# Poster Abstracts

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### PyLith 1.0: A Finite-Element Code for Modeling Quasi-Static and Dynamic Crustal Deformation

*Aagaard, Brad (USGS), Charles Williams (RPI), and Matthew Knepley (ANL/CIG)*

We have developed open-source finite-element software for 2-D and 3-D dynamic and quasi-static modeling of crustal deformation. This software, PyLith 1.0, combines the quasi-static modeling functionality of PyLith 0.8 and its predecessors (LithoMop and Tecton) and the dynamic modeling functionality of EqSim. The target applications contain spatial scales ranging from tens of meters to hundreds of kilometers with temporal scales for dynamic modeling ranging from milliseconds to minutes and temporal scales for quasi-static modeling ranging from minutes to hundreds of years. This software, PyLith 1.0, is part of the NSF funded Computational Infrastructure for Geodynamics and runs on a wide variety of platforms, from laptops to Beowulf clusters (executables are available for OSX, Linux, and Windows). PyLith uses a general, parallel, graph data structure called Sieve for storing the finite-element mesh. This permits use of a variety of 2-D and 3-D cell types including triangles, quadrilaterals, hexahedra, and tetrahedra. Current features include kinematic fault interface conditions, Dirichlet (displacement) boundary conditions, linear elastic and Maxwell linear viscoelastic materials, and quasi-static and dynamic time-stepping. Future releases will add traction and absorbing boundary conditions, dynamic fault interface conditions (employing fault constitutive models), generalized Maxwell viscoelastic materials, and automated calculation of suites of Green's functions. We also plan to extend PyLith to allow coupling multiple simultaneous simulations. For example, this could include (1) coupling an interseismic deformation simulation to a spontaneous earthquake rupture simulation (each using subsets of the software), (2) coupling a spontaneous earthquake rupture simulation to a global wave propagation simulation, or (3) coupling a short-term crustal deformation simulation to a mantle convection simulation and an orogenesis and basin formation simulation.

### SCEC/SURE: Economic Preparations

*Abbott, Corey (Occidental)*

I participated in a 10-week internship program called the Summer Undergraduate Research Experience, working for a USGS project led by economist Rich Bernknopf. I compiled and analyzed information about short term and long term economic consequences of a magnitude 7.8 earthquake along the San Andreas Fault in Southern California. The ultimate goal of the project is to use scientific information to stimulate policy-making regarding damage mitigation, preparedness, and resiliency. I spearheaded a questionnaire sent to SoCalFirst, a financial institution consortium, seeking feedback on expected consequences in the financial sector. I gathered baseline economic data for eight counties, including population, unemployment, employment by industry classification, wages, and worker commute modes and patterns over the past few years. I compiled the information into Microsoft Excel spreadsheets and analyzed recent trends. I researched the movement of goods in Southern California, with emphasis on the ports including the viability of alternative options if the ports and/or trucking routes are damaged in a quake. I studied business recovery following previous quakes to determine the factors that most influence a firm's ability to recover. I digested the relevant policies and regulations and economic information from the Palm Springs comprehensive plan.

### A high-frequency secondary event during the 2004 M6.0 Parkfield earthquake

*Allmann, Bettina (SIO, UCSD) and Peter Shearer (SIO, UCSD)*

We image the rupture propagation of the 2004 M6.0 Parkfield earthquake by analyzing records from a dense network of local strong motion sensors. We employ a waveform backprojection method, similar to a reverse time migration, for imaging of high-frequency radiated seismic energy. We use waveform cross-correlation to align the initial S-wave arrivals and correct for small static time shifts in the records. This forces a coherent image at the hypocenter and the quake origin time. We observe a distinct secondary event in the waveform data, which images to a location about 12.5 km northwest of the hypocenter with an onset of seismic radiation about 5 sec after the rupture initiation, resulting in an average rupture velocity of 2.5 km/s between hypocenter and subevent. The secondary event is also clearly visible in the waveform data and can be inverted to the same location by using picked arrival times of the subevent at local and regional stations. Our image of the rupture shows two separate events at the hypocenter and at the subevent, rather than a continuous rupture. This indicates that much less seismic energy was radiated between the hypocenter and the subevent in the investigated frequency band. The subevent is located at the edge of a high-slip patch that was found by a number of slip inversions using low-frequency seismic as well as geodetic data. The location of high-frequency seismic energy being radiated from the edge of areas of high slip is consistent with seismic source theory. Furthermore, we determine the ratio of radiated seismic energy between the main shock and the subevent, which suggests a lower stress drop for the subevent compared to the main shock. This stress-drop difference between the main shock and the subevent correlates with lateral stress-drop variations observed from background seismicity and small-magnitude aftershocks.

### Cracks, pulses and macroscopic asymmetry of dynamic rupture on a bimaterial interface with velocity-weakening friction

*Ampuero, Jean-Paul (ETH Zurich) and Yehuda Ben-Zion (USC)*

We study in-plane ruptures on a bimaterial fault governed by a velocity-weakening friction with a regularized normal stress response. Numerical simulations and analytical estimates provide characterization of the ranges of velocity-weakening scales, nucleation lengths and background stresses for which ruptures behave as cracks or pulses, decaying or sustained, bilateral or unilateral. With strong velocity-weakening friction, ruptures occur under a wide range of conditions as large-scale pulses with a preferred propagation direction, that of slip of the most compliant material. Such ruptures have macroscopic asymmetry manifested by significantly larger seismic potency and propagation distance in the preferred direction, and clearly quantified by the directivity ratio derived from the second moment of the spatio-temporal distribution of slip. The macroscopic rupture asymmetry of the large-scale pulses stems from the difference in the criticality conditions for self-sustained propagation in each rupture direction, induced by the asymmetric normal stress changes operating in bimaterial interfaces. In contrast, crack-like ruptures show macroscopic asymmetry under restrictive conditions. The discussed mechanism is robust with respect to regularization parameters, ranges of stress heterogeneities and a proxy for off-fault yielding, and should operate similarly for crustal-scale rupture pulses even in the absence of velocity-weakening. Small-scale pulses, driven by the bimaterial normal stress reduction at the scale of the process zone, can detach from the rupture front of the large-scale pulses that propagate in the preferred direction. However, their occurrence depends on the relaxation scale in the regularization of the normal stress response and their development can be hindered by off-fault yielding.

### Low-latency high-rate GPS data streams from the EarthScope Plate Boundary Observatory

*Anderson, Greg (UNAVCO), Mike Jackson (UNAVCO), Chuck Meertens (UNAVCO), and Keith Stark (Stark Consulting, LLC)*

Real-time processing of high rate GPS data can give precise (e.g., 5-10 mm for data recorded once per second) recordings of rapid volcanic and seismic deformation. GPS is also an inertial sensor that records ground displacement with very high dynamic range, which allows the use of high rate GPS as a strong-motion seismometer. Such processing applied to low-latency streams of high sample rate GPS provide an emerging tool for earthquake, volcano, and tsunami geodesy and early warning.

UNAVCO, as part of the EarthScope Plate Boundary Observatory project, has developed a system to provide such streams from some PBO and other UNAVCO-operated GPS stations, which we call UStream. UStream is based on the Ntrip standard, a widely used protocol for streaming GNSS data over the Internet. Remote GPS stations provide a stream of BINEX data at 1 sample/sec to an Ntrip server at UNAVCO's Boulder offices, while at the same time recording data locally in the event of communications failure. Once in Boulder, the data fork into three output streams: BINEX files stored at the UNAVCO archive and streams of data in BINEX and RTCM format. These data flow to an Ntrip broadcaster that will distribute data to Ntrip clients, which can be anything from low-latency processing systems to external data archiving systems.

This system is now operating in a public beta test mode, with data available from about 40 PBO and Nucleus GPS stations across the western United States. Data latencies from stations operating on mobile telephone communications are under 1.1 seconds at 95% confidence, and data completeness is typically more than 95% barring transient communications disruptions. Data from the system are available to the community for use in scientific research and educational activities at no cost; please contact Greg Anderson to participate in this public beta test and to provide feedback to UNAVCO as we further develop this community service.

**The EarthScope Plate Boundary Observatory Unified Geodetic Network**

*Anderson, Greg, Mike Jackson, Karl Feaux, David Mencin, Brian Coyle, Barrett Friesen, Katrin Hafner, Wade Johnson, Ben Pauk, Chris Walls, PBO Data Management/IT Team, and Chuck Meertens (UNAVCO)*

The Plate Boundary Observatory (PBO), part of the NSF-funded EarthScope project, is designed to study the three-dimensional strain field resulting from deformation across the active boundary zone between the Pacific and North American plates in the western United States. To meet these goals, UNAVCO will install 880 continuous GPS stations, 103 borehole strainmeter stations, 28 tiltmeters, and five laser strainmeters by October 2008, as well as manage data for 209 previously existing continuous GPS stations through the PBO Nucleus project and 11 GPS stations installed by the USArray segment of EarthScope.

As of 1 August 2007, UNAVCO had completed 658 PBO GPS stations and had upgraded 88% of the planned PBO Nucleus stations. Highlights of the past year's work include the expansion of the Alaska subnetwork to 90 continuously-operating stations, including coverage of Akutan and Augustine volcanoes and reconnaissance for future installations on Unimak Island; the installation of nine new stations on Mt. St. Helens; and the arrival of 33 permits for station installations on BLM land in Nevada. The Augustine network provided critical data on magmatic and volcanic processes associated with the 2005-2006 volcanic crisis, and has expanded to a total of 11 stations. Please visit http://pboweb.unavco.org/?pageid=3 for further information on PBO GPS network construction activities.

UNAVCO is also installing and operating the largest borehole seismic/strainmeter network in North America, as well as tiltmeters and laser strainmeters. As of February 2007, 27 PBO borehole stations had been installed and three laser strainmeter stations were operating, with a total of 60 borehole stations and 4 laser strainmeters expected by October 2007. In response to direction from the EarthScope community, UNAVCO installed a dense network of six stations along the San Jacinto Fault near Anza, California; installed three of four planned borehole strainmeter stations on Mt. St. Helens; and has densified coverage of the Parkfield area. Please visit http://pboweb.unavco.org/?pageid=8 for more information on PBO strainmeter network construction progress.

The combined PBO/Nucleus GPS network has now provided almost 330 GB of raw standard rate data, with special downloads of more than 130 GB of high-rate GPS data following large earthquakes in Russia and the Tonga Islands, as well as for community requests. The standard rate GPS data are processed routinely to generate data products including station position time series, velocity vectors, and related information, and all data products are available from the UNAVCO Facility archive. The PBO seismic network seismic network has provided 185 GB of raw data, which are available via Antelope and Earthworm from PBO and via the IRIS Data Management Center (DMC); we provide data to seismic networks operated from Caltech, UCSD, UCSB, University of Washington, and the Pacific Geosciences Center in Sidney, BC. The PBO strainmeter network has provided 85 GB of raw data, available in both raw native format and

SEED format from the Northern California Earthquake Data Center and the IRIS DMC, along with higher-level products such as cleaned strain time series and related information. Please visit http://pboweb.unavco.org/gps_data and http://pboweb.unavco.org/strain_data for more information on PBO GPS and strainmeter/seismic data products, respectively.

### Extreme Accelerations and Velocities Caused by Past Earthquakes

*Anderson, John (UNR)*

This project aims to understand the characteristics of the ground motion records that have yielded the 100 largest peak accelerations and the 100 largest peak velocities. The peak is defined as the maximum magnitude of the acceleration or velocity vector during the strong shaking. This compilation includes 35 records with peak acceleration greater than gravity, and 41 records with peak velocities greater than 100 cm/s. The results represent an estimated 150,000 instrument-years of strong-motion recordings. The mean horizontal acceleration or velocity, as used for the NGA ground motion models, is typically 0.76 times the magnitude of this vector peak. Accelerations in the top 100 come from earthquakes as small as magnitude 5, while velocities in the top 100 all come from earthquakes with magnitude 6 or larger. Records are dominated by crustal earthquakes with thrust, oblique-thrust, or strike-slip mechanisms. Normal faulting mechanisms in crustal earthquakes constitute under 5% of the records in the databases searched, and an even smaller percentage of the extreme records. All NEHRP site categories have contributed extreme records, in proportions similar to the extent that they are represented in the larger database.

### Catalog of Precarious Rocks and Related Ground Motion Indicators at Yucca Mountain

*Anderson, John G., James N. Brune, Rebecca Brune, Yui Miyata, and David von Seggern*

Probabilistic seismic hazard analysis (PSHA) is based on statistical assumptions that are very questionable when extended to very low probability maximum ground motions (10-6 to 10-8 annual probabilities, with ground motions of the order of 10 g acceleration and 10 m/s velocity, respectively). The short historical database for instrumental recordings is not sufficient to determine the uncertainties in the statistical assumptions. This suggests that we look for geomorphic and geologic evidence constraining ground motions over long periods in the past. Since the extrapolated ground motions are so large, we might expect to find evidence for them if they have occurred in recent geologic time.

Over the past ten years, we have observed many features that might constrain the ground motions that have occurred in the past in the vicinity of Yucca Mountain. Numerous precariously balanced rocks are located in the vicinity of Yucca Mountain. There are unstable cliff faces with numerous loose rocks stacked on top of each other. Near large UNE explosions, precarious rocks are absent and cliff faces are shattered with accumulations of rock spall composed generally of large to very large boulders. Thus, a lack of evidence of large-clast rockfall deposits on Yucca Mountain slopes and along the San Andreas fault may be used as a constraint on extreme ground motions over the time period that such rockfall avalanches would be preserved.

We are preparing a catalog of all observations of precarious rocks, precipitous cliffs, and other geological features that may tend to constrain ground motions. The outline of the report will be:

1. General introduction
2. Tables listing and numbering all features, and summarizing the current state of knowledge
3. Maps showing locations of all features
4. One page per feature that will include:
    * Feature type
    * Feature number
    * Location
    * Photographs
    * Checklist showing general state of knowledge about this feature
    * Description of results
    * References to papers or reports that discuss the feature.

We currently estimate that organization and entry of information that has already been gathered into this catalog will be a multi-year project. We will prepare our catalog in a form suitable for publication as a single coherent report, and publish that catalog once per year. The initial focus is on rocks near Yucca Mountain, but we believe it should be extended also to include precarious rocks wherever we have observed them. As this catalog is developed, it will help us to set priorities for future studies of precarious rocks.

### Physical Limits on Ground Motion at Yucca Mountain

*Andrews, D. J. (USGS Menlo Park), T. C. Hanks (USGS Menlo Park), and J. W. Whitney (USGS Denver)*

Physical limits on possible maximum ground motion at Yucca Mountain, Nevada, the designated site of a high-level radioactive waste repository, are set by shear stress available in the seismogenic depth of the crust and by limits on stress change that can propagate through the medium. We find in dynamic deterministic 2D calculations that maximum possible horizontal peak ground velocity (PGV) at the underground repository site is 3.6 m/s, which is smaller than the mean PGV predicted by the Probabilistic Seismic Hazard Analysis (PSHA) at annual exceedance probabilities less than 10-6 per year. The physical limit on vertical PGV, 5.7 m/s, arises from super-shear rupture and is larger than that from the PSHA down to 10-8 per year. In addition to these physical limits, we also calculate maximum ground motion subject to the constraint of known fault slip at the surface, as inferred from paleoseismic studies. Using a published probabilistic fault displacement hazard curve, these calculations provide a probabilistic hazard curve for horizontal PGV that is lower than that from the PSHA. In all cases maximum ground motion at the repository site is found by maximizing constructive interference of signals from the rupture front, for physically-realizable rupture velocity, from all parts of the fault. Vertical PGV is maximized for ruptures propagating near the P-wave speed, and horizontal PGV is maximized for ruptures propagating near the Rayleigh-wave speed. Yielding in shear with a Mohr-Coulomb yield condition reduces ground motion only a modest amount in events with super-shear rupture velocity, because ground motion consists primarily of P waves in that case. The possibility of compaction of the porous unsaturated tuffs at the higher ground motion levels is another attenuating mechanism that needs to be investigated.

### Reduction in the Uncertainties in the Ground Motion Constraints by Improved Field-Testing Techniques of Precariously Balanced Rocks

*Anooshehpoor, Rasool (UNR), Matthew D. Purvance (UNR), James N. Brune (UNR), and Tom Rennie (UNR)*

The precarious rock methodology has matured to the point where it is important to further reduce the uncertainties in the ground motion constraints that they provide. An extensive series of shake table tests in 2005 demonstrated that our fragility estimates are robust provided that we obtain relatively precise estimates of the geometric parameters for individual rocks. This initiative documents our implementation of these refined measurements in the field. A sensitive digital inclinometer operates in conjunction with a digital force meter, allowing us to determine an accurate restoring force versus tilt curve. This information provides an estimate of the basal complexity of each precarious rock, an important factor affecting the rock's stability (e.g., the presence of multiple rocking points for approximately two-dimensional rocks – most of our data are included in this category). Also, we have recently acquired a photogrammetry software package that facilitates accurate estimates of the precarious rock masses and the center of mass locations. This method of mass calculation has been validated with rocks of known mass that have used in previous shake table experiments. In particular, we have found that our current mass estimates are within 5-10% of the true masses and further accuracy may be achieved with some minor modifications to our current methods. These advances will allow for increased precision in calculating the overturning responses of precarious rocks and applying the resulting ground motion constraints to seismic hazard analyses.

We have undertaken these improved methods during field tests of several precariously balanced rocks near Palm Springs and Pioneer Town in southern California. Preliminary results indicate that the quasi-static toppling accelerations of these rocks are less than 0.2 g, the point where ground motions act to initiate rocking motion. These findings are especially interesting in light of the close proximity of the precarious rocks at Pioneer Town (within 10 km) to the Pinto Mountain Fault. This fault is reportedly capable of M

6.5-7.5 earthquakes which would overturn these precarious rocks assuming that standard ground motion prediction equations are applicable.

### *Products and Services Available from the Southern California Earthquake Data Center (SCEDC)*

*Appel, Vikki, Ellen Yu, Shang-Lin Chen, Faria Chowdhury and Robert Clayton*

The Southern California Earthquake Center established the Southern California Earthquake Data Center (SCEDC) facility at Caltech in 1991. At that time, our primary mission was to archive the seismograms recorded by the Southern California Seismic Network (SCSN) and to provide a simple mechanism for scientists to retrieve these data electronically. When the Data Center came online in January 1992, we had 95 scientific users and 214 GB of seismic and geodetic data, including short-period network data recorded by the SCSN from April 1981 to 1992 and the TERRAscope triggered waveforms from September 1990 forward.

In the years since, the SCEDC has continued to archive new data and compiled and converted all available historic seismic data to create a single source of southern California earthquake data from 1932-present. The TriNet project created a close coupling of the TriNet real-time data acquisition functions with the Data Center's post-processing, archiving and distribution capabilities. This poster will describe the most significant seismic data products and services that provide access to the station, parametric and waveform data archived at the SCEDC.

### The Velocity of Earth's Center

*Argus, Donald (JPL)*

Earth's center is fundamental to geodesy and geoscience because motions of sites on the surface are estimated relative to it. International Terrestrial Reference Frames ITRF2000 and ITRF2005 are defined by the center of mass of Earth's system (CM), consisting of solid Earth, the ice sheets, the oceans, and the atmosphere. Satellite LAGEOS rotates about CM; SLR (satellite laser ranging) is used to estimate the velocity of CM relative to sites on the surface. But ITRF2000 and ITRF2005 differ by 1.8 mm/yr, suggesting that the velocity of CM is constrained poorly by SLR.

In this study we define Earth's reference frame with the center of mass of solid Earth (CE). Site velocities estimated using SLR, VLBI (very long baseline interferometry), GPS (global positioning system), and DORIS (Doppler Orbit and Radiopositioning Integrated by Satellite) are corrected for a postglacial rebound model and inverted for the rotational velocities of the plates and the rotational and translational velocities of the four space techniques. Because the postglacial rebound predictions are relative to CE, the velocity of CE relative to sites on the surface is estimated. Because the input SLR site velocities are relative to CM, the output SLR translational velocity is the velocity of CM relative to CE.

The velocity of CE does not depend strongly on the postglacial rebound model corrected for. Equal within uncertainties and having a root mean square of 0.5 mm/yr are estimates of the velocity of CE determined assuming that plate interiors are deforming radially as predicted by the postglacial rebound models of Peltier [1994], Peltier [1996], and Peltier [2004], and an estimate of the velocity of CE determined assuming that parts of plate interiors neither beneath nor along the margins of the late Pleistocene ice sheets are not deforming laterally.

The velocity of CE equals within uncertainties [probability greater than 5%] the velocity of CM in ITRF2000. The velocity of CE differs significantly [0.05% probability] from the velocity of CM in ITRF2005.

Earth's reference frame should be defined with the tightly-constrained velocity of CE, not with the poorly-constrained velocity of CM. We recommend that Earth's reference frame be defined with the velocity of CE estimated using the lateral assumption because then Earth's reference frame would not depend on a specific postglacial rebound model. We advise scientists to transform from ITRF2000 to this study's Earth's reference frame by adding 0.1 mm/yr to X (0N 0E), -0.1 mm/yr to Y (0N 90E), and 0.6 mm/yr to Z (90N). This Earth's reference frame is roughly 1/3 of the way from ITRF2000 to ITRF2005.

ITRF's should be defined using the velocity of CE not the velocity of CM. Because CE is believed to be moving relative to CM no faster than 0.5 mm/yr, the velocity of CE estimated in this study is likely to be nearer the true velocity of CM than is the velocity of CM estimated using SLR.

### InSAR Accuracy: Uncertainty in Range Change and Rate

*Argus, Donald (JPL) and Paul Lundgren (JPL)*

To quantify how long an InSAR mission must be to resolve plate boundary deformation and interseismic strain accumulation, we assess InSAR accuracy. Lateral variations in troposphere delay are the main error source in InSAR range. SCIGN GPS estimates of troposphere delay in southern California show the error to increase with lateral distance [Emardson et al., JGR 2003]. The range error is 8 mm across 10 km, 18 mm across 50 km, and 25 mm across 100 km (standard errors). Range rate error across 50 km is 6 mm/yr for a 3-year mission, and 3.6 mm/yr for a 5-year mission. Because troposphere delay is nearly uncorrelated over times longer than a day, range rate error can be reduced by stacking interferograms if rates are nearly constant. Stacking interferograms every 24 days reduces range rate error by 62% to 2.3 mm/yr for a 3-year mission and by 70% to 1.1 mm/yr for a 5-year mission. Because InSAR accuracy of 1 mm/yr is needed to usefully constrain earthquake strain buildup and fault slip rates, a 5-year mission is needed. We present comparisons between InSAR and GPS estimates of range and range rate supporting this conclusion.

### GEODVEL: Plate Motions From Space Geodesy

*Argus, Donald (JPL), Richard Gordon (Rice University), Richard Eanes (Center for Space Research), Michael Heflin (JPL), Chopo Ma (Goddard Space Flight Center), Susan Owen (JPL), Pascal Willis (Insititut Geographique National and JPL), Zuheir Altamimi (IGN)*

We determine two sets of estimates of the angular velocities of the 11 largest plates using four space techniques (VLBI, SLR, GPS, and DORIS). The first, GEODVEL, is determined from four velocity solutions, one for each space technique. The second, ITRFVEL, is determined from the ITRF2005 [Altamimi et al., 2007] estimates of site velocity. GEODVEL and ITRFVEL are similar, but the two are very different from REVEL, the estimates of plate velocity that Sella et al. [2002] determined primarily from GPS data. In the tightly constrained plate circuit Eurasia-North America-Nubia-South America-Pacific-Australia-Antarctica, the median difference between the GEODVEL and REVEL estimates of angular velocity is 0.027 deg./Myr (which is up to 3.0 mm/yr on Earth's surface), and the 95% confidence limits in GEODVEL exclude REVEL for 20 of the 21 plate pairs. The GEODVEL and REVEL estimates of plate velocity differ so much because the GEODVEL and REVEL estimates of the velocity of Earth's center differ by 2 mm/yr. In REVEL the velocity of Earth's center is assumed to be that in ITRF1997, which defines Earth's center to be the (CF) center of figure of Earth estimated assuming geologic plate motion model NUVEL1A is exactly correct. In GEODVEL we simultaneously estimate plate velocities and the velocity of Earth's center, defining Earth's center to be (CE) the center of mass of solid Earth, and assuming places not beneath the late Pleistocene ice sheets are moving negligibly relative to CE. In GEODVEL estimates of uncertainty in plate velocity account for uncertainty in the velocity of Earth's center.

### Modeling uncertainty of nonlinear site response in the Los Angeles Basin

*Assimaki, Dominic (Georgia Tech), Wei Li (Georgia Tech), Jamison H. Steidl (UCSB), and Jan Schmedes (UCSB)*

There exists nowadays general agreement between the earthquake engineering and seismological community that the assessment of local site effects is of great significance, both for mitigating seismic hazard and for performing detailed analyses of earthquake source characteristics. Although, however, it is widely accepted that nonlinear effects should be accounted for in strong motion site response assessment methodologies, there still exists large degree of uncertainty concerning: (i) the site categorization scheme to be used for quantifying the susceptibility of local soil conditions to nonlinearity, (ii) the mathematical model to be employed for the computationally efficient evaluation of these effects, and (iii) the optimal site investigation program to ensure cost-effective strong ground motion predictions given the target level of design sophistication. Towards reducing these uncertainties, seismic observations of site response -and downhole instrumentation in particular- can provide critical constraints on interpretation methods for surface observations, as well as information on the real material behaviour under the in-situ state of stress subjected to a wide range of loading conditions.

We here present results of a parametric study, complemented by downhole observations obtained in the Los Angeles Basin, through which we investigate the variability in ground-motion estimation introduced by existing nonlinear site-response methodologies. For this purpose, site-specific regional velocity and attenuation structures are initially compiled using: (i) near-surface geotechnical data collected at seven downhole geotechnical arrays operated by a variety of agencies and organizations (SCEC, USGS, CSMIP, Caltrans); (ii) inverse low-strain velocity and attenuation profiles at these sites obtained by inversion of weak motion records; and (iii) the crustal velocity structure at the corresponding locations obtained from the Southern California Earthquake Centre Community Velocity Model III. Successively, broadband ground motion simulations are conducted using the hybrid low/high-frequency finite source model with correlated random parameters for rupture scenaria of weak, medium and large magnitude events (M =3.5 - 7.5). Observed estimates of site response at the stations of interest are first compared to simulated small magnitude rupture scenaria. Parametric studies are next conducted for each fixed magnitude (fault geometry) scenario by varying the source-to-site distance and source parameters for the ensemble of site conditions investigated. Elastic, equivalent linear and nonlinear simulations are implemented to assess the variability in ground motion predictions as a function of ground motion amplitude and frequency content and nonlinear site response methodology. Results of this study are currently used to develop supplementary criteria to the NEHRP site categorization scheme for nonlinearity susceptibility of sedimentary deposits, opting to establish a cost-effective and computationally-efficient framework for site parameterization and response simulation of nonlinearity-prone cohesive profiles, defined as a function of source-path-site-effects and design sophistication level.

### SCEC/UseIT: Mitigating Hazardous Objects

*Aung, Lily (USC)*

SCEC / Undergraduate Studies in Earthquake Information Technology interns use the most advanced computer technology to create multifaceted earthquake visualizations and displays. Every summer, UseIT interns are given a grand challenge that directs most of the work and goals. To accomplish the grand challenge, the interns are divided into smaller groups with individual responsibilities. This allows each participant to have an independent learning experience amidst a group environment.

This summer's grand challenge involved the creation of three serious games. While I was initially worked on the decision making game, I later developed a fourth serious game, a new mitigation game, which centers on identifying and reducing earthquake hazards in an apartment, a house, a neighborhood, and a city.

I defined the user choices for each level and the coding of the game. I accessed earthquake mitigation websites, including SCEC's, to find different methods of reducing hazards. I used ActionScript on Adobe Flash to write the code for all levels of the game. For the game's images, I employed Google SketchUp. Using what I learned from my teammates, I was able to create and develop the entire tenant level on my own, complete with scoring, restarts, and different outcome scenarios. Not bad, even though our group started our game a lot later than the others.

### Computation and Analysis of M < 5 Southern California Potency Tensors

*Bailey, Iain (USC), Thorsten Becker (USC), and Yehuda Ben-Zion (USC)*

We investigate properties of earthquake source mechanisms by analysis of ~176,000 potency tensors computed from M < 5 earthquakes in southern California for the period 1983-2004. The potency tensor representation allows us to concentrate on geometrical properties of the earthquake source while removing any assumptions about material properties required for a moment tensor.

Assuming a point-source double-couple approximation for all events, we use a catalog of focal mechanisms generated with the HASH program (Hardebeck & Shearer, 2002) and an empirical magnitude-potency scaling relation (Ben-Zion & Zhu, 2002) to compute potency tensors for the maximum feasible number of events. We then investigate the properties of these potency tensors in relation to spatial structures and earthquake size by summation of the tensors for various data subsets. Test cases applying increasingly strict quality restrictions to the HASH data are used to assess the robustness of our results. Comparing summations of the potency tensors with summations of normalized tensors allows us to investigate results dominated by large earthquakes as well as those dominated by the statistical properties of smaller events.

The summed tensors are firstly interpreted in terms of the principle strain axes, which appear to remain constant with regard to earthquake magnitude but vary in space, indicating a strong dependence of earthquake behavior on controlling spatial structures. Using summations over a 1 km grid, we are able to image such structures persistently with several ranges of earthquake magnitude. These structures appear related to surface fault geometries, and have a large range of scales (~5-75 km), such that the dominating structure depends on the size of the sampling region.

We analyze second-order features of the summed tensors in terms of the size of their compensated linear vector dipole (CLVD) component, which we interpret as a measure of mixing of fault styles. The CLVD components show a strong sensitivity to the spatial sampling biases of different magnitude earthquakes, which are not manifested in the principle axes orientations. In several cases the CLVD component becomes larger for summations of smaller magnitude earthquakes, which may reflect the greater spatial resolution provided by the large numbers of small events. The existence of CLVD components in summations over scales of 1 km indicates that although spatial structures appear to control earthquake behavior, these structures cannot be thought of in terms of simple planar faults.

### Validation of ground motion simulations for engineering applications

*Baker, Jack W. (Stanford) and Nirmal Jayaram (Stanford)*

The successful adoption of ground motion simulations for rupture-to-rafters analyses depends not only upon the quality of the science underlying the models, but also on empirical validation of observed ground motion parameters used by engineers. Ground motions simulated by SCEC researchers are used here to study several parameters of interest to the engineering community. Rather than study validations of ground motion simulations for specific earthquakes, this work considers the gross statistical properties of ground motions over a range of earthquake scenarios, with a focus on studying more subtle properties that are nonetheless known to affect the response of structures. Statistical properties of response spectra are studied, to determine correlations among spectral values at multiple periods, and spatial correlation of spectral values. Results are presented for Puente Hills simulations produced by Rob Graves and URS Corporation. It is found that the simulated ground motions are generally consistent with recorded ground motions in stiff soil regions. In soft-soil regions (with low surface shear wave velocities), simulated and recorded ground motions appear to differ in their statistical properties. It is not yet known whether these differences indicate a shortcoming in the simulations, or whether the limited empirical data from these conditions has resulted in a lack of understanding as to the properties of strong ground motions on soft soil. These results will aid engineers in understanding the extent to which state-of-the-art ground motion simulations can supplement or improve upon empirical ground motions, as well as provide feedback to seismologists as they continue to refine their simulation models. Further study of the Puente Hills simulations is planned, in addition to a study of pseudo-dynamic simulations produced by Martin Mai.

### SCEC/UseIT: Better, Stronger, Faster

*Bansal, Ranna (Princeton)*

The Undergraduate Studies in Earthquake Information Technology (UseIT) is a multidisciplinary internship devoted to computer science and programming and their relation to the problems posed by modern seismology. One of the vital parts of this application is making it accessible to the public in an easily understandable and appealing manner. The evolving nature of video games presented itself as an interesting, challenging, and effective route. This summer I was working with a training game for SCEC-VDO, a visualization software created by past interns. SCEC-VDO, or the Southern California Earthquake Center's Virtual Display of Objects, is a powerful application, but can be difficult to become proficient with. The training games were designed to introduce new users to the software as well as refine returning users' skills at several tasks. The two main tasks I focused upon were navigation and movie-making. The games I helped design and implement function as plug-ins, or self-contained add-ons which make use of SCEC-VDO's visualization capabilities. These plug-ins, written in Java and Java3D, walk the user through rotating the world to line up visuals as well as learning the sequence to display earthquake catalogs and render movies. Though the games are not polished, they are fully functional and the design layout is nearly completed.

### 3-D models of deformation in arbitrarily heterogeneous elastic half-space

*Barbot, Sylvain (UCSD), Yuri Fialko (UCSD), and David Sandwell (UCSD)*

We present a new semi-analytical method to compute 3-D models of deformation in an arbitrarily heterogeneous elastic half-space. The method consist in applying integral transforms to the momentum equation to obtain a Fredholm equation of the second kind which is solved by the method of successive over-relaxation. This approach was successfully compared to numerous analytical solutions in the case of anti-plane strain and to other available numerical modes of 3-D deformation in a horizontally stratified elastic half-space. Our method allows one to account for realistic models of 3-D elastic structure in a simple framework. Using this approach, we model the observed enhanced deformation around the Pinto Mountain and the Calico faults in California due to the stress changes following the 1993 Landers and the 1999 Hector Mine earthquakes.

### Efficient Approach to Vector-valued Probabilistic Seismic Hazard Analysis of Multiple Correlated Ground Motion Parameters

*Bazzurro, Paolo (AIR), Polsak Tothong (AIR), and Jaesung Park (AIR)*

In the process of evaluating the seismic response of a structure to different level of ground shaking, engineers usually (a) quantify the intensity of ground motion using convenient parameters, such as peak ground acceleration (PGA) or spectral acceleration (Sa); (b) establish a relationship between these parameters and measures of building response, such as maximum peak interstory drift, that are critical to the stability and vulnerability of structural (e.g., beams and columns) and non-structural (e.g., partitions and cladding) components; through this process engineers identify response thresholds corresponding to limit states of interest (e.g., onset of damage, immediate occupancy, life safety, and collapse); (c) compute, via probabilistic seismic hazard analysis (PSHA), the likelihood that any values of such ground motion parameters will be experienced at the building site in a given period of time; and (d) estimate the chance (via an operation called convolution) that structural response measures may exceed the available capacity (or the threshold of any other lesser limit state) and bring the building to collapse.

The relationship between ground motion parameters and response measures is, of course, the critical link that allows the application and maintains accuracy of this procedure. Engineers often seek to obtain a high accuracy in structural response assessment by developing complex 2- and 3-dimensional (2D and 3D) models of their structures and by using several (i.e., vector) ground motion parameters to estimate the structural response. In these cases, the spectral accelerations at the first mode of vibration in longitudinal (Sa(TL)) and transversal (Sa(TT)) directions are natural choices for response predictors. If the structure in question is, for example, a mid-rise building, a more accurate estimate of building response may be achieved by including higher-mode elastic spectral acceleration and first-mode inelastic spectral accelerations (e.g., Luco and Cornell, 2000) in the pool of predictors. Conventional scalar PSHA, however, computes the mean rate of occurrence (or exceedance) of Sa(TL) and Sa(TT) and other parameters separately, not jointly. The building response in the two directions and the parameters Sa(TL) and Sa(TT)–as well as others that may be utilized–are, in general, correlated. The tool necessary to accomplish this task is vector-valued PSHA (VPSHA; Bazzurro, 1998; Bazzurro and Cornell, 2001 and 2002). Unfortunately, the widespread use of VPSHA has been hindered so far by the lack of VPSHA computer codes that were easy to use by engineer practitioners who may not be experts in probability and engineering seismology. In this study we explore the application of a novel and potentially very efficient approach to VPSHA that is based on appropriately combining results from standard scalar PSHA analyses and the covariance matrix of the ground motion parameters. One of the distinct advantages of this methodology is that it can be written as a standalone post-processor routine of a standard PSHA code. Given the joint lognormality of the ground motion parameters (Jayaram and Baker, 2007) usually adopted for structural response prediction, the joint Mean Annual Rate (MAR) of occurrence of a pool of ground motion parameters can be computed with the knowledge of the following input: (1) Site-specific seismic hazard curves for all the ground motion parameters. The vector of ground motion parameter could include, for example, three parameters: the spectral acceleration at the first 2 periods of vibration of the building in the transverse direction and at the first period of vibration in the longitudinal direction. These three hazard curves can be obtained with any standard PSHA code. (2) The variance-covariance matrix of all the ground motion parameters. Inoue (1990) and Baker and Cornell (2005) have empirically derived the correlation structure for spectral accelerations with different periods and accelerogram orientations that is instrumental for this task. (3) The disaggregation results from scalar PSHA. The joint distributions of all the basic variables used in the ground motion prediction equation of choice (i.e., the magnitude M, the source-to-site distance, R, the error term, and all the other variables, such as the style of faulting, the directivity parameters, the distance to the top of the coseismic rupture, and dip angle, that are needed to compute the level of ground motion for every earthquake rupture) conditional on the value of one or more ground motion parameters is a straightforward extension of the disaggregation results routinely available from standard scalar PSHA codes. Again, one of the distinct appealing qualities of this methodology is that it can be written as a standalone post-processor routine of a standard PSHA code.

### Characteristics of the brittle damage zone of simulated propagating mode II ruptures

*Beeler, N. M. (USGS)*

Field observations thought to be associated with dynamic earthquake rupture propagation such as pseudotachylyte and pulverized rock contain structure (conjugate fracture sets, injection veins) that may indicate the orientation of the local dynamic stress field during propagation. And these field exposures may have additional geometric features (damage zone width and asymmetry) that reflect the magnitude of the local dynamic stress and direction of rupture propagation. If an appropriate dynamic yield criteria is applied in numerical calculations stress orientation, magnitudes and other characteristics within a damage zone can be simulated. I report on calculations of mode II rupture with off-fault Coulomb plasticity using the finite difference method of Andrews [2004]. Calculations explore the density and width of the damage zone and the orientation of conjugate fracture sets within the damage zone as the dynamic stress drop, distance of propagation and propagation velocity are varied. Notable provisional results are that damage is almost entirely restricted to the extensional regions of the stress field, that the dynamic stresses do not reach true tension unless cohesion is high relative to the starting fault normal stress, and that conjugate fracture sets tend to cluster about a dynamic greatest principal stress direction that is at a high angle to the fault when the dynamic stress drop is complete.

### Constitutive relations for shear induced weakening

*Beeler, N. M. (USGS), D. L. Goldsby (Brown), T. E. Tullis (Brown), and B. J. deMartin (Brown)*

In controlled laboratory faulting experiments [e.g., Tsutsumi and Shimamoto, 1997; Goldsby and Tullis, 2002], significant weakening resulting from phase changes on the fault surface is activated at slip speeds greater than 1 mm/s, even when shear heating of the fault surface is insufficient for bulk melting. While these discoveries may be related to dynamic fault slip in the Earth, more observations are required and reliable physics-based constitutive equations are needed to describe the data and extrapolate them to the Earth. We are developing such relations, focusing on mechanisms of shear melting, flash heating, unexpected weakening due to silica gel formation, and shear-induced dehydration weakening. These modeling efforts will be supplanted with new laboratory experiments to further constrain the constitutive behavior and the underlying physics of the various weakening mechanisms. In this SCEC presentation we report on simulations of laboratory data using constitutive relations for flash weakening and for the weakening of silica-rich rocks due to gel formation. The flash weakening relations modified from Rice [1999] to include non-steady state response are applied in dynamic simulations to model stress oscillations observed in laboratory data and in quasi-static calculations to simulate the slip dependence of strength recovery during slip arrest. The newly formulated relation for weakening due to gel formation combines shear weakening with a competing exponential re-strengthening with time that represents a chemical reaction.

### A revised slip rate estimate for the Mission Creek-Coachella Valley strand of the southern San Andreas fault at Biskra Palms Oasis, Indio, California

*Behr, Whitney (USC), Ken Hudnut (USGS Pasadena), John Platt (USC), Katherine Kendrick (USGS Riverside), Warren Sharp (BGC), Kathryn Fletcher (BGC), Bob Finkel (LLNL), and Dylan Rood (LLNL)*

Reconciliation of slip rate estimates from the instantaneous to millennial time scales is of particular current interest in active tectonics. Discrepancies have become increasingly common and have caused us to consider closely both the accuracy of our data sets and the possible implications of temporal changes in slip rate for the mechanics of faulting. The Biskra Palms alluvial fan, located near the intersection of the Coachella Valley, Mission Creek and Banning strands of the San Andreas fault, and on the fringe of the southern half of the Eastern California Shear zone, has proven an ideal locality to weigh the effects of epistemic uncertainty, in both geologic offset measurements and dating techniques, on our estimates of fault slip rate.

At Biskra Palms we excavated a series of trenches, which revealed 1) that the section of the T2 fan between the two strands of the Mission Creek fault is offset by a sub-vertical cross-fault that accommodates predominantly scissoring motion; and 2) the western edge of the lower remnant of the T2 fan is not overridden by a thrust fault, but is buttressed against bedrock of the Ocotillo Fm. The geomorphology at Biskra Palms, however, is not entirely clear-cut, and we thus present several alternative offset models ranging from 455 m to 680 m in an effort to represent the entire range of possibilities.

We also present five new cosmogenic 10Be surface exposure dates from large boulders on the T2 surface, for which model ages range from 35-49 ka. These boulder-top samples are systematically older than the mean age derived from cobble-sized clasts (35 ± 2.5 ka; van der Woerd et al., 2006). The largest boulder yields an age of 49 ± 4.6 ka, which is comparable to 1) the oldest age of the van der Woerd et al. dataset and 2) the oldest U-series ages from pedogenic carbonate (Fletcher et al., this meeting). We interpret these data to indicate that the oldest boulder-top samples yield minimum exposure ages that closely approximate the true depositional age of the T2 fan, whereas the cobble-sized samples may reflect erosion rates of a surface nearing secular equilibrium. Our future efforts will go toward ruling out the effects of inheritance in the boulder-top samples.

Based on these new data, we tentatively estimate the minimum age for the T2 fan to be 45-50 ka, which when coupled with our offset measurements, brackets the slip rate for the Mission Creek strand of the San Andreas fault to between 9 and 15 mm/yr. This has implications for the long-term interactions between the San Jacinto fault, San Andreas fault, and the Eastern California shear zone, and for seismic hazard. Our ongoing research at this site will seek to better constrain the depositional age of the T2 fan through additional cosmogenic and U-series dating.

### SCEC/SURE: A Finite Differences Model for Dynamic Ruptures along Rough Faults

*Belanger, David (Harvard) and Eric M. Dunham (Harvard)*

Many earthquake source models assume that slip occurs across a planar interface between identical linear elastic materials, for which the assumption that the walls of the fault do not open implies that the normal stress remains unaltered by the rupture. However, when we examine ruptures along rough, nonplanar faults, there will certainly be changes in normal stress. Both the no-opening assumption and the assumption of an ideally elastic material response seem less reasonable. To better understand the validity of these assumption in rough fault models, it is useful to develop a model that assumes the no-opening condition and elastic response, and then to investigate the magnitude of stress changes as a function of fault roughness. If normal stress on the fault ever becomes tensile, it would contradict the no-opening assumption. Additionally, we would like to quantify the degree of roughness necessary to invoke an inelastic material response.

We are developing a dynamic rupture model in which we can parameterize and adjust the roughness of the fault as desired. First we specify a smooth curve describing the shape of the fault. Next, we generate a curvilinear coordinate system that conforms to the fault and the other boundaries of the physical domain. We then construct a mapping that transforms between curvilinear coordinates in the irregular physical domain and Cartesian coordinates in a rectangular logical domain. A regularly spaced distribution of grid points in the logical domain maps to an irregularly spaced mesh that conforms to the boundaries of the physical domain; this mapping is obtained by numerically solving an elliptic partial differential equation given a control function that specifies grid spacing at every point in the domain, a feature that allows us to "zoom in" on certain regions.

We transform the elastodynamic equation into the coordinate system of the logical domain, and numerically solve it there using second-order finite differences. The particular numerical method used to integrate the system relies on generating an orthogonal grid, one in which all coordinate lines meet at right angles. The use of an orthogonal grid allows us to avoid troublesome cross terms that would couple adjacent points on the fault.

The code exhibits second-order convergence for specified traction boundary conditions on the fault, and we are implementing rate- and state-dependent friction laws that will permit us to model dynamic ruptures along rough faults.

### Mechanical models of folding above blind-thrust faults: Implications for assessing fault activity, slip rates, and paleo-earthquake histories

*Benesh, Nathan P. (Harvard), Andreas Plesch (Harvard), John H. Shaw (Harvard), and Erik K. Frost (USC)*

Using the discrete element method, we examine the relationship of fold development to slip on an underlying blind-thrust fault. Our two-dimensional models were composed of numerical disks bonded together to form pregrowth strata lying above a fixed fault surface. This mechanically layered hangingwall was produced through a process of gravitational compaction that in some ways mimics the natural compaction process occurring in sedimentary basins. Slip on the underlying fault was then imposed by driving the hangingwall strata along the fault surface using a vertical backstop moving at a fixed velocity. Folding was localized above a fault bend located where the thrust ramp joins an upper detachment. New particles were generated and deposited onto the pregrowth strata at a fixed rate to produce sequential growth layers. Models with varying degrees of mechanical layering were examined, and the resulting growth and pregrowth fold architectures were analyzed in comparison to kinematic theories often used to relate various fold characteristics to fault activity and slip.

Our analyses show that the folds produced by our models follow to first order the predictions of fault-bend folding, a kinematic theory commonly invoked to relate fold and fault parameters. It is noted, however, that our models do exhibit a deviation from fault-bend folding manifest as a decrease in dip of the younger growth layers within the fold limb. On the basis of comparisons to natural examples of fault related folds in sedimentary basins, including seismically imaged sections above the Puente Hills and Compton thrust faults, we believe this deviation from kinematic fault-bend folding to be a realistic feature of fold development resulting from an axial zone of finite width produced by materials with mechanical strength. The effective width of the axial zone, and thus the degree to which the models deviate from growth fault-bend folding theory, seems to be influenced by the effectiveness of bedding slip surfaces within the growth strata. This result has important implications for seismic hazard assessment in terms of how growth fold architectures have – and still are – used to constrain slip and paleo-earthquake ages for blind-thrust faults. Notably, relief across the fold limb and deformation localized about axial surfaces appear to be the most robust observations that can readily be used to constrain fault activity and slip. In contrast, changes in shallow growth layer dips and fold limb width appear to be more variable features of folding that depend to a greater degree on the mechanical properties and layering within the strata.

### Next Steps to Improve Rupture Scenarios for the Southern San Andreas Fault

*Biasi, Glenn (UNR), Ray Weldon (University of Oregon), and Kate Scharer (Appalachian State)*

We have recently developed a method to automate and explore correlations among earthquakes from the combined paleoseismic investigations on the southern San Andreas fault. In its first implementation, the correlation method first finds all ruptures that could have occurred based on the evidence in the paleoseismic record. The rupture pool thus includes single-site earthquakes, and ruptures spanning two, three, etc. sites. Correlation requires some measure of overlap in time among the contributing paleoearthquakes.

The rupture pool is then sampled in a way that every site paleoearthquake is included once into a scenario for southern San Andreas ground rupturing earthquake occurrence. After constructing a large suite of scenarios that could have happened, each scenario is "graded" by the quality of time overlap in the paleoseismic data and by the implied total displacement compared to the secular slip rate of the fault. A manuscript submitted to BSSA (Biasi and Weldon, in review) provides details.

We are improving the basic correlation and evaluation system described above to include some new classes of information:

1. Site data where the number of ground rupturing earthquakes and the total time for them is known. We use Bayesian ordering constraint methods to develop date pdf's to include such events into ruptures. These pdf's do not materially constrain the measured dating evidence, but they otherwise contribute to scenarios like sites with per-event dating. Sites with an event count and time of the oldest event are important for constraining rupture extent. We illustrate the usefulness of this data with new results from Frazier Mountain in the northern Mojave region of the San Andreas fault (Scharer et al., this meeting).

2. Slip constraints for data where the total amount of slip is known among a known number of earthquakes, but the dates of the earthquakes are poorly known. The total displacement among a set of earthquakes constrains the suite of likely scenarios to those matching the total within some uncertainty. We illustrate this constraint with data from Lost Lake in the Cajon Pass. We anticipate that some displacements at Wallace Creek may also be shared among multiple events, based on revised (shorter) recurrence interval estimates at the Bidart Ranch site.

3. Slip-per-event data for individual earthquakes is most useful in constraining the actual recent history of the San Andreas. Scenario grading by total displacement in a time period does not constrain how that total is achieved among contributing ruptures, and is thus better suited to applications such as the Working Group on California Earthquake Probabilities. Per-event displacement data are presently limited to a few places on the fault, but at least the Wrightwood displacement estimates usefully constrain likely rupture scenarios involving the San Bernardino strand of the SAF.

### Experimental Observation of Stopping Phases Generated by Fault Barriers Associated with Short Fault Branches

*Biegel, Ronald (USC), Charles Sammis (USC), and Ares Rosakis (Caltech)*

Square plates of photoelastic Homalite were loaded in uniaxial compression. A rupture was nucleated by a small explosion on a preexisting fault having its normal vector at 25 degrees to the loading axis. A 1 cm long branch intersected the main fault at an angle of 15 degrees. For this configuration, preliminary simulations by Bhat (2007) predicted that the rupture should continue to propagate down the main fault past the branch. However, we observed that the rupture stopped on the main fault and generated an S-wave stopping phase. Also a healing phase could be observed propagating back along the main fault toward the nucleation point. The difference between our experiment and Bhat's simulation was that the branch fault slipped during loading which produced compression on the main fault, an effect not included in his simulation. Recent calculations by Duan and Oglesby (JGR, 2007) suggest that slip on such a branch induced by repeated earthquakes could produce the type of stress perturbation we observe on the main fault, and that fault branches might act as the barriers invoked by seismologists to explain heterogeneous slip during large earthquakes. These experiments in Homalite can be scaled to natural faults using the slip weakening distance Ro* which is about 1 cm in Homalite (Biegel et al., 2007) and 10 to 100 m in large earthquakes.

### PBO Nucleus Project Status: Integration of 209 Existing GPS Stations in the Plate BOundary Observatory

*Blume, Frederick (UNAVCO), Charles Meertens (UNAVCO), Greg Anderson (UNAVCO), Susan Eriksson (UNAVCO), and Eleanor Boyce (UNAVCO)*

Tectonic and earthquake research in the US has experienced a quiet revolution over the last decade precipitated by the recognition that slow-motion faulting events can both trigger and be triggered by regular earthquakes. Transient motion has now been found in essentially all tectonic environments, and the detection and analysis of such events is the first-order science target of the EarthScope Project. Because of this and a host of other fundamental tectonics questions that can be answered only with long-duration geodetic time series, the incipient 1400-station EarthScope Plate Boundary Observatory (PBO) network has been designed to leverage 445 existing continuous GPS stations whose measurements extend back over a decade. The irreplaceable recording history of these stations will accelerate EarthScope scientific return by providing the highest possible resolution. This resolution will be used to detect and understand transients, to determine the three-dimensional velocity field (particularly vertical motion), and to improve measurement precision by understanding the complex noise sources inherent in GPS.

The PBO Nucleus project supports the operation, maintenance and hardware upgrades of a subset of the six western U.S. geodetic networks until they are subsumed by PBO. Uninterrupted data flow from these stations will effectively double the time-series length of PBO over the expected life of EarthScope, and has created, for the first time, a single GPS-based geodetic network in the US. The other existing sites remain in operation under support from non-NSF sources (e.g. the USGS), and EarthScope continues to benefit from their continued operation.

On the grounds of relevance to EarthScope science goals, geographic distribution and data quality, 209 of the 432 existing stations were selected as the nucleus upon which to build PBO. Conversion of these stations to a PBO-compatible mode of operation was begun under previous funding, and as a result data now flow directly to PBO archives and processing centers while maintenance, operations, and meta-data requirements are continue to be upgraded to PBO standards. At the end of this project all 209 stations will be fully incorporated into PBO, meeting all standards for new PBO construction including data communications and land use permits. Funds for operation of these stations have been included in planned budgets for PBO after the construction phase ends and PBO begins an operational phase in 2008.

The data from these stations serve a much larger audience than just the few people who work to keep them operating. This project is now collecting the data that will be used by the next generation of solid-earth researchers for at least two decades. Educational modules are being developed by a team of researchers, educators, and curriculum development professionals, and are being disseminated through regional and national workshops. An interactive website provides the newest developments in tectonics research to K-16 classrooms.

### Search for Minimum-Magnitude Earthquakes in South African Gold Mines

*Boettcher, Margaret (USGS), Art McGarr (USGS), and Malcolm Johnston (USGS)*

The Natural Earthquake Laboratory in South African Mines (NELSAM) project has obtained data from 733,000 earthquakes, $-3<M<3$, from 1995 through 2007, within two deep (2-4 km) gold mines. Previous studies have identified two populations of mining-induced microseismicity: (A) $M<0$ events with characteristics that include moment tensors with explosive components, high frequency source spectra, and an affinity to active mining, and (B) earthquakes involving shear rupture of pre-existing faults, analogous to tectonic earthquakes. With our comprehensive near source data set we address the question of whether a minimum magnitude, Mmin, exists for the type B (tectonic-like) earthquakes. During quiet hours in 2006-2007 with no ore production, we find type B earthquakes with magnitudes as low as -3 and a catalog completeness threshold of -1.2. Earlier data with catalog completeness of approximately -0.5 were interpreted as evidence for Mmin of approximately 0 for type B earthquakes in these mines (Richardson and Jordan, 2002). The NELSAM data, with catalog completeness extending to lower magnitudes, indicate catalog detection limitations, not earthquake source physics, control the observed Mmin of type B earthquakes. Furthermore, based on laboratory data (Lockner and Okubo, 1983) we estimate that earthquake nucleation in the mines is limited by a moment release equivalent to about magnitude -3, with a patch radius and critical slip distance of ~20 cm and ~20 microns respectively. The estimated nucleation size is consistent with data from a magnitude -2.8 earthquake recently recorded in TauTona Mine. We find that the type A events, primarily $M<0$, occur only on days with ore production, but are not located as close to mine production as previously thought and can occur at distances exceeding 200 m from the working faces in the few hours after mine production. This indicates that the type A events are not only development blasts, as previously suggested (Spottiswoode and Linzer, 2004), but are still a consequence of mine activity. This study was supported by NSF Continental Dynamic grant 0409605.

### Mapping the Southern San Andreas Fault using the B4 LiDAR Dataset

*Bohon, Wendy (OSU), David Raleigh (OSU), and Lindsay Schoenbohm (OSU)*

The goals set out by the 2005 B4 Airborne Laser Swath Mapping (ALSM) project on the Southern San Andreas Fault were to capture high resolution images of the fault and produce the most geodetically accurate topographic data possible. With GIS software and high-resolution topographic data from LiDAR, it is now possible to create an extremely accurate comprehensive map of the fault traces of the southern San Andreas which can be used by scientists, developers and educators.

Many of the publicly available fault maps of the San Andreas are based on fieldwork and DEMs (Digital Elevation Models) which have on ground errors from around 2-15m. We are using the high resolution (50 cm) B4 data to precisely identify strands of the southern San Andreas Fault. Vector data will be produced using the B4 dataset in the mapping programs ArcMAP and Surfer. Our objectives are 1) to map the southern San Andreas Fault by identifying expressed geomorphic features in the B4 dataset such as offset ridgelines, streams and terraces, linear breaks in topography, sag ponds and shutter ridges 2) to create maps and shape files which can be downloaded and utilized by the SCEC community, regional planners, emergency officials and other interested persons and 3) to find geologically interesting areas of the fault and create maps/images for educational purposes, classroom use, etc.

Providing a high resolution, georeferenced, comprehensive, accurate map of the southern San Andreas Fault will benefit both the scientific community and the general public. It will contribute to seismic hazard analysis and city planning by providing officials with a dataset that can be used with ArcGIS software to show updated fault locations. The file maps created can also be used to further communication, education and outreach by providing a visual mechanism for the dissemination of fault information.

### Preliminary evaluation of high rate real-time GPS data processing by Real Time GIPSY (RTG)

*Borsa, Adrian (USGS), Aris Aspiotes (USGS), Yoaz Bar-Sever (JPL), Robert Dollar (USGS), Ken Hudnut (USGS), Nancy King (USGS), and Robert Meyer (JPL)*

The rapid conversion of continuous GPS stations in Southern California to "real time" telemetry has opened new possibilities for the use of GPS data, including the rapid determination of coseismic slip distribution and earthquake early warning. In both of these applications, obtaining the best possible station positioning is less critical than the speed of obtaining reasonable estimates of site displacement. Processing real time data requires different algorithms to mitigate the effects of clock and ephemeris errors than those used in double-difference GPS post-processing. Real Time GIPSY (RTG), developed by JPL to process real time GPS data streams, uses Internet-broadcast corrections to minimize clock and ephemeris errors. We report on several months of recent RTG results from two fixed sites, with particular emphasis on the suitability of RTG for rapid slip distribution determination and potential earthquake early warning. Noise levels for site GOLD are nominally quite good in both the horizontal (4 cm RMS) and vertical (7 cm RMS), with occasional periods when the solution exhibits much larger deviations from the mean station position. A second site in a very poor multipath environment showed larger errors (as expected) and more pronounced and frequent deviations from mean station position.

### SCEC/SURE: A MATLAB Program to Measure the Fractal Dimension of Seismicity with Application to Southern California

*Boyce, Brian (Lincoln University), Aaron Kositsky (USC), and Charles Sammis (USC)*

The fractal dimension of earthquakes epicenters in southern California is measured using a box-counting algorithm. A MATLAB program has been written that finds the minimum number of boxes in a grid that are required to “cover” the seismicity for a range of box sizes. The slope of a plot of the logarithm of the minimum box number as a function of the logarithm of the box length gives the fractal dimension. We investigate the variation of fractal dimension between different tectonic areas, and whether modern relocated catalogs yield fluctuations in slope that can be related to the structure of the regional fault network.

