high vectorization ratio and optimal performance on the Earth Simulator.

Preliminary results on 54 processors, i.e., only one percent of the machine, show that the calculations run several times faster than on a two-year old Pentium-III PC-cluster which was used to develop the SEM package. We will discuss a variety of synthetic seismograms that are accurate down to periods of several seconds by taking full advantage of the Earth Simulator to drastically increase the resolution of the mesh. Effects related to anisotropy, attenuation, self-gravitation, rotation and the oceans are included in the simulations.

## S51C-09 1050h

### The Spectral-Element Method, Beowulf Computing, and Global Seismology

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Progress in global seismology is to a large extent due to the tremendous growth in seismic data acquisition, particularly with the worldwide deployment of digital broadband networks over the past two decades. Based upon this wealth of data, models of shear and compressional velocity heterogeneity, anisotropy, and attenuation have provided important constraints on the Earth's composition and physical processes. While data acquisition continues to be a priority, it is clear that improving seismic models also requires the development, implementation, and application of theories and numerical methods that accurately incorporate the effects of mantle and crustal heterogeneities on wave propagation.

The recently developed spectral-element method enables us to accurately simulate global seismic wave propagation in three-dimensional models of the Earth without intrinsic restrictions on the level of heterogeneity nor the frequency content. The method accounts for effects due to lateral heterogeneity, anisotropy, attenuation, variable crustal thickness, topography, ellipticity, rotation, and self-gravitation. We review the development of the method and present seismograms computed on a PC cluster, a so-called Beowulf machine, that illustrate the sometimes profound waveform complications due to three-dimensional heterogeneity. Mantle shear-velocity model S20RTS combined with crustal model CRUST2.0 satisfactorily explain body-wave traveltime anomalies at periods of 18 seconds and greater, but surface-wave dispersion is only accurate at periods of 45 seconds and greater. Amplitude anomalies, which complement traditional travel-time measurements, need to be carefully corrected for three-dimensional elastic focusing effects before they can be interpreted in terms of lateral variations in attenuation.

URL: http://www.gps.caltech.edu/research/jtromp

## S51C-10 1105h

### The Coupled Spectral Element/Normal Mode Method: Application to the Testing of Several Approximations Based on Normal Mode Theory for the Computation of Seismograms in a Realistic 3D Earth.

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The spectral element method (SEM) has recently been adapted successfully for global spherical earth wave propagation applications. Its advantage is that it provides a way to compute exact seismograms in a 3D earth, without restrictions on the size or wavelength of lateral heterogeneity at any depth, and can handle diffraction and other interactions with major structural boundaries. Its disadvantage is that it is computationally heavy. In order to partly address this drawback, a coupled SEM/normal mode method was developed (Capdeville et al., 2000). This enables us to more efficiently compute bodywave seismograms to realistically short periods (10s or less).

In particular, the coupled SEM/normal mode method is a powerful tool to test the validity of some analytical approximations that are currently used in global waveform tomography, and that are considerably faster computationally. Here, we focus on several approximations based on normal mode perturbation theory: the classical "path-average approximation" (PAVA) introduced by Woodhouse and Dziewonski (1984) and well suited for fundamental mode surface waves (1D sensitivity kernels); the non-linear asymptotic coupling theory (NACT), which introduces coupling between mode branches and 2D kernels in the vertical plane containing the source and the receiver (Li and Tanimoto, 1993; Li and Romanowicz, 1995); an extension of NACT which includes out of plane focusing terms computed asymptotically (e.g. Romanowicz, 1987) and introduces 3D kernels; we also consider first order perturbation theory without asymptotic approximations, such as developed for example by Dahlen et al. (2000).

We present the results of comparisons of realistic seismograms for different models of heterogeneity, varying the strength and sharpness of the heterogeneity and its location in depth in the mantle. We discuss the consequences of different levels of approximations on our ability to resolve 3D heterogeneity in the earth's mantle.

## S51C-11 1120h

### ACCURATE FINITE DIFFERENCE CALCULATIONS FOR TRAVEL TIMES AND AMPLITUDES IN 3D HETEROGENEOUS MEDIA

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Finite frequency inversions of body wave travel times and amplitudes require the knowledge of travel times, geometrical spreading and Maslov index from all points in the Earth to both source and receiver. In models with low velocity zones or extensive heterogeneities, the highly efficient paraxial approach (Dahlen et al., GJI 2000) may become invalid and needs to be replaced by more brute force computational methods. Early attempts in seismology to compute the complete travel time field using finite difference techniques (Vidale, Geophysics, 1990) or graph theory (Moser, Geophysics, 1991) have since long been superseded by developments, many outside of seismology, to find fast, efficient solutions of the eikonal equation.

