S41E MCC: Level 1 Thursday 0830h

Three-Dimensional Computational Waveform Modeling and Applications I Posters

Presiding: **T S Anderson,** Cold Regions Research and Engineering Laboratory**; S A KETCHAM,** Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory

S41E-0128 0830h POSTER

Accuracy Investigation of Seismic Reciprocity Using 3D FDM code

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Application of Reciprocity theorem for the problem of marine seismology, which there is numerous shots on the surface and few receivers on the bottom of the ocean, is pivotal. The theory of reciprocity states that we can switch the location and direction of the force source and displacement component between source and receiver without changing in the observation waveform. In this work we performed a numerical simulation. In this simulation we solved wave propagation equations using Finite Difference method, which is 4th order in space and 2nd order in time. To investigate whether the discretizing affects the seismic reciprocity we calculate the 2D velocity components (x, z) respected to two orthogonal force components applied in the x and z directions. Finally reciprocal waveforms are compared. The degree of correlation between the reciprocal components is quite high which shows the excellency of the FDM method, which we employed. The structure for this work is obtained from 2D travel-time inversion estimated in the 1996 survey along North-South line at the Sanriku, Japan Trench. The size of this structure is 143km by 30 km (Fig.1), which discretized by 25 meter gird spacing. The structure is completely heterogeneous which any point has its own value of P-velocity, S-velocity and density. In this structure, two points for investigation of reciprocity are considered (Fig.1). A force source was applied in one point and the velocity measured in another point, further the directions and locations of source and receiver were interchanged to measure its reciprocal one. Figures 2 shows z-velocity component and its reciprocal one and the difference between them when a force source applied in the z-direction. Figures 3 shows x-velocity component and its reciprocal one and the difference between them when a force source applied in the x-direction. The source waveform is considered the Ricker wavelet with central frequency of 5 Hz. To gain faster computational time and further improvements, we used Earth Simulator to run our program. The program parallelized using classical method of parallelization on this supercomputer. The computational time is surprisingly faster than Earthquake Research Institute supercomputer; Origin 2000

S41E-0129 0830h POSTER

Pseudospectral Modeling in Whole Earth Models: Apparent Attenuation and Anisotropy from Small Scale Heterogeneity

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Broadband (0.01 to 1 Hz), 3-component, seismograms are synthesized to 180° range by 2-D pseudospectral methods in several models having statistically described heterogeneity in the mantle. Considered models include gradient increases in RMS heterogeneity power in the lowermost (D'' region) of the mantle, and bimodal models of D'' consisting of either two-phases (partial melt) or two chemically distinct members. A strong gradient in heterogeneity power of a laterally heterogeneous perturbation, superposed on a a laterally homogeneous ultra-low velocity zone, can produce an apparent anisotropy of SH and SV wavefields. Computational experiments also demonstrate that small scale (<100 km) heterogeneity can contribute to a pulse delay and broadening of body waves similar to that of intrinsic attenuation.

URL: http://www.sp.uconn.edu/∼ *cormier*

S41E-0130 0830h POSTER

FDM simulation of receiver function-laterally heterogeneous model including a subducting slab-