### Geometry and Segmentation of the Palos Verdes Fault, San Pedro Bay region, offshore Southern California

*Brankman, Charles M. (Harvard) and John H. Shaw (Harvard)*

We define the three-dimensional geometry of the Palos Verdes Fault (PVF), an active structure located along the western margin of the Los Angeles basin, California. Despite having one of the highest fault slip rates in the L.A. Basin, the subsurface geometry, segmentation, and style of deformation on the fault remain largely unconstrained, as illustrated by widely disparate PVF representations in the current SCEC CFM. To improve the subsurface characterization of the fault, we have used an extensive grid of petroleum industry 2D and 3D seismic reflection data and exploration well logs to map fault splays and stratigraphic horizons along the PVF in the region of San Pedro Bay and south towards Lasuen Knoll. Mapped horizons include the top of crystalline basement as well as several Miocene through Pleistocene statigraphic units. The data show that the sense and magnitude of stratigraphic offsets change character along strike, reflecting a complex pattern of tectonic inversion with oblique slip across originally distinct fault segments. In San Pedro Bay, the PVF is defined by a zone of near-vertical fault splays and intense folding within the upper 3-4km. At depth, the fault shallows its dip to 30-50° SW based on well-imaged hanging-wall and footwall fault cut-offs. In the hanging wall, a sequence of Miocene strata thickens eastward towards the fault. These patterns are consistent with the PVF beneath San Pedro Bay originating as a west-dipping, basin-bounding normal fault which controlled the Miocene syn-rift deposition. These strata were subsequently uplifted higher than their correlative footwall units, reflecting Plio-Pleistocene structural inversion of the PVF. Mapping of the extent and thickness of the syn-rift sediments outlines the original basin geometry and provides piercing points to calculate strike-slip displacements. Based on right-lateral offsets of the rift basin contours and our interpretation, based on syntectonic growth strata, that the fault was reactivated at some point since the middle Pliocene, we calculate a minimum strike-slip rate of 1.0±0.2 mm/year and a vertical uplift rate of 0.3±0.1 mm/yr. Further south, the character of the PVF changes. Neither Miocene growth strata nor evidence of tectonic inversion are present, and the shallow fault zone appears to dip steeply to the northeast, showing increasing reverse displacement along strike to the southeast. Shallow growth strata in emergent sea-floor folds above the PVF indicate that contractional deformation began in Pliocene time and continues to the present. We interpret that the southern strand of the PVF originated as an oblique, right-lateral reverse fault in the Pliocene, linking with the inverted normal fault segment beneath San Pedro Bay. Using empirical relationships between rupture size and moment magnitude, we calculate scenario earthquakes of Mw=7.2-7.3 for full rupture and Mw=6.5-6.7 for single segment ruptures. We conclude that the PVF is composed of at least two discrete but inter-related segments, whose geometry was largely inherited from the original Miocene rift basin architecture. This complex fault geometry and slip pattern may impact the character of coseismic ruptures by influencing rupture size and/or directivity, which may have important implications for regional earthquake hazards.

### The October 21, 1868 Hayward Earthquake, Northern California – 140 Years Later

*Brocher, Tom (USGS), Jack Boawright (USGS), Jim Lienkaemper (USGS), David Schwartz (USGS), Susan Garcia (USGS), and the 1868 Hayward Earthquake Alliance*

October 21, 2008 marks the 140th anniversary of the M7 1868 Hayward earthquake. This great earthquake, that occurred slightly before 8 AM, caused extensive damage to San Francisco Bay Area and remains the nation's 12th most lethal earthquake. Property loss was extensive and about 30 people were killed.

This great earthquake capped a remarkable decade-long series of earthquakes in the Bay Area that started with a M5.5 earthquake in the southern Peninsula in 1856, jumped to a series of at least three M5.8 to M6.1 earthquakes along the northern and central Calaveras fault, and ended with the M6.5 earthquake in either the Santa Cruz Mountains or western margin of the South Bay in 1865. Despite this flurry of quakes, the shaking from the 1868 earthquake was the strongest that the new towns and growing cities of the Bay Area had ever experienced. The effect on the brick buildings of the time was devastating. Walls were shaken down in San Francisco, Oakland, and San Jose, and buildings were cracked as far away as Napa, Santa Rosa, and Hollister. The area that was strongly shaken (at Modified Mercalli intensity VII or higher) includes about 2,300 km2. Strong aftershocks continued into November 1868.

Surface rupture along the southern end of the Hayward Fault was traced for 32 km from Warm Springs in Fremont to San Leandro. As Lawson (1908) reports, "the evidence to the northward of San Leandro is not very satisfactory. The country was then unsettled, and the information consisted of reports of cow-boys riding the range". Analysis of survey data suggests that the fault moved as far north as Berkeley, and from these data the average amount of horizontal movement along the fault is inferred to be about 1.9 meters.

The paleoseismic record since 170 A.D. from the southern end of the Hayward Fault provides evidence for 10 earthquakes prior to 1868. Altogether, the average interval between these earthquakes is 170 ± 80 years, but the past five have had an average interval of only 140 ± 50 years.

The great 1868 Hayward earthquake, and more recent analogs such as the 1995 Kobe earthquake, are stark reminders of the awesome power that lurks below the east side of the San Francisco Bay along the Hayward Fault. The population at risk from a Hayward Fault earthquake is now 100 times larger than in 1868. The infrastructure in the San Francisco Bay Area has been tested only by the relatively remote 1989 M6.9 Loma Prieta earthquake. To help focus public attention on these hazards, the 1868 Hayward Earthquake Alliance has been formed, consisting of public and private sector agencies and corporations (see their website: www.1868alliance.org). The Alliance is planning a series of activities leading up to the 140th anniversary on October 21, 2008, including public forums, conferences, commemoration events, publications, websites, videos, and public service announcements.

## Fluid Dynamic Evidence for Extremely Low Viscosity Coseismic Fault Fluids

*Brodsky, E.E. (UCSC), F. Meneghini, C. D. Rowe, and J.C. Moore*

Geological evidence for seismic rupture is sparse. Here we use textural evidence from fluidized fault rocks to directly determine important mechanical constraints on the fault zone during an earthquake. We analyze buoyant intrusive features in a fault zone that formed at 12-14 km depth in an accretionary prism. These features are Rayleigh-Taylor instabilities with an unusually short wavelength. The geometry can best be explained by a moderately high Reynolds number flow which necessitates velocities of several 10's of cm/s. These slip velocities are typical of an earthquake and thus require a coseismic origin of the rock. Further analysis requires extraordinary low viscosities (<<10 Pa s) locally and is consistent with other lines are argument suggesting dynamic weakening of fault zones.

## New Seismic CHIRP Evidence for Transpression and Transtension Beneath the Salton Sea, California

*Brothers, Daniel (UCSD), Neal Driscoll (UCSD), Graham Kent (UCSD), Alistair Harding (UCSD), Jeff Dingler (UCSD), and Jeff Babcock (UCSD)*

The Salton Trough is a critical structure that separates spreading center dominated deformation in the Gulf of California and dextral strike-slip deformation along the San Andreas Fault System (SAF). To date, however, a critical portion of this tectonic system remains poorly understood, in large part, due to a lack of geophysical subsurface data in the Salton Sea. Here, we present 350+ line-km of seismic CHIRP data acquired in 2006 and 2007 that imaged the different deformational styles in the Salton Sea. The Extra Fault Zone (EFZ), identified by Hudnut et al. (1989), is approximately 5 km wide and appears to separate compression to the north from extension to the south. Along the northern extent of the EFZ, ramp-flat deformation is observed with southward vergence. The maximum horizontal compression is oriented approximately SE-NW. A marked angular unconformity between the Brawley and Cahuilla Formation records the ramp-flat deformation and uplift. The uplift and truncation along the northern edge of the EFZ is observed across the entire sea and it appears to systematically increase towards the west. This deformation is manifested in the bathymetry, with the sill separating the southern and northern lake basins being structurally controlled. In contrast, extension and down-to-the-south normal faulting characterize the southern extent of the EFZ. There are two NE-SW oriented normal faults that are separated by a few hundred meters and offset the Lake Cahuilla (LC) sediments; these parallel faults align with the onshore trace of EFZ, and can be correlated for over 15 km offshore. The observed change in deformational style across the EFZ may be explained by the regional tectonics. North of Bombay Beach the SAF steps to the west engendering transpression along the cross faults in this portion of the dextral-slip system. To the south, the Brawley Seismic Zone (BSZ) connects the SAF and the Imperial Fault (IF) across a ~15 km releasing step that causes transtension across the cross faults. In addition to the regional transtension, several

down-to-the-east, en echelon normal faults are observed along the western edge of the BSZ recording recent deformation. Vertical offset across these faults increases with depth to a maximum of ~6-8 m, thus recording several earthquakes during the past ~1-2 Ka. The trend of these normal faults is N-NE, an orientation that is not aligned with either the "ladder or rung" earthquake lineaments observed in the BSZ (Lin et al., 2007) or the trend of the SAF. Based on the orientation of the en echelon normal faults, it appears they accommodate transtensional strain via the right-step between the SAF and the IF. Doming and uplift of LC sediments above the thrust ramp and extensional deformation along the southern EFZ, as well as en echelon normal faults along the western edge of the BSZ suggest transpression and transtension are currently active and play an important role in the late Pleistocene- Holocene tectonic evolution of the Salton Trough. Finally, we are collaborating with onshore researchers (S. Janecke) to place our offshore observations within a regional geologic framework.

### SCEC/SURE: Damage Zone Structure Along the Calico Fault

*Brown, Naomi (UH Manoa and UCR), Elizabeth Cochran (UCR), Daniela Herrera (UCR), Peter Shearer (UCSD), Yong-Gang Li (USC), Yuri Fialko (UCSD), and John Vidale (UW)*

By incorporating teleseismic events into the existing velocity model of the Calico Fault Zone we hope to better map the properties of the fault zone at seismogenic depths, including the width and depth of the compliant zone and changes along fault strike. Data used are from a grid of 70 seismic stations that were deployed along the Calico Fault Zone. Events are chosen from an Antelope database of continuous seismic data collected from June to December, 2006. Waveforms are extracted from the Antelope database and pre-processed using Seismic Analysis Code (SAC). Next, waveforms are cross-correlated to determine accurate P-wave arrival times that will be used in a forward model to estimate the 3D velocity structure of the fault zone. We will quantitatively compare the synthetic travel times determined by the forward model to the actual travel times by calculating the misfit. Testing various velocity models and minimizing the misfit will allow us to determine the best-fit velocity structure for the Calico Fault. Finally, we will compare the seismic velocity model with the InSAR observations that showed a roughly 1 - 2 km-wide compliant zone along the Calico Fault.

### Unfractured Sandstones along the San Andreas Fault: New Tensile Strength and Wave Velocity Data, and Implications for Constraints on Extreme Ground Motion and Absolute Stress

*Brune, James N. (UNR), Jaak Daemen (UNR), James B. Scott (UNR), John N. Louie (UNR), and Matthew D. Purvance (UNR)*

Un-fractured Tertiary sandstones exist within a few km of the San Andreas Fault at several locations between Cajon Pass and Tejon Pass (Brune et al., SCEC Annual Meeting abstract, 2005; Brune et al., SCEC Annual Meeting abstract, 2006). These sandstones have been exposed to three stresses: lithostatic stresses from overburden when buried, tectonic stresses related to faulting, and transient dynamic stresses from thousands of large (M~8) earthquakes. If the tectonic stresses are large enough, relatively low amplitude transient stresses will fracture these sandstones at depths less than about a km (in tension or in shear). Thus the observation that the sandstones are un-fractured places an upper bound on the combination of tectonic stresses and extreme transient dynamic stresses.

New tensile strength measurements of sandstones at several sites near the San Andreas Fault between Cajon and Tejon passes yield consistently weak values of 5 ± 3 bars. Using the information that these rocks have been as deep as 2 km during the history of the San Andreas Fault, it is possible to estimate the amplitude of dynamic stresses that will exceed the sandstone strength given different tectonic stress models. These calculations suggest that a "low" tectonic stress model (e.g., assuming a coefficient of friction, mu = 0.2) places an upper limit on particle velocities of about 1 m/s. A "high" tectonic stress model (mu = 0.6) reduces the permissible particle velocities to about 30 cm/s.

To address the possibility that tensile strength and other properties might show anomalous increases with depth (e.g., as a result of surface weathering), we have carried out ReMi measurements of shear velocities and short refraction lines at several sandstone outcrops. These surveys give results as volume averages over tens of meters. The shear wave velocities at the surface are between 400 m/s and 750 m/s, increasing to over 1000 m/s at 40 m to 100 m depth. These results are typical at the surface for sedimentary outcrop

of Tertiary or Quaternary age that is indurated, or is bouldery or cobbly. The changes in shear velocity within the upper 100 m of these monoliths is very similar to the velocity profiles of fluvial gravels (Thelen et al. 2006) and thus do not indicate drastically unusual rock properties.

Based on current attenuation models for peak particle velocity, 30 cm/s should have been exceeded for many of the large earthquakes that have occurred along the San Andreas Fault during its history. The observation that the sandstones are un-fractured is therefore evidence for the low stress model, and against the high stress model, adding a possible new consideration in the long-standing controversy about the absolute state of stress on the San Andreas Fault. At any rate, the un-fractured sandstones are evidence against the very low probability extreme ground motions being considered in the design of the designated nuclear waste repository at Yucca Mountain, Nevada.

### Distribution of Toppling Accelerations of Precarious Rocks with Distance from Active Faults: Lovejoy Buttes, Victorville, and Granite Pediment

*Brune, James N. and Richard J. Brune*

Precariously balanced rocks are usually not found closer than about 15 km from the San Andreas fault in the Mojave Desert. However with increasing distance the toppling acceleration (TAs) of the most easily toppled rocks decreases, roughly from about 0.4 g at 15 km to about 0.25 g at 30 km, a result of the attenuation of ground motion with distance from the fault. There are 100s of such rocks in the Mojave Desert. This allows us to roughly estimate, using reconnaissance surveys, the frequency of occurrence of rocks of different alphas (about 30% less than TAs) as a function of distance from active faults. We give preliminary results from reconnaissance surveys in three areas; Lovejoy Buttes (about 15 km), Victorville (about 30 km), and Granite Pediment (in the middle of the Mojave Desert, hundreds of km from the San Andreas fault, and about 100 km from the nearest active fault, source of the Hector Mine earthquake of 1999). At Lovejoy Buttes there are no rocks with alphas of 0.2 g, whereas at Granite Pediment there are a number of such rocks. The largest areas covered were at Lovejoy Buttes and at Granite Pediment, but we also did a smaller survey at Victorville to estimate an intermediate distribution. Table 1 shows the raw data, the approximate area covered in each case, the numbers normalized to 100 with alpha of 0.5, and the number normalized to area.

| Raw Data | | | | Normalized to 100 | | | | Distribution per $Km^2$ | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $\alpha$ | Lovejoy | Victorville | Granite Pediment | $\alpha$ | Lovejoy | Victorville | Granite Pediment | $\alpha$ | Lovejoy 0.46 $km^2$ | Victorville 0.11 $km^2$ | Granite Pediment 0.23 $km^2$ |
| 0.1 | 0 | 3 | 6 | 0.1 | 0 | 30 | 6.82 | 0.1 | 0.00 | 27.27 | 26.09 |
| 0.2 | 0 | 5 | 37 | 0.2 | 0 | 50 | 42.05 | 0.2 | 0.00 | 45.45 | 160.87 |
| 0.3 | 22 | 9 | 68 | 0.3 | 21 | 90 | 77.27 | 0.3 | 47.83 | 81.82 | 295.65 |
| 0.4 | 69 | 10 | 83 | 0.4 | 66 | 100 | 94.32 | 0.4 | 150.00 | 90.91 | 360.87 |
| 0.5 | 105 | 10 | 88 | 0.5 | 100 | 100 | 100 | 0.5 | 228.26 | 90.91 | 382.61 |

The obvious rough interpretation of these data is that rocks with alphas of 0.1 and 0.2, and many with alphas of 0.3 have been knocked down at Lovejoy Buttes, but many remain at Granite Pediment, with Victorville being intermediate. Here we only present a rough interpretation. First consider the fact that the number of rocks per unit area with alphas of 0.5 are not greatly different (only a factor of 4, explainable by an observed difference in characteristic jointing dimension), suggesting that this is approximately the number of rocks naturally occurring with this alpha when no earthquake shaking has knocked any down (this is, of course, very likely the case at Granite Pediment, far from active faults, where hazard maps show very low shaking hazard). Furthermore, the distribution of alphas at Granite Pediment is approximately flat for alphas between 0.5 and 0.3, suggesting that the distribution of naturally evolved alphas is approximately independent of alpha, consistent with the fact that there is no known reason why there should be a drastically different number of rocks with any particular alpha. For very precarious rocks, alphas of 0.1 and 0.2, mechanisms other than earthquakes might topple the rocks, e.g., wind and animals, including humans, or very distant earthquakes (several rocks in the region were toppled by the Hector Mine earthquake, with ground accelerations of about 0.1g, at a distance of about 100 km). Thus the distribution at Granite Pediment might have been flat to alpha 0.1 without these effects. This suggests that at Lovejoy Buttes most of the rocks with alphas of 0.1 to 0.3 have been knocked down by earthquakes, whereas those with alphas of about 0.4 (TAs of about 0.5 g) have not been, i.e., frequent ground motions of up to about 0.4 g have occurred, but few if any of 0.5 g. These results argue against the suggestion by some that the precarious rocks near the San Andreas fault, e.g., Lovejoy Buttes, are remnants, "statistical outliers", from a much more numerous original distribution (as pointed out by Brune et al., American Scientist, 2006, since the rocks have been exposed to many earthquakes along the San Andreas fault, the original numbers of rocks would have to have been huge, especially for larger alphas. There is no evidence for such large numbers of precariously balanced rocks at Granite Pediment, or for that matter, anywhere on earth). These preliminary results suggest that individual rocks may be considered valid constraints on ground motion.

### Precariously Balanced Rocks at Silverwood Lake, Seven Kilometers from the San Andreas Fault in Cajon Pass: What's Going On?

*Brune, James N., Glenn Biasi, and Richard J. Brune*

Precariously balanced rocks are generally not found closer than about 15 km from the southern San Andreas fault. Previous exceptions have been noted in San Gorgonio Pass just south of Banning and Beaumont. Olsen and Brune (2007) suggested two possible explanations: (1) Most large earthquakes in the area nucleate in San Gorgonio Pass and rupture away from there, so that directivity focuses the energy away, and/or (2): the faulting in San Gorgonio Pass is thrust faulting with the energy concentrating in the hanging wall and decoupling energy from the foot wall, where Banning and Beaumont are located.

This spring we discovered a number of precariously balanced rocks at Silverwood Lake, about 7 km northwest of the San Andreas fault in Cajon Pass, where offsets of several m were documented for the 1812 earthquake. The preliminary toppling accelerations for these rocks is 0.2 to 0.3, unexpectedly low to have survived an earthquake with such a large offset. The rocks are formed in relatively soft granitic materials, and thus could have formed relatively recently compared to other balanced rocks in the Mojave region. Nevertheless they probably are at least 1000 yrs old, and thus survived the 1812 earthquake (and also the more distant 1857 earthquake), and probably several prior earthquakes. Further study will be required to verify the ages and toppling accelerations of the rocks, however we feel our preliminary assessments are likely enough to warrant speculation on possible explanations.

The speculations of Olsen and Brune (2007) seem less likely to apply to the Silverwood Lake rocks. They are on the hanging wall side of the faults in San Gorgonio Pass, and it is difficult to assume nucleation points which would explain low accelerations at points as far apart as Silverwood Lake and Banning. Here we explore other possible explanations:

(1) Ground accelerations are unexpectedly low even though the offsets may be large – possibly a result of the lack of any nearby strong asperity, a low stress drop anti-asperity, or other causes for local extreme deviation of the ground motions from the expected median.
(2) The intersection of the San Andreas fault with the San Jacinto fault NW of Silverwood Lake create a regional releasing-bend geometry that systematically decreases fault-normal stresses.
(3) Aside from a possibly anomalous 1812 earthquake, the fault may not have slipped in a major earthquake in 500-1000 yrs, long enough for the rocks to form.
(4) The rocks are located in some special topographic or geologic situation that somehow isolates them from strong ground motions.

We review the possibilities in light of available nearby paleoseismic data and also the Baysian probability methodology of Biasi and Weldon (in review) Presently it appears that the explanation requires low ground motions at the precarious rock sites, despite their proximity to the fault.

### SCEC/SURE: A Test of Two Earthquake Modeling Methods

*Burrill, Christine (MHC), Keith Richards-Dinger (UCR), James Dieterich (UCR), and David Oglesby (UCR)*

A primary challenge in earthquake modeling is to decide which fundamental mechanisms are required to accurately reproduce the earthquake process, and which are less important. With this in mind, we compared two modeling methods that incorporate different levels of approximation in the earthquake process. The first model, DYNA3D, solves the full dynamic equations of motion (including the frictional interaction on the fault and wave propagation) by the finite element method, but uses a simple slip-weakening friction law. The second model rapidly simulates large earthquake sequences by applying quasi-static approximations with rate- and state- dependent friction and long-range elastic interactions. We investigated how different aspects of the model (e.g. initial stress, and rupture location) affect different features of the simulated ruptures (e.g. slip and stress drop) and to what extent the models agreed with each other on the resulting properties. We found the quasi-static model can qualitatively reproduce the general slip and stress drop patterns of earthquake rupture given by the fully dynamic model as well as produce different modes of rupture (crack-like and rupture pulses). As expected, rupture velocity and the details of the slip rate function agreed the least.

**Using TDR, Helium density, digital grain size analysis, and chemical data to characterize the physical properties of near surface fault zones: a proof-of-concept approach**

*Campbell, Cameron D. (SDSU), Afton Van Zandt (SDSU), Peter Winther (SDSU), Matt Burgess (SDSU), Aaron K. Hebeler (SDSU), Sarah L. Johnson (SDSU), Adam Cosentino (SDSU), and Gary H. Girty (SDSU)*

We have mapped a conjugate set of strike-slip faults consisting of over 35 individual faults that are probably younger than ~0.5 - 0.6 million years in the San Felipe Hills, SE, California. The faults have been exhumed from a minimum of 300 meters depth. Hinge lines of early formed folds serve as piercing points for determining amounts of offset for many of the faults, and indicate that displacements mostly vary from 1-3 meters to as great as 250+ meters. The faults cut poorly consolidated mudstones and sandstones of the Pliocene-Pleistocene Borrego Formation and sandstones and minor gravels of the overlying Pleistocene Ocotillo Conglomerate (~1.1 to ~0.5 Ma).

Fault zones in the San Felipe Hills vary from ~10 to 615 cm in thickness, and fault zone thickness (fzt) correlates with fault displacement (fd) (fzt = 0.003*fd + 0.222; R2 = 0.67). From the initial set of 35 faults, we selected two faults for detailed study, one recording dextral, and the other sinistral slip. Eleven samples were collected beginning ~9 m outside the dextral fault zone, the last 2 samples being within the fault core. Samples were spaced ~1.5 m apart in sandy siltstone just below and above the contact separating the Ocotillo Conglomerate and Borrego Formation. For the sinistral fault beginning ~9 m outside the fault zone 5 samples were collected at a spacing of ~ 2 m within laminated siltstones of the lower Ocotillo Conglomerate. At each sample site dry bulk density was measured using time domain reflectometry (TDR), while collected samples yielded helium density (grain density), digital grain size distributions, and chemical data. From these data porosity and volume strains are calculated. Preliminary data from one traverse show that porosity systematically decreases from ~42% outside the fault zone to ~14% within the fault zone. This change in porosity translates into an ~47% decrease in volume. Thin sections of the damaged zone show that granulation and fragmentation did not accommodate observed volume strains or porosity reduction. Though we are currently completing our analyses of data collected from other traverses, we suggest based on the above observations, that when faults transect sandy to silty intervals, the majority of slip occurs along a single slip surface (the principal slip surface), while packing and reduction of pore space is a major process operating within a narrow ~1 m zone adjacent to the fault zone.

**SCEC/UseIT: Helping Users Better Utilize SCEC-VDO**

*Chan, Alysha (Scripps College)*

The Southern California Earthquake Center (SCEC) provides undergraduates the opportunity to work in a unique interdisciplinary environment to achieve a "Grand Challenge" in its Undergraduate Studies in Earthquake Information Technology (UseIT). Our "Grand Challenge" was to communicate earthquake concepts through serious games. Although "serious game" sounds like an oxymoron, it's actually a popular concept where education is combined with entertainment. There were four gaming teams: educational game, training game, and two decision-making games. I was on the training team, which made games to train SCEC-VDO users. We decided there are two important functionalities users commonly have difficulties with: navigation and movie-making. I spearheaded the movie-making game, which will teach users how to make a movie in SCEC-VDO. Since I didn't have coding experience, I first experimented with aspects of movie-making to determine what to include in the game. Then I wrote down the steps to make that specific movie. To implement these steps into SCEC-VDO, I was required to learn Java as well as Eclipse, an integrated development environment. Although coding was daunting at first, I learned it quickly and created the graphical user interface (GUI). All of the text and buttons in the movie-making game were made by me, and a structured game wouldn't exist without it.

### Simulations of small repeating earthquakes that reproduce the observed scaling of seismic moment with recurrence time

*Chen, Ting (Caltech) and Nadia Lapusta (Caltech)*

Observations show that the recurrence time T of small repeating earthquakes in Parkfield is proportional to 0.17 power of the seismic moment M (Nadeau and Johnson, 1998). This is different from the typical scaling with the power of 1/3, which can be explained by a simple model of circular ruptures with stress drop independent of M and slip proportional to T. Several explanations for this discrepancy have been proposed, including high stress drop (Nadeau and Johnson, 1998), shading asperity (Sammis and Rice, 2001) and aseismic slip due to strain hardening (Beeler et al., 2001). These events are the targets of the San Andreas Fault Observatory at Depth (SAFOD) drilling project.

We use the methodology of Liu and Lapusta to simulate repeating events in a 3D model of a strike-slip fault embedded into an elastic space and governed by rate and state friction laws. On the fault, a small circular patch with steady-state velocity-weakening properties is embedded into a larger region governed by velocity strengthening. The model incorporates tectonic-like loading and all dynamic effects during unstable sliding. In our simulations, preseismic slip and afterslip constitute a progressively larger part of the total slip for smaller earthquakes, resulting in the scaling of T and M with power of 0.21, very similar to the one observed. Hence we provide a laboratory-based foundation to the idea of Beeler at el. (2001) that much of the overall slip at the places of small repeating earthquakes is accumulated aseismically. Stress drops of the simulated events are within the typical range. Our current and future goals include exploring the parameter space of the model, comparing results of 3D and 2D models, simulating repeating earthquakes with different state evolution laws and laws that incorporate dynamic weakening effects such as flash heating, and comparing the simulated behavior with detailed SAFOD observations.

### Improvement of the SCEC-3D Model of the Los Angeles Basin Using Teleseismic Receiver Functions

*Chu, Risheng (SLU) and Lupei Zhu (SLU)*

A three-dimensional velocity model of the Los Angeles Basin has been developed by the Southern California Earthquake Center (SCEC) for simulating strong ground motion, site effects, and locating earthquakes. P-wave velocities in the model are derived from oil logs, stratigraphic surfaces, and seismic tomography. S-wave velocities and densities are determined by empirical rules. To verify and refine the SCEC model, we obtained 509 teleseismic receiver functions of five broadband stations in the LA basin. Receiver functions of all five stations show strong azimuthal variations related to basin geometry. We modeled those variations using the generalized ray theory and the finite-difference method. Preliminary results show that the SCEC-3D model is inadequate in predicting the observed receiver function waveforms. Certain modifications of basin thicknesses, Vp/Vs ratios, and the geometry of the bottom interface in the model need to be made.

### Calico Fault Structure Determined Using Traveltime Data from Seismicity and Explosions

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A dense array of 100 seismometers deployed near the Calico Fault, located in the eastern California shear zone, recorded explosions and seismicity between June and December, 2006. Seismic velocity reductions associated with the fault damage zone are mapped in detail along and across strike; in addition, the depth extent of the velocity reduction is investigated. Three shots exploded in and out of the fault zone reveal seismic velocities in the very shallow crust. The first shot was located within the array, a second in the fault approximately 6 km from the array, and a third outside of the fault, also about 6 km away. In addition, we use local, regional, and teleseismic earthquake body waves to measure the width of the low-velocity zone and investigate variations in that width along strike and with depth.

We use the SCEC velocity model as a starting point and then perturb the velocity model in a finite zone along the Calico fault to find a match to the observed travel times. Results suggest a 1 to 2 km wide low-velocity zone, in good agreement with the InSAR-derived compliant zone. Our measurements are in accord with InSAR observations showing that the Calico fault suffered twice the strain of the surrounding bedrock during the Hector Mine and Landers earthquakes, confirming a zone of reduced shear modulus around the fault. These findings indicate that faults can affect rock properties at significant distances from the primary fault slip surfaces, a result with implications for the portion of energy expended during rupture to drive the cracking and yielding of rock.

## SCEC/ACCESS: Examining Earthquake Magnitude Errors

*Coddington, Amy (Macalester College), Jeremy Zechar (USC), and Thomas Jordan (USC)*

When an earthquake is recorded at multiple stations, the reported magnitude has some measurement uncertainty due to the location and infrastructure of the stations. In formulating and testing earthquake forecast models – such as those under investigation by the Collaboratory for the Study of Earthquake Predictability (CSEP) – magnitude uncertainty is often neglected or assumed to be normally distributed and independent of the reported magnitude. Using synthetic earthquake catalogs, we have investigated the effect of different magnitude error distributions on the Gutenberg-Richter a and b-values. Our results show that, for all of the distributions considered, the a value is increased, whereas the b-value effect varies with the form and parameters of the error distribution. We have begun analyzing the SCSN and NCSN catalogs to determine the observed error distribution in Southern and Northern California. Our findings will be useful to CSEP testing as they seek to account for magnitude uncertainty in their testing program. This research has been supported by the Advancement of Cyberinfrastructure Careers through Earthquake System Science-Undergraduate (ACCESS-U) program, initiated to provide a link between the purely scholastic nature of undergraduate programs and the problem-solving nature of graduate programs.

## Direct measurement of slip-weakening distance from near-fault strong motion data

*Cruz-Atienza, Víctor M. (SDSU), Kim B. Olsen (SDSU), and Luís A. Dalguer (SDSU)*

It is imperative to obtain reliable estimates of the frictional behaviour on earthquake faults, particularly the characteristic breakdown slip Dc, which has an important role on rupture propagation through the earthquake energy budget. Several studies have attempted to estimate Dc during fault rupture (e.g., Ide and Takeo, JGR, 1997). However, indirect estimates of Dc are complicated by the limited frequency bandwidth of the observed seismograms used to image the rupture process and the rapid decay of high frequencies with distance from the fault. Mikumo et al. (BSSA, 2003) proposed a method to estimate Dc on the fault plane as the slip at the time of the peak sliprate function (Dc'). Fukuyama and Mikumo (GRL, 2007) proposed to extend this method beyond the fault plane, by estimating Dc as twice the rake-parallel particle displacement at the time of the peak particle velocity. The factor of two arises from an equal amount of opposite displacement on either side of the fault. They concluded that such method allows reliable Dc' estimates with negligible dependence on the perpendicular distance from the fault, and used it to obtain Dc' estimates for the 2000 M6.6 Tottori (0.3 m) and the 2002 M7.9 Denali (2.5 m) earthquakes.

The study by Fukuyama and Mikumo was based on simple two-dimensional Green's functions in a homogeneous full space for an anti-plane kinematic crack, and suffers from three fundamental omissions: 1) the free surface and heterogeneous structure, 2) the finiteness of the rupture surface and 3) the dynamic rupture complexity of real 3D earthquakes. Here, we re-examine the methodology proposed by Fukuyama and Mikumo by means of a more realistic approach. We use spontaneous rupture propagation simulated by a recently developed and highly accurate approach, namely the staggered-grid split-node (SGSN) method in a fourth-order staggered-grid finite difference method (Dalguer and Day, JGR, 2007). We assume a vertical strike-slip fault governed by a linear slip-weakening friction law. Preliminary results show that both the free surface and the stopping phases strongly affect Dc estimates. The particle motion recorded by surface instruments is amplified roughly by a factor of two due to the presence of the free surface. As a consequence, the method by Fukuyama and Mikumo over-estimates Dc when applied to strong motion data recorded on the earth's surface. Moreover, contrary to the results by Fukuyama and Mikumo, we observe a strong distance-dependence of the Dc estimates perpendicular to the fault. This variation includes a minimum near the fault, increasing up to about 140% of the target Dc value at a distance 2-3 km from the fault. At further distances from the fault the Dc estimate decreases to about 60% of the target value 10 km away. This distance dependence of the Dc estimate is presumably caused by stopping phases propagating from the fault boundaries. In summary, the accuracy of the method for estimating Dc by Fukuyama and Mikumo is strongly affected by the presence of the free surface and finite fault extent, and likely by complexity in velocity structure and rupture propagation.

### PetaSHA Simulations Optimization

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The PetaSHA project is optimizing seismic wave propagation codes to enable simulations of the effects of large earthquakes in Southern California. The optimizations enable use of the fastest supercomputers available within the NSF TeraGrid to solve both dynamic rupture and seismic wave propagation. The codes can be used on the Teragrid Dell clusters Lonestar and Abe, the Cray XT3 Bigben computer, and the IBM Blue Gene/L computer. We present an approach that enabled easier adaptation of the applications to different architecture through use of flexible configuration settings and distributed data management. The resulting code is a factor of four faster than the original version. We have demonstrated excellent scalability of the PetaSHA application on 40,960 Blue Gene/L processors at the IBM TJ Watson Center. We also present data management strategies required to manage petabytes of simulation output. At SDSC, data management systems are under development that automate the execution of management policies. The iRODS (integrated Rule-Oriented Data System) is the first step towards this goal. Finally, we discuss the lessons learned in visualization of the simulation output in the areas of animation, annotation and automation.

### A three-dimensional numerical investigation of San Andreas Fault configuration through the San Gorgonio Pass

*Dair, Laura and Michele Cooke (UMass-Amherst)*

The faults in the San Andreas Fault zone have for many years been modeled as vertical strike-slip faults, without considering the observed the north-dipping fault geometry of several strands. This study investigates alternative three-dimensional configurations of the San Andreas Fault through the San Gorgonio Pass to show how fault geometry can exert significant influence on uplift patterns and slip rates. Using three-dimensional Boundary Element Method models we have set up three different fault configuration of the San Gorgonio Pass, which include the primary segments of both the San Andreas and San Jacinto Faults. One model has vertical strike slip faults typical of previous numerical models of the region. Another model uses the SCEC Community Fault Model (CFM) with north dipping alternatives for the Garnet Hill and San Gorgonio fault stands. However, in the CFM, these faults are not connected to the San Bernardino strand and Coachella Valley segment of the San Andreas at depth. We developed a third model that smoothly connects the north dipping fault segments to adjacent San Andreas Fault segments at depth. The faults in all three models were extended to 30km depth where they sole into a horizontal detachment. This detachment serves to simulate the effects of the lower crust within the elastic half-space model. Regional transcurrent loading is applied as slip at the distal edges of the deep detachment as well as along the distal portions of the San Jacinto and San Andreas faults. Loading of the model with vertical faults fails to produce uplift directly north of the San Gorgonio Pass. Both of the north-dipping models produce significant uplift that may correspond to observations of recent uplift within the San Bernardino Mountains (e.g. Spotila et al, 1998). As for slip-rate comparison, the vertical system has the fastest strike-slip rates whereas the north-dipping and discontinuous fault system has the slowest strike-slip rates. While the vertical San Andreas fault configuration has the greatest net slip and more efficiently transmits transform deformation through the San Gorgonio Pass, the two north dipping fault configurations may better match uplift patterns. Further paleosiesmic investigations along the southern San Bernardino near Mill Creek and Garnet Hill strands of the San Andreas Fault could help to better distinguish between these possible fault configurations.

There has been an ongoing debate as to the slip partitioning between the Coachella Valley segment of the San Andreas and the San Jacinto fault. Published slip rates along the San Jacinto vary from as low as 10 mm/yr to more then 20 mm/yr. To one suite of models we apply 10 mm/yr to the San Jacinto and 25 mm/yr to the Coachella Valley segment and in another suite of models we apply 20 mm/yr to the San Jacinto and 15 mm/yr to the San Andreas Fault. Our results indicate that slip portioning between the two faults has less of an effect on the slip rates and off fault deformation than fault geometry within the San Gorgonio Pass.

**Unstable unilateral rupture at bimaterial interface with slip-weakening friction model**
*Dalguer, Luis A. (SDSU) and Steven M. Day (SDSU)*

Under some circumstances, pulse-like rupture propagation at a bimaterial interface becomes strongly asymmetric, and can be characterized as unilateral in the sense that slip diminishes and eventually dies out in one direction while growing unstably in the other. Pulse-like ruptures capable of this mode of evolution can sometimes be induced for inplane (2D) models with strongly velocity-weakened friction (Ampuero and Ben-Zion, 2007), but have not been seen for 2D slip-dependent friction models (e.g., Harris and Day, 1997). However, we have found that 3D effects (leading to pulse-like rupture) can induce the strongly asymmetric rupture mode even with purely slip-weakening friction. In the slip-weakening case, rupture of faults much longer than their down-dip width initially develops in a crack-like, bilateral mode, and subsequently (due to stopping phases from the top and bottom edges) evolves into two separate slip pulses traveling in opposite directions (e.g., Day, 1982). Under a restricted range of initial conditions, when the fault is at a bimaterial interface (we have so far investigated wavespeed contrasts of ~20%), the slip pulse in the preferred direction propagates indefinitely, while the one in the non-preferred direction dies out. This mode only occurs when the rupture initiates from a localized stress concentration and then propagates into a lower-stress background for which the critical dimension for unstable rupture is tuned closely to the fault width. When initial conditions permit this mechanism to originate, the subsequent propagation distance in the non-preferred direction depends on the value of the quotient (1 + phis)/(1-phid), where phis and phid are, respectively, the static and dynamic friction coefficients (with the die-out distance reducing for high values of this quotient and increasing or transitioning to bilateral rupture for low values). For a surface-rupturing fault, similar relations govern the transition of the rupture mode, provided one interprets the width of the fault as the half-width of an equivalent embedded fault. Both free surface effects and initial normal stress also have some effect on the die-out distance of the non-preferred pulse. If there is no tensile limit imposed on the fault stresses, the preferred-direction slip velocity grows indefinitely with propagation distance, but when fault opening (mode I displacement) is permitted in order to enforce a tensile limit, pulse slip-velocity approaches a steady state value. Whether this 3D mechanism is important in real earthquakes may depend upon a number of phenomena that we have yet to explore, including its sensitivity to natural heterogeneities in initial and frictional stresses, the extent to which it may be amplified by velocity-dependent friction, and the effect of stress limits imposed by off-fault material damage.

**DynaShake platform and dynamic source models for the southern San Andreas Fault ShakeOut scenario**
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We are developing the DynaShake Computational Platform, as part of the SCEC PetaSHA project. DynaShake assembles algorithms, codes, and computational and geoscience expertise for high-performance simulation of dynamic rupture at high resolution, directed toward investigations of the physics of rupture and ground-motion excitation. An essential element of DynaShake is the development of highly scalable codes for 3D rupture simulation, with dynamic simulations of the SoSAFE (Southern San Andreas Fault Evaluation) ShakeOut scenario serving as a testbed for this development. The ShakeOut rupture scenario initiates near Bombay Beach and propagates unilaterally 300 km toward the northwest up to near Lake Hughes, posing a considerable computational challenge for dynamic rupture simulation because of the very large outer scale length of the problem.

The ShakeOut scenario defines not only the rupture-surface and moment magnitude of the event, but also prescribes the final surface slip distribution resulting from the rupture. We developed a "slip-matching" technique for constraining initial (shear and normal) stress conditions in simulations such that they conform to scenarios defined in this form. The slip-matching method iteratively performs kinematic and dynamic simulations at low resolution to find initial stress distributions that (i) have stochastic irregularities

compatible with seismological observations, (ii) satisfy frictional strength limits at shallow depth, (iii) are slip-matched to surface displacement scenarios, and (iv) rupture the full length of the specified scenario. Source models were derived from stochastic slip distributions using Gaussian (G) and Von Karman (VK) correlation functions. While the series of models show a wide variety of complex rupture patterns, all closely reproduce the target surface-slip distribution and moment magnitude (Mw 7.8). The G and VK models vary greatly in their fault-plane distributions of stress drop, peak slip velocity, final slip and rupture time, even though averages are nearly identical. For example, compared with the G models, the VK stress models entail higher peak values of the dynamic stress drop, show smaller-scale spatial fluctuations in slip and the rupture front is developed with smaller wavelength structure. This work has thus far been done with 400m grid spacing, using the new Staggered-Grid Split-Node (SGSN) Method for rupture simulation, which has well-verified accuracy and efficiency. The current results are guiding the design of higher-resolution models to investigate the effects of realistic friction laws, geologic heterogeneity, and stress states on rupture and wave propagation. The DynaShake platform includes friction modules for both linear and nonlinear slip-dependent frictions laws, as well as prototypes of rate- and state-dependent friction modules, including a generalized formulation with strong velocity weakening to represent thermal weakening. When the latter is integrated into the SGSN method, the coupled system (state variable, slip-rate vector, fault traction vector) can sometimes become very stiff, requiring an implicit ODE solver based on backward differentiation, as described in a companion poster presented by Rojas et al. These friction modules will be used to compare the effects of different friction laws on rupture behavior and examine their compatibility with ground-motion observational constraints.

### A constitutive model for fault gouge deformation in dynamic rupture simulations

*Daub, Eric (UCSB) and Jean Carlson (UCSB)*

In the context of numerical simulations of elastodynamic ruptures, we compare friction laws, including the linear slip-weakening (SW) law, the Dieterich-Ruina (DR) law, and the Free Volume (FV) law. The FV law is based on microscopic physics, incorporating Shear Transformation Zone (STZ) Theory which describes local non-affine rearrangements within the granular fault gouge. A dynamic state varable models dilation and compaction of the gouge, and accounts for weakening and re-strengthening in the FV law. The prinicpal difference between the FV law and the DR law is associated with the characteristic weakening length scale. In the FV law, the length scale grows with increasing slip rate, while in the DR law the length scale is independent of slip rate. In simulations of spontaneous elastodynamic rupture, the FV law produces ruptures with smaller nucleation lengths, lower peak slip velocities, and increased slip-weakening distances when compared to ruptures governed by the SW or DR laws for equal frictional energy dissipation. We also examine versions of the DR and FV laws incorporating rapid velocity weakening. The rapid weakening laws produce self-healing slip pulse ruptures for low initial shear loads. For parameters which produce identical net slip in the pulses of each rapid weakening friction law, the FV law exhibits a much shorter nucleation length, a larger slip-weakening distance, and less frictional energy dissipation than equivalent ruptures with the DR law.

### Analog modeling of the San Andreas Fault at the San Gorgonio knot

*Del Castello, Mario (UMass-Amherst) and Michele Cooke (UMass-Amherst)*

The San Andreas Fault shows significant internal complexity in the San Gorgonio Pass area of southern California. Although many earthquake and crustal deformation models consider the San Andreas Fault to be vertical through the San Gorgonio pass, some evidence suggests that the active fault surface may be discontinuous and north-dipping between the San Bernardino and Coachella segments. We show some preliminary results of a series of analog models that show how this technique might be useful for discriminating between contrasting proposed models. With analog models we can study both the short-term mechanical interaction between faults in different configurations and the long term fault evolution. We believe analog modeling can well team up with other modeling techniques to provide great insight into the Southern San Andreas Fault system.

A new research apparatus was designed at the Geomechanical laboratory at UMass-Amherst. The research rig is composed of two plates, one movable and the other stationary, that can slide past each other to simulate a transcurrent setting. Motion is computer-controlled and a step motor allows for deformation rates as low as a few mm/hr. In order to investigate deformation near the San Gorgonio pass, two metal basal plates have been cut and arranged to approximate the configuration and slip rates of the SAF and San Jacinto fault. Analysis of the deformation within the apparatus is fully three-dimensional utilizing sequential photography and a 3D laser scanner.

We focus our first attempts onto two simplified fault geometries: 1) a vertical, continuous San Andreas Fault though the San Gorgonio pass and 2) a low angle thrust fault interposed between the San Bernardino strand and the Coachella strand. Different fault configurations are first cut in the clay and then reactivated in a dextral strike-slip field. Fault slip as well as off-fault deformation around faults were observed to markedly vary for the two cases. Decreased slip and a distributed upwarping characterized the vertical continuous fault (case 1). By contrast, the low angle fault quickly reactivated and slipped, producing a well defined, localized uplift in the area between the interacting fault strands (case 2). The preliminary results of our experimental work suggest that our analog models are able to portray first order fault interaction of faults within the SAF system at the junction between the Coachella and San Bernardino segments.

### Experimental observations of inelastic compaction during unstable sliding: implications for fault strength and stability

*deMartin, Brian J. (Brown), Terry E. Tullis (Brown), David L. Goldsby (Brown), and Nick M. Beeler (USGS)*

The conditions favoring stable (aseismic) or unstable (seismic) sliding on a fault depend on the interaction between the frictional properties of the sliding surface and the mechanical properties of the surrounding rock. The elastic parameters of the wall rock depend on loading conditions (e.g., confining pressure, pore fluid pressure, normal stress, and shear stress) and matrix microstructure (e.g. orientation of cracks and pores), both of which can evolve during sliding. We measured the mechanical behavior of 2 mm thick layers of quartz gouge and bare-surface Fontainebleau sandstone samples during large-displacement experiments at 25°C, a differential stress of 1 MPa, confining pressures ranging from 24 to 88 MPa, and pore fluid pressures ranging from 0.1 MPa to 79 MPa in the rotary shear apparatus at Brown University in order to understand the interplay between stress, pressure, and volumetric strain during stable and unstable sliding. We used deionized water as the pore fluid. At the start of the experiments, prior to the onset of localization and stick-slip behavior, increases in sliding velocity are accompanied by dilatancy. As the experiments proceed and stick-slip sliding is initiated, we observe the opposite phenomena: net compaction during rapid slip and stress drop. During unstable sliding it thus appears that two effects are important: one, inelastic shear-induced changes in pore volume, and two, poroelastic changes due to inhomogeneous and anisotropic faults. The former is related to changes in shear stress, while the latter has been associated with velocity changes. In the case of unstable sliding in the laboratory, elastic changes in thickness due to changing stress exceed the inelastic changes in thickness due to the rate-dependence. According to these observations, dilatancy-hardening effects may play a secondary role during unstable slip and thus may not play an important role in earthquake nucleation under wet undrained conditions.

### SCEC/SURE: Seismic Velocity Variations in California Middle and Lower Continental Crust: Observations from the San Gabriel Mountains

*DeWalt, Heather (Ohio University) and Andy Barth (IUPUI)*

There are several different numerical models for calculating seismic velocities (Vp) of rocks. Christensen and Mooney (1995) developed a model for calculating Vp from rock density (specific gravity). Hacker and Abers (2004) developed a model, based on mineral end member Vp values, which allows calculation of Vp from modal mineralogy or rock geochemistry. The purpose of this project was to use these models to calculate velocities of rocks from different rock units of the San Gabriel Mountains. The next objective was to compare a select few of these calculated velocities to measured Vp values (McCaffree and Christensen, 1998). The velocities calculated using the Christensen model increase with increasing specific gravity. The velocities calculated using the Hacker model increase with increasing iron content, and decrease with increasing silica content. Average Vp from each model for each rock type were converted to 3D plots and contour maps using SigmaPlot. While the models varied, they all showed higher Vp in the northwest portion of the range, and lower Vp to the south and east. This reflects the fact that the northwest portion of the range is dominated by mafic Mendenhall gneiss and Anorthosite complex, and the southeast portion is dominated by felsic intrusions.

### NASA's DESDynI InSAR Mission

*Donnellan, Andrea (JPL), Brad Hager (MIT), Paul Rosen (JPL), and Howard Zebker (Stanford)*

InSAR has been used to study surface deformation of the solid Earth and cryosphere and more recently vegetation for estimates of biomass. The NRC decadal survey recommends that DESDynI (Deformation, Ecosystem Structure, and Dynamics of Ice), an integrated L-band InSAR and multibeam LIDAR mission, launch in the 2010-2013 timeframe. The mission will measure surface deformation for solid Earth and cryosphere objectives and vegetation structure for understanding the carbon cycle. One of the objectives of DESDynI is to characterize the nature of deformation at plate boundaries and the implications for earthquake hazards. This requires that surface deformation be measured to discriminate between faults and assign potential hazard. In order to do so, it is recommended that DESDynI provide global coverage of actively deforming areas with 3-dimensional vector deformation at 100 m resolution, accurate to 5% of the rate of the deforming zone or 1 mm/yr. We require weekly sampling with 200 km width imagery across the deforming boundary. This should provide unprecedented measurement of crustal deformation throughout California with spatial sampling that complements the temporal resolution of the existing GPS networks.

### The QuakeSim Modeling Environment

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QuakeSim is a NASA-funded modeling and simulation environment for understanding earthquake and tectonic processes. The focus of QuakeSim is on the interseismic part of the earthquake cycle, including leading up to fault failure and postseismic crustal response using various boundary element, finite element, and analytic applications, which run on platforms including desktop and high end computers. We integrate and deliver paleoseismic fault, GPS, and seismicity data through our QuakeTables database. In the future we will make processed InSAR data available. One goal of the project is to test possible interpretations of faults through models and simulations; hence the database can house more than one record for a given fault. The QuakeSim modeling environment is integrated through a web-services portal environment, which can be accessed from the http://quakesim.org web page.

### Damage characterization in sandstones along the Mojave section of the San Andreas Fault with a new method: initial results and implications for the depth and mechanism of dynamic rock pulverization

*Dor, Ory (USC) , Yehuda Ben-Zion (USC), Judith S. Chester (Texas A&M), Jim Brune (UNR), and Thomas K. Rockwell (SDSU)*

Following theoretical expectations that pervasive rock damage is limited to the top few km of the crust (Ben-Zion and Shi, 2005; Rice et al., 2005), we evaluate the damage content in sedimentary rocks that have never been buried deeply while being displaced along the San Andreas Fault (SAF). Many of the examined sandstones in the vicinity of the Mojave section of the SAF display minimal or complete absence of significant SAF-parallel shear. For the analysis of damage in the sandstones we use a new method that compares the original perimeter length of a grain to the total perimeter length of its fragments, applied to a statistically representative population of grains from each sample. We employ this method on samples from the Juniper Hills formation, a tectono-stratigraphic unit that has been deposited adjacent to active strands of the SAF system. This sandstone is, in places, less cohesive compare to older sandstone units found along the SAF. The results delineate a damage zone of about a 100 m on the southwest side of the SAF and suggest, together with other considerations, that dynamic damage generation occurs very close to the Earth surface. When we apply the method on three mutually perpendicular sections of sample collected 10 m from the fault we observe an anisotropic damage pattern. In addition we observe preferred orientation of microfractures and many microscale damage elements associated with grain contact pressure. Those observations are compatible with failure in a compressional field. The orientation of microfractures in a sample near the fault is normal to the SAF and leaning to verticality, in agreement with modeling predictions for the possible orientation of maximum compressive stress during cyclic loading associated with slip events on rough frictional fault surface (Chester and Chester, 2000). A change in the preferred orientation of microfractures between this sample and a more distant sample indicates a variability of the stresses

throughout the damage zone that may be associated with strong dynamic reduction of normal stress or fault opening.

### Modeling the Reduction of High-frequency Seismic Radiation Due to Plastic Strain Localization at Fault Kinks

*Duan, Benchun (Texas A&M) and Steven M. Day (SDSU)*

We extend an elastodynamic finite element method to incorporate off-fault plastic yielding of Mohr-Coulomb form into a 2D dynamic rupture model. For straight faults under uniform stress conditions, we find two types of the off-fault plastic strain distribution: one in which the plastic strain is continuous and smooth, with the maximum magnitude adjacent to the fault, the other in which plastic strain spontaneously localizes into discrete bands. In the latter case, while the numerical simulations can capture the onset of localization, we have so far been unable in general to obtain fully regularized, convergent solutions. Attempts at regularization via viscoplastic relaxation sometimes result in a smooth, numerically convergent solution (as also shown by Andrews, 2005), while in other cases the result is simply to delay the onset of localization, without suppressing the smallest, numerically irresolvable scale lengths of localized plastic strain. A dimensionless parameter T that characterizes how close the off-fault material is to the yielding strength in the initial state is proposed to be the determining factor for plastic strain localization in straight-fault models. Supershear rupture can occur in elastoplastic dynamic models and it suppresses the off-fault plastic strain localization. . Off-fault plastic yielding lengthens the cohesive zone at the rupture front, such that the width of this zone tends to stabilize with rupture propagation distance (as already noted by Andrews, 2005), with the fault behavior under slip-weakening friction essentially reducing to that of a time-weakening friction law.

A discrete kink in fault strike also localizes rupture-induced plastic strain, and in this case we have succeeded in obtaining apparently convergent numerical solutions (as assessed by numerical element size reduction). Rupture through a kink is known theoretically to excite a strong radiated pulse (a velocity step) at high frequencies (Madariaga et al, 2006), but we find that localized yielding effectively filters this pulse above a high-frequency limit. The reduction may be significant at frequencies above several Hertz.

### SCEC/UseIT: Teaching Earth Science Through Games and Movies

*Dumbacher, Brian (USC)*

This summer I was an intern at the Southern California Earthquake Center (SCEC) as part of the Undergraduate Studies in Earthquake Information Technology (UseIT) program. UseIT brings together students from a broad range of academic backgrounds to work on projects that combine earthquake science and computer technology. The grand challenge for this summer was to prototype several serious games, i.e. games that use entertainment for training and educational purposes. As a member of the educational gaming team, I worked on many different mini-games designed to help college students learn introductory Earth science material. In particular, I made vector graphics and wrote code for the Hot Spots game, which teaches students the basics of island chain creation and hot spot/oceanic plate interaction. To make all of our mini-games, my teammates and I used the application Adobe Flash CS3 and its powerful object oriented scripting language ActionScript 3.0 to create animations and interactive features. Also incorporated into some of our games are movies made with SCEC-VDO, earthquake visualization software developed by UseIT interns. Additionally, I helped create a movie to showcase SCEC-VDO's global data sets, earthquake data, and image capabilities.

### Attenuation of Radiated Ground Motion and Stresses from Three-Dimensional Supershear Ruptures

*Dunham, Eric M. (Harvard) and Harsha S. Bhat (Harvard)*

Radiating shear and Rayleigh waves from supershear ruptures form Mach fronts that transmit large-amplitude ground motion and stresses to locations far from the fault. We simulate bilateral ruptures on a finite-width vertical strike-slip fault (of width W and half-length L with L >> W) breaking the surface of an elastic half-space, and focus on the wavefield out to distances comparable to L. At distances much smaller than W, two-dimensional plane-strain slip-pulse models (i.e., models in which the lateral extent of the slip zone is unbounded) [Dunham and Archuleta, 2005; Bhat et al., 2007] accurately predict the subsurface wavefield. Amplitudes in the shear Mach wedges of those models are undiminished with distance from the fault. When viewed from distances far greater than W, the fault is accurately modeled as a line source that produces a shear Mach cone and, on the free surface, a Rayleigh Mach wedge. Geometrical spreading of the shear Mach cone occurs radially and amplitudes there decrease with the inverse square-root of distance [Ben-Menahem and Singh, 1987]. The transition between these two asymptotic limits occurs at distances comparable to W. Similar considerations suggest that Rayleigh Mach waves suffer no attenuation in the ideally elastic medium studied here. The rate at which fault strength weakens at the rupture front exerts a strong influence on the off-fault fields only in the immediate vicinity of the fault (for both sub-Rayleigh and supershear ruptures) and at the Mach fronts of supershear ruptures. More rapid weakening generates larger amplitudes at the Mach fronts.

### Evaluating Thermoelastic Strain as an Earthquake Trigger

*Ebel, John E. (Boston College) and Yehuda Ben-Zion (USC)*

Spatio-temporal variations of temperature at the Earth's surface cause strains and stresses below the surface in two ways. The diffusion of heat into the ground leads directly to thermal deformation that may have an appreciable amplitude several meters below the Earth's surface. More importantly, variations of surface temperatures produce surface tractions that propagate stress variations into the deeper parts of the crust. This second mechanism causes stresses that can be significant at depths of many kilometers. Under the latter mechanism, seasonal temperature variations with spatial wavelengths of 10-30 km can produce thermoelastic strains with amplitudes of about 10-7 to 10-8 over the seismogenic depth range of 1-10 km in the crust. Since the threshold for triggering seismicity is expected to decrease with increasing period of excitation, these strain levels and associated stresses (about 5x102 to 5x103 Pa using a nominal rigidity of 50 GPa) may trigger seismicity. Previous work has shown that predicted thermoelastic strains generated by surface variations of temperature fit well the observed seasonal variations of borehole strain meters and GPS arrays, and that the amplitude of the thermoelastic strain is several times larger than that generated by 5-10 m water level variations in a nearby reservoir. We suggest that thermoelastic strains may explain the growing evidence for seasonal variations in the earthquake activity rates at a number of places in the western U.S. Seasonal variations of seismicity with increased activity in the summer and autumn was observed in California for earthquakes less than M1.5 during the several years following the 1992 Landers earthquake, for earthquakes with M>=2.0 in California and Nevada from 1990-2005, and for earthquakes with M>=4.0 in California and Nevada from 1932-2005. A similar seasonality with increased seismicity during the autumn and winter has been documented at some of the Cascades volcanoes and in the Himalaya. Explanations based on pore fluid pressure changes and other effects require unrealistic values of material parameters. It thus appears that thermoelastic triggering may be responsible for the observed seasonal seismicity patterns.

### Correlation of Static and Peak Dynamic Coulomb Failure Stress with Aftershocks, Seismicity Rate Change, and Triggered Slip in the Salton Trough

*Eddo, Jeff (SDSU) and Kim Olsen (SDSU)*

Numerous studies have found significant correlation of static Coulomb Failure Stress (sCFS, co-seismic earthquake induced stresses) with the occurrence of mainshocks, aftershocks, and triggered slip (e.g. Stein, 1999; Kilb, 2003; King et al., 1994, Arnadottir, 2003; Du et al., 2003; Freed, 2005). Static CFS estimates are primarily dependent on the final co-seismic slip distribution and fault geometry. Recently, complete or dynamic Coulomb Failure Stress, parameterized by its largest positive value (peak dCFS), has been proposed as an alternative triggering mechanism (Kilb, 2002). Peak dCFS estimates, in addition to the final slip dependence, have been shown to be strongly dependent on co-seismic source effects, such as rupture directivity (Kilb, 2002). However, most studies of stress transfer and earthquake triggering only incorporate sCFS and only a few studies have attempted to correlate seismicity rate change and triggered slip on surrounding faults.

