodetic data can be used to construct a new type of fluctuation metric, a Local Ginzburg Criterion. Since earthquakes are now interpreted as generalized phase transitions, techniques can be developed that make use of fluctuation-related phenomena to image the underlying dynamics from data. In particular, the form of our friction equations, which are based on laboratory experiments, suggest that the strain rate should be viewed as an order parameter, whose mean value is high immediate prior to a large earthquake, and jumps discontinuously to a low mean value immediate following the event. From ideas developed in these simulations, we propose a new mapping function, which we call a Local Ginzburg Criterion, that can be used to reveal information about the underlying dynamics using surface strain rate observations on fault systems.

NG

### NG52A-07 1520h INVITED

#### Creating a Distributed, Community-Modeling Environment in Support of the Working Group for the Development of Regional Earthquake Likelihood Models (RELM)

Edward H Field[1] ((626) 583-7814; field@usgs.gov)

Thomas H Jordan[2] ((213) 821-1237; tjordan@usc.edu)

[1]U.S. Geological Survey, 525 S. Wilson Ave, Pasadena, CA 91106-3212, United States

[2]Department of Earth Sciences, University of Southern California, Los Angeles, CA 90089-0740, United States

Several recent studies have concluded that improvements in seismic hazard analysis (SHA) will require a more physics-based, system-level approach. To this end, a working group for the development of Regional Earthquake Likelihood Models (RELM; www.relm.org) has been established to develop, test, and evaluate the hazard implications of a variety of viable earthquake-forecast models. One problem faced by this working group is the lack of a computational infrastructure capable of dealing with the wide variety of models under development. Therefore, a new effort known as OpenSHA (www.OpenSHA.org) is developing an object-oriented, open-source, and web-based community-modeling environment. The goal is to enable various SHA components (including the RELM forecast models) to plug in for analysis without having to change whats being plugged into. This infrastructure will also allow the models, as well as the various data repositories upon which they depend, to be geographically distributed and run-time accessible. Building such a community-modeling environment raises several issues related to computational speed, ease of use, error prevention, and repeatability of results in an environment where the models and data are continually being updated. The Information-Technology Research collaboration of the Southern California Earthquake Center is helping us resolve some of these issues.

URL: http://www.relm.org

### NG52A-08 1535h INVITED

#### The Solid Earth Research Virtual Observatory: A web-based system for modeling multi-scale earthquake processes

Andrea Donnellan[1] (818-354-4737; donnellan@jpl.nasa.gov); Geoffrey Fox[2] (gcf@indiana.edu); John Rundle[3] (jbrundle@ucdavis.edu); Dennis McLeod[4] (mcleod@pollux.usc.edu); Terry Tullis[5] (Terry_Tullis@brown.edu); Lisa Grant[6] (lgrant@uci.edu); Jay Parker[1] (Jay.W.Parker@jpl.nasa.gov); Marlon Pierce[2] (marpierc@indiana.edu); Gregory Lyzenga[1] (Gregory.Lyzenga@jpl.nasa.gov); Anne Chen[4] (yuanche@usc.edu); John Lou[1] (John.Z.Lou@jpl.nasa.gov)

[1]Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA 91109-8099, United States

[2]Indiana University, Community Grid Computing Laboratory 501 N. Morton, Suite 224, Bloomington, IN 47404-3730, United States

[3]University of California, Center for Computational Science and Engineering, Davis, CA 95616, United States

[4]University of Southern California, Mail Code 0781 3651 Trousdale Parkway, Los Angeles, CA 90089-0742, United States

[5]Brown University, Department of Geological Sciences, Providence, RI 02912-1846, United States

[6]University of California, Environmental Analysis and Design, Irvine, CA 92697-7070, United States

We are building a new Problem Solving Environment for use by the seismological, crustal deformation, and tectonics communities for developing an understanding of active tectonic and earthquake processes. The top-level operational architecture of our solid earth research virtual observatory (SERVO) shows science users interacting with interface programs as well as modeling, simulation, and analysis tools. The general architecture follows the Web Services model being developed by business interests, but is applied to scientific applications and supporting software resources (such as databases). The system is divided into three tiers: a user interface layer (implemented as a browser interface), a system resource layer, and a middle control layer that maintains proxies (or brokers) to the system resources. The middle tier provides a uniform interface to the resource layer. Following the Web Services approach, we define XML interface abstractions (in WSDL) for basic services (such as File Management) and implement the interface with appropriate technologies (such as with a relational database). Communication between the services is done with an XML messaging architecture (SOAP). Our initial focus is to integrate time-dependent crustal deformation models into the system including both layered analytical and heterogeneous finite element models.

URL: http://www.servogrid.org

### NG52A-09 1550h

#### Physics-Based Predictive Simulation Models for Earthquake Generation at Plate Boundaries

Mitsuhiro Matsu'ura (81-3-5841-4318; matsuura@eps.s.u-tokyo.ac.jp)

Department of Earth and Planetary Science, The University of Tokyo, Hongo 7-3-1, Bunkyo-ku, Tokyo 113-0033, Japan