In this talk I shall compare results obtained with various upwind finite difference techniques. Fast marching methods (Sethian and Popovici, Geophysics, 1999) which combine the accuracy of upwind finite difference schemes with the optimal evolution approach of Moser's method are extremely fast and their accuracy can be improved by adopting higher order finite differences, but still fall short of that needed to obtain correct amplitudes or geometrical spreading.

The most accurate results are obtained by combining several characteristics of finite difference methods that have been used separately and mostly in 2D, but that are here presented in combination for full 3D computations: we use algorithms of the Weighted Essentially Non Oscillatory type (WENO - Qian and Symes, Geophysics 2002), with variable grid size near the source and apply post sweeping to guarantee that first arrivals are chosen even if the wave has strong turning points (Kim and Cook, Geophysics 1999).

High accuracy in travel times is needed because calculations of amplitude $A$ (or geometrical spreading) from the transport equation $2\nabla A \cdot \nabla T + A\nabla^2 T = 0$ requires the travel time field $T$ to be three orders of magnitude more precise than the amplitudes. We found that the source differencing scheme of Vidale and Houston (Geophysics 1990), which we extend here to 3D, avoids the propagation of instabilities and generally produces amplitudes of sufficient accuracy for finite frequency tomography when combined with the WENO scheme. The Maslow index is obtained by projecting $\nabla^2 T$ on a plane perpendicular to $\nabla T$ and diagonalizing.

## S51C-12 1135h

### A Hybrid Finite-Difference Method for Global Wave Propagation

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Calculation of global wave propagation using numerical methods is undergoing a fast progress due to dynamically growing computation power. However, to achieve high frequencies in full 3D for arbitrary models, hybrid approaches are necessary.

In this study we combine finite-difference based solutions to the elastic wave equation in spherical coordinates in the axisymmetric approximation and the complete 3D solution for spherical sections. Wave propagation is initiated in the axisymmetric code with sources centered on the symmetry axis. Thus a high-frequency teleseismic wavefield with correct 3D geometrical spreading (but 2D computational domain) can be used as an input (boundary condition) to a spherical section at (e.g. large) distance from the source. The directly scattered wavefield from any structures inside the 3D block can be studied. This approach enables the simulation of scattering effects above plumes or subduction zones from teleseismic wavefields.

The advantage of this method is, that it avoids some drawbacks of the individual methods. The axisymmetric method suffers from the restriction that either the source or the desired mantle structure must have the form of a ring due to the axisymmetry. By placing a regional 3D domain at the place of the desired structure it is possible to model the structure as extended but local deviation of a background model (PREM). Moreover, the scattered waves can be observed in full 3D. On the other hand, a pure 3D-FD method would require a large amount of memory if one wants to model the global wavefield at large distances, thus limiting the frequency range of the calculation.

We will present the combination of these methods to a hybrid method in detail and show examples of results for a mantle plume in PREM

URL: http://www.geophysik.uni-muenchen.de/seismology

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# S51D MCC: 134 Friday 0830h

## Something in the Way She Moves: Earthquake Process *(joint with G, T, MR)*

***Presiding:*** **P Silver,** Carnegie Institution of Washington**; D D Jackson,** University of California, Los Angeles

## S51D-01 0830h

### The Spatial and Temporal Pattern of Shear Wave Splitting Along the Hector Mine Rupture Zone

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Extensive measurements of shear-wave splitting from aftershocks along the Hector Mine rupture zone show a broadly consistent fast direction, but also temporal and spatial variations in local stress directions.

Aftershocks were recorded by several deployments in the year following the mainshock. A week-long 20-station, 100m array (Geom99) was deployed a few days after the mainshock. A second deployment with two arrays was in place November, 1999. NA99 was located near Geom99, 5km south of the mainshock and SEA99 was 10km farther south. In 2000, these two arrays were redeployed (NA00 and SEA00) and a third array (SWA00) was deployed on a fault strand 2km west of SEA00. Each array had a 20-station, 500-m line normal to the fault. The deployment of NA and SEA in 1999 and 2000 allows for examination of temporal changes in splitting. The wide distribution of the arrays allows for investigation of spatial variations.

Rotation of the maximum compressive stress direction along fault strike is inferred from splitting measurements determined by cross-correlation technique. NA and SEA events were binned into three subsets based on local fault strike. The average measured splitting parameters indicate a 14.5 fast direction and a 33ms time lag. Significant rotation of the fast direction over one year was observed for the northern and central bins; however, sense of rotation varies along the fault. Also, measured time delays were lower in 2000 than 1999. Some spatial variation of splitting is observed. While splitting parameters measured at NA00 and SEA00 are fairly uniform, events recorded at SWA00 show very different fast directions and delay times. Delayed P and S arrivals indicate SWA00 is located atop low velocity material that appears to affect splitting measurements. Additionally, aftershocks within 0.25km of the fault have roughly fault-parallel fast directions.

