NG41B-0063 0830h POSTER

Numerical insights into 3-D microprocesses responsible for macroscopic granular shear

James F Hazzard[1] (j.hazzard@utoronto.ca)

Karen Mair[1] (k.mair@utoronto.ca)

Paul Young[1] (paul.young@utoronto.ca)

[1]Lassonde Institute, University of Toronto, Room 119, 170 College St., Toronto, ON M5S 3E3, Canada

Earthquakes commonly occur on faults containing significant accumulations of gouge therefore investigating the processes operating in granular material under shear is extremely relevant to earthquake and fault mechanics. We present a 3-D numerical model of a granular layer subjected to shear in which grains are represented by individual spheres interacting at points of contact. The 3-D models exhibit macro friction levels notably higher than corresponding 2-D models and values that approach those of recent laboratory experiments on spherical beads. The 3-D models and laboratory studies also show much smaller fluctuations in friction than the corresponding 2-D simulations. The numerical model enables an investigation of the microprocesses that produce this observed macro behavior including visualization of grain sliding, grain rolling and the evolution of transient force chains. In 3-D, an extra dimension of grain interaction reduces the ability of the grains to accommodate strain through rolling as is observed in 2-D resulting in an increase in the mean macro friction level. It is shown that fluctuations in friction are directly related to grain reorganization normal to shear. In 3-D, these fluctuations are reduced due to significant particle motion in the third dimension, leading to a steady frictional sliding curve. Since these geometrical fluctuations are small compared with 2-D models, our 3-D simulation offers potential to investigate small amplitude but extremely important second order rate and state friction effects that fundamentally control the strength and stability of fault zones.

NG41B-0064 0830h POSTER

Model of Dynamical Slip Events and the Generation of Propagating Slip Pulses

Jean E El Khoury[1] (1-310-8253179; elkhoury@ess.ucla.edu)

Leon Knopoff[1] (1-310-8251885; knopoff@physics.ucla.edu)

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

We describe a new model for the simulation of extended dynamical slip events and for the rapid calculation of the Statistical properties of repeated model seismicity events. The fault model generates 2-D in-plane dynamical ruptures. The discretization involves first- and second-nearest neighbors, is of Burridge-Knopoff type and is isotropic in both compression and shear properties. All rupture events are causal and numerical oscillations in slip velocity at crack tips due to discretization are minimized. The computational speed is fast in comparison with 3-D models; in sample tests of statistical compilations, 10^5 events can be simulated in about 1.5 hours on a contemporary PC. We use the model to study growth and healing of individual faults in an effort to understand the formation of propagating slip pulses. We consider an elongated rectangular model fault in which the upper surface is free and the lower boundary is rigid. The rupture velocities of fractures with homogeneous stress drop equal to the strength, are the P-wave velocity in the direction of the prestress and the S-wave velocity in the perpendicular direction. Two mechanisms for generation of isolated rupture pulses have been proposed, which are 1) an increase in the dynamical friction with decelerating slip and 2) encounter with elongated regions of large difference between the threshold fracture stress and the prestress. We have identified a third mechanism which is that of a velocity dependent friction that operates equally on the phases of increasing and decreasing slip velocities and has a characteristic length scale. This frictional mechanism is a parameterization of the absorption of near-fault fracture energy in large earthquakes during the formation of aftershock zones. Pulses develop due to the influence of stress waves reflected from the rigid bottom boundary of the seismogenic slab. In general, crack fracture speeds are controlled by excess of strength over stress drop; if it is too large, the crack stops. For given boundary conditions, slip velocities are higher where prestresses are higher. Isolated slip pulses have small static slips and rise times for small thicknesses of the seismogenic zone and for large values of the near-fault absorption.

NG41B-0065 0830h INVITED POSTER

Systematic Analysis of Shear-Wave Splitting in the Aftershock Zone of the 1999 Chi-Chi Earthquake: Evidence for Shallow Crustal Anisotropy and Lack of Temporal Variations

Yunfeng Liu[1] (yunfengl@terra.usc.edu)

Ta-Liang Teng[1] (lteng@terra.usc.edu)

Yehuda Ben-Zion[1] (benzion@terra.usc.edu)

[1]Dept. of Earth Sciences, University of Southern California, University Park, Los Angeles, CA 90089, United States

We analyze shear-wave splitting (SWS) in a high-quality waveform data set recorded at surface and downhole (0.2 km) seismometers in a region around the 1999 M_W 7.6 Chi-Chi, Taiwan, earthquake sequence. The data set was generated by events before, during and after the mainshock. The purpose is to investigate the spatial distribution of stress-induced crustal anisotropy and its possible temporal evolution in relation to the occurrence of large earthquakes. Results from downhole records show a stable polarization direction of the fast shear wave which matches well the local GPS velocity field. A slightly different polarization direction of the fast shear wave is obtained from surface data. This suggests a possible anisotropy change between the top 0.2 km structure and the deeper section of the crust. Measured time delays below the downhole station have an average value 0.16 sec without systematic changes for sources from about 8 km to 20 km in depth. Estimates of time delays in the top 0.2 km of the crust based on shear waves reflected from the free surface give a constant 0.04 sec. These two types of measurements and an S-velocity model indicate that the crustal anisotropy in the region is dominated by the top 2 - 3 km. The measured polarization directions and time delays give essentially constant values over the study period in the region adjacent to the Chi-Chi earthquake and within 10 km to the epicentral region of its two large M 6.0 aftershocks. Analysis of SWS in waveforms produced by earthquake multiplets confirms further the lack of temporal variations. This raises doubts on the usefulness of SWS measurements for earthquake forecasting.

