represented by the parameter γ. For $\gamma \gg 1$, extreme localization is allowed, with sharp profiles in porosity (weak zones), nearly discontinuous separation velocities and effectively singular dilation rates.

U21A-08 1050h INVITED

Are Oceans Required for Earth-Like Plate Tectonics?

Greg Hirth (ghirth@whoi.edu)

WHOI, Department of Geology and Geophysics, Woods Hole, MA 02543

A combination of rheological and geophysical observations suggest that the physical properties of the oceanic asthenosphere are strongly influence by the presence of small amounts of dissolved water, and that the oceanic plates may be defined by a dehydration boundary that is formed as a result of melting at oceanic spreading centers (e.g., Hirth and Kohsltedt, 1996; Karato and Jung, 1998; Gaherty et al., 1999). Thus, a key to understanding the uniqueness of Earth-like plate tectonics may be constraining the processes by which the asthenosphere remains hydrous. It is clear that water can be re-introduced into the mantle by subduction. Indeed, it is intriguing that olivine in a mantle residue of a basaltic melt with approximately 6wt% water, such as observed in volcanic arcs, has approximately the same water content as that estimated for the oceanic asthenosphere. The presence of oceans on Earth provides a source of water through both hydrothermal alteration of the lithosphere at the oceanic ridges and the relatively thick layers of fluid filled sediments on the surface. Thus, without oceans, it is possible that even if a subduction like process occurred, the rheological properties of a dry upper mantle would inhibit the formation of Earth-like plates.

U21A-09 1110h

The role of liquid water in maintaining plate tectonics and the regulation of surface temperature

Viatcheslav S. Solomatov (505-646-1248; slava@nmsu.edu)

Department of Physics, New Mexico State University, Las Cruces, NM 88003

Water plays an important role in mantle convection. In the ductile creep regime, the viscosity of wet rocks is weaker than the viscosity of dry rocks by several orders of magnitude. In the brittle regime, the most substantial effect is probably serpentinization which can reduce the friction coefficient by a factor of 2 or more. The difference between the strength of a wet lithosphere and that of a dry lithosphere seems to be big enough to control the very existence of plate tectonics. Because of dehydration due to partial melting the oceanic lithosphere is expected to be essentially dry above some critical depth, around 60-80 km. This would make the lithosphere strong enough to prevent plate motion. Percolation of water from the surface can be the main mechanism supplying water to the upper parts of the lithosphere. This implies that liquid water can be crucial for maintaining plate tectonics. On the other hand, the surface temperature is above the freezing point because of the greenhouse gases such as carbon dioxide. A simple model shows that if the blackbody temperature of the Earth is slightly below the freezing point of water, the feedback between plate tectonics, volcanism, and water and carbon cycles can result in an equilibrium state in which the surface temperature is established within the stability field of liquid water.

U21A-10 1125h

The Role of Bending Resistance at Subduction Zones on the Force Balance of Plate Tectonics through the Cenozoic

Clinton P. Conrad[1] (clintconrad@alum.mit.edu)

Carolina Lithgow-Bertelloni[1] (734-647-9938; crlb@umich.edu)

[1]Department of Geological Sciences, University of Michigan, 425 E. University Ave., Ann Arbor, MI 48108, United States

The temperature-dependent rheology of mantle rock is such that cold lithosphere should have an effective viscosity several orders of magnitude greater than that of the underlying mantle. As a result, the deformation required to bend plates at subduction zones may have a slowing effect on plate motions comparable to the slowing associated with the deformation of the shearing mantle interior. We examine the force balance of all plates during the Cenozoic, and include the effects of bending resistance at subduction zones. The added resistance provided by bending is added via a parameterization derived from theory and supported by numerical calculations (e.g., *Conrad and Hager*, 1999). The global force balance is achieved by requiring that viscous resisting forces - including those associated with plate bending at subduction zones - and plate driving forces be exactly equal. In our model, driving torques arise largely from the flow induced by subducted buoyancy over the last 200 my ("slab pull"), and from the lateral density contrasts of the oceanic lithosphere as it ages ("ridge push"). The predicted velocities can be compared to global reconstructions in the Cenozoic. In this way, a suite of mantle viscosity and lithosphere bending models can be examined, and the importance of lithosphere bending to the global force balance on plates evaluated. Because, for a viscous plate, the bending resistance depends on the cube of the thickness of the plate, older, thicker plates exert a strong influence on the rate of plate motions. Indeed, if the plate viscosity is about two orders of magnitude stronger than that of the upper mantle, the bending resistance can effectively control plate motions. In addition, because the thickness of subducting plates evolves over time, the inclusion of the bending resistance in the global force balance provides a source of time-dependent behavior by which plates can rapidly change their direction and speed, as is observed in the geologic record.

