S32B-0637 1330h POSTER

Lateral Variations in Upper Mantle Shear Wave Attenuation

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We study the lateral variations in shear wave attenuation in the upper mantle by analyzing the spectra from S and SS arrivals from selected seismograms in the IRIS FARM database between 1988 and 1999. We use seismograms from shallow earthquakes ($\leq$50 km depth) at epicentral distances of 40°–80° for S waves and 80°–160° for SS waves. Each spectrum is the product of source, receiver, and propagation response functions as well as local source- and receiver-side effects. We correct each spectrum for the known instrument response, a source model with an ω^{-2} falloff at high frequencies, and a one-dimensional Q_β model. Since there are multiple receivers for each source and multiple sources for each receiver, we can approximate the source- and receiver-side terms by stacking the appropriate S log spectra. The resulting source-specific response functions include any remaining source spectrum and the effect of near-source attenuation in the upper mantle; the receiver stacks include the site response and near-receiver Q structure. We correct the SS log spectra for the appropriate source- and receiver-side stacks found from the S waves. Since attenuation in the lower mantle is small, the residual SS log spectrum approximates attenuation in the upper mantle near the SS bounce point, and can be used to estimate $\overline{\delta t^*}$ at frequencies between 0.01 and 0.1 Hz. The resulting bounce point $\overline{\delta t^*}$ measurements, which we smooth into caps of 5°radius, show spatially coherent patterns of more and less attenuating regions. We will compare these patterns with our previous results using the same method for higher-frequency P wave attenuation and with other studies of lateral variations in shear wave attenuation.

S32C MC: Hall D Wednesday 1330h

Wave Propagation Theory and Modeling Posters *(joint with NG)*

Presiding: **B Milkereit,** Dept. of Physics, University of Toronto

S32C-0638 1330h POSTER

Modal Decomposition of the Scattered Teleseismic Wavefield

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The teleseismic P-coda contains energy scattered through a range of different mechanisms which include forward P-to-S scattering and back scattering created through free-surface reflection of the primary P-phase. Our focus in this study is the approximate separation of these different scattering modes in 1-D media using an inverse scattering formalism. It is well known that the forward problem of predicting wave scattering from heterogeneity can be described through the Born series, an iterated form of the Lippman-Schwinger equation. Individual terms in this series represent the contributions of different orders of scattering interaction to the scattered wavefield. The inverse-scattering series, by analogy, represents the heterogeneity in terms of different orders of the wavefield. The first term in the inverse series is derived through the Born approximation, and constitutes a distorted image of material property perturbations which possesses many attributes/artifacts of the data. By operating on this image with the appropriate component of the reference Green's function, it is possible to separate forward P-to-S conversions and free-surface P and S multiples. However, wavefield separation is complicated by i) contrasting sensitivities of different scattered modes to heterogeneity, and ii) instabilities incurred through finite frequency bandwidth. These complications may be alleviated to some degree through different forms of model regularization. We demonstrate this approach on synthetic seismograms and data collected from the Yellowknife Seismic Array, and consider the implications for multichannel waveform inversion.

S32C-0639 1330h POSTER

Improved Mesh Interpolation for Ray Tracing by Wavefront Construction Methods for Anisotropic Media

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Ray methods are useful for the calculation of Green's tensors for three-dimensional, anisotropic media because they are much faster than more exact algorithms such as finite differences. At the same time, there are significant challenges because of difficulties in implementation, particularly those related to the solution of the two-point problem. Classical shooting methods often either fail to determine a solution and can be very slow. Some approaches, such as eikonal methods, are fast, but they do not compute amplitudes, consider only first arrivals, and cannot be easily applied to anisotropic models. Therefore, they cannot be used to compute Green's tensors.

Wavefront construction methods, on the other hand, do evaluate both traveltime and amplitude throughout an earth model (e.g., Lambaré et al., 1996). By tracking propagating wavefronts, the geometry of an entire field of rays can be taken into account, and Green's tensors can be computed for the entire model space. These algorithms begin with a small number of rays traced directly from the source. At regular increments in traveltime, a mesh is constructed from the set of points on all rays at the time of interest. As the wavefront propagates away from the source, new rays are inserted into the mesh based on an interpolation criterion. Previous implementations for isotropic media have typically inserted new rays either when the separation between existing rays exceeds an arbitrary distance or when wavefront curvature exceeds some threshold value. Because most rays are computed for only a portion of the overall time of propagation, the simulation requires less time overall.