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We have so far executed receiver function (RF) analyses of teleseismic waveforms observed at a large number of dense F-net, Hi-net and J-array stations to reveal the seismic velocity discontinuities in the crust and the upper mantle beneath the Japan Islands. In these analyses, assuming the phases in RFs are produced by P to S conversion at depths, we use the 1-D reference model of iasp91 to execute depth-migration of RFs. In southwest Japan, the RF images of Conrad, Moho and the upper boundary of dipping Philippine Sea slab are well consistent with those obtained by recent explosion seismological studies. However, in northeast Japan, the Conrad and Moho depths are deeper beneath the low velocity volcanic regions than in tomographic studies. And the negative RF amplitudes of the Sp phase converted at the top of dipping oceanic crust are clearer down a depth of 70km than in southwest Japan, in addition to the positive RF amplitude converted at the boundary between the bottom of oceanic crust and the Pacific slab down to a depth of 200 km. Moreover, the undulation of 410 and 660 km discontinuities are well delineated related to the subducting Pacific slab. Especially, 410 km discontinuity is not clear locally close to or within the slab, which suggests the complex structure of 410 km within the slab due to undulation or metastable state of olivine-spinel transition in a cold slab. These interesting RF features suggest the importance of the use of 3-D heterogeneous reference velocity and Q structures. Our final goal is full-wave tomography of RF to reveal 3-D velocity and Q structure. As a first step toward this goal, we simulate RFs in several 2-D heterogeneous models employing a finite difference method with a frequency content lower than 1 Hz in 0.5 x 0.5 km grids. Referred to existing tomography P, S and Q models provided by Zho and Koketsu, we investigated 1) the effect of lateral heterogeneous velocity and Q structure in the crust on the RF images of the Conrad and the Moho, 2) the effect of heterogeneous velocity and Q structure in the mantle wedge and the dipping slab on the RF image of the dipping slab interface. 3) the existence of dipping oceanic crust above the slab on the RF images, 4) the effect of the undulation and the metastable state of olivine-spinel transition in a cold slab on RF images of 410 km discontinuities around the slab, 5) the effect of the lateral heterogeneous velocity and Q structure in the mantle wedge and the slab on the RF images of 410 and 660 km discontinuities.

S41E-0131 0830h POSTER

Finite-difference modeling of the P-SV wave equation with mimetic methods

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Finite-difference methods are often used to model elastic waves. Recently, mimetic finite-difference methods have been developed which attempt to match the underlying fundamental identities such as the gradient, divergence, and curl, which ensure physically meaningful results even on non-uniform grids. Computational experience with other equations (such as Maxwell's equations) has shown that these discretizations have excellent properties for both inhomogeneous and anisotropic materials on non-smooth grids. We have developed a fourth order 2D mimetic discretization of the P-SV wave equation and will compare accuracy and speed with standard finite-difference codes as well as with analytic solutions. We are working on a 3D implementation of the code. A primary goal is to test use of the discretization for problems involving near-surface seismic wave propagation in areas with significant surface topography and velocity gradients as encountered in reflection seismic static corrections or (at a larger scale) propagation of regional seismic waves such as Lg.

S41E-0132 0830h POSTER

3-D Voxel FEM Simulation of Seismic Wave Propagation in a Land-Sea Structure with Topography

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We have already developed the voxel FEM (finite element method) code to simulate seismic wave propagation in a land structure with surface topography (Koketsu, Fujiwara and Ikegami, 2003). Although the conventional FEM often requires much larger memory, longer computation time and farther complicated mesh generation than the Finite Difference Method (FDM), this code consumes a similar amount of memory to FDM and spends only 1.4 times longer computation time thanks to the simplicity of voxels (hexahedron elements). The voxel FEM was successfully applied to inland earthquakes, but most earthquakes in a subduction zone occur beneath a sea, so that a simulation in a land-sea structure should be essential for waveform modeling and strong motion prediction there. We now introduce a domain of fluid elements into the model and formulate displacements in the elements using the Lagrange method. Sea-bottom motions are simulated for the simple land-sea models of Okamoto and Takenaka (1999). The simulation results agree well with their reflectivity and FDM seismograms. In order to enhance numerical stability, not only a variable mesh but also an adaptive time step is introduced. We can now choose the optimal time steps everywhere in the model based the Courant condition. This doubly variable formulation may result in inefficient parallel computing. The wave velocity in a shallow part is lower than that in a deeper part. Therefore, if the model is divided into horizontal slices and they are assigned to CPUs, a shallow slice will consist of only small elements. This can cause unbalanced loads on the CPUs. Accordingly, the model is divided into vertical slices in this study. They also reduce inter-processor communication, because a vertical cross section is usually smaller than a horizontal one. In addition, we will consider higher-order FEM formulation compatible to the fourth-order FDM. We will also present numerical examples to demonstrate the effects of a sea and surface topography on seismic waves and ground motions.