U22A MC: Hall D Tuesday 1330h

Plate Tectonics and Self-Organization II

Presiding: **A Lenardic,** Rice University**; J Korenaga,** University of California, Berkeley

U22A-0001 1330h POSTER

Constraints on the Motions and Organization of Plates

Richard J O'Connell[1] (617-495-2532; oconnell@geophysics.harvard.edu)

Thorsten W Becker[1] (becker@geophysics.harvard.edu)

[1]Dept Earth & Planetary Sciences, Harvard University, 20 Oxford St, Cambridge, MA 02138, United States

Plate tectonics represents the top of the convecting mantle. Determining the mechanics (statistical or otherwise) of plate organization and tectonics must be constrained by the underlying dynamics. Heat transport out of the system is closely related to the geometry and motions of plates. However, the relation between the plate system and the underlying pattern of convection is not necessarily simple. Studies of the forces on plates indicate that roughly 1/3 can be accounted for by the thickening of the plates (i.e. the thermal boundary layer) as they move away from ridges and cool. The remaining forces come from convective flow in the interior; about half of this is associated with density anomalies in the lower mantle that are the result of past subduction. This implies that there is a relation between deeper convective downwelling and the locations of subduction zones, and that the motions of subduction zones are linked to the deeper pattern of convection. Ridges have no simple relation to deeper sources of buoyancy (although there are more hot spots apparent near ridges than near subduction zones) and seem to be associated with passive upwelling. New ridges form in back-arc environments and around microplates at existing ridges, which represents the formation of new plates that can grow. Examples of the initiation of subduction are not apparent, although models predict their formation at continental margins. Plate geometry evolves owing to symmetric spreading and asymmetric subduction. Plate motions correspondingly evolve, but relatively uniformly, as expected if body forces from plate evolution and convection are the dominant driving forces. The longer term evolution of the plate system requires the continual formation of new plates, which will depend on the forces available to fracture the lithosphere to create new plate boundaries; the most likely source of such forces is the underlying convection that drives plate motions, as well lateral variations in the lithosphere associated with plate cooling and continental topography.

U22A-0002 1330h POSTER

Incorporating Continents into a Theory of the Earth's Heat Loss

Adrian Lenardic[1] (713 348 4883; adrian@esci.rice.edu)

Louis Moresi[2] (61 8 6436 8633; louis.moresi@dem.csiro.au)

Catherine Cooper[1] (cmcooper@rice.edu)

[1]Dept. of Earth Science, Rice University, Houston, TX 77251, United States

[2]CSIRO Exploration and Mining, PO Box 437, Nedlands, 6009 Western Australia, Australia

Theories of global terrestrial heat loss have considered mantle convection and the associated creation and subduction of oceanic plates but to date the effects of continents have not been self-consistently worked in. Studies of continental thermal structure on the other hand have focussed on conductive thermal modeling with the effects of the convecting mantle incorporated as a free lower thermal boundary on a column of continental lithosphere. The lack of a unified theoretical approach has kept problems that involve the partitioning of mantle heat loss between oceans and continents over time from being fully addressed. We present simple theoretical ideas that allow the thermal effects of continents, of variable structure, to be self-consistently included into a theory of terrestrial heat loss. The ideas lead to heat flow scalings that predict local continental and oceanic heat flow as well as global heat flow. We test the main theoretical ideas behind the scalings using, at this stage, relatively simple numerical simulations. Although not complete, as yet, the theory does allow us to address the question of whether the global insulating effect of continents may be key to determining how the full mantle system organizes itself in terms of convective planform.