The rotation of fast azimuth with fault strike and time should help constrain the stress field evolution in the near-fault region following a major quake. We may be seeing stress regimes that were perturbed during the rupture relaxing over time to pre-event stress orientations.

## S51D-02 0845h

### Statistical confirmation of a relationship between excitation of the ultra-low frequency ground electric signals and magnitude $M \geq 4$ earthquakes in a 300 km radius region around Beijing

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Signals from 4 stations monitoring the ultra-low frequency components electric field in the vicinity of Beijing are used as explanatory variables in forecasting the occurrence of events with $M \geq 4$ within a 300 km circle centered on Beijing. The model used is a version of Ogata's LIN-LIN algorithm for examining the influence of an explanatory signal on the occurrence of events in a stochastic point process. The explanatory effect is shown to be highly significant, and greatly superior to the explanatory effect of the same signals applied to a randomized version of the earthquake data. All four stations show significant explanatory power, although in combination the two most effective tend to dominate the forecasts. The results are stable against perturbations in the time period or region of observation. The predictions appear to be most effective for events with $M \geq 5$, and for events closer to the observing stations, although some of the smaller events appear to produce detectable signals at distances of over 100 km from the source. Probability gains over the simple Poisson process are in the region up to 3 – 4 for the events of magnitudes 5 or larger. A special study is made of predicted and unpredicted events in the region around the $M_s$7.8 Tangshan earthquake of 1976, to reveal the common spatial pattern of the classified events corresponding to all indiviual stations.

## S51D-03 0900h

### On the Long-Term Interaction Among Earthquakes: Some Insight From a Model Simulation

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One of the main debated issue in seismology concerns the possible existence of a coupling among earthquakes distant in space and time.Here, we provide the results of a simulation that mimics the co- and post-seismic interactions in a spherical and viscoelastic earth. In particular, the model estimates the stress induced by remote earthquakes in selected points on the earth surface, and the effects on a simple fault model. The results obtained indicate that a seismic zone can interact significantly with other remote seismic regions. Clusters in seismicity, gaps, and nonstationary behavior in general might be induced by the occurrence of large earthquakes also at distances up to about one thousand kilometer. These findings suggest that the implied paradigm of the hazard studies, i.e., the seismic zones are isolated systems, should be regarded with extreme caution.

## S51D-04 0915h

### Postseismic Stress Diffusion and Fault Interactions at Long Distances: The Story up to now.

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We present the results of a series of investigations concerning the problem of fault interaction at long distances based on simulations performed by means of spherical models of postseismic stress diffusion. Our analyses can be divided in two main classes:

Global scale and global seismicity;

Particular case studies of postseismic stress diffusion at long distances but not on global scale.

The first class of investigations, analysing data not limited in space and time (i.e. limited only by the extension of the available datasets), allows us to minimize the possible biasing effects due to the operator choices while the second class, focusing the attention on a particular spatio-temporal region, allows us to study the effects of specific large earthquakes on selected areas, maximizing in this way the ratio between local information and global noise. Both of them can give us some important (but perhaps not definitive) information on this still controversial topic.

## S51D-05 0930h

### Stress-Induced Migration of Seismic Scatterers Associated with the 1993 Parkfield Aseismic Transient

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A major goal of seismologists is to identify temporal variations in the seismic structure of the crust in response to stress changes near a fault zone. One of the approaches to this problem is to compare waveforms generated by repeat earthquakes, which have nearly the same location and mechanism and produce nearly identical seismograms when recorded at the same station. We have chosen to measure the difference in waveforms of several tight clusters of repeat events that occurred on the Parkfield segment of the San Andreas Fault and recorded by a network of borehole seismometers in the same area (HRSN). An exceptionally well-documented aseismic transient took place on this segment around the beginning of 1993, and we wanted to determine whether it produced observable structural changes in the medium as well. We used two parameters: the lag time, $\tau(t)$, and decorrelation index, $D(t)$, to characterize the difference between two seismograms at elapsed time, $t$. The lag time $\tau(t)$ is evaluated at the maximum of the cross correlation, $C_m(t)$, and the decorrelation index $D(t)$ is defined as $1 - C_m(t)$. We have found a significant change in a particular section of the S-wave coda between two sets of events (1988-1992 and 1993-1997), which appears as a spike in both $\tau(t)$ and $D(t)$. We have run a series of tests which strongly suggests that the observed changes in waveforms are not due to variations in earthquake location (verified by relocating the events from the observed S-P times at different stations) nor due to a uniform change of the background medium. Instead, the likeliest explanation is that there has been a change in the location of distinct scatterer(s) by a few meters.

