change, as well as the response strategies undertaken by the regions residents, will be felt throughout the nation and the world. The national assessment of Climate Change Impacts on the United States has pointed out that the northern Great Plains could be favored under global warming scenarios in that future climates could increase crop yields [Reilly, Tubiello, McCarl, and Melillo, 2000]. Yield, though, is only one measure of the consequences that rapid warming might have on this region. Challenges to a changing environment must be met by people. Producers here, as well as in other agricultural regions, already function under multiple stresses that are completely separate from climate variability and change. These include falling prices, globalization, complex trade relations, changes in government policy, environmental constraints, and changing consumer preferences. It is against the backdrop of these stresses that pending climate changes must be considered.

Interactions with stakeholders through the NGP Assessment workshops, held in 1997 and 1999, identified key concerns and outlined potential mitigation and optimization strategies for the consequences of climate change in this region. We will present examples of the successful implementation of some of these strategies: actions that farmers and ranchers are employing to 1) increase their awareness of environmental factors, 2) enhance their ability to respond quickly to environmental change, 3) improve their economic returns, and 4) decrease environmental degradation. We will also highlight other no regrets actions and policies under consideration that may offer individual producers greater flexibility in their management decisions and provide a healthier environment for society at large.

U42A MC: Hall D Thursday 1330h

The Science of Abrupt Climate Change and the Implications for Public Policy II

Presiding: **R Alley,** Pennsylvania State University**; A R Isern,** National Science Foundation

U42A-0008 1330h POSTER

Possible role of different helio-geophysical factors in abrupt climate change

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As shown by recent investigations, galactic cosmic rays (GCR) exert a considerable influence on physical and chemical processes in the troposphere, including development of cloudiness. More intense (less intense) GCR fluxes result in the increasing (decreasing)lower cloudiness (Palló Bagó and Butler, 2000; Marsh and Svensmark, 2000) and, as a consequence, in lower (higher) near-surface temperatures. Modulation of GCR fluxes can be caused by variations in solar activity (from days to thousands of years on time scale) and changes in the geomagnetic field (from hundreds to thousands of years on the time scale).The additive effect of these factors, together with effect of other climatic processes in the Earth's atmosphere (for instance, Henrich events), can lead to an abrupt climate change. Examples of the additive effect of changes in the geomagnetic field and solar activity can be the Younger Dryas cooling event and abrupt climate change around 2,700-2,800 years BP. Both these cooling events occured, as follows from proxy data, during the minimum of quasi-2,400-year solar cycle and , hence, Gothenburg and Etrussia geomagnetic exursions. These effects lead to enhancement of the GCR flux, and, hence, to colling of the lower troposphere. At the Holocene boundary, the additive effect of three factors contributing to climate warming was observed. The first was an abrupt increase in the geomagnetic field, which resulted in weaker GCR fluxes. The second factor was the growth in the activity of the 2,400-year solar cycle, which enhanced solar radiation and weakened GCR fluxes. The third was astronomical factors (the Milankovitch effect) which also contributed to climate warming. The effects of the factors mentioned above enhanced each other, which could lead to the abrupt climate change at the Holocene boundary. Analysis has shown that abrupt climate change events occure as a rule, if several helio-geophysical and climatic factors are acting simultaneously in the same direction. This work was supported by EC (grant INTAS 97-3100 and IC 15CT98-0123 EXTRATERRESTRIAL) and RFBR (grant 00-05-64921).

U42A-0009 1330h POSTER

The Ice Core Correllation Game: What can we learn about global climate

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Prominent changes in oxygen qnd deuterium isotopic composition of the ice and in the methane concentrations in trapped atmosphere in ice cores allow a detailed correlation of ice core records from the arctic and antacrtic.

U42A-0010 1330h POSTER

The Rapidly Diminishing Arctic ice Cover and its Potential Impact on Navy Operational Considerations

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Observations made from U.S. Navy Fleet submarines during the 1990s have revealed a dramatic decrease in thickness, when compared to historical values, of the central Arctic Ocean pack ice cover. Estimates of this decrease have been as high as 40%. Remote sensing observations have shown a coincident decrease in the areal extent of the pack. The areal decrease has been especially apparent during winter. The overall loss of ice appears to have accelerated over the past decade, raising the possibility that the Northwest Passage and the Northern Sea Route may become seasonally navigable on a regular basis in the coming decade. The ice loss has been most evident in the peripheral seas and continental shelf areas. For example, during winter 2000-2001 the Bering Sea was effectively ice-free, with strong and immediate impacts on the surrounding indigenous populations. Lessening of the peripheral pack ice cover will presumably, lead to accelerated development of the resource-rich regions that surround the deep, central Arctic Ocean basin. This raises potential issues with respect to national security and commercial interests, and has implicit strategic concerns for the Navy. The timeline for a significantly navigable Arctic may extend decades into the future; however, operational requirements must be identified in the nearer term to ensure that the necessary capabilities exist when future Arctic missions do present themselves. A first step is to improve the understanding of the coupled atmosphere/ice/ocean system. Current environmental measurement and prediction, including Arctic weather and ice prediction, shallow water acoustic performance prediction, dynamic ocean environmental changes and data to support navigation is inadequate to support sustained naval operations in the Arctic. A new focus on data collection is required in order to measure, map, monitor and model Arctic weather, ice and oceanographic conditions.

