S12B-0396 1330h POSTER

Low Temperature Thermochronology From the SAFOD Pilot Hole: Constraining the Thermal History With Apatite Fission-Track and (U-Th)/He Analyses

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The San Andreas Fault Observatory at Depth (SAFOD) pilot drillhole traverses the upper ~2 km of a site 1.8 km west of the San Andreas fault near Parkfield, California. We use apatite fission-track and (U-Th)/He analyses of drillhole cuttings samples to document the thermal signature of downhole samples currently at a temperature range of $\sim$ 20 to 95 ^{o}C. Knowing the long-term thermal history of the site will be important for interpreting geochemical, structural, and geophysical observations in the SAFOD project. With these data we evaluate the geothermal gradient and exhumational history of the drillhole site. Preliminary (U-Th)/He analyses from drillhole samples decrease in age with depth, with He ages of $\sim$ 20 Ma for samples at 800 m (where the Pilot Hole first encounters Salinian granitic rocks; current temperature $\sim$ 50 ^{o}C) to a He age of 1 Ma in the deepest sample from the base of the hole (at 2.2 km depth; current temperature 95 ^{o}C). The pattern of ages is consistent with that expected for the observed geothermal gradient of $\sim$ 35 $^{o}Ckm^{-1}$ and shows little or no evidence of recent exhumation. Preliminary modeling of fission track length distributions also show that the block has been exhumed less than 1 km in the last 5 m.yr., despite its proximity to the active strand of the San Andreas fault and other related faults.

S12C MCC: 3011 Monday 1340h

Novel Ways of Analyzing the Seismic Coda II

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

S12C-01 1340h INVITED

Extracting and Using Time Domain Green's Functions From Ocean Acoustic Noise

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The long-time temporal correlation of random wave fields received at two receivers basically extracts the time domain Green's function (TDGF) between the receivers. This process applies to either scattered fields or noise, the former often referred to as signal-generated noise. We have shown with theory and data that the long-term temporal correlation of ocean noise between two points yields the effective TDGF between those two points. The deterministic nature of the random-noise extracted TDGF is further demonstrated by utilizing these TDGF's for time reversal (TR) focusing through the background ocean medium. The combination of extracting TDGF's from random fields and deterministic based TR processing suggests a potential for passive tomography and imaging.

S12C-02 1410h INVITED

Interferometric Imaging

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Seismic codas contain information about the environment in which the waves travel. How can this information be extracted and what can it be? I will present some recent work (jointly with L. Borcea and C. Tsogka) that models that behavior of cross correlations of seismic codas, which may also be called coda interferometry. I will use recent results about the time reversal of signals in randomly inhomegenous media which help delimit the information content of the cross correlations. I will also present the results of numerical simulations that illustrate the way in which interferometry can be used for imaging.

URL: http://georgep.stanford.edu

S12C-03 1440h INVITED

Ultrasonic Waves in Strongly Scattering Media: a Symphony of Ultrasound That is Almost all Coda.

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Waves traveling through strongly scattering materials can behave in unusual ways, and in this presentation, I will review recent progress in probing their behavior using ultrasonic techniques. In random systems, ultrasonic experiments on simple model materials (spherical beads suspended in a liquid, porous materials made from sintered glass beads) have shown how the coherent ballistic component can be separated from the dominant multiply scattered waves (the coda), allowing a rather complete picture of wave propagation in such systems to be established. These experiments have also helped to elucidate how multiply scattered waves diffuse, giving a unified physical picture of the relationship between the velocities of energy transport by diffusive and ballistic waves. These fundamental studies of wave transport by multiply scattered waves have facilitated the development of three new techniques in ultrasonic correlation spectroscopy (or coda wave interferometry) for measuring the dynamics of strongly scattering materials: Diffusing Acoustic Wave Spectroscopy (DAWS), Diffusing Reverberant Acoustic Wave Spectroscopy (DRAWS) and Dynamic Sound Scattering (DSS). Very different wave behavior can be observed by arranging the beads in an ordered crystalline array (a phononic crystal), giving rise to a complete bandgap through which the ultrasonic waves travel by tunneling. The presentation will end with a brief description of elastic wave diffusion in porous materials, where the multiply scattered ultrasonic energy is partitioned between P and S waves and remarkably strong scattering can be observed. Work performed with H.P. Schriemer, M.L. Cowan, Suxia Yang, J. Bobowskl, R. Holmes, J. Beck, J. de Rosny, D.A. Weitz, Ping Sheng and Zhengyou Liu.

