have investigated this for a range of Rayleigh numbers from $10^6$ to $10^9$. We have found that wavelets can provide a useful tool for extracting coherent features in mantle convection and can be applied to other types of problems in geophysics, such as geodynamo simulations and earthquake deformation.

### NG61A-12 1145h

## A LARGE-SCALE SPECTRAL PARALLEL IMPLEMENTATION OF 2-D POISSON EQUATION WITH APPLICATIONS TO MESOSCALE CRYSTAL SURFACES

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The Poisson equation is a partial differential equation with a universal applicability embracing gravity , porous flow, materials science, and biochemical surfaces.Thus far most Poisson equations have been restricted to a relatively low resolution on the order of a thousand grid points along each direction. The imaging of nano to meso features on lattices requires very high resolution. An example is given by the surface potential of inorganic crystals. Surface topography can be mapped out by using atomic force microscopy ( AFM), Kelvin probe microscopy and related solid-state techniques. A strong correlation between the surface topography and surface potential can be found. THe Si( 111) 7x7 is a very complex crystal. Defects have been observed with AFM on surface maps of 60 nm by 60 nm . Starting from a given charged distribution field, however complex, we can compute surface potential with such a map. Counting 8x8 points as a minimum resolution for each atom would then entail an order of between 100,000 and one million grid points along one direction for the characteristic mesoscale areas scanned by AFM. We demonstrate that we can , with an easy-to-program algorithm, reach a spatial resolution of 20,000 x 20,000 points for computing the electric potential on a 2-D periodic lattice. We have employed a spectral Fourier technique and parallelized Fourier transforms on 32 Silicon Graphics processors. The speed is about a few minutes for the largest grid. An out-of-core version of this code is needed to handle the extremely large grids involving one million points along each direction. This method can be extended easily to 3-D.

# NG62A MCC: Hall C Saturday 1330h

## Earthquake Fault Models: Current Practice and Future Challenges Posters *(joint with G, S, T)*

***Presiding:*** **K F Tiampo,** University of Colorado**; M Glasscoe,** University of California, Davis

### NG62A-0923 1330h POSTER

## Quasi-static and quasi-dynamic modeling of earthquake failure at intermediate scales

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We present a model for earthquake failure at intermediate scales (space: 100 $m$ - 100 $km$, time: 100 $m/v_{shear}$- 1000's of years). The model consists of a segmented strike–slip fault embedded in a 3-D elastic solid as in the framework of Ben-Zion and Rice (J. Geophys. Res. 98, 1993). The model dynamics is governed by realistic boundary conditions consisting of constant velocity motion of the regions around the fault, static/kinetic friction laws with possible gradual healing, and stress transfer based on the solution of Chinnery (Bull. Seism. Soc. Am. 53, 1963) for static dislocations in an elastic half space. As a new ingredient, we approximate the dynamic rupture on a continuous time scale using a finite stress propagation velocity (quasi–dynamic model) instead of instantaneous stress transfer (quasi–static model). We compare the quasi–dynamic model with the quasi–static version and its mean field approximation, and discuss the conditions for the occurrence of frequency-size statistics of the Gutenberg–Richter type, the characteristic earthquake type, and the possibility of a spontaneous mode switching from one distribution to the other. We also introduce time-dependent log ($t$) healing and show that the results can be interpreted in the context of the phase diagram framework of Dahmen et al. (Phys. Rev. E 58, 1998). To have a flexible computational environment, we have implemented the model in a modular C++ class library.

### NG62A-0924 1330h POSTER

## Instability of a Periodic System of Faults

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To investigate the effect of heterogeneity of resistance on a fault, we present an analysis of the behaviour of a canonical model, namely a periodic system of coplanar faults which can slip under a slip weakening friction law. The friction on the sliding patches is characterized by a weakening rate $\alpha$. We present a stability analysis based on the decomposition of the solution on a set of eigenfunctions of increasing periodicities which are multiple of the natural period of the system. We discuss the structure of the discrete spectrum of the static solution. For a given geometry, we show that it exists a transition value $\alpha_0$ of weakening rate defining two distinct regimes. When $\alpha$ is smaller than $\alpha_0$, the system is stable while when $\alpha$ is larger than $\alpha_0$, unstable modes with exponential growth are present. This stability limit can be regarded as a non-local criterion of sliding. A somehow surprising result is the fact that a system with infinite extension can exhibit a stable behaviour. Specifically, we show that even a fault with weakening almost everywhere can be stable. An infinite homogeneous fault, on the contrary, is always unstable as soon as weakening is assumed. To understand this apparent paradox, we refer to the concept of the effective friction law that describes the large scale behaviour of the fault system, and more precisely here to the effective weakening rate. The results presented here indicate that the effective friction law of a periodic fault system with weakening on the sliding parts can be either a weakening or strengthening law depending on the geometry of the surface of sliding.

### NG62A-0925 1330h POSTER

## On boundary-element models of elastic fault interaction

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We present the freely available, modular, and UNIX command-line based boundary-element program *interact*. It is yet another implementation of Crouch and Starfield's (1983) 2-D and Okada's (1992) half-space solutions for constant slip on planar fault segments in an elastic medium. Using unconstrained or non-negative, standard-package matrix routines, the code can solve for slip distributions on faults given stress boundary conditions, or vice versa, both in a local or global reference frame. Based on examples of complex fault geometries from structural geology, we discuss the effects of different stress boundary conditions on the predicted slip distributions of interacting fault systems. Such one-step calculations can be useful to estimate the moment-release efficiency of alternative fault geometries, and so to evaluate the likelihood which system may be realized in nature. A further application of the program is the simulation of cyclic fault rupture based on simple static-kinetic friction laws. We comment on two issues: First, that of the appropriate rupture algorithm. Cellular models of seismicity often employ an exhaustive rupture scheme: fault cells fail if some critical stress is reached, then cells slip once-only by a given amount, and subsequently the redistributed stress is used to check for triggered activations on other cells. We show that this procedure can lead to artificial complexity in seismicity if time-to-failure is not calculated carefully because of numerical noise. Second, we address the question if foreshocks can be viewed as direct expressions of a simple statistical distribution of frictional strength on individual faults. Repetitive failure models based on a random distribution of frictional coefficients initially show irregular seismicity. By repeatedly selecting weaker patches, the fault then evolves into a quasi-periodic cycle. Each time, the pre-mainshock events build up the cumulative moment release in a non-linear fashion. These temporal seismicity patterns roughly resemble the accelerated moment-release features which are sometimes observed in nature.

