S22G-07 1730h

An Efficient Approach for Computing the Frequency Response of Seismic Waves in Heterogeneous, Anisotropic Viscoelastic Media With FDTD+PSD Modeling

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Computation of the frequency response (phase and magnitude) of seismic waves propagating in heterogeneous, anisotropic, viscoelastic media is required for a number of seismology efforts, including frequency-domain full-waveform inversion and basin modeling. When the frequency response is required at a limited number of locations, it can be computed efficiently with a memory variable, staggered grid finite difference time domain (MV-SG-FDTD) code by taking the Fourier transform of the received waveforms generated by a broadband source. However, when the frequency response is required at many or all grid locations, as in frequency-domain full-waveform inversion, the memory requirements for storing the waveforms make this approach prohibitive. An alternative approach is to compute the frequency response by formulating the SG-FDTD equations in the frequency domain. For O(4) accuracy spatial differencing, the resulting 2-D system of implicit equations for the unknown particle velocities and stresses at the finite difference cell locations yields a complex system matrix of order equal to $[5xMxN]^2$, where M and N are the number of finite difference cells in the x and z directions, respectively, and the 5 comes from the five unknowns in a 2-D staggered grid finite difference stencil (2 particle velocities, and 3 stresses). The complex matrix equation has the following properties: (1) sparse (total number of unknowns equals [45xMxN-20xM-20xN]), (2) banded (4 bands of sparse 5x5 submatrices on each side of the main diagonal), and (3) non-Hermetian. We found that the resulting system matrix is typically much too large for direct matrix solvers such as sparse LUD for seismic problems of reasonable size. Additionally, our attempts to solve the frequency domain system of implicit equations using iterative sparse matrix solvers, such as QMR (quasi minimum residual method), tended to suffer from poor convergence problems when using standard preconditioning (e.g., Jacobi). In this presentation, we demonstrate that an efficient approach for computing the frequency response of a heterogeneous, anisotropic, viscoelastic medium can be achieved by running an explicit MV-SG-FDTD code with a harmonic wave source out to steady-state, and then extracting the magnitude and phase from the transient data via a phase sensitive detection algorithm (PSD). The PSD algorithm requires integration over only several cycles of the waveform to obtain accurate phase and magnitude estimates. Because this integration is performed on-the-fly, there is no need to store waveforms at the grid locations. Preliminary tests indicate that it should be possible to superimpose multiple frequencies at the source and extract the magnitude and phase for each frequency using the PSD algorithm, opening up the potential for obtaining the multi-frequency response of a heterogeneous, anisotropic, viscoelastic medium with a single FDTD run.

S22G-08 1745h

Numerical Simulation of Time-Dependent Wave Propagation Using Nonreflective Boundary Conditions

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Solving numerically the wave equation for modelling wave propagation on an unbounded domain with complex geometry requires a truncation of the domain, to fit the infinite region on a finite computer. Minimizing the amount of spurious reflections requires in many cases the introduction of an artificial boundary and of associated nonreflecting boundary conditions. Here, a question arises, namely which boundary condition guarantees that the solution of the time dependent problem inside the artificial boundary coincides with the solution of the original problem in the infinite region. Recent investigations have shown that the accuracy and performance of numerical algorithms and the interpretation of the results critically depend on the proper treatment of external boundaries. Despite the computational speed of finite difference schemes and the robustness of finite elements in handling complex geometries the resulting numerical error consists of two independent contributions: the discretization error of the numerical method used and the spurious reflection generated at the artificial boundary. This spurious contribution travels back and substantially degrades the accuracy of the solution everywhere in the computational domain. Unless both error components are reduced systematically, the numerical solution does not converge to the solution of the original problem in the infinite region. In the present study we present and discuss absorbing boundary condition techniques for the time-dependent scalar wave equation in three spatial dimensions. In particular, exact conditions that annihilate wave harmonics on a spherical artificial boundary up to a given order are obtained and subsequently applied in numerical simulations by employing a finite differences implementation.