U22A-0003 1330h POSTER

The nature of "small-scale" convection in the presence of plate tectonics

Jun Korenaga[1] (korenaga@seismo.berkeley.edu)

Thomas H. Jordan[2] (tjordan@usc.edu)

[1]University of California at Berkeley , 377 McCone Hall, Berkeley, CA 94720-4767, United States

[2]University of Southern California, SCI 103, Los Angeles, CA 90089-0740, United States

A systematic numerical study is presented on the dynamics of so-called small-scale convection modulated by large-scale plate-tectonic flow. With the currently estimated range of activation energy for temperature-dependent mantle rheology, an unstable thermal boundary layer can develop beneath a plate, leading to the generation of small-scale convection. If this second mode of mantle convection exists, first-order energetics predicts that the strength of such secondary convection is comparable with the overlying plate motion. Because of its coupling with plate-tectonic flow, vigorous small-scale convection is expected to show rich dynamical behaviors, and its proper understanding should help to define the normal state of multi-scale mantle dynamics in the presence of plate tectonics. In order to characterize the possible temporal and spatial scales of this secondary convection as well as its convective planform, we first derive basic scaling laws for (1) onset of convection, (2) stability of longitudinal rolls (or Richter rolls), and (3) breakdown of endothermic phase boundary, on the basis of 2-D numerical solutions. A whole-mantle convection model with a single plate is then investigated using 2-D and 3-D single-mode calculations, to test predictions from these scaling laws. Our results show that the effect of three dimensionality, i.e., the generation and stability of Richter rolls, is significant in controlling the overall structure of secondary convection. Furthermore, vertical mass flux associated with secondary convection is shown to be comparable to that with plate-tectonic flow, indicating the significance of secondary convection in whole-mantle material circulation.

U22A-0004 1330h POSTER

North America Plate is Driven Westward by Lower Mantle Flow

Peter Bird[1] (310-825-1126; pbird@ess.ucla.edu)

Zhen Liu[1] (310-208-7180; zliu@ess.ucla.edu)

[1]Department of Earth and Space Sciences, University of California, Los Angeles, CA 90095-1567, United States

The shear traction which the lower mantle exerts on the base of the North America plate has been controversial: is it Eastward (resistive, or passive drag) or Westward (forward, or active drag)?

To clarify this, we construct a thin-shell model of the lithosphere of the entire North America plate and use it in neotectonic simulations with various boundary conditions. The finite element grid has 5399 nodes, 7953 triangular continuum elements (ranging from 500 km size in the plate interior to 62 km size along plate boundaries), and 1223 linear fault elements. Fault elements are used to outline the plate, so that velocity boundary conditions are assigned to neighboring plates, but the velocity of North America is not fixed. Additional fault elements are used to represent active intraplate faults in the West. A 3-D thermal and density model is computed from ETOPO5 topography and our synthesized heat flow map by assuming local isostasy and steady-state heat conduction. An anelastic rheology including frictional plasticity and thermally-activated dislocation creep is chosen for both crust and mantle-lithosphere layers, based on laboratory results and previous modeling projects. The horizontal components of the momentum equation are solved with program SHELLS, which predicts long-term-average horizontal velocities, fault slip rates, anelastic strain rates, and vertically-integrated stress directions and magnitudes. Each model is scored by comparison with seafloor spreading rates [DeMets et al., 1990], geodetic velocities [Bennett et al., 1999], and stress directions [World Stress Map 1997].

To date, 18 models have been computed using 3 different values of effective fault friction (0.03, 0.10, 0.17) and 3 different limits on the shear traction in subduction zones (7.5E11, 2.5E12, and 4.25E12 N/m). The basal boundary condition is set in one of three ways: (a) for resistive drag, we assume that the lower mantle is static with respect to the Africa plate, and compute the shear traction from the rheology of an adiabatic asthenosphere of olivine at either 1200 or 1300C; (b) we also test models with no shear traction on the base; (c) for active drag, we assume that the lower mantle moves as a rigid plate but slightly (1-3 mm/a) faster than North America (with respect to Africa), and compute shear in an olivine asthenosphere of 1150, 1200, or 1300 C.