We utilize a simple procedure for locating spatially those scatterers whose properties have changed in time. For each station, we first construct a differential seismogram $\delta s(t)$ by taking the difference of the average of the pre- and post-1993 seismograms. For noise-free seismograms, $\delta s(t)$ will consist only of energy from any scatterers whose propagation characteristics (travel time or amplitude) have changed, while an unchanged scatterer will be removed by this procedure. We then performed an nth-root (n=1) stack of the amplitude, $A(\mathbf{x})$, of $\delta s(t)$ from each station, stacking on the predicted arrival time of a candidate scatterer originating from location $\mathbf{x}$. This function reaches a maximum about 2 kilometers to the southeast of the cluster and at about 3 km depth.

The migration of the scatterer(s) occurred at seismogenic depth and therefore is less likely due to the environmental effects. As the difference is almost absent in the P-wave coda, we infer that the scatterer(s) is probably related to the redistribution of fluid-filled fractures which are more efficient in scattering S-wave energy compared to P. The location and timing of this change in the medium strongly suggests that it is a manifestation of the 1993 Parkfield aseismic transient. As such, it likely represents the stress-induced redistribution of fluids in the crust at seismogenic depths.

## S51D-06 0945h

### Self-Consistent Spatial Heterogeneity of Crustal Stress

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We examined what ingredients are required in friction models so that they produce a self-consistent stress field, that is, the conditions following an earthquake do not prevent subsequent ruptures from displaying similarly realistic behavior. Intuitively, we seek friction models that produce spatially heterogeneous stress fields with steady state statistical properties in the confines of a finite-element model with a resolution capable of simulating wave propagation at periods of 2.0 seconds and longer. This means that in addition to generating distributions of slip with spatial heterogeneity that are compatible with kinematic source inversions, the earthquake ruptures must also not significantly alter the overall spatial heterogeneity of the stress field, so that later earthquakes will also produce heterogeneous distributions of slip.

In order to enforce consistency in the degree of spatial heterogeneity of slip and stress on a single, planar fault, we found that it was necessary to introduce spatial heterogeneity into the nominal sliding stresses. Pulselike ruptures created with rate restrengthening friction and smooth sliding stresses lead to a substantial decrease in the heterogeneity in the stress field, as do cracklike ruptures with smooth sliding stresses. Subsequent ruptures fail to produce slip distributions with adequate heterogeneity. Introducing moderate spatial variations in the failure stress and/or strong spatial variations in the fracture energy also fail to maintain the same degree of heterogeneity. However, both pulselike ruptures and cracklike ruptures succeed in maintaining heterogeneity in the stress field when we include strong spatial variations in the nominal sliding stresses. With a planar fault, strong spatial variations in the sliding stresses are likely a proxy for geometric complexity in the sliding surface (rough faults) as well as many other local processes, such as spatial variations in off-fault fracturing.

## S51D-07 1020h

### Mainshocks are Aftershocks of Conditional Foreshocks: How do Foreshock Statistical Properties Emerge From Aftershock Laws

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The inverse Omori's law for foreshocks discovered in the 1970s states that the rate of earthquakes prior to a mainshock increases on average as a power law $\propto 1/(t_c - t)^{p'}$ of the time to the mainshock occurring at $t_c$. Here, we show that this law results from the direct Omori's law for aftershocks describing the power law decay $\sim 1/(t - t_c)^p$ of seismicity after an earthquake, provided that any earthquake can trigger its suit of aftershocks. In this picture, the seismic activity at any time is the sum of the spontaneous tectonic loading and of the activity triggered by all preceding events weighted by their corresponding Omori's law. The inverse Omori's law then emerges as the expected (in a statistical sense) trajectory of seismicity, conditioned on the fact that it leads to the burst of seismic activity accompanying the mainshock. The often documented apparent decrease of the $b$-value of the magnitude distribution at the approach to the main shock results straightforwardly from the conditioning of the path of seismic activity culminating at the mainshock. However, we predict that the magnitude distribution is not

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modified simply by a change of $b$-value but that a more accurate statement is that the magnitude distribution gets an additive (or deviatoric) power law contribution with exponent smaller than $b$ and with an amplitude growing as a power law of the time to the mainshock. In the space domain, we predict that the phenomenon of aftershock diffusion must have its mirror process reflected into an inward migration of foreshocks towards the mainshock. Using this model, we show that foreshock sequences are special aftershock sequences which are modified by the condition to end up in a burst of seismicity associated with the mainshock. Foreshocks are not just statistical creatures, they are genuine forerunners of large shocks as shown by the large prediction gains obtained using several of their qualifiers.