In this study we have modeled the distributions of sCFS and peak dCFS for four recent historical earthquakes (1968 M6.7 Borrego Mountain, 1979 M6.6 Imperial Valley, 1987 M6.6 Elmore Ranch, and M6.5 Superstition Hills) using a fourth-order staggered-grid finite-difference method, which incorporates anelastic attenuation, a 3-D velocity model, and heterogeneous slip distributions derived from strong ground-motion and geodetic inversions. The study area is 150 by 150 km located in the Salton Trough of the Imperial Valley, California. A cross-correlation is calculated between the modeled stresses and seismicity rate change in terms of the Z-value (Habermann, 1983) with a background seismicity rate removed. Modeling results show that peak dCFS provides significantly better correlation with aftershock distributions, seismicity rate change, and triggered slip than sCFS for all four events. Both sCFS and peak dCFS provide significant goodness of fit (>55%) with seismicity rate change up to a month after the mainshocks, with decreasing correlation for longer time periods. However, on average, the peak dCFS fits the seismicity rate change 26% better than sCFS for time periods up to a month after the mainshocks, and peak dCFS correlates with aftershocks significantly better than sCFS up to two years after the mainshock events. The overall favored performance of the peak CFS may be attributed to its strong sensitivity to rupture parameters in addition to the crustal velocity model and regional stress among other parameters. It should also be noted that the sensitivity to the coefficient of friction, poroelastic parameters, crustal velocity model, and regional stress, in terms of the goodness of fit with seismicity rate change, is stronger for peak dCFS (up to 20%), as compared to sCFS (up to 11%). Thus, peak dCFS appears as a more flexible triggering parameter as compared to sCFS. However, both sCFS and peak dCFS should be incorporated in studies of stress transfer and earthquake triggering, as they both appear to affect aftershock seismicity in a complementary way for some of the studied earthquakes.

### Complexity of Earthquakes: An approach through fractals and An exploration through simple mechanical models

*Elbanna, Ahmed (Caltech) and Thomas Heaton (Caltech)*

It has long been recognized that earthquakes exhibit similarity at many length scales which suggests fractal characteristics of earthquake ruptures. One of the well known manifestations of earthquake complexity is the fractal nature of the Gutenberg-Richter law. Moreover, there is growing evidence that earthquakes ruptures are very complex processes; as the resolution of source inversions has increased, so has the temporal and spatial complexity of the rupture. What are the key physical parameters that control this complexity? Many methods have been tailored in an attempt to uncover the details of the complex rupture processes but due to different numerical and computational limitations scientists could not go beyond a few orders of magnitude on both of the spatial and temporal scales. Statistical methods provide an alternative way to overcome the difficulties associated with numerical models of spontaneous dynamic ruptures. Here, we present an outline for an innovative approach that aims at reproducing the different earthquake complex scaling laws using methods of statistical mechanics with the ultimate goal of finding the scaling behavior of the strength of the Earth's crust. the emphasis of this presentation is on exploring the conditions that might lead to complexity in earthquakes using simple mechanical models similar to the Burridge-Knopoff spring-block-slider models. Although there are limitations in the user of spring-block-sliders to interpret the real earthquakes, these models have the advantage that they are computationally efficient. This allows us to explore the nature of complexity that is produced by different types of models of dynamic friction. We show that chaotic behavior occurs for friction models with strong velocity weakening. We would briefly explain why this might be suggestive for assessing complexity using fractals and introduce an outline for an alternative method that could be a surrogate for solving the full equilibrium equations and reproduce the rough earthquake statistics.

### SCEC/SURE: Paleoseismologic Investigation of the Calico Fault, Newberry Springs, CA: Stratigraphy

*Elliott, Austin (USC), Plamen Ganev (USC), James Dolan (USC), Mike Oskin (UNC Chapel Hill), and Kim Lee (UNC Chapel Hill)*

We excavated two, 3-m-deep paleoseismologic trenches across the Calico fault – the longest and fastest moving fault in the Mojave desert (Oskin et al., 2006) – in Newberry Springs, CA (~30 km east of Barstow on I-40). The trenches, which were excavated across a desert playa, exposed fluvial, lacustrine, and playa sediments, consisting of gravel and coarse-grained sands, silts, and clays, respectively. Several of these strata also displayed well-developed carbonate soils that help us to establish rough constraints on the age of deposition. Preliminary field analysis of soil development suggests that the section exposed in the trenches encompasses latest Pleistocene through Holocene sediments (dating from ~15 or 20 ka), ideal for a recent paleoseismological record. In order to determine the absolute timing of deposition, we have collected over two dozen samples from stratigraphic units throughout the trenches to submit for OSL (optically stimulated luminescence) dating. To record stratigraphic relationships, we logged the trench walls both manually and photographically, describing each unit in detail and correlating stratigraphy across fault offsets. The stratigraphy spans a substantial portion of latest Pleistocene and Holocene time, and displays sufficient internal stratification and cross-fault thickening to provide a significant paleoseismologic record for the Calico Fault.

### Dynamic rupture verification for SORD, and application to the TeraShake scenario

*Ely, Geoffrey (IGPP/SIO), Steven Day (SDSU), and Bernard Minster (IGPP/SIO)*

The Support Operator Rupture Dynamics (SORD) code provides a highly scalable (up to billions of nodes) computational tool for modeling spontaneous rupture on a non-planar fault surface embedded in a heterogeneous medium with surface topography. SORD successfully performs the SCEC Rupture Dynamics Code Validation Project tests, and we have undertaken further dynamic rupture tests assessing the effects of distorted hexahedral meshes on code accuracy. We generate a family of distorted meshes by simple shearing (applied both parallel and normal to the fault plane) of an initially Cartesian mesh. For shearing normal to the fault, shearing angle was varied, up to a maximum of 73°. For SCEC Validation Problem 3, grid-induced errors increase with mesh-shear angle, with the logarithm of error approximately proportional to angle over the range tested. At 73°, RMS misfits are about 10% for peak slip rate, and 0.5% for both rupture time and total slip, indicating that the method – which up to now we have applied mainly to near-vertical strike-slip faulting – also is capable of handling geometries appropriate to low-angle surface-rupturing thrust earthquakes.

The SORD code was used to reexamine the TeraShake 2 dynamics simulations of a M7.7 earthquake on the southern San Andreas Fault. Relative to the original (Olsen et al, 2007) TeraShake 2 simulations, our spontaneous rupture models find decreased peak ground velocities in the Los Angles basin, principally due to a shallower eastward connecting basin chain in the SCEC Velocity Model Version 4 (used in our simulations) compared to Version 3 (used by Olsen et al.). This is partially offset by including the effects of surface topography (which was not included in the Olsen et al. models) in the simulation, which increases PGV at some basin sites by as much as a factor of two. Some non-basin sites showed comparable decreases in PGV. These predicted topographic effects are quite large, so it will be important to perform further tests to better quantify SORD accuracy in the presence of non-planar free surface geometry.

### QuakeML: an XML-based data exchange format for seismology

*Euchner, Fabian (ETH Zurich), Danijel Schorlemmer (USC), Jan Becker (GFZ Potsdam), Andres Heinloo (GFZ Potsdam), Philipp Kästli (ETH Zurich), Joachim Saul (GFZ Potsdam), Bernd Weber (GFZ Potsdam), and the QuakeML working group*

QuakeML is a new XML-based data exchange format for seismology. Adopting the XML standard family, it is designed for flexibility, extensibility and modularity.

The first release of QuakeML will cover a basic description of seismic events including picks, arrivals, amplitudes, magnitudes, origins, focal mechanisms, and moment tensors. Further extensions are in progress or planned, e.g., for macroseismic information, location probability density functions, slip distributions, and ground motion information.

We follow a collaborative and transparent development approach along the lines of the procedures of the World Wide Web Consortium (W3C). QuakeML currently is in working draft status. The standard description will be subjected to a public Request for Comments (RFC) process and eventually reach the status of a recommendation. The main development is carried out by a distributed international team with major contributions from ETH, GFZ, USC, USGS, IRIS DMC, EMSC, and ORFEUS.

To facilitate the use of QuakeML in software projects, we are employing a design process in which we can create C++ class libraries automatically from the data model description. This approach has been devised by GFZ Potsdam in the course of the SeisComP 3 development. The QuakeML library provides a mechanism to serialize (and deserialize) QuakeML objects to XML format or to an SQL database, giving users the possibility to easily read and write QuakeML documents. The library can also be used from other object-oriented languages, e.g., Python and Java, using SWIG wrappers.

QuakeML is already used in several software projects. The communication layer in SeisComP 3 is based on the QuakeML data model. Data exchange with external applications will be realized using QuakeML objects. ETH Zurich is currently developing a seismicity analysis toolkit based on Python and QuakeML. Parts of this development will be integrated in the next iteration of the CSEP testing center software.

## Structure of the San Andreas Fault at SAFOD from the Surface to 5 km depth

*Evans, James P. (Utah State), Sarah D. Draper, Kelly K. Bradbury, and Corey D. Barton*

We characterize the physical properties, microstructures, and composition of the faulted rocks of the San Andreas fault encountered in the SAFOD borehole. While a somewhat unexpected outcome, SAFOD provides a window into large-scale fault structure from the surface to 5 + km depth, when geologic data are merged with geophysical data sets. We use a combination of petrography, detailed analysis of electric image log data, borehole geophysical data, and previous XRD work [Solum et al., 2006] to constrain the structure of the faulted rocks at depth. The westernmost fault is the largest fault encountered and correlates to the Buzzard Canyon fault [Rymer et al], and was drilled at 1920 meters measured depth (mmd). It is approximately 45 m wide, separates Salinian granodiorite on the southwest from the arkosic section on the northeast and contains fine-grained quartzofeldspathic cataclasites and abundant calcite. The middle fault zone lies at 2530 mmd, is localized in a clay-rich sedimentary unit between the upper and lower arkoses and is a diffuse >65 mmd wide low-velocity, high gamma, clay-rich fault zone with numerous sheared clay-filled veinlets. Fault zone B may correlate to a fault mapped at the surface by Thayer and Arrowsmith (2005) on the west flank of Middle Mountain with a dip of 70 degrees SW, parallel to the Buzzard Canyon and San Andreas faults. The deepest fault juxtaposes arkosic rocks and fine-grained sedimentary rocks, and was cored during phase one drilling at 3067 mmd. It is brittly damaged with little textural or mineralogic evidence of fluid driven alteration and is an intraformational fault, and may be a small fault within the active San Andreas Fault zone. Each fault zone is marked by an increased abundance of altered and cataclastically deformed grains as seen in cuttings. Analysis of image logs indicates the presence of structural blocks with distinctly different bedding orientations, and fracture distributions throughout the section roughly correlate with the presence of faults and low Vp and Vs values [see Jeppson et al, this meeting].

In detail the seismic velocities, which appear to depend at least in part on the presence of fracture zones and faults, are highly variable. Each of the three larger faults zones has different characteristics. The Buzzard Canyon fault at depth contains abundant calcite and iron-oxide alteration; and fault zone B has numerous clay-filled veins, features consistent with extensive subsurface fluid flow. The deepest fault does not show evidence of alteration resulting from extensive fluid flow. The deepest fault is potentially up dip from the hypocenters of the small earthquakes that appear to occur below the borehole. The entire zone between the Buzzard Canyon and San Andreas [senso stricto] faults at depth appear to contain a series of southwest-dipping faults and damage zones that bound blocks with a variety of bedding and fracture orientations. We present several subsurface geologic models that are compatible with the current data, and these interpretations form the geologic background for the work of Jeppson et al [this meeting].

## Earthquake Nucleation on Geometrically Complex Faults: The Effects of Normal Stress Variation

*Fang, Zijun (UCR), James H. Dieterich (UCR), and Guanshui Xu (UCR)*

Earthquake nucleation determines the time and place of origin of earthquakes. Consequently nucleation processes may strongly affect space-time seismicity patterns including foreshocks, aftershocks and earthquake triggering. Previous nucleation studies employ highly idealized assumptions of planar faults and constant fault-normal stress during nucleation. In this study we explore earthquake nucleation on geometrically complex faults under generalized tectonic loading. We establish our model by employing a boundary integral formulation based on dislocation solutions in an infinite elastic medium, together with a rate- and state-dependent friction law, which includes evolution of frictional state under the combined effects of time, slip and changing normal stress. Three different fault and loading configurations are studied. For planar faults subjected to oblique loading, shorter nucleation times are obtained under conditions when normal stress decreases (unclamping of the fault) as shear loading increases. Longer nucleation time result when normal stress increases with shear loading. Furthermore, the dependence of the state variable on normal stress tends to reduce the effect of unclamping or clamping of the faults on nucleation time. For faults with periodic compressional and dilatational bends, earthquakes always nucleate on the dilatational ramps because the progressive unclamping of the fault due to the tectonic loading accelerates the nucleation process at those locations. The length of the inclined ramp, relative to the characteristic nucleation length, and ramp angle also affect the nucleation rate. For en echelon fault step-overs nucleation times are nearly independent of separation distance H between the parallel segments and the overlap length, suggesting that fault step-overs exert little control in determining the timing of earthquakes. However, nucleation location changes dramatically with H, migrating from regions near the overlapping ends to the center of the fault segments as H increases. The strongest determinate of nucleation locations and nucleation rates appears to be fault segment orientation with respect to the orientation of regional loading stresses. Normal stress changes due to geometric fault interactions from slip along the fault have smaller influence on the nucleation process. Our studies indicate that fault geometric features may control the location of the nucleation events, therefore significantly affecting rupture propagation and seismic wave generation in subsequent earthquake rupture.

### Southern California Modeling Of Geodynamics (SMOG-3D): Visco-plastic models of instantaneous lithospheric deformation

*Fay, Noah (University of Arizona), Boris Kaus (ETH Zurich, USC), Thorsten Becker (USC), and Gene Humphreys (University of Oregon, Eugene)*

We present preliminary results from 3-D, visco-plastic models of instantaneous deformation in southern California. Our goal is to understand fault and crustal stress levels and rheology, as well as fault interactions with the lower crust (i.e. the long-term behavior). We strive to integrate the effect of mantle and lithospheric density anomalies and explore which rock rheologies, fault strengths, and boundary conditions satisfy the observations. Our models include seismology-based (and gravity-consistent) density structure (viz. the Transverse Ranges drip, basic crustal structure, and the deep Farallon slab anomaly) and auxiliary information, such as heat flow observations. All data is incorporated into a mechanical model for general hypothesis testing, and we will later try to match stress and strain constraints (from GPS, geology, and anisotropy). The main new contributions are the use of, 1), diverse constraints to reduce non-uniqueness, 2), mantle-based tractions, and, 3), fully 3-D, visco-plastic rheology, as required for quantitative tests of lithospheric behavior, e.g. with regard to vertical coupling.

### Damage zone structure and deformation patterns along segmented strike slip faults

*Finzi, Yaron (UBC), Elizabeth H. Hearn (UBC), Vladimir Lyakhovsky (GSI), and Yehuda Ben-Zion (USC)*

Material and geometric properties of fault zones control the seismicity patterns and spatial distribution of the deformation. The goal of this work is to characterize the evolving structures and associated deformation along large strike slip faults. To simulate fault zone evolution, we use a thermodynamically-based continuum damage framework constrained by laboratory data of fracture and friction experiments (e.g., Lyakhovsky et al., 1997; Hamiel et al., 2004; Ben-Zion and Lyakhovsky, 2006). Three dimensional simulations with the damage rheology model are used to investigate fault evolution from a single segment scale to long-term plate-boundary scale. We first present how the damage healing parameters were constrained based on geophysical data from large strike slip faults. This calibration validates the use of our 3D code with the damage rheology for the study of natural fault system evolution. We also present results showing surface deformation patterns associated with the evolution of simple and complex strike slip fault systems. Our 3D simulations for a layered crust governed by damage rheology underlain by a visco-elastic upper mantle indicate that damage zones of strike slip faults form a flower structure with depth. The flower structure consists of broad damage in the top few kilometers that becomes highly localized at depth. The results also indicate that tectonic strain is primarily concentrated along the highly damaged cores of the main fault zones. A small portion of the strain is accommodated over a broader domain correlating with the overall width of the damage zone. Broader strain distribution could result from viscoelastic deformation of the lower crust and mantle. In our models of segmented faults, the results indicate that fault stepovers are locations of ongoing interseismic deformation. During the entire earthquake cycle, the material within the fault stepovers remains damaged to depth of about 10 km, exhibiting significantly reduced rigidity and shear wave velocity. We suggest that damage zones within fault stepovers could have important implications for earthquake dynamics, and that these zones of increased sustainable damage should be detectable by means of geophysical surveys.

### Dynamic triggering of high-frequency bursts by strong motions during the 2004 Parkfield earthquake sequence

*Fischer, Adam (USC), Zhigang Peng (Georgia Tech), and Charles G. Sammis (USC)*

High-pass filtering (>30Hz) of acceleration records from the USGS Parkfield Dense Seismograph Array (UPSAR) near Parkfield, CA reveals a series of short-duration bursts that occur only during the strong shaking of the 2004 M6 Parkfield earthquake (Mw 6.0) and its large aftershocks. These high-frequency bursts are probably associated with signals from small events that occur within 10 to 100 meters from the stations that are dynamically triggered by the strong ground motions of nearby earthquakes. Supporting evidence includes a lack of cross-correlation between waveforms from bursts with similar arrival times at closely spaced stations, and a measurement of array coherency as a function of seismic frequency and inter-station distance. Lack of correlation may be associated with the extremely high attenuation in the highly fractured layer that compromises the top 100-250m of crust in the region. The threshold stress required for triggering was found to be 0.07 to 2.1 MPa, consistent with a previous estimate based on strong motion data from the 1999 Chi-Chi earthquake in Taiwan (Fischer et al., in review: Bull. Seism. Soc. Am.).

### A New, Older Age for the 'T2' Fan Surface at Biskra Palms from U-series Dating of Pedogenic Carbonate: Implications for Landform Dating and Long-Term Slip Rates on the Southern San Andreas Fault

*Fletcher, Kathryn (UC Berkeley), Warren Sharp (BGC), Katherine Kendrick (USGS), Whitney Behr (USC), Ken Hudnut (USGS), and Tom Hanks (USGS)*

Dating of the T2 surface of the Biskra Palms fan near Indio (terminology of van der Woerd, 2006) by U-series on pedogenic carbonate indicates a depositional age of > 45 ka, about 30% older than the published cosmogenic surface exposure age determined using 10Be on cobbles from desert pavements (i.e., 35 ± 2.5 ka).

Analysis of soil development on the T2 surface reveals notably uniform soil profiles on the upper and lower fan surface, and the presence of dense, pure pedogenic carbonate coatings on gravel clasts at depths of 1.7-2.0 m. Carefully selected milligram-size samples of thin (< 0.3 mm) inner laminae of such coatings, analyzed by TIMS, yield U-series ages of 29 to 46 ka (n = 21) with median uncertainty of 0.9 ka (all uncertainties 2-sigma). Sub-samples from the oldest clast coating yield ages in good agreement, (e.g. 45.0 ± 0.8, 46.0 ± 1.8, 44.8 ± 1.0, and 45.7 ± 1.0 ka; mean = 45.2 ± 0.5 ka; upper surface), consistent with closed U-Th systems and formation of the dated coatings entirely within the T2 soil profile. Maximum U-series ages on carbonate are also similar from profile to profile; oldest clast coats from the lower surface are 44.4 ± 0.6 ka (T2L-05), 43.8 ± 0.9 ka (T2L-06), 43.8 ± 1.4 and 44.1 ± 2.0 (T2L-23), which overlap with the oldest ages from upper surface, stated above. The similar maximum ages from upper and lower fan profiles confirm our determination based on pedogenic descriptions, that soil with uniform properties and similar age is widely developed on the T2 surface, and that pedogenesis of the dated soil was initiated after abandonment of the T2 surface. We interpret the mean age of the oldest clast coat, 45.2 ± 0.5 ka, as a minimum estimate of the age of final deposition on the T2 fan surface. We infer that erosion of cobbles and exhumation of partially shielded cobbles on the T2 surface (by smoothing of primary topography, deflation, overland flow, and bioturbation) yields pavement clasts whose mean 10Be age is significantly younger than terminal fluvial deposition on the T2 landform. Thus, even in the case of late-Pleistocene landforms in arid regions, inferring accurate depositional ages of alluvial landforms by cosmogenic surface exposure dating requires consideration of the effects of post-depositional surface processes.

In combination with refined determinations of the offsets of T2 by the Mission Creek and Banning Faults (Behr et al., this meeting), we conclude that the mean slip rate on the Coachella segment of the San Andreas Fault (CSAF) since the late Pleistocene at Biskra Palms is lower than previously believed. If the Biskra Palms site records all slip on the CSAF, then our results (1) more clearly delineate a discrepancy with modern southern SAF rates inferred from geodesy, and (2) suggest that conventional analyses of slip partitioning in southern California may need to be revised.

### SCEC/UseIT: Earthquake & Disaster Preparations

*Flowers, Rosie (Rust College)*

During the summer of 2007, I received the pleasure of working with the Undergraduate Study in Earthquake Information Technology (Use IT) at SCEC where students of all different educational backgrounds learn about earthquakes world wide, such as monitoring fault lines that passes through the southern regions of California. The Use IT program allows the students to use computer technology to understand the different aspects of earthquakes. This summer's grand challenge was to create video games to educate people about earthquakes and disaster preparation. As a member of the mitigation game team, my task was to create the graphics for the game using the program Sketch-Up. There are four different levels of this game the tenant, house, neighborhood, and city. I worked on the city level. I created hospitals, police and fire stations, residential areas, nuclear power plants, and historical buildings. The graphics are very detailed and visual. My biggest challenge with using Sketch-up was that the more detailed the graphics are the slower the process was for finishing. I've now imported my work into Flash, to code and make movie clips.

## Observations from the Cajon Pass Crystalline Core, California

*Forand, David (USU) and Jim Evans (USU)*

We revisit the drilled crystalline core from the Cajon Pass, California drill hole, along the San Andreas (SAF), and Cleghorn faults, to perform a systematic structural analysis of deformation and alteration associated with strike slip faulting at the site. Previous lithologic descriptions of the core did not incorporate descriptions or interpretations of deformation processes at depth. The core and outcrop observations provide a sampling of a 4.5 km vertical column adjacent to the SAF. The shallowest level of deformation is represented by damage associated with the Cleghorn fault, which is composed of a > 100 m wide zone of brittle fractures and limited mineralization. Shallow rocks in the borehole are predominantly sandstones and augen granites, with few fault and fracture zones. Deeper in the core, gneisses, granite diorites, and granite gneisses dominate, and intense faults and fracture zones are present with epidote and potassium feldspar alterations. Damaged zones from deeper in the core have more intense potassium feldspar alteration. Fractures in the core include predominantly epidote, potassium feldspar alterations, as well as zeolites associated with fractures located throughout the core. Measurements of fracture length, thickness, and angle were taken throughout the all of the crystalline core. Fracture patterns, intensity, and fill were noted to determine where fault zones correlate with geophysical data. Several fault zones were preserved by the core, including a fully intact fault zone at 11,162 ft depth with potassium feldspar and epidote alteration. The fault zone appears to dip steeply but no evidence of slip was observed in the core. Associating all major core fracture and fault zones is of interest especially from the second phase of drilling, with previously published geophysical data that constrains fault locations within some depths of the borehole, but not the entire retrieved core. Potassium feldspar fracture fill increases in intensity in the vicinity of fault zones that are captured in the core; lack of slip direction indicators as well as slip surfaces; and inclusion of many < .5mm thick continuous semi-vertical fractures throughout the core were observed.

## The San Andreas Fault in Southern California is Almost Nowhere Vertical - Implications for Tectonics

*Fuis, Gary S. (USGS), Dan Scheirer (USGS), Vicki Langenheim (USGS), and Monica Kohler (UCLA)*

The San Andreas Fault (SAF) in southern California is in most places non-vertical, based on seismic-imaging, potential-field, earthquake-aftershock, and selected microseismicity studies of the crust. The dip on the SAF changes from SW (55-75°) near the Big Bend to NE (10-70°) southeastward of the eastern San Gabriel Mountains, describing a crude propeller shape.

A P-wave tomographic image of the mantle in southern California suggests, in cross sections across the SAF, that the plate boundary extends into the mantle with a dip similar to that of the SAF the crust. Mantle velocities southwest of this projected plate boundary, within the Pacific plate, are relatively high and constitute the well documented upper-mantle high-velocity body of the Transverse Ranges. This relationship is similar to that between the Alpine fault of New Zealand and its underlying mantle, and suggests that in both California and New Zealand, Pacific-plate lithospheric mantle is downwelling along the plate boundary.

The dip of the SAF is important for estimating shaking potential for scenario major earthquakes, and for calculating geodetic deformation.

### Detection of fault creep using PS-InSAR: the Rodgers Creek fault, northern California

*Funning, Gareth (UC Riverside), Roland Burgmann (UC Berkeley), Alessandro Ferretti (TRE Milano), and Fabrizio Novali (TRE Milano)*

A number of faults that creep interseismically have been identified in both northern and southern California. Given that some portion of the stress on such a fault is dissipated aseismically, models of the rates and extents of creep on active faults are important inputs into seismic probability estimates. Furthermore, an understanding of creep and the factors that promote it (be they friction, stress, lithology or geometry) may lead to a deeper understanding of fault mechanics.

In order to look for common factors that may allow faults to creep, it is desirable to develop a full inventory of the faults that do so. In the absence of obviously offset cultural features, creep can be difficult to detect, even with dense GPS networks. Here we demonstrate one technique that could be used to target active faults - Permanent Scatterer InSAR (PS-InSAR).

We show here a 30 image PS-InSAR dataset of the northern San Francisco Bay Area spanning the time interval 1992-2001. A good density of points is obtained across the region, despite widespread agriculture and viticulure, which do not favor conventional InSAR. A discontinuity is identified in observed surface velocities across the previously assumed locked Rodgers Creek fault, around Santa Rosa and further north. This is consistent with shallow creep at rates of up to 6 mm/yr. The creeping segments are located in areas of local transtension - a local releasing bend, and a 8 km stepover to the Maacama fault - suggesting that lowered normal stresses may play a role in allowing creep in this area.

### Paleoseismologic and Geomorphologic Analyses of the Northern Calico Fault

*Ganev, Plamen N. (USC), Kimberly Le (UNC), Austin Elliott (USC), James F. Dolan (USC), and Michael Oskin (UNC)*

The Calico-Blackwater is the longest fault system in the Mojave section of the Eastern California shear zone (ECSZ), and recent studies (Oskin et al., 2006a) indicate a long-term slip rate of 1.8±0.3 mm/yr for the Calico fault. This is the fastest slip rate among all six major faults that comprise the Mojave section of the ECSZ. The rupture history of the Calico fault, however, remains unknown. In order to better understand the spatial and temporal pattern of seismic activity on the Calico fault, we excavated paleoseismic trenches across a playa in Newberry Springs, California (~30 km east of Barstow). We also measured small-scale offsets of geomorphic features along a 10km stretch of the fault extending southward from the trench site. The trench exposures provide evidence for four latest Pleistocene-Holocene surface ruptures. Due to the absence of detrital charcoal, optically stimulated luminescence sand samples were collected to constrain the ages of these events. Preliminary evidence based on soil development suggests two latest Pleistocene surface ruptures, a latest Pleistocene or early Holocene penultimate event, and a MRE during the mid- or latest-Holocene time. These observations are consistent with geomorphic evidence from displaced alluvial surfaces cut by the Calico fault. Field observations of alluvial surfaces interpreted to be latest Pleistocene to early Holocene in age reveal only ~5.5 m of right-lateral offset of incised channels. Smaller offsets of bar-and-swale topography suggest that offset in the MRE along the northern Calico fault was only ~1.5-2 m. The occurrence of only two Holocene surface ruptures, coupled with the geomorphic evidence for only ~5.5 m of total slip during Holocene time, is in apparent conflict with the relatively rapid (1.8±0.3 mm/yr) long-term slip rate measured by Oskin et al. (2006a) over the past ~60,000 years. One possibility is that the Calico fault is in the late stages of strain-accumulation cycle (i.e. the MRE may be mid-Holocene in age). Even if a large displacement (5m?) event were to occur tomorrow, however, the Holocene slip rate for the fault would still only be on the order of ~1 mm/yr, much slower than the longer-term rate. This discrepancy may result from: (1) temporal variability in slip rate across faults within the Mojave section of the ECSZ with slip rates on the Calico fault decreasing during the Holocene; or (2) the absence of a latest Holocene rupture event on the Calico fault, with the possibility of occurrence of a near-future earthquake as part of the ongoing ECSZ seismic cluster.

### Flash Heating and Weakening of Crustal Rocks During Coseismic Fault Slip

*Goldsby, David (Brown) and Terry Tullis (Brown)*

During fault slip, rocks are heated by the dissipation of friction at transient, microscopic contacts on their surfaces. For sufficiently high slip rates, the intense, transient, so-called 'flash' heating of highly stressed contacts can yield high contact temperatures and even melting of contacts, resulting in severe degradation of contact shear strength. We have previously reported the results of an extensive series of experiments investigating flash heating/weakening phenomena for a variety of crustal rocks, including quartz rocks, feldspar rocks, granite, gabbro, and calcite marble. The experiments, employing conditions conducive to flash, but not bulk, melting (i.e., near-seismic slip velocities of up to 0.36 m/s over small slips of <4.5 cm), reveal an inverse relationship between friction and slip velocity V and slip weakening distances equal to the presumed contact size above a characteristic weakening velocity of ~0.1 m/s (for all rocks except calcite marble). Comparison of these friction data with theoretical estimates of friction as a function of slip rate and slip due to flash heating (Rice, 1999, 2006; Beeler et al., 2007), employing lab-like contact dimensions and appropriate materials parameters, yield very good agreement between theory and experiment, and suggests extrapolated values of the friction coefficient of 0.2 or less at seismic slip rates. The strong velocity dependence and nearly instantaneous healing with decreasing slip rate associated with flash weakening would be conducive to slip pulses during seismic slip.

Here we report the results of new tests on quartz rocks (novaculite) that have higher initial surface roughness than samples tested previously. Contrary to expectations, friction tests on these rougher samples, which presumably have larger contacts and therefore should obtain higher contact temperatures (and therefore lower friction) for a given slip rate, reveal no weakening at high slip rates up to 0.36 m/s. Previous and new experiments conducted at the same conditions on smoother novaculite samples and smoother, more wear-resistant quartzite specimens, respectively, reveal extraordinary weakening consistent with flash heating. The stark contrast in frictional behavior of the rough and smooth samples may result from differences in the amount of generated gouge. For the rougher samples, the increased degree of interlocking of asperities on the slip surface results in a wider generated gouge zone due to shearing off and grinding up of asperities. If such a gouge layer undergoes uniform shear during slip, then the contact-scale slip velocity is less than the far field slip velocity by a factor N, the number of gouge particles across the thickness of the gouge layer; equivalently, the apparent weakening velocity for flash weakening is increased by a factor N. Estimation of the apparent weakening velocity for flash weakening during uniform shear of modest gouge thicknesses (<1 mm) with lab-like contact dimensions suggests values of the apparent weakening velocity greater than seismic slip velocities, i.e., >1 m/s. Our experimental results suggest that whether significant dynamic weakening due to flash heating or melting occurs during earthquakes depends critically on the contact size and the degree of slip localization on faults.

### Widespread Triggering of Non-Volcanic Tremor in California

*Gomberg, Joan (USGS), Justin Rubinstein (U Washington), Zhigang Peng (Georgia Tech), Ken Creager (U Washington), and John Vidale (U Washington)*

Recognition of non-volcanic tremor has stimulated much excitement in the Earth sciences community. All but one of the many observations have come from subduction zones and most explanatory models appeal to conditions expected in such environments. We identify widespread triggering of non-volcanic tremor along the transform plate boundary in California, implying that tremor and the conditions required to generate it must exist in many tectonic environments. We find no correlation between ambient fault slip behavior and where tremor occurs and a paucity of tremor [relative to triggered earthquakes] in geothermal areas, contrary to models appealing to fluids, high temperatures and pressures.

### Preliminary Sample Collection and Methodology for Constraining Age of Precariously Balanced Rocks (PBR)

*Grant Ludwig, Lisa (UCI), Katherine Kendrick (USGS), Lesley Perg (UMN), James Brune (UNR), Matt Purvance (UNR), Rasool Anooshehpoor (UNR), Sinan Akciz (UCI), and Debbie Weiser (Occidental/SCEC Intern)*

Paleoseismic data, in the form of precariously balanced rocks (PBRs), provide validation of ground motions on the time scale necessary to evaluate CyberShake results and constrain National Seismic Hazard

Maps. Investigation by Bell et al. (1998) suggests that PBR shapes and stability have not changed significantly over the last 10,000 years. If true, locations of PBRs constrain the level of ground motions during the Holocene. This important finding warrants investigation by dating additional PBRs. Selection of the most appropriate PBRs for analysis is critical for success. Our goal for 2007 is to identify and date PBRs with the simplest history, greatest significance for validating ground motion, and greatest chance of yielding interpretable age results. In 2006 we identified the most promising PBR sites. In summer 2007 we sampled 4 different PBRs to develop constraints on the length of time they have been precariously balanced, and an understanding of how they became precarious. We sampled three rocks near Perris and one rock near Benton Road. These rocks constrain ground motions from earthquakes on the San Jacinto and Elsinore faults (Brune et al., 2006). Two of the Perris rocks were toppled in conjunction with our sampling to measure their stability (see Purvance et al., 2007). Our sampling strategy was to collect 5-6 samples per PBR: 1 on top, 3 on the sides, 1 on the pedestal, and 1 on the ground surface. The samples will be analyzed for cosmogenic nuclides, with initial efforts focused on the Benton Road PBR and the toppled "Perris3" PBR judged to have the most post exposure modification. We will develop a model of their temporal evolution within the context of landscape exhumation and erosion, lateral erosion and ground motion. Interpretation of dates will be complex. It will be important to date soils for cross-checking of ages. Where permitted, excavations will be made to describe the degree of soil development on the landscape adjacent to the PBR sites. Soils will be described and sampled according to established criteria (Soil Survey Staff, 1951, 1999; Birkeland, 1999). Characterization of soils will allow determination of periods of stability and sedimentation within the adjacent landscape. Degree of soil development will be compared to soil chronosequences in San Timoteo badlands, Anza, and Cajon Pass to provide estimate of soil age. Soils were described in a small, open basin downslope of Perris3 PBR. Degree of soil development was very minimal, suggesting young deposition (less than ~ 5 ka). This site is an open basin, and therefore not ideal to evaluate soil age, but the implication is that erosion of the outcrops has been ongoing. Soils will be described on the broad surface west of Perris PBR sites to provide minimum ages for the duration of the stability of this surface, and establish timing of initial erosion and exhumation of the PBRs. Additional sampling will help to constrain timing of exhumation of Van Buren and Benton Road PBRs. In both places, the PBR is part of an extremely old landscape, with minimal additional deposition.

### Broadband Ground Motion Simulations for ShakeOut

*Graves, Robert (URS), Brad Aagaard (USGS), and Ken Hudnut (USGS)*

The Great Southern California ShakeOut is a NEHRP coordinated, multi-hazard response exercise based on a Mw 7.8 rupture scenario of the southern San Andreas fault. The scenario event begins at Bombay Beach and ruptures 305 km northward through both the Coachella and Mojave segments, finally terminating at Lake Hughes. The slip distribution is derived by combining a slip-predictable model at long length-scales (> 30 km) with a stochastic model at short length-scales. Other features of the rupture model include: (1) rise times that depend on the local slip, (2) an average rupture speed of 85% of the local shear wave speed with local perturbations correlating with slip, (3) tapering of slip at the bottom of the rupture, and (4) increased rise times and reduced ruptures speed at the top and bottom of the rupture. Using this full kinematic description of the scenario rupture, we then compute broadband ground motions using the hybrid procedure of Graves and Pitarka (2004). Low frequency (f < 1 Hz) motions are calculated using a 3D visco-elastic, finite-difference algorithm with the 3D velocity structure derived from the SCEC CVM (v4.0). Over 2 billion grid nodes are required to represent this model and the calculation was performed at USC's center for High Performance Computing and Communication (HPCC). From the low frequency calculation, ground motions are saved on a 2 km grid (25,000 sites), and then for each of these sites, high frequency (f > 1 Hz) ground motions are calculated and summed with the low frequency response to produce broadband (0-10 Hz) time histories. Finally, site-specific non-linear amplification functions are applied to these ground motions to account for local soil properties (via Vs30).

The ground motion simulations predict near fault PGA and PGV values generally ranging from 0.5 to 1.0 g and 100 to 250 cm/s, respectively. The largest near fault motions tend to correlate with large fault slip, although the ground velocities are also strongly influenced by rupture directivity. Purvance et al (this meeting) find that these simulated motions are generally consistent with ground motion constraints inferred from precarious balanced rocks. For the southern hypocenter assumed in this scenario, low frequency energy is efficiently channeled into the Los Angeles region along the string of basins (San Bernardino, Chino, San Gabriel, Los Angeles) lying south of the San Gabriel Mountains. This combination of rupture directivity and basin response produces a significant amplification of low frequency motions throughout the Los Angeles region, and has been identified in previous 3D San Andreas earthquake simulations (e.g., TeraShake). The great density of broadband time histories produced in this simulation facilitates the generation of ground motion maps and wave field animations. These products are useful for scientific investigation (e.g., animations clearly demonstrate the coupling of directivity and basin response), as well as providing ground motion inputs that can be used for studies of damage potential and loss estimates.

### CyberShake 2007: An Update on Physics Based Probabilistic Seismic Hazard Calculations

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Deterministic source and wave propagation effects such as rupture directivity and basin response can have a significant impact on near-fault ground motion levels, particularly at longer shaking periods (> 1 sec). In most cases, these effects are not explicitly included in empirical ground motion models (other than through increased uncertainty), or they are included using averaged response terms, thus potentially diminishing their effectiveness in certain applications. CyberShake, as part of the PetaSHA Project, addresses this issue by developing hazard curves using 3D ground motion simulations rather than attenuation relationships. To calculate a waveform-based probabilistic hazard curve for a site of interest, we begin with the NSHMP-2002 ERF and identify all ruptures (excluding background seismicity) within 200 km of the site of interest. We convert the NSHMP-2002 rupture definition into multiple rupture variations with differing hypocenter location and slip distribution, which results in about 100,000 rupture variations per site. Strain Green Tensors are calculated for the site using the SCEC CVM (v4.0), and then, using reciprocity, we calculate synthetic seismograms for each rupture variation. Peak intensity measures (e.g., spectral acceleration) are then extracted from these synthetics and combined with the original rupture probabilities to produce probabilistic seismic hazard curves for the site. Recent improvements include (1) development of a parallel CVM mesh generator, (2) implementation of an efficient 3D visco-elastic finite difference algorithm, (3) efficient storage and retrieval of SGTs, (4) implementation of an efficient earthquake simulation code, and (5) development of an optimized and efficient workflow system. Thus far, we have produced hazard curves for spectral acceleration at a suite of periods ranging from 3 to 10 seconds at about 10 sites in the Los Angeles region. At low ground motion (high probability) levels, there is little difference between the CyberShake curves and attenuation relationship-based curves. For probabilities of more practical concern (e.g., 2% in 50 years), the methodologies produce similar results at some sites (e.g., Pasadena), but noticeably different results at others (e.g., USC, Whittier-Narrows). Our preliminary analysis suggests the increased ground motion levels generated in the CyberShake simulations result from rupture directivity and basin response effects. We are also using the CyberShake simulations to investigate the sensitivity in hazard level related to variations in the prescribed velocity and Q structure. For example, increasing Q values by a factor of 3 increases the computed hazard at USC by a factor of 20% at 3 second SA, 15% at 5 second SA and 2% at 10 second SA. However, (although not surprisingly) this change in Q has virtually no effect on sites outside the deep basins (e.g. Pasadena). These types of sensitivity analyses will be used to guide the future activities of the CyberShake program.

### Microseismicity of the Malibu Coast and Santa Monica-Dume Fault Zones

*Green, Joe (CSUN) and Gerry Simila (CSUN)*

The Santa Monica Mountains, in the western Transverse Ranges, are separated from Los Angeles and offshore Santa Monica sedimentary basins by the E-W, now predominantly left-lateral Raymond-Hollywood-Santa Monica-Dume fault system (Dolan et al., 2000). The western ~80 km-long stretch of this fault system has been investigated by Sorlien et al. (2006) using seismic reflection and earthquake data. The fault system is primarily left-lateral with a strain accumulation rate of 2.4 ± 1.1 mm/yr, based on GPS data (Meade and Hager, 2005). Thrust slip on a low-angle blind fault beneath the Santa Monica-Dume fault is proposed to account for the Santa Monica Anticlinorium (Dolan et al., 1995). The onshore Malibu Coast fault (MCF) and the onshore Santa Monica fault are probably oblique left-reverse faults (Dolan et al., 2000). The Malibu Coast fault shows evidence of reverse-oblique slip with a left-lateral strike-slip component along north-dipping strands ranging from 30-70 degrees (Cronin and Sverdrup, 1998). The convergence rate across the Malibu Coast fault is estimated to be about 18 mm/yr (Huftile and Yeats, 1995), and the

slip rate is estimated to be between 0.04 to 1.5 mm/yr (Dolan et al., 1995). Convergence is evident in focal mechanisms showing mostly compressional mechanisms, and some with strike-slip motion. Although Holocene surface displacements have been officially recognized across only two strands of the Malibu Coast fault zone to date, the Malibu Coast fault is still considered active and capable of producing a magnitude 6.5 to 7.0 earthquake. The seismicity (1996-present; M=1-3, 200 events) for the region has been relocated using Hypoinverse and the SCEC/LARSEII crustal velocity structure. In addition, three field RefTeks (UCSB PBIC) were installed in the Santa Monica mountains at (Pepperdine University, Charmlee Park, Westlake) to provide additional constraints on the location and focal mechanism solutions. The results show seismicity (map view and cross-sections) associated with the Malibu Coast, Santa Monica - Dume, and scattered events in the eastern region of the Santa Monica mountains. The focal mechanisms are primarily reverse with various components of strike-slip.

### Accelerating Moment Release in Areas of High Stress? Preliminary Results

*Guilhem, Aurelie (UC Berkeley), Roland Burgmann (UC Berkeley), Andrew M. Freed (Purdue University), and Tabrez Ali (Purdue University)*

Several retrospective analyses have proposed that significant increases in moment release occurred prior to many large California earthquakes of recent time. However, the finding of accelerating moment release (AMR) strongly depends on the choice of several parameters (magnitude range, area being considered surrounding the events, time period prior to large earthquake) and the AMR analysis may appear as a data-fitting exercise with no new predictive power. As AMR may relate to a state of high stress around the eventual next epicenter, it is interesting to compare the AMR results to models of stress accumulation in California. Instead of assuming a complete stress drop on all surrounding fault segments implied by the back-slip stress lobe method of Bowman and King (1992), we consider that stress evolves dynamically, punctuated by the occurrence of earthquakes and governed by the elastic and viscous properties of the lithosphere (e.g., Freed et al., 2007). We study the seismicity of California obtained from the ANSS catalog between 32N and 40N since 1911 and extract events for AMR calculations following the systematic approach employed in previous studies. To quantify the AMR, we examine the ratio (c-value) between the root mean square of a power-law time-to-failure function versus a linear fit to the cumulative energy of events. Using Nutcracker, a stress and seismicity analysis software (geology.fullerton.edu/dbowman/Site/Downloads.html), we generate several sensitivity tests of the method, as well as a first grid-search analysis for a few large events in Southern California (Kern County, Landers and Loma Prieta). With the same optimized AMR parameters as Bowman, the grid search results show that the regions surrounding the earthquakes have the smallest c-value. That may be interpreted as a positive result for the AMR analysis. However the AMR parameters are first chosen in order to get the smallest c-value at the epicenter of each particular event and they are different for each earthquake. We also present here a more general AMR analysis from 1955 to today with a fixed magnitude range, radius of area and period of time. We compare these results to the occurrence of large events in time and to maps of Coulomb stress changes due to all M>7.0 earthquakes since 1812, subsequent postseismic relaxation and interseismic strain accumulation. The goal of this comparison is to evaluate if areas inferred to be highly stressed also exhibit significant evidence of accelerating seismicity.

### U.S. National Center for Engineering Strong Motion Data

**Haddadi, Hamid (CGS), Moh Huang (CGS), William Leith (USGS), John Parrish (CGS),** *William Savage (USGS), Anthony Shakal (CGS), and Christopher Stephens (USGS)*

The U.S. Geological Survey (USGS) and the California Geological Survey (CGS) have established a cooperative U.S. National Center for Engineering Strong Motion Data (NCESMD), which will have mirrored operational centers in Sacramento and Menlo Park, CA. The National Center integrates earthquake strong-motion data from the CGS California Strong Motion Instrumentation Program, the USGS National Strong Motion Project, and the Advanced National Seismic System (ANSS), thus serving as a provider of uniformly processed strong-motion data for seismic engineering applications. The NCESMD builds on the Engineering Data Center of the California Integrated Seismic Network, and so will continue to serve the California region while expanding to serve other ANSS regions. The National Center will assimilate the Virtual Data Center, which was developed at U.C. Santa Barbara with support from the Consortium of Strong Motion Observation System (COSMOS), NSF and SCEC. A Center Management Group with an external Advisory Committee manages the NCESMD. Products will be generated by both CGS and USGS facilities, thus ensuring robustness. Each ANSS region is responsible facilities, thus ensuring robustness. Each ANSS region is responsible and credited for the data recorded by its regional network. The National Center is co-hosted by CGS and USGS at www.strongmotioncenter.org.

### SCEC/UseIT: Technology, Serious Games & Earthquake Mitigation

*Hairston, Jennifer (Wilberforce University)*

The SCEC/Undergraduate Studies in Earthquake Information Technology program (SCEC/UseIT) connects undergraduate students to work in a team-oriented research setting on a summer project. Some of the main goals for UseIT are to allow undergraduates to use technology to solve important problems in earthquake science, and teach students to succeed in a collaborative, multidisciplinary workplace setting in and out of research arenas. This summer's Grand Challenge was to prototype serious games. I worked on a serious game that focused on mitigation. The purpose of the game was to minimize damage and educate the player about the importance of seismic mitigation. The game is separated into four levels; tenant, house, neighborhood, and city. At the beginning of the game, which is the tenant level, the player is asked to select items in the apartment that he/she could secure in case of an earthquake occurs. Based on how well the player prepares, he/she may advance to the next level. With each advance in levels, the player is given more responsibility and options for securing space, strengthening structures, and educating citizens. After we designed our game we used Adobe Flash CS3 Professional to prototype it. This is an object oriented programming language which easily allows a programmer to create movies and show interactive images, without being an expert programmer. My duties were to program the city and house level.

### *SCEC/SURE: Investigations of the Superstition Hills Fault*

*Hanna, Alexander (CSUN and UCR), Elizabeth Cochran (UCR), Joan Gomberg (USGS), and Jennifer Stevens (UCR)*

My main objective during this internship was to search locally recorded seismic data for micro-earthquakes and tremor on the Superstition Hills Fault, California. I first spent a few weeks gaining familiarity with the mapping and seismic analysis software packages Generic Mapping Tools (GMT), Antelope, and Seismic Analysis Code (SAC). I then created an Antelope database of seismic data collected during an on-going temporary deployment of seven Portable Broadband Instrument Center (PBIC) stations along the Superstition Hills Fault. After analyzing this data I have identified ~250 events which were not in the SCEC or ANSS catalogs, but most have P-S wave times of 3-6 seconds indicating they are too far away to be on the Superstition Hills Fault. Only ~5 of these events had the appropriate P-S wave times to be on the Superstition Hills Fault, and only ~10 tremor-like events were identified. The Superstition Hills Fault does not appear to be a highly seismogenic fault, but it is possible that future analysis of the data in this on-going project will find enough micro-earthquake and tremor events to find a meaningful correlation between the two.

### Crustal and Upper-Mantle Structure of the Red Sea: a comparison to the Gulf of California

*Hansen, Samantha (UCSC), Susan Schwartz (UCSC), Arthur Rodgers (LLNL), James Gaherty (LDEO), and Abdullah Al-Amri (King Saud University)*

We have used a variety of techniques to investigate the crustal and upper-mantle seismic structure of the Red Sea. While not directly affiliated with SCEC, these results may provide useful information to those investigating the similar environment in the Gulf of California. Most of the data used to examine the Red Sea and Arabian Peninsula were recorded by the Saudi Arabian National Digital Seismic Network (SANDSN), but additional data were taken from the 1995-1997 Saudi Arabian IRIS-PASSCAL Deployment as well as from stations in Jordan and the UAE. Teleseismic P- and S-wave receiver functions reveal thicker crust in the Arabian Platform (40-45 km) and the interior of the Arabian Shield (35-40 km) and thinner crust along the Red Sea coast. S-wave receiver functions also provide constraints on the lithospheric thickness and reveal very thin lithosphere (40-80 km) along the Red Sea coast, which thickens rapidly toward the interior of the Arabian Shield (100-120 km). A step of 20-40 km in lithospheric thickness is also observed at the Shield-Platform boundary. Constraints on the upper mantle velocity and anisotropy have been obtained by jointly inverting the S-wave receiver function constraints with frequency dependent surface wave phase delays. The results demonstrate that the thin lithospheric lid is underlain by a pronounced low-velocity zone, with shear velocities as low as 4.1 km/s extending to a depth of 200-250 km, and that anisotropy is required in both the lithosphere and asthenosphere. Forward models, which are constructed from previously determined shear-wave splitting estimates, can reconcile surface and body wave observations of anisotropy. The low shear velocities extend to much greater depth than those observed in other continental rift environments, such as the Gulf of California. The depth extent of these low velocities combined with the sharp velocity contrast across the LAB may indicate the influence of the Afar hotspot and the presence of partial melt beneath Arabia. The anisotropic signature primarily reflects a combination of plate- and density-driven flow associated with active rifting processes in the Red Sea.

## Smooth, Mature Faults Radiate More Energy than Rough, Immature Faults in Parkfield, CA

*Harrington, Rebecca M. (UCLA) and Emily E. Brodsky (UCSC)*

Laser-based observations of fault surfaces indicate that cumulative slip is inversely related to fault roughness in the direction of slip, suggesting that older, more mature faults are smoother than younger ones with less cumulative slip (Sagy, et al., 2006). Given a difference in roughness between old and young fault surfaces, it is conceivable that earthquakes on older, smoother faults might radiate different amounts of seismic energy than earthquakes of comparable size on younger, rougher faults. Radiated seismic energy is the only directly observable parameter in the partitioning of earthquake energy, and the ratio of radiated energy to moment provides information about rupture velocity. If fault roughness affects radiated energy, then such geological observations could also provide information about rupture propagation.

We compare spectral shapes of earthquakes on old and young faults in the Parkfield area to observe if differences in roughness affect radiated energy. We use earthquakes of comparable magnitude below M 3.7, and assume that secondary faults have less cumulative displacement than the San Andreas Fault. The spectra of earthquakes on secondary faults have high-frequency bands depleted in amplitude relative to earthquakes on the San Andreas Fault. Additionally, the cumulative spectral energy based on these spectra give higher values of radiated energy to moment ratios for the earthquakes on the San Andreas Fault. This suggests that mature, i.e. smoother faults are more efficient radiators of seismic energy. Furthermore, differences in observed energy/moment ratios between earthquakes on faults of different cumulative displacement might be reflected by differences in fault-surface roughness.

## Experimental investigation of frictional properties of granite at seismic slip rates

*Hartsig, Colleen (UCSD), Kevin Brown (SIO), and Yuri Fialko (SIO)*

Recent experimental studies show that rock friction undergoes a substantial evolution at slip rates of the order of centimeters per second and higher. A rapid decrease in the coefficient has been interpreted in terms of a number of mechanisms, including macro- and microscopic melting and formation of new amorphous phases such as silica gel. Existing experimental data covers a range of shear velocities from less than a millimeter per second up to several tens of centimeters per second. We conducted a new series of measurements of the dynamic coefficient of friction of granite at slip rates ranging from 0.1 to 3 m/s (i.e., well within the seismic range), and at normal stresses between 0.5 and 1.5 MPa. Experiments were carried out on a rotary shear machine. We used ring samples with outer-to-inner radii ratio of 1.5 to minimize variations in slip rate across the sample interface. Efforts were made to restrict gouge ejection from the shear zone in order to maintain the effective contact area.

Our results reveal the dynamic coefficient of friction between 0.3-0.4, broadly consistent with the previously reported results (Goldsby and Tullis, Hirose and Shimamoto). However, we do not observe a monotonic drop in frictional strength with slip velocity, suggested by previous studies. Our results indicate that the coefficient of friction is nearly constant in the velocity interval between ~20 cm/s - 1 m/s. At higher slip rates, friction drops to as low as 0.1-0.2 (in experimental runs that did not produce melting). Therefore the data appear to indicate at least two major weakening phases. The non-monotonic weakening may result from complex thermo-mechanical processes within the gouge layer. Alternatively, it may be due to different homologous temperatures of the two dominant mineral phases in the granitic samples (feldspares and quartz), such that one phase weakens before the other. We are planning an additional series of experiments on samples made of gabbro to discriminate between these models. New experimental data suggest that the evolution of friction during seismic slip is likely complex, and a better theoretical understanding of the underlying physics is warranted.

### Available 3-D Crustal Travel-time Velocity Models for Southern California: How do They Compare and What are the Standard Errors?

*Hauksson, Egill (Caltech)*

Two 3-D crustal velocity models of southern California have been determined from local earthquake data (Hauksson, 2000; Lin et al., 2007). Both models use the same inversion code (SIMULPS from Thurber, 1993) and travel time picks from the Southern California Seismic Network. However, the methodology differs in detail because different starting models, iteration approach, data selection were used. The Hauksson (2000) starting model was similar to the standard southern California 1D layered model with a near-surface low velocity later, while the Lin et al. (2007) starting 1D model is a continuous gradient model. The Hauksson (2000) model used a coarse grid inversion first, followed by an interpolation to a more detailed gird and repeat of the inversion. The Lin et al. (2007) model used only the detailed grid but uses more of the travel time data by forming composite events. We have added the velocity structure of the basins to these models, which was determined independently by Shaw et al. (2007), and repeated the inversions using the travel-time data set from Hauksson (2000). By adding three new iterations, with and without the near surface basins, we obtain four additional models. We use all six models to determine an independent standard error estimate, which is usually underestimated in damped least squares inversions. We also compare the 1D profiles of these models as well as reduction in weighted root-mean-square (rms), and the reduction in norm of the model and data. The 3D patterns in these models are similar where the models are well resolved. They differ significantly along the edges, where the model resolution is poor.

### A general method for calculating gravity changes in complex fault networks

*Hayes, Tyler (UWO), Kristy Tiampo (UWO), and John Rundle (UC Davis)*

The gravity signal contains information regarding changes in density at all depths and we suggest it can be used as a proxy for strain accumulation in complex fault networks. Within stike slip systems, such as the San Andreas Fault (SAF) network, our model shows that the dilatational gravity signal highs are coincident with subsequently faulting segments when modeling the Joshua Tree-Landers-Hector Mine sequence. In addition, the dilatational gravity signals are within in the range of portable instrumentation; dip slip system yield even higher values. The method is easily applied to complex fault geometries with mixed type faulting mechanisms.

### Slip localization within a complex fault-zone: The Pretorius fault, Tautona mine, South Africa (NELSAM project)

*Heesakkers, Vincent (U of Oklahoma), David Lockner (USGS), and Ze'ev Reches (U of Oklahoma)*

We analyze the reactivation mechanism of the Pretorius fault, TauTona mine, South Africa. The analysis is based on our mapping of the fault-zone structure, the observations of the rupture zone associated with an m2.2 earthquake, and rock mechanics testing of fault rocks and host rocks. The slip localization mechanisms of the earthquake were modeled with the finite element method.

The Pretorius fault is a 10 km long Archean fault with a right-lateral displacement about 200 m and vertical displacement of 30-60 m. Its complex fault-zone is 25-30 m wide and composed of tens of anastomosing segments, containing a massive, well-cemented cataclasite. We mapped the rupture zone of the m2.2 earthquake of December 12, 2004, which is in mining tunnels exposed for at least 25 m horizontally and 5 m vertically at depth of 3.6 km. The rupture reactivated four main, quasi-planar, crosscutting segments within the Pretorius fault-zone, and generated 1-5 zones (each 0.5-1.0 mm thick) of fresh fine-grained rock-powder. The rock-powder formed predominantly along the contacts of the quartzitic host rock and the ancient massive cataclasite, indicating slip localization. Displaced rock bolds displayed dextral-normal slip with maximum displacement of 2.5 cm during the earthquake slip.

We conducted rock mechanics experiments on samples of the fault-rock (quartzitic cataclasite) and host rock (quartzite) that were collected from boreholes drilled across the fault zone. The elastic properties of the host quartzite (E = 81 GPa, nu = 0.17) are similar to those of the cataclasite (E = 71 GPa, nu = 0.15), but the former is twice as strong as the later (Uniaxial strength of 200 MPa vs 100 MPa). On the other hand, the host quartzite is severely damaged and it shows significant strain hardening with inelastic deformation starting at ~25 % of the total axial strain. The cataclasite is undamaged, with only minor inelastic deformation occurring at 85% of the axial strain. We thus regard the host quartzite as brittle-plastic and the cataclasite as brittle-elastic.

We developed a 2D finite element model in which an elliptical inclusion composed of cataclasite-like rock is embedded within a quartzite-like medium; we used the elastic and plastic properties determined in the experiments. The model shows an abrupt increase of the shear stress at the contact between the inclusion and the medium. The plastic shear strain shows a similar trend, suggesting that the shear stress gradient is a result of the plastic behavior of the medium. It is proposed that the mechanical contrast between the plasticity of the damaged host quartzite and the brittle cataclasite results in steep shear stress gradient across the contact that leads to slip localization.

