

and the government is announcing that it will evacuate Botolan and induce the breach as early as September 5. Spontaneous breaching during rainstorms remains very possible.

U32A-0021 1330h POSTER

**The Crater Lake and Hydrothermal System of Mount Pinatubo, Philippines: Evolution in the Decade After Eruption**

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We document a decade of change in the lake and hydrothermal system of Mount Pinatubo, Philippines following the climactic eruption of 1991. A shallow lake formed by early Sept. 1991 and has shown a long-term trend of growth even during dry periods (~1 m/month). It was initially dominated by meteoric influx and the residuum of the pre-eruptive hydrothermal system, but quickly became more acid (pH ~2-3) as magmatic discharges continued to condense into the rapidly accumulating water. Acidity and rock dissolution peaked in late 1992, during and immediately after eruption of a lava dome on the crater floor (July-Oct. 1992). The pH of the lake remained ~3.0 to 3.3 from late 1992 to early 1999, whereas temperature showed a slow decline from ~40 to 30°C. Samples taken since cessation of dome growth suggest that magmatic degassing and rock dissolution have declined significantly relative to magmatic-hydrothermal brine and meteoric input. This is indicated by trends toward higher Cl, Na, K, Li and B and lower Mg, Ca, Fe, SO<sub>4</sub> and F with time. Samples taken in 2001 indicate dilution, increase in pH (5.5), and decline in temperature (~27°C) resulting from a growing contribution of meteoric water. The rapid transition from a small and hot acid lake to moderately large and warm near-neutral pH lake is related to the rapid cessation of direct magmatic degassing, large size of the catchment, and large volume of hydrothermal input compared to lakes hosted by more restive andesitic volcanoes.

The pre-existing hydrothermal system was invaded by an increased flux of magmatic gas and eventually by magma itself. As the impermeable caprock of the system was progressively fractured, extensive boiling and steam loss occurred. A dry conduit system that conducted volcanic gases and magma to the surface was maintained locally until late 1992. As the magmatic flux waned and the magmatic system plugged itself, a liquid hydrothermal system encroached on this direct pathway. Current hydrothermal input is neutral-Cl fluid that equilibrated with rocks at ~200°C and has similarities to geothermal fluids in wells drilled below the same area prior to eruption. This indicates that either very rapid fluid/rock interaction has occurred, or hydrothermal outflow that previously flowed south from the volcano now vents through the ruptured cap of the system.

Considering evidence for declining magmatic input, edifice failure and due to rising lake-level and consequent lahars pose the greatest present risk to local populations. Two low areas on the crater rim, the Maraunot Notch and the O'Donnell River headwall are a few meters above lake level (late Aug. 2001), but the water level will probably top these points sometime in late 2001 or 2002. Several meters of ash deposits from the 1991 eruptions can be easily eroded from these areas if overtopping occurs. The most likely failure point is along structurally controlled zones of weakness and hydrothermal alteration that control the Maraunot Notch.