S31A MCC: 3009 Wednesday 0800h

Stress Transfer, Triggered Earthquakes, and Time-Dependent Seismic Hazard I *(joint with G, T, NG)*

Presiding: **S Steacy,** University of Ulster**; E S Cochran,** Institute of Geophysics and Planetary Physics, University of California, Los Angeles

S31A-01 0800h INVITED

A Fresh Look at the Triggering of Earthquake Pairs, Such as the Landers-Big Bear, Landers-Hector Mine, Izmit-Duzce, and Nenana-Denali, and March-May 1997 Kagoshima Events

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Recent precise hypocentral information provides opportunities to study how secondary earthquakes are spatially and temporally triggered by mainshocks. Most studies regard the second shock in the pair as an aftershock triggered exclusively by the mainshock, with its likelihood decreasing with time after the first event. Here we argue that small aftershocks occurring near the future hypocenter of the second shock play an important role in enhancing the likelihood of the pair. For such multiple-order triggering calculations, we incorporate ate/state friction of Dieterich (1996) into stress transfer. The results may answer two riddles: The first is to ask why there is a net probability gain during the aftershock sequence when there must be equal areas of stress enhancement (trigger zones) and stress depression (shadows) near the mainshock. The Omori law describes only the behavior in the trigger zones. The answer appears to be that the net probability gain occurs because the seismicity rate increases exponentially in response to the stress change, so the seismicity rate gain in the trigger zones dwarfs the seismicity rate drop in the shadows. The second riddle is to ask how small aftershocks triggered by the mainshock affect the likelihood of the second large earthquake in the pair. The answer is that because the state variable (gamma) in the Dieterich earthquake formulation has already plummeted as a result of the mainshock, the effect of small aftershocks on the nearby seismicity rate is highly amplified relative to the effect of the mainshock, even if the mainshock and the small aftershock change the stress by the same amount. The implication is that that probability of the second shock is not necessarily highest immediately after the mainshock, as we typically assume. Instead, it might be highest when the distribution of first-order aftershocks expands (as also predicted by rate/state friction) to a potential earthquake source, such as an active fault. A more complete probability calculation would thus need to include the effects of smaller aftershocks, as advocated by Felzer et al (2002), a very challenging task.

URL: http://quake.wr.usgs.gov/research/deformation/modeling/refs/ross_refs.html

S31A-02 0815h

Slip Partitioning and the Regional Stress Field

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Oblique motion along tectonic boundaries is commonly partitioned into slip on several faults with different senses of motion. This partitioning can be explained by the upward propagation of a localized fault at depth. The static stress field ahead of the propagating fault separates into zones of predominantly normal, reverse and strike-slip faulting. Elastic approximations to plastic behavior have been used to explain the distribution of faults observed along the San Andreas (California, USA) and the Haiyuan faults (Tibet, China). Slip partitioning in a single earthquake rupture has also been documented for the 2001 Kokoxili, Tibet earthquake. This process has important implications for regional stress fields in areas where the strain is partitioned onto structures with different senses of motion. In particular, the notion of a partitioned stress field driven by slip at depth can be used to generate a realistic background stress field for models of Coulomb stress interactions. This can be incorporated into more accurate calculations of the stress interactions in aftershock sequences of large earthquakes, which is crucial to determining real-time aftershock probabilities.

S31A-03 0830h

Detecting Seismicity Shadows at Short Time Scales

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Stress changes following the occurrence of an earthquake can lead to significant changes of the seismicity rate. While triggering (eg, aftershocks on the main fault) is clearly observed, regions of seismicity rate decrease can be harder to detect. We here address this detectability issue, which becomes particularly severe at short (eg days-weeks) time scales. A robust method is proposed in order to estimate the probability that a given region has experienced a seismicity rate decrease. This probability is generally (for large, recent California earthquakes) found to be low: seismicity shadows are significantly not as common as activated regions. The role of crustal heterogeneities in promoting triggering is discussed.

S31A-04 0845h

Testing the stress shadow hypothesis

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According to current theoretical understanding an earthquake may decrease the rate of other earthquakes in a particular area (create a stress shadow) if earthquakes influence each other via static stresses, but not if they primarily interact via dynamic stresses (Toda and Stein, 2003). Using the California ANSS catalog from 1978 to 2001, we find that the occurrence of stress shadows is difficult to prove, indicating that dynamic earthquake interaction may be a viable alternative. Stress shadows are often identified by measuring seismicity rates before and after a large earthquake and then noting where rate decreases are larger than those expected from a random Poissonian process (Matthews and Reasenberg, 1988). These counts by themselves offer no proof that the mainshock is the cause of the observed rate decreases, however. Marsan (2003) projected the decay rates of pre-existing aftershock sequences to demonstrate that in many cases measured "shadows" were actually caused by ongoing localized aftershock sequence decay. We use an alternative method to verify the results of Marsan (2003) to test whether rate decreases after large earthquakes can be attributed in general to independent causes. We compare the degree and extent of seismicity rate changes around the times of large earthquakes and around other points in time. Like the method of Marsan (2003) this method does not require declustering, often a somewhat subjective process. Preliminary results indicate that while the amount of localized rate increases after large earthquakes is much larger than at other times, the amount of rate decreases may not be significantly different. In Southern California, for example,

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preliminary results indicate that 31% of 8 by 8km cells experienced a significant (one sigma) increase in seismicity rate during the first year after the 1992 M_W 7.3 Landers earthquake (in comparison with the preceding six years), while the number of cells experiencing significant rate increases in other one year increments, from 1984 to 1991, ranged from 16% to 20%. For rate decreases, 8% of cells experienced a significant downturn in the year after Landers, while a similar percentage of cells (ranging from 7% to 10% and averaging 8.5%) experienced significant rate decreases from 1984 to 1991.