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### Incorporation of all SCIGN GPS sites into PBO processing

*Herring, Thomas (MIT), Robert King (MIT), Simon McClusky (MIT), and Nancy King (USGS)*

The Plate Boundary Observatory (PBO) includes about 200 GPS sites that were established across the Pacific North America plate boundary before the start of the deployment of new PBO stations in January 2004. Of these existing sites in PBO, only 125 of the 250 Southern California Integrated GPS Network (SCIGN) GPS sites were included. The data from the 125 SCIGN sites not included in PBO are processed with the same techniques and on the same timetable by the US Geological Survey (USGS) and these additional sites are now being included into the routine PBO processing. In this poster, we show results from the merger of the USGS rapid (latency of 24 hours) and USGS final (latency 2-3 weeks) processing into the standard PBO processing. The rapid processing by both USGS and PBO analysis centers uses IGS rapid GPS orbits while the final processing uses IGS final orbits. In the PBO processing scheme, there is a supplemental processing step that is used in to include data from stations with long latencies on data retrieval and the USGS products will be incorporated into older PBO products when these supplemental analyzes are performed. Ultimately, during the next year, all PBO and USGS products will be re-generated when the IGS releases updated orbits and clocks files that are generated with absolute GPS phase models. With this reprocessing, all the SCIGN GPS sites will be processed in a PBO consistent North America reference frame.

### SCEC/SURE: Basin Data Collection for Post-Fire Debris Flow Analysis for Southern California

*Hiller, James (Diablo Valley College/SCEC/USGS Landslides Hazards Team)*

The USGS Landslide Hazards Team is tasked with identifying the conditions that can lead to debris flows from recently burned basins in southern California. A database of information on rainfall, basin conditions and storm response was compiled for this analysis from a variety of sources, including rain gages, field studies, digital elevation models (DEMs), burn severity mapping and soil databases. One of the challenges of this project was identifying the best source of data to quantify the morphologic condition of the study basins. ARCGis was the main program used to gather this information, however it could not provide use with all of the data we needed. For this project, we explored the use of three supplemental programs that provide different measures of gradient distributions within a basin and of drainage structure to identify the most useful suite of potential variables and to assess relative ease of use. We evaluated the public domain databases of StreamStats and EDNA (Elevation Derivatives for National Applications) and the privately-marketed Rivertools. Streamstats is a web based program that can provide measures of basin area, gradient, drainage area, rock type, available water content, and many other useful basin and stream flow characteristics derived from 30-m DEMs. Unfortunately, the data is not presently complete for the state of California. Test maps were created evaluate the practical application of Streamstats. The program was easy to access and the information gathered was useful. However the basin delineation tool was imprecise and hard to manually edit. This caused problems with the accuracy of the data because the outlines of the delineated basins did not match those needed. EDNA also provides access to similar hydrologic and slope data, and can be based on either a 10-m or 30-m DEM. EDNA was very difficult to use and navigate. It took a long time to figure out how, but eventually maps were created. Unfortunately there was no way to gather any values from them without approval to access internal files by the administrators of the program. Overall, this process was slow and did not turn out desirable results. Rivertools is used to identify watersheds and drainage pathways within basins. Importing a DEM is very easy and any resolution can be imported, once done there is a plethora of information available, including different measures of area, slope, drainage density, and bifurcation ratio. Due to its ease of use and the variety of available information, I believe Rivertools is a good resource for data compilation for this study. By using both ARCGis and Rivertools we were able to successfully create a complete database that can be used for analyzing debris flow hazards in the southern California area.

### Scaling Relations of Strike Slip Earthquakes With Different Slip Rate Dependent Properties at Depth

*Hillers, Gregor (UCSB) and Steve Wesnousky (UNR)*

Empirical observations suggest that earthquake stress drop is generally constant. To investigate the effect of rupture width on earthquake scaling relations, we analyze synthetic seismicity produced by a 3D vertical strike slip fault model using two different profiles of frictional slip rate behavior below the seismogenic zone. Within the rate-and-state framework, a relatively abrupt transition of the a-b profile from velocity weakening to strengthening at the base of the seismogenic crust produces increasing slip and stress drop with increasing event size. Choosing a smoother transition allows large earthquakes to propagate deeper, leading to similar slip-length scaling but constant stress drop scaling. Our numerical experiments show that a downward continuation of large events explains the observed constant stress drop scaling. The results thus support the idea that the maintenance of constant stress drop across the entire range of observed earthquake magnitudes may be achieved by allowing coseismic slip to rupture to depths below the seismogenic layer.

### SCEC/SURE: Collaborative Effort to Constrain Slip Along Southern San Andreas Fault and Digitize Active Faults of Pakistan

*Hinojosa, Jessica (Stanford), Kandace Kelley (Purdue), Nick Rousseau (CSUN), and Doug Yule (CSUN)*

This joint SCEC/SURE, CSUN Catalyst Program internship is a collaborative effort to: a) provide a reconstruction of beheaded canyons to constrain offset across the San Andreas fault at Biskra Palms near Indio, CA, and b) digitize the active fault map of Pakistan to present to the Geological Survey of Pakistan. Our methods for the Biskra Palms project include visiting trenches in the area of study, analyzing LiDAR data, and creating multiple, possible alignments of the canyons in order to find the best fit. With our work with digitizing the Pakistan fault maps, our methods involve using GIS ArcMap to turn hard copy maps into digital images. The largest implication of the work is support for a revised reconstruction of an alluvial fan previously assessed by van der Woerd et. al., 2006. The result of digitizing the Pakistan faults is an initial step toward seismic hazard analysis in Pakistan.

My research this summer developed my ability to successfully use ArcGIS and other computer programs (list here...) to interpret geomorphic evidence to both reconstruct offset canyons across the San Andreas fault near Indio, CA and to digitize active fault maps in Pakistan. The hands-on approach of research helped to deepen my understanding of paleoseismology, structural geology, and active faulting.

### Bridging The Deformation Spectrum: The PBO Borehole Strainmeter Network

*Hodgkinson, Kathleen, D. Brent Henderson, Greg Anderson, David Mencin, James Matykiewicz, Jim Wright, Wade Johnson, Tim Dittman, PBO Data Management/IT Group, and Mike Jackson (UNAVCO)*

UNAVCO will install 103 borehole strainmeters along the western US Plate Boundary as part of the Plate Boundary Observatory (PBO), the geodetic component of the Earthscope program. Borehole strainmeters are ideal for capturing strain transients that occur in periods of hours to weeks, hence they are being installed in arrays in regions where they may record deformation that lies between the spectral coverage of seismometers and GPS. As of August 2007, UNAVCO has installed 39 borehole strainmeters from Vancouver Island in British Columbia to Anza in southern California. The first volcanic strainmeter array was installed in July 2007 on Mt St Helens. So far, the strainmeter network in the Olympic Peninsula has recorded strain transients associated with the 2005 and 2007 Cascadia events.

PBO strainmeter sites are multi-instrumented sites. All but one borehole contains a Malin seismometer, 18 holes have pore pressure sensors and several are co-located with GPS sites. All installations include meteorological instrumentation. The Anza boreholes also have accelerometers. The strainmeters collect data at 20-sps, 1-sps and 10-minute intervals. The data are archived at the NCEDC and the IRIS DMC in SEED and native data logger formats. The SEED data are available from the archives within minutes of being downloaded from the loggers. Processed data sets, produced by UNAVCO's Borehole Strainmeter Analysis Center are updated every 10 days and are available from the NCEDC and IRIS DMC in XML format. Users may also download raw strainmeter data via interactive plotting tools on the PBO web site or use SQUID, a GUI tool developed by PBO, to generate processed strainmeter data. A complete list of all strainmeter data products including metadata, borehole drawings and maintenance records is available at http://pboweb.unavco.org/strain_data.

### Why BASS instead of ETAS

*Holliday, J.R. (UCD), J. Van Aalsburg, D.L. Turcotte, and J.B.Rundle*

The epidemic type aftershock sequence (ETAS) model has been widely used to model the statistics of seismicity. We have proposed the branching aftershock sequence (BASS) model as an alternative to ETAS (Turcotte et al., GRL 34, 12303, 2007). BASS utilizes the modified form of Bath's law as an additional constraint on the ETAS formulation. This constraint eliminates one of the free parameters in ETAS. BASS is a fully self-similar distribution of aftershocks independent of the mainshock magnitude and imposed cutoffs on very large and very small aftershocks. Results presented will include:
(1) The statistical variability of the largest aftershock
(2) The statistics of foreshock occurrence
(3) The statistical relationship of aftershocks to other earthquakes.

### California's Largest Historical Earthquake?

*Hough, Susan E. (USGS Pasadena)*

The 26 March 1872 Owens Valley earthquake is among the largest earthquake that has occurred in California during historical times. The felt extent and maximum fault displacement have long been regarded as comparable to, if not greater than, those of the great San Andreas fault earthquakes of 1857 and 1906, but mapped surface ruptures of the latter two events were 2-3 times longer than that of the mapped 1872 rupture. The official USGS/NEIC magnitude is listed as 7.4, consistent with expectations given a ~100-km rupture length. Reinterpreting accounts of the Owens Valley earthquake, I infer generally lower intensity values than those estimated in earlier studies. Nonetheless, as recognized in the early 20th century, the earthquake caused more dramatic effects at regional distances than the 1906 San Francisco earthquake. Even interpreted conservatively, the macroseismic observations imply a magnitude of 7.7-7.9, a range that is consistent with the geological observations given their uncertainties. I estimate a preferred Mw value of 7.8 for the earthquake, based in part on a comparative analysis of macroseismic effects of the event with those of the 1906 earthquake. I further show that, while macroseismic observations from the 1906 earthquake are consistent with ground motions predicted by the new NGA relations, the documented macroseismic effects during the Owens Valley earthquake appear to be at odds with predictions, even assuming a larger magnitude. Regardless of the magnitude of the Owens Valley earthquake, these observations thus lend support to concerns that the NGA relations might be derived from earthquakes that do not represent the full range of earthquake sources (i.e., high- versus low-stress drop events) and/or propagation effects that can occur in California.

Additionally, I consider the predicted static stress change of the Owens Valley earthquake and explore whether regional seismicity patterns before and after 1872 are consistent with expectations for a stress shadow.

### Asymmetric motion along the San Francisco Bay Area faults. Implication on the magnitude of future seismic events

*Houlié, N. (UC Berkeley) and B. Romanowicz (UC Berkeley)*

The San Francisco Bay area is one of the tectonically most deformed areas in the world. This deformation is the result of relative motion of the Pacific and North-America plates. A large part of the strain (75 %) is accommodated along structures lying in a 50 km wide land stripe.

At least two major seismic events (Mw>6.5) are expected along the San Andreas (SAF) and Hayward faults (HAY) within the next decades. Triggering effects between the two seismic events may not be excluded (Lienkaemper et al., 1997).

The BARD network is a permanent GPS network comprising 40 GPS sites, installed since 1994 in Northern California ( Romanowicz et al., 1994). Originally started as a collaborative effort of different Bay Area institutions, since the establishment of the Plate Boundary Observatory, it is now focused on real-time data acquisition from stations operated by UC Berkeley, with plans for expansion in collaboration with USGS/Menlo Park. The BARD network is streaming data to the Berkeley Seismological Laboratory in real-time (sampling rates of 1s and 15s, depending on the site). All sites are transmitting data using Frame Relay technology which make them safer in case of earthquake occurrence. Data are archived at the Northern California Earthquake Data Center (NCEDC, http://www.ncedc.org) and are freely available ( Neuhauser et al., 2001). The BARD network is currently able to provide high accuracy (error<1mm/yr) velocities in Northern California.

We use the BARD data to show that the motion across the San Andreas and San Gregorio faults may be asymmetric. Therefore, the common assumption that the deformation is symmetric across the fault could lead to a biased location of the region of maximum strain in the San Francisco Bay Area. The new location of the maximum static strain based on asymmetry influences estimates of the response of the Hayward Fault to deformation associated with the San Andreas fault. We also present preliminary velocities for PBO sites located in the San Francisco Bay Area and discuss them in the light of BARD reference frame.

### Are fault-cored anticlines built by repeated earthquakes on the fault?

*Huang, Wen-Jeng (Indiana) and Kaj M. Johnson (Indiana)*

A primary goal of studies of blind faults underlying actively growing anticlines is assessment of earthquake hazard associated with slip on the faults. It is generally assumed that the amount of slip on the fault is directly related to the amplitude of the fold. Under this assumption, the potential for earthquakes on blind faults can be determined directly from fold geometry. However, anticlines grow over slipping reverse faults can be amplified by a factor of two to ten by buckling of mechanical layering under horizontal shortening. Studies that attempt to estimate fault slip from fold geometry may therefore overestimate fault slip by a factor of two or more if the contribution to fold growth from buckling is ignored. Furthermore, the surface uplift pattern produced by an earthquake on a reverse fault may not necessarily reflect the geometry of the underlying fold. We construct boundary element models to demonstrate that fault-cored anticlines in mechanically layered media subjected to layer-parallel shortening are not built solely by slip on the underlying fault. We compare the model results with data from fault-cored anticlines in the western United States. Pitchfork Anticline on the western flank of the Big Horn Basin in Wyoming likely formed by the combined mechanisms of fault slip and buckling. Geometric features of Pitchfork Anticline such as a localized anticlinal dome shape with tight hinges and amplitude that increases away from the fault tip are characteristic features of buckle folds produced in our numerical simulations. The coseismic uplift pattern produced during the 1985 earthquake on a fault under the Kettleman Hills Anticline and subsurface fold geometry of the anticline inferred from seismic reflection images are consistent with folding produced by the combined mechanisms of fault slip and buckling.

### SCEC/SURE: Multi-Hazards Demonstration Project: It's Your Fault... Prepare Now!

*Hyung, Eugenia (OSU)*

The Southern California Earthquake Center/Summer Undergraduate Research Experience (SCEC/SURE) internship program unites students with the world's preeminent earthquake scientists and specialists.

Though most interns still work one-on-one with a mentor, the SURE program has done something different this summer. SCEC/SURE gathered a group of four interns Eugenia Hyung, Stephanie Kelly, Robert Leeper III and Rosie Santilena to work with internship mentor Dr. Lucile Jones of the United States Geological Survey (USGS) on Southern California's section of the USGS's Multi-hazards Demonstration Project. A scenario is being created that combines the latest knowledge about Southern California's natural hazards, specifically earthquakes; with the impact they have on the physical, social, and economic fabric of our society. The interns' task for the scenario was to act as an interface between the scientific communities and the general public, interpret Southern California Geologic map data, find innovative ways to communicate the project's results to various audiences, and collaborate with the different project leaders to create a cohesive scenario.

My work here this summer has consisted of many different projects. One of them was to analyze PGVs (peak ground velocity) and PGAs (peak ground acceleration) of cities that were designated by my internship mentor Lucy Jones, by matching coordinates and city boundaries to "ShakeMaps" (maps with regions that are color-coded to show different intensities of motion) of the scenario earthquake. I've also collected material for a logarithmic timeline marking the events that will be expected to happen following the earthquake by getting information from past documents, participating in conferences, and getting help from my colleagues, other scientists and my mentor. Along with my colleagues, I've categorized deposit types in Southern California according to liquefaction and landslide susceptibility, to be compiled into an ArcGIS database.

### Rupture process and strong ground motions of 2007 Chuetsu-oki earthquake – Directivity pulses striking the Kashiwazaki-Kariwa Nuclear Power Plant

*Irikura, Kojiro (AIT, Japan), Takao Kagawa (Geo-Institute), Ken Miyakoshi (Geo-Institute), and Susumu Kurahashi (AIT)*

The 2007 Chuetsu-Oki earthquake occurred on July 16, 2007 northwest-off Kashiwazaki in Niigata Prefecture, Japan, causing severe damages of ten people dead, about 1300 injured, about 1000 collapsed houses and major lifelines suspended. In particular, strong ground motions from the earthquake struck the Kashiwazaki-Kariwa nuclear power plant, triggering a fire at an electric transformer and other problems such as leakage of water containing radioactive materials into air and the sea, although the effect of the radiation was less than natural environment. Preliminary results of the source inversions show a reverse fault with the NE-SW strike and NW dip. The rupture propagated to SW direction. The shortest distance from the nuclear power plant to the source fault to is estimated to be about 5 km.

Strong ground motions were recorded at more than 300 stations by the K-NET of the NIED including very short distance stations less than 10 km from the source fault. The nuclear power plant has their own network with 22 three-components' accelerographs locating at ground-surface, underground, buildings and basements of reactors. The station closest to the source fault is one of those in the site of the nuclear power plant. The peak horizontal ground accelerations of the strong ground motions generally follow the empirical relations in Japan, for example, Fukushima and Tanaka (1990) and Si and Midorikawa (1999). However, the strong ground motions in the site of the nuclear power plant had very large accelerations and velocities more than those expected from the empirical relations. The surface motions there had the PGA of more than 1200 gals and even underground motions at the basements of the reactors locating five stories below the ground had the PGA of 680 gals.

We found that strong ground motions in the site of the plant had three significant pulses which are generated as directivity pulses in forward direction of rupture propagation. We successfully simulated ground motions at the stations off and in the site of the plant using the characterized source model (Kamae and Irikura, 1998) with three asperities and the empirical Green's function method (Irikura, 1986).

### SCEC/UseIT: Educational Game Design and Development

*Jameson, Doreen (UNM)*

SCEC/UseIT (Undergraduate Studies in Earthquake Information Technology) is a research program that brings together students from various disciplines to collaborate upon and develop softwares and technologies designed to assist or be utilized by the earth sciences community.

The summer 2007 UseIT grand challenge was to create "serious games" aimed at communicating important earthquake science concepts. Interns chose to be a member of one of three gaming teams. As a member of the educational gaming team, I collaborated to design a serious game intended to teach students the fundamentals of plate tectonics, and earthquake science. Our team designed a game in which there was one main game board and various "sub-games" to be played within the main game. Using Adobe Flash CS3 I was able to create graphics and short animations for the Hot Spot "sub-game" as well as learn some Flash coding. For the main board game I assisted in writing and inputting into Flash geology questions to be answered by the player throughout the game. For the Plate Puzzle "sub-game" I used SCEC-VDO (Virtual Display of Objects), to create a movie of a 3D rotating Earth displaying the plate boundaries. To create this movie I imported and georeferenced a 2D plate boundary map into SCEC-VDO.

### The width of dextral faults and shallow decollements levels in the San Jacinto fault zone, southern California

*Janecke, Susanne and Benjamin Belgarde*

Cross-sectional, structural, geomorphic and map analysis of recently relocated earthquakes (Shearer et al., 2005) reveals steep NE dips and transpression across much of the San Jacinto fault zone in accord with growing evidence for widespread transpression across the southern San Andreas fault (Fuis et al., 2007). The seismically defined San Jacinto fault zone in the Peninsular Ranges is typically 9-10 km wide perpendicular to microseismic alignments, 12-15 km wide in map view, and consists of several identifiable steeply NE-dipping alignments of seismicity in the middle to lower seismogenic crust. The geologically defined fault zone is narrower in the same area. The width of the Clark fault zone in the Salton basin, on the other hand, is up to 13 km wider at the surface than the seismically active central part of the fault zone in the subsurface between 3 and 12 km depth (Belgarde, 2007). Mismatching shallow structures and deeper structures require flake tectonics and shallow decollements in some areas. These shallow decollements must have limited lateral extents because many parts of the adjacent fault zone persist as steep NE-dipping faults to 10-12 km depth from previously and newly mapped dextral faults at the surface. We correlate some NE-striking left-lateral faults with subsurface alignments of microseismicity; there are more right-lateral faults highlighted by microseismicity then left-lateral ones. A secondary concentration of earthquakes between 3-5 km depth may be the locus of decollements within the Salton basin or might be a zone of greater fluid pressures.

In some places there are excellent correlations between active surface structures and seismicity at depth. In other areas active fault zones produced no earthquakes in the last 25 years. We interpret those seismically quiet areas as locked or inactive during the period of study. Examples include many segments of the Coyote Creek fault, the Extra fault, the San Felipe Hills fault, and the northern third of the Clark fault zone in the Arroyo Salada segment. Another such area is a broad band along the SW margin of the Coachella Valley where numerous E and NE-facing fault scarps show Quaternary activity within a newly hypothesized fault zone that we here name the Torres Martinez fault zone. If further work confirms this fault zone it would have significant hazards implications because it projects northward to the most populated areas of the Coachella valley. We propose that deep Quaternary sedimentary basins SW of the dextral reverse parts of the San Jacinto and San Andreas fault zones are the result of the component of contraction across the strike-slip faults that likely dates back only 1-2 m.y., and are not as transtensional as previously thought.

Deep Quaternary sedimentary basins SW of the dextral reverse parts of the San Jacinto and San Andreas fault zones are the result of the component of contraction across the strike-slip faults and are not as transtensional as previously thought.

Belgarde, Benjamin, 2007, Structural characterization of the three southeast segments of the Clark fault, Salton Trough, California [M.S thesis]: Utah State University: 4 plates, map scale 1:24,000. 216 p.

## Relationship Between Sonic Velocity Data and Fracture Densities at the San Andreas Fault Observatory at Depth

*Jeppson, Tamara (USU) and Jim Evans (USU)*

Relating physical properties of fault-related rock with their geophysical signature helps constrain the nature of energy release along faults. We examine the geophysical structure of fault zones so that we can understand the composition of materials in the fault zone and relate composition and geophysical character. In order to develop a better understanding of fault behavior at depth, the San Andreas Fault Observatory at Depth (SAFOD) project provides borehole geophysical data and rock samples from a borehole in part of the San Andreas Fault Zone located near Parkfield, California. We examined the sonic logs [Vp and Vs] from the SAFOD borehole starting at an approximate depth of 3 km to the end of the drill hole at 4 km; this area includes the region interpreted to be the main and active part of the San Andreas Fault. Vp values over the 3 to 4 km interval range from approximately 3 to less then 6 km/sec. The Vs data ranges between 1.5 and 3 km/sec. For this study the sonic logs were compared to fracture data, derived from image logs, obtained by M. Zoback and S. Draper [2007; in prep]. In addition to the fracture data, we can compare the velocity data to the compositional data of Bradbury et al., in press. The fracture and velocity data sets were binned in five-meter intervals and Vp, Vs, and calculated Poisson's ratio (Vp/Vs) were cross-plotted against the fracture data. We compare the sonic velocity data with the fracture density data and see a correlation between the number of fractures and the range of velocity values. In regions where there are few fractures, Vp and Vs data show a large distribution of velocities, however, as the fracture density increases the range of velocities decreases. The Vp shows an increase in the minimum velocity values, from 3 km/sec at zero fractures to about 4.4 km/sec at 6 fractures. The maximum Vp values remain between 5 and 5.5 km/sec as the fracture density increases. The maximum (~3.39 km/sec) and minimum (1.64 km/sec) Vs values appear to be converging towards approximately 2 km/sec as fracture density increases. Most of the Vp/Vs values are gathered around 2 to 2.5 km/sec for low fracture density however at higher fracture densities the velocity values are more in the range of 2.49 to 2.54 km/sec. At low fracture densities the velocity is determined by lithologic variability, porosity, and other material properties. At a fracture density of zero most of the higher velocities correspond to the lower arkose section and the lower velocities to the siltstone section of the borehole. At higher fracture densities the distribution of velocity data could be due to anisotropy, suppression of lithology, and fluid content.

## Implementation of Finite Element Models Using the SCEC Community Fault Model: Meshing and Test Computations

*Jiangning, Lu (MIT), Carl W. Gable (LANL), Bradford H. Hager (MIT), and Charles A. Williams (RPI)*

Improved understanding of the evolution of stress and deformation in the California fault system requires substantial improvement in computational capabilities, particularly realistic meshing of the fault system. An ongoing goal of SCEC has been to develop finite element models based on the SCEC Community Fault Model. Substantial progress towards this goal has been achieved. We have implemented an approach to embed detailed fault geometries into a regional mesh using the LaGriT meshing package (http://lagrit.lanl.gov/). Our newly developed method permits tetrahedral meshing of all or a subset of the Southern California Community Fault Model(CFM) faults. The method uses a point placement strategy outlined in Murphy et al.(2001) to produce a Delaunay tetrahedral mesh that conforms to the facets of the triangulated CFM faults. There are trade-offs between mesh resolution, mesh size (number of nodes and elements), mesh quality and computational time. Mesh quality is improved by elimination of high aspect ratio elements using a combination of edge merging to eliminate wedge type elements and a combination of refinement and merging to eliminate sliver type elements.

We carry out a suite of model calculations, first by Building meshes that include just major faults, then developing progressively more complex models by adding faults one or two at a time. We use the PyLith 1.0 (http://www.geodynamics.org/cig/software/packages/short/pylith) finite element code for proof-of-concept calculations modeling deformation by applying block rotation poles that yield typical slip rates on the faults of interest (Meade and Hager, 2005). Memory usage and run time as a function of mesh size are documented in order to estimate the complexity of problems that can be addressed with available resources.

### Nonlinear Inversion for Dynamic Rupture Parameters from the 2004 Mw6.0 Parkfield Earthquake

*Jimenez, Rosa (SDSU) and Kim Olsen (SDSU)*

The Parkfield section of the San Andreas Fault has produced repeated moderate-size earthquakes at fairly regular intervals and is therefore an important target for investigations of rupture initiation, propagation and arrest, which could eventually lead to clues on earthquake prediction. The most recent member of the Parkfield series of earthquakes, the 2004 Mw6.0 event, produced a considerable amount of high-resolution strong motion data, and provides an ideal test bed for analysis of the dynamic rupture propagation. Here, we use a systematic nonlinear direct-search method to invert strong-ground motion data (<1 Hz) at 37 stations to obtain models of the slip weakening distance and spatially-varying stress drop (8 by 4 subfaults) on the (vertical) causative segment of the San Andreas fault (40 km long by 15 km wide), along with spatial-temporal coseismic slip distributions. The rupture and wave propagation modeling is performed by a three-dimensional finite-difference method with a slip-weakening friction law and the stress-glut dynamic-rupture formulation (Andrews, 1999), and the inversion is carried out by a neighborhood algorithm (Sambridge, 1999), minimizing the least-squares misfit between the calculated and observed seismograms. The dynamic rupture is nucleated artificially by lowering the yield stress in a 3 km by 3 km patch centered at the location of the hypocenter estimated from strong motion data. Outside the nucleation patch the yield stress is kept constant (5-10 MPa), and we constrain the slip-weakening distance to values less than 1 m. We compare the inversion results for two different velocity models: (1) a 3-D model based on the P-wave velocity structure by Thurber (2006), with S-wave and density relations based on Brocher (2005), and (2) a combination of two different 1-D layered velocity structures on either side of the fault, as proposed by Liu et al. (2006). Due to the non-uniqueness of the problem, the inversion provides an ensemble of equally valid rupture models that produce synthetics with comparable fit to the observed strong motion data. Our preliminary results with the smallest misfits, out of about 2000 tested rupture models, suggest an average slip-weakening distance of 40-95 cm and an average stress drop across the fault of 6.7 - 8.4 MPa. Compared to the kinematic inversion results by Liu et al. (2006) our models with the smallest misfits produce a larger maximum slip (up to about 95 cm) and smaller rupture area, but similar rupture duration (5-7s). The inversions carried out for the layered models tend to produce smaller misfit between data and synthetics as compared to the results using the 3D structure. This suggests that our 3D structure needs improvement, including the Vs-Vp and density-Vp relation. We expect further decrease in the misfit values by increasing the number of tested rupture models.

### Coupled afterslip and viscoelastic flow following the 2002 Denali Fault, Alaska Earthquake

*Johnson, Kaj M. (Indiana), R. Burgmann (UC Berkeley), and Jeffrey Freymueller (Alaska)*

We investigate the processes of postseismic deformation following the 2002 Denali Fault, Alaska earthquake using continuous and campaign GPS data. Afterslip is modeled on a fault in an elastic lithosphere overlying a viscoelastic asthenosphere. We assume afterslip is governed by a velocity-strengthening friction law. Postseismic GPS time-series are best explained by a combination of two mechanisms: viscous flow in the lower crust and upper mantle and afterslip on the fault above 30 km depth. Models with only afterslip only (no distributed viscous flow) underestimate displacements at sites more than 100 km from the fault. The rate-state frictional parameter a-b, is estimated to be in the range 10-3-10-2 for typical confining pressures, about an order of magnitude lower than experimental values for granite at conditions well above or below the transition from potentially unstable (a-b < 0) to nominally stable (a-b > 0) friction. The Denali earthquake may have caused increased locking at the interface of the subducting Pacific plate south of the Denali Fault. Northeast directed horizontal surface velocities at GPS sites over 100 km south of the Denali fault increased following the earthquake. The magnitude of the acceleration at these sites in southern Alaska cannot be explained by postseismic deformation associated with afterslip and viscous flow directly below the Denali fault. The stresses induced on the subduction interface by the Denali earthquake promote increased coupling on the interface. Increased coupling of the interface would generate the observed velocity increase in southern Alaska.

### SCEC/SURE: The International Earthquakes and Mega Cities Initiative

*Johnson, Steven (Grinnell College)*

Los Angeles is only one city in the world which is affected by major natural disasters. Though the City of Los Angeles is different from other cities because it is one of the biggest cities in the United States with a population that surpasses 3 million. Though it is not much different from other global cities in regards to population size. Many global cities have a shared identity in disasters, rather natural or manmade. It is imperative for cities around the globe to be able to learn from what other nations or large cities have done when it comes to preparing for a natural disaster. The idea that all cities can learn from others strengths or weaknesses when it comes to a disaster is effective on any scale.

### Simplified algorithms for calculating double-couple rotation

*Kagan, Yan (UCLA)*

We derive new, simplified formulae for evaluating the 3-D angle of earthquake double couple (DC) rotation. The complexity of the derived equations depends on both accuracy requirements for angle evaluation and the completeness of desired solutions. The solutions are simpler than my previously proposed algorithm based on the quaternion representation designed in 1991.

We discuss advantages and disadvantages of both approaches. These new expressions can be written in a few lines of computer code and used to compare both DC solutions obtained by different methods and variations of earthquake focal mechanisms in space and time.

### Shear Wave Velocity Structure beneath the central Basin and Range Province, eastern California: Implications for crustal-scale tectonic models

*Kamath, Nishant (USGS), Shannon Leslie (USGS), and Walter D. Mooney (USGS)*

Broadband seismic data from three seismic stations located within the central Basin and Range Province of eastern California were analyzed in order to image the shear wave velocity structure of the crust and upper mantle in the region. The stations include: (1) Manual Prospect Mines, Trona, (2) Cottonwood Creek, Lone Pine, and (3) Slate Mountain, Trona. The area of the study is characterized by a complex geologic history predominantly involving the Mesozoic Nevadan Orogeny with the emplacement of the Sierra Nevada batholith as well as the later, large-magnitude extension and uplift during the Tertiary. Lateral and vertical velocity variations deduced from receiver function analyses indicate intricate crustal dynamics associated with this region. The crustal configuration beneath the stations depicts a low-velocity zone (LVZ) that is present within the mid- to lower-crust, initiating at 16-18 km depth and terminating at about 30 km, where it reaches the Moho. These results have significant implications for crustal-scale tectonic models of the region which may include lateral flow of mid- to lower-crustal material and/or delamination of the lower crust.

### Quantifying uncertainties in source parameter estimation using a small aperture array

*Kane, Deborah (UCSD), German Prieto (Stanford), Frank Vernon (UCSD), and Peter Shearer (UCSD)*

The ability to estimate source parameters is crucial for studying the physics of earthquake rupture. Many studies have estimated source parameters in the past, but have neglected to calculate the uncertainties of these measurements. We use waveforms of co-located earthquakes recorded at closely spaced surface stations to quantify variations in similar waveforms. Our data are from a small aperture array at Pinon Flats Observatory, California, that recorded ~150 local earthquakes (M0.7 to M3.7) over a one month period. The array consisted of 58 high frequency surface stations; 36 stations were placed in a square grid with 7m spacing and 22 stations were in two orthogonal linear arrays with 21m spacing. Two borehole stations were centered in the grid at depths of 150m and 300m. We use empirical Green's function (EGF) techniques to remove path effects, which leaves the signal of the earthquake source and local site effects intact. In the frequency domain, we use multitaper methods to compute source spectra and subsequently estimate moments, corner frequencies, and their respective uncertainties by fitting to an w-2 source model. We calculate source-time functions (STFs) using the Projected Landweber Deconvolution method and determine a second estimate of moment, corner frequency, and uncertainties for each earthquake. The close spacing of the stations allows us to examine the source parameter uncertainties because all records for each earthquake have essentially the same source-receiver geometry and use identical recording equipment.

**Spectral element modeling of dynamic rupture and long-term slip on rate and state faults**
*Kaneko, Yoshihiro (Caltech), Nadia Lapusta (Caltech), and Jean-Paul Ampuero (ETH Zurich)*

In this work, the spectral element method (SEM) is used to model earthquake rupture and longer-term slip on a vertical strike-slip fault governed by rate and state friction. Previous studies of long-term slip behavior on rate and state faults mostly used boundary integral methods (BIM) which cannot include, at least in their current implementation, complex crustal structures such as variable bulk properties, fault damage zones, and non-planar fault geometries. SEM approach will allow to include those factors into models that simulate long histories of seismic and aseismic slip.

We have extended SEM to dynamic rupture simulations on rate and state faults and validated it by comparison with BIM solutions for a 2D test problem. We use the 3D dynamic SEM formulation to study several problems, including the effect of a shallow steady-state velocity-strengthening fault region (or layer) on a single simulated earthquake. In the absence of the layer, the rupture speed becomes supershear near the free surface due to a phase conversion, as also observed on linear slip-weakening faults. In contrast, when a velocity-strengthening layer exits, the supershear pulse is suppressed, which could explain the lack of universally observed supershear rupture near the free surface.

We are also advancing towards a SEM formulation for modeling long-term slip histories, by combining the dynamic SEM with a quasi-static SEM formulation that we developed for simulations of aseismic slip. We have used the combined formulation to simulate slow nucleation, dynamic rupture, and postseismic response in a 2D test model, and find that the results are in agreement with those of BIM. We will report our current effort to extend the combined SEM formulation to 3D.

**SCEC/CSUN Catalyst Program A) An alternative approach to restoring slip across the San Andreas fault at Biskra Palms, B) Towards digital active fault map of Pakistan**
*Kelley, Kandace (Purdue), Jessica Hinojosa (Stanford), Nick Rousseau (CSUN), and Doug Yule (CSUN)*

Our internship is a collaborative effort to a) reconstruct the offset canyons across the San Andreas fault, near Indio, CA and compare the result with previous reports, and b) digitize the known faults of Pakistan for use by the Geological Survey of Pakistan. Near Indio, we visited trenches, analyzed "B4" LIDAR data, and restored the offset canyons whose estimate broadly agrees with previous estimates. Our main conclusion supports a moderate revision of the reconstruction by van der Woerd et al., 2006. In digitizing the Pakistan fault maps, we used ArcMap to turn hardcopy maps into digital images. The result is an initial step towards better understanding the seismic hazards there.

My personal contribution in reconstruction of the offset canyons included my interpretation of where the canyons were located along the fault and computing the offset for each canyon along each strand of the fault. In digitizing the faults in Pakistan, I located and marked each fault along the southwest edge of Pakistan and helped to compile the overall data and geo-referencing of that data.

**SCEC/SURE: The Multi-Hazards Demonstration Project: It's your fault...prepare now!**
*Kelly, Stephanie (Cornell University)*

The Southern California Earthquake Center/Summer Undergraduate Research Experience (SCEC/SURE) internship program brings students to work as interns with the world's preeminent earthquake scientists and specialists. Though most interns still work one-on-one with a mentor, the SURE program has done something different this summer. SCEC/SURE gathered a group of four interns Eugenia Hyung, Stephanie Kelly, Robert Leeper III and Rosie Santilena to work with internship mentor Dr. Lucile Jones of the United States Geological Survey (USGS) on Southern California's section of the USGS's Multi-Hazards Demonstration Project. A scenario for is being created that combines the latest knowledge about Southern California's natural hazards, specifically earthquakes, with the impact they have on the physical, social, and economic fabric of our society. The interns' tasks for the scenario were to act as an interface between the scientific communities and the general public, interpret Southern California Geologic map data, find innovative ways to communicate the project's results to various audiences, and collaborate with the project leaders to develop a cohesive scenario.

A cohesive scenario requires both a cohesive process and a coherent product. It was part of my job to communicate our ideas for a public-friendly scenario to the scientists on the project and to gauge how well their various pieces would fit into our proposed framework. This framework included a website about the scenario that could be used by both the scientific and the public communities, and a timeline-based document to integrate the myriad facets of the scenario. I also worked closely with another intern to research, consolidate and summarize the major changes made to the building code. From this research I created a simplified chart to help homeowners determine the earthquake preparedness of their houses. This chart symbolizes my desire to communicate effectively the scenario's results to the public.

### Southern California Adjoint Source Inversions

*Kim, YoungHee (Caltech) and Jeroen Tromp (Caltech)*

Southern California Centroid-Moment Tensor (CMT) solutions with 9 components (6 moment tensor elements, latitude, longitude, and depth) are sought to minimize a misfit function computed from waveform differences. The gradient of a misfit function is obtained based upon two numerical simulations for each earthquake: one forward calculation for the southern California model, and an adjoint calculation that uses time-reversed signals at the receivers. A conjugate gradient algorithm is used to iteratively improve the earthquake source model while reducing the misfit function. We test the inversion code by perturbing each component of the CMT solution, and see how the perturbed value converges. Next, we demonstrate full inversion capabilities using the 9 September 2001, ML 4.2 Hollywood event. We compare our result with that obtained by performing an automated moment-tensor inversion introduced by Liu et al. (2004). Finally, we provide a table containing map view figures of the vertical-component adjoint wavefield near the original source for all of the basic beachball earthquake mechanisms, thereby illustrating the relationship between the mechanism and the adjoint wavefield.

### Strike-slip fault terminations at seismogenic depths; the structure and kinematics of the Glacier Lakes fault, Sierra Nevada, U.S.A.

*Kirkpatrick, James D. (U of Glasgow), Zoe K. Shipton (U of Glasgow), Jim P. Evans (Utah State), S. Micklethwaite (Australian National University), S.J. Lim (Utah State), and P. McKillop (Utah State)*

Structural complexity is common at the terminations of earthquake surface ruptures; similar deformation may therefore be expected at the end zones of earthquake ruptures at depth. The 8.2km long Glacier Lakes fault (GLF) in the Sierra Nevada, U.S.A., is a left-lateral strike slip fault with a maximum observed displacement of 125m. Within the fault pseudotachylyte cross-cuts cataclasites, showing that displacement on the GLF was accommodated at least partly during seismic events. The western termination of the GLF is defined by a gradual decrease in the slip on the main fault, accompanied by a 1.4 km wide zone of secondary faulting in the dilational quadrant of the GLF. The secondary faults splay counter-clockwise from the main fault trace forming average angles of 39 degrees with the main fault. Slip vectors defined by slickenlines are more oblique for these splay faults than for the GLF. Static stress transfer modelling shows that the orientations of the splays, and the rake of slip on those splays, are consistent with slip on the main fault. The GLF termination structure shows that structural complexity is present at the terminations of faults at seismogenic depths, therefore ruptures that propagate beyond fault terminations, or through stepovers between two faults, will likely interact with complex secondary fault structures. Models of dynamic rupture propagation must account for the effect of pre-existing structures on the elastic properties of the host rock. Additionally, aftershock distributions and focal mechanisms may be controlled by the geometry and kinematics of structures present at fault terminations.

### On the Probability Law Governing Ground Motion Metrics: A Case Study the 2004 Parkfield Earthquake

*Lavallée, Daniel (UCSB)*

Based on the superposition of seismic waves and the Central Limit Theorem, we have laid the basis for a unified picture of earthquake variability from its recording in the ground motions to its inference in source models. This theory stipulates that the random properties of the ground motions and the source for a single earthquake should be both (approximately) distributed according to the Levy law. Computation of the probability density function (PDF) of the peak ground acceleration (PGA) of the 1999 Chi-Chi, the PDF of the PGA and the PDF of the peak ground velocity (PGV) of the 2004 Parkfield earthquakes confirms this theory. As predicted by the theory, we found that the tails of the PDF, characterizing the slip and the PGA, are governed by power law behaviors with exponents (called the Levy indexes) that take almost the same values close to 1. Computation of the PDF of the PGA recorded at the surface and the PDF of the PGA recorded in borehole during the 2003 Tokachi-oki earthquake leads to a similar conclusion. The PDF tail controls the frequency at which large events occurred and thus quantifies the probability to observe large acceleration values and large velocity values during an earthquake.

We extend our analysis of the random properties to other ground motion metrics. To lessen the dependency due to the source-to-site distance, we consider the ratio of the PGV to the PGA, the ratio of the two horizontal components of the PGA to the vertical component of the PGA, and the ratio of the horizontal components of the PGV to the vertical component of the PGV. In this analysis, we used the ground motion recorded during the 2004 Parkfield earthquake, arguably the best-recorded earthquake in history for the density of near-source data. We select stations located within a closest distance to the rupture surface that varies from 0 to 180 km. To test the effect of the distance on the computed random properties, these stations are divided into several subsets or windows. The size of the window varies and thus number of stations included in the analysis. For each subset of stations, we compute the PDF and characteristic function (CF) of the ground motion metrics and compile the parameters of the Levy law that best fit the PDF and CF. We find that the tails of PDF of ground motions metrics decrease with power law behaviors controlled by Levy indexes with values close to 1.

### Temporal Slip Rate Variability along the Southern San Jacinto Fault

*Le, Kimberly and Mike Oskin (UNC Chapel Hill)*

We present new Late Quaternary slip rates for the San Jacinto fault using B4 ALSM topography, field mapping and 10Be exposure-age dating of alluvial fan surfaces in the Anza Borrego Desert. The Clark fault (CLF) and Coyote Creek fault (CCF) define the most active strands of the southern San Jacinto fault zone. These faults form numerous NW-striking scarps that offset three generations of Quaternary alluvial fan surfaces, Q2b, Q3a, and Q3b. Q2b surfaces are typically planar, lack bar and swale morphology and contain strongly weathered and varnished surface clasts. Bar and swale topography is muted on Q3a surfaces but well-preserved on Q3b surfaces. Q3a surfaces are also characterized by light brown rock varnish and moderate weathering of susceptible clasts. Offsets of Q2b and Q3a are higher on the CCF (105±18m, 31±7m) than on the CLF (68±8m, 19±2m). Conversely, Q3b surfaces are offset 7±1m by the CLF but are not ruptured along the CCF. We dated alluvial fan surfaces along both the CCF and CLF using 10Be sampling methods adapted for available material and degradation of the fan surface. For samples of younger surfaces, we amalgamated 12 to 20 chips from quartz-bearing boulders lodged within a single channel bar. For older surfaces we either sampled individual meter-sized boulders or collected samples from a 2 m-deep depth profile. Surface ages are consistent between CCF and CLF sites: 40±12 ka and 31±6 ka for Q2b, 7.1±1.6 ka and 4.6±1.6 ka for Q3a. Samples from Q3b near the CLF yielded ages of 1.0±0.2 ka and 2.1±0.3 ka. CCF samples have not yet been corrected for pre-depositional 10Be ingrowth (inheritance), thus we use the CLF ages to calculate preliminary slip rates. Late Pleistocene to present rates are CLF: 2.2±0.5 mm/yr, CCF: 3.4±0.9 mm/yr, and 5.6±1.4 mm/yr combined. Mid-Holocene to present rates are CLF: 4.1±1.5 mm/yr, CCF: 6.7±2.8 mm/yr, and 10.9±4.3 mm/yr combined. Latest Holocene CLF slip rate exceeds 3 mm/yr. The combined Late Pleistocene to present slip rate for the southern San Jacinto fault is less than one third the rate deduced from the onset of faulting ca. 1 Ma. Mid-Holocene to present slip rates for both the CLF and CCF are about double their ca. 35 kyr rates, but are less than the 16-20 mm/yr geodetic loading rate and the >16 mm/yr slip rate since 1 ka at Hog Lake. We conclude that (1) overall slip rate of the San Jacinto fault has probably decreased significantly since fault inception, (2) slip rates vary over 1 to 5 kyr time scales and may be presently elevated due to a cluster of activity, and (3) other structures such as normal faults and folds could be accommodating up to one half of the deformation across the fault zone.

### SCEC/SURE: Multi-Hazards Demonstration Project: It's Your Fault... Prepare Now!

*Leeper III, Robert (Cerritos College), Eugenia Hyung (Ohio State University), Stephanie Kelly (Cornell University), and Rosie Santilena (CSU Los Angeles)*

The Southern California Earthquake Center/Summer Undergraduate Research Experience (SCEC/SURE) internship program unites students with the world's preeminent earthquake scientists and specialists. Though most interns still work one-on-one with a mentor, the SURE program has done something different this summer. SCEC/SURE gathered a group of four interns Eugenia Hyung, Stephanie Kelly, Robert Leeper III and Rosie Santilena to work with internship mentor Dr. Lucile Jones of the United States Geological Survey (USGS) on Southern California's section of the USGS's Multi-hazards Demonstration Project. A scenario is being created that combines the latest knowledge about Southern California's natural hazards, specifically earthquakes; with the impact they have on the physical, social, and economic fabric of our society. The interns' task for the scenario was to act as an interface between the scientific communities and the general public, interpret Southern California Geologic map data, find innovative ways to communicate the project's results to various audiences, and collaborate with the different project leaders to create a cohesive scenario.

As a member of the Multi-Hazards Demonstration Project for my 2007 SCEC/SURE internship, I was presented with exciting challenges and exposed to cutting edge Earth Science. I interpreted geologic map data to determine the susceptibility to landslides and liquefaction that certain areas of southern California will face in our M7.8 scenario earthquake. The data was input into ArcGis and will soon be processed by FEMA's "HAZUS" risk assessment software for use in the scenario. I also wrote narratives that blend the science of the M7.8 scenario earthquake with the lives of characters chosen to represent southern California's population and describe how the earthquake affected them.

### Late Cenozoic Tectonic Evolution along the Pacific-North America Transform Boundary as Recorded in Borderland Basins

*Legg, Mark R. (Legg Geophysical), Marc J. Kamerling (Venoco, Inc.), and Robert D. Francis (CSU Long Beach)*

Basin sediments in the California Continental Borderland provide a high-resolution record of Late Cenozoic tectonic events along the Pacific-North America transform fault plate boundary. As the basins occur at a wide variety of scales, from local pull-apart (stepover) basins to large-scale transtensional sags or rift basins, the scale of tectonic events recorded varies from local to regional. On the regional scale, changing orientations in the relative plate motion vector produced a sequence of transtensional basin formation followed by transpressional basin inversion. This process is responsible for the widespread occurrence of restraining bend pop-up structures throughout the southern California region and particularly well expressed offshore in the Borderland. Local progression of crustal blocks past irregular strike-slip fault traces produce predictable patterns of subsidence and sedimentary sequence thickening at releasing bends or stepovers followed by uplift and onlap or growth wedge sequences at restraining bends. The latter process has been demonstrated along the Palos Verdes fault in San Pedro Bay (Rigor, 2003). Major tectonic events, such as the late Quaternary Pasadenan Orogeny, have been defined by sedimentation patterns in the Los Angeles Basin region (Wright, 1991), a filled basin of the Inner Borderland Rift. Recent studies of turbidite deposition from Borderland submarine canyons and fan valley systems into Santa Monica basin (Normark et al., 2004) suggest a very recent, ca. 22 ka, tectonic event that may signify important changes to the Holocene tectonic style and earthquake potential in the southern California area. We consider that this event is also represented by the unconformity above a tilted late Quaternary sedimentary sequences observed on the northeast flank of the Palos Verdes Anticlinorium and may involve local seafloor upwarp along the Palos Verdes fault in San Pedro Bay. Further investigation of this latest Pleistocene event is necessary to determine the scale, whether local to the offshore area or regional throughout southern California, and cause, which may imply significant changes in the Holocene earthquake potential in southern California. Clearly, the style of deformation along the Palos Verdes fault and adjacent region has been affected.

We do not know, as yet, whether this event has affected other important southern California fault systems including the San Andreas.

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### Paleoseismology of Blind thrust faults in the Los Angeles basin

*Leon, Lorraine A. (USC), James F. Dolan (USC), John H. Shaw (Harvard), and Thomas L. Pratt (USGS)*

Over the past eight years we have been developing methodologies to understand the paleoearthquake history and structural evolution of blind thrust faults and their associated folds. Much of this research has focused on two major blind thrust systems beneath metropolitan Los Angeles; the Puente Hills thrust fault (PHT) and the Compton fault. These studies have demonstrated that both the Puente Hills and Compton blind thrust faults have generated multiple, large-magnitude (Mw >7) earthquakes during the past 14 ka.

The PHT is a major blind fault that underlies the heart of Los Angeles, extending from northern Orange County to near Beverly Hills. This highly segmented fault system consists of three distinct thrust ramps. Our early research focused on the central Santa Fe Springs segment, where we observed four stratigraphically discrete uplift events, which we infer to be associated with large-magnitude earthquakes, during the past 11,000 years. A preliminary study of the western Los Angeles segment has also identified punctuated periods of uplift associated with large-magnitude events. Studies of our Los Angeles segment are ongoing, and future plans call for the acquisition of a 220-m-deep, continuously cored borehole drilled directly into the growth triangle we imaged on high-resolution seismic reflection profiles. This hole will provide slip rates for the PHT over a wide range of timescales. These studies, in conjunction with studies of the eastern, Coyote Hills segment, will provide a synoptic view of earthquake occurrence of this segmented blind thrust system.

The Compton fault extends northwest-southeast for 40 km beneath the western edge of the Los Angeles basin and consists of two thrust segments. Our studies have focused on a site on the northern segment of the Compton fault, where we have documented the occurrence of six discrete uplift events that occurred in large-magnitude (Mw >7) earthquakes during the past 14,000 years. We have also excavated several reconnaissance boreholes from a study site above the backlimb of the southern segment.

In addition to using these newly developed methodologies to delineate the paleoearthquake history of the PHT and Compton fault, our data also provide insights into the detailed kinematics of earthquake-by-earthquake fold growth above the underlying blind thrust ramps. At all four study sites, folds are well expressed as classic fold-bend folds growing predominantly by kink-band migration, generally as predicted by folding theory. In all examples, however, we see that the folded strata within the kink bands acquire their dips incrementally. This suggests that fold kinematics involves components of both kink-band migration and limb rotation, the latter probably a reflection of the finite width of the axial surfaces and fold hinge, as well as the governing deformation mechanism of loosely consolidated near-surface sediments. Our ongoing research should provide further insights into both the earthquake history above individual thrust ramps, as well as the kinematics of fold growth above these segmented blind-thrust systems.

### SCEC/SURE: Rainfall intensity-duration thresholds for debris flows in post-burn areas of Southern California

*Leone, Lindsay (Dartmouth College)*

Previous studies of debris-flow hazards within Southern California have demonstrated that wildfires increase the risk of debris flows in the affected basins. However, the exact relationship between post-burn precipitation and the generation of debris flows is still under investigation. My research this summer has focused on defining thresholds for rainfall intensity-duration conditions that can trigger life and property-threatening debris flows from recently burned basins in Southern California, and to verify existing thresholds. To record the winter storms that impacted areas burned during the summers of 2003-2005, the USGS established rain gage networks in drainage basins within Ventura, San Bernardino, and San Diego Counties. The response of each basin (debris flow, proto-debris flow, flood, or no response) to individual storms was also documented. For this study, proto-debris flow refers to a small, localized debris-flow event that does not coalesce to occupy an extensive drainage network (as a life- or property- threatening event would). For each storm of interest, we calculated the peak precipitation intensity for 10-minute, 15-minute, 30-minute, 1-hour, 3-hour and 6-hour durations (keeping intensity intervals suitable to storm length), and examined this data to identify the threshold conditions unique to the debris flow and proto-debris flow producing storms.

Rainfall and response data from the Day, Gorman, School and Topanga Fires in Ventura County, the Harvard, Thurman, Blaisdell, Grand Prix, Old, Soboba and Mill Creek/Emerald Fires in San Bernardino County, and the Horse Fire in San Diego County, revealed that measures of rainfall intensity and duration can clearly define the threshold conditions at which debris flows are produced in each recently burned region. The existing threshold for the San Bernardino Mountains was verified using data from the Thurman Fire, where a debris flow was produced in response to rainfall intensities and durations greater than the previously-defined threshold for the area. Data from the Harvard Fire debris flows also verified the San Bernardino debris flow threshold even though the events affecting the Harvard burn area were short convective thunderstorms, unlike the longer winter storms evaluated in San Bernardino and San Diego. In Ventura County, the previously-defined debris flow threshold and a threshold for proto-debris flow activity, defined using data from the Day Fire, are a convincing distance apart, and the storm conditions that produced both debris flows and proto-debris flows were higher than those which showed no response. Data from the School Fire in coastal Ventura County verified the pre-existing Ventura County Threshold. This indicates within the same county, coastal and inland zones can be considered together when determining debris flow thresholds. The Horse Fire basins were the only burn regions which experienced no response to the documented storms. Therefore, a lower threshold line for San Diego County was established using the peak precipitation of non-event storms. All of these thresholds can be considered as realistic guidelines for predicting the likelihood of debris-flow events in a rudimentary warning system, and will be incorporated into the existing USGS/NWS Early Warning System for Debris Flows from Recently Burned Areas in Southern California.

### The Velocity Contrast Across the Parkfield section of the San Andreas Fault near the SAFOD drill site

*Lewis, Micheal (USC), Yehuda Ben-Zion (USC), Zhigang Peng (GT), Zheqiang Shi (USC), and Peng Zhao (GT)*

We investigate the existence and strength of bimaterial interfaces in the Parkfield region of the San Andreas fault (SAF), focusing on the 15 km to the NW and SE of the SAFOD drill site. The research is based on fault zone head waves (FZHW) that refract along an interface separating materials with different seismic properties. These waves provide the best diagnostic and imaging tool of the properties of bimaterial interfaces. We examine waveforms from the temporary PASO deployment and nearby stations from the permanent High Resolution Seismic Network (HRSN) and Northern California Seismic Network (NCSN) over the time intervals July-December 2001 and April-August 2002. The study is part of a larger project on imaging bimaterial interfaces in the Parkfield region using data of multiple seismic networks. The analysis done so far employs records of about 50 events located very close to the SAF and recorded by as many as 70 stations. We obtained accurate picks of head and direct P wave arrival times, with FZHW identified at 26 stations on the slow (NE) side of the fault. For stations on the slow block that are about 1-5 km from the fault there is a clear continuous head wave propagation for ~30 km along strike, from the creeping sec-

tion NE of the SAFOD site to ~15 km SE of the HRSN station Middle Mountain. This implies a velocity contrast that is geometrically coherent throughout the portion of the fault on which we have events recorded at our stations. Stations within a few hundred meters of the fault show head waves only from events to the NW in the creeping section of the SAF. These stations are likely affected by small-scale structural complexities, such as damage zones, multiple fault branches or step-over. The average values of the velocity contrast, estimated from the arrival time moveouts between the head and direct P waves at the different stations, fall in the range of ~3-8%.

### Seismic Documentation for Rock Damage and Heal on the San Andreas Fault Involved in the 2004 M6 Parkfield Earthquake

*Li, Yong-Gang (USC), Po Chen (Lamont), Elizabeth S. Cochran (UCR), John E. Vidale (UW), and Peter E. Malin (Duke)*

The M6 Parkfield earthquake that occurred on 28 September 2004 provides us a rare opportunity to examine the variations in the volume and magnitude of the low-velocity anomalies on the San Andreas Fault (SAF) over the earthquake cycle. After this earthquake, we deployed a dense seismic array at the same sites as used in our experiment in the fall of 2002. The data recorded for repeated explosions and microearthquakes before and after the M6 Parkfield earthquake show a few percentage variations in seismic velocity within a ~200-m-wide highly damaged fault zone. The measurements using moving-window cross-correlation of waveforms for the repeated explosions and microearthquakes recorded at our arrays in 2002 and 2004 show a decrease in shear velocity of at least ~2.5% most likely owing to co-seismic damage of fault rocks caused by dynamic rupture in this M6 earthquake. The width of the damage zone characterized by larger velocity changes is consistent with the low-velocity waveguide model on the SAF near Parkfield derived from fault-zone trapped waves [Li et al., 2004]. The estimated ratio between the P and S wave traveltime changes is 0.57 within the rupture zone and ~0.65 in the surrounding rocks, indicating wetter cracks within the damaged fault zone, probably due to the ground water percolating into the cracks opened in the mainshock. The measurements of traveltime changes for repeated aftershocks in 21 clusters, with a total of ~130 events, located at different depths along the rupture in 2004 show that the maximum shear velocity increased by ~1.2% within the fault zone in 3.5 months starting a week after the mainshock, indicating that the fault heals by rigidity recovery of damaged rocks in the post-seismic stage due to the closure of cracks. The healing rate is logarithmically decreasing through time with greater healing rate in the earlier stage of the inter-seismic period. Recently, we analyzed the data recorded at seismograph installed in the SAFOD mainhole passing the San Andreas fault zone at ~3-km depths and in the pilot borehole ~1.8 km away from the main fault trace for repeated aftershocks occurring in December of 2004 and later, showing that seismic velocities changed by less then 0.3% within the fault damage zone in a month but no changes were registered at the pilot borehole. The magnitude of fault damage and healing varies along the rupture zone and with depth, but is most prominent at depths above ~7 km and roughly correlating with the slip distribution on the SAF in the 2004 M6 Parkfield earthquake [Johanson et al, 2006]. Our observations of fault zone damage and healing associated with this M6 event illuminate the faulting-healing progression on an active fault in the major earthquake, in general consistent with our previous observations of velocity evolution owing to damage and healing for Lander and Hector Mine earthquakes. However, the magnitude of damage and healing observed near Parkfield on the SAF is smaller than those on the Landers and Hector Mine rupture zones, probably related to the smaller magnitude mainshock, and smaller slip, and possibly differences in stress drop, pore-pressure, and rock type. With the successful drilling and instrumentation of the SAFOD mainhole, new information on this process should be forthcoming in the next cycle of the Parkfield earthquakes.