U32A-0022 1330h POSTER

**Mount Pinatubo's Volcanic Lake Geochemistry**

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A geochemical investigation of Mount Pinatubo's volcanic lake indicates mixing between neutral chloride spring discharge from springs in the crater walls and meteoric waters from precipitation and runoff. I originally hypothesized that the lake water is a mixture of deep hydrothermal acid sulfate fluid representative of magmatic input into the hydrothermal system, neutral chloride fluid representative of the hydrothermal input directly into the lake via crater wall springs, and meteoric water. Lake water was periodically sampled and analyzed for temperature, pH, major element concentration, and isotopic composition. This study utilizes lake samples collected in 1992, 1994, 1999, 2000 and 2001. Solution speciation and mixing models do not support the mixing scenario originally hypothesized. Further investigation of major element concentrations and isotopic composition supports mixing between the neutral chloride spring discharge and meteoric water. A series of Cl vs. major element plots of end member solutions and sampled lake waters delineate a mixing line between the meteoric water and the neutral chloride spring discharge. For conservative elements such as Li, Na, and K, lake samples plot on or near this mixing line. For less conservative elements such as Mg, Ca, Fe, Mn, and SO<sub>4</sub><sup>2-</sup>, lake samples plot between the two end members but above or below the mixing line indicating enrichment or depletion in the lake. The significant enrichment of Ca and SO<sub>4</sub><sup>2-</sup> in the 1992 lake sample and less-enriched later samples can be explained by initial anhydrite dissolution in the early lake followed by elimination of source anhydrite and dilution from meteoric water in more recent lake samples. A strong correlation between Ca and SO<sub>4</sub><sup>2-</sup> supports this hypothesis. Further, the slope of a regression line on a Ca vs. SO<sub>4</sub><sup>2-</sup> plot of the lake samples is ~2.8 in good agreement with the expected SO<sub>4</sub><sup>2-</sup> to Ca ratio of ~2.5 in anhydrite. The slight deviation can be accounted for via substitution of Mg for Ca. This is supported by a similar enrichment of Mg and a strong, positive correlation between Ca and Mg. Redox conditions in the lake are such that Fe and Mn depletions can likewise be explained through precipitation of secondary Fe and Mn oxides. A Cl vs. δD plot also delineates a mixing line between meteoric water and neutral chloride spring discharge and, along with δO-18 vs. δD data, negates any acid sulfate hydrothermal influence on the lake chemistry. Although this mixing scenario can reasonably explain the major element concentrations and isotopic composition of the lake water, it does not account for periods of extreme acidity and temperature fluctuations. The pH fluctuated from an initial 6.0 in October 1991 to its most acidic, 1.9, in December 1992 before neutralizing to 6.2 by January 2001. There is evidence of a gas phase bubbling through Pinatubo's volcanic lake. I observed surface bubbling, an area of upwelling, and an extreme inverted temperature profile over the submerged dome in August 2000. Modeling with previously published CO<sub>2</sub>, SO<sub>2</sub>, H<sub>2</sub>O, and Cl gas ratio and flux data will illuminate the feasibility of explaining pH and temperature fluctuation via volcanic gas flux through the lake.

**U32B MC: 134 Wednesday 1330h Biogeophysics of Global Warming Mitigation**

**Presiding:** M Hoffert, New York University; K Caldeira, Lawrence Livermore National Laboratory; J Edmonds, Pacific Northwest National Laboratory

U32B-01 1330h

**Influence of Geoengineered Climate on the Biosphere**

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Several geoengineering schemes have been proposed to counteract anthropogenic climate change by reducing the solar radiation incident on the Earth's surface. It has been shown in a recent study (Govindaswamy and Caldeira, 2000) that geoengineering schemes that

involve reduction of solar radiation incident on the Earth's surface could noticeably diminish regional and seasonal climate change from increased atmospheric carbon dioxide (CO<sub>2</sub>). However, the response of terrestrial biosphere to reduced solar radiation in a CO<sub>2</sub> rich climate has not been explored. Atmospheric CO<sub>2</sub> and incident solar radiation are critical prerequisites for photosynthesis in plants. Studies have indicated that elevated CO<sub>2</sub> in the atmosphere stimulates photosynthesis resulting in increased primary production of land vegetation. On the contrary, diminished solar radiation would not only affect plant metabolism through photosynthesis but also leaf morphology, as temperature of plants is light-controlled. In this study, we use a dynamic global ecosystem model, IBIS (Integrated Biosphere Simulator) to simulate the response of terrestrial ecosystem to a geoengineered climate conditions. Particularly, we analyze the influence of reduced solar luminosity in a CO<sub>2</sub> rich climatic conditions on the terrestrial carbon balance (e.g., net primary productivity, net ecosystem exchange, and soil carbon) and vegetation structure (biomass, leaf area index, and vegetation composition).