U42A-0011 1330h POSTER

Reconstruction of the Surface Temperature Change in Central Greenland During D/O 12, 45 Kyr B.P.

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Air bubbles preserved in polar ice cores are unique archives of past atmospheric composition. Recently, it has been shown that air bubbles isotopic composition (N-15, Ar-40) enables to quantify past abrupt changes in polar regions. In this study, a high resolution measurement of nitrogen and argon isotopes in an ice core from Greenland allows to determine past surface temperature variations and the ice age-gas age difference during the Dansgaard-Oeschger event 12 recorded around 45,000 years before present. These results imply a mean surface temperature change of 8.2 $\pm$ 0.8 °C and permit to determine a $\delta^{18}O_{ice}$-temperature coefficient of 0.54 $\pm$ 0.05 $^{o}/_{oo}/^{o}$C and therefore bring a new constraint to calibrate the isotopic paleothermometer during glacial period. Moreover, a direct comparison with methane concentration will be presented to discuss the phase relationship between the warming and the methane increase.

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U42A-0012 1330h POSTER

Rapid Climate Change at Siple Dome, Antarctica

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The 1004 m deep ice core from Siple Dome, Antarctica contains a paleoclimate record that spans at least the last 100,000 years. The most striking features of the paleoclimate record are two intervals at roughly 15 and 20 kyr BP. Both events are characterized by a transition period of reduced ice accumulation followed by an abrupt and persistent increase in surface temperatures. For the 15 kyr event the duration of the transition period was less than a few hundred years and ice accumulation dropped to zero or negative rates. The magnitude of the increase in surface temperature was at least 3 degrees and ice accumulation rates where similar before and after the event. For the 20 kyr event the duration of the transition period was less than 100 years and possibly as short as 50 years. The magnitude of the step increase in surface temperature was about 5 degrees and the ice accumulation rate was at least one-third lower after the event than before. Deuterium excess measurements indicate the two events had differe

U42B MC: 134 Thursday 1330h

Virtual Earth Laboratories II *(joint with NG, GP, S, T, DI, MR)*

Presiding: **H Bunge,** Princeton University**; L Stixrude,** Univ. of Michigan**; J Tromp,** California Institute of Technology**; R Hollerbach,** Univ. of Glasgow

U42B-01 1335h INVITED

Prospects for Realistic Models of Planetary Dynamos

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The current generation of numerical dynamo models powered by convection in rotating, electrically conducting fluid spheres now reach magnetic Reynolds numbers of several hundred, comparable to the geodynamo. They qualitatively reproduce many of the important characteristics of the geomagnetic field, including axial dipole dominated main fields, strong radial flux concentrations at high latitudes, low flux over the poles, secular variation with westward drift, and occasional polarity reversals. However current numerical dynamos are not scale models of planetary dynamos because τ, the ratio of long time scale (measured by the dipole diffusion time) to short timescale (measured by the length of day), is too small. In numerical dynamo models $\tau \simeq 5\times10^4$ whereas in the Earth's core $\tau \simeq 5\times10^6$. An increase in computational speed by a factor 10^4 would provide at least one order of magnitude increase in τ, with full spatial resolution. This would place numerical dynamos on the threshold of scale similarity with the geodynamo, and also with dynamos in the other terrestrial planets.

U42B-02 1355h INVITED

Towards a Virtual Solid Earth for Simulating the Long-Term Thermo-Chemical Evolution of the Plate-Mantle System

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Mantle convection and plate tectonics are two aspects of a single system that involves both thermal convection and chemical differentiation, recycling and mixing. Temperature and composition are inextricably linked because both affect density, rheology, and other dynamically-important properties. A major goal in geodynamics is thus to develop a Virtual Solid Earth (VSE), i.e., an integrated, thermo-chemical dynamical model of Earths plate-mantle system, capable of simulating Earths evolution over billions of years in order to test hypotheses regarding the evolution and present day structure of Earths mantle and lithosphere (including crust). This virtual solid Earth would integrate constraints from mineral and rock physics, seismology, geochemistry and geology within a self-consistent dynamical framework.