In our current implementation for anisotropic media, we pose the wavefront construction method as a process of adaptive mesh construction, and we seek to increase the speed of the algorithm in several ways that distinguish it from other approaches. First, rather than applying dynamic ray tracing, we perform only kinematic ray tracing, relying on finite-difference methods to compute derivatives of traveltime and other quantities with respect to ray coordinates. This provides a much simpler algorithm, especially for anisotropic media, and we suggest that because the equations are simpler, it can be faster. Secondly, we have developed a new interpolation criterion that tests the true error in traveltime across the mesh. Specifically, we test calculations of traveltime at an existing mesh point by extrapolating from nearby rays using the paraxial method. Because the correct traveltime at the test point is accurately known from ray tracing, we can calculate the mismatch between this true value and the paraxial approximation. If the error exceeds a threshold level, we interpolate the mesh, ensuring that paraxial methods allow us to compute traveltimes and amplitudes throughout the model. This new test is an improvement over previous algorithms because the error is easily related to numerical error in the traveltime computation, unlike, for example, the distance threshold approach which requires an *ad hoc* definition of a maximum distance of accuracy. We will illustrate the implementation of the new interpolation scheme and show examples of applications to anisotropic media.

S32C-0640 1330h POSTER

Validation of Born Traveltime Kernels

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Most inversions for Earth structure using seismic traveltimes rely on linear ray theory to translate observed traveltime anomalies into seismic velocity anomalies distributed throughout the mantle. However, ray theory is not an appropriate tool to use when velocity anomalies have scale lengths less than the width of the Fresnel zone. In the presence of these structures, we need to turn to a scattering theory in order to adequately describe all of the features observed in the waveform. By coupling the Born approximation to ray theory, the first order dependence of heterogeneity on the cross-correlated traveltimes (described by the Fréchet derivative or, more colourfully, the *banana-doughnut* kernel) may be determined.

To determine for what range of parameters these *banana-doughnut* kernels outperform linear ray theory, we generate several random media specified by their statistical properties, namely the RMS slowness perturbation and the scale length of the heterogeneity. Acoustic waves are numerically generated from a point source using a 3-D pseudo-spectral wave propagation code. These waves are then recorded at a variety of propagation distances from the source introducing a third parameter to the problem: the number of wavelengths traversed by the wave. When all of the heterogeneity has scale lengths larger than the width of the Fresnel zone, ray theory does as good a job at predicting the cross-correlated traveltime as the *banana-doughnut* kernels do. Below this limit, wavefront healing becomes a significant effect and ray theory ceases to be effective even though the kernels remain relatively accurate provided the heterogeneity is weak.

The study of wave propagation in random media is of a more general interest and we will also show our measurements of the velocity shift and the variance of traveltime compare to various theoretical predictions in a given regime.

S32C-0641 1330h POSTER

Fréchet kernels for body wave amplitudes

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We derive a 3-D Fréchet sensitivity kernel relating the root-mean-square amplitude of a far-field, broadband body-wave pulse to laterally heterogeneous seismic slowness variations within the earth. Unlike the "banana-doughnut" sensitivity kernel for a cross-correlation traveltime, the amplitude Fréchet kernel for a turning wave is maximally sensitive, rather than completely insensitive, to the 3-D slowness perturbation along the central source-to-receiver ray. In the asymptotic limit of an infinite-frequency pulse, our 3-D amplitude kernel formulation is consistent with the dominant 1-D integral involving the double cross-path derivative of the slowness perturbation along the unperturbed geometrical ray.

S32C-0642 1330h POSTER

Full Waveform Seismic Inversion With a Time-Variant Sensitivity Equation

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A general approach toward solving the 3D full waveform seismic inverse problem entails iteratively refining a candidate earth model until an acceptable match is obtained between predicted and observed data. On each iteration, we calculate spatially distributed updates to the current model parameters by solving a large system of linear algebraic equations. This system is obtained by determining the sensitivity of each predicted seismic datum (particle displacement) to small perturbations in every model parameter (mass density and elastic moduli) as a function of recording time. These time-variant sensitivity equations are derived by applying the reciprocity principle and the first Born approximation to the velocity-stress equations governing isotropic elastic wave propagation.

Construction of the time-variant sensitivity equations is computationally expensive, and thus requires parallel computation capability. For a given source-receiver pair, we obtain matrix elements by convolving velocity vector and strain tensor components of two wavefields, one activated at the source position and the other activated at the receiver position. Wave propagation through the current estimate of the 3D model is performed with a finite-difference algorithm that solves the elastodynamic velocity-stress system on staggered spatial and temporal grids. For all source-receiver pairs of the acquisition geometry, convolution products are stored at every subsurface gridpoint where parameter updates are desired. The right-hand vector in the linear system consists of displacement residual traces appended end-to-end. We can apply additional linear equations arising from *a priori* constraints imposed on the model (e.g., if the recording geometry leaves portions of the model space under-constrained). We then use an iterative algebraic solver (also implemented in a parallel computational environment) to seek the minimum-norm, least-squares solution of the entire.