URL: http://www.physics.umanitoba.ca/~jhpage

S12C-04 1510h INVITED

Partitioning between P and S energies in the long-period seismic coda

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Long-period seismic signals excited by large ($M> 8$) earthquakes remain above the noise level for tens of hours. This long-period seismic coda is composed of surface and body waves that circle or cross the Earth many times and, therefore, can be used to study its average anelastic and scattering properties. Because both direct and scattered waves remain trapped in the Earth, the scattering does not change the average energy balance of the long-period coda. As a consequence, traditional methods based on average time decay cannot be applied to the long-period coda to extract information about the Earth's scattering. Therefore, we propose here another approach that is based on recent theoretical developments of the radiative transfer theory and uses a partitioning between P and S energies as a marker for presence of multiple scattering. Without scattering, the P-to-S energy ratio and, as a consequence, the vertical-to-horizontal energy ratio (VHR) would grow infinitely with time because the quality factor inside the Earth is much higher for P waves than for S waves. This behavior is well predicted by synthetic seismograms computed in an average spherically symmetrical model (PREM). However, VHR calculated using the observed seismograms tend to stabilize after certain time (typically 40000 s at 100 s period) at a value that is independent of earthquake and station locations. We interpret the observed stabilization as an indication of the presence of the multiple scattering and the diffuse waves. This motivates further investigations of a possibility to use the long-period seismic coda, and specifically the cross-correlations between records at two stations, to extract a coherent information about the elastic response of the Earth.

S12D MCC: 2002-2004 Monday 1340h

Theories of Earth's Interior III *(joint with T, V)*

Presiding: **P J Tackley,** University of California, Los Angeles**;** **J D Bass,** University of Illinois

S12D-01 1340h INVITED

20 years of seismic tomography

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With the papers by Masters *et al.* (1982), Nakanishi and Anderson (1982), Woodhouse and Dziewonski (1984) and Dziewonski (1984), global seismic tomography was well on its way to becoming one of the most important geophysical tools in the investigation of the Earth's interior. These early studies demonstrated the power of the method to discover new, unexpected features, such as the degree-two signal in the transition zone, the ring of fast velocities above the core-mantle boundary, and the Pacific and African megaplumes. Since then, tomography has moved towards higher resolution and the mapping of additional structural details, such as the topography of the internal boundaries and azimuthal and radial anisotropy. Anisotropy, in particular, is turning out to be a property that is likely to map the dynamic history of the Earth's interior. Tomographic studies extend to the very center of the Earth, where the inner core has been found to be anisotropic and, recently, to have an inner-most structure with a 300-km radius, which was discovered by identifying its distinct anisotropic properties. Higher resolution has its limits, and reports of slabs penetrating directly into the lower mantle and the detection of mantle plumes extending from the CMB to the surface remain controversial. An irreplaceable resource that has made this progress possible is the Global Seismographic Network, now transmitting most of the data in nearly real time, as envisioned 20 years ago by a small group of forward-looking seismologists.

S

S12D-02 1405h INVITED

Mantle Mineralogy and Mineral Physics: Paradigms and Paradoxes

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Don Anderson has made important contributions to our understanding of the mineralogy and mineral physics of the earth's mantle and core for more than 4 decades. For example, Don's elucidation of elasticity systematics and his perceptive application of such knowledge to understanding the Earth's mantle has been one of the prime motivations for more than a generation of experimental studies. In this talk, we summarize the current status of laboratory experimentation on the mineralogy of the deep mantle, focusing on the areas of elasticity and phase changes. The connection of mineral physics to seismology, a particular area of interest to Don Anderson, will be emphasized. Recently, the study of elastic properties of mantle and core materials has mushroomed as a result of new experimental capabilities. These include the development of several synchrotron-based tools including, for example, x-ray inelastic scattering and lattice strain anisotropy measurements. These have greatly

extended the accessible pressure range and sound velocities have now been reported in iron and other materials to pressures up to 1 MBar. New high-precision studies of compositional variations in garnets, olivines, and high-pressure silicates are placing tight constraints on compositional and structural effects on seismic velocity at upper mantle pressures. In the $(Mg,Fe)_2SiO_4$ system, there is now broad agreement among different research groups on the relevant pressure and temperature derivatives of the aggregate elastic moduli. To first order, the results support Anderson's longstanding proposal for an olivine-poor transition zone, although the presence of volatiles and the non-linear nature of the transformation have been used to argue for more olivine-rich compositions. New synchrotron x-ray diffraction capabilities together with advanced laser heating techniques have also led to important developments in understanding of phase relations in the mantle. In the transition zone, new in situ studies have reopened controversy surrounding the location and slope of the post-spinel transition in Mg_2SiO_4. Phase relations in $MgSiO_3$, SiO_2, and $CaSiO_3$ have been carefully explored at deep lower mantle pressures as have some more chemically complex systems. Broadly speaking, these studies have revealed the existence of structurally subtle phase transitions that nevertheless could have important geophysical implications. Minor chemical elements may also have a major effect on physical and chemical properties under deep mantle conditions. A few key advances and some of the outstanding problems will be highlighted.