NG41C MCC: Level 1 Thursday 0830h

Critical Point Theory and Space-Time Pattern Formation in Precursory Seismicity II Posters *(joint with S, T)*

***Presiding:* K Tiampo,** University of Western Ontario**; M Anghel,** Computer and Computational Sciences Division

NG41C-0066 0830h POSTER

An Observational Test of the Stress Recovery Model for Seismicity Preceding Landers.

Shoshana Z. Levin[1] (1-213-821-2518; shoshanl@earth.usc.edu)

Charles G. Sammis[1] (1-213-740-5836; sammis@earth.usc.edu)

David D. Bowman[2] (1-714-278-5436; dbowman@fullerton.edu)

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

[2]Cal-State Fullerton, Department of Geological Sciences, Fullerton, CA 92834-6850, United States

We test the Bowman and King [GRL, 2001] "stress recovery" model by examining the pattern of strain released by small events prior to the 1992 Landers earthquake. The stress recovery (SR) model was developed to explain observations of accelerating seismicity preceding large earthquakes. The model proposes that the accelerating seismicity sequences result from tectonic loading that erodes the stress shadow from a prior event and increases elastic strain across the locked portion of the main fault. We test the prediction of the SR model that the pattern of strain released by the precursory seismicity should correlate with the strain building across the locked portion of the main fault. Our results show correlation of the seismicity-based strain field with the pre-Landers model strain field, and weak anti-correlation with the post-Landers model strain field. The correlation and anti-correlation are optimized when an approximately N-S compressive stress of 8 to 20 bars is added to the model.

NG41C-0067 0830h POSTER

Forecasting Earthquakes in Southern California Using the Stress Accumulation Method

Julia Clark[1] (714 278-5436; malichan99@hotmail.com)

Nancy Ikeda[1] (714 278-5436; nikeda@qwickconnect.net)

David Bowman[1] (714 278-5436; dbowman@fullerton.edu)

[1]California State University, Fullerton, 800 N. State College Blvd, Fullerton, CA 92834-6850, United States

Many large earthquakes are preceded by a regional increase in seismic energy release. This phenomenon, called "accelerating moment release" (AMR), is due primarily to an increase in the number of intermediate-size events in a region surrounding the mainshock. Bowman and King (GRL, 2001) and King and Bowman (JGR, 2003) have described a technique for calculating an approximate geologically-constrained loading model that can be used to define regions of AMR before a large earthquake. While this method has been used to search for AMR before large earthquakes in many locations, most of these observations are "postdictions" in the sense that the time, location, and magnitude of the main event were known and used as parameters in determining the region of precursory activity. With sufficient knowledge of the regional tectonics, it should be possible to estimate the likelihood of earthquake rupture scenarios by searching for AMR related to stress accumulation on specific faults. Here we show a preliminary attempt to use AMR to forecast strike-slip earthquakes on specific faults in southern California. The false-alarm rate for this method is also estimated using synthetic earthquake catalogs.

NG41C-0068 0830h POSTER

Short-Term Premonitory Rise of the Earthquake Correlation Range

Vladimir Keilis-Borok[1,2,3] (vkb@ess.ucla.edu); Peter Shebalin[2] (shebalin@mitp.ru); Andrei Gabrielov[4] (agabriel@math.purdue.edu); Ilya Zaliapin[1,2] (zal@ess.ucla.edu); Seiya Uyeda[5] (suyeda@st.rim.or.jp); Toshiyasu Nagao[5] (nagao@scc.u-tokai.ac.jp)

[1]Institute of Geophysics and Planetary Physics, UCLA, 3845 Slichter Hall, Los Angeles, CA 90095-1567, United States

[2]International Institute for Earthquake Prediction Theory and Mathematical Geophysics, Russian Ac. Sci., Warshavskoe sh., 79, korp. 2, Moscow, C 119556, Russian Federation

[3]Department of Earth and Space Sciences, UCLA, 3845 Slichter Hall, Los Angeles, CA 90096-1567, United States

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

[5]Earthquake Prediction Research Center, Tokai Univ., 3-20-1, Orido,, Shimizu 424-8610, Japan

This study explores the possibility of short-term earthquake prediction, with the lead-time months to weeks. Prediction considered is based on the evolution of seismicity preceding a strong earthquake. We have found the following two-steps sequence: 1) Within years before a strong earthquake — rise of seismic activity, rise of earthquakes clustering in space and time, and specific transformations of Gutenberg-Richter relation. 2) Within weeks before that earthquake — rise of earthquakes correlation range. These phenomena have been captured by premonitory seismicity patterns previously established in the studies of observed and theoretically modeled seismicity. We have used the same formal definitions of premonitory patterns as in these studies. Change of their scaling allowed us to narrow down the time and territory within which a strong earthquake is predicted. Summing up these findings we formulate a hypothetical short-term prediction algorithm. Territorial accuracy of prediction is considerably increased by reverse order of the analysis: First, we determine the chains of earthquakes exhibiting short-term rise of the earthquakes correlation range. Then, we check for each chain whether the patterns from stage 1 did emerge in its vicinity. If the answer is yes, algorithm declares a short-term alarm. Suggested algorithm was applied retrospectively to 27 large earthquakes: 18 in Japan (M = 7) and 9 in California (M = 6.4). The results are highly encouraging. However the only decisive test will be advance prediction. In conclusion we outline the possible physical interpretation of the suggested algorithm.