In the last decade there has been great progress in the physics of earthquake generation; that is, the introduction of laboratory-based fault constitutive laws as a basic equation governing earthquake rupture and the quantitative description of tectonic loading driven by plate motion. Incorporating a fault constitutive law into continuum mechanics, we can develop a physics-based@simulation model for the entire earthquake generation process. For realistic simulation of earthquake generation, however, we need a very large, high-speed computer system. In Japan, fortunately, the Earth Simulator, which is a high performance, massively parallel-processing computer system with 10 TB memories and 40 TFLOPS peak speed, has been completed. The completion of the Earth Simulator and advance in numerical simulation methodology are bringing our vision within reach. In general, the earthquake generation cycle consists of tectonic loading due to relative plate motion, quasi-static rupture nucleation, dynamic rupture propagation and stop, and restoration of fault strength. The basic equations governing the entire earthquake generation cycle consists of an elastic/viscoelastic slip-response function that relates fault slip to shear stress change and a fault constitutive law that prescribes change in shear strength with fault slip and contact time. The shear stress and the shear strength are related with each other through the boundary conditions on the fault. The driving force of this system is observed relative plate motion. The system to describe the earthquake generation cycle is conceptually quite simple. The complexity in practical modelling mainly comes from complexity in structure of the real earth. Since 1998 our group have conducted the Crustal Activity Modelling Program (CAMP), which is one of the three main programs composing the Solid Earth Simulator project. The aim of CAMP is to develop a physics-based predictive simulation model for the entire earthquake generation cycles in and around Japan. The total simulation system is divided into three components: a crust-mantle structure model, a tectonic loading model and a dynamic rupture model. For a San Andreas type of plate boundaries we have already developed a standard model. In the case of convergent plate boundaries, although the basic equations governing the earthquake generation cycle are essentially the same as those in the case of transcurrent plate boundaries, the practical modelling is much more difficult, because of complexity in geometry of plate interfaces. For the present we have developed a 3-D standard structure model of plate interfaces in and around Japan, the viscoelastic slip-response functions for this structure model, and the slip- and time-dependent fault constitutive law with an inherent strength-restoration mechanism. Combining all these elements, we can construct a quasi-static tectonic loading model. For the dynamic rupture process, we have developed a simulation algorithm for rupture propagation on a 3-D curved fault surface by applying BIEM. In the last stage of CAMP the quasi-static loading model and the dynamic rupture model are connected with each other through a simulation platform on the Earth Simulator. Outputs of the simulation system are the crustal deformation, internal stress change and seismic wave radiation associated with the progress of seismic and/or aseismic slip on the plate interfaces. From comparison of these computed data and observed data, we can extract useful information to estimate the past slip history and the present stress state on the plate interfaces by using a technique of inversion analysis.

### NG52A-10 1605h

#### A Proposed Physical Model of Strain Accumulation in the San Francisco Bay Region

Fred F. Pollitz[1] (650-329-4821; fpollitz@usgs.gov)

Marleen C.J. Nyst[1] (650-329-4897; nyst@geo.uu.nl)

[1]U.S. Geological Survey, 345 Middlefield Rd., MS 977, Menlo Park, CA 94566, United States

Strain accumulation in tectonically active regions is dependent on several factors, including background tectonic loading, steady-state dislocation processes such as creep, and transient deformation. In the San Francisco Bay (SFB) region, the most uncertain of these processes is transient deformation, which arises primarily in association with large historic earthquakes. As such it depends upon the history of faulting and the rheology of the crust and mantle, which together determine the pattern of longer-term (decade-scale) post-seismic response to earthquakes. We utilize a set of 99 GPS velocity vectors in the SFB region in order to characterize the strain field and construct a physical model of its present deformation. We first perform an inversion for the continuous velocity gradient field from the discrete GPS velocity field, from which both tensor strain and rotation may be extracted. We then fit this strain field to a model of time-dependent deformation within a 135 km-wide, arcuate shear zone bounded by strong Pacific plate and Sierra Nevada block lithosphere to the SW and NE, respectively. Driving forces are purely lateral, consisting of shear zone deformation imposed by the relative motions between the thick Pacific plate and Sierra Nevada block lithospheres. Assuming depth-dependent viscoelastic structure within the shear zone, we account for the effects of steady creep on faults and viscoelastic relaxation following the 1906 San Francisco and 1989 Loma Prieta earthquakes, subject to constant velocity boundary conditions on the edges of the shear zone: 38 mm/yr fault-parallel motion and variable fault-perpendicular motion. Fault creep is realized by evaluating dislocations on the creeping portions of faults in the fluid limit of the viscoelastic model. The present strain pattern is well-described as a nearly uniform shear strain oriented approximately N35°W (140 nanostrain/yr) plus a more heterogeneous N55°E uniaxial compression averaging 20 nanostrain/yr across the shear zone. A grid search based on fitting the observed strain pattern yields a mantle viscosity of $1.2 \times 10^{19}$ Pa s and a fault-perpendicular convergence rate of $\sim 3$ mm/yr. Most of this convergence appears to be accommodated in a zone much narrower than the Pacific-Sierra Nevada plate boundary zone.

## NG52B MCC: 103 Friday 1630h

## The Lorenz Lecture Series: Donald Turcotte

*Presiding:* **J Rundle,** University of Colorado**; S Tebbens,** University of South Florida

### NG52B-01 1635h INVITED

#### Self-Organized Complexity in Geophysics

Donald L. Turcotte (607-255-7282; turcotte@geology.cornell.edu)

Cornell University, Snee Hall, Ithaca, NY 14853, United States

It is easy to give examples of self-organized complexity in geophysics, examples include fluid turbulence, earthquakes, drainage networks, and many others. It is much more difficult to define what is and what is not self-organized complexity. Two common characteristics are: (1) fractal behavior and (2) chaotic behavior. Two simple models that have been introduced in statistical physics typify self-organized complexity: (1) diffusion limited aggregation (DLA) and (2) site percolation. DLA is a random branching network that exhibits Horton-Strahler and Tokunaga branching statistics. So do stream networks. Site percolation is