U32B-02 1345h

**Enhanced Carbonate Weathering: Helping Nature Capture and Sequester Carbon Dioxide**

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Various methods have been proposed for mitigating anthropogenic CO<sub>2</sub> release to the atmosphere, including ocean storage via enhanced biological uptake and via deep-sea injection of captured CO<sub>2</sub>. We propose an alternate capture and sequestration method that we believe would be less expensive and more environmentally friendly than the preceding methods. Specifically, it is suggested that CO<sub>2</sub>-rich power-plant gases be hydrated with seawater to produce a carbonic acid solution that in turn is reacted on-site with limestone to form Ca<sup>2+</sup> and HCO<sub>3</sub><sup>-</sup>. This calcium bicarbonate solution is then released and diluted in the ocean where it would add minimally to the existing, large pool of these ions in the sea. Such a process simply speeds up natural carbonate weathering and dissolution which will otherwise consume anthropogenic CO<sub>2</sub>, but over many millennia.

Using a schematic model of ocean chemistry and transport we show that this process would increase ocean alkalinity, effectively neutralizing CO<sub>2</sub> acidity and isolating anthropogenic carbon from the atmosphere. Relative to atmospheric release or direct CO<sub>2</sub> injection, this method would greatly expand the capacity of the ocean to store anthropogenic carbon while minimizing environmental impacts of this carbon on ocean biota. This technique also is less energy intensive and less expensive than other abiotic CO<sub>2</sub> capture and sequestration schemes. We calculate an energy penalty that may be <2% with a CO<sub>2</sub> capture efficiency which may exceed 50%. Estimated sequestration costs could be as low as \$12 per tonne CO<sub>2</sub> sequestered, dependent on reactor configuration and on limestone and water availability and transport. These compare with \$90 to \$180/tonne CO<sub>2</sub> and >>20% energy penalties estimated for direct ocean CO<sub>2</sub> injection.

U32B-03 1400h

**Control of Global Warming by Enhancement of the Albedo and Longevity of Low-Level Maritime Clouds**

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A technique is proposed for controlled and significant enhancement of the droplet concentration in low-level maritime clouds, with a corresponding increase in their albedo for incoming sunlight and their longevity. The concomitant cooling effect could be regulated and sufficiently powerful to neutralise global warming. The technique involves dissemination at the ocean surface of small seawater droplets which, if in sufficient quantities and with appropriate salt mass, can act as the dominant cloud condensation nuclei (CCN) on which droplets form in marine stratocumulus. It has a short response time and low ecological impact, requiring only seawater and air as raw materials.

## U32B-04 1415h

## A Carbon-Free Energy Future

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It is generally agreed that hydrogen is an ideal energy source, both for transportation and for the generation of electric power. Through the use of fuel cells, hydrogen becomes a high-efficiency carbon-free power source for electromotive transport; with the help of regenerative braking, cars should be able to reach triple the current mileage. Many have visualized a distributed electric supply network with decentralized generation based on fuel cells. Fuel cells can provide high generation efficiencies by overcoming the fundamental thermodynamic limitation imposed by the Carnot cycle. Further, by using the heat energy of the high-temperature fuel cell in co-generation, one can achieve total thermal efficiencies approaching 100 percent, as compared to present-day average power-plant efficiencies of around 35 percent.

In addition to reducing CO<sub>2</sub> emissions, distributed generation based on fuel cells also eliminates the tremendous release of waste heat into the environment, the need for cooling water, and related limitations on siting.

Manufacture of hydrogen remains a key problem, but there are many technical solutions that come into play whenever the cost equations permit. One can visualize both central and local hydrogen production. Initially, reforming of abundant natural gas into mixtures of 80% H<sub>2</sub> and 20% CO<sub>2</sub> provides a relatively low-emission source of hydrogen. Conventional fossil-fuel plants and nuclear plants can become hydrogen factories using both high-temperature topping cycles and electrolysis of water. Hydro-electric plants can manufacture hydrogen by electrolysis.

