depths collected during the dense industry seismic program cover approximately 70 percent of the Great Salt Lake and allow a unique opportunity to construct a detailed bathymetric map of part of the Great Salt Lake. Geostatistical analysis of the water depth reveals the expected relatively smooth overall bathymetric surface of the floor of the Great Salt Lake, but also shows that it is disrupted by several abrupt changes in the bathymetry. A plot of the gradient magnitude, or rate of change of the bathymetry, indicates several linear features with steep surfaces much like fault scarps that trend along the regional fault fabric. Areas of highest gradient magnitude may indicate areas of most recent offset and may delineate the aerial extent of more recent fault activity. These anomalous surface gradients correlate well with seismically defined normal faults that run along the western margin of Promontory Point and Antelope Island, as well as along the northern side of Carrington Island, suggesting that major intra-basin and basin-bounding normal faults do breach the surface over much of their lengths. Development of laterally continuous fault scarps in a flat, internally drained basin indicates very recent fault activity beneath the Great Salt Lake.

URL: http://www.geo.arizona.edu/∼/ahennes/Research.htm

S11D-0333 0830h POSTER

Geophysical Studies of Seismic Hazard in the Tahoe City Sub-basin, Lake Tahoe, California

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The Lake Tahoe basin has the potential for serious earthquakes and earthquake-related tsunamis. The history of lake level fluctuations should be recorded in sediments beneath the Lake's outlet at Tahoe City. Borehole data show the sediments consist primarily of a thick sequence of lacustrine silts and clays with interbedded sands. Beneath this unit is an older Q-T (?) sand and gravel sequence of unknown origin. The lacustrine deposits locally rest upon 2.0 Ma latites, which in turn rest upon the older sand and gravel sequence. Near the outlet, several fault scarps displace units less than 2.0 m.y. old. These scarps may influence the stability of the dam across the outlet and the sequence and extent of lake level high stands. Our project is integrating geophysical and stratigraphic data to further define and describe the Tahoe City sub-basin. We collected new gravity data to provide an estimate of basin depths across the outlet and help define subsurface faults. Preliminary data suggest the maximum basin depth is 180 m, near the outlet. Refraction microtremor surveys yielded information about stratigraphy and shear velocities of the Quaternary deposits. The average shear wave velocity to 30-m depth obtained for this area is 334 m/s. These values correspond to a NEHRP soil hazard class of D, similar to that found in other lacustrine basins of the region. Soils in this NEHRP class tend to show a significant amplification of shaking, posing increased hazard to structures. We are combining stratigraphic with gravity and seismic data to produce geologic cross sections having information on basin depths and Quaternary faults.

S11E MCC: Level 1 Monday 0830h

Novel Ways of Analyzing the Seismic Coda I Posters

Presiding: **R Snieder,** Center for Wave Phenomena/Colorado School of Mines; **M Campillo,** Universite Joseph Fourier

S11E-0334 0830h POSTER

Passive Seismic Imaging

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Traditionally, passive seismology connotes the use of earthquake signals from continuously recording receivers. Small time windows around the arrivals of earthquakes are then analyzed in myriad fashion. I will distinguish from this body of work, the notion of passive seismic imaging, which requires no knowledge of the time or characteristics of a source event. Instead, by using the ambient noise in the subsurface with all orders of scattering and thus randomized directionality, passive seismic imaging can produce results analogous to conventional controlled source experiments. Mathematical proof of the concept of passive seismic imaging has been presented in the literature from several foundations. The results reduce to the simple concept of cross-correlating many long recordings within a simultaneously deployed array. This generates panels with the kinematics of a shot-gather from a standard reflection seismic acquisition effort. Results from synthetic data sets show the validity of the method for point diffractor, and layered earth models. Noting the similarity of form of the standard approach to produce shot-gathers with the imaging condition of shot-profile migration, I then show that migrating the raw passive seismic data without the correlation step produces the the correct image. The synthetic data from above is used to demonstrate the technique. By comparison, this image is of better quality, and demands less compute time, than migrating the data having been cross-correlated first. Finally, both techniques are used to process a 2x2 meter, 72-channel array recorded on the beach sand of Monterey Bay, California. Approximately one meter below the sand, a six inch diameter plastic pipe was buried to serve as a target.

S11E-0335 0830h POSTER

Wave-equation Imaging of Teleseismic Body-wave Coda

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Historically, characterization of the lithosphere with information in teleseismic body-wave coda has been realized with collections of 1-D receiver functions. However, the promise of larger, fully 3-D teleseismic data sets with finer spatial sampling (e.g. the US-ARRAY project) motivates the investigation of industry-oriented imaging algorithms in the context of crustal/upper mantle studies. In this milieu, we present a multi-dimensional structural imaging method based on wave-equation migration of multi-component teleseismic array data for v(x,y,z) media. Although the advantages of wave-equation methods are well known to explorationists, these methods are rarely used in teleseismic investigation. Possible reasons for their disuse are unconventional source characteristics, and the heretofore limited number, and irregular distribution, of receivers. However, given sufficient receiver density teleseismic body-wave coda may be readily imaged with a wave-equation processing strategy through the use of a modified shot-profile migration algorithm. Shot-profile migration requires separate depth extrapolation of source and receiver wavefields. The source wavefields are modeled using the slowness vector of the incident body-wave that dictates the time-slope of the impulsive line (in 2-D) or plane sources (in 3-D). The receiver wavefield is the scattered energy in the body-wave coda after a deconvolution with the estimated source-signature. The two wavefields are then independently extrapolated through separate velocity models according to the wave-equation, and an imaging condition is applied at each model location to generate the image. The presence of forward- and backscattered arrivals of P,SV and SH polarity within the coda requires various combinations of migration parameters to independently focus different scattering modes. Accordingly, seven different images can be produced through appropriate permutations of velocity models and source wavefield propagation direction. Importantly, the application of this imaging technique to 3-D data sets needs only a 3-D velocity model. We present multi-event, stacked, migrated images of all possible scattering modes for both synthetic and field data sets. The imaging strategy is tested on a 2-D, finite-difference modeled data representing a subduction/suture earth model. The method is then applied to the IRIS-PASSCAL CASC93 data acquired in central Oregon, USA, and generates interpretable images of the Cascadia subduction zone.