We demonstrate this inversion methodology with synthetic seismic data computed for several illustrative earth models, including isolated point diffractors embedded within a smooth background. Point diffractor models allow us to assess the spatial resolving power of the approach, as well as the algorithm's ability to distinguish perturbations in different material properties. For a reflection geometry with sufficient recording aperture, we can recover point perturbations to ρ, λ, or μ with as few as 10 sources recorded into 11 receivers.

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S32C-0643 1330h POSTER

The Computation of Seismograms in 3D Heterogeneous Media Using Maslov Theory

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The most efficient methods for modeling seismic waves in heterogeneous media are asymptotic. However, the simplest of these methods (asymptotic ray theory or ART) breaks down near caustics. Caustics are abundant in heterogeneous media. It is therefore necessary to replace ART by a method that is more generally valid. Such methods typically consist of one or two-dimensional integrals over initial slowness or takeoff angles. One such method is Maslov asymptotic ray theory (MART). We present a two-dimensional integration method based on Maslov theory. We show how a Maslov amplitude for the integrand can be derived using the method of stationary phase. Then, away from caustics where ART is valid, MART agrees asymptotically with ART. The amplitude function has the desirable property that it is zero at pseudo-caustics so artifacts are of lower order. The terms needed for the Maslov integrand can all be obtained by standard kinematic and dynamic ray tracing. In order to minimize the number of rays shot, triangular ray tubes are formed using the Delaunay algorithm, and an error criterion imposed in each tube. Rays are added until the paraxial approximation is accurate for interpolation in all tubes. Thus the integration domain is irregularly sampled and the integration reduces to an integral over irregular triangles. The resultant algorithm is both efficient and accurate. The method is applied to a number of heterogeneous models (both 1D and 3D). It is shown that care must be taken in choosing the integration domain large enough so that all the relevant rays are taken into account.

S32C-0644 1330h POSTER

Seismic Wavefield Extrapolation by Finite–Differencing a One–way Propagator for Anisotropic Elastic Media.

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The narrow–angle approximation to the elastic–anisotropic one–way wave equation derived by Thomson (1999, GJI, v.137, p.364) lends itself to solution by finite–differences. Several alternative formulations of the finite–difference calculation have been examined (i.e. using the "original" partial differential equation, transformation of the PDE into a system of two coupled first–order PDEs and transformation into the frequency domain). Finding the optimum finite–difference approach is made complicated by the high dimensionality (3D in space and 1D in time) of the PDE, the presence of mixed derivatives and the existence of variable coefficients. In part because of these complications, the frequency–domain approach has received most of the development.

We have devised two practical extensions to the theory. The first involves modification of the "complete" propagator into "separated" wave propagators. This separation allows for the isolation of wavefield modes (i.e. ability to track quasi–compressional or quasi–shear waves individually). The second allows reference phase removal, which improves numerical stability with increased step lengths.

Preliminary numerical examples have been obtained for (i) the folding (i.e. triplication) of an initially concave wavefront in an isotropic medium and (ii) for quasi–shear waves travelling within a range of directions surrounding a conical point (i.e. around an acoustic axis). The latter shows the characteristic effects of eigen–polarization rotation. Initial computations have used an equi–spaced Cartesian coordinate grid within a homogeneous model. We have also examined a variable–grid scheme for the lateral/transverse coordinates, in order to improve accuracy of the necessary one–sided finite–differences at the boundaries of the domain.

Cartesian coordinates become too limiting for inhomogeneous media, where steeply–dipping and turning waves are possible. For such cases an extension to curvilinear coordinates has been applied. These coordinates are defined by rays and wavefronts tracked in a possibly–anisotropic reference medium close to the physical medium. Numerical examples using these curvilinear coordinates are in progress, for instance turning waves with a triplication, turning waves with a shadow zone and possibly fractured reservoir and salt structure anisotropy.

S32C-0645 1330h POSTER

PML Absorbing Boundary Method: an Application to 3D 4th-order Velocity-Stress Finite-Difference Schemes

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Robust absorbing boundary conditions are central to the utility and advancement of 3D numerical wave propagation methods. In general, it is preferred that an absorbing boundary method be capable of broadband absorption, is easily tuned and is efficient in terms of memory and computational time. Here, we present results on the application of such a method, PML (perfectly matched layers; Collino and Tsogka, 2001), to a 3D velocity-stress finite-difference scheme. Our elastic scheme incorporates a free surface (Gottschämmer and Olsen, 2000) in the internal propagation space as well as in the PML regions. The internal propagation space, which utilizes 4th-order difference operators, is combined with 2nd-order operators in the PML regions. The PML model is formed, for a particular plane region, by partitioning the velocity-stress system based on perpendicular and parallel spatial derivative separation, with a damping term being added to the perpendicular component. For the edges and corners, damping terms are added in all directions for which there are bounding planes. This particular construction theoretically results in a reflection-free interface between the internal propagation space and the PML absorbing regions.