While we have now reached the stage where thermal-only convection models of Earths mantle (essentially an infinite-Prandtl number fluid with strongly temperature-dependent viscosity) can approach Earths convective vigor in 3-D spherical geometry, a full VSE presents much stronger modeling challenges because of (i) the huge variations in rheology and associated lengthscales (from elastic faults to distributed viscous creep) over the range of temperature, pressure and stress conditions, and (ii) the negligible diffusivity of chemical variations, leading to small-scale structures. Much progress has been made over the past few years on the two key aspects of integrating plate tectonics with mantle convection, and including the differentiation and mixing of geochemical species, both major and minor, in mantle convection models. This talk will discuss the general framework and challenges involved in developing such models, and present sample results from a preliminary, two-dimensional VSE, which demonstrates the strong sensitivity of Earth evolution to poorly-known quantities such as the variation of density with composition in the deep mantle.

U42B-03 1415h

Noble gas Records of Early Evolution of the Earth

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Comparison between atmospheric noble gases (except for He) and solar (or meteoritic) noble gases clearly suggests that the Earth should have much more Xe than is present in air, and thus that up to about 90 percent of terrestrial Xe is missing from the Earth (1). In this report, we discuss implications of these observations on I-Pu chronology of the Earth and on the origin of terrestrial He3.

Whetherill (2) first noted that an estimated I129/I127 ratio (3x10-6) in the proto-Earth was about two orders of magnitude smaller than values commonly observed in meteorites (10-4), and pointed out the possibility that Earth formation postdated meteorites by about 100Ma. Ozima and Podosek (1999) came to a similar conclusion on the basis of I129/I127-Pu244/U238 systematics (1). In this report, we reexamine I-Pu systematics with new data for crustal I content (295 ppb for a bulk crust, (3)). With imposition of an estimated value of 86 percent missing Xe as a constraint on terrestrial Xe inventory, we conclude that the best estimate for a formation age of the Earth is about 28Ma after the initial condensation of the solar nebula (at 4.57Ga). The formation age thus estimated is significantly later than the generally assumed age of meteorites. We also argue from the I-Pu systematics that the missing Xe became missing place about 120Ma after Earth formation.

Assuming that the Earth is mostly degassed, the I-Pu formation age of the Earth can be reasonably assumed to represent a whole Earth event. Therefore, we interpret that the I-Pu age of the Earth represents the time when the Earth started to retain noble gases. More specifically, this may correspond to the time when the proto-Earth attained a sufficient size to exert the necessary gravitational force. A giant impact could be another possibility, but it remains to be seen whether or not a giant impact could quantitatively remove heavier noble gases from the Earth. It is interesting to speculate that missing Xe was sequestered in the core during core formation. Core formation time would then be related to the time of the missing Xe event. The above estimated missing Xe age is close to the core formation age suggested from Nb-Zr systematics (4) and from U-Pb systematics (5), but considerably later than that suggested from Hf-W systematics (6).

From a comparison of relative elemental abundance of noble gases between the Earth and the solar composition, we show that terrestrial He3 may be totally unrelated to heavier noble gases. This requires independent origin of terrestrial He3 from heavy noble gases.

1.Ozima M. and Podosek F.A. (1999) JGR, 104(BII), 25493. 2.Whetherill G.W. (1975) Ann. Rev. Nuclear Science, 25, 283. 3.Muramatsu Y. and Wedepohl K.H. (1998) Chemical Geology, 147, 201. 4. Jacobsen S.B. and Yin Q.Z. (2001) Lunar Planetary Science, XXXII, 1961.pdf (abstract). 5.Galer S.J.G. and Goldstein S.L. (1995) in Geophysical Monograph 95, 75-98, AGU. 6.Halliday A.N., Lee D.-C. and Jacobsen S.B. (2000) in Origin of the Earth and Moon, 45-62, Univ. Arizona Press.

U42B-04 1430h INVITED

Inner core elasticity and temperature from first principles

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The observations of inner core anisotropy and local heterogenity, as well as possible differential rotation of the inner core with respect to the mantle, have generated considerable interest in the physical state and dynamics of the inner core. Of particular importance are the structure and elasticity of its main constituent, iron, at the appropriate conditions of pressure and temperature. Here we report results on the structure and elasticity of dense hcp iron at high temperature based on a combination of first principles total energy methods with a mean field approach to the lattice vibrations. We find that the axial ratio c/a of hcp iron increases almost to 1.7 at a temperature of 5700 K, where aggregate bulk and shear moduli agree with those of the inner core. This suggests that thermal effects in dense crystalline iron alone can explain the low shear wave velocity in the inner core, and additional mechanisms are not necessary. As a consequence of the increase in c/a we have found that the single crystal longitudinal anisotropy of hcp iron at high temperature has opposite sense from that a low temperature, calling into question previous attempts to explain inner core anisotropy. Combining our results for the single crystal elastic constants with a simple model of polycrystalline texture of the inner core, in which basal planes are partially aligned with Earth's rotation axis, we can account for major features in the seismological observation of inner core anisotropy.