### High-Resolution Imaging of the San Andreas Fault from Fault-Zone Trapped Waves Recorded at the SAFOD Borehole Seismograph and Surface Array

*Li, Yong-Gang Li (USC), Peter M. Malin (Duke), John E. Vidale (UW), and Elizabeth S. Cochran (UCR )*

Highly damaged rocks along the San Andreas Fault (SAF) at Parkfield create a low-velocity waveguide to trap seismic waves from both earthquakes and explosions. We recorded prominent fault-zone trapped waves (FZTWs) at a seismograph installed in the SAFOD mainhole at ~3 km depth where the borehole passes the SAF and at a dense linear seismic array deployed across the fault surface trace for sources located within the fault zone. A systematic waveform analysis of borehole seismograms from ~300 after-

shocks of the 2004 M6 Parkfield earthquake and surface seismograms from ~100 local earthquakes recorded in the fall of 2003 allowed us to evaluate the variations in rock damage magnitude and extent on the SAF with high-resolution. These events occurred at depths from ~2 km to ~12 km and with epicenters in the distance range of ~15 km from seismic stations the recorded FZTWs are characterized by relatively large amplitudes and dispersive wavetrains at 3-12 Hz following S-waves. The duration time of dominant FZTWs after S-arrivals increase with the travel distance between the source and receiver either along the fault strike or with the depth, showing the continuous low-velocity waveguide existing on the SAF at Parkfield. We measured duration time of FZTWs after S-arrivals for the events at different depths with raypath incidence angles from these events to the seismic station smaller than 30o from vertical. The wavetrain lengths of FZTWs measured at surface stations within the fault zone show a progressively increasing trend from ~1.2 s to ~2.2 s as the event depths increase from 2.6 km to 11.7 km. These measurements are confirmed by the data recorded at the SAFOD mainhole seismograph. In contrast, the seismograms recorded at seismographs installed in the SAFOD pilot borehole ~1.8 km away from the SAF and the surface stations deployed out of the fault zone show much brief wavetrains after body waves. These observations indicate that the low-velocity waveguide formed by the damaged rock on the SAF likely extends across seismogenic depths with prominent seismic velocity reduction at depths above ~7-8 km. The smaller velocity reduction on the deeper portion of the fault damage zone is probably due to the larger confined stress at greater depths. The surface array data show that the damage zone on the SAF is not laterally symmetric but extends farther on the southwest side of the main fault trace. This could be due to rocks already weakened from previous faulting. It could also be due to greater damage in the extensional quadrant near the propagating crack tip of Parkfield earthquakes.

We modeled these FZTWs using 3-D finite-difference methods. The models suggest that, on average, the fault zone cross section consist of a composite of two nearly vertical layers, one a 30-40-m-wide fault core, the other a surrounding ~150-250-m wide damage zone depending on the depth. The damage zone velocities range between 70-80% of the fault zone wall rocks, while those of the core are even less, going as low as 40-50% of the intact rock. The widths and velocity reductions of the fault core and damage zone at ~3-km depth in our model are consistent with the direct measurements of fault-zone properties in the SAFOD mainhole [Hickman et al., 2005] as well as the borehole observations of fault guided waves following P-waves [Ellsworth and Malin, 2006]. We interpret the distinct low-velocity waveguide on the Parkfield SAF as being a zone of accumulated damage from recurrent major earthquakes, including the 2004 M6 earthquake. This type of damage varies with depth and also along the strike, and may relate to the on- and near-fault variations in stress and slip distribution during earthquake rupture.

### Elastodynamic simulations of seismic and aseismic slip history of a planar strike-slip fault in 3D

*Liu, Yi (Caltech) and Nadia Lapusta (Caltech)*

Simulations of spontaneous slip accumulation in three-dimensional (3D) models enjoy a lot of interest because of their ability to clarify earthquake physics. Extending from 2D studies by Lapusta et al. (2000), we present an efficient numerical procedure for elastodynamically simulating sequences of dynamic events on a planar fault interface subjected to rate and state friction and slow tectonic loading in 3D configuration.

As an implementation example, we consider a strike-slip fault embedded in an elastic half-space, and under slow tectonic loading from below. On the fault, a seismogenic region (30 km by 15 km) with velocity-weakening property, is surrounded by velocity-strengthening regions. The simulations produce realistic earthquakes and complicated seismic and aseismic slip patterns. Although each individual earthquake prefers to propagate unilaterally towards one direction, statistically both directions are equally preferable in sequences. After each earthquake, there is an accelerated post-seismic creep in the surrounding velocity-strengthening regions. During interseismic periods, the fault exhibits patterns of aseismic slip, with accelerating and decelerating patches and slow propagation of faster creep along the interface. When a stronger asperity (a small circular patch 20% stronger than the surrounding fault) is introduced in the seismogenic zone, it causes a supershear burst for the first event in the simulation but not for subsequent events, due to stress redistribution by prior slip histories. We also compare the results produced this fully-dynamic model with the widely-used quasi-dynamic model, and observe that the quasi-dynamic model produces more sluggish earthquake behavior, and cannot reproduce some dynamic features.

### Transition of shear cracks from sub-Rayleigh to supershear speeds in the presence of favorable heterogeneity

*Liu, Yi (Caltech) and Nadia Lapusta (Caltech)*

Understanding sub-Rayleigh-to-supershear transition of shear cracks is a fundamental problem in fracture mechanics with important practical implications for earthquake dynamics and seismic radiation. In the Burridge-Andrews mechanism, a supershear daughter crack nucleates, for sufficiently high prestress, at the shear stress peak traveling with the shear wave speed in front of the main crack. We find that supershear transition and sustained supershear propagation occurs in a number of other models that subject developing cracks to supershear loading fields. We consider a spontaneously expanding sub-Rayleigh crack (or main crack) which advances, along a planar interface with linear slip-weakening friction, towards a place of favorable heterogeneity, such as a preexisting subcritical crack or a small patch of higher prestress (similar behavior is expected for a patch of lower static strength). For a range of model parameters, a secondary crack nucleates at the heterogeneity and acquires supershear speeds due to the supershear stress field propagating in front of the main crack. Transition to supershear speeds occurs directly at the tip of the secondary crack, with the tip accelerating rapidly to values numerically equal to the Rayleigh wave speed and then abruptly jumping to a supershear speed. Models with favorable heterogeneity achieve supershear transition and propagation for much lower prestress levels than the ones implied by the Burridge-Andrews mechanism and have transition distances depending on the position of heterogeneity. We investigate the dependence of supershear transition and subsequent crack propagation on model parameters in 2D configuration. The preliminary study on 3D suggests qualitatively similar, but quantitatively different results as 2D models.

### The CSEP Testing Center

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The Collaboratory for the Study of Earthquake Predictability (CSEP) has established the initial hardware and software infrastructure for conducting earthquake forecast experiments. This system provides a controlled integration environment with a standardized software stack for developing and installing forecast models. CSEP development maintains a single source repository using open-source Subversion and conforms with continuous integration software practice by using open-source CruiseControl package as a framework for continuous build process. CSEP uses web-based software project management approach based on the open-source Trac project. Modular design of the CSEP software seeks to meet the requirement of experiment reproducibility; the processing infrastructure allows for automated evaluation of forecast experiments and manual processing for research activities. Furthermore, CSEP program codes are validated and distributed to other earthquake forecast testing facilities outside of California. We will discuss the design challenges and present the software concept, development strategies, ways for participating in development, and the ability to customize our open-source software. More information available at the project web site: www.cseptesting.org.

### A novel mechanism for compressing multi-terabyte wavefields

*Lopez, Julio (CMU), Leonardo Ramirez (CMU), Jacobo Bielak (CMU), and David O'Hallaron (CMU)*

Increasingly larger wavefield datasets have become the norm. Improvements in simulation techniques, advances in computer systems and growing storage system capacity enable scientists to generate and save more data. State-of-the-art ground-motion numerical solvers used at SCEC produce Terabyte-size wavefields per execution. Operating on these datasets becomes extremely challenging due to decades of declining normalized storage performance both in terms of access latency and throughput. Data access and transfer rates at the storage system have not kept pace with the increase in storage capacity or CPU performance. The ratios of seek time to disk capacity and transfer bandwidth to disk capacity have decreased. The consequence is that as dataset sizes increase, it takes much longer to access the data on disk. Common analysis queries on these datasets result in difficult to handle I/O workloads with mostly random access patterns.

We present new mechanisms that allow the querying and processing of large wavefields in the compressed domain, i.e, directly in their compressed representation. These mechanisms combine well-known spatial-indexing techniques with novel compressed representations in order to reduce bandwidth requirements when retrieving data from storage to main memory.

The compression technique uses a frequency-domain representation to take advantage of the temporal redundancy found in wave propagation data. This method is coupled with a new compressed format based on boundary integral representations, taking advantage of spatial coherence found in ground-motion wavefields. These combined techniques achieve compression factors as high as 10:1.

This approach transforms a large I/O problem into a massively-parallel CPU-intensive computation. We evaluate our approach in the context of data-intensive analysis tasks performed on wavefields generated by the CMU Hercules toolchain.. Read access patterns on the compressed representation are largely sequential, e.g., in the order of megabytes at once. The decompression stage for this approach places heavy demands on the CPU. The good news is that the decompression can be performed in parallel, and is well-suited for the emerging many-core processors.

### SCEC/UseIT: Point System for the Mitigation Game

*Love, Portia (Rust College)*

The Undergraduate Studies in Earthquake Information Technology (Use IT) combines earthquake science and computer programming to make and distribute useful products information to the public and students. Every summer this program issues out a grand challenge ours was to prototype serious games to make the games we were then broken up into teams and I was part of the decision making game team. Our team could not stay with one particular game plan. So a while we came up with two separate ideas and teams, I joined team four to work on the newest game. In group four I was responsible for developing the point system for different mitigation options. For example, if you click on a window to bolt the furniture to the floor it would take 100 points, while securing pictures to a wall may cost you 30 points to do. I distributed the points as to where the level of importance is indicated. I also developed the content of the popup windows in the games city level that explains the mitigation choices and importance. If the player does not retrofit their historical buildings a tab will pop up that lets them know the consequences of not doing so. I would definitely like to come back next summer to see this project finished and maybe even start on another one.

### Pulse-like and Crack-like Ruptures in Experiments Mimicking Crustal Earthquakes

*Lu, Xiao (Caltech), Nadia Lapusta (Caltech), and Ares Rosakis (Caltech)*

Theoretical studies have shown that the issue of rupture modes has important implications for fault constitutive laws, stress conditions on faults, energy partition and heat generation during earthquakes, scaling laws, and spatio-temporal complexity of fault slip. In theoretical models, earthquake ruptures are frequently assumed to behave like cracks, but seismic inversions indicate that earthquake ruptures may propagate in a self-healing pulse-like mode (Heaton, 1990). A number of explanations for the existence of slip pulses have been proposed and continue to be vigorously debated. These include strong weakening of the interface with sliding rate, interaction of rupture with local heterogeneities, and normal stress variation for ruptures propagating at interfaces between two different elastic materials.

In the present study, we have experimentally observed pulse-like and crack-like rupture modes, and a systematic transition between them, in an experimental configuration that contains an interface prestressed both in compression and in shear, similarly to faults in the Earth's crust. Our results indicate that pulse-like ruptures can exist on such interfaces in the absence of a bimaterial effect or local heterogeneities. The systematic transition of rupture modes from pulse-like to crack-like presented in this work is qualitatively consistent with the theoretical study of velocity-weakening interfaces by Zheng and Rice (1998). We also establish experimentally, for the first time, that both pulse-like and crack-like rupture modes can transition to supershear speeds. The resulting supershear rupture speeds are consistent with the analytical predictions of the velocity-weakening model of Samudrala et al. (2002). The agreement between our experimental observations and models of velocity-weakening faults suggests that velocity-weakening friction plays an important role in dynamic behavior of ruptures and implies that expressing dynamic weakening of friction solely in terms of slip may not be a sufficiently general description.

Some recent numerical studies have pointed out the importance of the rupture initiation process for subsequent rupture dynamics, especially for supershear transition but also for the establishment of the mode of rupture (Lu et al., 2005; Festa and Vilotte; 2006, Shi et al., 2006; Liu and Lapusta, 2007). Our current work is focused on modeling the experimental setup numerically to gain further insight into implications of the presented experimental observations, including the role of the nucleation procedure employed in experiments. To make a meaningful comparison between simulations and experiments, we plan to quantify independently a number of input parameters, including parameters of the rupture nucleation mechanism and friction properties of Homalite interfaces.

### Scaling relations of earthquakes in a damage rheology model

*Lyakhovsky, Vladimir (Geological Survey of Israel) and Yehuda Ben-Zion (USC)*

We perform analytical and numerical studies of scaling relations of earthquakes and partition of elastic strain energy between seismic and aseismic components using a thermodynamically-based continuum damage model. Brittle instabilities occur in the model at critical damage level associated with loss of convexity of the strain energy function. A new procedure is developed for calculating stress drop and plastic strain in regions sustaining brittle instabilities. The formulation connects the damage rheology parameters with dynamic friction of simpler frameworks, and the plastic strain accumulation is governed by a procedure that is equivalent to Drucker-Prager plasticity. The numerical simulations use variable boundary forces proportional to the slip-deficit between the assumed far field plate motion and displacement of the boundary nodes. These boundary conditions account for the evolution of elastic properties and plastic strain in the model region. Three-dimensional simulations of earthquakes in a model with a large strike-slip fault produce scaling relations between the scalar seismic potency, rupture area, and stress drop values that are in good agreement with observations and other theoretical studies. The area and potency of the simulated earthquakes generally follow a linear log-log relation with a slope of 2/3, and are associated with stress drop values between 1 and 10 MPa. A parameter-space study shows that the area-potency scaling is shifted to higher stress drops in simulations with parameters corresponding to lower dynamic friction, more efficient healing, and higher degree of seismic coupling.

### Geothermal Features Southeast of the Salton Sea and a Possible Extension of the San Andreas Fault

*Lynch, David K. (Thule Scientific & USGS Volunteer) and Kenneth W. Hudnut (USGS)*

Following the early work of Muffler and White (GSA Bull., 1969), we have surveyed the mud pots, mud volcanoes and related geothermal vents between Wister and Obsidian Butte including the active vents near Mullet Island. The entire area falls within the Brawley Seismic Zone (BSZ) and is generally believed to be the transition zone between the right-lateral San Andreas Fault transform system and an extensional basin representing the northern-most spreading center of the East Pacific Rise. Our survey revealed approximately 50 features – 35 of which are new – that appear to form a series of NW trending en echelon structures like those suggested by Kelley and Soske (1936). A study of aerial photographs of the area, in situ investigations and interviews with personnel in the area from the US Wildlife Service and the California Dept of Fish and Game revealed that the structure are active and changing on time scales of months to decades: at least three features have appeared since 2005. The northern-most lineament coincides with the putative Sand Hills Fault (Algodones Fault) and with a virtually straight SE extrapolation of the SAF from Durmid approximately 20 km to the NW. The area immediately surrounding this extension (+/- 1 km) is largely aseismic in modern times though there are a number of SE and SW trending seismic lineaments in the BSZ in the southern part of our study area.

### Rupture Dynamics on a Bi-material Interface for Dipping Faults

*Ma, Shuo (Stanford University) and Greg Beroza (Stanford University)*

Dip-slip faulting will juxtapose different geologic materials with different properties, such that a strong material contrast will naturally tend to form. Both material contrast across a fault, and dip-slip motion on a non-vertical fault, lead to normal stress variations during earthquake rupture. This normal stress variation

will significantly affect dynamic rupture propagation. To demonstrate this, we model dynamic rupture propagation on 45-degree dipping, 2-D, reverse and normal faults with 20% material contrasts. We find that normal stress variations due to the free surface and material contrast can either reinforce or counteract each other depending on the configuration. For reverse faults, we find a larger stress drop for a more compliant hanging wall, and lower stress drop for a more compliant footwall. For normal faults, we find a larger stress drop for a more compliant footwall, and lower stress drop for a more compliant hanging wall. For both reverse and normal faults, ground motion will be more symmetric between the hanging wall and footwall with compliant material on the footwall and more asymmetric if more compliant materials are on the hanging wall. Our results have important implications for the dynamics of crustal, and perhaps subduction-zone, earthquake faulting, where strong bi-material contrasts across dipping faults are likely. In continental settings, reverse faulting will tend to advect rigid materials from greater depth onto the hanging wall, such that the effects of fault dip and material contrast will counteract one another. In subduction zones, the hanging wall is likely to be more compliant, and hence the two effects may reinforce one another.

## SCEC/UseIT: Visualization Grand Challenge

*MacLeod, Eric (College of the Desert)*

The Undergraduate Studies in Earthquake Information Technology (UseIT) interns are presented a grand challenge that has to be met by the end of the internship. This year's grand challenge was to create a "serious game" that presents to the gamer knowledge of earthquake science that is understandable and fun to play. There were twenty interns in four groups to develop an education game, a training game, and two decision-making games. Each person in a group works on different levels of their game. We used scientific visualization, image processing, computer graphics, animation, and simulation in order to help present information in a new way so that the gamer can recognize patterns, understand scientific reasoning and societal problems that a geoscientist may encounter during a catastrophic earthquake. I was involved in the decision-making game called Breaking Point and for ten weeks I designed earthquake imageries of areas most prone to seismic activities using 3-D images from Live.com and doctoring them to give them that disaster look. I spent time familiarizing myself with SCEC-VDO and using Google Sketch-Up 6 to design our games visuals. In addition I started to learn how to write computer code in Flash 9 which is the gaming engine for our game. Throughout the internship I have met a diverse range of majors, which brought a new insight to geo-visualization from those who are not geosciences majors. And that to me is a goal well achieved.

## Accelerating SCEC Seismic Hazard Research through the use of High Performance Computing on the PetaSHA Project

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During the first year of the NSF-funded PetaSHA project, the SCEC CME collaboration has continued to advance SCEC's seismic hazard research program through the use of high performance computing. The PetaSHA research areas including dynamic rupture modeling, wave propagation modeling, probabilistic seismic hazard analysis, and full 3D tomography. The PetaSHA computational capabilities are organized around the development of robust, re-usable, well-validated simulation systems we call computational platforms. Member of the PetaSHA Project are currently developing the DynaShake Platform (dynamic rupture simulations), the TeraShake Platform (wave propagation simulations), the CyberShake Platform (physics-based probabilistic seismic hazard analysis), the BroadBand Platform (deterministic and stochastic modeling of high frequency synthetic waveforms), the Full 3D Tomography (F3DT) Platform (improvements in structural representations), and utilizing the existing OpenSHA Platform. In this poster, we describe several current PetaSHA research projects including the application of the DynaShake Platform to dynamic rupture modeling of the ShakeOut source, the use of the TeraShake Platform, including both the SDSU and CMU AWP codes, to model 1Hz ShakeOut simulations, the use of the CyberShake Platform to investigate physics-based PSHA hazard curves, and the use of the F3DT Platform to produce an improved structural model for a large region in southern California.

### Properties of large-slip asperities from the updated database of finite-source rupture models

*Mai, P. Martin (ETH Zurich)*

SRCMOD – the online database of finite-source rupture models – has been updated and expanded, and now features a number of important improvements. It includes exact geographical data about fault-plane and fault-segmentation parameterization used in the source inversion. Meta-data on the slip inversion setup used in each study are given, the temporal rupture evolution is fully represented (if provided by the source modeler), and rupture models are checked for internal consistency. We also added a large number of source models such that the database now contains more than 150 rupture models for more than 80 earthquakes in the magnitude range 4.1 ≤ Mw ≤ 8.9. As such, the SRCMOD-database represents an important tool for studies on simulation-based ground-motion prediction, earthquake dynamics, fault mechanics, static stress change calculations due to earthquake slip.

Here I introduce the latest version of the database and argue for a common standardized format on how earthquake rupture models should be presented and which meta-data need to be provided in any publication. I also examine several properties of large-slip asperities and their contribution to near-source radiation, i.e. the number and size of asperities, the slip-contrasts between asperities and surrounding low-slip regions, the asperity stress-drop, rise-time on and rupture velocity over the asperity (only possible for models with data on temporal rupture evolution). Studying slip asperity properties helps to address the general topic of "radiation strength" of asperities. I also distinguish single-segment from multi-segment source models in terms of their asperity behaviour, since earthquakes on immature and geometrically complex faults may show different rupture characteristics than earthquakes on mature and geometrically simple faults.

### Strain localization in a continuum model for fault gouge and amorphous materials

*Manning, M. Lisa (UCSB), James Langer (UCSB), and Jean Carlson (UCSB)*

Fault gouge may play an important role in determining friction on an earthquake fault. At small displacements, the gouge is homogeneous and shear strengthening, but at intermediate displacements in the post-yield region, experiments have shown that the gouge develops shear bands and becomes slip weakening (Logan et. al 1992, Beeler et. al, 1996). This has important implications for the friction law on the fault. Currently, phenomenological rate and state friction laws do not explicitly model spatial variations within the gouge, such as shear banding. Our goal is to develop a physics-based model for friction on the earthquake fault that accounts for shear localization. We develop and analyze a physically motivated mesoscopic model for the granular material based on the theory of shear transformation zones. Our analysis shows that an "effective temperature," which is a generalized free volume, is the relevant state variable that permits shear localization. We show that the model quantitatively matches shear banding in simulations of glassy materials, and prove that a transient instability is responsible for the localization process. Our work suggests that although the homogeneous state is shear strengthening, the transient state with a shear band exhibits novel behavior and might be slip weakening. We also discuss work in progress to improve the model and use it in dynamic rupture modeling.

### Interseismic Deformation along Intersecting Faults: Application to the Greater Los Angeles Region, CA

*Marshall, Scott T. (UMass), Michele Cooke (UMass), and Susan Owen (USC/JPL)*

We present a new methodology for simulating interseismic deformation along interacting faults in tectonically complex regions. We show that the analytical solution for a semi-infinite vertical strike-slip fault is identical to that of a vertical fault of finite height that soles into two horizontal detachments with opposite senses of slip. Because this solution is independent of depth to the detachment, we choose the detachment to be located at Moho depth, where the crust may be decoupled from the mantle. Based on this analytical solution, we formulate a two-step numerical simulation of the earthquake cycle that allows three-dimensional fault surfaces to interact and accumulate mechanically and kinematically sound slip rates and distributions. In the first step, we solve for the distribution of total (i.e. entire earthquake cycle) fault slip along multiple faults within a three-dimensional geologic model that permits slip at all crustal levels. Then, to simulate interseismic deformation, slip from the geologic model below the seismogenic locking depth is mapped onto fault surfaces; above the locking depth slip is zero. Because the slip results from the geologic model are applied to the interseismic, this technique does not require inversion and can be used to investigate fault systems with any degree of complexity. Using this two-step technique, the interseismic model results match well the conventional velocity profile for a single transform fault. We apply this technique to the Los Angeles region and find that geologic model results match well geologic slip rate data and interseismic model results match well the heterogeneous GPS velocity pattern in the Los Angeles region including localized convergence in the San Gabriel basin noted in previous geodetic studies. The modeled rates of convergence in the San Gabriel basin match well geodetic rates with geologically reasonable fault slip rates implying agreement between recent GPS and geologic shortening rates. This new modeling technique offers the first methodology for simulating interseismic deformation along finite, intersecting, nonplanar faults.

## Late Neogene structural and stratigraphic relations in the Santa Rosa Mountains, southern California: implications for Quaternary strain distribution in the southern San Andreas Fault system

*Matti, J.C. (USGS), V.E. Langenheim (USGS), D.M. Morton (USGS), B.F. Cox (USGS), and G.P. Landis (USGS)*

Structural and stratigraphic relations in the Santa Rosa Mountains (SRM) on the west side of the Salton Trough can be used to evaluate the Quaternary history of transtensional and transpressional strain in the southern San Andreas Fault system. Key to this evaluation is a late Neogene sequence of terrestrial and marine sedimentary rocks (Zosel sequence) that is faulted against crystalline basement rocks of the southern SRM by a top-to-the northeast normal fault (Zosel Fault). The Zosel sequence accumulated syntectonically in the hanging wall of the Zosel Fault from at least 6 Ma to ~1.1 Ma while footwall crystalline rocks to the west were uplifted, suggesting that the Zosel Fault and Zosel sequence formerly were part of the West Salton Detachment system of Axen and Fletcher (1998). The Zosel sequence contains distinctive hornblende tonalite clasts that uniquely match with bedrock now exposed ~24 km to the northwest in the White Wash (WW) area, west of the Clark strand of the San Jacinto Fault (SJF). Restoration of 24 km of right-slip on the Clark strand positions the WW source opposite the Zosel sequence in the SRM where it shed clasts northeastward parallel with paleocurrent trends in Zosel strata.

If their present elevations are retained, the restored WW basement is ~300 m lower than the highest Zosel sequence near the SRM range crest. Between the restored WW source and the Zosel deposits are the down-dropped upper Clark Valley and the profound west-facing escarpment of the southern SRM. Gravity data suggest that sedimentary fill in upper Clark Valley is about 1.2 km thick. Thus, not only does an elevation mismatch exist between sediment source and sediment sink, but a deep structural depression has developed along the former Zosel sediment-dispersal pathway. This requires that the relative vertical positions of sediment source and sediment sink have reversed by at least 1.5 km since hanging-wall deposition of the Zosel sequence ended, an event that may have initiated as recently as 1.1 Ma.

Two alternative scenarios can account for these anomalous relations. (1) The Zosel sequence became attached to the footwall during later stages of detachment faulting, and was thereby uplifted isostatically to its current elevation. (2) Contractional deformation of the SRM block unrelated to detachment faulting uplifted both footwall and hangingwall blocks. We favor (2), and propose that the SRM block was elevated by regional transpression coeval with Quaternary development of the SJF zone.

Our main findings include: (1) Our estimate of ~24 km of displacement on the Clark strand of the SJF agrees with Sharp's (1967) estimate (22-26 km); (2) the SJF has a maximum long-term slip rate of 22 mm/yr since about 1.1 Ma; (3) the SRM block has a minimum long-term uplift rate of 1.4 mm/yr, which should be factored into the overall strain budget for the southern San Andreas Fault system; (4) transpressional uplift of the SRM block may result from a regional left step between the San Andreas and San Jacinto faults in Quaternary time (Matti and Morton, 1993).

### Pleistocene and Holocene slip rate of the San Andreas fault at Badger Canyon, San Bernardino, California

*McGill, Sally (CSU San Bernardino), Katherine Kendrick (USGS Pasadena), Ray Weldon (University of Oregon), and Lewis Owen (University of Cincinatti)*

Four alluvial fans of differing ages been offset from the mouth of Badger Canyon (near the campus of California State University, San Bernardino), along the San Bernardino strand of the San Andreas fault. No other nearby drainages are large enough nor have the correct clast lithologies to have been the source of the fans. Trenches excavated by a consulting firm in the fall of 2005 offered an opportunity to view the subsurface stratigraphy within the fans and to collect samples for radiocarbon and optically stimulated luminescence dating, as well as for descriptions of soil profiles. The oldest fan remnants, Qf1, have not yet been dated, but are offset about 715 meters from Badger Canyon. OSL dates from this unit are pending.

The next oldest fan, Qf2, is composed of 3 lobes. A detrital charcoal sample from near the apex of the central lobe has a radiocarbon age of 24,380 years before present (BP). Alignment of this apex with the center of Badger Canyon suggests an offset of 350-380 meters and a preferred slip rate of about 15 mm per radiocarbon year. There is a wide range of allowable offsets for this fan, but the maximum possible offset would be 460 meters, to the east edge of Badger Canyon. This yields a maximum slip rate of 19 mm per radiocarbon year. The geologic history of the western and eastern lobes of the Qf2 fan is less certain, but the most reasonable interpretation we can think of suggests similar slip rates.

Three radiocarbon dates from the Qf3 fan range from 12.5 to 13 ka. The feature that appears to give the clearest estimate of the slip rate for this time period is the somewhat subtle terrace riser that separates the Qf3 fan from the younger and lower, Qf4 fan. This riser is offset at least 85 meters from the riser that separates the Qf4 terrace from the next higher terrace north of the fault. The maximum age of this riser would be the age of abandonment of the Qf3 fan, at or shortly after 12.5 ka, suggesting a minimum slip rate of 7 mm per radiocarbon year. Of course, the upstream channel may have continued to widen, after the riser initially incised, thus lessening the apparent offset. However, the maximum offset of this riser is 150 meters to the east edge of Badger Canyon, which suggests a maximum slip rate of 12 mm per radiocarbon year, or perhaps slightly faster, if the Qf3 fan continued to aggrade for a short time after the youngest samples were deposited and before the surface was abandoned by incision of the riser.

The apex of the Qf4 fan appears to be offset 15-20 meters right laterally, suggesting a slip rate of 11.5-15 mm per radiocarbon year given the 1315 BP radiocarbon age for a detrital charcoal sample from with the Qf4 terrace north of the fault. One could argue for a larger or smaller offset of this fan, however.

Thus the preliminary slip rates at three different time periods (~24 ka, ~12.5 ka and ~1.3 ka) all suggest that the slip rate at this location is probably slower than the 24.5 mm/yr rate measured near Lost Lake, 17 km to the northwest (Weldon and Sieh, 1985), though not as slow as the 5 mm/yr rate estimate from geodetic modeling (Meade and Hager, 2005). The lower slip rate here than at Lost Lake may reflect transfer of slip from the San Andreas fault to the San Jacinto fault a short distance southeast of the Lost Lake slip rate site.

### A Five Year Seismic Cycle on EPR Transform Faults

*McGuire, Jeff (WHOI)*

The concept of a seismic cycle, where the stress on a fault repeatedly builds up over a long period of time and then is rapidly released in a large earthquake, influences studies of both the basic physics of faulting and applied research aimed at estimating earthquake hazards. This hypothesis suggests that large earthquakes might be quasiperiodic and that the probability of a particular portion of a fault rupturing twice in quick succession should be low. However, this basic hypothesis has been difficult to verify in detail owing to the long repeat times of the largest earthquakes on most faults. East Pacific Rise (EPR) transform faults are an advantageous location to evaluate the seismic cycle hypothesis owing to their fast slip-rates and the moderate size (~Mw 6) of their largest earthquakes. Using surface-wave based determinations of the relative separations between earthquake centroids, I document 16 pairs of Mw ? 5.5 events that had overlapping ruptures. The distribution of interevent times for these pairs is tightly clustered around 5 years (with a coefficient of variation ~0.15) indicating that quasiperiodicity may be prevalent for the largest events on

these faults. Moreover, I find no pairs of overlapping Mw 5.5-6.2 earthquakes that were separated by less than 50 cm of elapsed plate motion indicating that the two basic features of the seismic cycle hypothesis are evident in the timing of large EPR transform mainshocks. Our results suggest that at least for the largest earthquakes (M ? Mc) on highly localized plate boundaries, there is a considerable degree of intermediate term (years) predictability.

### Aseismic Transients and Earthquake Triggering in the Salton Trough

*McGuire, Jeff (WHOI) and Tom Herring (MIT)*

To investigate the role of aseismic fault slip in earthquake triggering, we compare the timing of fault creep transients and earthquake swarms in the Salton Trough. The increased density of cGPS stations deployed by the Plate Boundary Observatory since late 2005 allows for much higher detection levels for transient aseismic fault slip. Rock mechanics theory predicts that seismicity-rates on the deeper portion of the fault should increase during shallow creep events owing to the increased stressing-rate but this has not been quantitatively tested.

Owing to the short time scales of most creep events (days), we utilize 6 hr GPS solutions for a subset of stations in the Salton Trough region. The solutions are inverted for fault-slip using the extended Network Inversion Filter (NIF) method (Segall and Mathews 1997, McGuire and Segall 2003). The large seasonal signals at many sites are modeled using a random walk with a scale of 3 mm/yr(1/2). The 2005 transient near Obsidan Buttes at the southern end of the Salton Sea (Lohman and McGuire, 2007) is easily detected despite having only ~8 relatively distant stations operating during the transient and hence a total offset of only 2-4 mm on any component. We have not detected any transients on the same fault since the September 2005 swarm.

We are also searching for aseismic transients directly from the seismicity catalogs using the time-dependent version of the Epidemic Type Aftershock Sequence (ETAS) methodology [Hainzl and Ogata, 2005]. In this approach, aseismic transients are expected to be identified as periods of high background seismicity-rate ( $\lambda$ (t)). The ETAS parameters are optimized by maximum likelihood fitting in a sliding time window. In practice, for this approach to identify transients, the length of the time-window must be on the order of the duration of the transient, otherwise, the ETAS model is unable to fit the observed cumulative number of earthquakes vs time trajectory in a time period that includes a swarm. The 2005 swarm requires window lengths smaller than 3 months to resolve the aseismic stressing transient. Thus, this approach will likely only work for catalogs with extremely low detection thresholds that allow the ETAS parameters to be resolved in short time windows.

### SCEC/UseIT: The Simulation Game in 3D

*McQuinn, Emmett (Clemson)*

Undergraduate Studies in Earthquake Information Technology (UseIT) is a program hosted by SCEC at the University of Southern California. Each summer the program poses undergraduate interns with a grand challenge in seismic information technology. The Grand Challenge of 2007 was to research and create several serious games. As a member of the Decision-Making Team, my summer was focused on creating a 3D game using Java and OpenGL. This game, called "The Simulation Game," is similar to Sim City based on earthquake damage mitigation. The objective is to reduce casualties after an earthquake by choosing to establish emergency response centers, prepare buildings, or research areas for hazards. I researched many different 3D Java Application Programming Interfaces, but OpenGL was chosen over other 3D programming interfaces because of the ability to display greater detail in visual effects and the most elemental 3D function calls. The Simulation Game was the result of team coding, so I was responsible for other aspects of the game including, earthquakes, buildings, and architecture. When not working on The Simulation Game, I helped other game teams with technology questions and solved several bugs in SCEC-VDO, including fixing the save and load functionality of SCEC-VDO.

## Effect of Rupture Complexity on Near-Field Strong Ground Motion: Aspects of Rupture Directivity

*Mena, Banu (ETH Zurich) and P. Martin Mai (ETH Zurich)*

Near field velocity seismograms resulting from forward directivity are dominated by pulse-type motions. These pulse-type motions impose large demands on structures and have significant influence on exciting soil liquefaction. We propose a procedure utilizing spectrogram analysis for automated search, classification and quantification of forward directivity velocity pulses. We defined several condition indicators (pulse period, dominant frequency, number of cycles, total duration of pulse-like motion/effective pulse period, potential higher-frequency content in the dominant pulses) to characterize these pulses. Making use of the NGA (New Generation Attenuation) strong motion database and the recently improved finite source rupture model database (http://www.seismo.ethz.ch/srcmod) we investigate relationships between ground motion parameters and the detailed source rupture process. Particular emphasis is given to on-fault and global directivity effects, affecting the pulse-like character of near-field velocity recordings, and their relation to geometrical rupture complexity. Using the geometrical directivity model of Rowshandel (2006) we investigate directivity both for homogeneous and heterogeneous rupture. A comparison between the near-field data, classified and quantified by the proposed spectrogram analysis, and the geometrical directivity model reveals that size and location of the large slip asperities determine whether we should expect forward or backward directivity properties at the site of interest. We found strong correlation between the number of asperities and the number of cycles in the velocity time history. Besides the number of asperities, the asperity distribution along multiple fault segments also needs to be considered when looking for an estimate of number of velocity cycles. Although we confirm previously reported general scaling relation between pulse period and magnitude, a new parameter defined in this study, the effective pulse period, better represents the pulse characteristics and has stronger correlation with magnitude. The geometrical directivity parameter well estimates the existence of a directivity pulse but we found no correlation between pulse period/effective pulse period and geometrical directivity parameter. In addition, we examine the dominant frequencies of the pulse-like motions and higher-frequency wave-field components, determined for the near-field forward-directivity recordings in the NGA database.

## SCEC Science Workflows - Reducing the Time to Insight

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Significant computing capabilities are required for the advancement of SCEC science goals. Fundamental to these goals is a need to reduce the time to insight. The SCEC Community Modeling Environment (SCEC/CME) Project and the current SCEC PetaSHA Project have demonstrated that scientific workflow methods enable a significant reduction in multi-step computatational time, allowing SCEC researchers to focus on the analysis of results.

In the last year, a number of software and systems improvements in the design and execution of science workflows have been incorporated in the CyberShake platform and the SCEC Earthworks Science Gateway. These improvements have resulted in an enhanced facility for members of SCEC to explore high throughput and high performance grid computing for reducing time to insight. We examine adaptation of CyberShake workflows to the Teragrid and new capabilities in the SCEC Earthworks Science Gateway that increase the analysis options for the scientist.

## SCEC/UseIT: Interactive Education

*Millar, Alexandra (Hamilton College)*

Each summer the SCEC/UseIT (Undergraduate Studies in Earthquake Information Technology) program challenges approximately twenty interns to utilize their knowledge in a team setting to accomplish a series of tasks under the grand challenge. The 2007 grand challenge asked the interns to create three different “serious games,” including an educational, training and decision making game.

As a 2007 intern, I was a member of the Educational Gaming team whose goal was to create a serious game to communicate introductory level geology concepts to a broad range of students. With future de-

velopment in mind, our game was designed to allow easy accommodation of new information, additional "mini-games" and several levels of increasing complexity. The current edition of our game has been built through the first level in Adobe Flash CS3 and is organized into five separate parts. My principal contribution to the team is the conceptualization and creation of the main board game. This game is the primary screen that allows the player to access the four "mini-games" and introduces pertinent geology concepts essential to the player's success later on. I am excited to leave the program having gained exposure and familiarity with writing computer code and creating computer animations.

**Fate of slip along the Calico fault north of its intersection with the Manix fault, central Mojave Desert**

*Miller, David M. (USGS) and David J. Lidke (USGS)*

The Calico fault is a northwest-striking dextral fault of the Eastern California shear zone that traverses much of the Mojave Desert. Along the southern part, it is a high slip-rate (1.6 ± 0.2 mm/yr; Oskin et al., 2007) fault with pronounced tectonic geomorphic features such as scarps, offset channels, and shutter ridges. At the south end of the Calico Mountains (near Minneola) the fault bends to the west-northwest and there and farther north apparently has reduced slip rate. Its interaction with the Manix fault at Minneola is complex, and many fault relations there bear on changes in slip along the Calico fault.

Preliminary studies by field methods and aerial photographic interpretation provide information on changes in fault behavior at the Minneola intersection. Northwest of Minneola, no Holocene offset along the Calico fault is documented and only minor scarps in late Pleistocene deposits are present. The east-striking sinistral Manix fault lies east of Minneola, where it typically is comprised of three splays that can be identified in outcrop in a few locations. Between these locations, position of faults is inferred from subtle ridges, pop-ups, and lineaments. A pop-up at the intersection between the Dolores Lake fault and the Manix fault raises middle to late Pleistocene Lake Manix beds a minimum of 50 m (Reheis et al., in press), marking shortening at a corner of a tectonic block or a complex stepover. West of the Minneola intersection of the Manix and Calico faults, a sinistral east-striking fault is on trend with the Manix fault, suggesting that the Manix fault system cuts or is interleaved with the Calico fault. North from Minneola, the Tin Can Alley fault (Dudash, 2006) cuts late Pleistocene (~75 ka; Maher et al. 2007) deposits and may accommodate some of the slip north of the Minneola intersection. We suggest that since the middle Pleistocene much of the slip along the southern Calico fault system has been transferred northeastward from the Minneola intersection to the Tin Can Alley and Manix faults. Presumably, the slip is then transferred to faults farther north and east, rather than northwest along the Calico fault and its extensions such as the Blackwater fault.

**SCEC/UseIT: Topography/Satellite Images Anywhere!**

*Milner, Kevin (USC)*

This summer I participated in the Southern California Earthquake Center (SCEC) Undergraduate Studies in Earthquake Information Technology (UseIT) program, a collaborative IT research internship with 20 interns and numerous mentors in the scientific community. The Grand Challenge, or goal for the summer was to develop and prototype serious yet entertaining games that convey important earthquake science concepts, which was a departure from previous summer's work doing software development for SCEC-VDO (Virtual Display of Objects). As a computer science major and returning intern from last year, I spent most of my time developing features for SCEC-VDO, including a Navigation Training game that teaches the user how to navigate in the 3-Dimensional world inside of SCEC-VDO. I also added the ability to import Digital Elevation Models (DEMs) with bathymetry and satellite images from the internet for any region of the earth. The satellite images are from the National Aeronautics and Space Administration (NASA) Blue Marble Next Generation project and are obtained from a NASA web service, but the DEMs are downloaded from a web service that I wrote (in collaboration with University of Southern California geophysicist Dr. David Okaya who supplied the data and data extraction code) now running on a SCEC server.

## ShakeOut Scenario 2008: Performance of Tall Steel Buildings

*Muto, Matt (Caltech) and Swaminathan Krishnan (Caltech)*

Currently, there is a significant campaign being undertaken in southern California to increase public awareness and readiness for the next large earthquake along the San Andreas Fault, culminating in a large-scale earthquake response exercise. The USGS ShakeOut scenario is a key element to understanding the likely effects of such an event. In support of this effort, a study is being conducted to assess the response of tall steel structures to a M7.8 scenario earthquake on the southern San Andreas Fault.

Presented here are preliminary results for two structures. The first is a model of an 18-story steel moment frame building that experienced significant damage (fracture of moment-frame connections) during the 1994 Northridge earthquake. The second model is of a very similar building, but with a structural system redesigned according to a more modern code (UBC 97).

Structural responses are generated using three-dimensional, non-linear, deteriorating finite element models, which are subjected to ground motions generated by the scenario earthquake at 1447 points spaced at 2 km throughout the San Fernanado Valley, the San Gabriel Valley and the Los Angeles Basin. The kinematic source model includes large scale features of the slip distribution determined through community participation and short length scale random variations. The rupture initiates at Bombay Beach and extends northwest to Lake Hughes, with a total length of just over 300 km and a peak slip of 12 m at depth. The resulting seismic waves are propagated using the SCEC community velocity model for southern California, with ground velocities up to 2 m/s and ground displacements up to 1.5 m in the region considered in this study.

Initial results indicate a high probability of collapse for the pre-1994 building in areas of southern California where many high-rise buildings are located, with predicted peak inter-story drifts as high as 0.07 in downtown Los Angles, Long Beach, and Anaheim and as high as 0.09 in Santa Monica (peak inter-story drifts of 0.05 may be indicative of incipient collapse). Additionally, there is the potential for damage in other areas, with drifts of 0.02 in Westwood and Hollywood, and up to 0.04 in Encino, Pasadena and Irvine.

Performance of the redesigned buildings is substantially improved, with peak inter-story drifts dropping down into the 0.04 to 0.05 range for areas where the pre-1994 structure experienced drifts of 0.07 to 0.09. Ground motions that produced drifts of 0.02 to 0.04 in the pre-1994 building model result in peak drifts in the range 0.01 to 0.03 for the redesigned building.

Results from a similar study involving an 1857-like M7.9 scenario earthquake on the Parkfield-Wrightwood section of the southern San Andreas Fault showed strong influence of directivity with the north-to-south rupturing event having a much more severe impact on tall steel buildings than a south-to-north event. For the Bombay Beach-Lake Hughes section of the San Andreas fault, however, the effect of directivity can be expected to lead to more intense ground motions in the south-to-north rupture simulated here rather than a north-to-south rupture. From a seismic hazard analysis point of view, it would be important to consider this alternate scenario associating suitable probabilities with both scenarios. In fact, for a quantitative seismic hazard analysis one would need to perform many scenarios with different source models (varying source parameters such as hypocenter, rupture direction, slip distribution, etc.)

## Structural Damage Detection Using Numerical Techniques: Prototype Study of the UCLA Factor Building

*Muto, Matt (Caltech), Thomas Heaton (Caltech), Swaminathan Krishnan (Caltech), and Monica Kohler (UCLA)*

The 72-channel UCLA Factor building array is providing valuable earthquake data for use in dynamic analysis model verification. It is one of only a handful of buildings in the U.S. permanently instrumented on every floor, providing information about how a common class of urban structures, mid-rise moment-frame steel buildings, responds to strong ground shaking and how the response may change as the building is damaged. The advantage of such dense arrays is that they allow for high-resolution examination of alternative wavefield representations of wave propagation through buildings. Ultimately such data can be used

to calibrate and verify structural models in end-to-end simulations for their reliable use in damage assessment and mitigation.

We are conducting numerical simulations of the Factor building subjected to damaging seismic events using FRAME3D, a finite-element method-based nonlinear structural analysis program that can simulate fracture in the moment-frame connection welds. The structural model uses elastofiber beam elements for columns and beams, and 3D cruciform joint elements to model panel zones. The segments at each end of the beam element are discretized into 20 fibers in the cross section. The behavior of each fiber is modeled using a non-linear hysteretic stress-strain law. Damage to the Factor building model is introduced by reducing the fracture strain of the fibers and computing building properties before and after large-amplitude motions. We are investigating the scenario where the fracture strain of both top and bottom flange welds is reduced, resulting in failure of the shear tab that is bolted to the web of the beam and welded to the column. In reality the failure usually occurs at the line of bolts at the beam web, not at the weld to the column, though we are not modeling the line of bolts or the failures associated with bolt friction and shearing. We apply the strain reductions to the flange welds on the east wall in three separate cases: floors 3-5, floors 6-8, and floors 9-11.

After fracturing the welds in the model, we compute the building response to the impulsive December 16, 2004 ML=3.6 Santa Monica Bay earthquake and record changes in both modal and traveling wave properties such as drift mode shapes, frequencies, and torsional mode excitation. The drift mode shapes for the first three modes show small but sharp changes in the locations of the fractured welds. When we input a pure north-south impulse into the damaged model, newly excited floor rotations (torsions) are observed in and around the damaged floors due to the resulting asymmetry in building stiffness. We present a new method of detecting failure events such as fractured welds that uses the property of wave propagation reciprocity and time-reversed reciprocal Greens functions using impulse force sources recorded in 500 sps Factor array data.

## Evaluating SCEC 3D Community Fault Model v3.0 and Regional Seismicity Catalogs

*Nicholson, Craig (UCSB), Andreas Plesch (Harvard), Guoqing Lin (UCSD), Peter Shearer (UCSD), and Egill Hauksson (Caltech)*

This collaborative project is currently evaluating 3D fault representations in the SCEC Community Fault Model (CFM) v3.0 [Plesch et al., 2006] using recently developed relocated earthquake catalogs, including a new seismicity catalog (LSH_1.11) that combines improved 3D P and S velocity models, more extensive waveform cross correlation, and refined relocation of similar event clusters [Shearer et al., 2006; Lin et al., 2007]. This comparison forms the basis for identifying and developing new and alternative fault representations for CFM, as well as helping to identify possible systematic biases in hypocentral location or fault models. This is particularly critical in areas like the Imperial Valley and along the southern San Andreas and San Jacinto fault systems, where significant contrasts in velocities exist across active faults, and where different velocity models and location procedures can significantly shift earthquake hypocenters (by up to 4 km) relative to their mapped surface fault traces. In several places, aligned hypocenters are still systematically offset from CFM 3D fault representations. This offset could be the result of: a) incorrect extrapolation of mapped surface fault traces to depth; b) earthquake mislocation owing to velocity models or location procedures used; or possibly c) existence of a previously unidentified active, blind sub-parallel fault strands. To resolve these issues and the possible source of the observed offset, we are attempting to identify and establish a set of calibration control points, such as reference 3D fault surfaces and principal earthquake hypocenters and focal mechanisms, which based on kinematic consistency and other independent data sets can be used to define the orientation and position of active fault segments at depth. These control points can then provide a reference framework within which to further calibrate and evaluate CFM and the new earthquake catalog, and thus provide a means to independently check trade-offs in model changes to either 3D fault surfaces or earthquake locations.

### Self-healing vs. crack-like rupture propagation in presence of thermal weakening processes: The effect of small, but finite width of shear zone

*Noda, Hiroyuki (Kyoto), Eric M. Dunham (Harvard), and James R. Rice (Harvard)*

We have conducted rupture propagation simulations incorporating the combined effects of thermal pressurization of pore fluid by distributed heating within a finite width shear zone, and flash heating of microscopic contacts. These are probably the primary weakening mechanisms at high coseismic slip rates. For flash heating, we use a rate- and state-dependent friction law in the slip law formulation, accounting for extreme velocity weakening above a slip rate of ~0.1 m/s that depends on the background temperature, and a very short state evolution distance of ~10 microns, which is comparable to the asperity length.

Under the assumption that shear heating is confined to a mathematical plane, Noda et al. [2006 SCEC Annual Meeting] proposed a criterion for the type of solution (crack-like and self-healing pulse-like) by using an analytical solution by Rice [2006] and modifying a theorem proved by Zheng and Rice [1998], which state that there is a critical background shear stress, taupulse, below which an expanding crack-like solution does not exist for mode III rupture propagation. The model of slip on a plane may be valid if width of shear zone is negligibly thin compared to the other length scales perpendicular to the fault (for example, the diffusion lengths of temperature and pore pressure). In our calculations, even without thermal pressurization, the slip rate at a node at the rupture tip reaches its maximum value ~1 microsec after its rupturing, probably due to the short evolution distance. Over this short time, fluid and heat diffuses over ~1 micron, which is much shorter than the typically observed width of a shear zone of hundreds of microns [Chester et al., 2003 for Punchbowl fault, Beeler et al., 1996 for low velocity friction experiments of granite gouge, Mizoguchi et al., 1994 for high velocity friction experiments of Nojima fault gouge]. Therefore, the width of the shear zone is not negligible even below 100 microns. Our calculations show that the width of the shear zone strongly influences the type of rupture propagation, with a wide shear zone favoring a self-healing pulse-like solution. Noda et al. [2006 SCEC Annual Meeting] reported that, using a model of slip on a mathematical plane, crack-like solutions were obtained even if the background shear stress, taub, is below taupulse defined by the steady state shear stress as a function of slip rate evaluated with the initial values of temperature and pore pressure. In the case of a heat source distributed uniformly or in a Gaussian shape over a finite width zone, crack-like solutions, including a case with taub just below taupulse, become self-healing pulse-like as the width of the shear zone is increased up to 200 microns.

### Rupture Termination and Jump in Parallel Strike-Slip Faults

*Oglesby, David D. (UC Riverside)*

Proper evaluation of seismic hazard depends on accurate estimates of potential earthquake size. In areas with complex, multi-segment fault systems, such an estimate in turn depends on an ability to predict the circumstances under which rupture may jump between fault segments. Many observational and numerical studies have analyzed the phenomenon of jumping rupture, but none has focused on how the process of rupture termination on the primary (nucleating) fault segment affects the ability of rupture to jump to a secondary fault segment. In the current study, I model the dynamics of a simple 2D fault system with 2 parallel segments arranged with either a compressional or extensional stepover. I vary the suddenness with which the initial shear stress tapers to zero on the primary section. If the initial shear stress goes to zero over a very small (100 m) distance, rupture readily jumps both compressional and extensional stepovers of 1 km. If the initial shear stress tapers to zero over 1 km, rupture can jump the compressional stepover, but not the extensional stepover. If the initial shear stress tapers to zero over 2.5 km, rupture can not jump either the compressional or the extensional stepover. The results illustrate the importance of the slip gradient (and the resultant static stress field) and the acceleration of the rupture front (and the resultant generation of stopping phases) in determining the probability of jumping rupture.

### SCEC/SURE: Velocity Contrast Along the Hayward Fault From Analysis of Fault Zone Head Waves

*Ohlendorf, Summer (UC Berkeley), Zhigang Peng (Georgia Tech), and Yehuda Ben-Zion (USC)*

The Hayward fault is a major branch of the San Andreas system in northern California. It juxtaposes the Franciscan Complex (fast) to the SW side against the Great Valley Sequence (slow) to the NE side. Previous studies based on 3D seismic tomography suggested ~5-10% seismic velocity contrast in the upper 10 km, consistent with geological observations. Here we systematically investigate the velocity contrast along the entire Hayward fault using fault zone head waves (FZHW) that refract along the fault interface. The FZHW provide the most diagnostic seismic signal for the existence of sharp bimaterial interfaces, and the highest-resolution tool for imaging their seismic properties. A total of 10,952 earthquakes recorded by the Northern California Seismic Network (NCSN) between January 1984 and June 2007 are used in the study. We perform waveform cross correlation for all possible event pairs, and group them into similar event clusters if they are located within 3 km and have a median cross-correlation coefficient of at least 0.85. A total of 250 clusters have been identified between 20 km north and 70 km south of Point Pinole along the Hayward fault strike. The waveforms generated by each event clusters are stacked for each station within 10 km on the slower (NE) side of the fault. Next we align the peak and trough of the direct P waves assuming right-lateral strike-slip focal mechanisms, pick the FZHW arrivals, and plot the waveforms against the along-fault-interface distances. The results at many stations on the slow side of the fault show clear propagation of FZHW from most event clusters, implying a velocity contrast that is geometrically coherent along the entire 90 km of the Hayward fault. The strength of the velocity contrast varies somewhat along strike and with depth. For stations in the central portion, the travel time moveout between the FZHW and direct P waves increases continuously with distance over ~75 km, whereas for stations closer to the ends the moveout is continuous only over distances of ~30 km. The moveout analysis indicates average velocity contrasts of ~4-10%, with higher values for the central region and the upper 6 km. The FZHW do not show clear breaks between the Hayward and Mission faults, suggesting a continuous transition between these two fault zones. The existence of a coherent bimaterial interface in the structure of the Hayward fault can have significant implications for properties of earthquake ruptures on this fault.

### How Scientific Workflows Work - a FAQ for SCEC Scientists

*Okaya, David (USC), David Meyers (SCEC), Mona Wong-Barnum (SDSC), Ewa Deelman (ISI), Phil Maechling (SCEC), and Carl Kesselman (ISI)*

In order to make progress on his or her research within a scientific collaboration, a researcher often needs to receive results from a cooperating scientist. When the collaboration involves a progression of research steps, traditionally within a team of individual scientists, each manually hand-offs his or her results to the next "down-stream" researcher. When the progression of research is highly computational, the use of scientific workflows can create an environment wherein research codes can be sequenced to run one after another on different computers across the Internet. In doing so, outputs of one code can become available as inputs to the next, expediting the hand-off process. These scientific workflows provide the following advantages: (a) can carry out a series of computational tasks using computers across the Internet, (b) chaining of individual research codes accelerates the creation of end products, (c) with the right portal (GUI) a non-expert can access a sophisticated code, (d) provides repeatability and reliability in running codes, and (e) provides a framework wherein different codes of the same functionality can be made available as choices.

This poster aims to explain to the SCEC audience how scientific workflows conceptually work and what software and hardware pieces need to be put in place by SCEC (earth) scientists, participating computer scientists, and by software developers. We describe levels of task orchestration and 'scripting' (from high level management down to the actual research codes). The workflow environment allows for access to diverse computer resources (compute hosts, storage, archival digital libraries, visualization and distribution mechanisms) and provides the tools to transfer materials between the resources. In addition there are three phases of activity in order to run a workflow: (1) pre-definition of what is permissible (the workflow framework), (2) definition of the specific list of tasks (an "instantiated" workflow), and (3) execution of the list. The first step is done by a community of earth scientists and computer scientists with the aid of software developers and must occur before any specific workflow can be run. The second step is done by a user of the workflow, with the infrastructure to do so (e.g., GUI or portal) developed ahead of time. The third step is done by computers using workflow tools. We present analogies which help explain the levels and phases of a scientific workflow and the workflow environment.

### Response of Moment Frame Buildings to Earthquakes on the Puente Hills Fault

*Olsen, Anna (Caltech) and Tom Heaton (Caltech)*

This work considers the simulated response of steel moment frames to simulated earthquakes on the Puente Hills fault beneath Los Angeles. The simulated, hypothetical earthquakes include: five realizations (i.e. different slip distributions and/or hypocenter locations) of a M 7.2 earthquake with broadband energy content; six realizations of a M 6.8 earthquake with long-period content; and one realization each of M 6.7 and M 7.1 events with long-period content. The ground motions excite non-linear models of six- or twenty-story, steel, special moment-resisting frame buildings, with either non-fracturing or brittle welds and one of two considered building strengths. We evaluate the results for multiple realizations, and we compare the variability in building responses due to simulations with different magnitudes on the Puente Hills fault. We also compare the responses of the six- and twenty-story models in the broadband ground motions.

### Long-Period Building Response to Earthquakes in the San Francisco Bay Area

*Olsen, Anna (Caltech), Brad Aagaard (USGS), and Tom Heaton (Caltech)*

We model long-period building responses to ground motion simulations of earthquakes in the San Francisco Bay area. The earthquakes include: scenarios of the 1989 Loma Prieta and 1906 San Francisco earthquakes; and two hypothetical magnitude 7.8 events on the northern San Andreas fault, each with a hypocenter north or south of San Francisco. The peak spectral accelerations from the 1906 scenario and the hypothetical earthquakes are larger than the design spectral values in the 2006 International Building Code. We use the simulated ground motions to excite nonlinear models of twenty-story, steel, special moment-resisting frame (SMRF) building models. We consider SMRF buildings designed with two different strengths and modeled with either ductile or brittle welds. Using peak inter-story drift ratio (PISDR) as a performance measure, the SMRF building responses in the Loma Prieta scenario are significantly smaller than those in the M 7.8 simulations. In the urbanized areas for the M 7.8 simulations, SMRF models with brittle welds show responses that threaten life safety on an area 5-10 times that of models with ductile welds. The hypothetical M 7.8 earthquake with a hypocenter north of San Francisco and north-to-south rupture causes large building responses on a greater area then the other two M 7.8 simulations. We use linear, single-degree of freedom models to estimate isolator displacements for base-isolated buildings. Many urbanized areas show isolator displacements in excess of 0.5 m for 10% damped, three-second isolator systems. This suggests that base-isolated structures must be designed with space to accommodate at least this much motion between the ground and structure.

### Constraints From Precariously Balanced Rocks on Preferred Rupture Directions for Large Earthquakes on the Southern San Andreas Fault

*Olsen, Kim (SDSU) and James Brune (UN Reno)*

We have compared near-fault ground motions from four TeraShake-1 and three TeraShake-2 scenario earthquake simulations with precariously balanced rock (PBR) locations to constrain the preferred rupture direction of the southern San Andreas fault. The observed PBRs closest to the segments of the San Andreas fault rupturing in the TeraShake simulations are located near Banning and Beaumont, approximately 1/3 of the distance from the NW end to the SE end of the rupturing fault. Analysis of near-fault rupture patterns for the TeraShake simulations suggests that the epicentral area generally experiences smaller PGVs as compared to sites along the fault in the rupture direction. This observation is consistent with the effects of rupture directivity for large, shallow-crustal earthquakes on near-vertical faults. Thus, the presence of the two near-fault PBRs suggests that large earthquakes on the southern San Andreas consistently generate lower strong ground motions along the fault in this area. We conclude that the distribution of PBRs is in agreement with persistent nucleation of large earthquakes on the southern San Andreas fault near Palm Springs. The PGVs for the bi-lateral rupture scenario TS1.5, with epicenter close to the Banning and Beaumont PBRs, and the NW-SE rupture scenario TS2.3, produce the best correlation with the location of near-fault PBRs. Two different possibilities for a preferred rupture direction, both with nucleation toward the north-central or northern part of the causative fault in the TeraShake scenarios, are consistent with the results: (1) that successive ruptures on the southern San Andreas have propagated both directions, or (2), that the ruptures propagate bi-laterally.