S31A-05 0900h INVITED

Assessment of Spatial Aftershock Probabilities: a Feasibility Study in Earthquake Hazard

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Non-linearity in the generating dynamics of earthquakes which may forbid deterministic earthquake prediction does not preclude the estimation of earthquake probability and, in particular, how this might change in space and time. Recent developments in the understanding of stress triggering of earthquakes allow us satisfactorily to explain the special variation of aftershock distributions following any large earthquake. To date, however, this assessment of aftershock probability has only been by the back analysis of completed aftershock sequences. The power of modern microcomputers, the great number of local and telemetered seismic networks, the rapid acquisition of data from satellites coupled with the speed of modern telecommunications and data transfer, all mean that it may be possible that these techniques may be applied in a forward sense. Here we describe the PRESAP Project which has been funded by the European Community and which reported this autumn. The aims of the project were: 1) to assess the extent to which our scientific understanding of the physical phenomena controlling the variation and seismicity following a large event permits the forward modelling of aftershock sequences; 2) to assess the extent to which data which is presently collected is sufficient to allow inversions for slip and stress perturbation fields to be calculated in useful time-frames of between say 0.1 days and 10 days following the main shock; 3) to assess the extent to which current date transfer speeds are sufficient to allow access to the appropriate data within these time-frames. In this presentation, we describe the main work packages of the PRESAP Project and outline its findings. In particular, we describe the pseudo real time scenario which was used to assess the success of the protocols which have emerged from the project.

S31A-06 0915h

Coulomb Stress Modelling as a Practical Tool in Real-time Aftershock Hazard Assessment: the Example of the PRESAP Blind Test

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We present results of a pseudo real-time scenario that was performed in the framework of the PRESAP (Practical, Real-Time Estimation of Spatial Aftershock Probabilities) project. The aim of the PRESAP project is to assess the feasibility of using Coulomb stress modelling to make real time estimations of the likely spatial distribution of off-fault aftershocks following a large event. As part of this project, the scenario was designed to test the practicality of making such assessments in real time. Data from a recorded earthquake, not studied in the PRESAP project and not known in advance by the participants, were made available in the time ordered sequence and in the raw form as it would have arrived. The test was managed through a website where data and results were continually posted by the participants located all over Europe. Results show that CST may indeed provide useful guidance in the identification of potential fault sources. The location of aftershocks in association with a-priori knowledge of the kinematics of potentially active faults played a key role in decision-making. In the case where the number of available aftershocks would have been sufficient, statistical tests could have also been used. The success of the blind-test was in part due to the "simple" vertical strike-slip faulting tectonics of the region concerned but in particular due to the good knowledge of the active faults. In regions where the tectonics is more complex (e.g. Athens 1999 earthquake, Umbria-Marche 1997 sequence), the exercise may not be so straightforward. Nevertheless, real-time estimates may be improved by pre-computing a range of potential fault scenarios for both Coulomb stress perturbations and expected ground motions that are likely to affect the critical sites of interest.

URL: http://www.errigal.ulst.ac.uk/

S31A-07 0930h

Are foreshocks explained by cascades of triggered seismicity: empirical tests and comparison with the Olami-Feder-Christensen SOC model

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The observation of foreshocks preceding large earthquakes and the suggestion that foreshocks have specific properties that may be used to distinguish them from other earthquakes have raised the hope that large earthquakes may be predictable. Among proposed anomalous properties are the larger proportion than normal of large versus small foreshocks, the power law acceleration of seismicity rate as a function of time to the mainshock and the spatial migration of foreshocks toward the mainshock, when averaging over many sequences. Using Southern California seismicity, we show that these properties and others arise naturally from the simple model that any earthquake may trigger other earthquakes, without arbitrary distinction between foreshocks, aftershocks and mainshocks. With the quality of available catalogues, we do not find a convincing dependence of the foreshocks precursory properties on the mainshock size. Taken at face value, this would imply that earthquakes (large or small) are predictable to the same degree as seismicity rate is predictable from past seismicity by taking into account cascades of triggering. We also find that cascades of triggering give rise naturally to long-range and long-time interactions, which can explain the observations of correlations in seismicity over surprisingly large length scales. Most of these properties are found at a qualitative level in synthetic earthquake catalogs generated by the OFC spring-block model. Following S. Hergarten and H.J. Neugebauer, Phys. Rev. Lett. 88.238501, 10.1103, 2002, we apply the same analysis to synthetic catalogues generated by the OFC model. In addition, and in contrast with the ETAS model and with observations, we find in the OFC model a dependence of foreshock rate on the size of the mainshock, which can be explained by the concept of the"critical earthquake. In the OFC model, large events are therefore slighly more predictable than smaller events.