Later, photovoltaic and wind farms could be set up at favorable locations around the world as hydrogen factories. If perfected, photovoltaic hydrogen production through catalysis would use solar photons most efficiently. For both wind and PV, hydrogen production solves some crucial problems: intermittency of wind and of solar radiation, storage of energy, and use of locations that are not desirable for other economic uses.

A hydrogen-based energy future is inevitable as low-cost sources of petroleum and natural gas become depleted with time. However, such fundamental changes in energy systems will take time to accomplish. Coal may survive for a longer time but may not be able to compete as the century draws to a close.

## U32B-05 1430h

Experiments on the Deep Ocean Disposal of Fossil Fuel CO<sub>2</sub>Peter G. Brewer<sup>1</sup> (831-775-1706; brpe@mbari.org)Edward T Peltzer<sup>1</sup> (831-775-1851; etp3@mbari.org)Gregor Rehder<sup>1</sup> (831-775-1982; grehder@mbari.org)

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Deep ocean ROV experiments for the controlled release of CO<sub>2</sub> have so far been limited by the small volume available for deployment, thus inhibiting observation of long life time effects, biological interactions, and macroscopic properties associated with sediment penetration. Early (1996) experiments released about 500ml per dive; later (1998) studies released volumes up to 7 liters per dive. We have developed and used a new large volume apparatus based upon a carbon fiber cylinder accumulator (79.5 long, 11 diameter, 150 lbs empty in air) with an internal volume of about 45 liters. For perspective present US CO<sub>2</sub> releases are about 55 kg/person/day. The system is filled with liquid CO<sub>2</sub> at about 1000 psi, and CO<sub>2</sub> internal pressure is maintained above ambient by frequent hydraulic pumping of sea water to the open side of the accumulator during the dive.

We have used this system to release 20-30 liter quantities into 20 diameter experimental corrals on the sea floor at 3600m depth, where the density of CO<sub>2</sub> exceeds that of sea water. Earlier studies have shown the strong immiscibility of CO<sub>2</sub> with sea water, and the apparent effect of a hydrate skin in inhibiting sediment penetration. We have now observed for the first time the formation of a large frost heave of CO<sub>2</sub> hydrate within the surficial sediment 24 hours after the initial release. This is apparently caused by relatively rapid (2 micromoles/cm<sup>2</sup>/sec) dissolution of CO<sub>2</sub> hydrate at the sediment-CO<sub>2</sub> interface, thus creating flow of dense

CO<sub>2</sub> saturated pore waters, followed by nucleation and growth of a hydrate mass which pushes apart the sediment matrix. Very large changes in pore water chemistry must follow, with pH < 3.7. Core recovery shows large releases of CO<sub>2</sub> during retrieval, leading to the need for in situ measurement and/or pressure retaining samplers for accurate assessment.

## U32B-06 1445h

Global Climate Strategy with CO<sub>2</sub> Capture From the AirMinh Ha-Duong<sup>1</sup> (+1 412 268 4640; minh.ha.duong@cmu.edu)David Keith<sup>2</sup> (david.keith@cmu.edu)<sup>1</sup>Centre International de Recherche sur l'Environnement et le Développement, Campus du Jardin Tropical, 45bis avenue de la Belle Gabrielle, Nogent sur Marne 94736, France<sup>2</sup>Engineering and Public Policy Department, Carnegie Mellon University 5000 Forbes Avenue, Pittsburgh, PA 15213-3890, United States

It is physically possible to capture CO<sub>2</sub> directly from air and immobilize it in geological structures. Today there is no demonstrated technique that can achieve air capture at reasonable cost. But in a time frame compatible with the climate change issue, there are strong arguments suggesting that it will be possible to develop the necessary technologies without any fundamentally new innovation [Elliott S. et al., 2001, Geoph. Res. Lett. 28(7) 1235-1238].