U42B-05 1450h

Elasticity of $(Mg_{1-x},Fe_x)SiO_3$-Perovskite at High Pressures

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One major goal of high pressure research is the interpretation of the dynamical state, the mineralogy and the composition of the earth's interior. Our ability to extract this information from the rich source of seismological observations is largely limited by our lack of knowledge of mantle elasticity for major mantle phases such as magnesium rich $(Mg_{1-x},Fe_x)SiO_3$-perovskite.

To address the issue how iron affects the elastic properties at lower mantle pressures we perform spin-polarized first-principle calculations with variable cell shape. We employed the planewave pseudopotential method and investigated simulation cells up to 80 atoms with iron contents up to 25 at%. We focus on Mg⇒Fe substitutions. In all calculations we fixed iron in its high spin state which is thought to persist throughout the earth's lower mantle. In our calculations we optimize the cell shape and the internal coordinates simultaneously. This allows us to investigate the variation of the equilibrium structure with applied pressure and to obtain the equation of state of iron bearing perovskite. The application of small strains to the equilibrium cell enables us to determine the induced stress and to obtain the full elastic constant tensor. These results can be used directly to determine the effect of iron on aggregate properties such as the shear-modulus and single crystal elastic wave velocities at high pressures.

The preliminary results of our athermal calculations for $(Mg_{1-x},Fe_x)SiO_3$-perovskite with x=0.25 show that the unit cell volume increases as iron is added and that the unit cell becomes less distorted in agreement with experimental observations. Our equation of state calculations show that K_0 is almost independent of iron content and the arrangement of iron in the simulation cell (for fixed iron-content). The shear modulus as obtained from our calculated elastic constant tensor shows a much more pronounced dependence on iron content, it is reduced by ≈7.7% for x=0.25 as compared to $MgSiO_3$-perovskite at 135 GPa. The calculated elastic single crystal anisotropy depends only weakly on iron content and the results for x=0 and x=0.25 differ by less than 2% at core mantle boundary pressures.

U42B-06 1505h

The diamond anvil cell as a deformation apparatus for investigating the rheology of the deep Earth

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Considerable progress has been made in establishing deformation mechanisms for minerals and rocks from the Earth's crust and and upper mantle. However, much less is know about the deeper Earth's minerals because the pressures are beyond the conditions reached by ordinary deformation apparatus such as the Griggs, Heard or Paterson apparatus.

Diamond anvil cells allow investigations of the whole pressure and temperature range of the lower mantle. In pilot experiments on hcp-Fe at 54 and 220 GPa development of a strong textures was observed and slip systems of the hexagonal closed packed iron could be identified (Wenk et al., 2000). The technique has now been further refined in order to study in situ the shear strength and deformation mechanisms at high pressure in great details.

In this study, we apply this technique to pure periclase (MgO) to pressures of 47 GPa. The uniaxial stress component in the pollycrystalline MgO sample is found to increase rapidly to 8.5 GPa at a pressure of 10 GPa in all experiments. According to our measurements, the preferred orientation is due to deformation by slip. A quantitative comparison between the experimental textures and results from polycrystalline plasticity suggest that the 110<110> is the only significantly active slip system under very high confining pressure.

These data demonstrate the feasability of determining deformation mechanisms and shear strength under pressures relevant for the Earth's lower mantle. This approach can now be extended to study variations of the properties with both pressure and temperature and can also be used to study other deep Earth's materials such as magnesiowustite and perovskite.

Wenk, H.R., S. Matthies, R.J. Hemley, H.K. Mao, and J. Shu, Nature, 405, 1044-1047, 2000. Merkel, S., H.R. Wenk, J. Shu, G. Shen, Ph. Gillet, H.K. Mao, and R.J. Hemley, J. Geophys. Res. submitted

U42B-07 1535h INVITED

Recent Developments in Computational Seismology Using the Spectral Element Method