Numerical results for a homogeneous structure, realistic source mechanisms and different thickness PML zones are excellent. In general, seismograms produced in conjunction with PML absorbing regions result in no observable reflections compared to the amplitude of the primary phases. Typical amplitude reduction factors (with respect to the maximum trace amplitude) in the presence of Rayleigh waves, are 1/100, 1/250 and 1/500 for PML thicknesses of 5, 10 and 20, respectively. Reduction factors are even greater for body waves only. The PML results are also compared with those of a basic Cerjan et al. (1985) absorbing boundary region of thickness 20, with the PML region of thickness 5 still outperforming the Cerjan et al. method by a factor of 2. Although the PML method requires additional memory for storage of the perpendicular and parallel wavefield variables in the absorbing regions, its computing efficiency and storage requirements, compared to Cerjan et al., are actually reduced due to the need for only narrow absorbing regions. For example, for our particular model space, a thickness 5 PML scheme required about 80% the memory and 40% the computation time as compared to a thickness 20 Cerjan et al. scheme.

S32C-0646 1330h POSTER

Frequency Domain Seismic Forward Modelling: Staggered Stencils or Star Stencils?

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Modelling seismic wave propagation is essential to quantify site effects and local seismic risk. Numerical results from finite difference (FD) methods are particularly useful as they provide the complete wavefield response.

Frequency domain forward modelling is of special interest for multisource seismic experiments because of their computational efficiency (Pratt, 1990).

The system of second-order hyperbolic partial differential equations is discretized using standard finite difference second-order approximations of derivatives (5-point stencil) on a Cartesian grid. Reduced numerical dispersion is obtained by combining derivative discretizations along the Cartesian axis and along the diagonal bisection, which then gives a 9-point star stencil. This stencil incorporates all eight surrounding points of the center point. In other words, additional averaging coefficients of the FD system are introduced into the equation in order to force the coupling of nearby nodes. Therefore, these coefficients control the numerical dispersion of the FD scheme. Numerical accuracy is guaranteed by an optimization technique that determines the averaging coefficients such that the velocity dispersion is minimized.

We analyze the strict staggered stencil strategy rather than the ad-hoc star stencil strategy. We consider a frequency-space velocity-stress finite difference scheme (1st order hyperbolic system) where derivatives are discretized using the second-order centered difference stencil (-0.5,0,0.5) on a non-staggered grid. Impulsive punctual source excitation automatically leads to two uncoupled staggered grids: one is associated with the source node, the other one is left unexcited. This was the reason to cancel out the second grid in order to save memory requirements and lead to the staggered grid geometry.

In case of fourth-order FD derivative approximations, the standard centered FD-stencil (1/12,-2/3,0,2/3,-1/12) does not automatically lead to uncoupled staggered grids. The fourth-order extension, namely the 1/12 coefficient, weakly couples the two existing staggered grids, creating unexpected numerical dispersion. Only centered stencils, such as the fourth-order staggered grid stencil (-1/24,0,9/8,0,-9/8,0,1/24), here described on the full non-staggered grid, correctly excites the ad-hoc staggered grid, leaving the second grid untouched.

Therefore, we have compared this 9-point staggered stencil and the 9-point star stencil. Numerical dispersion will be investigated for both the wavelength content and azimuthal variation. We illustrate these results on an example of frequency-domain seismic wave propagation in 2D media.

Pratt, R. G. (1990). Frequency-domain elastic wave modelin by finite-differences: A tool for crosshole seismic imaging. Geophysics, 55(5):626-632.

S32C-0647 1330h POSTER

Scattering of P and S Waves by a Spherical Obstacle using the Canonical Solution

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An analysis of the scattering of longitudinal and transverse elastic waves by a single spherical obstacle using the analytic solution is presented. Our aim is to provide a comprehensive review of this canonical problem and of the resonant scattering theory proposed by Gaunard and Uberall in early eightys. This theory describes the scattering and diffraction of elastic waves by a fluid filled spherical cavity within an elastic solid in terms of a set of summed scattered waves. These partial solutions, when analyzed one at a time, are seen to consist of two interfering contributions. One is a smooth background corresponding to scattering from an empty cavity, and the other is a superimposed set of resonant spectral spikes (lines with narrow width) of the filler fluid. In this work we discuss how these modal resonances and their band widths, which have been only calculated for incident P waves and very specific locations, can be studied also for incident S waves and arbitrary observation points. In fact, we propose that the usefulness of this theory to establish an identification pattern for the fluid filler is not restricted only to the P waves.