URL: http://sepwww.stanford.edu/sep/people/jeff/agu2003SHRAGGE.txt

S11E-0336 0830h POSTER

Breakdown of wave diffusion in 2D due to loops

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There is a growing interest in incorporating the multiply-scattered coda into our understanding of the earth's interior using energy transport theory. Using energy transport, the envelopes of seismograms are modeled and interference effects between individual arrivals in the coda are ignored. Also known as radiative transfer, this picture of the coda leads to the so-called diffusive regime at late times. There are several novel applications at this level, among them obtaining the Vp/Vs ratio from the partitioning of P- and S-energies and the ability to separate scattering and intrinsic Q. However, that individual wave arrivals in the coda may interfere constructively, and the underlying wave character of the multiply-scattered seismic energy emerges. Constructive interference in the coda renders the usually diffusive regime "non-diffusive", most notably in the presence of a coherent backscattering peak at the source position. Here, we test the validity of the diffusion approximation for the average intensity (squared envelope) of multiply-scattered waves with numerical simulations in a strongly scattering 2D medium of finite extent. We show that the diffusion equation underestimates the intensity and attribute this to both the neglect of recurrent scattering paths and interference within diffusion theory. We present a theory to quantify this discrepancy based on counting all possible scattering paths between point scatterers. Interference phenomena, due to loop paths, are incorporated in a way similar to coherent backscattering. This may ultimately help to bridge the conceptual gap between the regimes of "weak" and "strong" localization. In addition, the work suggests a new way in which the microstructure of a discrete random medium can become imprinted in the average transmitted intensity. This could lead to sample size dependencies as have been previously reported for coherent backscattering. [Haney, M. and R. Snieder, R., Breakdown of diffusion in 2D due to loops, Phys. Rev. Lett., 91, doi:10.1103/PhysRevLett.91.093902, 2003.]

S11E-0337 0830h POSTER

Volcano monitoring using continuous data

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Mt. Arenal is a volcano that has been heavily instrumented. In this study we used continuous recordings of air pressure and ground motion to monitor Mt. Arenal. The pressure record shows a sequence of distinct pulses. The time interval between these pulses changes with time. The associated ground motion resembles a superposition of overlapping exponentially decaying signals. We carried out a deconvolution of the ground motion with the pressure for a number of non-overlapping time intervals. Under the assumption that the pressure pulses are related to the excitation of the seismic waves, this should give the seismic impulse response of Mt. Arenal. The deconvolved signals obtained from the different time intervals display the typical character of coda waves with a diffusive character. Even though the waveforms are complex, they are highly reproducible. The deconvolved waves from adjacent time windows have a high correlation with a correlation coefficient of about 0.95 or more. This correlation coefficient decreases to about 0.80 for the deconvolved waveforms that are from time windows with a separation in time of about 10 minutes. On the basis of the employed data, the cause of the change in the waveforms cannot be established unambiguously. However, the de-correlation of the deconvolved waves can be explained by a change in the location of the seismic source over about 60 meters during a 10 minute interval. The reproducible character of the deconvolved signals and their gradual and systematic change with time open up the possibility of passive volcano monitoring using coda wave interferometry [Snieder, R., A. Gret, H. Douma, and J. Scales, Coda wave interferometry for estimating nonlinear behavior in seismic velocity, Science, 295, 2253-2255, 2002].

S11E-0338 0830h POSTER

Volcano Monitoring with Coda Wave Interferometry at Mount Erebus, Antarctica

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Multiply-scattered waves dominate the late seismic coda. Small changes in the medium that would have no detectable influence on the first arrivals can be highly amplified by multiple scattering and readily observed in the coda. We apply coda wave interferometry to monitor subsurface temporal changes at Mount Erebus Volcano, Ross Island, Antarctica. Erebus is one of the few volcanoes known to have an open conduit system hosting a persistent convecting lava lake. Strombolian eruptions, caused by the explosive decompression of large bubbles of exsolved volatiles disrupt the lake itself, which subsequently refills within a few minutes. Because of the recoverability of this system, these eruptions provide a repeatable seismic source of seismic waves for sampling the strongly scattering volcano. Repeating eruption seismograms have been recorded at fixed station sites over several years, and the coda is seen to be highly reproducible over extended periods of time. We find waveform correlation coefficients as high as 0.98 for short-period seismograms recorded up to several days apart. However, in comparing seismograms separated by approximately a month, we note a small decrease in correlation. Furthermore, we see a much larger decorrelation of the waveforms spanning a time period of one or even two years. Coda energy is thus providing information on systematic source and/or subsurface changes.

S11E-0339 0830h POSTER

Empirical Synthesis of Green functions from the correlation of diffuse waves

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We show the existence of long range field correlations in the seismic coda of regional records in both Mexico and Alaska. The cross-correlation tensor between the coda records at two points is measured for a set of distant earthquakes. Remarkably, while individual correlations have a random character, the source- averaged correlations exhibit deterministic arrivals that obey the same symmetry rules as the Green tensor between the two points. In addition, the arrival times of these waves coincide with propagating surface waves between the two stations. Thus, we propose to identify the averaged correlation signals with the surface wave part of the Green tensor. However, while time reversal symmetry theoretically imposes that the Green function appears at both negative and positive times, we find experimentally this symmetry to be broken when the distribution of earthquakes is not isotropic around the stations. We explain this observation by the long lasting anisotropy of the diffuse field. This point is further discussed in a companion paper where we prove both experimentally and theoretically that a dominant flux of energy coming from the source can persist in the late coda. Finally, we show that averaged cross-correlations of ambient noise enable the reconstruction of some coherent arrivals. These examples illustrate a novel empirical method that provides synthetic seismograms between two stations, without the knowledge of the precise location and origin times of the sources.