Only models with active drag are successful. All models with resistive drag, or no drag, predict only a few mm/a of spreading on the Mid-Atlantic Ridge, little or reversed slip on the NA/CA transform boundary, and excessive spreading (~30 mm/a) in the Basin and Range province. Only models with active (Westward) drag and an asthenosphere of 1150 or 1200 C are kinematically successful. These models also have smaller errors in the directions of predicted stresses, although this difference is modest (31° in best models vs. 45° in the worst). The best models give a good approximation of Northwestward flow in the Basin and Range province, although unphysical spreading of the Sierra Madre Oriental is a persistent problem.

This detailed study of one plate supports the general conclusion of Bird [1998] that slow-moving continents are linked to, driven by, and indicators of the average lower mantle flow beneath them.

URL: http://element.ess.ucla.edu

U22A-0005 1330h POSTER

The Viability and Style of the Modern Plate-Tectonic Subduction Process in a Hotter Earth

Jeroen van Hunen[1] (+31 30 2535141; hunen@geo.uu.nl)

Arie van den Berg[1] (+31 30 2535072; berg@geo.uu.nl)

Nico J Vlaar[1] (vlaar@geo.uu.nl)

[1]Faculty of Earth Sciences, Utrecht University, Faculty of Earth Sciences, Budapestlaan 4, Utrecht 3584 CD, Netherlands

The Earth was probably warmer during the Archean and Proterozoic, and a 50 to 300 K mantle temperature increase has been suggested. This resulted in a thicker basaltic oceanic crust and underlying harzburgitic layer, and increased buoyancy of the lithosphere. This phenomenon has raised questions about the style or even the existence of plate tectonics in a younger Earth. Buoyant, low-angle subduction (e.g. below overriding plates) could have been more important, but also alternative tectonic styles, such as small-scale layered convection within the thickened crust have been proposed. We conducted 2-D Cartesian numerical model calculations to quantify the viability of the subduction process for an Earth with a higher potential temperature.As the basalt-to-eclogite transition in the crust plays an important role in the buoyancy of the oceanic plate and slab, and therefore also in its propensity to subduct, the kinetics of this phase transition is included in the numerical model.

One set of model results suggest that flat subduction below a continuously overriding lithosphere, or lithospheric doubling, can give rise to flat subduction up to a mantle temperature, which is not much higher (38 to 75 K) than today. An even hotter mantle is too weak to support the flat slab, so that fast, steep Benioff subduction develops. We performed another set of model calculations to examine the possibility of modern-style subduction in a hotter Earth, without extra driving forces such as lithospheric doubling. We use again the mechanism of lithospheric doubling, but only to trigger the subduction process, and switch it off after a few million years, when 'active' subduction developes. For a mantle temperature increase up to 150 K, we find subduction to be essentially the same as today, but subduction rates increase with increasing mantle temperature and increasing eclogitisation rates. For a 225 K mantle temperature increase, considerable amounts of the dense eclogitic crust delaminate from its mantle lithosphere, and sink rapidly into the mantle, which leaves the remainder of the slab too buoyant to continue the subduction process. For a 300 K hotter mantle, the mechanical coherence of the descending slab is reduced to such extent that frequent detachment of small pieces of the slab occur. These results indicate that the eventual viability and 'mode' of the plate tectonic mechanism in a hotter Earth is determined by a complicated interaction between crustal thickness, eclogitisation rate, slab age, and the rheology of both crust and mantle.

U22A-0006 1330h POSTER

Subduction of the Indian Lithospheric Slab Beneath Tibet

Hua-wei Zhou[1] (713/743-3424; hzhou@uh.edu)

Michael A Murphy[1] (713/743-3413; mmurphy@bayou.uh.edu)

[1]University of Houston, Department of Geosciences, 4800 Calhoun Street, Houston, TX 77204-5007, United States

In order to characterize the dynamics of continent-continent collisions, it is essential to define its present geometry and physical state. We report the results of a seismic tomography study of the Tibet-Himalayan collision zone, using a global data set, which indicates that the Indian lithospheric slab has been subducted subhorizontally beneath nearly the entire Tibetan plateau to depths of 165-260 km. Tibetan velocity structure is low in the crust and high in mantle lithosphere at depths between 75-120 km. An asthenospheric layer overlies the subducted Indian slab at depths between 120-165 km beneath the Tibetan plateau. There is a large low-velocity anomaly north of the Indus-Yalu suture zone between 85°E and 93°E that extends from the crust down to at least 310 km depth beneath the plateau. This low-velocity anomaly is indicative of mantle upwelling through a weakened zone of the subducted slab. The extent to which India has subducted beneath Tibet, as revealed by these seismic images, is comparable to estimates of crustal shortening across the Himalaya. Moreover, we hypothesize that the buoyancy due to heating of the subducted Indian slab and the existence of the asthenospheric layer contribute to the elevation and flatness of the Tibetan plateau.