The Mw 6.1 1986 North Palm Springs and 1948 ML 6.3 Desert Hot Springs earthquakes occurred near the proposed persistent nucleation area. The focal mechanisms for both events occurred on NE-dipping faults with a thrust component (e.g., Nicholson, 1996). The stress conditions required for nucleation of an earthquake depends the geometry of the fault (e.g., King et al., 1994), and it is possible that the regional stress accumulation may be more favorable for nucleation on a dipping fault, rather than a near-vertical fault geometry. An example of such scenario was the 2002 M7.9 Denali, Alaska earthquake, which was initiated by a thrust earthquake at one end. Moreover, Freed and Lin (2002) showed that the nearby 1992 Mw 7.3 Landers and 1999 Mw 7.1 Hector Mine earthquakes brought the San Andreas fault closer to failure in the San Gorgonio Pass area. Finally, it should be noted that the concentration of PBRs near Banning and Beaumont might be explained by reduced ground motions on the footwall of the San Gorgonio Pass fault zone (Abrahamson and Somerville, 1996).

The TeraShake simulations currently only contain frequencies less than 0.5 Hz, while near-fault peak motions oftentimes occur at much larger frequencies. Thus, near-fault peak ground motions estimated from the simulations, in particular PGAs required to determine the toppling threshold for the PBRs, are likely underestimated. Future efforts should therefore work toward increasing the maximum frequency of the synthetic seismograms for the southern San Andreas scenarios.

### ShakeOut: 1 Hz ground motion simulations for the southern San Andreas fault

*Olsen, Kim (SDSU), Steven Day (SDSU), Yifeng Cui (SDSC), Jing Zhu (SDSC), Gideon Juve (USC), and Phil Maechling (USC)*

We present preliminary results from kinematic simulations of the SoSAFE (Southern San Andreas Fault Evaluation) ShakeOut scenario. The M7.8 ShakeOut rupture scenario initiates near Bombay Beach by the Salton Sea and propagates unilaterally 300 km toward the northwest up to near Lake Hughes, and poses a considerable computational challenge due the very large outer scale length of the problem and frequency content up to 1 Hz. A 600 km by 300 km by 80 km area (same as used for the SCEC TeraShake simulations) from the CMU etree representation of the SCEC Community Velocity Model (CME) version 4 was extracted at a constant grid spacing of 100 m into 14.4 billion grid points. The lowest S-wave velocity was truncated at 500 m/s, and Qp and Qs values were based on the Qp-Vp and Qp-Vp regression formulas by Brocher (2006). The source description (Aagaard) contains slip that combines a long length scale background distribution with short length scale random variations, and a spatially-variable distribution of rake, rise time, peak slip rate, and rupture speed. The source is specified on non-planar fault geometry derived from the SCEC Community Fault Model (CFM) version 3 and mapped onto a regular grid. The simulation is carried out on the 62 Tflop Dell Linux cluster at the University of Texas at Austin on 2000 processors using the Olsen-AWM, a fourth-order staggered-grid finite-difference code. The Olsen-AWM is parallelized using MPI and has been optimized extensively for large-scale wave propagation simulations.

### Resolution of GPS Data from the 2004 Mw6.0 Parkfield Earthquake

*Page, Morgan (UCSB), Susana Custodio (UCSB), Ralph J. Archuleta (UCSB), and J. M. Carlson (UCSB)*

The long-awaited 2004 Mw6.0 Parkfield Earthquake provides a unique opportunity to probe the resolution limits of source inversions due to the large amount of near-field geophysical observations, including a dense network of strong-motion seismographs and 13 GPS 1-Hz receivers. We investigate the spatial resolution of the GPS data, which provides a constraint on the static field. Even for a well-recorded earthquake such as Parkfield, static GPS inversions are poorly resolved at depth and near the edges of the modeled fault plane. We demonstrate how in underdetermined inversions such as this, it is possible to obtain structure in poorly resolved areas of the fault that is in fact an artifact of the inversion method. Therefore, much of the structure shown in conventional GPS inversions of Parkfield is highly uncertain. We demonstrate that a nonuniform grid, whose grid spacing matches the local resolution length on the fault, outperforms small uniform grids, which generate spurious structure in poorly resolved regions, and large uniform grids, which lose recoverable information in well-resolved areas of the fault. With a synthetic test, we show that our nonuniform grid correctly averages out large-scale structure in poorly resolved areas while recovering small-scale structure near the surface. We then apply our nonuniform grid to an inversion of the Parkfield GPS data.

### Empirical site response and comparison with measured site conditions at ANSS sites in the Reno area

*Pancha, A., J. G. Anderson, G. Biasi, A. Anooshepor, and J. N. Louie*

The Advanced National Seismic System (ANSS) is an effort to modernize, expand, and integrate earthquake monitoring and notification in the United States. Key goals of ANSS include dense instrumentation in high risk urban areas to monitor and improve predictability of strong ground shaking, to provide emergency response personnel with real-time earthquake information, and to provide engineers data on the response of buildings and other structures. Western Nevada is one of the locations targeted by this effort. The cities of Reno and Sparks, Nevada, are located in a fault-controlled basin that is about 13 km wide and 21 km long. The small basin size and the growing Advanced National Seismic System (ANSS) accelerograph network within it makes this an ideal location for investigating the relationship between basin structure, near-surface geology, and ground motions.

We evaluate site conditions at each of the ANSS strong motion stations in the Reno-Sparks area. Ground motions from local earthquakes are used to ascertain empirical site amplification effects within the basin using the soil to rock spectral ratio technique. A rock site, RFNV, located near the basin edge, is used as a reference site. The site response functions within the basin are mainly flat, but do show relative amplification, with some sites showing resonant peaks. These empirical site effects are compared with site conditions evaluated using average shallow shear wave velocities, measured using the refraction microtremor (ReMi) technique (Louie, 2001), in addition to local geological classifications. While the geology rock group has a lower mean amplification, the separation with those of the sedimentary groups not large. The Vs30 groups have distinct means that are well separated, indicating that velocity is a useful predictor of amplification.

### GeoFEST elastic calculation using LaGriT-meshed CFM fault

*Parker, Jay (JPL/Caltech), Carl W. Gable (LANL), Gregory Lyzenga (JPL/Caltech), and Charles Norton (JPL/Caltech)*

Recent meshing techniques using the LaGriT system have enabled conforming tetraheral volumetric finite element domains that contain SCEC Community Fault Model (CFM) meshes consisting of triangular faceted surfaces, with minor adjustments of the fault geometry to improve computational mesh quality. We present very early results of computing elastic solutions using the QuakeSim finite element software, GeoFEST. A three-layer elastic model containing the San Andreas fault (from about Wrightwood to the Salton Sea) with an imposed 5 m slip is used to compute the change in stress on the nearby Cucamonga and Sierra Madre faults. The domain is 1000x1000x1000 km in extent, containing nearly 2 million linear elements representing deformation at over 3 hundred thousand node points. The mesh has variable resolution with elements of size 100 km in the far field and 200 m near the faults. We anticipate this technique for including CFM fault models in LaGriT meshes will be used for large-scale simulations of the Southern California fault system, including earthquake interactions and geodetic interpretation

### Occurrence Patterns of Earthquake Sequences in Southern California

*Peng, Zhigang (Georgia Tech)*

The occurrence patterns of earthquake sequences in southern California are systematically investigated. A total of 557 earthquake sequences are identified from the relocated catalog of Lin et al. [2007], and further classified into three types: 317 sequences with no immediate foreshocks, 192 sequences with immediate foreshocks, and 48 earthquake swarms. Different types of earthquake sequences show interesting geographic patterns, and correlate with the mainshock faulting style, depth, and surface heat flow. Mainshocks with thrust-type focal mechanisms, larger depth, and low heat flow values tend not to have foreshocks. In comparison, swarms are mostly associated with high heat flow regions, strike-slip to normal faulting environment, and shallower depth. However, some swarms do occur in low heat flow regions. These observations may be explained by reductions of small-scale heterogeneities with increasing depth and normal stress by crack closure, changes of seismic coupling, presence of fluids, or a combination of these factors. The observations suggest that systematic studies of earthquake sequences would result in a better understanding of the relationship between structural properties and seismic behaviors, and could provide valuable refinements to forecasting the evolution of seismic sequences.

### Non-volcanic tremor near Parkfield, CA excited by the Denali and Sumatra earthquakes

*Peng, Zhigang (Georgia Tech), John Vidale (UW), Ken Creager (UW), Justin Rubinstein (UW), Joan Gomberg (USGS), and Paul Bodin (UW)*

Non-volcanic tremors triggered by teleseismic waves were recently found along the subduction zones in Japan and Cascadia, and along the transform plate boundary in CA. We present a detailed study of non-volcanic tremors along the San Andreas fault (SAF) near Parkfield, CA triggered by both the surface waves of the 2002 Mw7.8 Denali and 2004 Mw9.1 Sumatra earthquakes. We identify triggered tremors as bursts of high-frequency (~3-15 Hz) non-impulsive seismic energy that is coherent among many stations, and is in phase with the passage of the surface waves. In the case of the Denali earthquake, the tremors emanate from at least two source regions deep in the SAF. The first source region is ~38 km NW of the SAFOD in the creeping section of the SAF, and the second region is ~38 km SE of the SAFOD near Cholame, close to the location where most of the tremors were found previously. The wavetrain for the Sumatra earthquake was long and strong enough that tremors were also excited by the diffracted P waves, and tremors continued for at least an hour after the passage of the surface waves. The tremors triggered by both earthquakes could be explained by induced shear slip along the plate interface following a simple Coulomb failure criterion, although the prolonged duration requires more complicated mechanics. However, creep and strain data suggest that if it occurred, the slip was too small to generate a detectable, broad-scale, coherent pattern of surface deformation. Our observation, in concert with those of Gomberg et al. [this meeting], suggests that non-volcanic tremors triggered by teleseismic events are much more widespread than previously thought, and the effective stress, or the frictional coefficient is very low at depth along the SAF near Parkfield.

### Variations of the velocity contrast and rupture properties of M6 earthquakes along the Parkfield section of the San Andreas Fault

*Peng, Zhigang (Georgia Tech), Yehuda Ben-Zion (USC), Peng Zhao (Georgia Tech), Zheqiang Shi (USC), and Michael Lewis (USC)*

We perform a comprehensive high-resolution imaging of bimaterial interfaces along the Parkfield section of the San Andreas Fault (SAF) based on analysis of fault zone head waves (FZHW) that refract along the fault interfaces. The employed seismic data are generated by 8993 earthquakes since 1984, and recorded by the NCSN and HRSN permanent seismic networks along with two temporary PASSCAL deployments: the 2001-2002 PASO and the 2004 Parkfield Guided Waves experiment. We stack waveforms of events in repeating earthquake clusters to increase the signal-to-noise ratio and confidence levels of FZHW identification. Next we align the peak or trough of the direct P waves assuming right-lateral strike-slip focal mechanisms, pick the FZHW arrivals, and plot the waveforms against the along-fault interface distances. Clear FZHW are observed for many stations on the NE (slow) side of the fault in the creeping section of the SAF north of Middle Mountain (MM), indicating a presence of a sharp bimaterial interface in that region with variable values of velocity contrasts. The obtained velocity contrasts are 5-10% north of MM, and systematically decrease towards Gold Hill (GH). No clear head waves are observed at stations on the NE side of the SAF for ray paths sampling the fault around GH, indicating an absence or reversal of the velocity contrast in this region. The obtained along-strike variations of velocity contrasts are consistent with geological observations of a sliver of high-velocity rock immediately to the NE of the SAF associated with the GH fault and 3D seismic tomography results. The observation of a local reversal of velocity contrast near GH offers a simple explanation for the opposite propagation directions of the M6 1966 and 2004 Parkfield earthquakes, and could also partially explain the apparent segmentation of the M6 events. The 1966 earthquake nucleated near MM and propagated to the SE, as expected for rupture on the bimaterial interface in that region. The local reversal of the velocity contrast near GH may have prevented the rupture from propagating further to the SE. On the other hand, the 2004 earthquake nucleated near GH and propagated to the NE, again as expected for rupture on a bimaterial interface. The rupture stopped at MM where the preferred rupture direction is to the SE.

### Utility of LiDAR and NAIP/ADS40 Imagery in updating/revising Alquist-Priolo Earthquake Fault Zone Maps

*Perez, Florante (CGS), William Bryant (CGS), and Christopher Wills (CGS)*

The Alquist-Priolo Earthquake Fault Zoning (AP) Act mandates the State Geologist (California Geological Survey) to establish regulatory zones around the surface trace of active faults and to issue Earthquake Fault Zone (EFZ) maps to affected cities, counties, and state agencies to assist in their responsibility to prohibit the location of developments and structures for human occupancy across the trace of active faults. Initial EFZ maps were compiled in 1973 and issued July 1, 1974. Prior to 1976, most of the maps were compiled based on available mapping. To date, 161 EFZ maps have been revised.

We evaluated traces of the southern San Andreas Fault originally zoned in 1974 in the Mescal Creek and Mount San Antonio quadrangles, located in eastern Los Angeles and western San Bernardino counties. In addition to using conventional aerial photo interpretation and field checking, we employed high-resolution imagery - B4 LiDAR DEM (0.5 m resolution) and NAIP/ADS40 RGB (1.0 m resolution) - to delineate fault-related geomorphic features. This high-resolution imagery was used singly and in tandem, thus taking advantage of LiDAR's very high-resolution topography, spatial accuracy, and capability to filter out vegetation and ADS40's ability to display natural and cultural features in color.

Fault traces interpreted from the imagery are overlaid with the existing EFZ maps for comparison and evaluation. Fault-related geomorphic features interpreted from the imagery have more or less substantiated or corroborated the presence and location of active fault traces as portrayed on the EFZ maps. Furthermore, additional fault traces have been recognized and positional accuracy of several traces have been improved. Use of B4 LiDAR and NAIP/ADS40 data in combination has improved the accuracy and the speed of the mapping of faults to be zoned under the AP Act. Use of this imagery in the future will allow CGS to revise more efficiently the EFZ maps.

### Precariously Balanced Rocks (PBR) Surface Exposure History, Constrained by In-Situ Terrestrial Cosmogenic Nuclides (TCNs)

*Perg, Lesley (UMN), Lisa Grant Ludwig (UCI), Katherine Kendrick (USGS), James Brune (UNR), Matt Purvance (UNR), Rasool Anooshehpoor (UNR), Sinan Akciz (UCI) and Debbie Weiser (Occidental/SCEC Intern)*

Precariously balanced rocks (PBRs) act as natural seismometers constraining maximum ground acceleration over the surface exposure history of the PBR. These key paleoseismic indicators have the potential to validate ground motions on the timescale necessary to test earthquake rupture forecasts and Seismic Hazard Assessment estimates, and are an active topic of research to validate CyberShake results and constrain National Seismic Hazard Maps. This research focuses on examining the post-exhumation history of PBRs using in-situ terrestrial cosmogenic nuclides (TCNs).

In-situ terrestrial cosmogenic nuclides (TCNs) provide a record of near-surface exposure history. The measured concentrations are a function of the residence time in the upper ~20 m of the subsurface (inherited concentration), the timing and rate of exhumation, and post-exhumation surface spalling and chemical erosion. Our goal in the project is to provide reasonable constraints on the post-exhumation history, specifically the age of the PBRs and evolution of precariousness: we should be able to constrain whether the rocks were of similar precariousness 2.5 ka, 5 ka, and 10 ka ago. These specific targets will provide important constraints on time since exceedance for the CyberShake models.

PBRs were selected to meet a variety of considerations. These rocks constrain ground motions from large earthquakes on the San Jacinto and Elsinore faults (Brune et al., 2006). The Perris rocks were the most severely weathered, and provide the "worst-case" PBR, while the Benton Road rock provides the "best case" PBR. Two of the Perris rocks were toppled to measure their stability (see Purvance et al., 2007), also making them an attractive target for sampling. The third Perris rock (Perris-1) was toppled by vandals 1.5 years previously and also provided shielded interior samples.

We developed our sampling strategy to address subsurface inheritance, exhumation rate and timing, and post-exhumation spalling and chemical erosion. Inheritance: a deep, shielded sample (>15 m) from a quarry near Perris will provide an estimate of the background TCN concentration in the PBRs prior to exhumation. Also, samples from the interior of the three Perris rocks, when compared with the surface samples, will provide information about inheritance and erosion rates. Exhumation / Age: initiation of exhumation is recorded in the topmost sample of the PBR. The transect of 2-4 samples down the rock also provides information on the exhumation rate. Current landscape age and stability is being examined through soil characterization and soil TCN concentrations. Erosion / Precariousness: Comparing the concentrations from samples near the pivot toppling point, on the balanced and pedestal rock, with the other samples in the transect should constrain whether the rocks are becoming more precarious though time. Samples were also selected to target sections of the rock that looked least eroded, displayed large joint spalls, and looked most chemically weathered. We also collected an additional sample for in-situ 14C analysis at the Perris-3 rock, which displayed the most intense chemical weathering.

### Preliminary Results for Using Pattern Informatics to Image Fault Systems in Three Dimensions

*Perlock, Patricia A. (University of Western Ontario) and Kristy F. Tiampo (University of Western Ontario)*

Pattern Informatics (PI) is conventionally used as a way to produce long term forecasts for the locations of future earthquakes by quantifying the spatio-temporal variations in the seismicity of a seismogenic region. Historically, 2-D maps of "hotspots" are produced to forecast earthquakes that are to occur in a future 10 year time span. We propose that the PI method can also be used to image faults systems in both 2-D and 3-D. There is an inherent link between increased seismicity and the buildup of stress on a fault system. As stress accumulates on a fault, the probability of an earthquake occuring increases resulting in hotspots. Because stress builds preferentially on a fault, the hotspots should also be preferentially located on the fault, outlining its structure. Here, we show preliminary results for the 2004 Parkfield earthquake as well as the recent earthquake that occurred beneath the Los Angeles basin on the Puente Hills thrust system on August 9, 2007. Our results show that adding a third dimension to the PI method is a valid way to forecast future earthquakes at depth as well as image the underlying fault system. However, there tends to be a large amount of inaccuracy associated with depth in seismic catalogs that can be due either to poor calculations or no calculations at all resulting in the use of a default depth (~6 km). This is especially evident in the earlier years of the catalog (~1932-1968) and can skew the results of the PI index to create clusters of hotspots at the default depth instead of the true epicentre. Our study shows that the depth calculations begin to become more accurate around 1968 so we can somewhat compensate for these inaccuracies by restricting the data set to subsequent years. Ultimately, our preliminary results confirm that the PI method can be used at depth to produce images of the underlying faults systems.

### The SCEC Internship Programs, 2007

*Perry, Sue (SCEC)*

SCEC currently manages three successful research internship programs to attract, retain, train, and diversify the next generation of scientists. In summer 2007, there were 45 SCEC research interns, with posters and software demos at this meeting.

The team-based, multi-disciplinary, SCEC/UseIT (Undergraduate Studies in Earthquake Information Technology) program was established to attract women and underrepresented ethnic minorities to science and technology careers, and to attract IT-savvy students to earthquake science. A UseIT intern may be any major or class standing. Since UseIT began in 2002, interns have designed and engineered open-source, 4D, interactive, visualization software for earthquake scientists. This summer, while visualization software development continued, the focus shifted to the design and implementation of serious games for earthquake education, training, and decision-making. This shift provided a special opportunity for students new to computer and earthquake sciences to explore those fields, to discover new interests and capabilities.

The SCEC/ACCESS (Advancement of Cyberinfrastructure Careers through Earthquake System Science) program exists to create a more diverse scientific workforce and to train upcoming scientists to employ advanced technologies in system science research. ACCESS supports students to research and write a thesis within the broad domain of SCEC IT research. This summer, the first ACCESS-U (Undergraduate) intern, Amy Coddington, conducted senior thesis research within the CSEP (Collaboratory for the Study of Earthquake Predictability) project, overseen by Tom Jordan and PhD student Jeremy Zechar; and the first ACCESS-G (Graduate) student, Gideon Juve, began his masters research within the PetaSHA (Petascale Cyberfacility for Physics-based Seismic Hazard Analysis) project. Amy, Gideon, and Jeremy are all UseIT alumni, and although participation in UseIT is not required for ACCESS, it provides an important foundation for success. Thus, this summer two additional ACCESS interns were placed in UseIT to prepare for ACCESS research.

The SCEC/SURE (Summer Undergraduate Research Experience) program began in 1994 to retain students majoring in geoscience or related disciplines. Typically these are juniors and seniors with some interest in research careers. Each year, members of the SCEC community volunteer to serve as mentors, and SCEC recruits students suitable for each mentor from the pool of 100-120 internship applicants. Unlike the IT-related programs, which have stable support through multi-year grants from NSF and University of Southern California, support for SURE internships fluctuates yearly, with 3-13 stipends annually. Consequently, geoscience students often have more difficulty landing a SCEC internship than students from outside geoscience; and because funding decisions are often delayed, we lose many candidates to other programs. In order to improve this situation, this year we recruited SCEC mentors who could provide funding from outside sources, and this year we welcomed a record number of 23 SURE interns, with projects spanning a broad and exciting range of SCEC research interests.

### Recurrence of ground rupturing earthquakes on the southernmost San Andreas fault at Coachella, CA

*Philibosian, Belle (U of Oregon), Ray Weldon (UO), Katherine Kendrick (USGS), Kate Scharer (Appalachian State), Sean Bemis (UO), Reed Burgette (UO), and Beth Wisely (UO)*

The southernmost ~200 km of the San Andreas Fault has not generated a significant ground rupturing earthquake in historical time. It is imperative to determine its rupture history so as to better predict its future behavior. This paleoseismic investigation in Coachella, California establishes a chronology of five major or great earthquakes during the past 1100 years, for an average interval of 220 years, including the current open interval. This average interval and the ages of most individual events agree well with the nearby 1000 Palms (Fumal et al., 2002) and Indio (Sieh, 1986) San Andreas paleoseismic records. Vertical separations and dips of beds suggest average horizontal offset of 2-6 m per earthquake, consistent with a slip rate of 10-30 mm/yr. This study also provides an unmatched C-14 dated history of ancient Lake Cahuilla over the past millennium and evaluates potential effects of the lake cycle on the earthquake cycle. The most recent earthquake occurred in ~1680 A.D., more than 300 years in the past, suggesting that this stretch of the fault has accumulated a large amount of tectonic stress and is likely to rupture in the near future, assuming the fault follows a stress renewal model.

### GeoEarthScope: Aerial and Satellite Imagery and Geochronology

*Phillips, David (UNAVCO), M.E. Jackson (UNAVCO), and C.M. Meertens (UNAVCO)*

UNAVCO is acquiring aerial and satellite imagery and geochronology as part of GeoEarthScope, a component of the EarthScope Facility project funded by the National Science Foundation. Recent activities include: 1) high resolution airborne LiDAR imagery was collected for the San Andreas and other fault systems in northern California in Spring 2007, this dataset complements the B4 LiDAR data acquired previously in southern California; 2) high resolution airborne LiDAR imagery was collected for the Death Valley-Fish Lake Valley fault system in Fall 2006 as part of a project led by PI James Dolan; 3) InSAR imagery is being acquired from several satellites, including ERS-1/2, ENVISAT and RADARSAT, for targets throughout the EarthScope study area; and 4) twelve geochronology labs have been funded to provide analysis services including 14C, OSL, Cosmogenic, (U-TH)/He, Fission Track, 40Ar/39Ar and U-Pb dating techniques. We will present an overview of GeoEarthScope activities to date as well as future plans.

### A new velocity model for southern California: CVM-H 5.0

**Plesch, Andreas (Harvard), Peter Suess (Harvard), Jason Munster (Harvard), John H.** *Shaw (Harvard), Egill Hauksson (Caltech), Toshiro Tanimoto (UCSB), and members of the USR Working Group*

We present a new velocity model for southern California, the CVM-H 5.0. Based on earlier version of CVM-H, improvements in the new model were defined during a USR workshop held in June of this year. The updates to the model include: 1) the addition of a geo-technical layer (GTL); 2) improvements to the velocity structure in the Santa Maria basin based on well data and an updated top basement surface; 3) revised crust and upper mantle velocities based on a newly inverted P and S wave tomographic velocity models, and a new upper mantle teleseismic and surface wave model. The workshop participants advocated that CVM-H 5.0 should be considered the new standard velocity model within SCEC, and thereby see widespread use in ground motion prediction, fault systems modeling, and seismic hazards assessment.

The GTL was implemented by sampling the rule-based SCEC CVM 4.0 at input depths above 1000ft in the sedimentary basins. These data were used to populate a high-resolution voxet within the CVM-H 5.0, which is embedded within the coarser resolution voxets of the basin models. The Santa Maria basin velocity structure is based on newly acquired well log data and a revised structural model of the basin, which is based on integration of various geologic maps and cross-sections. Sonic logs from more than 50 wells were used to guide geostatistical interpolation of the basin velocity structure using kriging methods employed in the CVM-H. To ensure that the new sediment velocity parameterization is compatible with the underlying velocity structures, P and S wave tomographic models were re-calculated with velocities specified by the CVM-H 5.0 at grid points lying within the sedimentary basins. In turn, these new tomographic models were used to further refine upper mantle velocity structure using teleseismic P-wave and surface wave data.

The CVM-H 5.0 is delivered as code with accompanying data files (voxets and tsurfs) available through the SCEC/Harvard web sites (http://structure.harvard.edu). We have made a number of improvements to the code that were requested by the USR working group to assist with its use in developing and parameterizing meshes and grids. The code now provides the location of the nearest neighbor cell used to specify the velocity values at user defined coordinates, and outputs the topographic, top basement, and Moho elevations for each user-defined x and y location. To aid in meshing models, additional code is made available which computes the closest vectorial distance to a velocity interface, such as the top basement surface, from user defined coordinates.

In terms of longer-term goals for development of the USR/CVM-H, we are exploring options for:
1) incorporating results from 3D waveform inversion models into the USR;
2) developing new parameterization of geotechnical layer, including shallow seismic reflection data and additional wells;
3) delivering independent density models in sedimentary basins; and
4) adding/improving basin representations, perhaps including the Central Valley.

### Observations and Interpretaton of Fundamental-Mode Rayleigh Surface Wavefields Recorded by the Transportable Array (USArray Component of Earthscope)

*Pollitz, Fred (USGS)*

The Transportable Array (TA) provides a wealth of broadband surface wave data throughout the western US generated by global seismic events. I measure complex spectral amplitudes of fundamental-mode Rayleigh waves from 10088 vertical-component seismograms generated by 37 shallow-focus teleseismic events of magnitude $\geq 6.5$, at periods 20-100 sec, at up to 397 TA stations from April 2006 to August 2007. This dataset is augmented with similar measurements made on 2164 seismograms generated by 173 teleseismic events at up to 17 stations of the Berkeley Digital Seismic Network (BDSN) from 1993-1998. In order to derive phase velocity structure, these measurements are interpreted using the "non-plane wave" tomography method of Friederich and Wielandt (1995) and Pollitz (1999). This method addresses the large non-structural phase and amplitude anomalies that generally arise from multipathing of the surface waves prior to entering the array area. Measured spectral amplitudes are interpreted as the product of wavefront distortion along the teleseismic propagation path and the seismic structure beneath the array. For a given source and period, the incident wavefield is represented as a superposition of numerous spherical-membrane waves (the spherical equivalent of plane waves) arriving from a continuum of directions centered on the source-array backazimuth. This is the wavefield that would be observed, in principle, if there were no laterally heterogeneous structure within the array. Observed surface wavefields across the TA typically have long wavelength (≥ ~200 km) lateral variations which are largely inherited from the incident wavefields. The wavefields resulting after subtracting the incident wavefields from the observed wavefields may be interpreted in terms of laterally heterogeneous phase velocity structure governed by scattering theory. I present examples of observed wavefields and preliminary estimates of phase velocity structure using the combined TA and BDSN data sets. Characteristics of estimated phase velocity patterns include: a sharp velocity contrast across the San Andreas fault system (west side faster); a sharp velocity contrast across the Intermountain Seismic Belt (east side – Colorado Plateau and Rocky Mountains – faster); slow velocities throughout most of the Basin and Range Province, the Columbia Plateau, and the Yellowstone-Snake River Plain; fast velocities associated with the Juan de Fuca slab; fast velocities associated with the southern Cascade Range.

### Analysis of focal mechanism variability about strike-slip faults in California

*Powers, Peter (USC) and Thomas Jordan (USC)*

We have demonstrated that earthquake rate decays with distance from strike-slip faults in California, obeying a power-law of the form R~(x2 + d2)(-g/2), where x is distance from a fault, g is the decay rate of seismicity, and d is a near-fault inner scale. Scaling parameters vary by region and fault-type: g=1.3 for creeping faults in northern California; g=0.8 for locked faults in southern California. Because these observed values are a function of the stress state and the underlying (and possibly fractal) fault network, we now extend our analysis to include focal mechanisms.

As with our earthquake rate analysis, we use a fault-based coordinate system, which allows us to aggregate data from multiple, linear fault segments and enhance any signal the data might contain. Although most fault segments have a dominantly right-lateral sense of motion, we first reverse the focal mechanisms of the few that are left-lateral. As a simple measure of focal mechanism variability, we take the angular difference between observed double-couples and an ideal double-couple (i.e. pure right-lateral motion). The angular difference is the angle required to rotate one double-couple about a unique axis into alignment with another. We find that creeping fault segments have lower average angular differences (are more aligned with the ideal fault) while locked faults have higher values (are less aligned). Moreover, the average angular difference increases with distance from a fault for both fault types, suggesting an increase in the heterogeneity of stress, the fault network, or both.

### SCEC/UseIT: Serious Game Design

*Punihaole, Tom (USC)*

This summer I was a SCEC/UseIT (Undergraduate Studies in Earthquake Information Technology) intern. I collaborated in a team of 20 interns to complete a Grand Challenge. This challenge guided the research of our group throughout the summer. We were asked to implement three serious games that would teach the player about earthquakes, train the player in the use of SCEC-VDO (Virtual Display of Objects) software, and to make decisions to better prepare for an earthquake. I participated in the implementation of the first game; in particular, I coded a mini-game that would teach the player the names of different tectonic plates, as well as their location on a three-dimensional globe versus on a or two-dimensional map projection. To do this, I used the popular multimedia software, Adobe Flash 9.0. Flash has the advantage that it can be programmed via Action Script, which has a powerful set of libraries as well as an object-oriented implementation and the familiar JavaScript syntax. Action Script gave me a lot of flexibility in coding the elements of the game to do exactly what I wanted. In addition to making the Flash game, I worked on adding new datasets to SCEC-VDO, in particular, I added tectonic plate boundaries, and isochron data.

### Fragility Estimation for Precipitous Cliffs and a Rock Stack on Yucca Mountain, Nevada

*Purvance, Matthew D. (UNR) and James N. Brune (UNR)*

As current law dictates, disruptive events with a probability of 0.0001 that may occur once every 10,000 years must be considered in the design specifications of any nuclear waste repository, including the designated waste repository at Yucca Mountain, Nevada. From another perspective, these correspond to disruptive events with annual occurrence probabilities of 0.00000001, or equivalently events that occur once every 100,000,000 years on average. Such events are well beyond the human experience, as the Genus Homo first appeared around 1,800,000 years ago and Homo sapiens have existed for at most the past 300,000-400,000 years! The Yucca Mountain Project, in order to gain some information about seismic disruptive events on these time scales, elicited experts to undertake sophisticated probabilistic seismic hazard analyses for the site. Given our current knowledge base, the probabilistic seismic hazard analysis results suggested that earthquakes can cause extraordinarily extreme ground motions, with accelerations greater than 10 times the force of gravity and velocities in the 10's of meters per second.

Can earthquakes produce such amazing ground motions? Have any ground motions like these ever occurred? This initiative focuses on the second question: is it possible to bound the level of the maximum ground motions that have occurred over some very long time periods? James Brune and others have found a number of sensitive geological features on Yucca Mountain, including precariously balanced rocks, precipitous cliffs, and fragile rock stacks. This analysis focuses on precipitous cliffs and rock stacks on the flanks and crest of Yucca Mountain, perhaps some of the oldest ground motion constraints, that have been in place for 200,000 years or more (Whitney, synthesis report to ExGM Committee). Damage to these fragile landforms would result in significant downhill migration of boulders into Solitario Canyon. As a result of the very low erosion rates in the vicinity of Yucca Mountain, any ejected material would likely remain for upwards of 1,000,000 years, as evidenced by approximately 1,000,000 year minimum ages dates obtained on rocks on the western slope of Yucca Mountain (Keefer et al., in press). The pronounced absence of such boulders en masse suggests that the cliffs constrain the ground motions up to 1,000,000 years.

Numerical simulations have been undertaken of these features with the Universal Distinct Element Code (UDEC) to obtain approximate fragilities of these landforms. 20 waveforms were selected from the set of ground motions collected by John Anderson for the Extreme Ground Motion Project and scaled with PGA from 200 cm/s/s to 2600 cm/s/s. Various cliff fracture patterns and friction coefficients have been investigated, and their implications for the fragilities have been assessed. Ground motions with amplitudes consistent with both the 1 in 100,000 and 1 in 1,000,000 year values produced for the crest of Yucca Mountain destroy the cliffs, suggesting that these extreme ground motions have not occurred over at least the last 200,000 years, if not the last 1,000,000 years. Future investigations will utilize realistic 3D cliff topographies.

### Ground Motion Catalog of 6832 Foamquakes - Implications for Extreme Ground Motions

*Purvance, Matthew D. (UNR), John G. Anderson (UNR), James N. Brune (UNR), and R. Anooshehpoor (UNR)*

The predictions of truly extreme ground motions by the probabilistic seismic hazard analysis (PSHA) for Yucca Mountain, Nevada, have raised fundamental questions regarding the assumptions inherent in the PSHA methodology. One particular assumption is that the ground motions follow untruncated lognormal distributions. When extrapolated to exceedingly long repeat times, this assumption results in very large ground motions due to the long-tailed nature of this distribution. In practical terms, this assumption requires that as the intended lifetime of a structure increases, the structure must be built for practically unbounded ground motions. To circumvent this problem, experts often truncate the lognormal distributions; such measures are based on opinion, though, in the face of insufficient data to delineate the tails of the ground motion distributions.

This project investigates the ground motion distributions produced by an analog rupture model consisting on foam rubber blocks that are forced past one another, producing dynamic ruptures or foamquakes. In all, 6832 foamquakes have been recorded in a model instrumented with 6 two-component displacement sensors, 36 single-component accelerometers embedded near the rupture surface, and 28 single component accelerometers on the free surface. Of the surface accelerometers, half are oriented fault-perpendicular and half are oriented fault parallel. The forcing and normal stress conditions have been nominally maintained throughout the experiments. Variations in ground motions result from small variations in the initial stress state on the fault. Though this model is very homogenous, three distinct distributions of foamquakes are observed - Mode II forward away from the forcing piston, Mode II backward toward the forcing piston, and Mode III ruptures. Approximately 64% of ruptures are Mode II forward, 22% are Mode II backward, and 14% are Mode III.

The particle motion distributions vary significantly depending on the rupture style, sensor location, and sensor orientation. These distributions clearly demonstrate that directivity influences the particle motion distributions. Sensors lying in forward directivity directions record larger amplitude particle motions. The peak particle motion distributions show a pronounced departure from lognormality in the tails. When grouped based on closest fault distance, as commonly done in PSHA, the distributions describing the strongest 1% of the particle motions fall off more rapidly than lognormal. Use of the full set of recordings should eventually allow us to understand the physical causes of these extreme records. Further analyses, including the continued recording of foamquakes, are ongoing.

### Field Tests of Doomed Precariously Balanced Rocks between the San Jacinto and Elsinore Faults

*Purvance, Matthew D. (UNR), Rasool Anooshehpoor (UNR), James N. Brune (UNR), Richard Brune, Deborah Weiser (Occidental/SCEC Intern), Katherine Kendrick (USGS), Sinan Akciz (UCI), and Lisa Grant Ludwig (UCI)*

A line of precariously balanced rocks exists nearly equidistant (~15 km) between the San Jacinto and Elsinore Faults, spanning over 200 km of fault length. The absence of spatial asymmetry (e.g., rocks closer to one fault than the other) suggests that both of these faults produce similar maximum ground motions and that the ground motion attenuation is roughly comparable. Consequently these rocks place important constraints on earthquake ground motions, seismic hazard, and provide some information regarding earthquake rupture variability, at least for the events that produce the largest ground motions.

Recent field surveys for the age dating initiative outlined in Grant Ludwig et al. (2007) revealed that a residential housing development was planned in an area occupied by two large precariously balanced rocks near Perris, Ca. Prior to their destruction, the property owner agreed to assist with overturning these boulders, allowing for the collection of valuable data to better delineate their sensitivities to ground shaking. Such full-scale tests of these large precarious rocks (rock Perris-2 weighed ~ 16 tons while Perris-3 weighed ~ 47 tons) were accomplished by the use of an excavator and a backhoe. The force required to tip the rocks was measured as a function of the angle by which they tilted, allowing for an accurate representation of the overturning fragilities. In addition, highly refined volume estimates were achieved through the use of photogrammetry software (see also Anooshehpoor et al. 2007).

These field tests found that Perris-3, standing over 3m in total height, would initiate rocking with ground accelerations less than 0.1g due to the presence of basal irregularities about which rocking motion occurs. Perris-2, which was approximately 2.5m tall, was somewhat less precarious with rocking initiating around 0.25g. These precarious rocks were more fragile than previously estimated from field reconnaissance and photographic analysis, underscoring the importance of such field tests. These data strengthen the conclusions of Purvance et al. (submitted 2007) that precarious rocks at this site are inconsistent with the USGS National Seismic Hazard Maps assuming 10,000 year residence times. The level of inconsistency will be further refined with the age constraints outlined in the Grant Ludwig et al. (2007) abstract.

### Comparison between Precariously Balanced Rocks and the ShakeOut Simulation: Ground Motion Constraints and Implications for Electric Substation Damage

*Purvance, Matthew D. (UNR), Robert W. Graves (URS), James N. Brune (UNR), Brad Aagaard (USGS), and Ken Hudnut (USGS)*

In 2008, NEHRP will oversee a massive multi-hazard response exercise based on the damage inflicted by an M=7.8 rupture scenario on the Southernmost San Andreas Fault. Vital aspects of the Great Southern California ShakeOut exercise are the realistic depictions of both the spatial distributions and intensities of

damage resulting from strong ground shaking produced by such an event. For instance, unrealistically intense ground shaking in certain locations may focus the attention of emergency responders on hazards which are very improbable in actuality. Thus it is crucial that the rupture scenario produces ground motions that fit within the context of expected earthquake ruptures on the San Andreas Fault.

In this vein, simulated ShakeOut ground motions have been compared with precariously balanced rocks (PBR) at 20 sites in Southern California. The simulated ground motions cover a broad frequency range (0-10 Hz) and incorporate effects of complex fault rupture and 3D wave propagation (see poster by Graves et al., this meeting). The PBRs are sensitive geological structures that have been in place for perhaps 10,000 years or more, surviving the entire set of earthquake ground motions during their lifespans. Therefore these rocks supply independent constraints on both the spatial distributions and amplitudes of strong ground motions. Should the ShakeOut ground motions be unrealistically intense, they would imply the destruction of a significant number of the precariously balanced rocks. Consequently these geological features place a constraint on the maximum ground motions expected from these types of scenario earthquake ruptures.

This analysis demonstrates that the ShakeOut ground motions do not overturn a significant number of precariously balanced rocks with high probability. Precarious rocks at two sites within 15 km of the San Andreas Fault would overturn with greater than 50% probability as a result of this rupture scenario, though. This may indicate that the very near source ground motions are somewhat elevated at these sites. Maps of precarious rock overturning probabilities for stereotypical rock shapes demonstrate that the spatial ground motion distributions are consistent with the precarious rock distributions. In addition, this analysis has been extended to assess the overturning potential of electric transformers similar to those that overturned in the 1957 Kern County Earthquake. The transformers at several electric substations are at a high risk of overturning from this scenario earthquake.

**ShakeOut and its effects in Los Angeles and Oxnard areas**

**Ramirez-Guzman, Leonardo (CMU), Ricardo Taborda (CMU), Julio Lopez (CMU), John** *Urbanic (PSC), Jacobo Bielak (CMU), and David O'Hallaron (CMU)*

Three-dimensional simulations of earthquakes have given a deeper understanding of wave propagation and site effects in urban regions. In this work we study the impact of a potential major earthquake on the San Andreas Fault with significant seismic hazard in the Greater Los Angeles Basin. We present results for the ShakeOut simulation – a rupture beginning near Salton Sea, California, heading 270 km northwest along the fault, that produces a Mw 7.8 earthquake in a geographical region which includes all major populated areas of Southern California and northern Mexico, in a 600 km by 300 km by 80 km volume, for a maximum frequency of 1.0 Hz and a minimum shear wave velocity of 200 m/s. For the material model, we use a discretized version of SCEC's CVM4 velocity model, called CVM-Etree. The simulation was performed at the Pittsburgh Supercomputing Center using Hercules, a finite element octree-based, parallel software developed by the Quake Group at Carnegie Mellon University. Hercules implements a highly efficient end-to-end algorithm for solving the wave field in highly heterogeneous media due to kinematic faulting. We verify our results by comparing synthetic seismograms computed with a parallel finite difference code by Robert Graves (URS) for a similar scenario earthquake, for a maximum frequency of 0.5 Hz and minimum shear wave velocity of 500 m/s.

We focus our analysis of the results of the 1.0 Hz ShakeOut simulation on the Los Angeles Basin area, and the Santa Clara River Valley and Oxnard Plain. We examine the site effects present in these two areas and their proneness to capture and amplify seismic waves due to their geological features. Results show a direct correlation between the amplification levels and the local soil and basin profiles.

**Multi-Hazard Demonstration Project Preliminary Liquefaction Deformation Analysis at Lifeline Crossings for the Mw 7.8 Southern San Andreas Earthquake Scenario**

*Real, Charles (CGS), Cindy Pridmore (CGS), and Ralph Loyd (CGS)*

The California Geological Survey has made quantitative estimates of ground failure at critical lifeline crossings as part of the Multi-Hazard Demonstration Project sponsored by the U.S. Geological Survey. Part of the demonstration project includes preparation of a credible Mw 7.8 earthquake scenario that entails rupture of the San Andreas Fault from Bombay Beach in Imperial County to Elizabeth Lake in Los Angeles County. A principal objective of the scenario includes a detailed assessment of the impact to critical lifelines that are concentrated in four fault-rupture focus areas in southern California: 1) Palmdale, 2) Cajon Pass, 3) San Gorgonio Pass, and 4) Coachella. Lifelines include petroleum, water, and fiber optic lines, truck and rail freight traffic, and electrical power lines among others, which provide goods and services to and from southern California. They present a particular vulnerability because of their geographic extent, co-location in the focus areas, and inherent susceptibility to physical distress.

This poster describes exposure of lifelines passing through the prescribed focus areas to liquefaction-induced ground failure; descriptions of ground failure hazards caused by fault rupture and landslides are presented in companion posters. Conservative estimates of liquefaction deformation are made that range from about 1 to 10 meters of lateral-spread ground displacement at a few selected sites where several lifelines are co-located. Inferences are made from these analyses as to the magnitude and pervasiveness of the hazard throughout each of the focus areas. This information is passed along so engineers can assess the impact and overall performance of the various lifelines, and the potential economic impacts can be better quantified so appropriate mitigation can be given informed consideration.

### New observations of gouge powder from rupture-zones of recent earthquakes, laboratory rupture experiments, and an active fault-zone

*Reches, Ze'ev (U of Oklahoma), Mishima D Tetsuya (U of Oklahoma), Gregory Strout (U of Oklahoma), David Lockner (USGS), and Vincent Heesakkers (U of Oklahoma)*

We present preliminary results of grain characteristics and estimates of particle size distribution (PSD) in siliceous gouge collected from three sources: rupture-zones of two recent earthquakes in South African mines (m3.7 event in 1997 and m2.2 event in 2004); an unstable faulting experiment of a quartzite cylinder; and the San Andreas fault-zone at Tejon Pass, California. PSD measurements of fine powders are susceptible to major erroneous results due to aggregation and agglomeration of extremely fine particles that cause a systematic bias toward coarser PSD. For examples, we measured the PSD of a commercial amorphous silica powder with a laser particle analyzer (Coulter LS230) and found a mean grain size of about 6.8 micron; however, the actual mean grain size is 100 nanometers as evident by TEM observations. Our central analytical objective is to determine the true grain size of the gouge that forms during an earthquake (without agglomeration). To achieve this objective, we have employed several techniques. The best current results are from the TEM (Jeol-2010F) using bright-field and dark-field modes for magnifications smaller than 200,000, and high-resolution (HREM) and FFT-filtering modes for magnifications of 200,000-500,000. We also experiment several methods to disperse the agglomerates (with ethanol, silanes and toluene) for PSD measurement in a laser particle analyzer (Coulter LS230) and a Zeta particle analyzer (Brookhaven, ZetaPALS).

We report here preliminary results from the TEM analysis of five samples (two from South African earthquakes, two from the San Andreas fault, and one from rock mechanics experiment). In general, the grains in the examined powders display similar shapes: aspect ratios range up to 1:3 with only small amounts of very elongated grains, and most grains are angular to very angular; grains of the rock mechanics experiment are the most angular. The TEM samples display wide ranges of grain sizes (5 nm to 5 microns), however, quantitative PSD cannot be determined as most grains appear in clusters and aggregates that are inseparable by optical means. We thus used the dark-field and FFT-filter methods to map the internal structure of tens of grains ranging in size from a few nanometers to about 2 microns. With the exception of one grain, all examined grains are composites of 3 to more than 15 secondary grains that are as small as a few nanometers in size. These direct observations of the grain structure indicate that the true grain size of gouge powder is in the sub-micron range, probably within the 0.1 micron and below. Our current efforts are devoted to the development of effective particle dispersion techniques following nanotechnology methods to quantify the true PDS. The apparent abundance of particles in the 10-100 nanometer range in gouge powder has significant implications to earthquake energy balance and to slip weakening mechanisms.

This study was supported by a SCEC 2007 grant and by NSF Continental Dynamic grant 0409605.

### Developments in earthquake forecast modelling and testing

*Rhoades, David (GNS Science) and Matthew Gerstenberger (GNS Science)*

We describe progress in developing mixture models for improved short-term earthquake forecasting, and computationally efficient tests for evaluating model performance.

The short-term earthquake probability (STEP) forecasting model applies the modified Omori law and the Gutenberg-Richter law to clusters of earthquakes. It is intended mainly to forecast aftershock activity, and depends on a time-invariant background model to forecast most of the major earthquakes. On the other hand, the long-term earthquake forecasting model EEPAS – "Every Earthquake a Precursor According to Scale" – exploits the precursory scale increase phenomenon and associated predictive scaling relations to forecast the major earthquakes. Both models have been shown to be more informative than time-invariant models of seismicity. By forming a mixture of the two, we aim to create an even more informative forecasting model. Using the ANSS catalogue of California, the optimal mixture for forecasting earthquakes with magnitude $M > 5.0$ is found by adding a fraction (0.63) of the EEPAS forecast to the time-varying component of STEP. This mixture gives an average probability gain of about 4 compared to each of the individual models.

The methods that are presently being implemented for testing regional earthquake likelihood models in the CSEP Testing Centers involve generation and storage of thousands of synthetic earthquake catalogues for each model. The three tests are the so-called N-test (of the number of earthquakes occurring during the test period), L-test (of the likelihood of a catalogue, given a model) and R-test (of the likelihood ratio of a catalogue, comparing two different models). It is possible to devise equivalent, or near-equivalent, tests without having to generate synthetic catalogues at all. These alternative tests utilise either the known distribution of the statistic concerned or a normal approximation to it justified by the central-limit theorem. It is proposed that the R-test should be replaced by an alternative test which more directly answers the question of interest. The saving in computer resources is most likely to be appreciable in cases where a large number of daily forecasts need to be evaluated.

### Earthquake occurrence in geometrically complex systems of faults with rate- and state-dependent frictional properties

*Richards-Dinger, Keith (UCR) and James Dieterich (UCR)*

Long-term (~10,000 year) catalogs of simulated earthquakes can be used to address a host of questions related to both seismic hazard calculations and more fundamental issues of earthquake occurrence and interaction (e.g. Ward [1996], Ziv and Rubin [2000, 2003], Rundle et al. [2004]). With a goal of simulating earthquake occurrence in geometrically complex, regional-scale fault networks (such as the SCEC Community Fault Model) at a resolution on the order of 1 km2, we have extended the models of Dieterich [1995] and Ziv and Rubin [2000, 2003] for faults which obey rate- and state-dependent frictional laws to handle fault elements of arbitrary orientation and slip mode. These simulations are computationally very efficient as they use analytic expressions for the nucleation process that include the effects of time-varying normal stress. We will present work on our exploration of how both geometry (fractal roughness, offsets, bends, and other simple but non-planar) and material property heterogeneities affect aspects of earthquake occurrence such as a) frequency-magnitude distribution, b) spatial and temporal clustering, c) multi-segment ruptures, and d) recurrence statistics in our simulations. Interesting results so far include: the surprisingly small effect of random fractal roughness on the frequency-magnitude distribution for single-fault models driven by uniform backslip but a profound effect in such models driven by tapered backslip; contrasting preferential nucleation locations for small and large events; the occurrence of paired large events with time separations of seconds to years in models consisting of two parallel faults separated by an offset; and the transition of the recurrence time distribution for large events from nearly periodic (coefficient of variation of ~0.04) to much more random (coefficient of variation of ~0.9) with the addition of large-scale bends and additional sub-parallel fault strands in models loosely based on southern California.

### SCEC/UseIT: Serious Gaming for Serious Situations

*Richardson, David (USC)*

The grand challenge this summer at the Southern California Earthquake Center's Undergraduate Studies in Earthquake Information Technology (UseIT) involved the study, creation and development of serious games to better educate people on earthquake issues. My work for the summer can be divided into three main categories: gaming research, game design, and game development. The gaming research involved coming up with a general strategy for all interns to follow in order to have satisfactory results at the end of the summer in their game development process. Games are usually developed over years by large teams, so scaling the process to work for teams of 3-7 in a 10 week program was no small problem. The second part of my summer consisted of designing a decision-making game to educate the general public on the challenges and importance of earthquake research and preparedness. The last part of my summer was spent developing the strategy game previously devised. I designed a non-graphical version of the game to run in the terminal as a proof of concept and testing platform and then combined that with the graphical framework done by intern and colleague Emmett McQuinn.

### InSAR measurements of secular deformation in Southern California over a time period between 1992 and 2006

*Rivet, Diane (UCSD) and Yuri Fialko (UCSD)*

We analyzed secular deformation in Southern California using an extensive catalog of InSAR data that spans 15 years between 1992 and 2006. We generated a map of the satellite line-of-sight displacements based on a stack of ~300 interferograms from 4 adjacent tracks. The main limitation to the accuracy of InSAR measurements of tectonic deformation is the atmospheric phase delay. We introduce a new method aimed to improve the signal-to-noise ratio in the InSAR- derived maps of secular deformation. The method involves identifying SAR acquisitions that are highly affected by atmospheric noise, and an optimal choice of interferometric pairs for stacking. We begin by generating a set of all possible interferometric pairs having baselines and time spans within prescribed limits. We then select interferograms with sufficiently high correlation. Subsequently, we identify noisy SAR acquisitions by means of calculating RMS of the phase signal. Finally, we generate a stack of interferograms by following a "connectivity tree" that eliminates contributions of noisy scenes. Using this method we obtained a continuous velocity field characterizing surface deformation in Southern California over the last 15 years. We identify interseismic deformation on a number of major faults, including those of the southern San Andreas system, and the Eastern California Shear Zone (ECSZ). Variations in the line-of-sight velocity across the Eastern California Shear Zone are non-monotonic, with the maximum along the strike of the Hector Mine fault of ~4 mm/yr, and total LOS velocity between the eastern and western boundaries of the shear zone of less than 2 mm/yr. We observe increases in the radar range to the east of ECSZ. This signal most likely results from subsidence east of the Death Valley-Mule Springs fault system, either due to hydrologic effects, or dip-slip tectonics. No resolvable interseismic deformation is detected across the Garlock fault. The Blackwater fault is associated with line-of-sight velocity of 2 mm/yr. By combining data from the ascending and descending satellite orbits, we infer that most of that strain is associated with the differential vertical motion across the fault (east side up), so that the accelerated strike-slip motion on the deep extension of the Blackwater fault is not required.

### Finite Difference Modeling of Rupture Propagation with Strong Velocity-Weakening Friction

*Rojas, Otilio (SDSU), Eric Dunham (Harvard), Steven Day (SDSU), Luis A. Dalguer (SDSU), and Jose Castillo (SDSU)*

We present second- and fourth-order finite difference (FD) implementations for simulating dynamic rupture on faults with rate- and state-dependent frictional resistance, extending a FD method previously verified only for slip-dependent friction (Rojas et al, 2007). The methods are tested by modeling ruptures when the frictional stress follows a slip evolution law, with thermal weakening due to flash heating of asperities (Rice 2006) represented through a strong velocity-weakening behavior at high slip rates. We also consider friction laws with moderate velocity weakening, such as the classic aging and and (low-velocity) slip laws. In some cases, we find stiff ODE integration techniques (based on backward differentiation formulae and Rosenbrock methods) to be necessary to resolve different time scales of fault-variables (slip rate, traction, and state) in their transition from initial interseismic conditions to dynamic values. A convergence analysis is carried out using highly-resolved reference solutions from a Boundary Integral Equation Method and error metrics based upon RMS differences in rupture time, final slip, and peak slip rate, as well as L-infinity misfits of time histories of fault-variables.

**SCEC/SURE: Collaborative Research: SCEC/SURE, CSUN Catalyst Program a) An alternative approach to restoring slip across the San Andreas fault at Biskra Palms b) Towards a digital active fault map of Pakistan**

*Rousseau, Nick (CSUN), Jessica Hinojosa (Stanford), Kandace Kelley (Purdue), and Doug Yule (CSUN)*

Our internship is a collaborative effort to: a) reconstruct offset canyons across the San Andreas fault near Indio, CA and compare the result with previous reports, and b) digitize the known active faults of Pakistan for use by the Geological Survey of Pakistan. Near Indio, we visited trenches, analyzed "B4" LIDAR data, and restored the offset canyons whose estimate broadly agrees with previous estimates. Our main conclusion supports a moderate revision of the reconstruction by van der Woerd et al., 2006. Our work digitizing the Pakistan fault maps used ArcMap to turn hardcopy maps into digital images. The result is an initial step towards better understanding the seismic hazard there.

My contributions to this project involve using Adobe Illustrator/Photoshop to produce figures that show both the B4 LIDAR data of Biskra Palms and our collaborative interpretation of its geomorphology, faulting, deposition and slip rates. I was also involved in working with QT Modeler to learn how to further explicate these figures by additionally adding on elevation schemes. This has assisted the team in lining up offset canyons and provided us with viable evidence to further constrain offset at Biskra Palms. Furthermore, learning how to create a digital elevation model (DEM) for Pakistan was an important introduction into using GIS ArcMap. Working with GIS, I participated in producing a section of digitized faults for the region.

**Strong Tidal Modulation of Non-Volcanic Tremor**

*Rubinstein, Justin (UW), Mario La Rocca (INGV), John Vidale (UW), Ken Creager (UW), and Aaron Wech (UW)*

Episodes of non-volcanic tremor and accompanying slow slip recently have been observed in Japan and the Cascadia subduction zone. Such episodes typically last up to weeks, and differ from normal earthquakes in their source location and moment-duration scaling. The most recent tremor episodes in the Cascadia subduction zone near Seattle and Victoria have been strong and exceptionally well recorded. During the last three major tremor episodes in 2004, 2005, and 2007, we see clear pulsing of tremor activity with a period of 12.4 hours, the same as the principal lunar tide. We find that the small stresses associated with the earth and ocean tides influence the genesis of tremor much more than they do "normal" earthquakes at comparable depths. This indicates that tremor occurs on very low-stress faults, as it nucleates on surfaces that are sensitive to stress variations approximately 105 times smaller than the lithostatic loads compressing them.

**Non-Volcanic Tremor Driven by Large Transient Shear Stresses**

*Rubintein, Justin (UW), John Vidale (UW), Joan Gomberg (USGS), Paul Bodin (UW), Ken Creager (UW), and Steve Malone (UW)*

Tremor, i.e., non-impulsive seismic radiation, has long been observed around volcanoes and more recently around subduction zones. The mechanical details of non-volcanic tremor remain unresolved. Here, we identify bursts of tremor that radiated from the Cascadia subduction zone near Vancouver Island, Canada during the strongest shaking from the MW7.8 2002 Denali, Alaska earthquake. The Love waves triggered most of these bursts, which are similar to non-volcanic tremor in that they have no clear onset, an extended duration, and a spectrum depleted in high frequencies relative to earthquakes. The tremor was triggered when the Love wave displacement, building shear stresses of approximately 43 kPa, was to the southwest (the direction of slip of the overriding plate on the megathrust) and shut off when the surface was displaced northeast. Our observations suggest that tremor and slow-slip can be induced nearly instantaneously by shear stress increases on the subduction interface, effectively a simple frictional failure response to the driving stress.