### NG62A-0926 1330h POSTER

## Two-Dimensional Stick-Slip: How the Seismic Activity Depends on the Direction of Tectonic Plates Motion

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We consider a two-dimensional slider-block model subject to the rate and state dependent friction. The block interacts with a slowly moving substrate through static and dynamic friction coefficients defined separately in the stick and slip phases of motion. The rebound strain is described by a tensor, which in the simplest case can be reduced to two stiffness coefficients in mutually orthogonal directions. The model is capable of reproducing complicated oscillatory patterns of stick-slip motion, starting from simple periodic oscillations to quasiperiodic, chaotic, and intermittent behavior. In contrast to the Dieterich and Ruina description of friction where the complexity is produced by the intrinsic dynamics of the hidden state variables, the complex behavior in this model appears due to the interaction of two spatial degrees of freedom defined by the fault geometry.

It has been found out that the oscillatory patterns shown by the model can be roughly attributed to two big classes of creep and strong motions, and the system can demonstrate sudden transitions between the oscillations of different classes, either periodically or in an irregular intermittent manner. This behavior looks similar to the temporal distribution of seismic events in some areas, where long time intervals of creep motion are interrupted by large events. On the other hand, the model can be used for the study of those regions where only creep behavior or only strong motions are observed.

In this presentation, we focus on the dependence of the model behavior on the geometry of fault structure it can simulate. The transitions between the two classes of behavior are analyzed in detail, depending on the direction of motion of the substrate. This setting corresponds to the analysis of dynamics of a fault segment with respect to the angle between the fault surface and velocity vector of the tectonic plates constituting the fault. We show that even small changes in the angle value can switch the dynamics shown by the fault segment from creep to stick-slip motion of high amplitude. This result can be used for interpreting the observations where geographically close fault segments demonstrate qualitatively different dynamics, i.e. some part of the fault produces only creep motion while the adjacent parts generate big events.

### NG62A-0927 1330h POSTER

## Slip-Weakening Distance in Dynamic Rupture of Inslab Normal-Faulting Earthquakes

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It is now one of the important issues in rupture dynamics to estimate the critical slip-weakening distance at which the shear stress drops to the final level during natural earthquakes. In this study, we estimate the slip-weakening distance on inslab earthquake faults in a subduction zone, by applying a recent approach proposed by Mikumo et al. (2002). This approach is to find the a relation between the breakdown time of shear

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stress Tb, the time of peak slip-velocity Tpv, and the slip-weakening distance Dc, from the time histories of shear stress, slip and slip-velocity at each point on the fault. The previous results show that Dc at Tb can be well approximated by Dc' at Tpv for faults even with heterogeneous stress drop distribution, except at locations near strong barriers and fault edges (Fukuyama et al., 2002).

We apply the above method to one of large inslab, normal-faulting earthquakes in the Mexican subduction zone. To do this, we calculate the spatial distribution of slip-velocity functions and final slip from kinematic waveform inversion of strong-motion and teleseismic records, and the stress history and final stress change from dynamic rupture calculations. By integrating the slip-velocity functions obtained from the inversion, from the rupture arrival time to the time of peak slip-velocity, we obtain the slip Dc' at Tpv and then correct it for Dc at Tb through dynamic calculations. We also estimate the lowest resolvable limit and probable errors of Dc from the slip-velocity functions, and its upper bound from a theoretical constraint between dynamic stress drop and Dc. We found that the slip-weakening distance Dc estimated in the frequency band between 0.05 and 0.5 Hz ranges between 40 and 120 cm on the inslab fault of the 1999 Oaxaca earthquake (Mw=7.4). The largest Dc was detected in the central fault and in part of the deeper sections, and Dc in the zone around the hypocenter ranges between 50 and 70 cm. The estimated Dc-values appear to be less depth-dependent but rather more dependent on the local maximum slip. This possible slip-dependence might be interpreted by the degree of fault roughness, in addition to stress heterogeneities. The fracture energy G in the central section and in the hypocentral zone are roughly estimated to be of the order of 10 - 15 and 5 - 8 MJ/m2, respectively. Both of the estimated Dc and G values are somewhat larger than those on the vertical fault of two recent shallow, strike-slip earthquakes in western Japan.

## NG62A-0928 1330h POSTER

### Static and Dynamic Models of an Overlapping Thrust Fault System

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The behavior of complex fault systems has become the focus of much recent activity in the fault dynamics community. One of the key issues is the ability of rupture to jump or propagate around segment boundaries such as offsets and changes in orientation. Such studies generally solve the full dynamic equations of motion to determine the short-term time history of rupture and slip propagation on very closely spaced fault segments. On the other end of the timing and distance scale, much work has been devoted to the interaction between more distantly spaced faults through stress transfer analysis. Such studies generally take the final slip from some historical or potential earthquake, and calculate the coulomb stress increment on nearby faults to determine the potential for triggering subsequent events. In the present work, we use both methods (including the three-dimensional finite element technique and a static boundary element technique) to analyze the rupture and slip behavior of a system of overlapping thrust faults. We find that in some cases, in which the fault interaction is essentially one-way, the static stress transfer analysis can predict where rupture will jump across segment boundaries. However, in cases in which the interaction is strongly two-way, the static analysis fails to capture the complicated rupture behavior, and leads to an underprediction of the potential for jumping rupture. Time-dependent coulomb analysis, capturing the effects of dynamic waves, gives a much more realistic impression of the faulting behavior in these cases.