S41E-0133 0830h POSTER

Revised Boundary Perturbation Theory for the Direct Solution Method

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The method for computing perturbed synthetic waveforms due to boundary perturbations is formulated by Woodhouse (1980, GJRAS). However, because it is based on the perturbation theory of free oscillations, it is not obvious whether the formulation works when the frequency is not in the vicinity of the reference frequency. It also is not obvious whether the discretization error is small especially when we use basis functions other than the eigenmodes. Because the Direct Solution Method (DSM; e.g., Takeuchi et al. 2000, PEPI) is an efficient computational method based on the optimally accurate discretization method (Geller & Takeuchi 1995, GJI), if we appropriately re-formulate the previous boundary perturbation theory, we can expect further improvement of the efficiency and accuracy for the forward and inverse approach for 3-D heterogeneous Earth structure. In this study, we express the equation of motion for the perturbed boundary in terms of the solution of the compulsory oscillation with the appropriate boundary conditions (Geller & Hatori 1995, GJI). Using the similar approach to Woodhouse (1980, GJI), we can derive the matrix elements which are guaranteed to be valid for arbitrary frequencies. Because the basis functions used in DSM are converged

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to the above basis functions, the obtained results can be applied without any modifications. Error analysis of Geller & Takeuchi (1995, GJI) shows that the obtained formulation allows the optimally accuracy. We also confirm this fact by numerical experiments.

S41E-0134 0830h POSTER

Coupled Modeling of Time-Lapse Change in Seismic Propagation and Permeability in Fractured Reservoirs Due to Fluid Injection

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For porous rock, the elasto-dynamic and fluid flow properties can be strongly dependent on effective static stress. Independent models (and computer codes) are typically used to study elasto-mechanical and hydro-mechanical changes in the subsurface due to changes in subsurface properties. We have coupled finite-difference elastic seismic and finite-element hydro-mechanical modelling codes and proposed constitutive relationships between effective stress and fracture properties (both mechanical stiffness and fracture permeability) thereby allowing us to model temporal and spatial variations in pore pressure, permeability and elastic (anisotropic) constants for fluid injection in a fractured reservoir. We assume that change in rock properties is due to pore pressure changing the effective stress which then affects the behavior of aligned microcracks and fractures much more than the behavior of the rock matrix background (which for this study is assumed essentially insensitive to changes in pore pressure). This implies that only the parts of the elastic compliance tensor and permeability tensor associated with the aligned fractures depend on changing stress. We then propose a constitutive relationship between fracture stiffness and effective stress and between fracture permeability and effective stress. These relationships are used to give the temporal and spatial changes (seismic and hydrologic) for a specific modeling problem. The 3D example presented is a vertically fractured layer within an otherwise homogeneous, impermeable medium. The fractures are assumed closely spaced (relative to a seismic wavelength) and parallel. Using the 2D hydro-mechanical code (Rocmass), we model the injection of fluid into the permeable, fractured layer. The spatial variation in pore pressure, permeability and elastic stiffness are calculated at different time steps. As the subsurface pore pressure changes due to injection, permeability changes and thus effects the spatial pore pressure distribution. Symmetry properties are used to map the results to 3D. The 3D variations in elastic stiffness (for a given time step) are used as input to a 3D, anisotropic, elastic, finite-difference seismic modeling code (Anisg3Dmpi) to calculate the seismic response. Different seismic acquisition geometries are investigated, including 3D surface seismic, VSP and horizontal well cross-well. For our initial fluid injection parameters, the VSP and cross-well geometries show measurable effects due to the fluid injection.