S11E-0340 0830h POSTER

Synthesis of Green functions from Coda Correlation: Ultrasonic experiments.

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Recent works in seismology show that cross-correlation functions between signals recorded at two points and averaged for several earthquakes contain deterministic arrivals. This is discussed in a companion paper. Weaver and Lobkis (2001) successfully retrieved the Green function between two points from the correlation of diffuse fields in a cavity at ultrasonic frequencies. We present here laboratory experiments with ultrasound that show that the principle remains valid in an open scattering medium for which the normal mode representation of the field does not hold. We designed a set of experiments to test the feasibility of imaging from correlations of coda waves produced by distant sources. The scattering is caused by a random arrangement of steel rods in water. The experiments show that the quality of the reconstruction of the Green function is enhanced in the presence of scattering because scattering tends to spread the energy in the different directions of propagation. We show that stacking cross-correlations allows the precise measure of velocity between two sensors in a medium with velocity changes. The reflection from a strong interface can be detected as well as the diffraction from a single scatterer. In practice the quality of the reconstruction is controlled by the duration of the time windows, by the number of sources but also by the spatial distribution of source and scatterers relative to the two sensor locations. This is made easily understandable by the analogy between the empirical synthesis of Green function from field correlation and time-reversal experiments. This analogy gives also a physical interpretation for the loss of time symmetry of the cross-correlations observed both with seismological data and in the laboratory.

S11E-0341 0830h POSTER

Flux Anisotropy, Equipartition and Their Role in Field-Field Seismic Correlations: Theoretical and Numerical Investigations.

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Recent seismic experiments have reported the emergence of coherent propagating waves in averaged cross-correlations of diffuse seismic waves. The remarkable result is that coda records of several distant earthquakes at stations A and B yield the Green function G_{AB} between the two stations. While existing theories -relying on the presence of equipartition of modes- predict that the averaged cross-correlations should be symmetric in time, -i.e. both the retarded and the advanced Green functions should emerge- the experiments have reported a clear asymmetry. We argue that this property can be explained by the persistence of an angular anisotropy in the diffuse field of seismic waves, caused by a nonzero energy current. We show theoretically that the existence of a current that transports the energy released by seismic sources to the stations entails the appearence of an antisymmetric term to the field-field correlation. Numerical solutions of the elastic radiative transfer equation reveal that while a stabilization of total P and S energies - known as equipartition - rapidly occurs in the seismic coda, the angular distribution of the energy flow remains strongly anisotropic even after a large number of scattering events. Although the flow must become isotropic at very late times, in the coda window of most seismic experiments the energy is mostly transported by waves coming from the source. Hence, an anisotropic source coverage is a very good candidate to explain the absence of symmetry in the observations.

S11E-0342 0830h POSTER

Acoustic Wave Attenuation and Scattering in Anisotropic Random Media

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Most theoretical investigations of seismic wave scattering rely on the assumption that the underlying medium is statistically isotropic. However, deep seismic soundings of the crust as well as geological observations often reveal the existence of elongated or preferentially oriented scattering structures. In this paper, we develop mean-field and radiative transfer theories to describe the attenuation and multiple scattering of the acoustic wavefield in an anisotropic random medium. The scattering attenuation length is found to depend strongly on the propagation direction, while the phase velocity develops a very weak anisotropy. We derive the anisotropic radiative transfer equation from the exact Bethe-Salpeter formalism and propose a Monte-Carlo method to solve the transport equation numerically. At late times, the acoustic energy is shown to obey a tensorial diffusion equation. The components of the diffusion tensor are obtained in closed form and excellent agreement is found between Monte-Carlo simulations and analytical solutions of the diffusion equation. The theory has important potential implications for crustal models where scatterers are (e.g.) flat structures preferentially aligned along the surface. In this simple geometry, analytical expressions of the Coda Q parameter will be given explicitly. It will be further argued that pulse broadening and Coda decay are controlled by different parameters -the eigenvalues of the diffusion tensor- that can differ by more than one order of magnitude.

S11E-0343 0830h POSTER

Lg Phase Propagation Characteristics in Northern Eurasia from Peaceful Nuclear Explosion Data

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Regional phases (Pn, Pg, Sn and Lg) play a significant role in monitoring small events for Comprehensive Test-Ban Treaty (CTBT). In all the regional phases, the Lg phase is usually the strongest, which is usually used to identify nuclear explosions from earthquakes. However, the Lg is weak or disappears in some tectonic areas. Therefore, studying propagation characteristics of the Lg phase and the factors affecting Lg phase propagation is necessary for the use of the Lg in nuclear monitoring. In order to quantitatively describe the variations in crustal attenuation across Northern Eurasia, we measure amplitude ratios and the Lg coda Q values from 21 Peaceful Nuclear Explosions (PNEs) recorded along six linear, long-range three-component profiles. These historic data provide unique opportunities to study the regional phase propagation characteristics in Northern Eurasia. Lg/Sn and Lg/Pgcoda amplitude ratios are significant parameters to constrain the variations of crustal structures. These ratios are higher (> 1) within the Siberian Craton and decrease at tectonic boundaries and thick sedimentary basins. In agreement with the previous studies, Lg(1-2Hz)/Lg(6-8Hz) ratios are about 10 times higher for the PNEs than for earthquakes. Frequency-domain Lg coda Q measurements show large scatter due to the noise and limited frequency band; however, the Lg coda Q computed from the time domain method shows that the variations of the crustal structure are the most important factors to affect the Lg coda attenuation. It appears that thick sediments can block the Lg phase propagation. From the seven PNE profiles, we map the Lg coda Q distribution in Northern Eurasia and demonstrate the frequency dependence of the Lg coda Q.