## Investigating Creep on the Central San Andreas Fault using InSAR and GPS

*Ryder, Isabelle (UC Berkeley) and Roland Burgmann (UC Berkeley)*

The San Andreas Fault is locked along most of its length, but the 170 km-long section between San Juan Bautista and Parkfield undergoes creep. Measurements from creepmeters, alignment arrays and GPS over the last 25 years have shown that rates of creep reach 20-30 mm/year in the central portion, tapering off towards the locked segments at either end. Though useful, these measurements have been spatially isolated and intermittent in time. We present InSAR observations of creep across the fault. The new dataset covers a period of time from 1992 to 2001, and has superior spatial coverage than previous data. From multiple ERS-1 and ERS-2 descending interferograms processed using ROI_PAC, we produce a stack, which gives the spatial distribution of creep rate up to about 50 km either side of the fault. We find a maximum creep rate of about 24 mm/year. We perform a linear inversion for shallow and deep sliding velocity on the San Andreas Fault using both the InSAR stack and GPS velocities from continuous (PBO) and campaign networks. The deep (> 12 km) sliding velocity is constrained to be less than or equal to the estimated long term relative plate velocity, and we estimate it to be about 35 mm/yr. Creep in the top few kilometers is variable along strike, with patches of faster creep interspersed with more slowly-moving patches. Creep at intermediate depths is greatest in the centre of the segment, reaching a few mm/yr less than the plate rate. The depth-averaged creep rate profile along the fault segment agrees to first order with that estimated by Nadeau and McEvilly (2004) from characteristic repeating microearthquakes.

## Fault surface topography and its relation to fault zone internal architecture

*Sagy, Amir (UCSC) and Emily E. Brodsky (UCSC)*

Fault zones in the brittle crust have a hierarchy of structures as a function of distance from the principal slip surface. In the core, principal slip surfaces accommodate most of the displacement during earthquakes. The topography of these surfaces is integral to all aspects of earthquake and fault mechanics.

We use a combination of fault topography measurement with ground-based LiDAR and fault zone structure analyses to identify some major mechanical processes involved in faulting at a site southwest of Klamath Falls, Oregon. The fault has a net slip of ~150 m and is located in a seismic active zone. Ongoing quarrying exposed ~6000 m2 of fresh fault surface which is comprised of three main segments.

We identified three different general geometrical features on the fault surfaces. The first of these is the set of fault segments that are generated by branching, forking or merging of fractures in the fault area and appear in all measured scales. These processes are scale-independent as manifested by self-affine roughness.

Polished surfaces with gentle elongated striations comprise the second set of features. The smooth surfaces are clear evidence of on-going abrasion. Abrasion is also demonstrated by the few millimeters-thick fine-grained layer adjacent to the surface. Profiles of a few centimeters length parallel to the slip measured with a laboratory profilometer showed a very weak correlation between profile lengths and the topography.

The third features are elliptical bumps at wavelengths of a few meters with amplitudes of dozens of centimeters. In many faults the bumps are not spread equally on the surface and some zones can be bumpier than others. Their thickness is closely related to the local width of cohesive granulated cataclasite, which appears to be the strongest layer in the fault zone. Under protruding bumps the layer is always thickened and the width can locally achieve more than one meter. Field and microscopic analyses show that the layer contains grains with dimensions ranging from less than 10 microns and to a few centimeters. There is clear evidence of internal flow, rotation and fracturing of the grains in the layer. We suggest that the amalgamation of topographical bumps and hardening of the internal structure near them generate asperities capable of supporting larger than average stresses on the fault.

### SCEC/UseIT: Flash! Savior of the Universe!

*Sain, Jared (USC)*

The Undergraduate Studies in Earthquake Information Technologies program (UseIT) is a summer-long, multi-disciplinary internship that brings students from across the country to work on a grand challenge. This summer's challenge was to create serious games that will help educate people on earthquakes and earthquake safety. I worked on a team that developed multiple games about both earthquakes and plate tectonics. We used Adobe Flash CS3, which has an object oriented scripting language and contains its own graphics creation tools. I was one of the main programmers so while I focused on the Fault Motion Game (FMG) I helped on all of the other games as well. In the FMG the player has to release sheep from their maze-like pens by controlling the motion along faults. The player can control the direction of the faulting (left lateral or right lateral) and the amount of motion along the fault by simulating earthquakes of different magnitudes. I also helped our team set up a CVS repository for our Flash and ActionScript files, which allowed team members to work on the same game and share game information more easily.

### The integration of GPS and DINSAR data for high resolution deformations studies

*Samsonov, Sergey (UWO), Pablo Gonzalez (University of Madrid), Kristy Tiampo (UWO), Jose Fernandez (University of Madrid), and John Rundle (UC Davis)*

In the following work we propose a new technique for combing two complementary geodetic data sets: Differential Synthetic Aperture Radar and Global Positioning System. The proposed technique benefits from both, high temporal resolution and high accuracy of the GPS measurements at sparse locations and high spatial resolution and high accuracy of DInSAR observations at sparse times. The methodology of this techniques is based on analytical optimization of the Gibbs energy function (and Markov-Gibbs random fields equivalency) within Bayesian statistical framework, which is constructed for the case when local interactions of the ground are considered independent. In this case Gibbs energy function can be greatly simplified and the solution (three components of velocity) can be found analytically by the inversion of a set of three linear equations. The technique is used to investigate the creep motion of the southern San Andreas fault around the Salton Sea. Previous works suggest that the fault in that region creeps with constant velocity in a horizontal strike-slip direction. This work, however, suggests that either the creep velocity is not constant over time or the motion is not completely horizontal. These conclusions are derived from the analysis of two velocity fields for 1992-1998 and 1997-2001 which show different signals. Also the technique is applied to campaign GPS data and SBAS differential interferogram from Tenerife island (Canaries). The goal of this work is to fuse both geodetic data sets, observe surface deformations and better characterize potential precursors of volcanic activity. Currently some source inversion studies are performed in order to identified potentially hazardous areas.

### Accuracy and Resolution of ALOS Interferometry: Coherence Matters!!

*Sandwell, David (SIO), Meng Wei (SIO), Yuri Fialko (SIO), Rob Mellors (SDSU), and Masanobu Shimada (JAXA)*

PALSAR is the first L-band synthetic aperture radar having the duration and orbital accuracy needed to monitor slow crustal deformation globally. The main advantages of the L-band (23 cm wavelength) PALSAR over C-band (5.8 cm wavelength) are: deeper penetration of vegetated areas results in less temporal decorrelation enabling interferograms having longer time separation; and the longer wavelength increases the critical baseline resulting in more usable interferometric pairs. The potential disadvantages are: the lower fringe rate may results in less precise crustal motion measurements; and the ionospheric refraction should be 16 times worse at L-Band versus C-band. In addition to these fundamental wavelength-dependent issues, PALSAR is operated in a number of different modes that could both enhance and detract from its interferometric capabilities. In particular, the Fine Beam Single Polarization (FBS - HH) has 2 times better range resolution than most previous InSAR instruments, which further increases the critical baseline and could improve the spatial resolution of the interferograms. The Fine Beam Dual polarization (HH and HV) has 2 times worse range resolution than the FBS mode.

Over the past 1.5 years since the launch of ALOS, JAXA has imaged the area of the Pinon Flat corner reflectors 41 times. In particular, PALSAR data have been collected 10 times along an ascending track (T213), which contains sections of the San Jacinto, San Andreas, and Pinto Mountain faults. The terrain along this track has more than 3000 m of relief, and includes forested and desert areas; images were acquired during both dry and snow-covered conditions. The same area has been images at 74 times at C-band by ERS-1/2. These L and C-band data are optimal for exploring the strengths and limitations L and C-band interferometry.

The analysis of these large data sets is an ongoing project. Nevertheless through analysis of about 20 PALSAR interferograms from California, Hawaii, and Canada we have found: 1) Only one interferogram had uniformly low coherence (< 0.15) because of snow cover. 2) All of our interferometric pairs have acceptable baselines and small Doppler centroid (< 8% of the PRF) - baseline decorrelation is not an issue with PALSAR. 3) The phase is easily unwrapped using the Goldstein algorithm and a single seed point. 4) Based on a comparison with GPS measurements in Hawaii, the interferometric range precision (FBD-FBD) is 2.4 cm and phase noise is less than 1 cm - this is comparable to C-band. 5) In addition, the Hawaii GPS comparison shows the precision of azimuth offsets is about 6 cm; this provides a second orthogonal component of deformation for a single interferogram. 6) FBS and FBD modes are easily mixed by interpolation of the raw FBD data; FBD-FBS interferograms have similar fringe quality to FBD-FBD interferograms. Examples can be found at the following web site http://topex.ucsd.edu/kilauea. We plan to perform a quantitative analysis of the phase noise and resolution through sums and differences of interferograms over the Pinon/SAF site using the 10 repeats along track 213.

## SCEC/SURE: Multi-Hazards Demonstration Project: It's Your Fault... Prepare Now!

*Santilena, Rosie (CSULA), Eugenia Hyung (OSU), Stephanie Kelly (Cornell), and Robert Leeper III (CSU Fullerton)*

The Southern California Earthquake Center/Summer Undergraduate Research Experience (SCEC/SURE) internship program brings students to work as interns with the world's preeminent earthquake scientists and specialists. Though most interns still work one-on-one with a mentor, the SURE program has done something different this summer. SCEC/SURE gathered a group of four interns Eugenia Hyung, Stephanie Kelly, Robert Leeper III and Rosie Santilena to work with internship mentor Dr. Lucile Jones of the United States Geological Survey (USGS) on Southern California's section of the USGS's Multi-Hazards Demonstration Project. A scenario is being created that combines the latest knowledge about Southern California's natural hazards, specifically earthquakes; with the impact they have on the physical, social, and economic fabric of our society. The interns' task for the scenario was to act as an interface between the scientific communities and the general public, interpret Southern California Geologic map data, find innovative ways to communicate the project's results to various audiences, and collaborate with the different scientists to develop a cohesive scenario.

My concern when starting this internship was that the Multi-Hazards project leaders would produce vitally important results, which would not effectively be communicated to the public. Part of my internship consisted of developing ways to effectively communicate. We interns decided on a multi-layered approach to getting the science to the general public. I was pleased to help develop strategies to make our information relevant and understandable to the community. I helped set up and add events to the timeline. I created an interesting and informative narrative, a preliminary public service announcement, and a character named Joe, an average college student whose life was drastically altered by the earthquake. I also created an animated introduction about The Shake Out as well as an animated banner visible immediately upon opening The Shake Out web pages.

## Evidence for 4-5 earthquakes at the Frazier Mountain paleoseismic site since A.D. 1400

*Scharer, Kate (Appalachian State U), Ray Weldon (UO), Tim Dawson, Robert Sickler, Helen-Mary Sheridan (U Chicago), Kate McGinnis (Appalachian State U), Teri Gerard (Appalachian State U), Nick Weldon (Colorado C), and Sarah Hunt (UO)*

A record dry year (and diligent pumping!) in southern California provided a great opportunity for further work at the Frazier Mountain paleoseismic site, the only known high-resolution site on the longest (200 km) poorly constrained section of the southern San Andreas fault. Originally excavated in 1997 and 1999, Lindvall et al. (BSSA, 2002), reported evidence for two earthquakes since A.D. 500, but heavy rainfall flooded the closed basin and limited additional work. During July, 2007, our multi-institution team (including Tom Fumal) excavated a deeper, V-shaped trench along the same location as the Lindvall trenches and found evidence for an additional 2 -3 earthquakes. All of the evidence is of excellent quality (e.g., faults with clear upward terminations, large vertical separations, fissures, growth strata) and multiple lines of evidence identify each earthquake horizon. Preliminary dating of five detrital charcoal samples indicates that all of the earthquakes occurred since cal. A.D. 1400 -1600. Future dating of ubiquitous charcoal and organic rich layers will provide better constraints on the earthquake ages and recurrence intervals at the site, but initial results indicate an average interval of 60-150 years, comparable to adjacent Mojave and Carrrizo sections. Deeper excavations at the site could unravel older earthquakes, making this site a critical constraint for models of rupture histories of the southern San Andreas fault.

### 3D Fault Geometry and Offshore Basin Evolution in the Northern Continental Borderland

*Schindler, C. Sarah (CSUB), Craig Nicholson (UCSB), and Christopher C. Sorlien (UCSB)*

Grids of recently released high-quality industry multichannel seismic (MCS) reflection data, combined with multibeam bathymetry and offshore well data are used to map and construct digital 3D fault surfaces and stratigraphic reference horizons in the offshore northern California Continental Borderland. These 3D surfaces of structure and stratigraphy can be used to better understand and evaluate regional patterns of uplift, subsidence, fault interaction and other aspects of plate boundary deformation. Our most recent mapping in Santa Cruz basin, and on Santa Rosa and Santa Cruz-Catalina Ridge reveals a similar pattern as seen farther east of interacting high-and low-angle structures, fault reactivation, basin subsidence, folding, and basin inversion. This subsidence is significant (up to 3-4 km since early-Miocene) and is responsible for the development of several major Borderland basins. Vertical motions of uplift and subsidence can be estimated from an early-Miocene unconformity that likely represents a paleo-horizontal, near-paleo-sea-level erosional surface. As such, it can be used to reconstruct Borderland forearc geometry prior to rifting, subsidence and subsequent basin inversion. To date, major findings include: (a) a better characterization of the complex 3D geometry and pinch-out of the eastern edge of the northern forearc Nicolas terrane and its implications for Borderland basin development, plate reconstructions, vertical motions associated with oblique rifting, and continued plate boundary deformation; (b) recognition that the East Santa Cruz Basin fault, previously thought to be a predominantly high-angle, large-displacement right-slip fault representing the eastern edge of the Nicolas terrane, is in fact a series of reactivated right-stepping, low-angle NE-dipping reverse-separation faults; (c) discovery that NW-trending faults associated with Santa Cruz-Catalina Ridge bend west into a horse-tail structure to interact with and contribute to the southern frontal fault system of the Northern Channel Islands anticlinorium; and (d) recognition that both Santa Cruz-Catalina Ridge and the even larger Santa Rosa Ridge represent complex inverted basins resulting from uplift and subsidence on both high- and low-angle structures with complex tectonic histories.

### On the Spatial Correlation of Earthquake Source Parameters

*Schmedes, Jan (UCSB), Ralph J. Archuleta (UCSB), and Daniel Lavallée (UCSB)*

Most predictions of ground motion from finite faults are based on kinematic models of the rupture process. However, the parameters that represent the kinematic model are not that well known. In particular, the correlation between the parameters is often ignored. To compute ground motion that is more grounded in the physics of the earthquake process, we are simulating fully dynamic ruptures to infer more accurate kinematic parameters and their correlations. This approach allows us to find the descriptions of the parameters for the low-frequency (generally less than 1.0-2.0 Hz) part of the spectrum. However, the goal is to predict ground motion over a broad frequency range.

We follow the approach of Liu, Archuleta and Hartzell (BSSA, 2006) who use correlated distribution functions for each of the parameters. Based on the simulations of dynamic ruptures we can determine the appropriate correlation functions. To get good statistics, many dynamic models – using different random initial stress distributions – have to be computed. We use Shuo Ma's finite element code that we have parallelized using MPI. In a first step we compute a suite of dynamic ruptures for different initial stress distributions. The amplitude of the initial stress is determined from either a Gauss or a Cauchy distribution. The spatial distribution of stress is determined from the power spectrum of the spatial variability. Several models have been proposed in the literature to describe the spatial correlation – or equivalently the power spectrum – associated with the slip or the stress spatial variability. In these models, the power spectrum is attenuated according to a power law with exponent $\nu$. In this presentation, we consider two values for the initial stress: $\nu=2$ (short correlation length) and $\nu=4$ (long correlation length). Thus we have four combinations: 1, 2) Cauchy distribution of amplitude with either short or long correlation length and 3,4) Gauss distribution of amplitude with either short or long correlation length. For each combination we compute the distribution of rupture velocity.

In all cases we found correlation between rupture velocity and initial stress. For the longer correlation length we find a larger correlation. Furthermore, for the simulations with initial stress characterized by a longer correlation length, we find that the distribution of the amplitude of the rupture velocity is characterized a by a bimodal function. One mode (or maximum) of the distribution appears at about 80% of the shear wave velocity Vs; the other at about √2 of the shear wave velocity. Both of these modal values have particular significance in seismology. Composite study of kinematic models found 0.8 Vs to be the representative value (e.g., Geller, BSSA, 1976; Heaton, Phys. Earth & Planetary Interiors, 1990). The √2 Vs is the value where all of the energy flows into the fracture and there is no seismic radiation (e.g., Dunham and Archuleta, GRL, 2006); thus it is an optimum value for propagating a supershear rupture.

## Face to Phase: Probabilistic Estimates of Monitoring Completeness of Seismic Networks

*Schorlemmer, Danijel (USC) and Jochen Woessner (ETH)*

The monitoring completeness of seismic networks is heterogeneous in space and time. It strongly depends on station distribution and recording quality per station. We present a probabilistic method to estimate the detection capability of seismic networks to spatially and temporally monitor completeness based on phase data, station information, and the network specific attenuation relation.

We derive detection probability distributions for each station, from which we compute either completeness maps for a particular probability level or probability maps for the detectability of earthquakes with a particular magnitude. This approach has several advantages over alternative ways in completeness estimation: Contrary to estimating completeness based on the Gutenberg-Richter distribution, our approach does not assume any event-size distribution and is based solely on empirical data. Because the method does not rely on earthquake samples, no averaging over space and time occurs. It also offers the possibility of estimating the completeness in low-seismicity areas where methods based on parametric earthquake catalogs fail due to sparse data. Additionally, the probability distributions per station allow to analyze single station performances, intrinsically including site effects.

We present case studies from California in comparison to estimated completeness levels of other methods. Because the only ingredients to the probabilistic estimates of monitoring completeness are the phase data, the station list, and the networks attenuation relation, this approach is easy to adopt to other seismic networks. We envision this method to become a viable additional tool for the design and management of seismic networks from local to global scales and to provide further insights into station site conditions.

## Probabilistic Completeness Studies of the INGV Seismic Network in Italy

*Schorlemmer, Danijel (USC), Francesco Mele (INGV), and Warner Marzocchi (INGV)*

An important characteristic of any seismic network is its detection completeness, which should be considered a function of space and time. Many researchers rely on robust estimates of detection completeness, especially when investigating statistical parameters of earthquake occurence. We apply the newly developed probabilistic magnitude of completeness (PMC) method to the INGV network in Italy and report on completeness and earthquake detection capabilities. We have (1) investigated the variation of detection completeness with time over the last two years, (2) conducted scenario computations on possible system failures, (3) estimated the completeness drops due to random failures of stations. The results show that the INGV network is largely stable and strongly affected only by large-scale station outages. This stability indicates that Italy can provide data of required quality for CSEP (Collaboratory for the Study of Earthquake Predictability) testing.

## Defining and Implementing CSEP Natural Laboratories

*Schorlemmer, Danijel (USC), Jeremy D. Zechar (USC), and Thomas H. Jordan (USC)*

For the purposes of the Collaboratory for the Study of Earthquake Predictability (CSEP), a natural laboratory consists of two elements: a precisely defined geographic region in which earthquake models are tested and the test specifications. Delineating a natural laboratory requires precise characterization of available data, particularly regional earthquake catalogs. This includes information about data generation processes, measurement uncertainties, and derived properties such as catalog completeness. CSEP employs working groups for data, test, and model standards to develop guidelines for natural laboratory developments. We present the details of the California CSEP natural laboratory and describe the ongoing efforts to establish comparable natural labs in New Zealand, Italy, Basin & Range, and the Western Pacific region. The unique challenges of global testing are also addressed.

### Coupled Poro-Thermo-Mechanical Effects and the Tendency for Slow vs. Fast Fault Slip

*Segall, Paul (Stanford), A. Rubin (Princeton), T. Matsuzawa (NIED, Japan), and S. Schmitt (Stanford)*

Slow slip events and associated non-volcanic tremor have been discovered in a number of tectonic settings, yet the processes giving rise to these phenomena are as yet not understood. Transient slip in subduction zones appears to occur between the locked megathrust and the steadily creeping fault below. This has suggested to some that slow slip occurs in regions near neutral stability. However, the transiently slipping zone must be large enough to allow non-steady slip but not so large that the rupture becomes dynamic. For the preferred slip-law form of rate-state friction, the size range for which transient, quasi-static slip is allowed is small. We suggest that rate-state friction nucleates slip under drained conditions but that as slip accelerates and deformation becomes effectively undrained, dilatancy induced pore-pressure reductions quench the instability.

We study this process using 2D elasticity, rate-state friction and Segall-Rice [1996] dilatancy. Pore-pressure is treated either with simplified membrane diffusion; dp/dt = (Prem - p)/t_f + (1/beta) d phi/dt, (p and Prem are fault and remote pore-pressure, t_f a characteristic diffusion time, beta pore and fluid compressibility and phi fault zone porosity), or with a one-dimensional diffusion equation. For a step change in slip speed, v, the peak dilatant suction for membrane diffusion scales with (epsilon/beta)*log (v theta/d_c) *g(v t_f/d_c), where epsilon is the dilatancy parameter, theta the state in front of the rupture, and g a function depending on the ratio of diffusion time to that for state evolution. For full diffusion we have obtained analytical solutions only by excluding elastic fluid storage in the shearing zone. In this case the peak suction scales similarly to the membrane diffusion case, although the decay in pore-pressure change is far slower. These results show that the ratio of dilatant strengthening to frictional weakening scales with E = f_0 epsilon/ beta b (sigma - Prem), where b is the rate-state parameter and sigma is the fault normal stress. Indeed, numerical simulations with E ~ 1 exhibit slip that accelerates to limiting speeds well below inertial, followed by stable propagation. Simulations with E <~ 0.1 accelerate to radiation damping limits. This suggests that stable slip is favored by low effective stress, consistent with some seismic observations. When the dimensions of the weakening zone are large relative to the drained critical dimension, the behavior becomes complex, with localized zones of faster slip, even with uniform material properties. Whether this provides a possible explanation for tremor will require additional work.

We have also conducted simulations including the effects of thermal pressurization. Neglecting dilatancy, Segall and Rice [2006] estimate that thermal pressurization overwhelms rate-state weakening at slip-speeds well below seismic rates, ~1 mm/s. Numerical results, including coupling between friction, pore-fluid diffusion and thermal pressurization show that the transition to thermally dominated weakening occurs at even lower rates. Together these results suggest a paradigm in which frictional weakening controls quasi-static nucleation, but thermal weakening controls strength during dynamic slip. The tendency for dynamic versus slow slip may be controlled by the competition between dilatant strengthening versus frictional and thermal weakening.

### Slip-Predictable Earthquake Model On The Southernmost San Andreas Fault is Supported By Multiple Event Offsets Measured by a Ground-Based Lidar Survey, Southern Mecca Hills, California

*Seitz, Gordon (SDSU), Jeff Dingler (SIO), Danny Brothers (SIO), Liz Johnstone (SIO), and Neal Driscoll (SIO)*

The southernmost San Andreas fault (SSAF) is one of the most likely faults to generate a great earthquake in southern California in the foreseeable future (WGCEP, 1995). The long-term geologic slip rate of 15.9

± 3.4 mm/yr (Van der Woerd et al., 2006) and present day space geodetic rate of 25 ± 3 mm/yr (Fialko, 2006), combined with a ~325 year quiescence suggest a significant amount of strain accumulation in excess of the average ~180 year recurrence interval.

We conducted a ground-based Lidar investigation along 200 m of the fault in the Mecca Hills with well-developed offset gullies. The site was previously studied and resulted in a published 5-event paleoseismic record (Schifflet et al., 2002). The conclusions of that study are different than those based on paleoseismic trench investigations, such as at the following sites: Thousand Palms Oasis (Fumal et el., 2002), Indio (Sieh et al, 1986), Salt Creek North (Williams, 1987), and Salt Creek South (Williams and Seitz, 2004, 2005), Paso Fino (Philibosian et al., 2006).

We measured offset gullies using multiple fault-parallel topographic profiles derived from scanner-generated DEMs with 0.05 m and 0.10 m grid spacing. The results show offset modes at 1.52 m, 5.15m and 7.37 m. At Salt Creek North, Williams and Sieh (Williams and Sieh, 1987; Sieh and Williams, 1990) concluded that 1.15 m of displacement was the result of creep during the time period from AD 1703-1987. Given the proximity to the Salt Creek site, we infer an alternative where the 1.5 m offsets observed in the ground-based lidar data are entirely the result of creep.

Correlating these values to the nearest paleoseismic record at Salt Creek South allows the following interpretation. The most recent event (MRE) ~ 1700 AD experienced 5.15m of slip, and the penultimate event ~1500 AD experienced the remaining 7.37m-5.15m=2.22 m.

A consideration of the interseismic periods allows a cursory test of earthquake models. The interseismic period before the penultimate event is approximately 100 years, which we correlate to the 2.2 m slip, and the 200-year interseismic period between 1500 AD and 1700 AD corresponds with the 5.15 m slip. The total slip for the MRE is considered to be 5.15 m at depth with the 1.52 m mode merely reflecting shallow slip related to creep. These results support the slip-predictable earthquake model remarkably well and suggest that the next "big one" will be significantly bigger with slip exceeding 7 meters.

### Uncertainty analysis of finite fault inversions: A back-projection approach

*Shao, Guangfu (UCSB) and Chen Ji (UCSB)*

Generally, the quality of inverted sources of large earthquakes is controlled by frequency contents of "coherent" (or "useful") seismic observations and their spatial distribution. Here, we investigate the resolution of finite fault inversions by back projecting the data to the source regions and then analyzing the spatial-temporal variations of the focusing regions, which arbitrarily defined as the regions with 90% of the peak focusing amplitude. To simplify the problem, we only use teleseismic P waves in this study, though the following conclusions are held for more general cases. Our synthetic tests indicate that:

1) The spatial-temporal resolution at a particularly direction is controlled by regions of pcos(daz) within the seismic network, where p is the horizontal slowness from the hypocenter to the station and daz is the difference between the station azimuth and this direction. Therefore, the network aperture is more important than the number of stations.
2) Simple stacking method is a robust but usually very rough method to resolve the rupture process. It is possible to enhance the spatial resolution in a particular direction by weighting the observations in advance, though the smallest spatial resolution is dependent of the network aperture, the highest frequency of the "coherent" seismic signals, and cross-correlations of corresponding phases.
3) The results based on the teleseismic P waves of a local network usually surfers the trade-off between the source's spatial location and its rupture time.

### Slip-Length Scaling in Large Earthquakes: The Role of Deep Penetrating Slip Below the Seismogenic Layer

*Shaw, Bruce E (Columbia) and Steven G Wesnousky (UNR)*

Coseismic slip is observed to increase with earthquake rupture length for lengths far beyond the length-scale set by the seismogenic layer. The observation, when interpreted within the realm of static dislocation theory and the imposed limit that slip be confined to the seismogenic layer, implies that earthquake stress drop increases as a function of rupture length for large earthquakes and, hence, that large earthquakes differ from small. Here a three-dimensional elastodynamic model is applied to show that the observed increase in coseismic slip with rupture length may be satisfied while maintaining constant stress drop across the entire spectrum of earthquake sizes when slip is allowed to penetrate below the seismogenic layer into an underlying zone characterized by velocity-strengthening behavior. Is this deep coseismic slip happening during large earthquakes?

We point to a number of additional associated features of the model behavior which are potentially observable in the Earth. These include the predictions that a substantial fraction, of order a third of total coseismic moment, is due to slip below the seismogenic layer, and that slip below the seismogenic layer should be characterized by long risetimes and a dearth of high frequency motion.

### A method for forecasting the locations of future large earthquakes: An analysis and verification

*Shcherbakov, Robert (UCD), James Holliday (UCD), Donald Turcotte (UCD), and John Rundle (UCD)*

The objective of this paper is to quantify the use of past seismicity to forecast the locations of future large earthquakes. To achieve this the binary forecast approach is used where the surface of the Earth is divided into 2x2 cells. The cumulative Benioff strain of m > 5.5 earthquakes that occurred during the training period 1/1/1976 to 12/31/2000 is used to retrospectively forecast the locations of large earthquakes with magnitudes > 7.0 during the forecast period 1/1/2001 to 12/31/2006. The success of a forecast is measured in terms of hit rates (fraction of earthquakes forecast) and false alarm rates (fraction of alarms that do not forecast earthquakes). This binary forecast approach is quantified using a relative operating characteristic (ROC) diagram and an error diagram (ED). An optimal forecast is obtained by taking the maximum value of Pierce's skill score. The result for this optimal choice is that 64% of the locations of m > 7.0 earthquakes occurred in 1.8% of the earth's surface area.

### The complex evolution of transient slip derived from precise tremor locations in western Shikoku, Japan

*Shelly, David (Stanford University), Greg Beroza (Stanford University), and Satoshi Ide (University of Tokyo)*

Transient slip events, which occur more slowly than traditional earthquakes, are increasingly being recognized as important components of strain release on faults and may substantially impact the earthquake cycle. Surface-based geodetic instruments provide estimates of the overall slip distribution in larger transients but are unable to capture the detailed evolution of such slip, either in time or space. Accompanying some of these slip transients is a relatively weak, extended duration seismic signal, known as non-volcanic tremor, which has recently been shown to be generated by a sequence of shear failures occurring as part of the slip event. By precisely locating the tremor, we can track some features of slip evolution with unprecedented resolution. Here, we analyze two weeklong episodes of tremor and slow slip in western Shikoku, Japan. We find that these slip transients do not evolve in a smooth and steady fashion but contain numerous sub-events of smaller size and shorter duration. In addition to along-strike migration rates of ~10 km/day observed previously, much faster migration also occurs, usually in the slab dip direction, at rates of 25-150 km/hour over distances of up to ~20 km. We observe such migration episodes in both the up-dip and down-dip directions. These episodes may be most common on certain portions of the plate boundary that generate strong tremor in intermittent bursts. The surrounding regions of the fault may slip more continuously, driving these stronger patches to repeated failures. Tremor activity has a strong tidal periodicity, possibly reflecting the modulation of slow slip velocity by tidal stresses.

### Improvement and Earthquake Predictability Test of the Load/Unload Response Ratio Method

*Shen, Zheng-Kang (UCLA), Yuehua Zeng (USGS), and Yongge Wan (CEA/China)*

We have produced a source code for the Loading and Unloading Response Ratio (LURR) computation, verified its performance by completing two performance tests between our code and the code used by Yin and others (1995, 2000). The basic assumption and algorithm of LURR are that large earthquakes occur in response to critical loading stress surrounding the seismogenic fault, whose criticality could be detected through monitoring anomalous responses of the regional seismicity to the Coulomb stress change on faults induced by Earth tides. Our code utilizes the code ertid developed by Agnew (1996) to compute the Earth tide induced stress field on a given fault. When the computation is performed at the location and time of an earthquake, the tidal triggering effect of the Earth tides to the event may be evaluated. Our first test verifies the tidal stress computation. We compared a tidal stress time series produced by our code against the same time series produced by Yin's group, and obtained very good agreement between the two in both of their shapes and phases. There is, however, a small phase difference of about a few minutes at certain periods of time, whose origin is still under investigation. Our second test is to verify the computation of tidal induced Coulomb stress change and its application to a real earthquake catalog. We have used the code to evaluate the tidal loading and unloading effects for about one thousand small earthquakes occurred in southern California in the early 1990s, and compared that with the result produced for the same group of events by Yin's group. The two results agree to each other for 87% of the events evaluated. The cause of the 13% of the event discrepancy is being investigated, but considered most likely due to baseline difference in tidal induced Coulomb stress change, associated with the difference in media elasticity built in the two codes. The difference is much reduced if the loading/unloading criterion is changed from "state" to "rate" of the Coulomb stress change. We are testing the loading/unloading criterion and its implications to the earthquake precursor evaluation. In the meantime we are also using our code to retrospectively evaluate the possible LURR anomalies, both in space and time, prior to some large earthquakes occurred in California. The result will be presented at the SCEC annual meeting.

### SCEC/SURE: Paleoseismic Investigation of the San Andreas Fault at Frazier Mountain, California

*Sheridan, Helen-Mary (SCEC/SURE, UChicago)*

We investigated a paleoseismic site on Frazier Mountain, near Frazier Park, California, on the Northern Big Bend section of the San Andreas fault. We cut a 60 m long, 3-4 m deep trench on the site of the Lindvall et al. (2002) trench, beginning at the base of the northern scarp and extending south across a late Holocene fan. The trench walls were cleaned, gridded into 1 x 0.5 m sections, photographed, and logged in the field at a scale of 1:7 or 1:12. Silt, sand, and gravel are interfingered in the trench. The stratigraphy indicates that the primary source of sediment is the late Holocene fan to the northwest, carrying sand and gravel sourced from the Precambrian gneiss of Frazier Mountain. A smaller volume of sediment is shed off the slope that forms the southern slope of the site and is composed of the Hungry Valley Formation. Numerous faults run through these deposits, presenting evidence for episodic earthquake recurrence. Using field logs, I will determine the source of each sedimentary package in the southern portion of the trench in order to understand the relative contributions of each sediment source and to build a sedimentary history of the site.

### Energy Partition during In-Plane Dynamic Rupture on a Frictional Interface

*Shi, Zheqiang (USC), Yehuda Ben-Zion (USC), and Alan Needleman (Brown)*

We study properties of dynamic ruptures and the partition of energy between radiation and dissipative mechanisms using two-dimensional in-plane calculations with the finite element method. The model consists of two identical isotropic elastic media separated by an interface governed by rate- and state-dependent friction. Rupture is initiated by gradually overstressing a localized nucleation zone. Our simulations with model parameters representative of Homalite-100 indicate that different values of parameters controlling the velocity dependence of friction, the strength excess parameter and the length of the nucleation zone, can lead to the following four rupture modes: supershear crack-like rupture, subshear crack-like rupture, subshear single pulse and supershear train of pulses. High initial shear stress and weak velocity dependence of friction favor crack-like ruptures, while the opposite conditions favor the pulse mode. The rupture mode can switch from a subshear single pulse to a supershear train of pulses when the width of the nucleation zone increases. The elastic strain energy released over the same propagation distance by the different rupture modes has the following order: supershear crack, subshear crack, supershear train of pulses and subshear single pulse. The same order applies also to the ratio of kinetic energy (radiation) to total change of elastic energy for the different rupture modes. Decreasing the dynamic coefficient of friction increases the fraction of stored energy that is converted to kinetic energy. In the current study we use model parameters representative of rocks instead of Homalite-100, by modeling recent results of Kilgore et al. (2007) who measured and estimated various energy components in laboratory friction experiments with granite. We are also incorporating into the code ingredients that will allow us to study rupture properties and energy partition for cases with a bimaterial interface and dynamic generation of plastic strain off the fault.

### Analysis of fault zone head waves in the San Andreas and Southwest Fracture Zone around the hypocenter of the 2006 M6 Parkfield earthquake

*Shi, Zheqiang (USC), Yehuda Ben-Zion (USC), Zhigang Peng (Georgia Tech), Michael Lewis (USC), and Peng Zhao (Georgia Tech)*

We investigate the velocity contrast along the Parkfield segment of the San Andreas fault (SAF) and the southwest fracture zone (SWFZ) near the hypocenter of the 2006 M6 Parkfield earthquake by analyzing fault zone head waves (FZHW) that refract along the bimaterial fault interface. This study is a component of a larger project on imaging bimaterial interfaces in the Parkfield region with multiple seismic networks. The employed dataset has 1282 events recorded by the 2004 Parkfield Guided Wave Experiment (Michael et al., 2005) during the period of October 2004 to January 2005. This temporary network has 15 stations with L22 short-period sensors that are arranged in pairs on the main traces of the SAF and SWFZ. Due to the close proximity of the stations to the faults, complicated fault-zone-related phases are present in most waveforms. For accurate identification of FZHW and P wave arrivals, only waveforms with very high signal-to-noise ratios are used. By assuming right-lateral strike-slip focal mechanisms for all the events, we align the first peak or trough of the P wave arrival and examine the moveout of head wave with increasing along-fault propagation distance. So far we have identified clear FZHW signals at stations NE1O (near Gold Hill) and NE2O (near Parkfield Bridge) for propagation path along the SAF between SAFOD and Gold Hill. Analysis of head wave moveouts indicates that the average velocity contrast for the SAF near Gold Hill is ~1-2% and increases towards Middle Mountain to ~15-23%. Cross-section views of the seismicity reveal two concentrated bands of earthquakes: a shallower band around a depth of 5 km and a deeper band around a depth of 10 km. Head wave analysis on these two separate groups of events shows a slight increase of velocity contrast with depth. The obtained results probably reflect the velocity contrast between the northeast bounding block and the fault damage zone as stations NE1O and NE2O are extremely close to the SAF. Similar head wave studies with stations of other seismic networks (e.g., HRSN and NCSN) located ~1-5 km away from the fault on the slow side of the SAF give much smaller degrees of contrast associated with properties of the bounding crustal blocks. Analysis of the waveforms recorded at stations across the SWFZ is currently in progress.

### The San Fernando Valley - High School Seismograph (AS-1) Project

*Simila, Gerry (CSUN)*

Following the 1994 Northridge earthquake, the Los Angeles Physics Teachers Alliance Group (LAPTAG) began recording aftershock data using the Geosense PS-1 (now the Kinemetrics Earthscope) PC-based seismograph. Data were utilized by students from the schools in lesson plans and mini-research projects. Over the past decade, several new geology and physical science teachers are now using the AS-1 seismograph to record local and teleseismic earthquakes. This project is also coordinating with the Los Angeles Unified School District (LAUSD) high school teachers involved in the American Geological Institute's EARTHCOMM curriculum. The seismograph data are being incorporated with the course materials and are emphasizing the California Science Content Standards (CSCS). The network schools and seismograms from earthquakes in southern California region (2003 San Simeon, 2004 Parkfield) and worldwide events (e.g. Alaska 2002; Sumatra 2004,2005; 2007 Peru) are presented. In addition, CSUN's California Science Project (CSP) and Teacher Retention Initiative (TRI) conduct in-service teacher (6-12) earthquake workshops. CSUN hosted the 2007 IRIS seismology teacher training project.

### Pulverized Tejon Lookout Granite: Attempts at Placing Constraints on the Processes

*Sisk, Matthew (SDSU), Thomas Rockwell (SDSU), Gary Girty (SDSU), Ory Dor (USC), and Yehuda Ben-Zion (USC)*

We have described and analyzed pulverized Tejon Lookout granite recovered from several transects of the western segment of the Garlock fault on Tejon Ranch in southern California. Observations and data collected at this location are compared to a sampled transect of the San Andreas fault at Tejon Pass previously studied by Wilson et al. (2005), also exposing the Tejon Lookout granite. The purpose of this study is to characterize the physical and chemical properties of the pervasively pulverized leucocratic rocks at multiple locations and to hopefully place constraints on the processes producing them. To accomplish this we performed particle size analysis with the use of both laser particle analyzer and pipette methodology; major and trace chemistry analyses determined by XRF; clay mineralogy determined by XRD; and we evaluated fabric and texture through the study of thin sections.

Recovered samples met the field criteria of pulverization - that is, the individual 1-2 mm-sized crystals can be recognized in the field but the granite (including quartz and feldspar) can be mashed with ones fingers and exhibits the texture of toothpaste. All samples were analyzed on a Horiba LA930 Laser Particle Analyzer in an attempt to reproduce the earlier results of Wilson et al. (2005) with similar methodology. We also utilized the classic pipette methodology to ensure complete discrimination of particle sizes. Our PSD analysis shows that the dominant particle size falls in the 31-125 micron range, much coarser than previously reported by Wilson et al. (2005), with >90% of the total sample falling in the >31 micron size range. We can reproduce the previously documented results by allowing the samples to circulate for long periods of time at slow circulation speeds in the laser particle size analyzer, during which time the coarse fraction settles out, thereby leaving only the fine fraction for detection. However, subsequent increase in the circulation speed leads to a complete recovery of the original PSD. Our XRF and XRD analyses provide evidence of the lack of major weathering products and their inability to skew the PSD results in a significant way.

Dor et al. and Stillings et al. (this meeting) document evidence that support theoretical predictions and previous inferences of pulverization occurring in the upper few kilometers, especially along faults of the southern San Andreas system. Geophysical observations of Lewis et al. (2005, 2007) provide evidence that low velocity fault-parallel layers, which are likely made of pulverized or highly damaged material, are dominant in the upper few kilometers of the crust. Their asymmetric position with respect to the slipping zone, in agreement with asymmetric patterns of small scale mapped rock damage (Dor et al., 2006), suggest that pulverized rocks are likely the product of a preferred rupture direction during dynamic slip. Our results combined with the above mentioned works imply that pulverized fault zone rocks at multiple locations are much less damaged than suggested in previous studies.

### Nonlinear attenuation and rock damage during strong seismic ground motions

*Sleep, Norman H. (Stanford) and Paul Hagin (Stanford)*

The shallow subsurface behaves nonlinearly and anelastically during strong ground motions. There are two easily observable effects. (1) The S-wave velocity of the shallow surface decreases after strong ground motions. The S-wave velocity then slowly increases with the logarithm of post-seismic time. (2) The strong seismic wave attenuates nonlinearly. Rate and state friction explains both effects. Dynamic stresses approach lithostatic stresses in the upper quarter wavelength of the dominant frequency of the seismic wave. Nonlinear effects occur at depths scaling to the inverse of the wave number, that is ~30 m for VS30 = 300 m/s and an angular frequency of 10 s-1. Scaling relationships between S-wave velocity and porosity change provide an energy balance. Work to open pore space against lithostatic pressure is a major cause of nonlinear attenuation. Micromechanically, shear failure allows irreversible dilatation. Failure occurs over a range of macroscopic dynamic stresses because the rock is heterogeneously prestressed. Nonlinear attenuation leads to observable S-wave travel time anomalies in compliant rocks VS30 ~300 m/s, but not in intact rocks VS ~2000 m/s. With regard to practical matters: (1) S-wave velocity changes locally calibrate the threshold (sustained) acceleration for nonlinear attenuation. (2) Semi-empirical rules for site characterization already have nonlinear attenuation increasing over a range of accelerations. (3) Waves trapped in basins attenuate nonlinearly each time they reflect off the free surface. This effect cannot be represented as a local site response. (4) There is a maximum sustained acceleration above which a seismic wave does not propagate to the surface. We represent state as a function of S-wave velocity as a modification of the Linker and Dieterich (1992) relationship for friction after changes in normal traction. The limiting acceleration for extreme ground motions is less than 1.5 g and does not depend strongly on rock type.

## Stress Evolution of the San Andreas Fault System: Dependencies on Paleoseismicity, Recurrence Intervals, and Fault Locking Depths

*Smith-Konter, Bridget (JPL) and David Sandwell (SIO)*

Major ruptures along transform faults such as the San Andreas Fault System (SAFS) are driven by stress that has accumulated in the upper locked portion of the crust. While the present-day stress accumulation rate on any given fault segment of the SAFS is fairly well resolved by current geodetic measurements, the total accumulated stress depends on the rupture history of the fault over the past few thousand years, which is only poorly constrained by paleoseismic data. Using a simple 3-D kinematic model of the earthquake cycle, we show that stress accumulation rate is highly dependent on the fault locking depth. Model stress accumulation rates vary between 0.5 and 7 MPa per century and are inversely proportional to earthquake recurrence intervals (500-20 yrs). Assuming complete slip release during major ruptures, we simulate accumulated stress at crustal depths for both past and present-day conditions, examining a suite of plausible historical rupture scenarios. These more speculative results indicate that the southern San Andreas, which has not ruptured in a major earthquake in over 300 years, is currently approaching a historically critical stress level.

## Effect of 3D Stress Heterogeneity on Aftershock Sequences

*Smith, Deborah Elaine (UCR) and James Dieterich (UCR)*

Observations of spatially varying slip along fault zones and in earthquakes suggest that both slip and stress are spatially heterogeneous and possibly fractal in nature. We model seismicity in spatially heterogeneous stress fields, including the temporal response to static stress perturbations. Starting with 3D models of the crust with fractal-like heterogeneous stress, we add a stress perturbation due to a major earthquake, and couple this system to rate-state seismicity equations to explore the temporal evolution of seismicity during an aftershock sequence. We find that the stress perturbation can generate an increased focal mechanism orientation scatter and a sizable rotation of the average P-T orientation. Both of these effects have been observed in the real Earth. Previous models (without 3D stress heterogeneity) assumed these effects reflected real changes in the stress orientation, and hence required small background differential stresses of 10 MPa or less to satisfy the observations. In our model, the presence of stress heterogeneity can bias the failures, creating an apparent stress rotation much larger than the actual stress rotation. Consequently, our model can generate rotations similar to that observed in the real Earth with background differential stresses in the range of 20-50 MPa. We also explore how the focal mechanism orientations rotate and scatter throughout the aftershock cycle. Woessner (2005), observed a step increase in focal mechanism orientation scatter at the onset of a major earthquake with a decay back to smaller scatter during the aftershock sequence. Using rate and state friction seismicity rate equations, we model this temporal evolution of seismicity in our 3D heterogeneous stress volumes.

## Rate-State Modeling of Stress Relaxation in Geometrically Complex Faults Systems

*Smith, Deborah Elaine (UCR) and James Dieterich (UCR)*

Slip of geometrically complex faults involves interactions and processes that do not occur in standard planar fault models. These include off-fault yielding and stress relaxation, which are required to prevent the development of pathological stress conditions on the fault (or in extreme cases fault lock-up). Nielsen and Knopoff [1988] introduced yielding through a simplified form of viscoelastic stress relaxation. However, the mechanical characteristics of the brittle seismogenic crust indicate that faulting processes will dominate the stress relaxation processes. The fractal-like character of fault systems and fault roughness, together with the finite strength of rocks, insures that slight movements of secondary faults, at all scales, will be necessary to accommodate slip of major through-going faults. To model the integrated effect of these processes, we employ an earthquake rate formulation [Dieterich, 1994], which incorporates laboratory-derived rate- and state-dependent frictional properties, on geometrically complex faults. With the rate-state formulation we find that stress relaxation occurs co-seismically during large earthquakes, as delayed stress relaxation in the form of aftershocks, and as spatially distributed background seismicity. During aftershocks the spatial mean of stresses decay at a rate proportional to 1/t. We find large spatial and temporal differences in models of slip of faults with relaxation compared to faults in purely elastic media. We conclude that that yielding and relaxation are important controlling processes that are the mechanics of slip on geometically complex faults.

### SCEC/UseIT: Development of a Decision-Oriented Game

*Solomon, James Bodie (Pasadena City College)*

My research this summer in the Undergraduate Studies in Earthquake Information Technology program (UseIT) focused on creating a decision-making game in a team of three interns. SCEC/UseIT is an intern-oriented program, and our job this summer was to break into small teams and create serious games. With the current working title of "Geomancer", our team's game is intended to communicate the importance of earthquake preparedness in metropolitan areas with significant hazard. The player manages a simplified city environment, with a multiple hazard index assigned to each location in the city. Three funding choices are given to the player: Research increases the player's awareness of seismic hazard regions; Preparedness reduces shake damage to a block; and Response reduces loss of life in a local area. Each of these choices must be used strategically with the others, based on hazard and high-risk city regions, to save the city from catastrophe. My personal work was mainly oriented toward the creation and intuitive display of hazard-index maps, which tell the player where regions of highest damage will occur in an earthquake. The program uses bilinear interpolating algorithm to fade hazard between "control points", or regions of predefined hazard. The game's message, strategy, and visual design were all developed from scratch by our team, with the main focus of communicating complicated data and hazards in a simplified, abstracted fashion.

### Pseudo-Dynamic Modeling of Large Strike-Slip Earthquakes

*Song, Seok Goo (URS Corporation), Arben Pitarka (URS Corporation), and Gregory C. Beroza (Stanford University)*

Accurate prediction of the intensity and variability of near-field strong ground motion for future large earthquakes strongly depends on our ability to simulate realistic earthquake source models for those events. Guatteri et al. (2004) developed a pseudo-dynamic source modeling method to generate physically self-consistent finite source models without high-cost, full dynamic rupture simulation, but still retaining important characteristics of dynamic faulting. We improve their method and extend its magnitude coverage to extend efficient finite-source characterization for ground motion predictions to larger strike-slip events ($M > 7.2$). For this we constructed 15 spontaneous dynamic rupture models with different slip realizations and hypocenter locations for large, Mw 7.5, strike-slip earthquakes. These earthquakes have a very long and narrow rupture dimension (150 km long and 15 km wide), which leads to behavior that is substantially different from the smaller events used by Guatteri et al. (2004). We also allow greater latitude for supershear rupture in the present study, because it has been observed recently for a number of long strike-slip earthquakes (Bouchon et al., 2001; Bouchon and Vallée, 2003; Dunham and Archuleta, 2004; Song et al., 2008). A set of empirical relationships, derived from the analysis of these spontaneous rupture models outputs, exhibit interesting features that were not observed in the previous study. Supershear rupture is widely observed in our modeling, and we find that instantaneous (local) rupture velocity extracted from the rupture time distribution of the modeling outputs correlates strongly with local slip amplitude. Our study also shows that the relatively fixed fault width of the long, narrow ruptures plays a critical role in controlling rupture behavior as the rupture dimension increases in the along-strike direction, as predicted by Day (1982). Our improved pseudo-dynamic modeling method can be used to generate realistic finite-source earthquake models for simulating near-field ground motion from large strike-slip events.

### The giant low-angle fault system beneath the Palos Verdes anticlinorium, California

*Sorlien, Christopher (UC Santa Barbara) and Leonardo Seeber (LDEO)*

Southern California thrust earthquakes during the late 20th century reveal hazard from blind faults. These faults deform sedimentary rocks above them, and are often imaged by seismic reflection profiles. The Palos Verdes anticlinorium (PVA) as we define it is an active fault-fold structure, critical for earthquake hazard because of its large size and location near Los Angeles (L.A.). The PVA is a NW-trending 70 km-long structure between the L.A. Basin and the Santa Monica-San Pedro Basins offshore and implies an active thrust fault system of similar dimensions. The onshore restraining segment of the right-lateral Palos Verdes fault contributes locally some contraction that may account for enhanced uplift of the Palos Verdes Hills, but cannot account for the PVA. We have identified members of the same southwest-verging fault system that may account for the PVA (Broderick, 2006). The NE-dipping San Pedro Escarpment fault (SPEF) below the southwest forelimb of the PVA aligns in 3D with the Compton thrust ramp and may be the same fault. The Compton ramp is beneath the northeast backlimb of the PVA, and, in turn, connects farther down-dip with the lower Elysian Park fault (Shaw et al., 2002). These three previously known elements are thus merged into a single upper-crustal thrust fault that accounts for the PVA.

The growth rate of the PVA and thus the slip rate on the thrust system are controversial. The tops of Miocene rocks in Santa Monica and Los Angeles Basins have subsided respectively to 4 km and 5 km depth. Much of or all of this subsidence occurred in the last 5 million years and is the likely result of post-extensional cooling and thrust plus sediment loading. Late Pliocene and early Quaternary angular unconformities with geometries similar to wavecut platforms are now at 600 to 1000 m depth in San Pedro Basin and the Gulf of Santa Catalina, suggesting that subsidence is ongoing. Active thrust faulting and folding are thus required to keep the Palos Verdes Hills and adjoining continental shelves from sinking concurrently with the adjacent basins. More direct evidence of the youth of the blind thrust system is seen along the southern part of the 700 m-high seafloor San Pedro Escarpment. In this area, Pliocene strata do not thin onto the southwest-dipping limb of the anticlinorium; therefore its southern limb did not start folding until Quaternary time. Structural relief of the ~1.8 million year top lower Pico is about 1 km beneath part of southern San Pedro Escarpment. Assuming constant Quaternary slip rates and that simple motion up a fault ramp causes structural relief, the slip rate would be 1.3 mm/yr for a fault dip of 25 degrees and 2.1 mm/yr for a fault dip of 15 degrees.

Seismic reflection profiles across the base of the San Pedro Escarpment image a stack of folded unconformities highly suggestive of ongoing forelimb growth and shortening. This shallow folding 50 km southwest of downtown LA may be the most direct structural observable related to seismogenic thrust faulting below L.A. Despite different names for its different parts, a single major thrust fault may account for the west flank of the LA Basin and be a potential source of rare but catastrophic ruptures. A significant portion of the hanging-wall of this system is offshore and thus could be tsunamigenic, including immediately offshore of Long Beach and the port of Los Angeles.

Broderick, K.G., (2006), Giant blind thrust faults beneath the Palos Verdes Hills and western Los Angeles Basin, California: Mapping with seismic reflection and deep drilling data, unpublished M.S. thesis, 68 pp., University of California, Santa Barbara, Santa Barbara, California

Shaw, J. H., A. Plesch, J. F. Dolan, T. L. Pratt, and P. Fiore, 2002, Puente Hills blind-thrust system, Los Angeles, California, Bull. Seism. Soc. Am., 92, p. 2946-2960.

Others involved: Kris Broderick (UCSB, now ExxonMobil); Bruce Luyendyk (UCSB); Mike Fisher, Ray Sliter, Bill Normark (USGS); Doug Wilson (UCSB).

### Rock Pulverization in the Horse Canyon Double Restraining Bend

*Stillings, M. (SDSU), T. Rockwell (SDSU), G. Girty (SDSU), O. Dor (USC), N. Wechsler (USC), and Y. Ben-Zion (USC)*

The relationship between damage in fault zone rocks and rupture dynamics is not fully understood despite the importance to theory and practical applications. Through detailed field observations, petrographic analysis, and quantitative chemical analysis, we describe the damage zone properties along a portion of the Clark strand of the San Jacinto fault zone. We focused our attention on a double restraining bend, where detailed field mapping reveals an asymmetric pattern of damage with the most highly damaged and pulverized fault zone rocks (PFZR) located primarily southwest of the main fault strand. Field relationships reveal that the pulverization is not directly related to the restraining bend, but rather is spatially related to a complex series of secondary faults within the step-over region. Chemical analysis shows that the grain size reduction of the PFZR is not due to chemical alteration. In addition to the damage asymmetry with respect to the fault, there is also a variation in damage degree with relation to lithology. The metamorphic rocks within the study area remain resistant to fault related grain size reduction, while the granitic rocks within the damage zone undergo a grain size reduction of several orders of magnitude. Quantitative analysis of the grain size reduction reveals a unimodal particle size distribution ranging from approximately 7-500 microns. This study demonstrates that the pulverization cannot be attributed to the presence of the restraining bend, but is specifically related to proximity to faults, and is therefore most likely related to the dynamic rupture process. The sense of symmetry (damage on the southwest side of the fault) is opposite to that documented near Hog Lake to the northwest of Anza by Dor et al. (2006) and suggests that the direction of rupture propagation in this area is from NW to SE.

### Precarious rocks and near-fault earthquake motions from a reverse fault in New Zealand: Cross Validating the North American Studies

*Stirling, Mark (GNS Science), Matthew Purvance (Nevada Seismology Lab), and Rasool Anooshehpoor (Nevada Seismology Lab)*

Precariously balanced rocks (PBRs) exist within 5 km of the Dunstan Fault, a major active reverse fault in the Central Otago province of New Zealand. This study serves as a preliminary cross validation of studies carried out in western North America, and builds on an older field-based pilot study of PBRs in New Zealand. Cosmogenic age dates find that these PBRs have survived the set of all earthquakes that have occurred for perhaps as much as 77ka, suggesting that they may provide an important constraint on the associated ground motions. Simplified seismic hazard analyses assuming repeated characteristic earthquakes with ground motions based on a number of ground motion prediction equations (GMPE) are compared with the PBR fragilities (e.g., overturning probability as a function of the peak ground motion amplitudes). The GMPEs include a commonly utilized worldwide GMPE (the Abrahamson & Silva model) along with a New Zealand specific GMPE (the McVerry model) and newly developed Next Generation Attenuation (NGA) GMPEs. The New Zealand specific and NGA GMPEs predict significantly lower median ground motions than the commonly used worldwide (Abrahamson & Silva) GMPE with about the same level of expected variability about the medians. Various scenarios regarding ground motion recurrence are investigated, including characteristic ground motions (e.g., repeating peak ground motion amplitudes) with and without waveform variability, along with random ground motions taken from the GMPE distributions. The PBRs do not overturn with high probability during their residence times when exposed to median characteristic ground motions without waveform variability, while median plus one standard deviation ground motions result in significantly higher overturning probabilities for one of the PBRs. Repeated characteristic ground motions with waveform variability enhance the overturning probabilities, especially for the commonly used worldwide (Abrahamson & Silva) GMPE. Random ground motions taken from the GMPE distributions produce significantly higher overturning probabilities for all of the GMPEs investigated for one of the PBRs. Consistency between the PBRs and the GMPEs may result from additional reduction in the median ground motions and/or the presumed level of ground motion variability. The ergodic assumption used to determine the GMPEs may therefore be in error for this PBR site. Future work is required to greatly reduce the age uncertainties in the PBRs at the site (a conservative age range of 10ka to 77ka is based on dating and geomorphic interpretation), and incorporate newly available Dunstan Fault paleoseismic data into the analysis. There remains a small possibility that the PBRs are of a similar age to the elapsed time since the last Dunstan Fault earthquake.

### A review of the current approach to CVM-Etrees

*Taborda, Ricardo (CMU), Julio Lopez (CMU), David O'Hallaron (CMU), Tiankai Tu (CMU), and Jacobo Bielak (CMU)*

One of the major aspects of the ongoing efforts to push the limits on earthquake simulations, from the computational point of view, is I/O performance. At the front end, the lack of ready accessibility of the input data (velocity model) is one of the major factors affecting the efficiency of mesh construction. Unfortunately, the traditional information that the community possesses in this area is in the form of low-performance computational tools. For several years now, we have been using the in-house developed etree-library to construct etree versions of SCEC's Community Velocity Model (CVM). We call them CVM-Etrees. They are discrete octree-based representations of the original CVM, with properties that greatly enhance the accessibility of the data base. Although the construction of CVM-Etrees does not yet directly solve the performance issue by itself, it is a one time effort which results in a high-performance database that does speed up the process of repetitive mesh generations and material model exploration for pre- and post-processing analysis. This work explains our approach to storing the SCEC-CVM into etrees and examines their advantages and disadvantages compared to the current version of the CVM. We analyze the querying performance for data exploration and mesh construction processes, and the differences induced by the discretization procedure at different points in the Southern California region. We also present the current CVM-Etrees available to the community, which were recently used by different simulation groups as the primary material database source for the PetaSHA's ShakeOut earthquake scenario.

### Rupture directivities of the 2003 Big Bear sequence

*Tan, Ying (Caltech) and Don Helmberger (Caltech)*

We have developed a forward modeling technique to retrieve rupture characteristics of small earthquakes (3<5), including rupture propagation direction, fault dimension, and rupture speed. The technique is based on an empirical Green's function (EGF) approach, where we use data from co-located smaller events as Green's functions to study the bigger events.