NG41C-0069 0830h INVITED POSTER

Long-Term Earthquake Forecasts in the San Francisco Bay Area: A Contrarian Perspective

Allan Goddard Lindh (831-457-8848; aglindh@cruzio.com)

U.S. Geological Survey, 277 Molina Drive, Santa Cruz, CA 95060, United States

In historic time the San Francisco Bay Area (SFBA) has been the site of four large earthquakes, including the M7.8 1906 San Francisco earthquake, and most recently, the M6.9 1989 Loma Prieta earthquake. Of the eight major fault segments considered here, two have not experienced large earthquakes in about 200 years, and the SF Peninsula segment of the 1906 rupture on the San Andreas appears from my calculations to be close to fully reloaded as well. I have used simple geophysical and statistical models (elastic rebound model and Weibull distribution) to estimate the probability of large earthquakes (M7 or larger) in the SFBA in the coming decades. I have used seismicity, geology, and geodesy to estimate segment boundaries, recurrence intervals, and the associated uncertainties. The results indicate that the SFBA has an approximately 80% chance of a large earthquake in the next 30 years, with four segments dominating the 30 yr probabilities; San Francisco Peninsula (32%), Southern Hayward (39%), Northern Hayward (28%) and Rodgers Cr (30%). Because of the proximity of these four segments to the urban portions of San Francisco and Oakland, the probability of these most vulnerable areas experiencing strong ground motion (an M7 within 25 km or less) one or more times within the next 30 years is about 70%. Because of the breadth and quality of our understanding of the earthquake machine in the SFBA, these probabilities depend in large part on the intrinsic variance in the earthquake recurrence process itself – most conveniently expressed as the ratio of the standard deviation to the mean recurrence time, or intrinsic coefficient of variation (CV_I). I have applied a new approach to estimating CV_I, using the time since the last characteristic event (the "open-interval") on well characterized segments. Combined with an estimate of the mean recurrence time on each segment, an estimate of the likelihood of each open interval can be computed, and a simple maximum likelihood procedure used to choose the best fitting value of CV_I. This approach has significant advantages over the more common approach of using a sequence of paleoseismic dates to estimate CV_I, since the completeness of paleoseismic records is always in question, and even one missed event seriously biases estimates of CV_I. The power in the technique lies not in establishing that a sequence of earthquake recurrence dates is very regular, but rather in establishing that there are no very short intervals; large values of CV_I imply a large fraction of short recurrence intervals. Analysis of 10 major segments in California for which the requisite data are available yields an estimate for CV_I of 0.2 or less; this value was used in the calculations outlined above. If we use this model to "backcast" seismicity rates for the last few centuries, we can fit reasonably well the large decrease in moderate seismicity following the 1906 earthquake, even though each segment is modeled independently. That is, no far-field stress perturbations from 1906 have been used in this work, nor do they appear to be needed to account for the gross variations in seismicity rate. This may call into question the wide-spread assumption that a "stress shadow" is self-evident following 1906, and suggests that more careful modeling is required to establish whether far-field stress changes are necessary to fit the observations. Prior statistical tests have shown that the observed variations are extremely unlikely, given a Poisson model for a null hypothesis. From the work presented here it appears one could not reject a simple time-dependent model in the same manner, even though it includes no far-field stress effects.

NG41C-0070 0830h POSTER

Evaluation and Development of the Pattern Informatics Method of Earthquake Forecasting

James Holliday[1] (530-752-6419; jholliday@physics.ucdavis.edu); John Rundle[1] (530-752-6416; jbrundle@ucdavis.edu); Kristy Tiampo[2] (ktiampo@uwo.ca); Andrea Donnellan[3] (andrea.donnellan@jpl.nasa.gov); W Klein[4] (klein@buphy.bu.edu); Don Turcotte[5] (turcotte@geology.ucdavis.edu)

[1]Ctr. Comp. Sci. & Eng., University of California One Shields Ave., Davis, CA 95616, United States

[2]Dept. of Geology, University of Western Ontario, London, Ont N6A 5B8, Canada

[3]Earth and Space Science Division of Earth and Space Sciences, Jet Propulsion Laboratory 4800 Oak Grove Drive, Pasadena, CA 91109, United States

[4]Dept. of Physics, Boston University 590 Commonwealth Ave., Boston, MA 02215, United States

[5]Dept. of Geology, University of California One Shields Ave., Davis, CA 95616, United States

We report results exploring the Pattern Informatics (PI) method of earthquake forecasting, in which state vectors are first constructed to characterize earthquake activity in seismically active regions, then used to compute a probability index forecasting future activity of large events. This method makes use of a description of the state of earthquake seismicity in terms of a phase-dynamical state vector in a Hilbert space. Using these state vectors, we compute the change in state over a period of time preceding the forecast interval. Probability change is then found by squaring the state vector difference, then subtracting off the average background rate. Here, we examine the influence of varying the amount of historic data included in formulating the forecast, and show that results are increasingly unreliable as the data set used is progressively truncated from below. We also report very preliminary results for other seismically active regions. Finally we discuss future work, including particularly the goal of using complex-valued state vectors constructed via a Hilbert transform instead of the real-valued state vectors currently used.

NG41C-0071 0830h POSTER

Rupture Source Identification Prior to the Occurrence of Large Events

Kristy F Tiampo[1] (ktiampo@uwo.ca)

John B Rundle[2] (jbrundle@ucdavis.edu)

William Klein[3] (klein@buphy.bu.edu)

[1]Department of Earth Sciences, University of Western Ontario, London, ON N6A 5B7, Canada

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

[3]Department of Physics, Boston University, Boston, MA 02215, United States

Large, extended fault systems such as those in California are known to demonstrate complex space-time seismicity patterns, which include, but are not limited to, repetitive events, precursory activity and quiescence, and aftershock sequences. Here a pattern informatics analysis technique, formulated based on the physical and theoretical understanding of complex, nonlinear fault systems, is employed to isolate emergent regions of coherent, correlated seismicity prior to their occurrence. This pattern informatics (PI) methodology is employed to identify systematic space-time variations in the seismicity of the California fault system. Analysis of data taken prior to large events reveals that the appearance of coherent, correlated regions that delineate the source regions associated with the future occurrence of major earthquakes, the nucleation zone anticipated as the crust approaches a critical state before a large event.