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S11E-0344 0830h POSTER

Coherence-Weighted Wavepath Migration of Teleseismic Data

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Migration of teleseismic records from earthquakes can image a selected set of reflections or converted

phases to their correct locations of origin, but will also image other phases to incorrect locations. For example, a migration algorithm tuned to ps conversions can correctly image the Moho but may also focus ghost reflections from the moho such as pPs or pSs to incorrect reflector locations. (Here, lower and upper case letters indicate upgoing and downgoing waves, respectively.) This coherent "noise" from other phases can be suppressed by stacking images migrated from many teleseisms but, in practice, the timely acquisition of well-recorded events can be impractical. To partly remedy this problem, we propose coherence-weighted wavepath migration of teleseismic data. The idea is to first apply wavepath migration to, say, ps, pPs, and pSs arrivals in receiver functions and pPp arrivals in autocorrelograms. Then, a local semblance analysis is applied to the resulting ps, pPs, pSs and pPp images to calculate the coherence among these images and a weighting factor proportional to it. Correctly migrated events are coincident at the same locations resulting in high coherence weights at these points. Smaller weights are computed elsewhere. The coherence weights are applied to the ps image to give the final image. In addition, selective migration of the ps arrivals is partly achieved by wavepath migration of receiver functions using special imaging conditions that account for the expected particle motion of ps conversions and their apparent moveout. To demonstrate the viability of this procedure, we computed elastic synthetic seismograms for a 4-layer crustal Utah model using a plane P wave source incident at a 40 degree angle. Receiver functions were computed and ps conversions were migrated to give the reflectivity distribution $r(\mathbf{x})^{ps}$. The pPp events were migrated from autocorrelograms to give $r(\mathbf{x})^{pPp}$. Semblance weights were computed for the $r(\mathbf{x})^{pPp}$ and $r(\mathbf{x})^{ps}$ images, and a final image was obtained by applying the semblance weights to the $r(\mathbf{x})^{ps}$ image. Comparing this image to the unweighted ps image shows the efficacy of this approach. Our poster will also show results from migrating teleseismic data recorded by the Utah Regional Seismic Network.

S11E-0345 0830h POSTER

Anomalous P-wave Attenuation Around an Active Volcano: An Interpretation Based on a Localized Random Inhomogeneity

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Around active volcanoes, strong attenuation bodies were often detected by seismic experiments and intrinsic absorption is considered as a physical mechanism of attenuation. Paying an attention to that seismograms near the attenuation bodies often contain incoherent later-phases, random inhomogeneity model would be a candidate to lead direct-wave attenuation and coda excitation due to scattering. In this study, I numerically simulate wave propagation through a medium having a localized inhomogeneity to explain the observed characteristics. In a 2D medium of background velocity Vp = 5km/s and Vs = 2.9km/s, a disk of localized random inhomogeneity with diameter of 6km is placed. The random inhomogeneity is given by fluctuation of velocities and density (30% in RMS fractional fluctuation and 500m in correlation distance). A P-wave source is 10km apart from the center of localized inhomogeneity and receivers are 15km apart from the source concentrically. Finite difference method is used for the simulation of wave propagation for a source radiation of Ricker wavelet with 10Hz dominant frequency. Receivers are divided into shaded receivers to which the direct ray travels across the inhomogeneity and unshaded receivers to which the direct ray avoids it. Significant differences of wave traces are seen. (1) Clear P-wave is seen at each unshaded receiver, while P-wave is attenuated at shaded receivers. Peak amplitudes at shaded receivers are about 1/5 times as large as ones at unshaded receivers. (2) At shaded receivers, scattered waves having amplitudes as large as attenuated direct P-wave continue for long duration as P coda in radial and transverse components. They are leaked from the localized inhomogeneity where waves are localized by multiple scattering. (3) At unshaded receivers, amplitudes of scattered waves in transverse component are much smaller than that of P-wave in radial component. On the other hand, at shaded receivers, amplitudes of P coda in transverse component increasing with lapse time are as the same order as attenuated direct P-wave in radial component. Scattering by a localized random inhomogeneity explains the features of seismograms around active volcanoes, anomalous peak-amplitude attenuation and excitation of coda. In addition, it predicts localization of scattered waves and P-wave leakage into transverse component.

