of spectral amplitudes. We will show that, using a typical infragravity wave source, one can explain not only the amplitudes of continuous oscillations but also the broad noise peak that exists at 0.01 Hz. This broad noise peak between 0.003 Hz and 0.015 Hz has been known before continuous oscillations were discovered (e.g. Peterson, 1993). Oceanic infragarvity wave hypothesis can explain not only continuous oscillaiton peaks but also this broad noise peak simultaneously. This is the major difference from previous atmospheric excitation models, because previous atmospheric hypotheses treated the background broad noise peak as unknown (Gaussian noise) and did not explain its origin. Secondly, modal peaks of continuous oscillations display a predominant 6-months periodicity (Tanimoto and Um, 1999; Ekstrom, 2001). This can be easily explained by the oceanic hypothesis due to its hemispheric, mid-latitudinal ocean-wave activity that generate large-amplitude ocean waves with 6-months periodicity. Using a satellite ocean wave data (TOPEX/POSEISDON), we will show that seismic modal amplitudes display similar seasonal variations to ocean wave data both in amplitude and phase. The scenario that emerges from this analysis is the following; the atmospheric winds generate ocean waves that fills the oceans in the world. Among those waves, long period waves (oceanic infragravity waves) perturb pressure at sea bottom and exert pressure on the solid Earth. This pressure fluctuation all over the oceans results in generation of ambient seismic noise for frequencies between 3 and 15 mHz, which is observed in the vertical component seismograms at all quiet broadband stations. Spheroidal modes for this frequency range are excited but clear modal peaks are seen only for 2-7 mHz mainly because of attenuation (which can be easily examined by simple calculations). These activity reaches semi-annual peaks in December-January-February and in June-July-August because of strong atmospehric activities at mid-latitudes in each hemisphere (North and South) that generate high amplitude ocean waves, including infragravity waves.

S12F-05 1710h

Theories of Mars' Interior: An alternative to plumes as the origin of Tharsis

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Mars' large-scale physiography is dominated by a hemispheric dichotomy (thin northern crust with low, smooth topography vs. thick southern crust with high, rugged topography) and by the Tharsis rise (an enormous volcanic plateau), both of which developed within the first 1 Gyr of Martian history. Using a 3-D spherical mantle convection model with temperature-dependent viscosity, we explore the effect of hemispheric-scale crustal thickness variations on Martian mantle convection. Thickened crust in the "southern" hemisphere of the model causes insulation of that hemisphere which may effect the underlying mantle circulation. This leads to a transient, regional-scale partial melting event sufficient to generate the Tharsis rise during the first 0.5-1.0 billion years following the formation of the crustal dichotomy. Our model avoids some problems of timing inherent in plume models, provides testable hypotheses regarding the history of Martian volcanism, and suggests a causal link between the formation of the N-S dichotomy and Tharsis.

S12F-06 1725h INVITED

On Planetary Evolution and the Evolution of Planetary Science During the Career of Don Anderson

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The planets of our solar system have long been viewed by Don Anderson as laboratories for testing general aspects of planetary evolution and as points of comparison to the Earth. I was fortunate to have been a student 39 years ago in a course at Caltech that Don taught with Bob Kovach on the interiors of the Earth and the planets. At that time, Mariner 4 had not yet flown by Mars, the lunar Ranger program was still in progress, and it was permissible to entertain the hypothesis that all of the terrestrial planets were identical in bulk composition. In the last four decades spacecraft have visited every planet from Mercury to Neptune; samples from the Moon, Mars, asteroids, and comets reside in our laboratories; and more than 100 planets have been discovered orbiting other stars. More importantly, traditionally distinct fields have merged to the point where planetary scientists must be conversant with the findings and modes of thinking from astronomy and biology as well as the geosciences. A few examples illustrate this confluence. Theoretical models for the structure of the atmospheres of gas-giant planets led to the first astronomical detection of an extrasolar planetary atmosphere for the transiting planet HD209458b. Although the atmospheric models were based on those for solar-system gas giants, the 3.5-day orbital period means that this planet is 100 times closer to its star than Jupiter is to the Sun, its effective temperature is 1100 K, and the detected signature of the planetary atmosphere was absorption by neutral sodium. Sodium in Mercury's exosphere, detected astronomically from Earth, figures into the question of how the terrestrial planets came to have distinct bulk compositions. Hypotheses to account for Mercury's high uncompressed density, and by inference its high ratio of metal to silicate, range from chemical gradients in the early solar nebula to preferential removal of silicates from a differentiated protoplanet by nebular heating or giant impact disruption, processes that would have affected the final composition of the other inner planets to lesser degrees. These hypotheses will be distinguishable by future remote sensing measurements from a spacecraft in Mercury orbit, but all lead to the prediction that volatile species such as sodium should be deficient in Mercury's silicate fraction. The most recent models for Mercury's exosphere are consistent with the idea that the required fresh supply of sodium from Mercury's surface is no greater than that predicted for meteorite infall. One of the leading questions driving the current exploration of Mars is whether the surface or subsurface was ever conducive to the origin and evolution of life. Sites of hydrothermal circulation within the crust may have provided the necessary energy and chemical building blocks. Remote sensing of candidate hydrothermal minerals at the Martian surface is the leading technique being used to seek such sites, but paleomagnetism may offer another route. Several hypotheses link hydrothermal activity to either the formation of magnetic carriers during the lifetime of the Martian dynamo or the alteration of such carriers after the dynamo ceased, leading to the possibility that high-resolution mapping of crustal magnetism may provide a prospecting tool for promising Martian biological habitats. As Don Anderson showed us by example throughout his career, students of the Earth need not confine their attention to a single planet or even a single planetary system. The lessons from diverse fields that planetary scientists must master to stay current will keep all of us — like Don — young and curious.