NG41C-0072 0830h INVITED POSTER

On the role of disorder upon the effective dimensionality and dynamic complexity of earthquake faults

Dion K Weatherley[1,2] (61 7 3346 9797; dion@quakes.uq.edu.au)

Marian Anghel[3] ((505) 667-9470; manghel@lanl.gov)

[1]QUAKES, Earth Systems Science Computational Centre, University of Queensland, St. Lucia, Qld 4072, Australia

[2]Australian Computational Earth Systems Simulator MNRF, University of Queensland, St. Lucia, Qld 4072, Australia

[3]Computer and Computational Sciences Divison, Los Alamos National Laboratory, Los Alamos, NM 87545, United States

We measure the role of quenched disorder (representing failure strength) upon the effective dimensionality of a driven, dissipative system describing the dynamics of an earthquake fault. The system consists of a discrete 2D cellular fault zone embedded within a 3D elastic solid (Y. Ben-Zion, J. Geophys. Res. 101, 5677, 1996) and is defined by a set of parameters that describe the dynamics, rheology, property disorder, and fault geometry. Depending upon the location in the system parameter space, the coarse dynamics of the fault can be confined to an attractor whose dimension is significantly smaller than the space in which the dynamics takes place. The dynamics of the fault system is probed by recording the surface deformations that indirectly reflect the brittle processes of the fault (which are observable by InSAR and GPS techniques). The asymptotic attractors of the system are studied by identifying coherent structures (or dominant modes) present in the surface deformation fields and projecting the system dynamics onto the principal directions defined by these coherent structures. We estimate the effective dimensionality by computing the number of modes needed to explain 95% of the statistical variation of the surface deformation fields and by probing the geometry of the attractor using an analysis of its correlation dimension. A sharp transition has been detected in the number of effective degrees of freedom as the dynamic weakening of failure strengths is varied (M. Anghel, Chaos, Solitons, and Fractals 19, 399, 2004). This transition is associated with a separation of time and length scales in the system dynamics. We extend these results by studying the impact of varying the statistical properties of the failure strength distribution upon the effective dimensionality of the fault dynamics. A demonstration of the robustness of the low dimensional coarse dynamics of the system to changes in quenched disorder, implies that simplified fault models may be employed for forecasting the seismicity of active fault zones. Simplified fault models need not capture precisely the detailed structure of the fault zone in order to be useful for development of data driven forecasting models based on statistical learning techniques (M. Anghel, Y. Ben-Zion, and R. Rico-Martinez, PAGEOPH, in press).

NG41C-0073 0830h POSTER

Fractional Kinetics of Volcanic Earthquake Time Series

Sebastien Chastin[1] (+44 131 650 8533; schastin@glg.ed.ac.uk)

Ian Main[1] (=44 131 650 4911; ian.main@ed.ac.uk)

[1]University of Edinburgh, School of GeoSciences West Mains Road, Edinburgh EH9 3JW, United Kingdom

We analyse the USGS earthquake catalogue for the effusive volcanoes of Hawaii from 1959 to 2001. The distribution of inter-event times Δt and inter-hypocentral distances Δr between $>10^5$ subsequent events is contrasted with a surrogate catalogue where time correlation is deliberately destroyed as null hypothesis. Both series are non-stationary. The distribution of Δr is normal, with a characteristic scale $\sim$ 20km and finite variance. The inter-event time distribution has three distict regimes. Two are power-laws, with a break of slope from a higher to a lower exponent around the mean value $< \Delta t > \sim 10$ hours, and then an exponential decay with a characteristic time of $\sim$ 3 years. The elevated probability of occurrence of the shortest inter-event times reflects the tightly time-clustered swarms commonly observed in volcano-tectonic (VT) sequences. The power-law exponent in the middle range is $\sim$ - 0.25. Its broad-bandwidth scaling suggests the system conserves the memory of an event for a very long period of time. This induces an anticorrelation between subsequent events in the Δt series, with a Hurst exponent H $\sim$ 0.77, compared to 0.5 for a memoryless process. The mean distance Δr evolves with Δt in a way that is characteristic of a self-affine object produced by fractional kinetic processes with two distinct scaling regions. A region of statistically-significant, rapidly-accelerating, increase in $\Delta r \propto \Delta t^n$ with $n \sim 1.6$ is found for $\Delta t < 10$ hours and $\Delta r < 20$ km. Outside this region the curve cannot be differentiated from the temporally random null hypothesis, and Δr increases only very slowly with time following a power law $\Delta r \propto \Delta t^{n'}$ with $n' \sim 0.1$. The cross-over in scaling relations at (20 km, 10h) implies that the layered rheology of the lithosphere may inhibit rapid triggered diffusion or migration of VT events beyond the seismogenic thickness.