The calculations presented here are carried out analytically, within the framework of elastic theory without any additional approximation. A catalog of the appropriate analytical expressions is provided in terms of both the spherical Bessels and Legendres functions. We believe our expressions are free of typographical errors (that have plagued the literature of the field). We study the cases in which the sphere is either (1) a cavity, (2) an elastic inclusion or (3) a fluid inclusion. Spectral amplitudes versus normalized frequency and synthetic seismograms for the three components of movement are depicted. 2D and 3D scattering patterns and real time snapshots are given to analyze the main propagation features.

S32C-0648 1330h POSTER

A Wavelet-Based Method for Simulation of Seismic Wave Propagation

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Seismic wave propagation (e.g., both P-SV and SH in 2-D) can be modeled using wavelets. The governing elastic wave equations are transformed to a first-order differential equation system in time with a displacement-velocity formulation. Spatial derivatives are represented with a wavelet expansion using a semigroup approach. The evolution equations in time are derived from a Taylor expansion in terms of wavelet operators. The wavelet representation allows high accuracy for the spatial derivatives. Absorbing boundary conditions are implemented by including attenuation terms in the formulation of the equations. The traction-free condition at a free surface can be introduced with an equivalent force system. Irregular boundaries can be handled through a remapping of the coordinate system. The method is based on a displacement-velocity scheme which reduces memory requirements by about 30% compared to the use of velocity-stress. The new approach gives excellent agreement with analytic results for simple models including the Rayleigh waves at a free surface. A major strength of the wavelet approach is that the formulation can be employed for highly heterogeneous media and so can be used for complex situations.

S32C-0649 1330h POSTER

Fast Phase Space Computation of Multiple Arrivals

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We present a fast, general technique for computing multiple-arrival traveltimes in seismological problems.Using the Liouville formulation of the characteristic equations as a starting point, we derive a set of "Escape Equations" which are static, time-independent Eulerian partial differential equations with prescribed boundary conditions which represent all arrivals to the surface from all possible sources in the subsurface. The solution may be parameterized as a family of hypersurfaces; which we numerically produce through a one-pass formulation, building on ideas from semi-Lagrangian methods and Fast Marching methods. Unlike a ray-tracing approach, which starts with a given set of sources and recomputes the entire solution each time these sources are changed, in this formulation the same result is achieved in postprocessing once the essential solution has been obtained. We demonstrate the algorithm by showing multiple arrivals in a variety of velocity fields, corresponding to complex geological situations. In addition, we show how the same techniques can be used to compute the wave amplitudes and extract the most energetic arrival.

S32C-0650 1330h POSTER

Scattering of elastic waves by an arbitrary shaped 3-D planar crack using the Indirect Boundary Element Method

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The scattering of elastic waves by various types of cracks is an important engineering problem. From a physical point of view the question that arises is up to what degree will a local perturbation in a medium modifies the scattered wave field. For instance, in the seismic monitoring to enhance oil recovery (due to extensive presence of cracks and cavities) a crucial problem is to determine zones where there are physical property changes. Modelling such highly heterogeneous media is critical to increased production from oil and gas. In order to study scattering effects caused by arbitrary-shaped cracks a simplified indirect boundary element method (BEM) is used to compute the seismic response of a 3-D crack under incident elastic *P* and *S* waves. The method is based on the integral representation for scattered elastic waves using single layer boundary sources. This approach is called indirect BEM in the literature as the sources strengths should be obtained as an intermediate step. Scattered waves are constructed at the boundaries from which they radiate. Therefore, this method can be regarded as a numerical realization of Huygens' principle. Boundary conditions lead to a system of integral for boundary sources. A simplified discretization scheme is used. It is based on the approximate rectification of the surfaces involved using circles for the numerical and analytical integration of the exact Green's function for the unbounded elastic space. Radiation patterns for penny-shaped and croissant-shaped cracks are explored. The scattering effects of the elastic waves in a homogeneous isotropic infinite elastic medium with a 3-D crack are displayed in both frequency and time domains.