S12D-03 1430h

What Mantle Processes Determine Isotopic

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Isotopic measurements on Mid Ocean Ridge Basalts and Ocean Island Basalts indicate effective 'ages' (from e.g., U-Pb or Sm-Nd systems) in the range 1-2 billion years- much less than the age of the Earth, even though melting should have been much more vigorous early on and skewed the mean time since melting to older values. This relatively young 'age' has generally been explained in terms of stretching of heterogeneities by mantle convection, which might reduce them to dimensions too small to be individually distinguishable in short timescales of less than 1 Gyr. On the other hand, published numerical models that use tracers to track differentiated material (Christensen and Hofmann, 1994, Davies, 2002) suggest that Earth-like 'ages' can be obtained without taking stretching-induced erasure of tracer signatures into account, although this might effectively happen if the lengthscale for sampling the isotope systems was large enough. In those models, the only explicit mechanism for resetting isotope systems was re-melting, but for this to explain the isotopic ages observed for basalts, the global rate of melting in the recent past would have had to be very much higher than present-day values. To investigate stretching vs. re-melting we have conducted numerical experiments of a cooling mantle with plate tectonics, differentiation and evolution of important isotopic systems. The time of last melting and the total strain is tracked on each tracer (in addition to isotopic information). The results confirm that a model matching today's crustal production rate and with a reasonable secular cooling history generates ages' that are substantially larger than those observed, with the extent of crustal settling above the CMB making some difference but not enough. The effect of sampling lengthscale on observed age' is also tested and found to be insufficient to explain the data. Thus, these results reaffirm the importance of stretching as a key mechanism for effectively deleting older heterogeneities. From analysis of strain vs. age and matching of the observed ages, it is estimated that erasure of heterogeneities occurs at strains of 10^3-10^4, somewhat larger than has often been assumed.

S12D-04 1445h

Partitioning of Oxygen During Core Formation on Earth and Mars

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Core formation on Earth and Mars involved the physical separation of Fe-Ni metal alloy from silicate, most likely in deep magma oceans. Although core-formation models explain many aspects of mantle geochemistry, they do not account for large differences between the compositions of the mantles of Earth (~8 wt% FeO) and Mars (~18 wt% FeO) or the much smaller mass fraction of the Martian core. Here we explain these differences using new experimental results on the solubility of oxygen in liquid Fe-Ni alloy, which we have determined at 5-23 GPa, 2100-2700 K and variable oxygen fugacities using a multianvil apparatus. Oxygen solubility increases with increasing temperature and oxygen fugacity and decreases with increasing pressure. Thus, along a high temperature adiabat (e.g. after formation of a deep magma ocean on Earth), oxygen solubility is high at depths up to about 2000 km but decreases strongly at greater depths where the effect of high pressure dominates. For modeling oxygen partitioning during core formation, we assume that Earth and Mars both accreted from oxidized chondritic material with a silicate fraction initially containing around 18 wt% FeO. In a terrestrial magma ocean, 1200-2000 km deep, high temperatures resulted in the extraction of FeO from the silicate magma ocean, due to the high solubility of oxygen in the segregating metal, leaving the mantle with its present FeO content of ~8 wt%. Lower temperatures of a Martian magma ocean resulted in little or no extraction of FeO from the mantle, which thus remained unchanged at about 18 wt%. The mass fractions of segregated metal are consistent with the mass fraction of the Martian core being small relative to that of the Earth. FeO extracted from the Earth's magma ocean by segregating core-forming liquid may have contributed to chemical heterogeneities in the lowermost mantle, a FeO-rich D" layer and the light element budget of the core.

S12D-05 1500h

Prograde and Retrograde Free Core Nutations Observed with VLBI

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VLBI nutation measurement series from Goddard Space Flight Center and the United States Naval Observatory have been analyzed for Free Core Nutation resonances. Our analysis implements Singular Value Decomposition to solve the least squares problem of fitting the Discrete Fourier Tranform to the non-equispaced VLBI nutation observations. A novel feature of our procedure is to use the Parseval relation to determine the number of singular values of the coefficient matrix to be eliminated. We report the observation for the first time of the prograde mode predicted by Jiang (1993). The long series of observations allow the determination of the time evolution of the Free Core Nutation. We report a ring down of the large retrograde mode. In addition to providing a value for the viscosity just below the Core-Mantle Boundary, it suggests an impulse excitation rather than a continuous excitation. The interest of one of us (DES) in the rotational dynamics of Earth's core was stimulated by a conversation with Don Anderson about the possibility of the inner core being titled with respect to the shell and that a gravitational restoring torque might result. Indeed a large gravitational coupling exists and plays an important role in the rotational dynamics of the inner and outer cores.