This paper presents arguments to justify the assumption that air capture costs in the order of a hundred to three hundred dollars per ton of carbon. Implications on global climate policy are then examined using in a simple integrated assessment model. Long- and short-term effects on optimal trajectories were determined using DIAM [Ha-Duong et al., 1997, Nature 390, 270-273]. We find that that air capture can fundamentally alter the temporal dynamics of global warming mitigation.

The reason for this is that air capture differs from conventional mitigation in three key aspects. First, it removes emissions from any part of the economy with equal ease or difficulty. Consequently, its price caps the cost of mitigation with a scope unmatched by any other kind of abatement technology. Second, because air capture allows the removal of CO<sub>2</sub> after emission it permits reduction in concentrations more quickly than can be achieved by the natural carbon cycle. Third, because it is de-coupled from the rest of the energy system its returns-to-scale may be better than for more conventional future energy technologies. Together these advantages limit the total cost of a worst-case climate scenario. In an optimal sequential decision, the consequence is a decrease the need for precautionary short term abatement.

On the other hand, if marginal carbon sequestration cost decreases with time and marginal climate change damage increases, then at some point in the future the most sensible target will be to return atmospheric greenhouse gases concentration to pre-industrial levels. Air capture changes the temporal dynamics of mitigation by making this response possible. This very long run target is consistent with the UNFCCC wording and with past global environmental policy such as the ozone hole negotiations.

## U32B-07 1515h

## The effectiveness of ocean carbon sequestration by direct injection: Leakage and discount rates

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Direct injection of CO<sub>2</sub> into the ocean is a potentially effective carbon sequestration strategy. Therefore, we develop an analytic framework to allow us to compare the effectiveness of this strategy with other carbon management options. We estimate the effectiveness of ocean carbon sequestration using one-dimensional and three-dimensional ocean models. We discuss a new measure of effectiveness of carbon sequestration in a leaky reservoir, which we denote "sequestration potential". The sequestration potential is the fraction of global warming cost avoided. We show how

these measures apply to permanent sequestration and sequestration in a leaky reservoir such as the ocean.

Under the assumptions of a constant cost of carbon emission and a 4% discount rate, injection at 900 m deep in the ocean avoids ~90% of the global warming cost associated with atmospheric emission; injection at 1700 m deep would avoid >99% of the global warming cost. However, if carbon emission costs rise faster than the discount rate and backstop carbon-free energy technologies do not become available for many centuries, then storage in a leaky reservoir such as the ocean may not be justifiable. This suggests that purposeful carbon storage in the ocean may be appropriate only as part of a strategy to transition to carbon-free energy sources.

## U32B-08 1530h

Biomimetic CO<sub>2</sub> Sequestration: Cation SourcesGillian M. Bond<sup>1</sup> (1-505-835-5653; gbond@nmt.edu);John Stringer<sup>2</sup> (1-650-855-2472;jstringe@epri.com); Margaret-Gail Medina<sup>1</sup>(magail@nmt.edu); Brian McPherson<sup>3</sup>

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Conversion of CO<sub>2</sub> to solid carbonates offers the possibility of a safe, stable product for long-term carbon sequestration. Naturally occurring carbonate minerals already comprise a massive carbon reservoir that has existed for millions of years. Large quantities of these carbonate minerals are of biogenic origin. We have demonstrated proof of principle for a novel biomimetic approach to carbon sequestration, which uses a natural catalyst, the enzyme carbonic anhydrase, to accelerate the formation of bicarbonate ions in aqueous solution. In the presence of suitable cations, this can then be precipitated out in carbonate form. One of the issues we are now addressing is the selection of suitable sources of cations. Along with seawater, and waste brines from desalination operations, brines from deep saline aquifers offer an attractive possibility. In this context, it is important to understand the effects of brine flow on geologic media, both during brine extraction and during possible reinjection of bicarbonate-enriched brines.