## S51D-08 1035h

### Competing Earthquake Forecasts Test Relationship Between Small and Large Earthquakes: Application to California

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Past earthquakes hold the key to the future (i.e., future large earthquakes) but there is plenty of debate about how to use this key. One important feature of seismicity in forecasting is the frequency-magnitude relationship. We present two forecast models that both assume future seismicity proportional to the past, but which have very different assumptions about the slope, or $b$-value in the frequency-magnitude relation. One model assumes that the $b$-value is constant throughout California, while the other assumes local variations inferred from past earthquake data. We present a pseudo-prospective test in which the two models learn from earthquakes before 1997. We test them against earthquakes after this time using a likelihood ratio test.

Our first case study covers the Parkfield segment of the San Andreas Fault. We show that the $b$-values remain stationary over several decades. Testing the two aforementioned hypotheses against each other results in significantly improved forecasts when using spatially variable $b$-values. Only this hypothesis can explain the seismicity in the observation period satisfactory. However, if testing larger magnitudes only (M4-M9), we reject both hypothesis because they overpredict the number of events. We found that the learning period as well as the forecasting period should span more than 5 years, allowing the seismicity to align to the b-value slope line. Moving on to all of California, we find similarly that the variable $b$ hypothesis forecasts the seismicity distribution significantly better if we test for the entire magnitude. Our next step is to set up a prospective test using earthquakes after the start of the test on January 1, 2003.

## S51D-09 1050h

### Relations Between Stress Change and Slip Distribution of Coupling Earthquakes

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It is now becoming more widely accepted that Coulomb stress triggering affects the timing and location of subsequent nearby events. Does it also have any influence or impact on the slip distribution and/or the hypocenteral location of following event? This question motivated us to investigate 6 pairs of spatially close and seismologically well studied earthquakes including the 1987 Elmore Ranch-Superstition Hills, the 1971 San Fernando-1994 Northridge, the 1997 Colfiorito earthquake sequence and the 1999 Izmit-Duzce earthquake couples. The three events that occurred in a simple tectonic environment and closely related in time seem to show a weak correlation between the stress load from the previous earthquake and the slip distribution of the rupture of the following event while no correlation at all is observed for the earthquakes in more complex tectonic environments. The hypocenters are generally located in positive Coulomb stress area of the rupture but not necessarily in areas where maximum slip occurred. These results suggest that Coulomb stress load has an important triggering effect, but does not have a strong impact on the rupture dynamics which may be largely controlled by the strength heterogeneity and the previous complex seismic history.

## S51D-10 1105h

### Re-examination of the Predicted Nov. 29, 1999 M=5.6 Xiuyan Earthquake by Double Difference Relocation

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The November 29, 1999 M=5.6 Xiuyan,Liaoning, China, earthquake was successfully predicted in short-term. Two days before the main shock the prediction was made and people in the epicentral area were evacuated (Liaoning Seismological Bureau, 1999). Therefore, although 1629 houses had either collapsed or been severely damaged, no casualty was caused. The prediction was mainly based on the observations of seismicity(foreshock sequence), though there were also some macro precursors showing up, such as groundwater physics and groundwater chemistry. In this study, we re-examined the whole seismic sequence by relocating each event with the Double Difference Method (Waldhauser and Ellsworth, 2000). The data analyzed are the P and S arrivals of the 291 events with magnitude greater than 1.3 in the sequence at the 42 seismic stations all over the Liaoning province during the year of 1999. The relocated sequence is well confined along the Haichenghe fault zone striking NWW, which was dated to $Q_1$ - $Q_2$ by the SEM analysis of the gouge in Xiuyan area. Thus, although the Xiuyan earthquake did not have the surface rupture, we show convincing evidence that it was caused by the re-activation of the Haichenghe fault zone which ruptured through Xiuyan area at depth before, during, and after this event. Based on the relocation results, the stress/strain accumulation and release on the Haichenghe fault zone before and after the earthquake could be divided into three stages. The first stage is before Nov. 9, during which 150 events occurred mainly on the section to the west of the main shock area, with the epicentral area being a quiescent zone for months. From Nov. 9 to Nov. 29 is the second stage, during which 60 events occurred mainly in the epicentral area before the mainshock. These 60 events are the foreshocks in the strict sense, which could be further divided into several groups. The third stage is the aftershocks, which spread along the whole fault zone. Our analysis suggests that the mainshock was caused by the current deformation along the Haichenghe fault zone. The Xiuyan earthquake sequence is similar to the sequence of the nearby 1975 Haicheng M=7.3 earthquake, which was also successfully predicted. However, even within China, such sequence is not characteristic in many other strong seismic zones.

## S51D-11 1120h

### Coulomb Stress Modeling of Aftershock Pattern and Fault Interaction for a Complex System of Normal Faults in Central Apennines (Italy).