S12G MCC: 3011 Monday 1600h

Novel Ways of Analyzing the Seismic Coda III

Presiding: **R Snieder,** Center for Wave Phenomena/Colorado School of Mines; **M Fehler,** Los Alamos National Laboratory

S12G-01 1600h

Hybrid Synthesis of Wave Envelopes in Random Media

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High-frequency seismograms of local earthquakes are mostly composed of incoherent waves that are scattered by distributed heterogeneities in the lithosphere. Although their phase variations are complex, their wave-envelopes are systematic, frequency dependent, and vary regionally. The time width of a wavelet is broadened with increasing travel distance due mostly to diffraction caused by long wavelength spectra of random velocity inhomogeneity. Coda waves are excited due mostly to large angle scattering by the short wavelength spectra. Stochastic approaches are superior to deterministic wave-theoretical approaches for modeling wave envelopes in random media. The Markov approximation for the parabolic wave equation is appropriate for the synthesis of wave envelopes around the direct arrival, and the radiative transfer theory is appropriate for modeling coda envelopes. For the synthesis of whole envelopes from the onset to coda, we propose to use the envelope derived from the Markov approximation as a propagator in the conventional radiative transfer integral equation. The effective isotropic scattering coefficient is given by the momentum-transfer scattering-coefficient, which is mostly controlled by the short wavelength spectra of random media. The envelopes resulting from the proposed hybrid method agree well with ensemble-average envelopes calculated by averaging envelopes from individual finite difference simulations of the wave equation for a suite of 2-D random media having rich short wavelength spectra.

S12G-02 1615h

Anomalous Spatial Distribution Of Coda-Wave Energy Observed In Northeastern Honshu, Japan And Its Interpretation

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Seismic coda waves of local earthquakes are considered to be scattered waves due to short wavelength heterogeneities in the lithosphere and to be distributed uniformly in space at large lapse times. This idea has been applied to the determination of earthquake magnitude of local events and to the measurement of seismic attenuation and site amplification. However, is the spatial uniformity of coda-wave energy observed even in tectonically very heterogeneous regions? We investigate the spatial distribution of S-coda-wave energy in northeastern Honshu, Japan, where a volcanic front is running from north to south. Seismograms recorded by the Hi-net from a large local event are used in this study. At large lapse times, root-mean-square amplitudes of coda waves at each station are calculated for frequency bands of 2-4, 4-8, 8-16 and 16-32 Hz. From this analysis, a clear spatial variation of coda-wave energy across the volcanic front from east (forearc-side) to west (backarc-side) is observed. The coda-wave energy is significantly smaller in the backarc-side than in the forearc-side. The energy is uniformly distributed in the forearc-side, whereas a monotonic exponential decrease with horizontal distance from the volcanic front is found in the backarc-side. The decay rate shows clear frequency dependence and increases with frequency, suggesting strong attenuation of high-frequency waves in the backarc-side. In order to explain this anomalous distribution of coda-wave energy, we propose a diffusion-absorption model that consists of two adjoined half-spaces with different absorption strength. We suppose strong absorption for one half-space to model significant seismic attenuation in the backarc-side. In the long-lapse-time limit, the spatial energy density in the strong absorption medium decays exponentially with the offset from the boundary. It is found that the magnitude of the decay rate is expressed by a simple function of the diffusion coefficient and the absorption coefficient. This indicates that, in northeastern Honshu, Japan, the volcanic front is a boundary between different seismic attenuation structures (forearc-side and backarc-side) and that the assumption of homogeneous spatial distribution of coda-wave energy is not valid in this case.