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With the increasing availability of high quality broadband digital data sets in both global earth and earthquake studies, new Direct Numerical Simulation (DNS) methods are now required in seismology to : understand the physics of wave propagation in heterogeneous models ; assess the impact of classical approximations used to compute synthetic seismograms ; assess the actual resolution of the seismological models, and seismic records, with respect to small scale heterogeneities. However, in contrast to the rapid progress of computational seismology in exploration geophysics, DNS methods are less advanced in global seismology and earthquake dynamics. With the advent of modern parallel computer architectures, recent progresses have been achieved in computational seismology in the last three years. In particular, Spectral Element Method (SEM) has been shown to provide an accurate and efficient tool for solving wave propagation at both regional and global scales. The method can be very efficiently implemented in distributed memory parallel architectures. After reviewing quickly the spectral element method and its implementation in the context of global seismology and earthquake dynamics, we will illustrate through various examples the new possibilities of this method in these two fields. spectral element method can also be extended in order to allow for non conforming domain decomposition and mesh refinements. Such a mesh refinement flexibility is crucial for an accurate representation of localized heterogeneities within a global model while reducing the computational cost. This can be considered as a first step toward a multiple scale method. Recent developments in this direction will be illustrated and potential potential applications in computational seismology will be discussed, as well as some of the future challenges.

U42B-08 1555h INVITED

Spectral-Element Method Simulations of Global Wave Propagation: Determining the Quality of Global Model S20RTS.

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Geodynamic modeling of large-scale mantle circulation (e.g., slab descent, plume formation) is to a large extent influenced by images of seismic velocity heterogeneity in the mantle. In order to discriminate among competing geodynamic models, it is key to interpret seismic tomographic models subject to rigorous analysis of their resolution.

Commonly, analyses of tomographic model resolution involve inversions of synthetic data sets (e.g., 'checkerboard' and 'spike' tests). These tests are designed to recognise artifacts that result from heterogeneous data coverage and smoothness constraints imposed on the model. However, model inaccuracies resulting from the application of simplified forward modeling theories have not been fully investigated. The construction of model S20RTS [*Ritsema et al.*, 1999], for example, utilises body-wave ray-theory, which ignores the fact that the propagation of (long-period) body-waves is affected by structure as far as 1000 km from the ray path.

With the Spectral Element Method (SEM) of *Komatitsch and Tromp* (1999) it is now possible to compute global seismic wave propagation at periods longer than 20 s for arbitrarily complex Earth models (including the effects of variable ocean depth, crustal thickness and seismic velocity anisotropy) The SEM is therefore useful to assess the extent to which the quality of large-scale S velocity models is compromised by simplified descriptions of seismic wave propagation. Focussing on S20RTS, we compare SEM synthetic waveforms with observed waveforms, determine whether there are systematic differences between SEM predicted ray-theoretical travel times, and verify whether SEM simulations reproduce the coherent geographic variations of SS-S travel times and SS/S amplitude ratios.

U42B-09 1610h

Spectral-Element Simulations of Global Seismic Wave Propagation: 3-D Models, Oceans, Rotation, and Self-Gravitation

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We use a spectral-element method (SEM) to simulate seismic wave propagation throughout the entire globe. The SEM is based upon a weak formulation of the equations of motion and combines the flexibility of a finite-element method with the accuracy of a global pseudospectral method. We include the full complexity of 3-D Earth models, such as lateral variations in compressional wave velocity, shear wave velocity and density, a 3-D crustal model, ellipticity, as well as topography and bathymetry. We also include the effects of the oceans, rotation, and self-gravitation. We show that these effects, which are often considered negligible in global seismology, can in fact play a significant role for certain source-receiver configurations. Anisotropy and attenuation are also incorporated.

The method is implemented on a parallel computer using a message-passing technique (MPI). The complex effects under study are introduced in such a way that we preserve the main advantages of the SEM, which are an exactly diagonal mass matrix and very high computational efficiency on parallel computers. The calculations are performed on a large Linux PC Cluster (a Beowulf) with 151 processors and 76 Gigabytes of distributed memory.

We benchmark spectral-element synthetic seismograms against normal-mode synthetics for spherically symmetric reference model PREM in order to validate our implementation of the oceans and self-gravitation. The two methods are in excellent agreement for all body- and surface-wave arrivals with periods greater than 20 seconds. We subsequently present results of simulations for real earthquakes in fully 3-D models for which the fit with data is very significantly improved compared to classical normal-mode calculations for PREM.

URL: http://www.gps.caltech.edu/∼komatits

U42B-10 1625h

Seismicity as the Conversation Among Faults, or Earthquake Interaction Viewed Through the Prism of Stress Transfer

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During the 75 years before the great 1906 M=7.6 earthquake on the San Andreas fault, the San Francisco Bay area suffered at least fourteen $M \geq 6$ shocks on all major faults; during the succeeding 75 years, there was but one $M \geq 6$ shock. No large shocks occurred on the central 1,000 km of the North Anatolian fault during the 150 years before the 1939 M=7.9 Erzincan earthquake. During the succeeding 60 years, twelve $M \geq 6.8$ shocks struck in a largely westward propagation. These examples furnish evidence that large earthquakes can inhibit or promote failure on nearby faults for decades to centuries. This phenomenon is not restricted to large shocks: For small shocks as well, seismicity rates are observed to increase at some sites (called aftershocks), while at other sites, seismicity rate decrease (which we might call antishocks). Neither the positive nor negative seismicity rate changes are permanent; instead they undergo an exponential recovery with time.