S32C-0651 1330h POSTER

Modeling and Processing of Continuous 3D Elastic Wavefield Data

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Continuous seismic wavefields are excited by earthquake clustering, induced seismicity in reservoirs, and mining. In hydrocarbon reservoirs, for example, pore pressure changes and fluid flow (mass transfer) will cause incremental deviatoric stresses sufficient to trigger and sustain seismic activity. Here we address three aspects of seismic wavefields in three-dimensional heterogeneous media triggered by distributed sources in space and time: forward modeling, multichannel data processing, and source location imaging. A power law distribution of seismic sources (such as the Gutenberg-Richter law) is used for the modeling of viscoelastic/elastic wave propagation through a realistic earth model. 3D modeling provides new insight in the interaction of multi-source wavefields and the role of scale-dependend elastic model parameters on transmitted and reflected/back-scattered wavefields. There exists a strong correlation between the spatial properties of the compressional, shear wave and density perturbations and the lateral correlation length of the resulting reflected or transmitted seismic wavefields. Modeling is based on the implementation of 3D elastic/viscoelastic FD codes on massive parallel and/or distributed computing resources using MPI (message passing interface). For parallelization, large grid 3D earth models are decomposed into subvolume processing elements whereby each processing element is updating the wavefield within its portion of the grid. Processing of continuous seismic wavefields excited by multiple distributed sources is based on a combination of crosscorrelated or slowness-transformed array data and Kirchhoff or reverse time migration for source location or source volume imaging. The appearance of slowness in both migration and array data processing suggests the possibility of combining them into a single process. In order to place further constraints on the migration, the directivity properties of 3-component receiver arrays can be included in the processing sequence. Continuous seismic array data from both borehole and surface seismic acquisition geometries are suitable for the proposed detection and mapping sequence for acoustic emission data in space and time.

S32C-0652 1330h POSTER

Efficient 3D Hybrid Ray-FD Modeling for Elastic Media with Locally Complex Structures

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A new hybrid ray-FD method combines the ray and the 2nd order finite-difference (FD) approaches. It was designed for computations in large (compared to the wavelength) 3D elastic models containing a complex local (inner) structure embedded in a considerably simpler medium (outer structure).

The hybrid method is based on two successive steps. In the first step, the wavefield propagating in the outer structure is calculated by the ray method. It is incident at the points along a two-fold formal boundary (excitation box, EB) surrounding the inner structure. This provides the input for the second step consisting in calculating the wavefield by the FD method. The FD computational domain contains the EB and its close vicinity. The EB remains fully permeable for all waves propagating within the FD domain.

Asymptotic high frequency solution makes the approach very efficient despite of the two-point ray tracing that is required to connect the source point with the excitation gridpoints. 3D rays are necessary due to arbitrary source-EB configuration, even in case the outer structure is less dimensional (2D, 1D, homogeneous). However, it is still much faster than the whole FD modeling (retaining the advantages of the FD solution) provided the outer structure does not contain too many layers. Then this approach benefits from the efficiency of the ray method in the outer structure while exploiting the wavefield completeness of the FD method.

The hybrid method is applied for models in which the locally complex structure is adjacent to the earth surface and includes topography. The wavefield is due to a double-couple source buried in the outer structure. The outer structure is 1D or 2D containing vertical as well as lateral gradients of medium parameters. The former case allows the results to be compared with DWN-FD hybrid approach replacing the ray method in the first step by discrete wavenumber (DWN) method.

S32C-0653 1330h POSTER

Rapid Generation of Synthetic Seismograms by Reduced Path Integration

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Recently, a path integral solution, or sum over all paths, for acoustic wave propagation has been developed. However, the difficulty with the application of the acoustic path integral is that the contribution of each path is highly oscillatory. In principle, constructive and destructive interference between nearby paths will smooth out the end result, but such interference is nearly impossible to achieve numerically. With a reasonable approximation, we can account for the contribution of all but the smoothest paths, greatly reducing the dimensionality of the path integral and smoothing the contribution of each path to yield a formula of considerable utility. Several comparisons between the reduced path integral method and slower, established numerical methods for nontrivial 3D media will be made.

S32C-0654 1330h POSTER

Time-Domain Sensitivities for Elastic Wavefield Data

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Exact mathematical expressions for the sensitivity of elastic wavefield data, with respect to small perturbations in mass density and Lame parameters, are derived by applying the reciprocity principle to solutions of the velocity-stress differential equations of isotropic elastodynamics. The formulae are valid for various types of sources (forces, moments, surface tractions) and receivers (displacement, velocity, acceleration, strain, rotation, pressure) used in seismic exploration, and apply to arbitrary data acquisition configurations in three spatial dimensions. Sensitivities with respect to variations in other elastic model parameters of seismological interest (wavespeeds, impedances, moduli) are readily obtained via linear combinations of the sensitivities due to perturbations in ρ, λ, and μ.