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S12G-03 1630h

Estimation of two dimensional von Karman stochastic parameters from the seismic coda

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Coda waves are generated from singly and multiply-scattered primary waves in the Earth. The scattered wavefield is composed of converted phases, transmissions, and reflections arising from three dimensional fluctuations in seismic velocities and density. Statistical models of the complex medium are customarily used to explain seismic scattering. Our goal is to invert the coda directly for stochastic properties of the medium through which the seismic energy travels. We characterize the medium with the von Karman autocorrelation model which can accurately model the statistical distribution of velocity/density variations of the crystalline portions of the Earth's crust. Synthetic data generated through von Karman media closely resemble real data. The von Karman autocorrelation model mimics the Earth's self affine nature and can be described in two-dimensions by three parameters; 1) the horizontal characteristic length, 2) the vertical characteristic length, and 3) the Hurst exponent, which describes the roughness of the statistical model. We present two inversion schemes to estimate von Karman parameters. In the first scheme, we show that inverting seismic array data for the lateral characteristic length is possible, but that the inversion has to be calibrated against the central frequency of the input seismic wavelet. In the second inversion scheme, we make use of the multiplicative relation between the power spectra of the observations and that of the source pulse and the stochastic medium. Thus, if we have a good estimate of the seismic pulse, we can invert directly for von Karman parameters. In the absence of complete knowledge of the pulse, we can formulate a nonlinear inversion and estimate the seismic pulse and the von Karman parameters simultaneously. The products of our inversions are cross sections of stochastic properties that can define different areas of texture and/or fabric in the Earth. We demonstrate our inversion on synthetic data as well as a seismic reflection section from the CDROM experiment in the western U.S. With two dimensional, synthetic seismic reflection data, we show that we can recover the dip-dependant lateral characteristic length. Additionally, we present results of inverting for the lateral characteristic length using the CDROM seismic reflection dataset. We claim that inverting for lateral characteristic length can be a useful tool to place bounds on the base of the crust, which is difficult to interpret deterministically in the processed seisic line. Although preliminary results of inverting for the vertical characteristic length with synthetic data are promising, we are still in the process of refining the process. Namely, we find that the primary limitation of the inversion is accurate information of the source pulse. However, with a reasonable estimate of the source pulse power spectrum non-linear inversion holds promise.

S12G-04 1645h

Green's Functions, Source Signatures and the Normalization of Teleseismic Wavefields

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We examine the canonical source/Green's function separation problem within the context of teleseismic body wave propagation and scattering from receiver-side lithospheric/upper-mantle structure. Our principal objective is the recovery of the intramodal *P*-impulse response for use in multi-parameter wavefield inversions. The time-normalized transfer operator that describes the response of a 1-D stratified, elastic half-space to a plane wave incident from below, can be factored into pure transmission and free-surface reverberation parts. Assuming pre-critical interactions, the intramodal entries of the reverberation operator are always minimum phase. The intramodal entries of the transmission operator are not generally minimum phase, but they will be for *P*-waves in weak to moderate contrast stratification; a characteristic that, we argue, persists for the class of laterally heterogeneous media representing real Earth environments. Transformation to minimum phase thus provides a means of normalizing the source within teleseismic *P*-seismograms and serves to emphasize weaker secondary arrivals. The shaping filter derived from this transformation can, moreover, be applied to additional non-minimum-phase wave components to effect a similar source normalization. Minimum-phase normalization facilitates the implementation of simultaneous, source-receiver, multichannel deconvolution within the log-spectral domain through the provision of statistical constraint equations, and facilitation of phase unwrapping. Examples using both synthetic data and seismograms from the Canadian National Seismograph Network demonstrate the recovery of accurate and reproducible estimates of the intramodal *P*-impulse response.

S12G-05 1700h

Energy Scaling for the Hector Mine and Landers Sequences Using Coda-Derived Source Spectra

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Unlike the well-established techniques of long-period waveform modeling for seismic moment (Mo), the measurement of radiated seismic energy (E) requires corrections at and beyond the corner frequency of the event. At these shorter length scales the Earth is considerably more complicated making path and site response corrections the two most important considerations. To minimize the problem of determining path corrections, we have chosen the 1992 Landers and the 1999 Hector Mine sequences in southern California for study using broadband recordings from both local and regional broadband stations. To minimize the effect of source heterogeneity (e.g., directivity and source radiation pattern effects) we have used the coda methodology of Mayeda et al. (2003) to obtain stable, broadband source spectra which are a factor of 3-to-4 more stable than those derived from the direct waves. This methodology also uses small empirical Green's function events to derive site corrections to account for near-site attenuation and amplification. We independently validate our source spectra by comparing against network averaged moment estimates using long-period waveform modeling. Results for events ranging between Mw 3 to 7+ for both sequences using the same methodology and stations clearly shows the scaled energy, e=E/Mo, increases with increasing magnitude. This departure from constant energy scaling had been observed elsewhere but has been questioned because of the large uncertainties in the path, site, and source heterogeneity corrections. We believe that this current study clearly points to a difference in rupture dynamics between small and large events in this sequence. This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