NG41C-0074 0830h POSTER

The role of heterogeneities as a tuning parameter of earthquake dynamics in relation to criticality

Gert Zoeller[1] (+49-331-977-1175; zoeller@rz.uni-potsdam.de)

Matthias Holschneider[2] (+49-331-977-1663; hols@math.uni-potsdam.de)

Yehuda Ben-Zion[3] (+1-213-740-6734)

[1]Institute of Physics and Institute of Mathematics, University of Potsdam POB 60 15 53, Potsdam 14415, Germany

[2]Institute of Mathematics, University of Potsdam POB 60 15 53, Potsdam 14415, Germany

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

We investigate the influence of spatial heterogeneities on various aspects of seismicity in a single-fault model. The model dynamics is governed by realistic boundary conditions consisting of constant velocity motion of regions around the fault, static/kinetic friction laws, creep with depth-dependent coefficients as in Ben-Zion (JGR 101, 1996), and 3D elastic stress transfer based on the solution of Chinnery (1963). The dynamic rupture is approximated on a continuous time

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scale using a finite stress propagation velocity ("quasi-dynamic model"). The model produces a "brittle-ductile" transition at a depth of about 12.5 km, realistic hypocenter distributions, and other features of seismicity compatible with observations. Ben-Zion et al. (JGR 108, 2003) suggested that the range of size scales in the distribution of strength-stress heterogeneities acts as a tuning parameter of dynamics, and that the evolution of this parameter in large earthquake cycles produces intermittent criticality. Here we test this hypothesis by performing a systematic parameter-space study with different forms of heterogeneities. In particular, we analyse spatial heterogeneities that can be tuned by a single parameter in two distributions: (1) a set of circular asperities with a different stress drop and variable range of radii and (2) spatial heterogeneities with fractal properties and variable fractal dimension. We analyze the influence of the tuning parameter of the heterogeneities on different measures of seismicity and discuss the results in terms of the phase diagram approach of Dahmen et al. (Phys. Rev. E 58, 1998).

NG41C-0075 0830h POSTER

Earthquake clustering in space as a percolation problem

Jordan Van Aalsburg[1] (jvan@cse.ucdavis.edu)

Robert Shcherbakov[1,2] (roshch@physics.ucdavis.edu)

John B Rundle[2] (jbrundle@ucdavis.edu)

Donald D Turcotte[3] (turcotte@geology.ucdavis.edu)

[1]Department of Physics, University of California, One Shields Ave., Davis, CA 95616, United States

[2]Center for Comp. Sci. and Eng., University of California, One Shields Ave., Davis, CA 95616, United States

[3]Department of Geology, University of California, One Shields Ave., Davis, CA 95616, United States

The clustering of earthquakes in space is a well established observational fact. This effect is directly related to the space-time correlations between events which play a critical role in earthquake processes. One of the main aims of this work is to investigate the dynamic evolution in time and statistical properties of earthquake clusters defined using the framework of a percolation problem. A seismogenic zone is divided into a grid of square boxes. We consider earthquakes greater than a specified magnitude that occur within a specified time window. A spatial box is occupied if one or more earthquakes occur within it. Adjacent occupied boxes define a cluster. Using this approach one can define the radius of gyration for each cluster and calculate the correlation length in the seismogenic region. The correlation length can be used as a measure of spatial correlations of seismicity and plays a fundamental role in studies of critical phenomena. Well defined variations in radii of gyration and correlation lengths are found for aftershock sequences. The change in correlation length might be also used as a precursor to large events, although this effect is not well observed and remains controversial. In the work, the physical basis of spatial correlations of earthquakes will be discussed in the context of critical phenomena and percolation problem. In addition we have obtained scaling laws for the correlation functions of earthquake clusters. We have also obtained the variations in time of the correlation function and correlation length associated with the spatial and temporal processes in seismogenic regions.

NG41C-0076 0830h POSTER

Regularized Deterministic Annealing Hidden Markov Models for Identificationand Analysis of Seismic and Aseismic events.

Robert A Granat[1] (818-393-5353; granat@aig.jpl.nasa.gov)

Robert Clayton[2] (clay@gps.caltech.edu)

Sharon Kedar[1] (sharon@cobra.jpl.nasa.gov)

Yoshihiro Kaneko[2] (ykaneko@gps.caltech.edu)

[1]Jet Propulsion Laboratory, 4800 Oak Grove Dr., Pasadena, CA 91109, United States

[2]California Institute of Technology, 1200 California Blvd., Pasadena, CA 91125, United States

We employ a robust hidden Markov model (HMM) based technique to perform statistical pattern analysis of suspected seismic and aseismic events in the poorly explored period band of minutes to hours. The technique allows us to classify known events and provides a statistical basis for finding and cataloging similar events represented elsewhere in the observations. In this work, we focus on data collected by the Southern California TriNet system. The hidden Markov model (HMM) approach assumes that the observed data has been generated by an unobservable dynamical statistical process. The process is of a particular form such that each observation is coincident with the system being in a particular discrete state. The dynamics are the model are constructed so that the next state is directly dependent only on the current state – it is a first order Markov process. The model is completely described by a set of parameters: the initial state probabilities, the first order Markov chain state-to-state transition probabilities, and the probability distribution of observable outputs associated with each state. Application of the model to data involves optimizing these model parameters with respect to some function of the observations, typically the likelihood of the observations given the model. Our work focused on the fact that this objective function has a number of local maxima that is exponential in the model size (the number of states). This means that not only is it very difficult to discover the global maximum, but also that results can vary widely between applications of the model. For some domains which employ HMMs for such purposes, such as speech processing, sufficient a priori information about the system is available to avoid this problem. However, for seismic data in general such a priori information is not available. Our approach involves analytical location of sub-optimal local maxima; once the locations of these maxima have been found, then we can employ a modified optimization procedure based on the application of statistical priors. These priors induce a regularized learning strategy that is designed to avoid the located sub-optimal points in the parameter space. The end result is a robust technique for estimating the optimal parameters of an HMM and thereby the statistical properties of the data. We compare this method to the method of deterministic annealing as applied to hidden Markov models, and discuss a combined algorithm that employs both techniques simultaneously to the advantage of each. We present preliminary results of the technique as applied to the TriNet data set, with particular emphasis on location and recognition of seismic and aseismic signals with a period of minutes to hours.