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We investigate fault interaction through elastic stress transfer in an extensional tectonic setting characterized by complex fault systems. We study a prolonged seismic sequence occurred in the Umbria-Marche region (central Italy) in 1997-98 consisting of several moderate magnitude ($5 \leq M_w \leq 6$) earthquakes that ruptured normal faults within few months. The availability of precise 1650 earthquake locations (with formal errors less than 100 m), 321 accurate fault plane solutions and the heterogeneous slip distribution for the 3 largest magnitude events of the sequence consents to perform an accurate modeling of earthquake interaction and aftershock pattern for normal faulting events. We use a 3D elastic dislocation model to calculate Coulomb stress changes and to investigate fault interaction for the largest magnitude events. We compute stress changes using two different pore-elastic models to calculate the effective normal stress changes caused by shear dislocations. Thus, we investigate if the aftershock pattern is consistent with the elastic stress changes caused by the different main shocks considering the regional tectonic stress field. The detailed images of the anatomy of this fault system enable us to distinguish the aftershock rupture plane between the two conjugate planes of each focal mechanism. This allows us to calculate the coseismic stress perturbation on each aftershock fault plane and to test if their distribution and focal mechanisms are consistent with the induced stress field. We also verify if there exists a correlation between the promoted aftershocks and their magnitude as well as the aftershocks temporal decay. We conclude that 6 out of 7 main shocks were located in regions of Coulomb stress increase; the only one that is inconsistent occurred on the same fault plane that ruptured during a previous large event. Preliminary results of seismicity pattern reveal that 2/3 of the aftershocks are consistent with main shock induced stress changes. We emphasize the importance of the detailed knowledge of the 3D fault geometry to evaluate the reactivation of inherited faults.

## S51D-12 1135h

### Short Term Warnings and Better Assessment of Hazard. Some Significant Achievements of Earthquake Prediction Research in the Iceland "Natural Laboratory"

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Earthquake prediction research projects based on international participation have been ongoing in Iceland since 1988. The SIL project 1988-1995 was a concerted effort of the Nordic countries, Denmark, Finland, Iceland, Norway and Sweden in earthquake prediction research. The test area was the earthquake prone region of the South Iceland seismic zone (SISZ). The path selected for the project was to study the physics of crustal processes leading to large earthquakes. It was considered that small earthquakes, down to magnitude zero, were the most significant for this purpose, because of the detailed information which they provide both in time and space of crustal conditions an ongoing processes. The most significant outcome was the SIL system, which besides interpreting high level information carried from below by microearthquakes, provided near real time information, a basis for an alert system, which has been in operation now for a decade.

The PRENLAB and PRENLAB-2 projects of several European countries, 1996-2000 (EC supported projects) were a direct continuation of SIL, but with a more multidisciplinary approach. PRENLAB stands for "Earthquake prediction research in a natural laboratory". The basic objective was to advance our understanding in general on when, where and how dangerous earthquake might strike. Methods were developed to study crustal processes and conditions using microearthquake information, continuous GPS, InSAR, modeling, detailed fault mapping and paleoseismology. New algorithms were developed for short term warnings.

Among practical outcomes of these projects and of other efforts to watch crustal processes can be mentioned: 1) The useful warning before a sudden outbreak of an eruption in volcano Hekla in the year 2000, 2) The useful warning, also in the year 2000, issued 25 hours before a magnitude 6.6 (Ms) earthquake in the SISZ, with correct location and size. This earthquake was a second in a sequence of two similar size earthquakes with different locations. Statements were presented in scientific journals 10-15 years ago assessing, within a few kilometers, the location of the faults of these earthquakes, as the probable locations of the two next large earthquakes inside the SISZ.

The results of the SIL project and the PRENLAB projects as well as successes in providing useful information and warnings have been encouraging. They encouraged, on one hand new, ongoing, research projects for practical applications of the basic results of the former projects and, on the other hand, the build up of an early warning and information system in Iceland (EWIS) for seismic and volcanic hazards. The objective is to utilize in full all relevant observations for possibly useful warnings, before, during and following large hazards.

**S51D-13 1150h**

### Recovering Permanent Displacements Produced by the June 9, 1994 Bolivia Deep Earthquake From Seismic Records

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Ground displacements of the 1994 deep Bolivia earthquake are recovered from 6 on-scale velocity records of the BANJO array located about 600 km south of the epicenter. I first remove the instrument (STS-2) response by a time-domain deconvolution. The response of the STS-2 sensor falls off at a period of about 120 s. So the deconvolution is not stable and produces long-period drift. I corrected for the drift by fitting the displacements before and after the transient deformation with a 4th-order polynomial. The "after-signal" window is chosen to avoid the transient displacement but be as close as possible to the "pre-signal" window so that a smooth background drift can be assumed. I chose a 200 s long time window, 400 s after the *P* onset. The amount of static offset is included together with the polynomial coefficients in the least-square fitting. I subtract the polynomial from the displacement to remove the drift. I found that this technique produces very robust waveforms. All 6 stations give similar results. The obtained vertical permanent subsidences on the Banjo stations range from 4.3 to 6.2 mm, which agree well with predictions by using normal mode summation. The vertical offsets are much smaller than the previous estimate value of 1.9 cm by Jiao et al. (1996) which is believed to be contaminated by long-period noise when deconvolving the instrument response. The north-south permanent displacements are 2.8 to 4.7 mm, about half of the predicted. This discrepancy might be caused by deformation induced tilts at the sites.