We have used numerical simulations to evaluate and compare the effects of supercritical CO<sub>2</sub> flow to the effects of bicarbonate solution flow on geologic media. Specifically, we examined diagenetic changes and time-scales of these changes associated with flow of the two different fluids. For these simulations we assembled and applied a model of reactive transport, including coupled groundwater flow, heat flow, and relevant geochemical reactions. Simulations have been conducted for laboratory-scale models, with the intention that these results will be used for calibration of and upscaling to larger-scale hydrogeologic models.

## U32B-09 1545h

Deep-Sea Field Studies of the Biological Consequences of Direct Ocean CO<sub>2</sub> SequestrationJames P. Barry<sup>1</sup> (831-775-1726; barry@mbari.org)Brad A. Seibel<sup>1</sup> (831-775-1862; bseibel@mbari.org)Chris Lovera<sup>1</sup> (831-775-1892; lovera@mbari.org)<sup>1</sup>Monterey Bay Aquarium Research Institute, 7700 Sandholdt Road, Moss Landing, CA 95039, United States

While the notion of carbon sequestration by direct ocean disposal of CO<sub>2</sub> in the deep ocean holds promise for mitigating atmospheric greenhouse warming, the consequences of this approach for deep-sea ecosystems are understood poorly, but are potentially large. Several factors suggest that deep-sea fauna may be more sensitive to deep-sea CO<sub>2</sub> releases than related groups inhabiting the upper ocean. The evolution of deep-sea species in the relatively invariant environment of the deep ocean has likely led to the intolerance of many species to perturbations in seawater chemistry associated with direct CO<sub>2</sub> injection (e.g. pH reduction) that may be more tolerable to shallow-living groups. Food

limitation and reduced metabolic rates typical in deep-sea ecosystems may also limit the ability of many organisms to tolerate changes in pH (i.e. pH compensation) or CO<sub>2</sub> (e.g. metabolic depression).

We recently performed field experiments at depths from 3000 to 3600 m to evaluate the biological responses of representative deep-sea organisms to changes in seawater chemistry caused by carbon dioxide sequestration. Several small pools (ca. 15 l) of liquid CO<sub>2</sub> were deployed on the seafloor from the ROV *Tiburon* operated by the Monterey Bay Aquarium Research Institute, using a novel CO<sub>2</sub> release system. Rates of survival and aspects of the physiological condition of various elements of the seafloor faunal community were compared between sites near (<1 m) and distant (control sites >30 m away) from CO<sub>2</sub> pools. Tidally oscillating currents swept a plume of CO<sub>2</sub>-rich water away from the pools as the liquid CO<sub>2</sub> dissolved, resulting in periodic reductions of pH around the pools to 6.0 to 7.0 units within 1 m.

Rates of survival for two common megafaunal echinoderms (echinoid 1 and holothurian 1) held in cages adjacent to CO<sub>2</sub> pools were very low compared were compared to control sites. Decalcification of urchin spines and skeletal elements was evident for animals near CO<sub>2</sub> pools. The abundances of infaunal worms and crustaceans were lower near CO<sub>2</sub> pools after 5 weeks than control sites. In addition, the physiological condition (gut fullness and tissue density) of infaunal amphipods exposed to CO<sub>2</sub> was poorer than in control groups. Additional studies of the response of sediment-dwelling meiofauna, the sediment microbial community, and mobile scavenger species (fishes, amphipods) to elevated CO<sub>2</sub> exposure are underway.

A wide variety of field and laboratory studies of a phylogenetically diverse suite of deep-sea species from benthic and midwater environments, coupled with careful estimation of the degree and areal extent of changes in seawater chemistry to be expected with any CO<sub>2</sub> disposal scenario, is required before any realistic estimate of the impacts of sequestration on deep-sea ecosystems is possible.