NG41C-0077 0830h POSTER

3D Simulation of the Entire Process of Earthquake Generation at Subduction-Zone Plate Boundaries

Mitsuhiro Matsu'ura[1] (81-3-5841-4318; matsuura@eps.s.u-tokyo.ac.jp)

Chihiro Hashimoto[2] (hashi@jamstec.go.jp)

Eiichi Fukuyama[3] (fuku@bosai.go.jp)

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

[2]Institute of Frontier Research for Earth Evolution, JAMSTEC, Kanazawa-ku, Yokohama 236-0001, Japan

[3]National Research Institute for Earth and Disaster Prevention, Tennodai, Tsukuba 237-0061, Japan

In general, the entire process of earthquake generation consists of tectonic loading due to relative plate motion, quasi-static rupture nucleation, dynamic rupture propagation and stop, and restoration of fault strength. This process can be completely described by a coupled nonlinear system, which 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 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. As a product of Crustal Activity Modelling Program (CAMP), which is one of the three main programs composing the Solid Earth Simulator project (1998-2003) promoted by MEXT, we have completed a physics-based predictive simulation model for the entire process of earthquake generation cycles in and around Japan, where the four plates of Pacific, North American, Philippine Sea and Eurasian are interacting with each other in a very complicated way. The total simulation system consists of a crust-mantle structure model, a tectonic loading model and a dynamic rupture model. First, we constructed a realistic 3D standard model of plate interfaces in and around Japan by applying an inversion technique to ISC hypocenter distribution data, and computed viscoelastic slip-response functions for this structure model. Second, we introduced the slip- and time-dependent fault constitutive law with an inherent strength-restoration mechanism as a basic equation governing the entire process of earthquake generation. Third, combining all these elements, we developed a simulation model for quasi-static stress accumulation due to relative plate motion. Fourth, we also developed a simulation model for dynamic rupture propagation on a 3D curved fault surface by applying BIEM. Finally, we connected the quasi-static stress accumulation model and the dynamic rupture propagation model through a simulation platform on the Earth Simulator, which is a high performance, massively parallel-processing computer system with 10 TB memories and 40 TFLOPS peak speed. Outputs of this simulation system are crustal deformation, internal stress changes and seismic wave radiation associated with seismic and/or aseismic slip at the plate interfaces. From comparison of these simulation outputs and observed data, we can extract useful information to estimate the past slip history and the present stress state at the plate interfaces by using an inversion technique. Given the past slip history and the present stress state, we can predict the next step fault slip and stress changes through computer simulation. In this presentation, as a demonstration, we show the result of 3D simulation of the entire process of earthquake generation cycle at the Tokachi-oki seismogenic region in northeast Japan.

NG41C-0078 0830h POSTER

Finite Element Analysis of Coupling Role of Multiple Fault Bends in the Stick-Slip Instability along the Faults

Huilin Xing[1,2] (61-733653464; xing@quakes.uq.edu.au)

Peter Mora[1,2] (61-733652128; morap@quakes.uq.edu.au)

[1]QUAKES, Earth Systems Science Computational Centre, The University of Queensland, St. Lucia, Brisbane, QLD 4072, Australia

[2]The Australian Computational Earth Systems Simulator (ACcESS), Earth Systems Science Computational Centre, The University of Queensland, St. Lucia,, Brisbane, QLD 4072, Australia

Earthquakes are recognized as resulting from the stick-slip frictional instability along the faults between deformable rocks. From both practical observations and laboratory experiments, the geometry of the fault significantly affects the faulting process. To investigate the coupling effects of multiple fault bends on the stick-slip instability based on mechanics concepts, a 3-dimension finite element code for modeling the nonlinear frictional contact behaviours between deformable rocks with an arbitrarily contact element strategy has been developed and applied to simulate a typical intraplate fault model with multiple fault bends. The coupling influences of the multiple fault bends on the relative slip velocity, the normal contact force, the initiation and termination of the stick-slip instability along the fault between the deformable rocks are investigated. The numerical results demonstrate that: (1) There exist several stages of the slip process (i.e. the stick-slip instability) corresponding to the numbers of the fault bends; (2). The stick-slip instability initiates on a fault segment and terminates near the fault bend, but restarts again with a larger relative velocity. This process repeats several times until the main instability event occurs. This means the fault bends terminate the stick-slip instability and the termination process of one stick-slip instability event sets up the initiation environment for the future larger event. (3). The stick-slip instability activity prior to a main instability event can occur at a longer distance from the location of the main event. (4). All the above phenomena are mainly due to the nonuniform distribution of fault strength (i.e. the normal contact force and variable friction coefficient) due to multiple fault bends and can be captured by the current numerical model. (5). The coupling influences of multiple fault bends on the stick-slip instability are significant and important, and thus should be monitored for earthquake forecasting research and practice.