Compared to deconvolution, this forward modeling approach allows full use of both the shape and amplitude information produced by rupture propagation. Assuming simple 1D Haskell source model (Haskell, 1964), we parameterize the source time function of a studied event as the convolution of two boxcars, featuring the rise time t1 and the rupture time t2, and we solve for t1 and t2 in a grid-search manner by minimizing the waveform misfit between the three-component data and the "synthetics" from the EGFs. Then by fitting the observed azimuthal pattern of t2 with the predictions from the model t2 = fl/Vrup - fl/Vc*cos(strike-azi), the fault length (fl) and rupture velocity (Vrup) can be estimated.

We have applied the approach to the 11 strike slip events with magnitude greater than ~3.4 of the 2003 Big Bear sequence. We generally chose smaller events with similar focal mechanisms for EGFs, however, we show that the smaller events with different focal mechanisms can work equally well if the radiation pattern effect can be appropriately corrected. The studied events show rupture propagation in all directions with wide-ranged rupture speeds (1.5-3.5 km/sec), implying the complexities of conjugate faulting.

### Localization of Deformation in Elastic-Plastic Analysis of Dynamic Shear Rupture

*Templeton, Elizabeth L. (Harvard) and James R. Rice (Harvard)*

Recent studies have allowed for off-fault inelastic deformation in analyses of dynamic earthquake rupture propagation (Andrews [JGR, 2005]; Shi and Ben-Zion [GJI, 2006]; Templeton et al. [AGU, Fall 2006]; Viesca et al. [AGU, Fall 2006]). These studies use Mohr-Coulomb or Drucker-Prager type pressure-dependent yield criteria, which are simple models for describing the onset of plastic deformation in granular or cracked materials.

We use a Drucker-Prager yield criterion (which coincides with Mohr-Coulomb for special cases of plane strain) to conduct plane strain elastic-plastic finite element analyses of dynamically propagating slip-weakening rupture. The results show features in the strain field that indicate strain localization into shear-band-like structures. Bifurcation analyses for states of spatially homogeneous quasistatic deformation have shown that instabilities in the constitutive description for certain classes of elastic-plastic materials can lead to such localization of deformation (Hill [JMPS, 1952]; Thomas [book, 1961]; Rudnicki and Rice [JMPS, 1975]; Rice [1976, Proc. ICTAM]), with localization conditions coinciding with those for a vanishing propagation speed of elastic-plastic body waves (Hadamard [book, 1903]; Mandel [1963, Proc. IUTAM]; Hill [JMPS, 1962]). Rudnicki and Rice [JMPS, 1975] found that localization can occur even for positive hardening in a material of Drucker-Prager or Mohr-Coulomb type, i.e., with a pressure-dependent elastic-plastic yield description, and determined that there is a critical hardening, above which localization will not occur. The critical value is typically positive in states of, or near to, plane strain deformation.

Thus elastic-plastic laws of the type we use are prone to shear localization in plane strain even when the plastic strain-hardening modulus is positive, and we typically use a non-hardening model. This results in an inherent grid dependence in our numerical solutions, with notable variations of plastic strain at the scale of grid spacing, and it precludes point-wise convergence with increasing grid refinement. Grid-dependent localization features signal that no continuum solution exists for the adopted model, and some localization limiting procedure (Bazant [JEM, 1984]; de Borst [IJNAMG,1988]; Needleman [CMAME,1988]; de Borst [EJM A/Solids, 1999]) would need to be added to the constitutive description in order for a solution to exist.

We investigate in detail the localization features we see in our elastic-plastic finite element analyses to understand how their shape, spacing, and extent change with grid refinement. A question is whether the dynamic solutions for rapidly propagating ruptures, without a localization limiting procedure, might perhaps converges in some average rather than point-wise sense. We show, in the dynamical problems we address, that overall sizes and shapes of off-fault plastic regions, and also the dynamics of rupture propagation, seem generally to be little different from what is obtained when we increase the assumed plastic hardening modulus above the theoretical threshold for localization and, thereby, obtain a locally smooth and presumably point-wise convergent numerical solution.

**Development of a State-wide 3-D Seismic Tomography Velocity Model for California**
*Thurber, Clifford (UW-Madison), Guoqing Lin (UW-Madison), Haijiang Zhang (MIT), Egill Hauksson (Caltech), Peter Shearer (UC San Diego), Felix Waldhauser (Lamont), Jeanne Hardebeck (USGS), and Tom Brocher (USGS)*

We report on progress towards the development of a state-wide tomographic model of the P-wave velocity for the crust and uppermost mantle of California. The dataset combines first arrival times from earthquakes and identified quarry blasts recorded on regional network stations and travel times of first arrivals from explosions and airguns recorded on profile receivers and network stations. The principal active-source datasets are Geysers-San Pablo Bay, Imperial Valley, Livermore, W. Mojave, Gilroy-Coyote Lake, Shasta region, Great Valley, Morro Bay, Mono Craters-Long Valley, PACE, S. Sierras, LARSE 1 and 2, Loma Prieta, BASIX, San Francisco Peninsula and Parkfield.

Our beta-version model is coarse (uniform 30 km horizontal and variable vertical gridding) but is able to image the principal features present in previous separate regional models for northern and southern California, such as the high-velocity subducting Gorda Plate, upper to middle crustal velocity highs beneath the Sierra Nevada and much of the Coast Ranges, the deep low-velocity basins of the Great Valley, Ventura, and LA, and a high-velocity body in the lower crust underlying the Great Valley. The new state-wide model has improved areal coverage compared to the previous models, and extends to greater depth due to the inclusion of substantial data at large epicentral distances.

We plan a series of steps to steadily improve the model. We are enlarging and calibrating the active-source dataset as we obtain additional picks from various investigators and perform quality control analyses on the existing and new picks. We will also be adding data from more quarry blasts, mainly in northern California, following an identification and calibration procedure similar to Lin et al. (2006). Composite event construction (Lin et al., in press) will be carried out for northern California to add to those available for southern California for use in conventional tomography. A major contribution of the state-wide model is the identification of earthquakes yielding arrival times at both the Northern California Seismic Network and the Southern California Seismic Network. These events are critical to the determination of the seismic velocity model in central California, in the former "no-mans-land" between the Northern and Southern California networks. Ultimately, a combination of active-source datasets, composite events, original catalog picks, and differential times from both waveform cross-correlation and catalog picks will be used in a double-difference tomography inversion.

**SCEC/UseIT: The Creation of the Educational Game**
*Tillman, Ashlynn (Rust College)*

UseIT (Undergraduate Studies in Earthquake Information Technology) is an educational program that helps people all over the world understand the concepts of earthquake science through a computer software program called SCEC-VDO (Southern California Earthquake Center-Virtual Display of Objects), which is a program that has been developed by interns.

This summer's grand challenge was to develop an educational game for an introductory geoscience course. The game concept consisted of a main board game that links to other mini-games. My research plan this summer consisted of helping create one of the mini-games. The mini game that I helped create was the Fault Game, which teaches that faults display different types of motion, and that a fault slips more during a higher magnitude earthquake. This information is communicated when the player changes fault motion and slip to release some sheep from a pen. I helped design the fence arrangement and other assets for the strike slip fault level of the game.

My biggest accomplishments this summer were learning how to develop games, and to use/learn software programs that I have never used. The challenge was learning the basics of the computer software programs, especially at a fast pace. The SCEC/ UseIT summer program was tough, but a good and valuable experience. I learned about the software program SCEC-VDO, which I will advertise at my school, and hopefully we can get the program on my school's computers.

## Fall 2007 paleoseismic and Holocene slip rate investigations along the San Andreas Fault, at Parkfield, California

*Toké, Nathan (ASU) and J Ramon Arrowsmith (ASU)*

Given the historic precedent of foreshocks occurring at Parkfield prior to the 1857 Fort Tejon M 7.9 earthquake, likely slip there associated with the main 1857 shock, and the decreasing aseismic strain release along the San Andreas Fault (SAF) to the southeast, numerous assessments of California earthquake hazard have placed importance on improving our understanding of the record of earthquakes at Parkfield. Coseismic slip along the Parkfield segment could propagate (or trigger an event) further southeast. Earthquake recurrence data, the role of sub-parallel surface-rupturing faults, and a long term slip rate for Parkfield are essential for studies of the temporal aspects of fault strain release histories, fault mechanics, and for characterization of earthquake hazard for south-central California.

To refine the SAF deformation record over timescales that include multiple large earthquake ruptures, to measure a Holocene slip rate of the SAF at Parkfield, and further assess Parkfield's role in the rupture of large central SAF earthquakes, we are conducting field investigation at Parkfield, California in October of 2007. Using the B4 LiDAR data we have identified several paleoseismic sites along the main SAF and Southwest Fracture Zone that may be suitable for paleoseismic and slip rate measurement near Parkfield. In fall 2007 we will excavate one of these sites for paleoseismic and slip-rate investigation. Specifically, we will address the following questions: What is the Holocene slip rate for the SAF at Parkfield? How is slip partitioned between the main SAF and the nearby southwest fracture zone? Is there evidence of earthquakes larger than Mw ~6. This work will expand upon our previous work in Parkfield at the Miller's field Paleoseismic site in 2004.

## San Andreas Fault Rupture Hazard to Lifelines – Part of a Mw 7.8 Earthquake Scenario

*Treiman, Jerome A. (California Geological Survey)*

The California Geological Survey (CGS) is participating in the preparation of a scenario for a Mw 7.8 earthquake on the southern San Andreas fault, as part of the USGS-sponsored Multi-Hazards Demonstration Project. One of our tasks is to assess the potential for geologic disruption of lifelines where they are concentrated at several "choke points" crossed by the scenario ground rupture. Lifelines are part of the linear infrastructure that provide vital transportation and communication avenues and include highways, railroads, aqueducts, power lines, pipelines (oil and gas) and fiber-optic lines. CGS has evaluated the potential impact to lifelines from surface fault rupture and seismically-induced landslides and liquefaction in four focus areas: Palmdale, Cajon Pass, San Gorgonio Pass and Coachella. This poster will present the fault rupture impacts; landslides and liquefaction will be presented in complementary posters. Each of the four focus areas presented different issues in locating and assigning potential slip at lifeline crossings.

The Palmdale focus area includes several parallel strands of the San Andreas Fault which cross the full spectrum of lifelines, including two crossings of the California Aqueduct and a dam. We have excellent and detailed geologic mapping of the fault traces in this area (Barrows and others, 1985) that allows the anticipation of some broader zones of deformation. Part of the task in this area has been to apportion the modeled slip (2.5-3.5 m) onto the several parallel fault traces.

The Cajon Pass focus area is characterized by a single main trace of the San Andreas Fault that includes a few small-scale extensional stepovers. From 2 to 6 meters of slip is modeled here in the scenario. Other nearby related fault strands were not assigned slip in this scenario. The fault crosses a major highway, critical rail lines and numerous key communication and power systems. Previous mapping, plotted on 1:24,000 topographic base maps by Weldon (1986), was relocated based on aerial photo interpretation and LiDAR imagery from the B4 project to more accurately locate potential lifeline failures.

The San Gorgonio Pass focus area includes a broad stepover from the Banning Fault to the Garnet Hill Fault. Slip (1.5-4 m) is modeled to transfer gradually from one fault to the other across the focus area. Fault traces are from aerial photo interpretation and field mapping by CGS and others. Disruption of a Metropolitan Water District aqueduct is anticipated both in cut and cover pipelines and a tunnel.

The Coachella focus area is characterized by a single fault trace with some minor extensional stepovers. Previous fault trace mapping on 1:24,000-scale topographic maps (Clark, 1984) was relocated based on new interpretation of vintage aerial photos and careful registration of the images within a GIS database. Several lifelines, including Interstate 10 and the Coachella Canal, would be affected by 3.5-7.5 m offset along this rupture segment.

### SCEC/SURE: Compton Blind-Thrust Fault: Compelling Evidence for Holocene Activity of Los Angeles Basin, California

*Tsang, Stephanie (UCLA), Lorraine Leon (USC), James Dolan (USC), and John Shaw (Harvard)*

Analysis of recently acquired borehole data from the Compton fault provides compelling evidence for multiple, large-magnitude earthquakes during Holocene time. Sediments extracted above the southern segment of this large blind thrust fault from a site in the city of Lakewood, California (~35km from downtown Los Angeles) record the details of fold growth during large-magnitude Compton thrust earthquakes. Shaw and Suppe (1996) originally identified the fault by means of industry seismic reflection data, which demonstrated growth of a major fault-bend fold above the thrust ramp. Data within the uppermost few hundred meters, however, are not recorded in the industry data. To document deformation in the uppermost section, we drilled a transect of five continuously cored boreholes, extending ~1077m in length, across the back-limb active axial surface of the fault-bend fold above the Compton thrust ramp. The borehole data reveal folding within a discrete kink band that is <~278m wide in the shallow subsurface. The stratigraphy of the borehole consists of alternating coarse-grained sand and gravel units with interbedded fine-grained silt and clay intervals that contain numerous organic-rich clay units and silt layers. The presence of abundant detrital charcoal within the boreholes yields several 14C dates, exhibited in the accompanying figures, within the range of 3595±40BP to 17770±60BP. Preliminary analysis of five 14C samples, including both bulk-soil and charcoal samples, indicates a sediment accumulation rate of ~1.9 mm/yr, which is comparable to other sites within the Los Angeles basin. These observations verify the active nature of the Compton blind thrust fault as well as its capacity to generate destructive, large-magnitude earthquakes directly beneath the metropolitan Los Angeles area. Additional evidence, however, is needed in order to assess the timing and nature of individual uplift events and the slip rate of the fault. Ultimately, further sediment extraction via boreholes will provide a greater understanding of this large blind thrust fault.

### Examining the style and rate of uplift along the Claremont segment of the San Jacinto Fault Zone

*Tung, Jack (CSULA) and Nate Onderdonk (CSULB)*

The San Jacinto Nuevo Potrero is a small basin in the northwestern-most San Jacinto Mountains that is currently undergoing uplift as a result of slip along the San Jacinto fault zone. This uplifted area is located in a restraining step-over between the Claremont and Hot Springs segments of the San Jacinto fault zone. Alluvial terraces preserved within the small basin record changes in local base level, which are due to vertical offset along the Claremont fault. These preserved alluvial terraces allow for determination of the deposition, incision, and uplift rates of the region and provide an estimate for rates of topographic development along the San Jacinto Fault Zone.

Radiocarbon dating was conducted on pieces of charcoal collected from the terraces. Based on the vertical separation and age difference between the samples, the rates of deposition, subsequent incision, and uplift can be inferred. The radiometrically dated samples suggest deposition rates of 1.7 to >5.4 mm/year during the Holocene, an incision rate of Potrero Creek of about 3.26 mm/year since the late Pleistocene, and an uplift rate of the region between 0.65 to 0.96 mm/year since the late Pleistocene. Kinematic indicators along fault surfaces suggest uplift is accomplished by right-lateral reverse oblique slip along segments of the Claremont fault and the Soboba-Campbell Ranch fault.

## Aftershock Productivity and Long-Range Triggerability Maps for California

*van der Elst, Nicholas J. (UCSC) and Emily E. Brodsky (UCSC)*

The triggering of earthquakes by dynamic stresses has been well-demonstrated to occur after large distant earthquakes, although the thresholds for such triggering remain obscure. Accordingly, the contribution of dynamic stresses to local aftershock sequences remains unquantified. To improve our qualitative understanding of triggering thresholds, we map susceptibility to long-range (dynamic) earthquake triggering and local aftershock productivity across California. The patterns are strongly correlated with each other and with high surface heat flow. The correlation indicates that thresholds for both short and long-range triggering are governed by the same fault properties, and that triggering occurs preferentially in hydrothermal areas. These maps also illustrate that aftershock rate is not adequately predicted by regionally averaged background rate, and that seismic hazard maps and aftershock predictions can be improved by taking into account recent shaking. We use the ANSS catalog of M2.1 and greater earthquakes since 1984 for the triggering susceptibility maps, filtered for quarry blasts and duplicate events, and the SMU geothermal database for heat flow mapping.

The long-range triggering maps were produced by collecting all local events in the days before and after all potential global triggering events, here defined as events that exceed an arbitrary magnitude-distance threshold and are located beyond some minimum distance. Cutoffs are informally optimized to achieve both high signal to noise ratio and a statistically significant assessment. Regional triggering susceptibility is mapped by binning and differencing pre- and post-trigger seismicity and applying a gaussian smoothing filter.

Short-range triggering susceptibility (traditional aftershock productivity) is mapped by counting the average number of early aftershocks generated by isolated mainshocks. We designate earthquakes as mainshocks if they are preceded by no larger events within 250km in the last 24 hours, and identify earthquakes as aftershocks if they fall within 15km and 1 hour of a mainshock. We bin and average the productivities of the mainshocks using the same smoothing scheme as used for the long-range map.

The long-range map demonstrates that triggering may be detected even when absolute changes in seismicity rate are not observed for a whole catalog. The clustering of triggered events within the codas of large earthquakes, as well as the temporary overwhelming of network analysts, may produce an apparent post-trigger quiescence in routine earthquake catalogs, but mapping rate changes across a region reveals residual secondary aftershock sequences and shows focusing of events into highly-triggerable areas.

The correlation of both maps with surface heat flow shows that degree of triggering, whether long- or short-range, is governed by local conditions – possibly fault strength, and/or the presence of fluids.

## New insights on Southern Coyote Creek Fault and Superstition Hills Fault

*Van Zandt, Afton J. (SDSU), Robert J. Mellors (SDSU), Thomas K. Rockwell (SDSU), Matt K. Burgess (SDSU), and Michael O' Hare (SDSU)*

Recent field work has confirmed an extension of the southern Coyote Creek branch of the San Jacinto fault in the western Salton trough. The fault marks the western edge of an area of subsidence caused by groundwater extraction, and field measurements suggest that recent strike-slip motion has occurred on this fault as well. We attempt to determine whether this fault connects at depth with the Superstition Hills fault to the southeast by modeling observed surface deformation between the two faults measured by InSAR. Stacked ERS (descending) InSAR data from 1992 to 2000 is modeled using a finite fault in an elastic half-space. An aseismic creep rate of 21 mm/yr to a depth of 5 km is assumed for the Superstition Hills fault. Several possible geometries are tested however the combination of both tectonic and groundwater-related deformation results in considerable uncertainty using data derived from only one line-of-sight.

### Incorporating undrained pore fluid pressurization into analyses of off-fault plasticity during dynamic rupture

*Viesca, Robert C. (Harvard), Elizabeth L. Templeton (Harvard), and James R. Rice (Harvard)*

When considering dynamic fault rupture in fluid-saturated elastic-plastic materials, it is sensible to assume locally undrained behavior everywhere except in small diffusive boundary layers along the rupture surface. To evaluate undrained pore pressure changes, we consider here not just the linear poroelastic effect expressed in terms of the Skempton coefficient B, like in our previous work [Viesca et al., AGU Fall 2006], but also include plastic dilatancy, which, when positive, induces a fluid suction. We work in the context of Mohr-Coulomb-like plasticity, but with a Drucker-Prager type model. Plastic parts of strain increments are controlled by the Terzaghi effective stress, elastic parts by the Biot stress combination. Following earlier work of Rudnicki, the elastic-plastic constitutive relation for undrained deformation has precisely the same form as for drained deformation, so long as we change the drained constitutive parameters into new undrained ones under transformation rules that we present.

Spontaneous slip-weakening fault rupture is analyzed using the dynamic finite element procedures with ABAQUS Explicit, and undrained elastic-plastic properties. Results are shown for plastic zones and effects on rupture propagation, and how they are influenced by such parameters as B and beta, for a range of principal orientations and magnitudes (relative to yield) of the pre-stress state.

The undrained approximation must fail in diffusive boundary layers along the slip surface [Rudnicki and Rice, JGR 2006; Dunham and Rice, AGU Fall 2006] because the predicted pore pressures will be discontinuous at the fault. We show how to extend the Rudnicki and Rice calculation of the actual pore pressure on the fault in terms of the undrained predictions to the two sides. However, because of difficulties thus far in representing this within the ABAQUS program, all results that we show neglect effects of pore pressure changes on the fault slip-weakening strength.

### Effects of Non-linear Terms on Pore Fluid Pressurization

*Vredevoogd, Michael (UCR), David Oglesby (UCR), and Stephen Park (UCR)*

Faults generate heat due to friction while slipping in earthquakes. If there are pore fluids along the fault, they will be heated and expand. The pore fluids will not affect faults in high permeability settings, as they will quickly escape. In a low permeability setting, the expanding pore fluids will not be able to escape quickly, and thermal expansion of the fluids will increase the fluid pressure, lowering the effective normal stress (and thus frictional stress) along the fault.

To investigate this process, we solve the non-linear equations presented in Mase and Smith (1985). These equations involve several non-linear terms that make it necessary to solve the equations iteratively. We have previously shown some results of this methodology for various permeability structures, and slip rates.

Here we focus on the importance of individual terms in the equations by running models with individual terms turned off. Among our results, we find that conduction is quite significant in affecting the temperature and pressure, while advection has a negligible effect on the solution. The implications may be important for researchers constructing simplified models of the pore fluid pressurization process.

### Spontaneous Seismicity Stationarity Analysis in California

*Wang, Qi (UCLA), Jiancang Zhuang (Institute of Statistical Mathematics, Japan), and David Jackson (UCLA)*

There are two types of earthquakes: the spontaneous ones and the triggered one. The spontaneous earthquakes seismicity indicates the situation of the stress field and the plate movement, so it is important and useful to find whether the spontaneous earthquake seismicity is stationary or not. We use epidemic-type aftershock sequence(ETAS) model to decluster the California catalog. We find that the spontaneous earthquake seismicity in southern California is stationary while it is not stationary in northern California.

## ALLCAL – An Earthquake Simulator for All of California

*Ward, Steven N. (UCSC)*

We continue to improve understanding of earthquake predictability and hazard by designing and tuning a California Earthquake Simulator. Our physics-based earthquake simulator produces spontaneous, dynamic rupture on geographically correct and complex systems of interacting faults. Recently, the simulator has seen two new important developments: (1) For the first time the computation involves a truly 3-dimensional fault system; (2) The simulation has been expanded to include 8000 km of faults spanning the entire State of California, hence the name ALLCAL. The simulation is tuned in two ways: 1) through input of measured slip rates, and 2) by comparison of computed recurrence interval and slip per event with actual field measurements. Independent validation comes through matching of synthetic and observed earthquake scaling laws such as Magnitude versus Fault Area.

The results of ALLCAL are best seen as Quicktime movies.

http://es.ucsc.edu/~ward/ALLCAL-1100.mov

The movie above shows a 1100 year simulation in map view. Ancillary information includes observed and predicted earthquake rate versus magnitude (left), mean stress and M5.5+ rate versus time (bottom).

http://es.ucsc.edu/~ward/SAF-2000.mov

The movie above expands a 2000 year simulation for the southern SAF. Current stress (red), current strength (green), stress drop (white) and surface slip (yellow) are plotted for larger quakes in the interval. Black number at top is year, yellow number is time within each event. ALLCAL incorporates fully dynamic ruptures, excepting the effects of inertia.

http://es.ucsc.edu/~ward/SAF-1000-3D.mov

In ALLCAL simulations to date, slip only varies along strike. In prospect are true 3-D models where earthquake slip can vary down dip as well. The movie above previews a 1000-year 3D prototype. The two white boxes show total slip and slip rate along strike and down dip. Ruptures are more complex now - many nucleate at depth and fail to reach the surface.

Finally, the movie below (118Mb or 18Mb, click to advance slides) has loads of information about the ALLCAL simulator that can't fit in this abstract. If you have an interest, please take a look:

http://es.ucsc.edu/~ward/powerpoint/ALLCAL(big).mov
http://es.ucsc.edu/~ward/powerpoint/ALLCAL(small).mov

## Ground Motion Selection and Modification Working Group

*Watson-Lamprey, Jennie (Watson-Lamprey Consulting), Yousef Bozorgnia (PEER), Norm Abrahamson (PG&E), Jack Baker (Stanford), Allin Cornell (Stanford), Christine Goulet (UCLA), Curt Haselton (CSU Chico), Erol Kalkan (CGS), Nico Luco (USGS), Tom Shantz (Caltrans), Jonathan Stewart (UCLA), Polsak Tothong (AIR Worldwide), and Farzin Zareian (UC Irvine)*

Many methods of time series selection and modification are available for use in nonlinear dynamic analyses. Presently, there is no consensus as to the best method, therefore the choice is largely subjective. This has had a great impact on the engineering community because nonlinear response is sensitive to the selection and modification of input time series.

The GMSM working group was formed by the Pacific Earthquake Engineering Research Center to determine a basis for evaluation of time series selection and modification methods. It aims to provide recommendations for method selection for applications currently employed in practice or under development. The evaluations and recommendations must depend on the application in which the time series are to be used. It is the ultimate goal of the working group to look at a range of applications and selection and modification methods.

A pilot study was initiated in 2006 examining one structure, a four story steel frame building in California, and a single deterministic seismic event. Results of the pilot study are presented. They demonstrate the large number of selection and modification methods available and the broad range of response values that can result. Preliminary conclusions are drawn with regard to classes of selection and modification methods.

### GPS-Explorer: A web-based GPS data and products exploration and modeling tool

*Webb, Frank (JPL), Yehuda Bock (UCSD), Sharon Kedar (JPL), Paul Jamason (UCSD), Ruey-Juin Chang (UCSD), Danan Dong (JPL), Ian Mcleod (UCSD), George Wadsworth (UCSD), Brian Newport (JPL), and Todd Ratcliff (JPL)*

"GPS DATA PRODUCTS FOR SOLID EARTH SCIENCE" (GDPSES) is a multi-year NASA funded project, designed to produce and deliver high quality GPS time series and higher-level data products derived from multiple GPS networks along the western US plate boundary, and to use modern IT methodology to make these products easily accessible to the community.

In the heart of the project is GPS-Explorer, a web-based tool for geo-spatial exploration and modeling of GPS data and products. GPS-Explorer enables users to efficiently browse several layers of data products from raw data through time series, velocities and strain by providing the user with a web interface, which seamlessly interacts with a massive, continuously updating archive of such products through the use of web-services. The current archive contains GDPSES data products beginning in 1995, all of EarthScope's Plate Boundary Observatory (PBO) GPS data products, and real-time products. The generic approach used in this project enables GDPSES to seamlessly expand indefinitely to include other space-time-dependent data products from additional GPS networks. The prototype GPS-Explorer provides users with a personalized working environment in which the user may zoom in and access subsets of the data via web services. It provides users with a variety of interactive web tools interconnected in a portlet environment explore and save datasets of interest to return to at a later date. In addition the user may carry out simple time series analysis and modeling tasks, provide feedback in the form of bug reports and feature requests, and interact with other users through a user's forum. Users are encouraged to come to our display for an interactive demonstration of GPS Explorer capabilities.

In addition to ongoing product generation GDPSES has a capability to reprocess and combine over a decade of data from the entire western US on demand, which enables a quick update of the Level-1 products and their derivatives, when new models are tested and implemented. GDPSES has also begun a collaboration with another NASA project, QuakeSim, to integrate data mining and modeling tools in an "on-the-fly" environment. The "Modeling and On-the-fly Solutions in Solid Earth Science" (MOSES) project is developing a unified Web Services-based observation/analysis/modeling environment for geophysical modeling and natural hazards research, a plug-in service for early warning systems and transfer of rapid information to civilian decision makers and the media, and an educational tool.

As part of its IT effort the project is participating in NASA's Earth Science Data Systems Working Groups (ESDSWG), and contributing to the Standards working group.

### Damage asymmetry from geomorphic signals along the trifurcation area of the San-Jacinto Fault

*Wechsler, Neta (USC), Thomas Rockwell (SDSU), and Yehuda Ben-Zion (USC)*

An important earthquake research topic is the question of whether there are geological controls on rupture propagation direction. A persistent preferred propagation direction should produce asymmetric damage structure that is recorded in the volume of rock surrounding a fault, and there may be geomorphic manifestations on active faults that can be recognized and analyzed in a quantitative fashion. The San-Jacinto Fault (SJF) is one of the most active faults in southern California, with well expressed geomorphology, a fast geologic slip rate, and a strong GPS strain signal. We use standard morphometric analysis to detect the damage asymmetry across a part of the SJF in the trifurcation area where the Clark, Coyote-Creek and Buck-Ridge segments meet. The analysis is done at two scales: 1. Small scale DEM with 30m per pixel resolution derived from SRTM data. 2. Large scale DEM with 1m per pixel resolution derived from LIDAR data, covering the fault at ~1 km width. The geomorphic analysis is done using the GIS software

ArcMap and the TauDEM tool box. We compare several morphometric parameters (drainage density, stream frequency, texture ratio, bifurcation ratio, ruggedness number) for drainages on both sides of the fault. North of the trifurcation point, the north-east side of the fault is more damaged, in agreement with Dor el at (2006) and Lewis et al (2005), but south of the trifurcation the situation is reversed. A number of factors can affect the results of the morphometric analysis, including the proximity of several fault strands, a restraining bend on the main strand, and different lithologies on the two sides of the fault. The current results are not conclusive since the morphometric analysis depends on various additional factors, such as different slopes, rates of erosion, vegetation, etc., that were only partially accounted for. Nevertheless, these preliminary results on reversed damage asymmetry suggest that large earthquakes on the SJF tend to nucleate in the trifurcation area and propagate from there to the NW and SE.

**The October 2006 Superstition Hills Creep Event: combined observations from creep-meter, field mapping, InSAR, and B4 altimetry**

*Wei, Meng (SIO), Karen Luttrell (SIO), Afton Van Zandt (SDSU), David Sandwell (SIO), Rob Mellors (SDSU), Yuri Fialko (SIO), and Ken Hudnut (USGS)*

During October 2006, an aseismic slip event occurred on the Superstition Hills Fault. This event was recorded by a creepmeter installed across the fault, but not by any local seismic or geodetic networks. Following the event, field mapping determined the creep event extended at least 11 km along the fault, and subsequent InSAR studies showed the creep extended along the entire 25 km stretch of the fault. InSAR profiles confirm in situ measurements of fault offset, showing that the magnitude of fault creep along most of the fault is about 2 cm, with a maximum of 3 cm. The along fault distribution of creep is consistent with previous Superstition Hills InSAR studies. We combine these data with B4 altimetry observations in Google Earth to fully characterize deformation along the fault.

**SCEC/SURE: Are Balanced Rock Orientations Controlled by Fracture Patterns?**

*Weiser, Deborah (Occidental College), Lisa B. Grant (UCI), James Brune (UNR), and Matthew Purvance (UNR)*

Precariously and semi-precariously balanced rocks can serve as indicators of past ground motions in seismically active areas. The focus of my SCEC internship has been on a group of balanced rocks in southern California that run approximately parallel and equidistant between the Elsinore and San Jacinto faults. The majority of these rocks are oriented with their long-axes sub-parallel to the strikes of the faults, or at about 130 degrees from north. A rock oriented as previously described will topple in a fault-perpendicular direction. Current ground motion models predict the highest levels of ground shaking on strike-slip faults to be perpendicular to the faults. Taking this into consideration, it is likely that rocks which are highly sensitive to fault-perpendicular motion, which describes the majority of the rocks found between the two faults, would have alreay toppled. In order to better understand this peculiarity, I have studied the fractures around five different balanced rocks at three sites. If fractures are randomly orientated, atypical ground motions might be responsible for this pattern of balanced rocks. My results however, show a fault-parallel fracture pattern in the vicinity of the balanced rocks which may influence the formation and stability of balanced rocks.

**SCEC/SURE: Dynamic Models of Earthquakes and Tsunamis**

*Wendt, James (Pomona College), David Oglesby (UCR), and Eric Geist (USGS)*

The abundance of inhabited cities lining the coasts of earthquake-prone regions serves as a motivation to investigate the effects of fault dynamics on tsunami generation. In particular, time dependent tsunami sources are important when investigating tsunami run-up in the near-field. While typical tsunami codes use a simple dislocation model with constant slip as a source, we link a fully dynamic earthquake model to tsunami generation. We construct a finite element model of a fault system based on the splay fault geometry inferred to exist in the Nankai subduction zone off of Japan (Cummins & Kaneda, 2000), and link the results to a finite-difference depth-averaged tsunami propagation code. We find that a simple regional stress field in the splay geometry is improbable since it is nearly impossible to produce a self-consistent model of an earthquake under such a condition. We also find that whether the earthquake ruptures the upper splay in addition to or instead of the main subduction fault depends upon the presence or absence of barriers along the main fault plane. The resulting tsunamis resulting from these two different rupture patterns differ strongly, emphasizing the effect of fault geometry on tsunami generation and near-source run-up.

### ETES: The Inverse Problem

*Werner, Max (UCLA) and David D. Jackson (UCLA)*

The ETES model (sometimes called ETAS) has rapidly become the preferred benchmark in hypothesis tests about earthquakes. In most cases, such tests rely on estimates of the model's parameters. For instance, parameter estimates may appear to show regional differences or temporal changes and may be used to test ideas about rheology, triggering mechanisms, or other properties of the Earth. Estimates are also crucial for earthquake forecasts in prediction experiments such as RELM and CSEP that aim to evaluate models by scoring their forecasts.

Given the importance accorded to parameter values, we investigate the estimation process and associated parameter uncertainties. We perform maximum likelihood estimation on synthetic and real data and analyze the likelihood landscape as a function of parameters. The standard method for calculating uncertainty estimates and correlations of the parameters involves calculating the Hessian of the likelihood function to obtain the covariance and standard errors. We compare this traditional method with two different approaches: a Bayesian, constrained maximum likelihood inversion and an entirely new approach, described as follows. For a given set of parameter values, we simulate earthquake catalogs and calculate their likelihood values using the known likelihood function of the model. We then calculate the likelihood of the actual data given this assumed set of parameter values. If the likelihood value of the data occurs less than 5 percent of the time according to the likelihood values of the simulated catalogs, we reject this set of parameter values. Searching the parameter space in this manner maps out a volume of acceptable parameter values at confidence levels 0.95. This approach can be expanded to include arbitrary sources of errors because it is simulation-based.

### Using Finite Element Meshes Derived from the SCEC Community Fault Model to *Evaluate the Effects of Detailed Fault Geometry and Material Inhomogeneities*

*Williams, Charles (RPI), Carl Gable (LANL), Bradford Hager (MIT), and Jiangning Lu (MIT)*

To make realistic assessments of fault slip inferred from surface geodetic observations, we need to know the sensitivity of our predicted surface deformation field to additional factors that may not be accurately represented in the model. Two primary factors that may influence our predicted results are the detailed geometry of the faults in the model and the variations in material properties in the region under investigation. As a step in addressing the potential importance of these factors, we compare finite element computations of varying model complexity against those obtained using the analytical model of Meade and Hager (JGR, 2005).

We use meshes derived from the Community Fault Model (CFM) to represent the detailed geometry for a small portion of the San Andreas fault system. This is a departure from previous work, where we used a derived Community Block Model (CBM) to provide airtight volumes for meshing. This new approach allows us to more easily include more faults and greater geometrical detail depending on the problem under consideration, and is more in keeping with the fractal nature of fault networks. Using this method, we have produced meshes including as many as 90 of the faults from the CFM, with the capability to include all CFM faults.

We perform three different comparisons using four different models. We first compare analytical results using CFM-R (a coarser rectangularized version of the CFM) against a finite element representation of CFM-R assuming homogeneous elastic properties. This allows us to evaluate the accuracy of the finite element solution to insure the validity of our results. We then compare finite element solutions using CFM and CFM-R to evaluate the effects of including detailed fault geometry, again assuming homogeneous material properties. Finally, we compare finite element solutions with homogeneous and vertically-layered elastic property variations, both using the same CFM-derived mesh, thus providing a first-order estimate of the influence of material property variations on the predicted surface deformation field.

### Southernmost Long-Term Earthquake Record for the San Andreas Fault

*Williams, Pat (SDSU) and Gordon Seitz (SDSU)*

The southernmost San Andreas fault (SSAF) is regarded by many to be the most likely to generate a great earthquake in southern California in the foreseeable future (eg WGCEP, 1995). Its high geologic and geodetic slip rate (15-25mm/yr) (Van derWoerde, 2005), regional deformation pattern Fialko, 2006), long quiescence (~325 years) compared to the average recurrence interval of 180 years, and single-event displacements of up to 3 meters for the last 3-4 events, make this portion of the fault appear ready for a rupture.

Closely spaced cycles of late Holocene filling and dessication of the large, closed Lake Cahuilla basin flooded much of the southernmost 70 km of the SSAF. Lacustrine sediments associated with the flooding events provide a unique high-resolution recorder of past earthquakes. Although other important sites have been developed in the Coachella Valley, they are all located at or above the lake's high shoreline. The SCS site is the only deep water Lake Cahuilla site, 65 m below the high shoreline, providing at least 50 additional years of lacustrine sediment record (in each of 5 lake episodes) relative to high shoreline sites (Sieh and Williams, 1986). This translates to an additional 300 years of sediment record, and a more complete and a higher resolution lake/event-record than the high shoreline sites near Indio: (Sieh, 1986; Philibosian et al., 2006). The longest published SSAF record (at Thousand Palms, Fumal et al., 2002) is located on one-of-two strands of the fault in the northern Coachella valley - the Mission Creek fault - and thus may not record all events.

Evidence developed to date indicate that the SCS paleoseismic site spans 1300 years and records at least 6 earthquakes. Extended models of rupture probability rely on long records of well-dated earthquakes. The SCS record will likely be a key resource for SSAF evaluation because:

1) Event timing is constrained by longer lacustrine (depositional) episodes low in the Lake Cahuilla basin, and by abundant in-situe and detrital radiocarbon materials.

2) Companion slip-per-event evidence has been recovered at the site for the past 3 events, and evidence for slip in the latest 4 (5?) events has been recovered within 20 kilometers of the site.

### Progress toward more detailed site-conditions maps in southern California

*Wills, Chris J. (CGS), Mike Silva (CGS), and Alan Yong (USGS)*

We have developed a map of geologic units that can be distinguished by their shear-wave velocity. In developing this map we build upon earlier work to determine the shear-wave velocity characteristics of geologic units in California (Wills and Silva, 1998) and grouping geologic units with similar Vs into NEHRP categories (Wills and others, 2000). We have further refined those categories and prepared a map showing geologic units with distinct Vs characteristics (Wills and Clahan, 2006). Further improvements of shear-wave velocity maps could take two courses: 1. Improvement in the precision of locations of the geologically-defined units and 2. Improvement in definition of shear-wave velocity classes.

We have made progress on both courses for southern California. We have compiled the available 1:100,000 scale maps for the Los Angeles, Long Beach, Santa Ana and San Bernardino quadrangles, which are based on and preserve the details of original 1:24,000 scale mapping. We have simplified the units shown on those maps to correlate with the shear-wave velocity defined units of Wills and Clahan (2006). The result is a map showing geologic units with defined Vs30 values based on the most detailed geologic mapping.

In preparing this map, the most important needed improvement in definitions of the shear-wave velocity classes is how to sub-divide the young alluvium. In the statewide map by Wills and Clahan (2006) we attempted to use very simple geographic criteria to subdivide the alluvium. We developed classes called thin alluvium, deep alluvium, fine alluvium and coarse alluvium. These categories appear to have differing shear-wave velocity characteristics, but we were not able to develop consistent geographic rules for defining what areas should be placed in these categories. In order to make the mapping more consistent, and more applicable to other areas, we are exploring the use of two simplified rules for sub-dividing young alluvium. Preliminary results suggest that distance from bedrock and slope may both correlate with shear-wave velocity in young alluvium. Further work will define the relations between these factors and shear-wave velocity, and result in methods for producing improved maps of Vs30 for estimating seismic amplification in southern California and elsewhere.

### SCEC/UseIT: Serious Educational Gaming

*Wilson, Anna (Occidental College)*

As a participant in the SCEC/Undergraduate Studies in Information Technology (UseIT) internship program, which explores the many implications and uses of Information Technology in an earthquake science setting, I worked with 19 other students to complete a Grand Challenge. This summer's challenge was to prototype several Serious Games to educate different audiences to SCEC's mission and research. Within a group, I conducted research on various technical aspects of Serious Games and built several levels of an educational earthquake science game from concept to reality. I participated in the brainstorming and conceptualization of many "mini-games" within the educational game, and played a primary role in generating the Plate Boundaries mini-game. Coded in ActionScript 3.0 in the Flash engine and graphically designed using Flash, the game has levels which require a user to place plates on a map of world seismicity, identify the names of the plates, and identify the 2D plates on a 3D globe. The game has both timed (hard) and untimed (easy) modes. In more advanced levels, the game would incorporate actual data sets, including tectonic data such as isochrons and geographic data, through embedded videos and images created in UseIT software SCEC-VDO (Virtual Display of Objects).

### SCEC/UseIT: Mitigation Graphic Design

*Wilson, Chesela (Philander Smith College)*

This summer our challenge was to make a video game that would teach a person how to prepare for an earthquake. In our Game, the player starts by securing an apartment to where it sustains an earthquake. If you pass, then you go onto the next level. My job in making this game was the design. I with my teammates was in charge of making buildings, offices, houses and neighborhoods. Once I finished making my designs, I put them into Flash where I applied some buttons to give the images interaction and features. From there, I gave my Flash work to other members in the group for coding and final touches.

The grand challenge was easy but still difficult in some places. My part wasn't as hard as coding. Difficulties that I encountered included not being able to get whole houses into Flash so that you would have the option of walking around freely, as you would in the Sims game. To get past that, I took snapshots of the house at different angles and different rooms and put those into Flash as 2D models. Not only does the game look appealing, the graphic just overall catch you eye. Once we figure out how to import the whole 3D house our game will have unbelievable graphics!

### Multi-Hazard Demonstration Project: Seismically Induced Landslide Hazard Analysis at Lifeline Crossings for the Mw 7.8 Southern San Andreas Earthquake Scenario

*Wilson, Rick (CGS), Tim McCrink (CGS), Jerome Treiman (CGS), and Michael Silva (CGS)*

As part of the Multi-Hazard Demonstration Project, the California Geological Survey (CGS) analyzed ground failure hazards related to seismically induced landslides in the Cajon Pass and San Gorgonio Pass areas for a scenario Mw 7.8 earthquake on the portion of the San Andreas fault that passes through both areas. These focus areas were selected because they are vital corridors for transportation and utility lifelines for Southern California. Although site-specific geotechnical data were limited in both areas, CGS's familiarity with the geologic and topographic conditions in similar Southern California settings provided background for analysis. Our assessment consisted of: 1) compiling landslide inventories within the focus areas, 2) performing pseudostatic slope stability and deformation (Newmark displacement) analyses on the interpreted "worst case" locations of landslides and landslide prone areas, and 3) creating a landslide hazard potential map covering the Cajon Pass focus area. Results from analyses indicate that large slope failures will be common in both areas due to the prevalence of steep slope conditions, weak geologic formations, and extremely high ground shaking levels. For some existing landslides, Newmark displacement values were calculated to be well over one-meter, which increases the potential for those landslides to change behavior from a sliding block to a flow-type failure. This style of slope failure could inflict considerable damage to lifelines because of their increased internal disruption and long run-out distances.

### SCEC/UseIT: Serious Games for Education

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The SCEC/Undergraduate Studies in Earthquake Information Technology (UseIT) program gives undergraduate students from a variety of majors the opportunity to work in a team-based research environment, focusing around the fields of computer science and geoscience.

A grand challenge is presented to the interns each summer. This summer, our focus was to create one or more serious games that would communicate important earthquake science concepts. Prototypes were to be made for an educational, training, and decision-making game.

I was involved with the educational game that hopes to teach players about basic earthquake concepts. The game consists of several mini-games that intend to teach more specific geological concepts: hot spots, plate boundaries, and fault motion. For the Fault Motion Game I used Adobe Flash CS3, where my aim was to create visual assets that would be incorporated into the game. I was able to draw block diagrams that mimicked cartoons found in college-level textbooks. The player is asked to help sheep trapped in fenced enclosures to escape and reach a feeding trough by generating earthquakes of different magnitudes and manipulating fault motion. Altering these parameters would ultimately break the fences and direct the sheep to the trough.

### Variations of strain-drops of aftershocks of the 1999 Izmit and Duzce earthquakes along the Karadere-Duzce branch of the North Anatolian fault

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We estimate the strain-drops of ~7500 earthquakes in the aftershock zone of the 1999 Izmit and Duzce earthquakes along the Karadere-Duzce branch of the North Anatolian fault. The employed data were recorded by a local 10-station seismic array operating for 6 months after the Izmit earthquake. We use a modified version of the Iterative Stacking Spectra Separation procedure of Shearer et al. (2006) to separate the source, travel-time and station spectra in the observed P waveforms. The strain-drops are obtained by fitting iteratively separated source spectra in different amplitude bins, produced by the above stacking procedure, to the $\omega 2$ source spectral model. This reduces the possibility that the obtained strain-drops reflect local minima of the fitting procedure. Synthetic tests show that the approach is robust and the derived strain-drops are stable. About 95% of the derived log10 strain-drops are in the range -4.3 to -2.6 (corresponding to 1.4 - 74 MPa stress-drops assuming a nominal rigidity of 30 GPa), with the mean log value of -3.5 (9.5 MPa). The obtained strain-drops generally increase with depth between 3 and 10 km and remain approximately constant for the deeper section. A local shallow patch of seismicity in the Karadere segment has relatively low strain-drop values. Along the relatively-straight Karadere segment the strain-drops are lower than along the geometrically complex bounding regions. The strain-drops for aftershocks of the Duzce earthquake in areas outside the aftershock zone of the Izmit mainshock are higher than those of the earlier events and follow an exponential temporal decay with a time scale of ~60-70 days. All the above spatial and temporal variations of strain-drops can be explained by increasing normal stress with depth along with geometrical properties and expected slip deficit along a given fault area.

### Z/H Rayleigh-wave analysis on broadband Southern California seismic data

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The SCEC Community Model Environment (CME) assembles and runs seismological and geophysical simulations using community velocity models (CVM) of southern California. Improvement in CVM, particularly in shallow depth velocity structure, is important for seismic hazard analysis. Investigation of the velocity structure is typically accomplished by using dispersion curves for either group velocity or phase velocity combined with body wave data. An alternative approach is the independent surface-wave method proposed by Tanimoto and Rivera (2005). This uses the ratio of the vertical-to-horizontal components of the Rayleigh wave's particle motion (ZH-ratio), which varies as a function of frequency. This ZH ratio approach is superior given that the range of depth sensitivity is sharper for shallow structure than the traditional method of using dispersion curves. We found out that we can measure the ZH ratio for the frequency range 0.1-0.4 Hz in southern California. The ZH ratio for this frequency range is sensitive to depths 0-10km. The ZH ratio is controlled only by the local structure beneath the seismic station, but the station density in southern California seems to be high enough to yield a cohesive model, particularly in the L.A. Basin. Here we invert this ZH ratio data for frequencies between 0.13-0.37Hz to investigate the shallow (0-10km in depth) velocity structure. This result, which inverted from ZH ratio using CVM as initial models, may lead to improve shallow velocity structure in community velocity models of southern California and will be useful for more accurate ground motion prediction.

### Geotechnical Site Characterization in California and Beyond: A Progress Report

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We report on our ongoing efforts to improve geotechnical site characterizations in California, and other seismically active regions, such as Pakistan, Turkey and Mozambique. The USGS effort is developing a map-based Internet portal for accessing site characterization information at broadband seismic station sites in the Southern California Seismographic Network (SCSN) using Open Source technology, including the new PHP-based Web-interface, an optional GoogleEarth KML display and MySQL relational database. Our database includes site characterizations of active and abandoned SCSN station sites with varying degrees of completeness regarding station information, Wills et al. (2000) site classification, average shear-wave velocity in the upper 30 m (Vs30), and local geology. We have also begun compiling shear-wave velocity measurements at Caltrans. This effort is made possible by an interagency collaboration between the USGS, CGS and Caltrans to publish borehole shear-wave velocity data, recorded and archived by Caltrans' Geophysics and Geology Branch in support of California's statewide transportation infrastructure. From that effort we estimate 300 borehole measurements will be extracted and made available to the research community. Finally, use of measured and estimated shear-wave velocity with ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) and semi-automated image analysis methods, that include our newly developed integration of pixel-based and object-oriented imaging approaches (Yong et al., 2007), appears to result in improved site characterization in seismically active regions of the world. A newly available ASTER mosaic of California may also help to improve the statewide site conditions map (Wills et al., 2000; Wills and Clahan, 2006) (also see related efforts by Wills et al. at this meeting).

### Evidence for Large Earthquakes on the San Andreas Fault at the Burro Flats Paleoseismic Site: A.D. 150 to Present

*Yule, Doug (CSUN), Kerry Sieh (Caltech), and Caryn Howland (CSUN)*

The Burro Flats site is located at the center of a M7.8 scenario rupture proposed by some for the southernmost San Andreas fault. Others have proposed that the structural complexity of the fault system in the San Gorgonio Pass region acts as a barrier to through going rupture and raises doubt about the validity of this scenario event. One way to explore whether such ruptures can occur here is to compare the paleoearthquake record of the Pass region with well-known records outside of this region. A 3-D network of trenches at Burro Flats has exposed evidence of nine paleoearthquakes that span the last 2000 years or so. Fissures and/or growth strata identify the paleosurface at the time of each rupture; upper termini of faults were also used when supported by corroborating evidence from fissures or folds. Peat layers provide good age constraints with the most reliable ages coming from hand-picked, layer-parallel plant fibers, probably pieces of annual reeds and grasses. Using a uniform sediment accumulation model provided by OxCal v4.0, twenty such ages constrain the timing of events as follows, with event, mean age, and 95% range reported: BF1 1812; BF2 1695 (1670-1730); BF3 1480 (1450-1520), BF4 1300 (1270-1360); BF5 1130 (1060-1160); BF6 (910-1100), BF7 (550-900), BF8 420 (370-510); BF9 210 (150-320). Comparing these results with other regions reveals that, of the most recent six events at Burro Flats, 1812 is the only earthquake that does not overlap in time with events in both the Coachella Valley and the Mojave regions. A shorter event record at sites in the Coachella Valley region precludes correlating events BF7, 8, and 9. The Burro Flats data therefore permit the correlation of large earthquakes through the San Gorgonio Pass region consistent with the M7.8 scenario rupture for the southernmost San Andreas, with A.D. 1690 being the most recent example. The average recurrence at Burro Flats not counting the current interval is ~210 years, most similar to the Coachella Valley record. This similarity suggests that southernmost San Andreas ruptures extend at least as far north as Burro Flats and likely extend to the central Mojave as portrayed by the scenario rupture.

**Mechanical modeling of the magma intrusion along the East Rift Zone of Kilauea, Hawaii**
*Yun, Sang-Ho (USGS), Zhong Lu (USGS), Charles Wicks (USGS), and Michael Poland (USGS)*

On June 17, 2007 a sudden seismicity increase was detected along the East Rift of Kilauea Volcano. This seismicity was associated with dike intrusion that opened up about 2 meters until June 20, 2007. This event was captured by ALOS PALSAR instrument operated by JAXA, the Japanese space agency. This instrument uses the L-band signal whose wavelength is about 4 times longer than the C-band signal, and thus better penetrate the vegetation resulting in better interferometric coherence. We formed interferograms from ascending and descending orbits with temporal baseline of 2007/05/05 - 2007/06/20 and 2007/02/28 - 2007/07/16. Our preliminary modeling indicates about 33 million cubic meters of volume increase in the dike. We estimate the geometry of the dike that is subject to a uniform excess pressure to explain these data sets.

**Statistical modeling of seismic moment release in California**
*Zaliapin, Ilya (UNR), Suresh Nathagoundenpalayam (UNR), Yan Kagan (UCLA), and Frederic Schoenberg (UCLA)*

Evaluation of the long-term regional seismic moment release from the observed seismicity is an important problem of statistical seismology tightly connected to the seismic hazard assessment and earthquake forecasting. Our SCEC 2006 project, "Estimating the long-term rate of seismic moment release from the observed seismicity," has developed theoretical and numerical methods to address this problem using the available seismological data. Our results have demonstrated that a heavy-tailed seismic moment distribution results in a non-linear character of the regional moment release. This, in turn, causes significant deviations of the observed seismic moment release from its long-range predictions. In this study we apply these results to the observed seismicity of California and to the SAF system in particular. The analysis is done for the entire region and for its most active subregions selected based upon fault orientation, subjective grouping, sense of slip, along with tectonic setting. We demonstrate that the general results on non-linear seismic moment release can be effectively applied on a regional scale.

**Optimizing earthquake forecasts based on smoothed seismicity**
*Zechar, Jeremy (USC) and Thomas H. Jordan (USC)*

Several models of earthquake occurrence incorporate the belief that the spatial distribution of past small earthquakes can be used to forecast the locations of future large earthquakes. Indeed, a model that produces forecasts based only on an empirical spatial distribution is a reasonable reference against which to test more complex models. The empirical seismicity distribution can be represented in many ways, but often the representation is a form of smoothing the epicentral locations. We consider optimization of these so-called smoothed seismicity forecasts using the area skill score. In a series of retrospective experiments in California and Taiwan, we tested different implementations of smoothed and non-smoothed seismicity forecasts, varying geographic cell size, minimum magnitude, and smoothing lengthscale. We find that smoothed forecasts tend to outperform non-smoothed. We also find that larger cell sizes and lower minimum magnitudes lead to increased performance. These experiments will yield the first set of time invariant CSEP forecasts optimized using the area skill score crtierion.

**Variations of velocity contrast along the rupture zone of the 2004 M6 Parkfield earthquake on the San Andreas Fault**
*Zhao, Peng (Georgia Tech), Zhigang Peng (Georgia Tech), Yehuda Ben-Zion (USC), Michael Lewis (USC), and Zheqiang Shi (USC)*

We systematically investigate the velocity contrast along the Parkfield section of the San Andreas Fault (SAF) that ruptured during the 2004 M6 Parkfield earthquake, using fault zone head waves (FZHW) that refract along the bimaterial fault interface. The analysis employs a total of 322 repeating earthquakes clusters identified from 8993 earthquakes in the relocated catalog of Thurber et al. (2006). The seismic data are recorded by 13 borehole stations in the High Resolution Seismic Network (HRSN) continuously since 2001. The study is part of a larger project on imaging bimaterial interfaces in the Parkfield region with multiple seismic networks. We stack waveforms of each repeating earthquake cluster, and align the peaks or troughs of the direct P waves assuming right-lateral strike-slip focal mechanisms. Clear FZHW are observed at several stations that are located on the NE side (slow) of the SAF. The obtained velocity contrast is about 10% north of Middle Mountain, and decreases rapidly toward Gold Hill near the epicenter of the 2004 event. This implies an abrupt change of velocity contrast along the Parkfield section of SAF near Gold Hill. The observed variation of velocity contrast is consistent with 3-D tomography models of the Parkfield section, which include a high velocity body near Gold Hill on the NE side that produces a local reversal of the velocity contrast in this region.

### Retrospective Earthquake probability forecasts in Southern California

*Zhuang, Jiancang (ISM), David D. Jackson (UCLA), Yan Y. Kagan (UCLA), Yosihiko Ogata (ISM), Maria Liukis (USC), Danijel Schorlemmer (ETH), and Philip J. Maechling (USC)*

Using the CSEP ETAS module, we made retrospective 1-day forecasts of earthquake probabilities in the southern California region from the beginning of 1995, in the format of contour images. The optimal parameters for the forecasts were obtained by fitting the ETAS model to the previous observations. Once the parameters are obtained, we simulated the seismicity for the next forecast interval for many times based on the ETAS model. The probabilities of earthquake occurrences were estimated with ratio of number of simulation that earthquakes occurs to the total number of simulations. These forecast were test against the reference model, the Poisson process which is stationary in time but spatially inhomogeneous.

### Realization of earthquake probability forecasts using the ETAS model

*Zhuang, Jiancang (ISM), Maria Liukis (USC), Danijel Schorlemmer (ETH), David D. Jackson (UCLA), and Philip J. Maechling (USC)*

The space-time ETAS model has been been implemented in the CSEP project. This presentation shows the usage the ETAS module and its user interface with the upper layer. This module includes three component: 1) optimization, which determines optimal model parameter for forecasts in next step; 2) simulation procedure, which simulates thousand copies of possibilities of earthquake occurrence in a single future interval; 3) smoothing procedure, which smooth the events generated in the simulation step to obtain stable and smoothed spatiotemporal occurrence rate; 4) forecast performance evaluation procedure, which use the CSEP common evaluation framework.

### Numerical Modeling of Relationships Between Magnitude and Surface Rupture Characteristics

*Zielke, Olaf (ASU) and J Ramon Arrowsmith (ASU)*

In order to determine the magnitude of pre-historic earthquakes, measurements such as surface rupture length, average and maximum surface displacement are utilized. We typically assume that an earthquake of a specific magnitude will cause surface features of correlated size. The well known Wells and Coppersmith (1994) paper and further work by Hanks and Bakun (2002) defined empirical relationships between these and other parameters, based on historic events with independently known magnitude and rupture characteristics. However, such relationships show large standard deviations and are based only on a small number of events. To improve these first-order empirical relationships, the regional tectonic setting as well as the observation location relative to the rupture extent should be accounted for. This, however, cannot be done using on natural seismicity because of the limited size of datasets on large earthquakes.

We have developed the numerical model "FIMozFric", based on derivations by Okada (1992) to create synthetic seismic records for a given fault or fault system under the influence of either slip- or stress boundary conditions. Our model features A) the introduction of an upper and lower aseismic zone, B) a simple Coulomb friction law, C) bulk parameters simulating fault heterogeneity, and D) a fault interaction algorithm. The joint implementation of these simple features produces well behaved synthetic seismic catalogs and realistic relationships among magnitude and surface rupture characteristics which are well within the error of the results by Wells and Coppersmith (1994). Using a synthetic seismic record of a 250 x 20 km strike-slip fault, we derive regional and observation-location specific relationships among magnitude and surface rupture characteristics and investigate their respective effect on them.

This model presented provides paleoseismologists with a tool to improve magnitude estimates from surface rupture characteristics by incorporating the regional and local structural context, which can be determined in the field. If a paleoseismologist measures the offset along a fault caused by an earthquake, our model can be used to determine the probability distribution of magnitudes that are capable of producing the observed offset, accounting for regional tectonic setting and observation location.