S12G-06 1715h

Detection of Seismic Stress-Drop Anomalies in the Mendocino Transform Using Coda-Derived Source Spectra

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The amplitude and decay rate of L_g or S_n phase coda waves can be measured over a range of narrow frequency bands to determine reliable source moment-rate spectra (*Mayeda and Walter,* JGR 1996). These spectra can be used to measure seismic moment and S-wave energy radiation using data from a single station. This information can in turn be used to calculate Orowan stress drop and investigate E_s/M_0 scaling. Events along the Mendocino transform show considerable variation in static stress drop, which is apparent in large magnitude differentials ($M_w - M_L$ as much as 1 order). Events with such large differentials exhibit enriched low frequencies as observed by examination of displacement seismograms and fourier amplitude spectra. Moment-rate spectra from the coda method confirm the anomalous properties of these events. In this study we discuss seismicity in the Mendocino transform region as observed using the coda method, in terms of static stress drop and E_s/M_0 scaling. We investigate possible explanations for the anomalous seismicity.

S12G-07 1730h

Separating Scattering from Intrinsic Attenuation

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The subsurface appears disordered at all length-scales. Therefore, wave propatation at seismic or ultrasonic frequencies is subject to complicated scatterings. A pulse propagating in the subsurface loses energy at each scattering off an impedance contrast, but also decreases in amplitude as the impulse interacts with fluids in the rock. We call the latter non-elastic effect "intrinsic Q", while the former is "scattering Q". It is often the fluids in the rocks that are of interest, but conventional reflection and transmission of the incident pulse only cannot deceipher the individual components of Q due to scattering and fluid movement in the pore-space. We present an approach that can unravel these two mechanisms, allowing a separate estimate of absorption. This method treats the propagation of the average intensity in the framework of radiative transfer (RT); the arrival of (what is left of) the incident pulse is modeled as the coherent energy, whereas the later arriving multiply scattered events form the incoherent intensity. The coherent pulse decays exponentially due to a combination of scattering and absorption, and so does the incoherent intensity. However, multiple scattering can re-direct energy back to the receiver, supplying a gain-term at later times that makes up the incoherent intensity. Strictly speaking, one can invert for scattering and absorption from the intensity at late times only, often modeled with the late-time equivalent of RT, diffusion. However, we will show that fitting both early- and late-time signal with RT constrains absorption and scattering constants more rigorously. These ideas are illustrated by laboratory and sonic-logging measurements.

S12G-08 1745h

Characterization of the Spectrum of a Random Medium from Trace Measurements

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Imaging provides the ability to determine the geometrical structure of the Earth. However, some portion of the structure cannot be reliably determined from seismic imaging so other approaches must be taken for characterization. Characterization of some portions of the structure can best be done using a random media approach. Such approaches provide valuable tools for understanding scattering and attenuation in the Earth. We have used numerical modeling of wave propagation through random media to better understand what characteristics of the medium can be inferred from analysis of seismic traces. We have recently developed an approach for using traces recorded along a receiver array within a 2D heterogeneous medium to characterize the spatial heterogeneity in the medium. We compare the spectrum of the spatial fluctuation of medium velocity with the spectrum of the spatial fluctuation in integrated rectified trace amplitudes measured along the receiver array. We find that the two spatial spectra are coincident over a wide spatial wavenumber range. We have also investigated the application of the method to surface reflection data calculated in simulations of a homogeneous layer over a heterogeneous half space. The method can determine not only information about the random component of structure but has also been shown to be capable of providing information about fracture characteristics, which is important in petroleum exploration and fluid-flow modeling.

S21A MCC: 3011 Tuesday 0800h

The Fate of Seismic Waves: Measurement and Interpretation of Q of the Earth I

Presiding: **J Xie,** Lamont-Doherty Earth Observatory; **C A Langston,** Center for Earthquake Research and Information, University of Memphis

S21A-01 0800h INVITED

Q in Earth's Core

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Observations of high frequency PKnKP waves, multiply reflected by the underside of the core-mantle