## NG62A-0929 1330h POSTER

### Dynamics of a dipping fault over multiple cycles

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Previous studies on the dynamics of a dipping fault show that the asymmetric geometry of such a fault can cause asymmetric near-source particle motion for one earthquake event: the motion of the hanging wall is large than that of the footwall, and there is great amplification of motion near the free surface. To study the effects of the asymmetric geometry on dynamics of earthquake over multiple cycles, we adopt a relatively simple model of earthquake cycles. We use the 2D finite-element method to simulate the earthquakes and loading on dipping faults. In the present simulation, the material properties are completely uniform. The cycles start from a homogeneous stress field. A constant-slip velocity loading below the main fault builds up the stress on the fault. When the nucleation area is enough to make the rupture propagate, the earthquake takes place. After earthquake waves die out, this cycle ends and stress buildup process is started for next cycle, with the stress output of the previous cycle used as the initial condition. We use a slip-weakening friction law for the fault: the frictional coefficient drops from static to sliding value over a critical slip (Dc); the coefficient recovers to the static level when next cycle starts (mimicing the strength recovery of the fault).

Based on a shallow-angle (20 degree, 20km long along down-dip direction) thrust fault model, we simulate 20 cycles. The preliminary results show some important features of the dynamics of a dipping fault over multiple cycles. First, the effects of asymmetric geometry mentioned above exist over multiple cycles. Second, stress heterogeneity can be developed on the fault over multiple cycles even though the cycles start from a homogeneous stress field. This heterogeneity is closely related to how much of the fault is ruptured in each cycle. Third, the stress heterogeneity can be smoothed out by a large event in which rupture propagates to the surface. Our results also indicate that more complicated stress heterogeneity and cycle patterns can be developed if we reduce the critical nucleation area.

## NG62A-0930 1330h POSTER

### Three Dimensional Dynamic Rupture Propagation on a Curved / Branched Fault based on Boundary Integral Equation Method with Triangular Elements

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In order to simulate a dynamic rupture process of large earthquakes along the subduction zone, it is quite important to take into account the fault geometry, such as the fault curvature along both strike and dip directions, subduction of seamounts, spray faults and so on. In the present analysis, a fault is modeled by triangular elements instead of using rectangular ones that Aochi et al. (2000, PAGEOPH) used. Based on the boundary integral equations for arbitrary shaped fault (Tada et al., 2000, Comp. Mech.), discretized kernel for triangular elements is derived. Following Fukuyama et al. (2002, PAGEOPH), the dynamic rupture propagation on a curved / branched fault is computed by assuming a pre-defined shaped slip-weakening friction and initial stress distributions.

Accuracy of the computation is examined by comparing with the result of Fukuyama and Madariaga (1998, BSSA) for a planar fault. They are very similar except for the details caused by different gridding scheme. Computation times are reduced by using parallelized code with MPI libraries. In the current code, parallelization coefficient, which is defined as a speed per CPU with respect to that with a single CPU, exceeded 0.9, which is a very good performance.

Some examples of the application of this code will be shown. First, a dynamic rupture is simulated on a curved fault toward both strike and dip directions. A tri-axial initial stress field with uniform slip-weakening friction law is assumed. The result shows that the dynamic rupture is strongly controlled by the initial stress distribution caused by the fault geometry. Next, a dynamic rupture is propageted along a bumped fault which causes the asperity / barrier of the rupture. Finally, a branched fault is examined with respect to the rupture velocity variation.

## NG62A-0931 1330h POSTER

### Neotectonic Velocity Field of the Western United States: A new Maximum-likelihood Solution

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New kinematic finite-element program NeoKinema solves for long-term-average velocity fields and fault slip rates in deforming lithosphere, based on three kinds of information: (1) geologic slip rates of an unlimited number of faults, with standard deviations (which may be large); (2) geodetic velocities of benchmarks, either in fixed or free-floating velocity reference frame, with covariance matrix; (3) stress-direction data. Faults need not be explicitly represented in the finite element grid. The geodetic data are corrected for local effects of temporary fault locking by an iterative procedure. The strain rates of non-faulting finite elements are determined by a balance between (a) minimization of viscous dissipation, and (b) conformity to principal strain rate directions interpolated from the stress-direction data.

NeoKinema has been applied to model neotectonics of the western United States, from the Gorda "plate" on the west, to the Gulf of California on the south, Yellowstone on the east, and Victoria on the north. Data comes from 378 active or potentially-active faults, 298 benchmarks of the WUSC002 solution [Bennett et al., 1999], and 2080 stress directions from the World Stress Map 2000 [Mueller et al., 2000]. The F-E grid has 1813 nodes and 3468 triangular elements of 30-km and 60-km dimensions. Results of this first application are very plausible, and confirm the concept of a Sierra Nevada-Great Valley plate moving 9 mm/a NW. After a few local artifacts are investigated and eliminated (primarily by better gridding), the model will be used to compute various measures of long-term seismic hazard. It is already apparent from the map of predicted strain rates that 20th-century seismicity levels in western Oregon, the Wasatch Front area of Utah, and the Las Vegas region have been less than their long-term-average expectations.

URL: http://element.ess.ucla.edu

## NG62A-0932 1330h POSTER

### Dynamic formation of fault system due to interactions between fault segments

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Natural fault systems generally have complex geometry and are constituted by several fault segments. It has been shown in recent theoretical or numerical studies that nucleationC propagation and termination of earthquake rupture growth are affected by non-planar geometry of fault system, such as bending, branching and stepping. However, most of these studies have assumed a pre-existing geometry of fault system and the formation process of fault system has not been considered. While the formation of fault system is studied in some of recent studies, they have two important limitations: quasi-static deformation is assumed when interacting faults are considered, an isolated fault is assumed when dynamic deformation is treated. We overcome these limitations and investigate the dynamic formation process of non-planar fault system.

We first develop a numerical, which can treat dynamic interactions between non-planar fault segments. Then, we simulate the dynamic growth of a fault segment that are affected by neighboring segments. We assume the system constituted by two fault segments as the simplest case; one of the segments is assumed to grow and to interact with the other segment that is assumed to be pre-existing. The pre-existing fault segment makes static stress change around it. We assume the rupture velocity is constant to clarify the effect of dynamic fault growth.