Surprising success has been achieved in explaining these observations by Coulomb stress transfer in an elastic medium, coupled with the time-dependence described by rate and state friction of Dieterich. While the mean Coulomb stress drops on the fault rupture, it is changed on surrounding faults. Where the shear stress increases and faults are unclamped, failure is promoted; where the reverse occurs failure is inhibited. Detailed studies reveal that off-fault aftershocks occur where the Coulomb stress is calculated to have risen, and antishocks occur where it is calculated to have dropped. Equally important, the correlation is seen in the global Harvard CMT catalog: During the first year after an $M \geq 7$ event, the rate of $M \geq 5$ shocks is twice as high at sites of calculated shear stress increase than at sites of stress decrease, and this difference persists for a decade. From this work emerges what may be a property of seismicity: the rate of shocks jumps where the Coulomb stress is suddenly increased, and the rate of shocks plummets where it is suddenly dropped. This applies regardless of earthquake magnitude, and has nothing to with whether the seismicity is on or off a fault rupture.

Researchers in the U.S., Japan, Italy, and France, are rapidly exhausting the limits of static elastic simulations of stress transfer, and are beginning to include inelastic processes. Dynamic stress changes may explain the tendency for off-fault seismicity to be preferentially triggered in the direction of rupture propagation. Postseismic viscoelastic stress transfer introduces other mechanisms for decade or longer delays in earthquake triggering as stress relaxes in the upper mantle, reloading the crust. Poroelasticity and fluid effusion may alter fault friction and change the effective normal stress with time, adding yet another time dependence. Finally, if stress transfer proves to be as ubiquitous as here envisaged, efforts to forecast long-term earthquake likelihood will suffer unless earthquake interaction is included. After all, given the order of magnitude decrease in earthquake rate after 1906, how can one estimate the $M \geq 6$ probability in the San Francisco Bay area during the next 30 years unless one understands why the rate plunged?

URL: http://quake.usgs.gov/∼ross

U42B-11 1640h INVITED

The Australian Computational Earth Systems Simulator

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Numerical simulation of the physics and dynamics of the entire earth system offers an outstanding opportunity for advancing earth system science and technology but represents a major challenge due to the range of scales and physical processes involved, as well as the magnitude of the software engineering effort required. However, new simulation and computer technologies are bringing this objective within reach. Under a special competitive national funding scheme to establish new Major National Research Facilities (MNRF), the Australian government together with a consortium of Universities and research institutions have funded construction of the Australian Computational Earth Systems Simulator (ACcESS). The Simulator or computational virtual earth will provide the research infrastructure to the Australian earth systems science community required for simulations of dynamical earth processes at scales ranging from microscopic to global. It will consist of thematic supercomputer infrastructure and an earth systems simulation software system. The Simulator models and software will be constructed over a five year period by a multi-disciplinary team of computational scientists, mathematicians, earth scientists, civil engineers and software engineers. The construction team will integrate numerical simulation models (3D discrete elements/lattice solid model, particle-in-cell large deformation finite-element method, stress reconstruction models, multi-scale continuum models etc) with geophysical, geological and tectonic models, through advanced software engineering and visualization technologies. When fully constructed, the Simulator aims to provide the software and hardware infrastructure needed to model solid earth phenomena including global scale dynamics and mineralisation processes, crustal scale processes including plate tectonics, mountain building, interacting fault system dynamics, and micro-scale processes that control the geological, physical and dynamic behaviour of earth systems. ACcESS represents a part of Australia's contribution to the APEC Cooperation for Earthquake Simulation (ACES) international initiative. Together with other national earth systems science initiatives including the Japanese Earth Simulator and US General Earthquake Model projects, ACcESS aims to provide a driver for scientific advancement and technological breakthroughs including: quantum leaps in understanding of earth evolution at global, crustal, regional and microscopic scales; new knowledge of the physics

of crustal fault systems required to underpin the grand challenge of earthquake prediction; new understanding and predictive capabilities of geological processes such as tectonics and mineralisation.

URL: http://www.quakes.uq.edu.au/ACESS

U42B-12 1655h

A Virtual Earth Simulator to Simulate Rupture Propagation on Earthquake Faults

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The particle-based Lattice Solid Model was developed to provide a basis to study the non-linear dynamics of earthquakes and the physics of rocks. A new approach, termed LSMearth, has been developed that allows different microphysics of earthquakes to be easily studied. The model - which runs in 2D or 3D is implemented using an object-oriented approach and enables the effect of different microphysics on macroscopic behaviour to be studied. The application provides a virtual laboratory where all measurable quantities can be visualized and where the simulation, running on a remote super-computer, can be controlled from any personal computer. Simulations are run in parallel using a message passing approached based on MPI.