S12D-06 1515h INVITED

Seismic Wave Attenuation and Dispersion: Insights From the Earth and the Laboratory

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The study of the 3D anelastic structure and its frequency dependence using seismological tools, combined with experimental data on Q provide potentially powerful constraints on the rheology and dynamics of the earth's interior. Since the pioneering work of D.L. Anderson and his colleagues in the 1970's and 1980's, progress has been hampered on the seismological side, by the difficulty of separating the effects of intrinsic attenuation from those of elastic scattering and focusing, and on the experimental side, by the difficulty of performing measurements in the combined relevant frequency, temperature, and pressure ranges. The last decade has seen the progressive build-up of a large global dataset of high quality seismic broadband data, as well as significant improvements in processing techniques. In parallel, there has been progress in our ability to model 3D elastic structure as well as its effects on the amplitudes of seismic waves. We focus on discussing recently developed global and regional models of lateral variations in Q in the crust and upper mantle. In particular, we illustrate how, for the first time, 3D global models obtained using different types of waves and processing techniques result in compatible Q distributions in at least the upper 250km of the mantle, which correlate well with global tectonics as well as higher resolution regional results. We discuss future challenges and directions. In parallel with seismological studies, there has been dramatic recent progress in laboratory study of seismic wave dispersion and attenuation - particularly in olivine-dominated upper-mantle materials. Torsional forced-oscillation and microcreep tests of fine-grained synthetic Fo90 polycrystals have revealed a broad absorption band within which Q^{-1} varies smoothly and monotonically with period (with a power-law exponent 0.3), temperature and grain size. Similar studies of melt-bearing olivine polycrystals typically reveal an enhanced level of background dissipation along with a clearly resolved dissipation peak. Superposition of the frequency dependences associated with the background and the long-period side of the dissipation peak results in nearly frequency-independent Q^{-1} for suitable combinations of period, temperature, grain size and melt fraction. The Q^{-1} peak for the melt-bearing materials is apparently not the result of melt squirt; instead it is plausibly attributed to elastically accommodated grain-boundary sliding. However, the behaviour of the melt-free materials is difficult to reconcile with classical models of grain-boundary sliding - suggesting that these need to be re-evaluated. Seismic-frequency laboratory data, extrapolated to the larger grain sizes and higher pressures of the upper mantle, are finally beginning to provide a robust basis for understanding the wave speed variability and attenuation in the mantle. The state-of-the-art will be illustrated with laboratory-based models for the depth dependence of shear wave speed and attenuation for the oceanic upper mantle.

S12E MCC: 3007 Monday 1600h

Seismic Hazards in the Great Basin II

(joint with G)

Presiding: **C M Snelson,** University of Nevada,, Las Vegas**; I G Wong,** Seismic Hazards Group, URS Corporation

S12E-01 1600h INVITED

Quaternary Extensional Tectonics of the Basin and Range Province

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The Basin and Range province is experiencing rapid growth, increasing water demand, and an average of about 11 mm/yr of NW-directed extension. None of these trends are compatible. Most Quaternary faults trend N, have a normal-dip movement, and border strongly uplifted or tilted ranges. Although these faults are spectacular, the slip rates and recurrence intervals for M 6.5+ ground ruptures are ca. 0.1 mm/yr and 10^4 yr, respectively. Obviously, some faults are considerably more active, such as the Genoa fault (2-3 mm/yr) and the Wasatch fault (1-1.5 mm/yr). However, the many hundreds of less remarkable Basin and Range (B&R) faults are poorly documented. Paleoseismic studies of some of these faults reveal average slip rates of 0.05-0.15 mm/yr and recurrence intervals measured in tens of thousands of years. Offsetting this relatively benign hazard are the sheer bulk of faults that riddle the province. A new USGS compilation of faults found ca. 600 structures in Nevada and 150 in New Mexico, 15% of which have been active in the past 15 k.y. Except for historic ruptures in the province, there is little spatial association of faulting and recorded seismicity. For example, the Wasatch fault zone is poorly expressed on Utah seismicity maps, and the Thousand Springs fault was aseismic well before 1983 Borah Peak, Idaho earthquake. Similar examples are common in the B&R, especially its southern half. For the most part, the normal faults are aseismic and locked, but can be loaded to near the point of failure. Conversely, the CNSB has been the preferred site for historic earthquakes larger than M 6.5. From 1872 to 1954, seven large earthquakes ripped through this NNE-trending belt: an average of one rupture every 14 years. Paleoseismic investigations of the CNSB have shown that this rate and spatial pattern of activity is anomalous. There is no evidence for similar precursory activity in the past 50 k.y. and there has been almost 50 years of quiescence since the last large earthquake. So one of the most perplexing questions is "why here and where next". With the advent of GPS monitoring we are starting to better identify