We show that resulting fault geometry significantly depends on the initial arrangement of the fault segments and rupture velocity. The newly grown segment is shown to coalesce to or repel from pre-existing one according to the initial fault arrangement; the two faults are assumed to be parallel at the initial state. We find the following important simulation results. The coalescence occurs when newly grown fault segment is non-overlapped, or partly overlapped, with the pre-existing one and the strike slip offset, d2, is much smaller than the half-length of the pre-existing one. On the contrary, the newly grown one tends to repel when d2 is larger than the half-length of the pre-existing one. Our simulation suggests that large earthquakes tend to occur with the evolution of a fault system if the strike slip offset of the fault system is much smaller than the lengths of the segments.

URL: http://www.eri.u-tokyo.ac.jp/ando

## NG62A-0933 1330h POSTER

### Is the Coulomb failure criterion valid on a fault governed by rate and state friction ?

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The influence of normal and shear stress static perturbations on a strike-slip fault are addressed on the basis of a 2D continuous and quasi-dynamic model. Friction along the fault plane is described using a Rate and State friction law with depth variable properties. Normal and shear stress perturbations result in similar effects in terms of earthquake triggeringif $\Delta\tau - \mu_*\Delta\sigma$ is constant, $\Delta\tau$ and $\Delta\sigma$ being respectively the amplitude of the shear and normal stress fluctuations, and $\mu_*$ a constant which can be interpreted as the static friction coefficient on the fault in a Coulomb failure model. Therefore, the Coulomb stress change $\Delta\mathrm{CFF} = \Delta\tau - \mu_*\Delta\sigma$ is a useful tool to account simultaneously for normal and shear stress variations in our model. We also show that when estimating the clock advance or clock delay of an earthquake, the simple Coulomb failure model is at first order in good agreement with our results during the first 90% of the earthquake cycle. However it differs significantly during the last 10% due to the sharp velocity increase predicted by the rate and state friction law before rupture. This suggests that as long as static variations of stress are concerned, realistic fault models using rich, laboratory based, friction laws like rate and state friction laws may lead to predictions fairly close to the ones made using one of the simplest failure model, i.e., the Coulomb failure model. This may explain why Coulomb stress change computations, although often based on drastic approximations, have been able in many occasions to explain earthquake triggering sequences. We finally compare predictions of the Coulomb failure model and of the rate and state friction model to field observations.

## NG62A-0934 1330h POSTER

### Rheologic Properties of an Extending Lithosphere from the Inversion of Postseismic Deformation (EDM and GPS) of the 1959 Hebgen Lake, Montana, Earthquake

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The 1959, M = 7.5, Hebgen Lake earthquake, the largest historic normal-faulting earthquake in the Basin-Range province, was located 20 miles northwest of the Yellowstone caldera. Models of the fault-stress interaction suggested that the earthquake rupture affected the nearby caldera stress-field and induced long-term aftershock activity, continuing to the present. The 90th-percentile distribution of focal depths from relocated, 1973-1997, background seismicity between the Yellowstone caldera and the southeast end of the Hebgen Lake fault increases westward from about 8 km to 20 km and marks a systematic increase in the depth of the brittle-ductile transition zone. In this study, we explored the rheological structure of this fault zone using geodetically derived deformation data beginning 13 years after the earthquake to 2000. Previous leveling surveys near Hebgen Lake (1923-1983) revealed 30 cm of postseismic uplift, and USGS trilateration data (EDM, 1973-1987) yielded horizontal extensional deformation rate at 4.0 mm/yr at N15°E. The University of Utah has conducted GPS surveys in this area from 1987 to 2000. These data revealed a continuation of extensional strain but decreasing to about 2 mm/yr at N31°E. With the assumption that the EDM and GPS methods provide consistent results, the exponential decrease of strain from 1973 to 2000 is interpreted to reflect the post-seismic viscoelastic relaxation. We fitted the time-dependent changes of fault-crossing baseline lengths using the viscoelastic 1-D code of Pollitz (1997) by the Monte Carlo method. The lithospheric layer-model was parameterized as elastic upper-crust over viscoelastic lower-crust and upper-mantle. Four parameters are resolved: the two layer thicknesses and the two viscosities of lower-crust and upper-mantle (ranging from $10^{18}$ to $10^{22}$ Pa-s). A set of 20,000 random models were generated for this task, where our preferred parameters are associated with models whose chi-square misfits are within 5% of the total from the smallest chi-square value. This study will examine the time-dependent postseismic deformation effected by rheological properties that provide an insight into understanding the cycle of large earthquakes in extensional stress regime.

## NG62A-0935 1330h POSTER

### Remote Triggering in Quasi-Static Fault Models

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Remote Triggering in Quasi-Static Fault Models

We present the results of time-space analyses of synthetic catalogs, generated using a quasi-static discrete fault model that is governed by rate- and state- dependent friction. These analyses reveal that the increase in the post mainshock earthquake production rate occurs over an area surrounding the mainshock rupture with dimensions that are several times larger than the mainshock dimensions. Some clues as to what may give rise to distant aftershocks may be gained through examination of the fault state prior to the mainshock. Snapshots of the fault state at progressive times prior to each mainshock show that the regions that evolved towards failure covered areas that were much larger than the final size of the mainshock ruptures. As a result, as time approached the mainshock time, the seismicity rate in these regions increased and the *b*-value of the earthquake size distribution decreased. This result implies that the increase in seismicity rate far from the mainshock (where the static stress changes imposed by the mainshock were extremely small) was possible, since these regions were already close to failure before the mainshock. It has been previously suggested that remote seismicity rate increase may be triggered by stress changes associated with the passage of seismic waves. However, the existence of remote triggering in a quasi-static model indicates that it is not necessary to invoke such a "dynamic effect" in order to explain distant aftershocks.