S31A-08 0945h

After the lightning and before the thunder; non-Omori behavior of early aftershocks?

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Mainshock rupture is immediately followed by the receding drumbeat of aftershocks, which have been known to obey Omori's law for nearly a century. Unfortunately, the initial few minutes of aftershocks are difficult to observe due to the mainshock coda, network clipping, and the confusion of nearly simultaneous events. Yet this interval holds valuable clues about how stress-induced ruptures may be delayed, often in fits and starts, and the friction laws that govern temblors. With the advent of continuous recording on dense networks, we can pry open a window to reveal aftershock activity 1 to 5 minutes after moderate and large earthquakes. We high-pass-filter 100-sample-per-second three-component recordings to minimize reverberating coda, and select stations for low noise and impulsive arrivals to reveal patterns of P and S arrivals. We have examined close-in recordings of six earthquakes recorded on TriNET in southern California (M4.0 2001-10-28 Compton, M4.7 2002-09-21 Yorba Linda, and M7.2 1999-10-16 Hector Mine) and on Hi-Net in Japan (M7.3 2000-10-06 Tottori, M5.1 2003-05-11, and M5.4 2003-5-17). Visual examination of high-passed seismograms typically detects several times more events in the first few minutes than are recorded in the best catalogs. Calibration of observed amplitudes with the magnitudes of those events that are in the catalogs allows all detected events to be assigned a magnitude. Preliminary results suggest a deficit of aftershocks by roughly a factor of two from 100 to 300 sec after the mainshock relative to 1/t rate decline with time. This deficit is comparable to the one tentatively found for much smaller M1 to M2 (Rubin, JGR, 2002, p 3-10). This pattern is consistent with the existence of such an interval in rate-and-state friction models prior to the 1/t aftershock decay rate that (Dieterich, JGR, 1994, interval b). We expect that capturing early aftershock rates will aid in the understanding of the transition from propagating rupture to sporadic aftershock activity.

S31B MCC: 3011 Wednesday 0800h

Pumping Iron: The Core *(joint with V, DI)*

Presiding: **D A Wiens,** Washington University**; Y Shen,** University of Rhode Island

S31B-01 0800h

Can we achieve consistent inner-core models from ISC travel-time data and waveform data?

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While it is now generally believed that the Earth's inner core is anisotropic to compressional wave propagation, the magnitude and existence of depth variations of seismic anisotropy are still controversial among the seismological community. Same is also true on whether there is a hemispherical variation in both the velocity (including the isotropic wavespeed and the magnitude of seismic anisotropy) and the attenuation structure at the top of the inner core. The discrepancy between the inner-core models is, however, deeply related to the type of data used in deriving them: hand-picked differential travel-time data (*PKiKP-PKIKP* and *PKP-PKIKP*), ISC absolute travel-time data of PKIKP, or normal-mode data. Models from the first type of data appear to have strong lateral and radial variations of seismic anisotropy, as well as the hemisphericity of the inner core, while the other two types of data tend to favor models with seismic anisotropy homogeneously distributed within the entire inner core. Such a discrepancy could result from the sparse and biased sampling of the differential travel-time data, or the large uncertainties in the ISC absolute travel-time data, or both. To solve this discrepancy, we analyzed a total of $\sim$2.1 million *PKIKP* travel time data reported to the International Seismological Center (ISC) in the period of 1964-1999. We first computed the ISC travel-time residuals of PKIKP with respect to the PREM model. We used high-quality relocation catalogs with relatively accurate earthquake locations and origin times in the calculation. We then calculated corrections on the *PKIKP* travel time due to the heterogeneous mantle structure. Our preliminary results suggested that the corrected travel-time residual data are, surprisingly, very consistent with differential travel-time data. For example, we found that travel times are systematically smaller, by about 0.5-2 s, for waves that travel the "eastern" hemisphere compared to those travel the "western" hemisphere. The consistence suggested that the ISC travel-time data, with its great coverage, has the potential to shed light on those unresolved regions, such as the innermost part of the inner core.