U22A-0007 1330h POSTER

Using Surface Observations to Constrain the Dynamics of Western North America

Lucy M. Flesch[1] ((631)632-1114; flesch@mantle.geo.sunysb.edu)

Bingming Shen-Tu[2] (bshentu@ptc.com)

William E. Holt[1] (wholt@mantle.geo.sunysb.edu)

A. John Haines[3] (haines@esc.cam.ac.uk)

[1]Department of Geosicences, SUNY - Stony Brook, Stony Brook, NY 11794-2100, United States

[2]Parametric Technology Corp., 140 Kindrick Street, Needham, MA 02494, United States

[3]Bullard Laboratories, University of Cambridge, Cambridge CB3 0EZ, United Kingdom

We investigate the forces involved in driving large-scale continental deformation in western North America. We have quantified the vertically averaged deviatoric stress field for western North America arising from internal buoyancy forces and the accommodation of relative plate motions. These two driving forces act approximately equally in driving most of the observed deformation, while stresses arising from basal tractions are second order. Using ~1200 GPS measurements, ridge spreading rates, and geologic fault slip data, we first determined a strain rate and velocity field for western North America extending from Alaska to the Rivera triple junction. Deviatoric stresses associated with gravitational potential energy (GPE) variations in the lithosphere are calculated over the entire North American Plate extending from off the western coast of North America to the mid-Atlantic ridge system. These stresses are determined by a finite element approach using the ETOPO5 topographic data set, the EGM96 geoid model, and the CRUST2.0 seismic crustal thickness model to determine the GPE estimates. Effects of the ridge system on the total deviatoric stress field will be discussed. In an iterative 66-parameter inversion, we then solve for a stress field boundary condition by fitting surface observables (i.e., the directions of the principal axes of the kinematic strain rates). The calculated vertically averaged deviatoric stress field is consistent with styles and directions of stress from the world stress map and has magnitudes ranging from 5 - 20 MPa. Dividing the magnitude of deviatoric stresses for each grid area by the magnitude of the strain rates yields a lateral distribution of the vertically averaged effective viscosity (0.5×10^{21} Pa-s 10^{22} Pa-s) for western North America that is in agreement with other studies. Combining our results for the vertically averaged effective viscosity field with published strength profiles requires that a significant portion of lithospheric strength to reside within the upper 15-km of the seismogenic crust where stress levels peak at 100 MPa. On the other hand the upper mantle is relatively weak. Moreover the good fit between our calculated deviatoric stress field and observed stress directions argues for a weak coupling, or small basal tractions, at the base of the lithosphere. Thus, much of the observed deformation field in western North America can be explained by density and strength variations within the lithosphere, as well as plate interaction, with mantle-lithosphere coupling playing only a minor role.

URL: http://geophysics.geo.sunysb.edu/~flesch

U22A-0008 1330h POSTER

Heat Transfer by Mantle Convection in a Plate Tectonic Regime: 2D Systematic Investigation

Stephane Labrosse[1] (+33 1 44 27 49 35; labrosse@ipgp.jussieu.fr)

Paul J Tackley[2] ((310) 206-9180; ptackley@ess.ucla.edu)

[1]Institut de physique du Globe de Paris, 4, place jussieu, Paris 75252, France

[2]Department of Earth and Space Sciences, UCLA, 595 Charles Young Drive East, Box 951567, Los Angeles, CA 90995, United States

We have conducted a systematic 2D investigation of Rayleigh-Bénard convection (convection between two iso-thermal horizontal boundaries) with volumetric heat sources, in a fluid with temperature-dependent viscosity (variations of five orders of magnitude) and a constant yield stress. This type of rheology, although probably much simpler than the real Earth's mantle's, allows the development of dynamical structures that are a good first order approximation of tectonic plates.