## NG62A-0936 1330h POSTER

### Deformation in the Los Angeles Basin and Transverse Ranges: Comparison of Finite Element Model Velocities With Geodetic Velocities Observed by SCIGN

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Sedimentary basins play an important role in how deformation is accommodated in southern California. Studies of the effects of the Northridge earthquake indicate that the high rates of deformation observed in the Ventura basin are controlled by afterslip in the upper crust, and possibly the anelastic deformation of the sediments within the basin. In the Los Angeles basin, observed strain rates are elevated between downtown Los Angeles and the San Gabriel Mountains, but not to the extent observed in the Ventura basin. This may be because the Los Angeles basin is bounded only by one main thrust (the north-dipping Sierra Madre fault) and also because of the presence of a possible downwelling beneath the San Gabriel mountains. In both basins the fault slip rates cannot account for the total deformation observed geodetically. We model deformation within the Los Angeles basin using the Jet Propulsion Laboratory's GEOFEST finite element code. In 2-D, we used a range of fault structures designed to model the Sierra Madre thrust and a second possible thrust fault, and we varied the rheology of the basin and of both the upper and lower crust. Shortening is imposed as a boundary condition at the edge of the model; the San Andreas is treated as a fixed backstop, and the shortening is balanced by a lithospheric downwelling beneath the basin. We compare the resulting calculated surface velocities to current observed velocities recorded by the Southern California Integrated GPS Network (SCIGN). In the 2-D models, crustal rheology appears to be a more important factor than fault geometry in controlling model velocities. A weak (low viscosity) basin embedded in a strong upper and lower crust provides the best match to current observed surface velocities; however, based on RMS misfits with the data, none of the 2-D models correctly predicts the horizontal velocities in a profile across the Los Angeles basin. We will present the results of a preliminary 3-D model of the region. The 3-D model allows more realistic representation of fault geometries, including the relationship of the Sierra Madre and San Andreas faults. Comparison with the observed geodetic data is also facilitated because the 3-D models produce a map of the velocity field rather than a linear profile.

## NG62A-0937 1330h POSTER

### Stochastic Model of Slip Spatial Complexities for the 1979 Imperial Valley, California, Earthquake

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Finite-fault source inversions reveal the spatial complexity of earthquake slip or prestress distribution over the fault surface. This spatial complexity is the macroscopic synthesis of the interplay of an irregular initial stress distribution with the irregular geometrical configuration of the fault. However, there is still a large debate in the seismological community on how to characterize earthquake complexities. Here, we discuss a stochastic model that reproduces the spatial variability and the long-range spatial correlation of the strike slip distribution of the 1979 Imperial Valley earthquake. We have found that non-Gaussian distributions are better suited to describe the spatial variability of slip over the fault. We show that a stochastic modeling of the slip amplitude based on a Gaussian distribution fails to reproduce the spatial variability, especially the extreme events, observed in the original slip distribution. Furthermore, we have found that interpolation of the slip spatial distributiona common procedure in numerical computation of rupture propagationintroduces spurious long-range spatial correlations. These results suggest that the heterogeneous spatial slip distribution of Imperial Valley is one realization of a stochastic process. This implies that by describing the statistical properties of earthquakes we can lay the foundation for equivalent scenario earthquakes. This will allow computation of ground motion for a range of earthquakes all of which will have the same inherent statistical properties. To test this hypothesis, the stochastic model is used to generate synthetic samples of the prestress spatial distribution statistically equivalent to the Imperial Valley prestress distribution. For each sample, scenario of rupture propagation and ground motion will be computed using dynamics rupture models.



## NG62A-0938 1330h POSTER

### Finite Element Modeling of Earthquake Dynamic Rupture on 2D Nonplanar Dipping Faults

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We simulate dynamic ruptures on 2D nonplanar faults by using a newly developed finite element (FE) method. Instead of solving the equations of motion in an element-by-element fashion as in Dyna2D and Dyna3D, we store all the nonzero terms in the global stiffness matrix, which provides all the coefficients to update the displacement field. The mass matrix is diagonalized. In this way, the new FE method is able to run in an explicit way as efficiently as the second-order finite difference scheme in terms of memory and speed. However, it deals with boundary conditions more naturally. Because the element size can change with material properties the FE method supports a nearly constant grids per wavelength resolution. We use the split-node scheme to model the fault boundary conditions. In our initial investigations of dynamic ruptures we consider 2D bending faults in an inhomogeneous earth with a stress-free surface. For faults that are unfavorably oriented with regard to Andersonian faulting we consider variations in normal stress through an effective stress. Slip weakening friction laws are used to normalize the stress at the crack tip.

## NG62A-0939 1330h POSTER

### Dynamic modeling of the 1999 Izmit, Turkey earthquake on non-planar fault models

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We simulated dynamic rupture propagation along various non-planar fault models proposed for the 1999

İzmit, earthquake in Turkey using a BIEM (boundary integral equation method). These models were inspired by those proposed by several authors from seismological, geological and geodetic observations. Once the dynamic rupture process was computed, we modeled seismic wave propagation from the fault to strong ground motion stations using a FDM (finite difference method). Our results indicate that near field strong motion is very much influenced by details of the rupture progress, which is in turn are very sensitive to small differences in fault geometry. Both observed and synthetic near-field seismograms, confirm a rapid and continuous rupture propagation from the İzmit-Sapanca lake segment to the Sapanca-Akyazı segment. Rupture under Sapanca lake appears to have propagated not across a discontinuous fault segment, but along a smooth fault structure with a bend of only a few degrees. In order to explain near-field seismogram at station SKR, located only a few km away from the fault, we had to force rupture to propagate at shallow depth near to the station. In order to obtain this we had to introduce a finite cohesive force in the friction law near the surface, so that stress accumulation and release can occur in the very shallow crust. The external stress field had to be large enough for rupture to propagate at very rapid speed. Our simulations show that details of the fault geometry have a substantial effect on rupture propagation and the generation of rupture pulses required to explain strong motion records at the available stations.

## NG62A-0940 1330h POSTER

### Tsunami Generation From the Santa Catalina Island Restraining Bend Offshore of Los Angeles, California

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We model the Santa Catalina Island platform as a pop up structure in a major restraining bend along a right-slip fault zone. We are assuming that the shape of the sea floor uplift replicates the finite deformation associated with combined right slip and reverse faulting during major earthquakes on the Catalina fault. We successfully model the seafloor and island uplift with two major fault sections comprised of seven individual segments. As observed in several other restraining bends, offshore southern California, the two major fault sections are arranged in a right stepping en echelon pattern. These two major fault sections are evident in bathymetry and topography as sea floor scarps and deflected drainages on the island.