S41E-0135 0830h POSTER

Structure of the African Superplume from Approximate and Numerical 3D Waveform Modeling

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We present a new method of generating analytical synthetics for tomographic-style models. These models are perturbations to a 1D layered model involving changes in block velocities producing 3D images. The procedure is broken into four steps: (1) construction of ray paths for the reference 1D model, (2) generation of perturbed paths, (3) construction of 2D synthetics in the plane containing the source and receiver, and (4) addition of out-of-place contributions from virtual receivers weighted by diffraction operators. In step one, the ray paths reflecting from the various interfaces (i) are established with ray parameter (p_i) and travel time (t_i). Next, these values are corrected after adding the velocity perturbations where ray segments in faster blocks grow relative to slower blocks. This new set of ray parameters can be used to generate 2D WKM synthetics or Cagniard-deHoop synthetics. Contributions from virtual receivers at neighboring azimuths are added by convolving with diffraction operators which are defined by the source duration and travel time to the 3D structure. We suggest a particularly simple approximation based on 4 virtual receivers which produces synthetics in agreement with 3D Spectral Element Method (SEM) synthetics . We applied both methods to study 3D structure of the African Superplume, which is modeled as a large scale ridge-like velocity anomaly beneath Africa. The structure starts from the southern Indian Ocean and extends northwestern to the Atlantic ocean, covering a space of 7000 km long, 1000 km across and extending 1200 km upward from the core mantle boundary (CMB). The structure seems to have sharp boundaries with shear velocity inside 3% lower than the ambient mantle while P velocity is quite normal. The 3D structure can be best illustrated by seismic waveforms recorded by South Africa array from earthquakes ocurring in western Pacific Ocean. Great circle paths for the Sdiff phase from these events travel along the axis of this structure for over 60 degrees with the northern and southernmost paths missing the structure. The Sdiff waveforms are simple but delayed up to 20 seconds for paths sampling the middle of the structure. Sdiff waveforms display two arrivals for paths along both boundaries. This complexity of waveforms can be explained by 3D multi-pathing due to the rapid lateral variation of shear wave velocity. Modeling of SS travel times for some events requires that the structure must be high (>1200 km), combined with previous analysis of S, SKS and ScS waveforms around 85-95 degree, we exclude any thin model of 300 km or less with very slow basal layer (up to 10% lower S velocity) at the bottom of the superplume. This large scale anomalous structure with sharp boundaries can be interpreted as a thermal-chemical plume.

S41E-0136 0830h POSTER

Computational Modeling of Seismic Wave Scattering by High-Porosity Geologic Inclusions in the Central Basin Platform of the Permian Basin

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Significant untapped domestic petroleum resources exist within oil-saturated high-porosity zones of the Central Basin Platform (CBP) geologic province of the Permian Basin in Texas and New Mexico. However, high-porosity inclusions are relatively small and deeply-buried, rendering detection and characterization via conventional surface seismic reflection methods difficult. A quantitative measure of "detectability" of an isolated porosity anomaly embedded within a typical CBP geologic section is obtained by numerical modeling of the 3D seismic wavefield scattered by the inclusion. The energy of scattered arrivals observed on a surface recording spread is determined, and is subsequently normalized by the energy of a prominent primary reflection event from the background 1D CBP section. Synthetic seismic data are calculated with an explicit, time-domain, O(2,4) finite-difference algorithm that solves the velocity-stress partial differential equations of isotropic elastodynamics. All arrivals (reflections, refractions, primaries, multiples, diffractions, surface waves) are generated with fidelity, provided spatial and temporal grid intervals are chosen appropriately. In order to accommodate the large size earth model (>27 million gridpoints), long trace durations (>8000 timesteps), and broadband wave propagation (to 100 Hz) in reasonable execution times, a parallel domain-decomposition algorithm is used. Incorporation of anelastic attenuation into the modeling study, via the memory-variables approach, is currently underway. Scattered energy from a sub-wavelength-size porosity inclusion consists of extremely low-amplitude P and S events observed on both horizontal and vertical motion components. These arrivals are effectively masked by larger amplitude (x100) reflections from interfaces of the CBP geologic model, and must be isolated by a subtraction technique. Repetitive parametric modeling allows the range of inclusion characteristics (size, shape, depth, impedance contrast) leading to detectable seismic responses to be inferred. *Sandia National Laboratories is operated by Sandia Corporation, a Lockheed-Martin company, for the USDOE under contract DE-AC04-94AL85000.*