URL: http://www.quakes.uq.edu.au

NG41C-0079 0830h POSTER

Triggered Seismicity in the Hydraulic Stimulation at Soultz (France): Evidence for the Control of the Multiplet Sequences by Major Aseismic Slip

Seid Bourouis[1] (33-1-44-27-39-15; bourouis@ipgp.jussieu.fr)

Pascal Bernard[1] (33-1-44-27-24-14; bernard@ipgp.jussieu.fr)

Francois Cornet[1] (33-1-44-27-38-97; cornet@ipgp.jussieu.fr)

[1]Departement de Sismologie, IPGP, case 89, 4, place Jussieu tour 24- 4eme etage, Paris 75252, France

In 1993, an hydraulic stimulation of the natural fracture system of the granitic rock mass of Soultz-sous-Forêts (Alsace, France), at a depth between 2850 m and 3400 m, and lasting 17 days, has generated more than 11,000 micro-earthquakes. These have been recorded by a network consisting of four seismic stations cemented at the bottom of the wells. First, these data have been classified in multiplets using the SPARS method. Second, in this dataset, only the multiplets (150) containing more than five events have been selected. Third, precise sources relative locations have been determined by a cross-spectrum analysis to compute a mean fracture plane for each multiplet. These planes have been correlated to the fractures observed by diagraphy in the injection well. One of the major fractures observed in this well experienced a slip of 4.3 cm during the injection. We selected the multiplets spatially correlated with the plane of this fracture, and estimated the source parameters of every event in each multiplet. The distance between them is much smaller than their size (as deduced from their corner frequency), showing that each multiplet consists of a repeating slip on the same asperity. The cumulative slip obtained for each multiplet is of the same order as the one observed in the well on the selected fracture. The calculations shows a clear relation in time between the increase of the pore pressure and the cumulative slip of the seismic fractures. There is also a decrease of the seismicity rate with time. We interpret these observations as resulting from the occurence of a mostly aseismic slip on a major fracture (size 100 m), forcing small asperities (size 10 m) to rupture repeatedly for accommodating this creep event, generating the multiplets, and decelerating with time, as pore pressure reaches an equilibrium. The resulting Omori law has therefore little to do with fault patches accelerating their slip towards rupture, such as in Dieterich's models, but would be linked to the contrary to some decelerating aseismic slip on destabilized, creeping faults. We suggest that such a model may apply, at least in part, for sequences of aftershocks from natural earthquakes.

NG41C-0080 0830h POSTER

Simulation of the Burridge-Knopoff Model with Long-Range Interactions

Junchao Xia[1] (508-793-7727; jcxia@physics.clarku.edu)

Harvey Gould[1] (508-793-7485; hgould@clarku.edu)

William Klein[2,3] (617-353-2188; klein@buphy.bu.edu)

[1]Clark University, Department of Physics, Worcester, MA 01610, United States

[2]Los Alamos National Laboratory, X7 Material Science, Los Alamos, NM 87545, United States

[3]Boston University, Department of Physics, Worcester, MA 02215, United States

We simulate the Burridge-Knopoff model in one dimension for various interaction ranges. The computed size distribution of the events shows that the scaling range of the nearest-neighbor model is poorly defined. For longer range interactions, our results suggest that the existence of two scaling regions, corresponding to different types of events. The scaling regions become better defined as the interaction range increases.

NG41C-0081 0830h POSTER

Search for Direct Empirical Spatial Correlation Signatures of the Critical Earthquake Model and a New Mechanism for Long-Range Interactions

Guy Ouillon[1] (ouillon@free.fr)

Didier Sornette[1,2] (310-825-28-63; sornette@moho.ess.ucla.edu)

[1]Laboratoire de Physique de la Matière Condensée, CNRS UMR 6622, Université de Nice-Sophia Antipolis, Parc Valrose, Nice 06108, France

[2]Department of Earth and Space Sciences and Institute of Geophysics and Planetary Physics, 3845 Slichter Hall, University of California, Los Angeles, CA 90095, United States

We propose a new test of the critical earthquake model based on the hypothesis that precursory earthquakes are "actors" that create fluctuations in the stress field which exhibit an increasing correlation length as the critical large event becomes imminent. Our approach constitutes an attempt to build a more physically-based time-dependent indicator (cumulative scalar stress function), in the spirit of but, improving on the cumulative Benioff strain used in previous works documenting the phenomenon of accelerating seismicity. Using a simplified scalar space and time-dependent visco-elastic Green function of a two-layers model of the Earth lithosphere, we compute spatio-temporal pseudo-stress fluctuations induced by a series of events before four of the largest recent shocks in Southern California. Through an appropriate spatial wavelet transform, we then estimate the contribution of each event in the series to the correlation properties of the simplified scalar stress field around the location of the mainshock at different scales. This allows us to define a cumulative scalar stress function which shows neither an acceleration of stress storage at the epicenter of the mainshock nor an increase of the spatial stress-stress correlation length with time, in contradiction with those deduced previously from the cumulative Benioff strain. The earthquakes we studied are thus either simple "witnesses" of a large scale tectonic organization, or are simply unrelated, and/or the Green function describing interactions between earthquakes has a significantly longer range than predicted for standard visco-elastic media used here. We then propose a simple mechanism for these long-range interactions, based on seeing the Earth crust as crisscrossed by faults and cracks filled with fluid at close to lithostatic pressures. We develop a model in which its elastic modulii are different in net tension versus compression. In 2D, for a given strike-slip earthquake source, such nonlinear elasticity is observed to (i) rotate, widen or narrow the different lobes of stress transfer, (ii) to modify the $1/r^2$ 2D-decay of elastic Green functions into the generalized power law $1/r^\gamma$ where γ varies with increasing tension-compression asymmetry and depends on the azimuth, and can reach values significantly lower than 1. Using reasonable estimates, this implies an enhancement of the range of interaction between earthquakes by a factor up to 5-10. This may explain certain long-range earthquake triggering and hydrological anomalies in wells and suggest to revisit the standard stress tranfer calculations which use linear elasticity.