## S52A MCC: Hall C Friday 1330h

**From the Slab to the Mantle Wedge Posters** *(joint with T, DI)*

***Presiding:*** **K Fischer,** Brown University**; J F Cassidy,** Geological Survey of Canada

**S52A-1055 1330h POSTER**

### Tomographic Inversion of Ground Motion Amplitudes for the 3-D Attenuation Structure beneath the Japanese Islands

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The attenuation structure beneath the Japanese Islands should hold similar 3-D complexities to those in the velocity structure. For example, we often observe abnormal distributions of ground motion amplitudes, which are very different from a circular distribution about an epicenter. Seismic attenuation implies inelasticity or scattering in the Earthfs materials, while seismic velocities imply their elastic properties. We can assume high attenuation under the volcanic fronts, and low attenuation along the subducting Philippine Sea plate similarly to the velocity structure. However, this similarity is not always expected in other parts of the Japanese Islands. Information on the seismic attenuation is also important for the simulation of strong ground motions

The Japan Meteorological Agency (JMA) has compiled maximum velocity amplitudes observed at stations distributed in the whole Japanese Islands. In this study, the vertical components of ground velocity amplitudes reported from January 1994 to December 2000 will be used, because reports of horizontal components are very few before October 1997. The seismic attenuation will be represented with the indexes called Qp and Qs, and their 3-D structure will be obtained for two frequency bands about 5Hz (0.1-0.3s) and 2Hz (0.4-0.6s) by selecting amplitudes with periods within the bands. For the 5Hz band, amplitudes from 2328 or 3236 earthquakes are used for P-wave or S-wave tomography, respectively. The number of stations where amplitudes were observed is 947.

There are four characteristic results in this study. First of all, clear low-Q zones can be found beneath the volcanic front in the northeastern Japan, and the distinct high-Q is recovered in the east of the front. This high-Q area coincides with the strata of 100Ma or older. Low-Q zones appear only just below volcanoes in the upper and lower crust, while the low-Q area extends continuously along the volcanic front at a depth of 40km. The Qp distribution show similar tendencies zone, but the averaged Qp in the crust is significantly lower than the averaged Qs, so that corresponding low-Qp zones are not obvious. The tendencies can also be found along the volcanic front related to the subduction of the Philippine Sea plate.

Secondly, a low-Qs area is found at a depth of 40 km in the Kanto region, central Japan. They considered the materials to be serpentine on the Philippine Sea slab. The resultant Qp in the area is not so low, since hydrated serpentine does not attenuate P-waves but S-waves.

Thirdly, a distinct low-Qp area is found at a depth of 65km in the Chubu region, central Japan. However, no low-Qs zone can be found in the area. This may imply a different attenuation process from that under the volcanic front in the northeastern Japan.

Fourthly, the high-Q area is found along the upper boundary of the Philippine Sea slab, which is determined from seismicity in the southwestern Japan. This area is more distinct in the Qp distribution with an average of 1000 than in the Qs distribution. In the Shikoku region, the low-Qp area does not extend beyond latitude of 34.2N, and the area looks falling down into a deeper part there. On the other hand, in the Kyushu region, the low-Qp area reaches a depth of 100km or larger coinciding with the slab boundary determined by the seismicity.

**S52A-1056 1330h POSTER**

### Seismic Anisotropy and Mantle Flow Beneath Japan

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The goal of this study is to provide new constraints on the strength, orientation, and location of seismic anisotropy in the vicinity of the Japan subduction zone. Determining seismic anisotropy parameters has important implications for understanding the dynamics of convergent margins and the nature of mantle flow in subduction zones. The Japan region is a tectonically unique area, as it contains several zones of active volcanism, is situated in the vicinity of two triple junctions, and therefore is a region in which multiple plates are subducting near one another. Additionally, it is an ideal region for examining seismic anisotropy, as a broad range of earthquake sources, both laterally and with depth, are recorded at numerous local stations of the FREESIA and IRIS networks.