Unlike laboratory experiments which are limited in scale and where direct observations of the contacts occurring between grains of rock in the gouge layer is not possible, the numerical simulations allow the study of the nucleation process as well as the propagation of the shear rupture in experiments performed with bare surfaces or a gouge layer. Because the size of a shear rupture zone is approximately one order of magnitude larger than the nucleation region size, large-scale numerical simulations are here executed to analyse both shear rupture and the nucleation process and to study the scaling of the size and the duration of the nucleation with the size of the eventual earthquake. Using such large-scale experiments, the model provides a means to improve our understanding of the nucleation process and to gain insights into the mechanisms that control the growth of the nucleation zone.

U42C MC: 134 Thursday 1730h

The Future of Climate Change Research; Presentation by Ari Patrinos; Associate Director, Health Environmental Research, U.S. Department of Energy

Presiding: **M K McNutt,** Monterey Bay Aquarium Research Institute

U42C-01 1730h

The Future of Climate Change Research

Aristides Patrinos

Department of Energy, Health and Environmental Research 5804 Tudor Lane, Rockville, MD 20852, United States

There is no abstract for this presentation.

U51A MC: 134 Friday 0830h

Origin and Early Evolution of the Earth I

Presiding: **K Righter,** University of Arizona; **D C Rubie,** University of Bayreuth

U51A-01 0830h INVITED

Habitability of Terrestrial Planets in the Early Solar System

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The Protoearth, Mars, Venus, and the Moon-forming impactor were potentially habitable in the early solar system. The interiors of larger asteroids had habitable circulating water. To see when the inner solar system became continuously habitable, one needs to consider the most dangerous events and the safest refugia from them. Early geochemical and accretionary processes set the subsequent silicate planet reservoirs and hence hydrospheric and atmospheric masses. The moon-forming impact made the Moon and the Earth sterile bodies. Following the impact, the Earth passed through a rock-vapor atmosphere on the scale of 1000s of years and an internally heated steam greenhouse on the scale of 2 m.y. Minerals bearing the principle volatiles (water, Cl, and CO2) were stable at the Earths surface by the time it cooled to 800K. The mass of reactable shallow material was insufficient to contain the available water and CO2. Habitable conditions were established after CO2 could be deeply subducted into the mantle. Vast quantities of H2 were vented during accretion and after the moon-forming impact and eventually lost to space. It is unknown whether significant amounts of this gas were present when the Earths surface cooled into the habitable range. The moon remained sterile because its interior is essentially devoid of water. The mantle of the Earth, in contrast, cannot hold the available water, leaving the excess to form oceans. Nitrogen may behave similarly with the excess going into the air. Impacts of large asteroids (and comets) were an ever-present danger on otherwise habitable planets. The safest niche on planets was kilometer or deeper crustal rocks habitable by thermophiles. It is inevitable that several objects, which would have left only thermophile survivors, struck the Earth. Such events were so infrequent that the conditions of such a bottleneck should not be confused with conditions for the origin of life. An alternative refugium involves ejection of life within rock fragments and return of such fragments to the surface of the home planet or transfer to another habitable planet. Mars and the larger asteroids were habitable first and provide likely sources of seed and also testable places to look for preserved evidence. Extant terrestrial life appears to have passed through thermophile bottlenecks. There are subtle hints of space transfer. The need of extant life for Ni may be a vestige of life on a young planet covered with ultramafic rocks.

U51A-02 0850h INVITED

An impact origin of the Earth-Moon system

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In the leading hypothesis for lunar origin, the Moon forms from debris ejected as a result of the collision of a roughly Mars-sized impactor with early Earth (Hartmann & Davis 1975; Cameron & Ward 1976). The likelihood of giant impact events has been substantiated by over a decade of planetary accretion simulations (e.g., Wetherill 1985, 1992; Agnor et al. 1999; Chambers 2001). The most recent simulations predict a median accretion time of 50 million years for an Earth analogue to reach 90% of its final mass (Chambers 2001), in good agreement with lunar and terrestrial formation times derived from Hf-W systematics (e.g., review by Halliday et al. 2000).