S11E-0346 0830h POSTER

Modeling of SH Wave Envelopes in Media With Many Cavities

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For revealing the stochastic nature of the heterogeneous earth by means of seismograms, wave envelopes in randomly heterogeneous media have been theoretically studied, and several models to describe them have been proposed. In such studies, heterogeneities were usually assumed as continuous fluctuation of medium parameters; it is not self-evident whether the models are valid even for discrete heterogeneities with sharp material contrasts, such as distributed cracks or inclusions. In this study, we dealt with 2-D circular cavities as a tractable example of discrete heterogeneities. We synthesized the envelopes of SH waves propagating in media with many cavities, and compared them with the predictions by some of the models stated above, thus examining their validity and limitations. We randomly distributed many identical cavities within a rectangular area, let a plane SH Ricker wavelet be incident on its one side, and synthesized the seismograms at points arrayed along the opposite side. Here we used a boundary integral method (Benites, Aki and Yomogida, 1992); free surfaces were not considered. We then calculated the RMS envelope and compared it with the solutions of the following theoretical models; the Foldy approximation (Kawahara and Yamashita, 1992; hereafter FA), the single isotropic scattering model (Sato, 1977; hereafter SISM) and the energy flux model (Korn, 1990; hereafter EFM), with some modifications according to the present experimental geometry. FA stochastically describes the attenuation and dispersion of direct waves, whereas SISM and EFM predict coda wave envelopes phenomenologically. The latter two require the scattering Q, that is given by FA. The total scattering coefficient, required by SISM, can be analytically evaluated with a wide-angle scattering approximation. It was shown that FA highly agrees with synthesized direct wave envelopes for any cavity volume concentrations, up to 20%. SISM explains well the synthesized coda wave envelopes only for very small concentrations. For higher concentrations (say, >1%), SISM underestimates the envelopes, but it always explains them if multiple-scattered coda waves are removed. This implies the dominance of multiple scattering over coda waves in these cases. In contrast, EFM seems to work well when multiple scattering is dominant. Generally, the agreement between the synthetic and EFM envelopes is better for longer lapse times or denser cavity distributions. Other geometries (e.g., cracked media with point sources) should be examined in future.

S11E-0347 0830h POSTER

Synthesis of Surface Wave Coda in Randomly Inhomogeneous Medium Based on the Single Scattering Approximation

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In long period seismograms, coda part of the surface waves have smooth envelopes as same as those in short period seismograms. These surface waves propagating in inhomogeneous structure are scattered by distributed inhomogeneities in the crust and upper mantle. In this research, we first synthesize the envelope of surface coda waves in randomly inhomogeneous medium based on the wave theory by using the single scattering approximation. We suppose that elastic medium in a half space is expressed by a superposition of random inhomogeneities on a layered structure. We imagine an ensemble of random inhomogeneities of which the stochastic character is given by an autocorrelation function. Surface waves radiated from the source for short duration time are scattered and mode-converted at arbitrary points of the medium. To describe the single scattering process from the source to a receiver, we divide the whole medium into many small prisms of which the dimension is larger than the correlation distance. Scattering of surface waves at each prism is well described by the Born approximation for surface wave modes in the layered structure for one realization of the random media. Summing up all surface wave modes scattered at distributed prisms, we get a wave trace at the receiver. By squaring this wave trace in time domain and taking average over an ensemble, the Mean Square (MS) envelope is calculated. In mathematical formulation of the single scattered MS envelope, the following assumptions are used: (1) a product of the source duration time and the average group velocity of surface wave mode is longer than the correlation distance of the random inhomogeneity; (2) the correlation of scattered waves at distant locations is sufficiently small; (3) inhomogeneity is statistically independent in lateral and vertical directions. For a given lapse time, scattering points are restricted on an isochronal scattering curve that is determined by the source-receiver location and the group velocities of incident and scattered surface wave modes. In the representation of the MS envelope, we succeeded in characterizing the energy of scattered surface wave by the vertical integral of the power spectrum density function of lateral random inhomogeneity and the sensitivity kernel.

S11E-0348 0830h POSTER

Imaging of 3-D Small-Scale Heterogeneities Around the Nagamachi-Rifu Fault in Northeast Japan by F-K and Polarization Analyses

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Seismic array observation enables us to estimate spatial distribution of heterogeneities in a deterministic manner from coherent arrivals in coda waves. We shall propose a new imaging method using F-K analysis together with polarization analysis based on an auto-regression (AR) model by a dense three-component seismic array. The spatial distribution of small-scale heterogeneities was estimated by the following two steps: (1) identifying the scattering mode, (2) correcting each effect of source, site, and propagation terms. (1) In order to determine the scattering mode of incoming waves for an array, we estimated the slowness vector and the direction of the maximum polarization of each distinct arrival phase in coda using F-K and polarization analyses, respectively. We applied an AR model in order to estimate F-K power spectra and covariance matrixes in the time-frequency domain of high resolution. We identified the character of each phase as a scattered wave from the angle between the slowness vectors and the polarization directions estimated above. Since the sources were explosions, we could determine whether a given phase is P-P or P-S scattered wave. (2) Amplitudes of the observed seismograms are affected by source, station, and propagation effects, so it is necessary to correct these effects before estimating the reliable values of image relative scattering coefficient. We used the coda-normalization method for correcting source and station effects. On one hand, the correction of the propagation effect (amplitude recovery) has assumed the least-square fit of an a priori of attenuation factor in previous studies. In order to remove this assumption, we adopted Akaike's Information Criterion (AIC) to select the optimal one among varians kinds of expressions of attenuation factor. We applied the above imaging methods to the seismograms recorded by three dense three-component seismic arrays around the Nagamachi-Rifu fault in Northeast Japan operated by the Research Group for Deep Structure of Nagamachi-Rifu Fault and GSJ, AIST. We could identify clear scattered waves, particularly in latter part with a lapse time greater than 8 sec after the above correction processes. In order to image the spatial distribution of their responsible scatterers from the arrival times of these phases, we adopted a 3-D seismic velocity structure estimated by Nakajima (2003). As a result, the following remarkably distribution of scatterers around the Nagamachi-Rifu fault was revealed: (1) A cluster of scatterers dipping to the west is located at depth less than 10 km. These scatterers may correspond to the deep extension of the Nagamachi-Rifu fault observed at the surface. (2) Localized P-S scatterers are clearly identified at depths around 8 km in the north-west of these arrays.