#### U32B-10 1600h

##### Greenland Ice Sheet Sublimation: Surface Mass Balance Implications with Climate Warming

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Maps of surface water vapor flux from the Greenland ice sheet are constructed using Greenland Climate Network (GC-Net) data spanning 1995-2001. Temperature distribution maps from 1950-1960 and the contemporary period indicate a general warming of 2 degrees C. The correspondence of water vapor fluxes with temperature anomalies suggest a reduction in the net water vapor loss from 1950-1960 to the 1995-2001 period of 10%. In a warmer climate, an increase in the water vapor deposition at high elevations offsets an increase of water vapor loss at low elevations. 87% of the ice sheet area is above 1000 m elevation. Using the best estimate of net annual surface water vapor flux based on GC-Net data (-73 Gt) and estimates for precipitation, melt runoff, direct runoff, and iceberg calving, the annual mass balance of the ice sheet is in negative balance by 9% of the annual precipitation input. Reducing the uncertainties of the ice sheet mass balance parameters is the focus of future work.

URL: <http://cires.colorado.edu/steffen/sublimation/>

#### U32B-11 1615h

##### Lunar Solar Power System and Minimization of Carbon Dioxide Emissions in the Production of Commercial Power for a Prosperous Global Economy

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A prosperous world requires at least 6.7 kWt/person of thermal energy or the equivalent of 2.5 3 kWt/person of electric energy (1, 2). Thus, a prosperous world of 10 billion people requires approximately 67 TWt or 25 to 30 TWe of commercial power that is low in cost, globally safe, and capable of providing 6,700 TWt-y/century to Earth for many centuries. These requirements preclude conventional terrestrial fossil-fuel, nuclear, and renewable systems. Cost-effective access of solar energy is required.

The Moon intercepts 13,000 TW of solar power. The proposed Lunar Solar Power (LSP) System collects a small portion of this solar power at bases located near the Earthward limbs of the Moon, converts the power to low-intensity microwave power beams (less than 20

percent the intensity of sunlight), and delivers the microwave power to receivers on Earth. The LSP lunar components are manufactured on the Moon using lunar materials. The receivers on Earth output utility-scale power. By 2050 the LSP System can provide abundant, clean, and low-cost commercial electric power to Earth that is independent of the biosphere. LSP energy can decouple physical and most service industry from the biosphere, stimulate healthy net growth of the global economy, and establish a two-planet (Earth-Moon) economy.

1. World Energy Council (2000) Energy for Tomorrow's World Acting Now!, 175pp., Atalink Projects Ltd., London. 2. Criswell, D. R. 1998 (13 - 18 September) Lunar solar power for energy prosperity within the 21st century, 17th Congress of the World Energy Council, Division 4: Concepts for a sustainable future issues session, 4.1.23, 277-289, Houston, TX (Also on WEC98 web site. Search for lunar.)

#### U41A MC: Hall D Thursday 0830h Virtual Earth Laboratories I

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

#### U41A-0001 0830h POSTER

##### Cretaceous Length of Day Perturbation by Mantle Avalanche

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These last ten years, numerical models of mantle convection including the effects of the main mantle phase changes have emphasized the role of the 670 km endothermic phase change in generating mantle avalanches. These events are characterized by catastrophic mantle mass anomaly perturbations. The influence of the mass transfers due to the avalanches on the Length of Day (L.o.d.) has been studied by resolving the reduced Liouville equation. The results show that the inertia tensor of the mantle remains approximately constant during the partial layering periods while it is mainly sensitive to the global mass transfers through the 670 km discontinuity during the avalanches. In spite of a tidal secular trend to L.o.d. lengthening, the paleontological records can be interpreted as a L.o.d. shortening between 200 and 80 My which would be synchronous with a strong True Polar Wander and a global warming of the upper mantle as witnessed by recent geochemical results and isostasy considerations. A L.o.d. shortening during the Cenozoic and Cretaceous brings one more clue to the possible implication of a mantle avalanche in generating the concomitant large scale events which have occurred during this very particular period of the Earth's history.