Bandlimited sensitivity coefficients are numerically calculated with a time-domain finite-difference algorithm that solves the velocity-stress system on staggered spatial and temporal grids. For a given source-receiver pair located within an elastic earth model, two wavefields are generated; one is activated at the source position and the other is activated at the receiver position. At a specific gridpoint in the model, convolving the velocity vector components of the two wavefields gives a time-varying sensitivity function for perturbations in mass density. Convolution of the stress tensor components yields analogous sensitivities with respect to Lame parameter variations.

Sensitivity coefficients are depicted and interpreted for a simple situation consisting of a single source-receiver pair situated within a homogeneous and isotropic elastic wholespace. Timeslice plots of λ sensitivity indicate that significant amplitudes are concentrated around the ellipsoidal locus of fixed-time P-to-P scattering from source to receiver. Plots of ρ and μ sensitivity are much more complex, containing multiple branches corresponding to P-P, P-S, S-P, and S-S scattering. Parameter sensitivities are used for solving the full waveform elastic inverse problem, and may provide useful information for design of seismic data acquisition experiments.

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S32C-0655 1330h POSTER

Array analysis of seismic signals considering an array beampattern

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Seismic array data have been widely used in researches such as the discrimination of nuclear explosions, the analysis of seismic scattering, measurements of surface wave dispersion, and monitoring of the seismic activity in volcanic areas. In this study, we present a simple and high-resolution array processing method whose estimators are not pseudo but true ones. We apply the method to estimations of high-frequency rupture processes by converting temporal variations in slowness vectors and their associated amplitude into power distributions and rupture times on the fault plane.

It has been shown that the minimum variance distortionless (HR) method and the multiple signal classification (MUSIC) method produce higher resolution for the location of the identified waves than the standard Fourier method (CV method). However, the estimators by the HR and MUSIC methods are pseudo ones.

In order to obtain true spectral estimators with high resolutions, we propose a frequency-wavenumber method considering an array beampatterm. The observed power spectrum obtained by the CV method is a convolution of the array beampattern with the true power spectrum. Since the array beampattern reduces the resolution of the spectral estimators, we deconvolve the observed power spectrum with the array beampattern in the wavenumber domain. The solution to this problem is determined using non-negative least squares because the power has a positive quantity.

To illustrate the utility of the present method in resolving two closely separated signals, numerical tests are performed with synthetic waves. The present method successfully resolved two separate peaks at almost the correct slowness vectors. The resolution was superior to CV and HR methods and similar to MUSIC method. We then investigate the applicability of the present array processing method to estimations of high-frequency rupture processes. Using synthetic S body-wave seismograms from extended earthquake sources, we show that it is possible to image high-frequency source locations and their associated rupture times with high resolutions.

S32C-0656 1330h POSTER

Estimation of the Wavelet Correlation Dimension of Surfaces in Acoustic Back-Scattering Experiments

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We show how to extract from the backscattering data in the 1 dimensional wave equation the wavelet correlation dimension of the scatterer. The wavelet correlation dimension is a generalization of the standard fractal correlation dimension defined for probability measures. This technique is applied to the estimation of the rugosity of a natural granite surface in an acoustic small scale experiment. We present a wavelet based procedure for deconvolution from the measurement device. A stacking method based on the small amlitude approximation allows the estimation of the orientation of the local incidence plane.

S32C-0657 1330h POSTER

Robust Waveform Inversion with Adaptive Regularization

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Derivation of detailed maps of elastic properties in the seismic frequency band and beyond is a highly challenging task. Global optimization methods have been highly successful in that they are not dependant on the choice of starting solution, they explore the model space extensively and reflections from all angles including post-critical arrivals can be included without difficulty. However for large models, they are computationally intensive and they are more prone to non-uniqueness. Regularization in global optimization is trivial, in theory but difficult in practice since it slows down the algorithm. We have developed local optimization methods with adaptive regularization that can be used efficiently in conjunction with global optimization for analysis of large volume of seismic data. In particular, our conjugate gradient-adaptive regularization scheme has been implemented on three processes that are vital to seismic data analysis, namely, wavelet estimation, impedance inversion from post-stack data and pre-stack inversion for estimation of Vp, Vs and density. Use of a new method of computing differential seismograms combined with sparse gradient matrix makes our algorithm computationally very efficient. We have applied these techniques successfully in the analysis of field data from the Gulf of Thailand and the Oregon coast.