NG41C-0082 0830h POSTER

Critical Threshold for Spontaneous Failure: Macro- and Micro- Behavior of Granite Loaded to Failure

Oded Katz[1] (+972-2-5314279; odedk@mail.gsi.gov.il)

Ze'ev Reches[2] (Reches@earth.es.huji.ac.il)

[1]Geological Survey of Israel, 30 Malkhe Yisrael St., Jerusalem 95501, Israel

[2]School of Geology & Geophysics, Univ. of Oklahoma, 100 E. Boyd st., Norman, OK 73019, United States

The ultimate strength, time-dependence creep and associated microstructure of granite samples are examined as an attempt to characterize the critical parameters of brittle rock failure. We loaded triaxially 27 cylinders of the medium grain-size Mount Scott granite (western Oklahoma) under dry, room temperature conditions. Thirteen of the samples were loaded under confining pressure ranging from 0 to 50 MPa, and the group of 14 samples was loaded under confining pressure of 41MPa, for which the ultimate strength is Us = 586+-16 MPa. The 14 samples were loaded up to preselected differential stress (NDS) that ranges from 0.54 Us to 1.05 Us, and were then held under constant stroke for periods as long as six hours. The failure could be reasonably well predicted by two macroscopic parameters. One is the maximum differential stress: the eleven samples loaded under NSD $\leq$ 0.95 did not fail during the six hours of hold period, whereas the three samples loaded by NDS>0.95 failed spontaneously after a few seconds to an hour of hold time. The high Weibull parameter (m=13-22) of strength distribution of a heterogeneous rock is in agreement with this observation. The second parameter is the "crack volumetric strain" (CVS) that increases monotonously for NDS$\leq$0.95, but at NDS>0.95 it reaches a critical value of 0.001 beyond which it is poorly constrained (with CVS approaching 0.005). We mapped the microfractures in thin-sections prepared from 5 deformed samples that cover the full loading range: 0.00, 0.57, 0.88, 0.96 of the rock strength and failure. The microstructural thin-section maps provided quantitative damage intensity (approaching 0.2) and fractal dimensions of the microfractures length distribution (1.5 for unloaded sample and 2.2-2.4 for loaded samples); these maps however, provide no critical failure indicator. Which of the examined parameters could be used to determine a critical failure state in an active fault-zone? We believe that the "crack volumetric strain" is the most promising one as in the experiments it displays critical behavior and in the field it could be detected by velocity decrease of guided waves.

NG41D MCC: 3010 Thursday 1020h

Scaling in Our Fluid Earth: Chaos and Multifractals in the Atmosphere, Oceans, Hydrology, and Climate II

(joint with A, B, GP, H, OS, PP, SA, AE, C, GC)

Presiding: **S Lovejoy,** McGill University**; D Schertzer,** Laboratoire de Modélisation en Mécanique, Université Pierre et Marie Curie

NG41D-01 1020h INVITED

Effects of Space-Time Multifractality of Rainfall on Hydrologic Regionalization

Alin Andrei Cârsteanu[1] (+52-55-5061-3800x6439; alin@math.cinvestav.mx)

Jorge Javier Castro[1] (+52-55-5061-3798; jjcastro@fis.cinvestav.mx)

[1]Cinvestav del IPN, Av. IPN 2508, Col. San Pedro Zacatenco, Mexico, DF 07360, Mexico

The effect of a space-time multifractal structure of rainfall fields on runoff scaling in nested basins is being analyzed in this work. The scaling relationship between runoff and watershed area is reevaluated as a consequence. The temporal filtering effect of the watershed on the temporal singularity structure of rainfall is also evaluated. Conclusions are drawn concerning the regional transposition of hydrologic statistics and regularities.

NG41D-02 1035h

Multifractals and plankton

Warren JS Currie[1] (wcurrie@socrates.berkeley.edu)

Shaun Lovejoy[2] (shaun@physics.mcgill.ca)

[1]Ohio University, Biological Sciences, Athens, OH 45701, United States

[2]McGill University, Physics Department 3600 rue University, Montreal, QC H3A 2T8, Canada

The scaling relationships (m-km) of plankton distributions from transects collected in-situ using CTD and Optical Plankton Counter have been analysed using the double-trace moment multifractal analysis. The scaling behavior has indicated distinct ranges. As expected with turbulence, passive scaling behaviour is seen for the temperature spectra down to the smallest scales. Zooplankton spectra have a scaling discontinuity below which they are no longer "prisoners of turbulence". Fluorescence (phytoplankton) indicated consistent multiple "breaks in scaling" with large-scale and a small-scale turbulence-growth dominated regime but an intermediate rougher region. Zooplankton modify the scaling relationships of the phytoplankton through grazing at these scales.

NG41D-03 1050h INVITED

Low Rain-Rates, Spurious Scale Breaks and a new Depth Based Analysis Technique

M. Isabel P. de Lima[1] (+351 239 802 284; lima@dec.uc.pt)

Shaun Lovejoy[2] (lovejoy@physics.mcgill.ca)

Daniel Schertzer[3] (schertze@ccr.jussieu.fr)

[1]IMAR/ESAC-Coimbra Polytechnic Inst., Bencanta, Coimbra 3040-316, Portugal

[2]McGill Univ., 3600 University st., Montreal, Quebec H3A 2T8, Canada

[3]Pierre and Marie Curie Univ., 4 Place Jussieu, Paris 75005, France

The non-linear variability of rainfall is present over a broad range of time and space scales; in addition, at a given scale it involves a huge dynamic range. Both of these characteristics challenge traditional measuring techniques; they require explicit modeling of the rain and the response of measurement devices - including tipping-bucket and siphon type rain gauges. Since they generically produce extreme variability over wide scale ranges, multifractal models of rain are the natural