S11E-0349 0830h POSTER

Differential Scattering Technique for Imaging of Open and Productive Fractures

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Scattered waves have been extensively used to characterize the heterogeneity and attenuation properties of the Earth's crust. Their sensitivity to Earth's discontinuities, like fractures in particular, makes them a potential tool for mapping fracture patterns and monitoring changes in their properties. We used an acoustic finite difference code to model the effect of small changes in the scattering coefficient for waves, traveling in a fractured medium. A small change is not easily seen on the seismogram, but this small change becomes obvious if one takes the difference in the seismograms. We are developing a technique to monitor changes in water productive fractures at shallow depth in crystalline rock. We utilize a repeatable seismic source to examine temporal variations in the response during periods of increased or decreased rate of pumping.

S11E-0350 0830h POSTER

Transparent Paths between Quaternary Volcanoes in Northeastern Japan Revealed from S-wave Envelope Analysis

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S-wave envelopes of deep and intermediate depth microearthquakes observed at stations located in the back arc side of northeastern Japan are significantly different from that observed in the fore arc side. Apparent durations and peak delays of S-wave envelopes are relatively long at stations in the back arc side, while are not prominent in the fore arc side (Obara and Sato [1995]). In this study, we examine the path dependence of S-wave envelope of shallow(35km∼100km) earthquakes which occurred along the subducting Pacific Plate to clarify the regional difference of medium heterogeneity. To characterize an S-wave envelope, we measure the peak delay time from the S onset t_p. By looking at the t_p obtained from the data having almost the same hypocentral distance (150km∼200km) and the same earthquake magnitude, we find significant difference in their t_p. For example, at a station located near the Iwate volcano, t_p in 16Hz∼32Hz band is 3.6s for a ray propagating beneath the volcano and that is as short as 1.7s for a ray passing far from the volcano. From the systematical examination of t_p for many different pairs of stations and events, we further find that t_ps are large for rays traversing beneath Quaternary volcanoes in northeastern Japan, while t_ps are small for the rays propagating in narrow paths between Quaternary volcanoes in depth down to about 40km. Our peak delay analysis revealed the spatial variation of medium heterogeneity and the existence of transparent and less scattering paths between Quaternary volcanoes in the back arc side.

S11E-0351 0830h POSTER

Crustal Heterogeneity in the Eastern Chugoku Region, Japan, Estimated by Coda Envelope Inversion: Toward Mapping the Nationwide Heterogeneity Using the Hi-net Data

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Recently coda envelopes from local earthquakes are inverted to estimate a 3D heterogeneous structure in the crust (Nishigami, 1991, 2000; Asano and Hasegawa, 2003). These studies suggest that the data of dense seismographic network is effective to image crustal heterogeneities such as the fractured zone along active faults, magma or melted bodies below active volcanoes, and reflective zones in the lower crust. Recently High Sensitivity Seismograph Network (Hi-net) has been constructed by NIED covering all over Japan. We are aiming at estimating systematic variation in the crustal heterogeneity in Japan and trying to detect a possible structure related to the earthquake generation, using the Hi-net data. First of all we analyzed the eastern Chugoku region, Japan. Coda envelopes from 138 local earthquakes were measured at 23 Hi-net stations, and their deviation from the average decay curve assuming a single isotropic scattering model was estimated as the observational data. The analysis area, about 200 km in horizontal and 60 km in depth, was divided into 5800 small blocks, and 3D distribution of relative scattering coefficient was obtained by solving the observational equation using a recursive stochastic inversion. The preliminary result shows strong scattering along the Yamasaki fault system and also the high seismicity zone along the Japan Sea coast. The resolution will be improved by adding more data including the University and JMA stations, and also the analysis area will be enlarged toward the nationwide mapping of the heterogeneity.

S11E-0352 0830h POSTER

Dead Sea Fault Structure From Seismic Pre-stack Migration

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With controlled seismic sources and specifically designed receiver arrays, we imaged a subvertical boundary between two lithological blocks at the Arava Fault (AF) in the Middle East. The AF is the main strike-slip fault of the Dead Sea Transform (DST) between the Dead Sea and the Red Sea. Our imaging (migration) method is based on array beamforming and coherency analysis of P-to-P scattered seismic phases. We use a 1-D background velocity model and the direct P arrival as a reference phase. A spread function describing energy dispersion at localised point scatterers and synthetic calculations for large planar structures provided resolution estimates of the images. We resolve a 7 km long steeply dipping reflector offset roughly 1 km from the surface trace of the AF. The reflector can be imaged down to about 4 km depth. Our results suggest that the AF consists of one dominant fault strand in the uppermost crust. Previous and ongoing studies in this region have shown a strong contrast across the fault: low seismic velocities and electrical resistivities west and high velocities and resistivities east of it. We therefore suggest that the imaged reflector marks the contrast between sedimentary fill in the west and precambrian rocks in the east. This implies that the boundary between the two blocks, i.e. the actual fault location, is about 1 km east of the surface trace of the AF.

S11E-0353 0830h POSTER

Multiparameter Inversion of Forward Scattered Teleseismic Data Using an Inverse Scattering Series Method

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A new approach is presented to invert the elastic properties of the earth from forward scattered teleseismic data using an inverse scattering series method. The forward problem is cast as the Born series in terms of Green's function in the reference medium and perturbations to material properties. The scattered wavefield can be described by the summation of terms of the Born series, in which the first term is the Born approximation. We are investigating the use of the inverse scattering series to solve the inverse problem for forward scattered body waves. Inverting for the first term in the inverse scattering series is the linear inversion approach on which most migration methods are founded. When the contrast of the reference and actual media is big, higher order terms of the inverse scattering series can be expected to correct the linearized inverted elastic properties closer to those of the actual medium. Thus, this algorithm is nonlinear and can be used for inverting the elastic properties in complex conditions with the practical seismic array geometry using an initial model with constant elastic properties. The inversion formula involves four different scattering modes (PP, PS, SS, SP) that contribute to the recovery of the earth either separately or in a whole. The equations of the first two terms in the inverse scattering series have been developed and work on higher order terms is in progress.