Simulations of potential lunar forming impacts using a method known as smooth particle hydrodynamics, or SPH, can now achieve resolutions sufficient to study the production of bound debris necessary to yield the Moon. A wide variety of works have found that off-center, low-velocity collisions yield material in bound orbit from which a satellite may then accumulate. However, identifying impacts capable of producing the Earth-Moon system has proven difficult (Cameron 1997, 2000, 2001; Cameron & Canup 1998, Canup et al. 2001). Previous works (Cameron 1997, 2000, 2001) identified only two types of impacts capable of producing the Moon. The first involved an impact by an object with about 3 times the mass of Mars, and about twice the angular momentum of the Earth-Moon system; the second involved an the impact of an object with about twice the mass of Mars with an Earth that was only about half formed. Both scenarios are more restrictive and problematic than that originally envisioned, since they require that the Earth-Moon system's mass or angular momentum be significantly modified after the Moon-forming event by either multiple large impacts, or selective subsequent accretion of material onto only the Earth and not the Moon.

Recent scaling trends identified in the SPH simulation results (Canup et al. 2001) implied that a smaller, Mars-mass impactor would be better able to simultaneously account for the Earth-Moon system mass and angular momentum (Canup & Asphaug 2001). This smaller scale impact had not been considered viable since early low-resolution SPH simulations found that it placed too much iron into orbit to yield an appropriately iron-poor Moon (Benz et al. 1986). However, recent work using high-resolution simulations (Canup & Asphaug 2001) found that impacts by an object with 10 to 12% of the Earth's mass produce orbiting debris that is less than 3% iron by mass, and that contains sufficient mass and angular momentum to yield the Moon outside the Earth's Roche limit. This type of impact leaves the Earth-Moon system with approximately its final mass and angular momentum, and implies that the Moon formed near the very end of Earth's accretional history.

U51A-03 0905h INVITED

Review of Early Intense Bombardment and Associated Problems

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Since pre-Apollo years of the 1960s, it has been recognized that cratering on the moon must have been much more intense, averaged over the first few hundred My, than the average after 3500 My ago. This phenomenon is known as the "early intense bombardment." Initial interpretation of Apollo data raised the possibility that much of this cratering occurred in a single episode, or "spike" on the flux vs time curve, at about 3950 My ago, with a width of about 150 My. In some interpretations this was the primary source of all early cratering, known as a "catastrophic terminal bombardment." In one model Ryder has suggested that there was very little cratering before this. In other models, this is a spike superimposed on a declining flux, and there may have been various spikes.

A host of problems remain.

(1) Do we really have adequate dates for the lunar basins? The predominant opinion seems to be that virtually all visible basin were created in a burst within about 300 My. Confirming these dates would resolve the existence of the proposed catastrophe, which would then be constrained to involve numerous 50 and 100-km scale bodies hitting the moon.

(2) How does intense cratering work to remove earlier samples of igneous crustal rocks and impact melts? The original suggestion of the catastrophe was in order to explain the paucity of pre 4000-My rocks in the lunar sample. Cumulative impacts tend to destroy early rocks whether or not they are concentrated in a catastrophe. In some models, the extended declining impact, due to megaregolith production, tends to destroy impact melts because they concentrate at the surface, while dredging up (and yet also pulverizing) crustal igneous samples from deep-seated reservoirs.

(3) How severe is the absence of pre-4000 My impact melts? Their absence has been used as an argument for the existence of a cataclysm at 3950 My ago. But the details of item (2) need to be combined with actual distributions of impact melt ages and igneous rock ages to refine these discussions.

(4) Do lunar meteorites show the same age distributions and properties as the front side Apollo samples? This may be a test of the hypothesis that Imbrium debris have contaminated the front side.

(5) Do asteroids show the same age distributions as the lunar samples? Available models of a cataclysm at 3950 My ago suggest the impactors came from the outer solar system and therefore they should have affected the asteroid belt as well.

(6) What is the significance of the "Genesis Rock," ALHA 84001, among the first 20 specimens from Mars given that astronauts were trained to look for lunar "Genesis Rocks" and couldn't find them? Mars should have been affected by the cataclysm, according to available models. Hartmann (2001) suggested it tells us that the Martian crust was not destroyed by plate tectonics as on Earth, and parts of the primordial Mars crust were exposed by erosion to provide the meteorite source. Hence Mars may be the only planet where we can access a primordial crust. The erosion must have happened after a putative cataclysm at 3950 My ago.

(7) In short, did a cataclysmic spike at 3950 My ago, how big was it in terms of forming most lunar basins and other features, and how much of the total lunar cratering was concentrated in it?

U51A-04 0920h INVITED

The Formation of a Water-Rich Earth

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It is now generally accepted that in the inner solar system the process of runaway growth ended with the formation of many "planetary embryos" of lunar to martian mass (1,2). The terrestrial planets then formed on a longer time-scale (from several tens to a hundred million years), by the high-velocity mutual collisions of these embryos (3,4,5).

The radial extent of the primordial population of planetary embryos is not known. In principle, a system of embryos originally within 2 AU from the Sun