URL: http://www.ig.utexas.edu

S32C-0658 1330h POSTER

Imaging of Crustal Layers by Teleseismic Ghosts

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We propose imaging of crustal reflector distributions by migrating ghost reflections extant in teleseismic records. Ghost reflections emanate from direct waves that reflect off the free-surface, and propagate downward to reflect from crustal layer interfaces. These ghost reflections can be imaged by the new method of cross-correlogram migration. The recording requirements for this passive seismic method are similar to those for exploration seismology: an unaliased recording array which might be attainable with the proposed US Array. Unlike controlled source seismology, the recorded traces are crosscorrelated with one another and the correlated traces are migrated using a special imaging condition (Schuster, 2001, EAGE Amsterdam annual meeting). The benefit is that the source location or the wavelet time history do not need to be known; the drawback is that correlation produces spurious events that can give rise to false reflector images. With special processing and records from different teleseisms, these spurious events can sometimes be suppressed. It can also be shown that crosscorrelogram migration with special imaging conditions is a generalization of receiver-function imaging of PS converted waves. We will show examples of imaging crustal reflectors by migrating ghost reflections in synthetic teleseismic data for a Utah crustal model.

S32C-0659 1330h POSTER

Velocity Structure Determination Through Seismic Waveform Modeling and Time Deviations

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Through the use of seismic waveforms recorded by TriNet, a dataset of earthquake focal mechanisms and deviations (time shifts) relative to a standard model facilitates the investigation of the crust and uppermost mantle of southern California. The CAP method of focal mechanism determination, in use by TriNet on a routine basis, provides time shifts for surface waves and Pnl arrivals independently relative to the reference model. These shifts serve as initial data for calibration of local and regional seismic paths. Time shifts from the CAP method are derived by splitting the Pnl section of the waveform, the first arriving Pn to just before the arrival of the S wave, from the much slower surface waves then cross-correlating the data with synthetic waveforms computed from a standard model. Surface waves interact with the entire crust, but the upper crust causes the greatest effect. Whereas, Pnl arrivals sample the deeper crust, upper mantle, and source region. This natural division separates the upper from lower crust for regional calibration and structural modeling and allows 3-D velocity maps to be created using the resulting time shifts.

Further examination of Pnl and other arrivals which interact with the Moho illuminate the complex nature of this boundary. Initial attempts at using the first 10 seconds of the Pnl section to determine upper most mantle structure have proven insightful. Two large earthquakes north of southern California in Nevada and Mammoth Lakes, CA allow the creation of record sections from 200 to 600 km. As the paths swing from east to west across southern California, simple 1-D models turn into complex structure, dramatically changing the waveform character. Using finite difference models to explain the structure, we determine that a low velocity zone is present at the base of the crust and extends to 100 km in depth. Velocity variations of 5 percent of the mantle in combination with steeply sloping edges produces complex waveform variations. Characteristics of this complex propagation appear from the southern Sierra Nevada Mountains, in the west, to Death Valley in the east. The structure does not cross the Garlock fault to the south, but we are unsure of the structures northern extent.

S32C-0660 1330h POSTER

Fractional Brownian Motion in Seismic Noise

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Here, we present a preliminary study of the statistical features of the seismic noise in the frequency range from 1 Hz to 40 Hz. In detail, we have investigated the 3-d average squared soil displacement r^2 and the distribution function of the displacement fluctuations in different geological sites. The anomalous scaling of the squared displacement $r^2 \simeq t^\alpha$ with $1.5 \leq \alpha \leq 2$, and the Gaussian shape of the fluctuation distribution function suggest that seismic noise, when studied in the limit of ground shaking, is consistent with a persistent fractional browian motion (FBM) characterized by a Hurst exponent $H > \frac{1}{2}$. A brief discussion of our results in connection with seismic radiation transport in heterogeneous geological media is also given.

S32D MC: 306 Wednesday 1330h

Strong Ground Motion Prediction for Scenario Earthquakes II *(joint with PA)*

Presiding: **R Graves,** URS Corporation**; D Wald,** U.S. Geological Survey

S32D-01 1330h INVITED

Practical Applications for Earthquake Scenarios Using ShakeMap

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In planning and coordinating emergency response, utilities, local government, and other organizations are best served by conducting training exercises based on realistic earthquake situationses that they are most likely to face. Scenario earthquakes can fill this role; they can be generated for any geologically plausible earthquake or for actual historic earthquakes. ShakeMap Web pages now display selected earthquake scenarios (www.trinet.org/shake/archive/scenario/html) and more events will be added as they are requested and produced. We will discuss the methodology and provide practical examples where these scenarios are used directly for risk reduction.

Given a selected event, we have developed tools to make it relatively easy to generate a ShakeMap earthquake scenario using the following steps: 1) Assume a particular fault or fault segment will (or did) rupture over a certain length, 2) Determine the magnitude of