S11E-0354 0830h POSTER

Imaging Inhomogeneous Crustal Structure Related with Arc Magma and Fluids beneath Northern Miyagi Prefecture, Northeastern Japan, by an Envelope Inversion Method

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We have estimated 3-D distribution of scattering coefficients by an envelope inversion method [Asano and Hasegawa, 2003] in the northern part of Miyagi prefecture, northeastern (NW) Japan. In this region, Nakajima and Hasegawa [2003] imaged a clear seismic low velocity zone (LVZ) extending from the uppermost mantle to the crust below an active volcano, Naruko volcano, and to the crust in a seismically active region, the focal area of 1965 M6.5 Northern Miyagi earthquake. We have tried to image short-wavelength inhomogeneous crustal structure by using a large number of observed envelopes of S coda. It is known that the seismic coda is a superposition of seismic waves scattered by such a short-wavelength inhomogeneous structure. Estimated distribution of scattering coefficients provides us information about the short-wavelength inhomogeneous structure, which is hardly imaged by travel-time tomography. We analyzed 1299 three-component seismograms recorded at 44 stations, whose separation is about 10 to 20 km. In the target area we set 2471 grids with a spacing of 7.5-km in the central part, and with a spacing of 15-km in the surroundings. Scattering coefficient values in each grid is unknown parameter to be estimated. The results show that there exist several zones with large scattering coefficients (LSZs). Predominant LSZs are distributed beneath active volcanoes in the backbone range, which indicates a strongly inhomogeneous structure related to the volcanoes. A clear LSZ is also detected around the mainshock fault of 1965 M6.5 Northern Miyagi earthquake. This LSZ in the upper crust suggest the existence of fault-damaged zones along the mainshock fault. The LSZ extends to the deeper extension of the fault and connects to another LSZ beneath Nuruko volcano in the lower crust. This characteristic distribution of the LSZ is well correlated with that of the LVZ imaged by Nakajima and Hasegawa [2003]. The LVZ is characterized by high V_p/V_s in the uppermost mantle and the lower crust, but by slightly low V_p/V_s in the upper crust. They interpreted that the LVZ in the uppermost mantle and the lower crust is caused by the existence of partial melt and that in the upper crust by the existence of H_2O supplied from the partial melting zone in the lower crust. The present observations suggest that the LSZs reflect the path of fluids from the lower crust to the upper crust, and such distribution of fluid filled cracks can effectively scatter seismic waves.

S

S11E-0355 0830h POSTER

Seismic Evidence for Slab Melting from Strong Scattering Waves

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Slab melting in some young and hot subduction zones has been reported from geochemical observations and thermal modeling, but there was still no seismic evidence to confirm it. Also the detailed geometry in the deep part of the melting slab is often ambiguous in that the intraslab earthquakes within the Wadati-Benioff zone are only limited to shallower depths. To improve the understanding of both the seismic features and the geometry found in a young and hot subducted slab, we analyze an anomalous moonquake-like seismogram that was generated by an intermediate-depth earthquake recorded in central Japan. Since the subducted Philippine Sea plate in central Japan is extremely young (0-2 Ma) and therefore hot, strong partial melting might have taken place to produce abundant melting spots in the subducted slab. Melting spots, identified as bright spot, could efficiently reflect or scatter much seismic energy and then generate many later phases with large amplitudes. As a result, slab melting can be identified in the deep bending part of the subducted Philippine Sea plate from strong seismic scattering.

S11F MCC: Level 1 Monday 0830h

Scale-Frequency Phenomena and Earth Structure Posters *(joint with NG)*

Presiding: **D A Wiens,** Washington University**; Y Zeng,** Seismological Laboratory, University of Nevada

S11F-0356 0830h POSTER

Fractal Model of Elastic and Electrical Properties of Porous Rock

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A theoretical model of elastic and electrical properties of porous rock was developed for quantitative joint analysis of collocated seismic velocity tomography and magnetotelluric (MT) experiments. A fractal model applied to elastic properties of rock by Spangengerg (1998) was extended to describe electrical properties of porous rock with the same microstructure for a percolation case. An inverted geometrical model of pore spaces and matrix was also developed to consider isolated pores and a system staying near percolation. The simulation results of electrical properties were compared with the empirical Archie's law and former theoretical models of electrical properties of porous rock for special cases of ellipsoidal isolated pores and for interconnected pore geometries, such as a system of tubes along cubic grain edges or films surrounding cubic grains. This comparison shows that the present model is consistent with the former models for special cases. The main advantage of the present model against other theoretical models is possibility to describe both elastic and electrical properties of rock with a single model for a wide range of microstructures including 3D grains and pore anisotropy and various degrees of pore interconnection. It provides us a simple way to obtain the dependency of a resistivity against a seismic velocity for an arbitrary microstructure. Obtained theoretical dependencies of seismic velocity vs. resistivity allow us to estimate a liquid fraction in a structure from explored seicmic velocity and resistivity distribution. Based on the developed model, an attempt have been successfully made to elaborate a quantitative method for solving the problem whether the variation of resistivity and seismic velocities in a region can be attributed to presence of liquid only or whether other causes should be considered. The developed model can be used for parameterization of a joint MT and seismic inverse problem in a variety of geological settings.