S41E-0137 0830h POSTER

Parallel Simulation of Wave Propagation in Three-Dimensional Poroelastic Media

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Parallelized velocity-stress staggered-grid finite-difference method to simulate wave propagation in 3-D heterogeneous poroelastic media is presented. Biot's poroelasticity theory is used to study the behavior of wavefield in fluid saturated media. In the poroelasticity theory, the fluid velocities and pressure are included as additional field variables to those for the pure elasticity in order to describe the interaction between pore fluid and solid. Discretization of governing equations for finite-difference approximation is performed for total of 13 components of field variables in 3-D Cartesian coordinates: six components for velocity, six components for solid stress, and a component for fluid pressure. The scheme has fourth-order accuracy in space and second-order accuracy in time. Also, to simulate wave propagation in an unbounded medium, the perfectly matched layer (PML) method is used as an absorbing boundary condition. In contrast with the pure elastic problem, the larger number of components to describe the poroelasticity requires a huge sum of core memory inevitably. In the case of modeling in a realistic scale, the computation is hardly to run on serial platforms. Therefore, the computationally efficient scheme to run on a large parallel environment is required. The parallel implementation is achieved by using a spatial decomposition and the portable message passing interface (MPI) for communication between neighboring processors. Direct comparisons are made for serial and parallel computations. The inevitability and efficiency of parallelization for the poroelastic wave modeling are also demonstrated using model examples.

S41E-0138 0830h POSTER

Anisotropic Seismic Response of Crustal Tectonic Features Using 3D Finite Differences

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Tectonic terranes within the crust often possess compositional changes and internal fabrics due to the deformational and metamorphic processes associated with tectonic modification. These material traits (composition, structural geometry, internal fabric) may alter seismic wave propagation as evidenced by anisotropic particle motions, travel time delays, and phase splitting. In addition, internal deformational fabrics may be oriented oblique to geological layer boundaries. All of these effects may produce anisotropic wave propagation. Observations of seismic anisotropy produced from within the crystalline crust are becoming increasingly common. Studies of crustal anisotropy are more complex because of the presence of pronounced geological heterogeneity and changing raypath orientations due to source-receiver configurations and strong seismic velocity gradients. Christoffel velocity equations for anisotropic media indicate large variation in P- and S-velocities can occur as functions of off-axis propagation angle. As a result, calculations of anisotropic effects are not simple in areas of complex crystalline crust and in some cases may only be solved numerically. Because we calculate multi-component seismograms within crustal anisotropic media using finite difference methods, we allow for full 3D variability in severity and orientation (tilt) of anisotropic material properties as expressed in composition, large-scale features, and internal textural fabrics. The full elastic stiffness tensor is used in the finite difference formulation; as a result, tilted hexagonal, orthorhombic, and lower order symmetries are possible. We present modeling theory plus 3-component synthetic seismograms from wave propagation within selected geometrical models of crustal features. We address two primary issues: (1) is the anisotropy observable within the seismograms, and (2) in sufficiently dense "arrays" are there systematics in the P- and/or S-wave phases which can be used to characterize the crustal feature. The selected features are calibrated using petrophysically measured velocities and densities. In particular, the one or three diagonal VP measurements (for hexagonal and orthorhombic symmetries) affect traveltime and shear wave splitting, as we confirm with modeling examples. We also discuss relationships between detectable anisotropy effects and internal configurations of the crustal features.