#### U41A-0002 0830h POSTER

##### A 3D Spherical Model of Mantle Convection and Continental Drift

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It has long been speculated that continents affect the large-scale heterogeneity structure of the Earth's mantle. Unusually slow seismic velocity anomalies under South Africa, for example, suggest some impact from the former supercontinent Pangea. Much progress has been made in understanding the effects of continents in mantle convection models. However, the influence of continents on vigorous 3D spherical mantle convection has not yet been studied. We address this problem using the 3D spherical mantle dynamics code TERRA implemented on a high performance Beowulf cluster. Our parallelized, finite element model approximates continental regions as unsubductable rigid lids whose motion is determined from the dynamics of the flow, in line with earlier Cartesian experiments. We study the effects of continents for a number of different flow regimes, including models with and without a significant viscosity increase in the lower mantle and models having either strong internal heating from radioactivity or strong bottom heating from the

core. We find that the nature of the heating mode is particularly significant in determining how effectively a continent promotes the formation of long-wavelength heterogeneities in the mantle.

#### U41A-0003 0830h POSTER

##### Modeling 3D Wave Propagation in Global Earth Models Using a Spectral/Mortar Element Method

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The Spectral Element Method (SEM) has been shown in recent years to provide an efficient, accurate solution to wave propagation in the Earth at both regional and global scales. Based on a high order polynomial approximation of the weak form of the wave equation, the SEM naturally takes into account the free surface condition (which is crucial for surface wave propagation) and allows for considering localized density/velocity heterogeneities.

For global wave propagation the method requires to tile the 3-sphere with hexaedra. This is achieved by paving the Earth's major interfaces with quadrangles and connecting them radially, with a cube being set inside the inner core to avoid any singularity at the center of the mesh. However, such a process yields a non-uniform grid-points distribution that causes the seismic wavelengths to be largely over-sampled for increasing depth. This drawback is overcome by coarsening the mesh through some special "non-conforming" interfaces, which do not necessarily coincide with composition or phase changes. The matching between the fine and the coarse grids is achieved by the mortar element method which consists in relaxing the continuity conditions across the non-conforming interfaces. Examples of the method will be presented for some radial Earth models where the local effects of gravity are taken into account during wave propagation. The approximation is based on a formulation in displacement for the solid parts and in the velocity potential for the fluid regions, and the non-conforming interfaces can be set either in the solid or in the fluid.

For realistic applications of the method to 3D Earth models, the possibility of refining the spectral element mesh laterally must also be considered. A striking example illustrating this need is the discretization of the Earth's crustal structure, for which thickness variations of a factor up to 10 can be encountered. Adapting the grid-points sampling to these lateral contrasts is a key ingredient to study the propagation of surface waves in presence of topography on both the surface of the Earth and the Mohorovicic discontinuity. We will present how the mortar element method must be adapted in order to deal with such local refinements, and show some examples for models of increasing complexity.

#### U41A-0004 0830h POSTER

##### A parallel implementation of the Lattice Solid Model for large scale simulation of earthquake dynamics

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The particle based lattice solid model has been used successfully as a virtual laboratory to simulate the dynamics of faults, earthquakes and gouge processes. The phenomena investigated with the lattice solid model range from the stick-slip behavior of faults, localization phenomena in gouge and the evolution of stress correlation in multi-fault systems, to the influence of rate and state-dependent friction laws on the macroscopic behavior of faults. However, the results from those simulations also show that in order to make a next step towards more realistic simulations it will be necessary to use three-dimensional models containing a large number of particles with a range of sizes, thus requiring a significantly increased amount of computing resources. Whereas the computing power provided by a single processor can be expected to double every 18 to 24 months, parallel computers which provide hundreds of times the computing power are available today and there are several efforts underway to construct dedicated parallel computers and associated simulation software systems for large-scale earth science simulation (e.g. The Australian Computational Earth Systems Simulator[1] and Japanese Earth Simulator[2]). In order to use the computing power made available by those large parallel computers, a parallel version of