S11F-0357 0830h POSTER

Elastic wave velocities anisotropy and dispersion in cracked rocks

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In the static regime (when cracks do not propagate), the simplest hypothesis that can be made is to neglect crack interactions. In fact, we show that such hypothesis takes better into account the interactions than most interactive models (especially the self-consistent and Hudson's approaches) because of the geometrical compensation of interactions that exist when cracks are distributed randomly or in parallel. Kachanov's [1993] non interactive model of solids with many cracks enables us to predict elastic wave velocity anisotropy for non-randomly orientated distribution of cracks. In the transversely isotropic case, we show that P wave anisotropy and S wave birefringence can be very different in the dry and saturated regimes. This model also enables us to quantify the damage in a rock in terms of crack density, as well as preferential orientation of the crack distribution and saturation using laboratory elastic wave velocity measurement data. Predictions are in agreement with microstructural analysis up to crack densities higher than 0.5. By coupling such a model to poroelasticity, we can also predict dispersion between high frequency and low frequency measurements in the saturated regime due to "squirt flow" mechanisms. Dispersion is lower when cracks are not parallel. However, when they are parallel, dispersion can be very high and therefore elastic wave velocity anisotropy observed on the field (at low frequency, i.e.<1KHz) can be very different from the one observed in the laboratory (at high frequency, i.e. 1MHz). S wave birefringence is particularly sensitive to saturation and thus to frequency.

S11F-0358 0830h POSTER

Quasi-Cylindrical FDM: an Ultra-Fast 2.5D Waveform Modeling Method for Explosion Seismic Experiments

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We propose a new efficient method for modeling 2.5D wavefields of explosion seismic surveys. The most common form of seismic exploration remains a nearly linear survey with data acquisition lines including the source and receivers. The interpretation of amplitude and waveform information for such linear acquisition requires consideration of 3D seismic wavefields. In many scenarios the structure is approximately 2D, but still modeling is needed for point sources. Recently 2.5D modeling methods have been developed for the simulation of 3D seismic wavefields in media varying in two dimensions, which require a storage only slightly larger than those of the corresponding 2D calculations. However, they require long computation times comparable to that of the corresponding 3D calculations, which is a major obstacle in routinely applying these conventional 2.5D methods to seismic surveys. To overcome this computation time problem, we have considered a new approach for modeling 2.5D seismic wavefields using a quasi-cylindrical representation, and implemented this approach using a velocity-stress finite-difference method (FDM). Our method requires similar computation time and storage as for 2D calculations, so that, with moderate computational resources, we may apply the method to routine analysis of seismic surveys where a number of trials of waveform modeling are inevitable. In this presentation we show some numerical examples to demonstrate the validity and feasibility of our method, with a simulation of a realistic large-scale onshore-offshore seismic experiment.

S11F-0359 0830h POSTER

Self-Affine Fracture Surface Topography and its Implications on Seismic Wave Propagation

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Over the past two decades, many field and laboratory observations have been made on the self-affine (fractal) properties of fracture surface geometry. In many cases, particularly for fractures in crystalline and granular rocks, the power spectrum of a fracture surface can be described by the power law with exponents limited to a relatively narrow range (e.g., Schmittbuhl et al., 1995). This number is directly related to the Hurst exponent which characterizes the self-affine properties of the fracture, i.e., the scaling relationship of the surface topography between the fracture-normal coordinate and the fracture-parallel coordinates. In this presentation, we will discuss the effect of self-affine fracture geometry on the scaling relationships of fracture compliance and, therefore, on the reflection and transmission of seismic (elastic) waves. The opening width of the fracture is assumed to have either 1) the same self-affine distribution as the fracture surfaces or 2) a distribution resulting from shear displacement across the fracture. Fracture compliances of three-dimensional, self-affine fractures subjected to stress are computed using a numerical model modified from the work of Hopkins (2000). Our preliminary study showed that for a self-affine fracture, normal fracture compliance is proportional to the scale of the fracture in the fracture-normal direction, and hence the fracture compliance follows a scaling relationship $\log(S/S0)=H \log(L/L0)$. Here, S and L are the normal fracture compliance and the characteristic length of observation, respectively, H is the Hurst exponent, and 0 indicates the quantities measured at the reference scale L0. By introducing this relationship to the seismic displacement discontinuity model (Schoenberg, 1980; Pyrak-Nolte et al., 1990), transmission and reflection coefficients of fractures at different scales and frequencies can be computed. The scaling relationship of fracture properties as shown in this paper is significant because it allows us to estimate the geometry and constitutive relationships of fractures in the field from laboratory measurements on small core and block samples. Once this is done, properties of interests such as stress state and gas and fluid contents of the fractures can be evaluated from field seismic measurements on the fractures.

S11F-0360 0830h POSTER

Optimum Time-Frequency Decomposition For Seismic Data Using Continuous Wavelet Transform

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Time-frequency decomposition is an important signal analysis tool for seismic data. The overall frequency content of a signal can be obtained from the Fourier transform. However, for a non-stationary signal, such as seismic signal, whose frequency content varies with time, 1D transformation in frequency is not sufficient. Traditionally, 2D representation in time and frequency space for a 1D signal is achieved by taking Fourier transform over a short-time window. This method is commonly known as short-time Fourier transform (STFT). Time-frequency resolution in STFT is limited by the choice of a window length. Windowing problem in time-frequency analysis is absent in the continuous wavelet transform (CWT) method. CWT utilizes the property of dilation and translation of a wavelet and produces time-scale map where scale, defined in terms of length of time support of a wavelet, represents a frequency band. However, scale can be converted to frequency and the time-frequency map thus produced is called TFCWT. It is produced from CWT in two steps: 1. producing time-scale map, and 2. converting the scale to frequency. TFCWT has optimum time-frequency resolution, i.e. higher frequency resolution at lower frequencies and higher time resolution at higher frequencies, which makes it useful for seismic data interpretation. Visualization and interpretation of seismic sections in frequency space using single frequencies from the TFCWT spectra can be utilized to enhance low frequency shadows caused by hydrocarbon reservoirs. This idea can also be extended in interpreting time slices from 3D seismic data in frequency space. This method has been used to identify thin beds below tuning thickness.