The best fit to the existing bathymetry and topography is achieved with a total fault length of 150 km with segments dipping from 60 to 90 degrees to the northeast. A fault width of 14 km extending from a depth of 0.5 to 1.5 km is used. Fault slips vary from 3.5 to 6.5 m and results in surface uplifts of up to 2.2 m centered on the island near Mt. Orizaba. The simulated earthquake has a moment magnitude of $\sim$ 7.6, and the predicted surface displacements are comparable to surface faulting measured in recent magnitude 7 to 7.6 earthquakes worldwide.

Tsunami generation as a result of this event generates effectively two wave fronts from the opposite submerged ends of the island platform with initial wave heights of up to 1.5 m. It is important to note that the maximum uplift in this scenario occurs on land and does not directly contribute to tsunami generation. Resulting wave interference patterns create zones of elevated runup along the coast.

With this initial fault model we will proceed to consider other faulting scenarios comprised of different segment combinations, slip distributions and earthquake magnitudes.

## NG62A-0941 1330h POSTER

### Effects of fault heterogeneities on seismicity patterns, dynamic dimension, and predictability of earthquakes

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We extend our numerical simulations of the discrete models of Ben-Zion and Rice (1993) and Ben-Zion (1996) for a cellular strike-slip fault zone in a 3D elastic solid in an effort to provide a quantitative description of the dynamical role played by various distributions of fault heterogeneity.

Previous analytical results have shown that the model has an underlying critical point at zero dynamic weakening and numerical simulations indicated that a realistic description of fault instabilities should include heterogeneities which cover a wide range of size scales.

In the present work we investigate disorder models that probe various generic properties of heterogeneous distributions of brittle fault properties: spatial variability (uncorrelated versus correlated Gaussian, exponential, or power-law distributions), amplitude, and anisotropy. Our extensive numerical simulations suggest that the degree of disorder in fault heterogeneities is another tuning parameter of the dynamics. As we change the disorder model, we characterize their dynamical role by measuring the change in the spatio-temporal correlation lengths of stress and seismicity fluctuations, and the power-law range of the frequency-size event statistics.

Using a phase space analysis of the dynamics, we estimate the effective dimensionality of the fault models and measure how changes in the model parameters affect their dimensionality. We also determine the empirical eigenfunctions and eigenvalues generated by the dynamics of each model by using the proper orthogonal decomposition (POD). In order to extract information on the attractor of each disorder model, we analyze the time histories and phase space projections of the modal coefficients that provide a representation of the surface deformation fields in terms of the empirical eigenfunctions. This information is used to derive low-dimensional models for the dynamics and to examine its predictability as a function of the model location in the phase space of disorder models.

## NG62A-0942 1330h POSTER

### Simple spring-mass model simulation of the earthquake cycle along the Nankai trough in southwest Japan

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Along the Nankai trough in southwest Japan, great earthquakes have occurred repeatedly due to the subduction of the Philippine Sea plate. The rupture zone is assumed to be divided into five segments $A-E$ from the west to the east. Historical documents show the characteristic features of the past several earthquake cycles as follows (e.g., Ishibashi and Satake 1998);

1. almost simultaneous ruptures occur in segments in spite of different convergence rates, which is increasing westwards from 4 to 6 cm/yr (and it is 2cm/yr at segment $E$ (Heki and Miyazaki 2001)).
2. the recurrence times are 90 to 150 years.
3. the segments slip in pairs in earthquake ruptures such as segment $A$ and $B$, or segment $C$ and $D$.
4. respective segments have the different coseismic slip behaviors (e.g., Tanioka and Satake 2001).

To investigate the physical mechanisms of earthquake cycle, we simulate these features using a simple block-spring model, based on the rate and state friction law. The model has five blocks which correspond to the actual fault segments. Considering the actual fault parameters related to the geometry and the kinematics of the convergent plate in five segments, we calculate the model parameters for the corresponding blocks in the simulation from the fault parameters. The features of the observed earthquake cycle are successfully reproduced by assigning the other following model parameters; (1) the stick-slip periods are almost the same for non-interacting blocks, (2) the different pairs of frictional parameters $a-b$ and $D_c$ are assigned in each segment with larger $D_c$ in segments $C$ and $B$ than in $D$ and $A$, (3) the interactions between segments are large, (4) the convergence rate in the eastern Tokai segment is about half of those in the other segments.

It has passed more than 10 years since Huang and Turcotte (1990) who presented a simple 2-block-spring model with velocity weakening friction. Here, employing a 5-block-spring model with rate and state friction, we succeeded in reproducing more realistic and complex features of earthquake cycle observed along the Nankai trough. Our simple model, including nonlinear interactions between segments through rate and state friction, will provide a basis to understand the physical mechanism of earthquake cycle and to predict the future occurrence of great earthquakes.

## NG62A-0943 1330h POSTER

### A New Supershear Transition Mechanism for Cracks

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We report the discovery of two new mechanisms by which a shear crack in three dimensions can make the transition from propagation at sub-Rayleigh velocities to approximately $\sqrt{2}$ times the shear wave speed. We numerically model a rupture front incident on a circular obstacle of either increased fracture energy or decreased prestress. The delayed breaking of the fracture energy barrier focuses the energy of the rupture front, releasing both a longitudinal wave parallel to the crack surface and a Rayleigh surface wave. In addition, strong barriers split the front as it moves around the obstacle. Convergence of these split fronts results in rapid stress drop and high slip velocity. These two focusing mechanisms induce the supershear transition. As this only rarely occurs for prestress obstacles, we suggest the use of these transient wave effects to distinguish between the variable prestress and variable fracture energy models of earthquakes.