We performed shear wave splitting analysis on local S phases recorded at a total of 70 broadband stations in the Japan area. We examined 378 local events with source depths ranging from 33 km to 506 km recorded between 1995 and 2001. Using these data, we determined 243 well-constrained shear wave splitting measurements for the region. Results from the shear wave splitting analyses provide important insights into the structural complexity of the area. First, across central and southern Honshu, fast directions demonstrate a rotation from N-S near Shikoku to the west, to E-W in Kinki, and continue to a N-S orientation across much of Chubu and Kanto to the east. This pattern of fast direction variations was also observed, although in less detail, by Fouch and Fischer [1996]. Splitting time variations for the region are also intriguing. First, we observe a general increase in splitting time with source depth, with a maximum splitting time of 1.9 s. Regional variations occur in this pattern, and appear to be related to the proportion of the raypath propagating within the mantle wedge. Second, a region of anomalously large splitting times with fast directions oriented roughly NW-SE exists slightly west of the central Japan volcanic front.

While the observed seismic anisotropy may be derived from a combination of structure in the subducted slab, mantle wedge, and overriding plate, the pattern of splitting, both laterally and with depth, strongly suggests that the bulk of the anisotropy is derived from fabric within the mantle wedge. In one possible model, complex mantle flow patterns near the triple junctions produce the bulk of the fast direction variations, marking a dramatic shift in flow direction over short spatial scales. Splitting time variations suggest that anisotropy exists to depths of at least 275 km and perhaps deeper. Additionally, the zone of large splitting times near the central Japan volcanic front may correspond to a local complex slab morphology, such as a sharp bend or tear in the slab. Our results, combined with results from several other regions, including Tonga, Kuriles, New Zealand, and South America, suggest that for many subduction zones, simple patterns of mantle flow are unlikely, and complex geometries of mantle flow must be fully assessed.

**S52A-1057 1330h POSTER**

### The Crust and Uppermost Mantle Structure Beneath Chugoku-Shikoku, Japan on the Basis of Receiver Function Analysis

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We apply the receiver function analysis to the teleseismic waveform data recorded at 118 stations of the High Sensitivity Seismograph Network (Hi-net) in Chugoku-Shikoku district, western part of Japan to study the seismic velocity structure for both P and S waves. We selected earthquakes with magnitudes 5.5 or higher and epicentral distances between 27 and 90 degree. Considering the response characteristics of the Hi-net system and reflection from the ground surface, we analyze waveforms in a frequency range from 0.1 Hz to 0.6 Hz. The inversion of the obtained receiver functions offers a precise velocity structure up to 60 km in depth.

Characteristics of the seismic velocity structure revealed from this study can be summarized as follows: (1) A high velocity layer with S wave velocity of about 4.2 km/s is subducting from the south to the north with a small dip angle. This layer corresponds to the Philippine Sea (PHS) plate. The upper boundary of this layer is 30km in depth beneath southern Sikoku, 45km beneath the Seto Inland Sea and about 60km, at least, beneath the central part of Chugoku region. A low velocity layer with S wave velocity of about 4.0 km/s and thickness of 10 km overlaps with this high velocity layer. This low velocity layer can be interpreted as the oceanic crust subducting as a part of the PHS plate. (2) Beneath most of all the stations, there is a clear velocity discontinuity corresponding to the Moho at a depth from 25 to 40km. The depth of the Moho is relatively shallower at northern and southern coastlines of the Chugoku-Sikoku district and deeper beneath the central part of this district. The geometry of the Moho has a high correlation with gravity anomaly. (3) There are remarkable low-velocity regions beneath Daisen, which is a Quaternary volcano, and the eastern Sikoku region at depth from 10 to 20km. In addition, there are weak low-velocity layers at 20km depth in a wide area. (4) Seismicity is very low in the low-velocity regions in the crust while many crustal earthquakes occur around the low-velocity regions.

**S52A-1058 1330h POSTER**

### Seismicity and Thermal Regime within the Subducting Philippine Sea Plate, South West Japan

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A three-dimensional plate model for the surface of the subducting Philippine Seas Plate was obtained to aid in the production of detailed 2-D and 3-D thermal models of the region. Recently Japan Meteorological Agency and a consolidated catalogue of university data (JUNEC) have been made available. Merging these data sets for the years 1985-1994 and relocating the hypocenters provides a useful tool in determining the geometry of the subducting Philippine Sea Plate. Plate structure determined from Seismic Surveys have been combined with the seismicity to obtain an accurate plate model for the entire SW Japan region. Results of re-located events indicate a plate interface within 5 km of previous studies with a few important differences. Previous studies have assumed the seismicity coincides with the subducting crust, however, from Kii Peninsula west to the edge of Shikoku Island, the seismicity appears to be mainly within the subducting mantle. This produces a plate model 5 to 10 km shallower than previous studies. Events are further relocated using HypoDD, an double difference relocation algorithm. Seismicity clustered along seismic survey line 9607 in Western Tokai appears to be contained exclusively within the subducting crust, while events beneath Shikoku Island show little or no clustering. Focal mechanism for the Kii Peninsula region have been calculate and stress inversion of these focal mechanisms

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