The system is controlled by 4 non–dimensional parameters: The Rayleigh number, the heating rate, the yield stress and the aspect ratio of the domain. All were varied systematically to investigate planform and heat transport. The different solutions can be grouped into two main families: the rigid-lid regime which is typical of convection with highly temperature-dependent viscosity, and the plate-like regime. In both of these regimes, the solutions can be steady-state, periodic or fully time-dependent.

In the plate-like regime, for a given Rayleigh number and yield stress it is found that the aspect ratio of the basic cell increases with the internal heating rate until it eventually breaks down to the rigid-lid regime. A scaling analysis is used to explain this behavior as well as the heat transfer characteristics in each regime. Implications of these results on the thermal evolution of the Earth are important: the dynamic regime of the mantle may have been of the rigid-lid type early in its history when the radiogenic heat was more important. It would then have evolved to the plate tectonic regime, with an aspect ratio decreasing with time. The efficiency of heat transfer would have increased accordingly. More primordial heat would thus be retained compared to what is usually obtained in thermal evolution models.

U22A-0009 1330h POSTER

Formation of Plates in Numerical Mantle Convection Models

Claudia Stein[1] (00492518333597; stein@earth.uni-muenster.de)

Ulrich Hansen[1] (00492518333592; hansen@earth.uni-muenster.de)

[1]Institut f. Geophysik, Westfaelische Wilhelms-Universitaet Muenster, Corrensstr. 24, Muenster 48149, Germany

In a threedimensional numerical model we demonstrate that with an appropriate rheology the mantle convection system organizes itself into a state, exhibiting essential features of plate tectonics. While a strongly temperature-dependent viscosity leads to a stagnant lid, mobilization of the surface appears if an additional yield-stress criterion is taken into account. During short periods, parts of the surface move like plates. These periods are interrupted by phases in which a stagnant lid exists. Besides plate-like motion we observe other features like the migration of subduction-zones. Adding further a pressure dependence of the viscosity leads to change from the episodic to a more continuous plate-like behavior. Once plates have formed, the surface moves essentially steady throughout the modelled time. This models evolves into a state displaying extended rigidly moving plates, surrounded by localized areas with high deformation.

U22A-0010 1330h POSTER

Plate-Tectonic Circulation is Driven by Cooling From the Top and is Closed Within the Upper Mantle

Warren B. Hamilton (whamilto@mines.edu)

Dept. of Geophysics, Colorado School of Mines, Golden, CO 80401

Subduction drives plate tectonics and is due to cooling from the top: circulation is self-organized, and likely is closed above the discontinuity near 660 km. The contrary consensus that plate tectonics is driven by bottom heating and involves the entire mantle combines misunderstood kinematics with flawed concepts of through-the-mantle plumes and subduction. Plume conjecture came from the Emperor-Hawaii progression, the 45 Ma inflection in which was assumed to mark a 60-degree change in direction of that part of the Pacific plate over a fixed plume. Smooth spreading patterns around the east and south margin of the Pacific plate, and paleomagnetic data, disprove such a change. Speculations that plumes move, jump, etc. do not revive falsified conjecture. Geochemical distinctions between enriched island and depleted ridge basalts (which overlap) are expected products of normal upper-mantle processes, not plumes. MORB traverses solidus-T asthenosphere, whereas OIB zone-refines through subsolidus lithosphere and crust, crystallizing refractories to retain T of diminishing melt while assimilating and retaining fusibles. Tomographic inference of deep-mantle subduction is presented misleadingly and may reflect methodological and sampling artifacts (downward smearing, and concentration of recorded body waves in bundles within broad anomalies otherwise poorly sampled). Planetological and other data require hot Earth accretion, and thorough early fractionation, from material much more refractory than primitive meteorites, and are incompatible with the little-fractionated lower mantle postulated to permit whole-mantle circulation. The profound seismic discontinuity near 660 km is a thermodynamic and physical barrier to easy mass transfer in either direction. Refractory lower mantle convects slowly, perhaps in layers, and loses primarily original heat, whereas upper mantle churns rapidly, and the 660 decoupling boundary must have evolved into a compositional barrier also.