## NG62A-0944 1330h POSTER

### Spatial and Temporal Patterns of Regional Seismicity Preceding the 1992 Landers California Earthquake

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We investigate regional seismicity patterns as a function of space, time and magnitude preceding the 1992 Landers California earthquake using both raw and declustered catalogs. In addition to the previously documented increase of intermediate earthquakes (and associated acceleration of seismic moment release), the occurrence of small earthquakes down to M=1.8 selected from the declustered catalog also accelerated before the Landers earthquake. During this time period, the raw catalog showed a pronounced increase of Gutenberg-Richter a-value in circular regions centered at the Landers mainshock having radii up to about 125 km, while no regular changes of Gutenberg-Richter b-value were observed. The increase of a-value is probably due to the acceleration in the declustered catalog plus aftershocks associated with the increased number of intermediate events. We also examined the distribution of intermediate events using single-link cluster analysis. We found that the average link length became longer while the width of the distribution became smaller with time approaching the Landers mainshock. Finally, the observed increase of seismicity was not isotropic, but was concentrated in discrete azimuths radiating from the Landers earthquake, as predicted by the King and Bowman stress accumulation model (J.G.R., 2002). These observations support the critical point concept for earthquakes where the regional stress field becomes smoother before a large event.

## NG62A-0945 1330h POSTER

### Origin of Selfhealing Pulses in Earthquake Dynamics

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One of the most interesting results of kinematic and dynamic earthquake models is the pervasive presence of what Heaton called self-healing rupture pulses. Similar pulses have been found recently in the decollement of gels in contact with metal by Rubio and Baumberger and in the slip between dissimilar surfaces by serveral authors. Thus pulses seem to be a quite common feature of unstable slip under shear. We examine two possible models of healing: an active one where healing is the consequence of rate dependence of friction as proposed by Heaton and Cochard and Madariaga. Another is spontaneous healing due to heterogeneity of initial conditions proposed by Mikumo and Beroza. These two mechanisms are very different, in the former healing propagates at supershear speeds, while in the second subshear healing was found in some initial models of self-similar self-healing faults. We report on some general results about healing in shear faulting. Using Kostrov's 1994-1966 theory we demonstrate that healing fronts are propagating singularities of lower order than rupture fronts with no localised energy flow into or out of the fault. In many models healing is incomplete leaving small residual slip rates, on others healing can be total. We demonstrate that healing is a very effective method to reduce energy release during seismic rupture and unstable shear slip. Partial or total healing reduces the energy available for rupture to propagate, favoring ruture arrest and reducing seismic radiation.

## NG62B MCC: Hall C Saturday 1330h

### Scaling, Cascades, and Predictability of Earthquakes Posters *(joint with S, T)*

***Presiding:*** **V G Kossobokov,** International Institute of Earthquake Prediction Theory**; I Zaliapin,** University of California, Los Angeles

### NG62B-0946 1330h POSTER

### Estimation of Maximum Magnitude (c-value) and its Certainty for Modified Gutenberg-Richter Formulas, Based on Historical and Instrumental Japanese Intraplate Earthquake Catalogs

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A-, b-, and c-values for the original Gutenberg-Richter formula (GR) and modified GR formulas (Utsu, 1978) were estimated using a dataset of combined historical (1595-1925 A.D.) and instrumental (1926-2000) Japanese earthquake data for 18 intraplate seismo-tectonic provinces depicted on a new tectonic map of Japan (Kakimi et al., 2002). The theoretical relationships between the b-values of the original and modified GR formulas, and the certainty of b- and c-values, were evaluated with respect to the dataset.

The GR formula generally used for earthquake magnitude and frequency relationships demonstrates that earthquake frequency in each magnitude class is about ten times that of the next highest class. This is expressed as: log n(M) = a-bM, where n(M) is the number of earthquakes of a given magnitude M, and a- and b-values are constants representing the level of seismicity and the ratio of small to large events, respectively. In this formula, the expected maximum magnitude (c-value) in a given earthquake catalog is calculated using one more assumption: a maximum-magnitude earthquake should occur only once in a given period, because the c-value is not a characteristic parameter of the original GR formula. Utsu (1978) proposed that the GR formula be modified by introducing the c-value, and presented two formulas: a truncated GR formula (TGR), expressed as log n(M) = a - bM (M is equal to or smaller than c); n(M) = 0 (M is greater than c); and a modified GR formula (MGR), expressed as log n(M) = a - bM + log (c-M) (M is smaller than c); n(M) = 0 (M is equal to or greater than c).

Calculations for 18 Japanese seismo-tectonic provinces revealed the following relation: b(GR) > b(TGR) > b(MGR). This is a theoretical relationship, which means that b- and c-values are relative parameters within one formula, and that comparison of b- and c-values between different GR formulas is meaningless. Furthermore, the distribution of b- and c-values in 18 intraplate seismo-tectonic provinces indicates that b- and c-values are very sensitive to the parameter Ms, which is the lower limit of magnitude above which the dataset is thought to be complete. Thus, it is necessary to ascertain that b- and c-values are stable with respect to Ms, and that c-values are appropriate to maximum magnitude when estimating these parameters within a given earthquake catalog and seismo-tectonic province.

Reference:

Kakimi, T., Matsuda, T, Kinugasa, Y., and Aida, I, 2002, A seismotectonic province map in and around the Japanese islands, submitted to Jour. Seimol. Soc. Japan (Zishin2).

Ustu, T, 1978, Estimation of Parameters in Formulas for Frequency-Magnitude Relation of Earthquake Occurrence, Jour. Seimol. Soc. Japan (Zishin2), 31, 367-382.

### NG62B-0947 1330h POSTER

### (Multi)fractality of Earthquakes by use of Wavelet Analysis

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The fractal character of earthquakes' occurrence, in time, space or energy, has by now been established beyond doubt and is in agreement with modern models of seismicity. Moreover, the cascade-like generation process of earthquakes -with one "main" shock followed by many aftershocks, having their own aftershocks- may well be described through multifractal analysis, well suited for dealing with such multiplicative processes.

The (multi)fractal character of seismicity has been analysed so far by using traditional techniques, like the box-counting and correlation function algorithms. This work introduces a new approach for characterising the multifractal patterns of seismicity. The use of wavelet analysis, in particular of the wavelet transform modulus maxima, to multifractal analysis was pioneered by Arneodo et al. (1991, 1995) and applied successfully in diverse fields, such as the study of turbulence, the DNA sequences or the heart rate dynamics. The wavelets act like a microscope, revealing details about the analysed data at different times and scales. We introduce and perform such an analysis on the occurrence time of earthquakes and show its advantages. In particular, we analyse shallow seismicity, characterised by a high aftershock "productivity", as well as intermediate and deep seismic activity, known for its scarcity of aftershocks. We examine as well declustered (aftershocks removed) versions of seismic catalogues.

Our preliminary results show some degree of multifractality for the undeclustered, shallow seismicity. On the other hand, at large scales, we detect a monofractal scaling behaviour, clearly put in evidence for the declustered, shallow seismic activity. Moreover, some of the declustered sequences show a long-range dependent (LRD) behaviour, characterised by a Hurst exponent, H > 0.5, in contrast with the memory-less, Poissonian model. We demonstrate that the LRD is a genuine characteristic and is not an effect of the time series probability distribution function. One of the most attractive features of wavelet analysis is its ability to determine a local Hurst exponent. We show that this feature together with the possibility of extending the analysis to spatial patterns may constitute a valuable approach to search for anomalous (precursory?) patterns of seismic activity.

URL: http://www.rcep.dpri.kyoto-u.ac.jp/∼benescu/

### NG62B-0948 1330h POSTER

### Evidences of Complexity of Magnitude Distribution, Obtained From a Non-parametric Testing Procedure

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Complexity of magnitude distribution, that is the presence of more than one mode or more than one bump in its density, is indicative for mixing of components in the population. Parametric testing procedures that test sample data against a specific assumed model often cannot provide convincing evidences of such a complexity. If a complex model of the distribution is not rejected its appropriateness is not certain yet. To the contrary, if a log-linear or smoothly non-linear model is rejected this does not indicate that no other model of this class fits the data.

To study the complexity of magnitude distribution we used a smoothed bootstrap test for multimodality, which is non-parametric, model-free and data driven. Two null hypotheses were investigated: H0(1): the number of modes in magnitude density = 1 and H0(2): the number of bumps in magnitude density = 1. The probability of the null hypotheses turned out to be extremely low for global large earthquake data and for some local catalogs e.g. the Southern California data. Since the tested hypotheses were very general the obtained results distinctly evidence multicomponental structure of magnitude distribution.

### NG62B-0949 1330h POSTER

### Fractal asperities, invasion of barriers, and prediction of the Tokai earthquake

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I present a model to explain seismicity variations along plate boundaries: (1) plate boundary fault zones consist of asperities and barriers, which are defined as having negative and positive a - b values, respectively, of rate and state dependent friction laws, (2) circular-shaped asperities are distributed in a fractal manner so that within an order n asperity, a number of Na order n+1 (smaller) asperities are contained, whose radius is $1/\lambda$ of that of an order n asperity, (3) pore fluid pressure can be elevated almost to the lithostatic only in barriers (called invasion of barriers), and (4) a region whose barriers are invaded can rupture as an earthquake when asperities inside break. I derive scaling relations of fault parameters between successive order asperities. The observed relation between fault area and seismic moment and the size-ratio between nearby repeating earthquakes off northern Honshu give Na = 9, $\lambda = 4.8$, and the fractal dimension of asperities to be 1.4.

I applied this model to predict the Tokai earthquake, a great interplate earthquake expected off central Honshu. I assume that the rupture zone is part of an order 0 asperity in which barriers have been invaded, and that the Tokai earthquake will happen when any one of order 1 asperities inside the rupture zone breaks. I also assume that barriers within any order 1 asperity are not invaded, because if they are, breakage of this order 1 asperity occurs easily, and the Tokai earthquake would have happened already. Then smaller asperities within the order 1 asperities slip slowly, which explains the gradual uplift relative to the steady subsidence, seen for the past decade, on the peninsula above the rupture zone. I calculate uplifts due to slow slips of the smaller asperities contained in the rupture zone, assuming that the probability of breakage of the smallest asperities increases linearly over time, and an order n asperity breaks when more than or equal to a number of Nb order n+1 asperities break within it. This produces a critical point for breakage of asperities, but an order 1 asperity breaks a little bit earlier. I conduct a least squares fitting to the residual uplift data and obtain the time of failure for the Tokai earthquake as AD 2007.6 (-5.4, +2.8).

URL: http://www.eri.u-tokyo.ac.jp/seno

NG

### NG62B-0950 1330h POSTER

### BATH'S LAW AS A CONSEQUENCE OF MAGNITUDE DISTRIBUTION

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We revisit the issue of the so-called Bath's law concerning the difference D1 between the magnitude of the mainshock, M0, and the second largest shock, M1, in the same sequence. Various authors, in the past, observed that this difference is approximately equal to 1.2. Feller demonstrated in 1966 that the D1 expected value was about 0.5 given that the difference between the two largest random variables of a sample, N, exponentially distributed is also a random variable with the same distribution. Feller's proof leads to the consequence that the mainshock comes from a sample, which is different from the one of its aftershocks. A mathematical formulation of the problem is developed here, the only assumption being that all the events belong to the same self-similar set of earthquakes following the Gutenberg-Richter magnitude distribution with a constant b-value. Assuming that the number of aftershocks in each aftershock series is known, and not extremely large, this model shows a substantial dependence of D1 on the magnitude thresholds chosen for the mainshock and its largest aftershock. In this way it explains the large D1 values reported in the past. Analysis of the PDE catalog of shallow earthquakes demonstrates a good agreement between the average D1 values predicted by the theoretical model and those observed. Limiting our attention to the average D1 values, Bath's law doesn't seem to strongly contradict the Gutenberg-Richter law. Nevertheless, a detailed analysis of the observed D1 distribution shows that the Gutenberg-Richter hypothesis doesn't fully explain the experimental observations. The theoretical distribution has a larger proportion of low D1 values and a smaller proportion of high D1 values than the experimental observations. A reasonable explanation for this mismatch, which appears a minor effect with respect to what was supposed in the past, seems to consist in the byes (not assumed in the model) that the selection of clustered events produces on the average b-value.