Plate motions are driven by subduction, the passive falling away of oceanic lithosphere which is negatively buoyant because of top-down cooling. Slabs have top and bottom rolling hinges and sink subvertically (inclinations of slabs mark their positions, not trajectories) into the transition zone, where they are laid down on, and depress, the 660-km discontinuity. Rollback of upper hinges into subducting plates is required by plate behavior at all scales. That fronts of overriding plates advance at rollback velocity is required by common preservation atop their thin leading edges of little-deformed fore-arc basins. Convergence velocity also commonly equals rollback but is faster in some arcs. Steeply-sinking inclined slabs push sublithospheric upper mantle forward into the shrinking ocean from which they came, forcing seafloor spreading therein, and pull overriding plates behind them. Continental plates pass over sunken slabs like tanks above their basal treads, and material from, and displaced rearward by, sunken slabs is cycled into pull-apart oceans opening behind the continents, thus transferring mantle from shrinking to enlarging oceans. Hot mantle displaced above slabs enables backarc spreading. Spreading ridges, in both shrinking and enlarging oceans, are passive byproducts of subduction, and migrate because it is more energy efficient to process new asthenosphere than to get partial melt from increasingly distant sources. A plate-motion framework wherein hinges roll back, ridges migrate, Antarctica is approximately fixed, and intraplate deformation is integrated may approximate an absolute reference to sluggish lower mantle, whereas the hotspot frame is invalid, and the no-net-rotation frame minimizes trench and ridge motions.

U22A-0011 1330h POSTER

Lithospheric thickness and seafloor topography inferred from a global seismic model

Michael H. Ritzwoller[1] (303 492 70 75; ritzwoll@merckx.colorado.edu)

Nikolai M. Shapiro[1] (nshapiro@anquetil.colorado.edu)

Shijie Zhong[1] (szhong@spice.colorado.edu)

William Landuyt[1] (William.Landuyt@Colorado.EDU)

Garrett M. Leahy[1] (Garrett.Leahy@Colorado.EDU)

[1]Center for Imaging the Earth's Interior, Department of Physics University of Colorado Campus Box 390, Boulder, CO 80309-390, United States

We present and discuss a new seismic model of the lithosphere/asthenosphere underlying the world's oceans to a depth of about 250 km. The data-set consists of broad-band Rayleigh and Love wave group-velocity (CU-Boulder; 15 - 200 s) and phase-velocity (Harvard, Utrecht; 40 - 150 s) dispersion curves. We construct the group and phase velocity maps using "diffraction tomography" which accounts for path-length dependent sensitivity, wave-form healing and associated diffraction effects that are particularly important for long ocean-crossing paths. Monte-Carlo inversion of the dispersion maps produces an ensemble of acceptable shear velocity models of the crust and uppermost mantle from which average characteristics and uncertainties are extracted. The model clearly shows lithospheric thickening with age.

We convert the seismic model into temperature and density using laboratory-measured properties of individual minerals, a mineralogical composition model of the oceanic mantle, and the Voigt-Reuss-Hill averaging scheme in order to estimate the thickness of the thermal lithosphere (TL) and to predict seafloor topography. The bottom of the TL is defined as the depth of intersection of the linear-conductive and adiabatic geotherms. We predict seafloor topography from the density model by assuming isostatic compensation to a depth determined by the maximum thickness of the TL ($\sim$150 km). The predicted topography falls off approximately as the square-root of lithospheric age from about 25 - 80 Ma, and then flattens at greater ages. This trend is observed most robustly for fast moving lithosphere and, therefore, we concentrate discussion on the Pacific. The residual topography (observed - predicted) for old lithosphere produced by the seismic model is reduced substantially relative to a half-space cooling model. This means that temperatures inferred from the seismic model are elevated relative to the half-space cooling model, which is evidence for cooling arrested in the old Pacific possibly by small-scale convection produced by instabilities associated with lithospheric thickening.

U22A-0012 1330h POSTER

Using Surface Observations to Constrain the Direction and Magnitude of Mantle Flow Beneath Western North America

William E Holt[1] (631 632 8215; wholt@mantle.geo.sunysb.edu)

Paul G. Silver[2] (202 478 8834; silver@dtm.ciw.edu)

[1]SUNY at Stony Brook, Department of Geosciences, SUNY at Stony Brook, Stony Brook, NY 11794-2100, United States

[2]Carnegie Institution of Washington, DTM, Carnegie Institute of Washington, DTM, Washington, DC, United States

While the motions of the surface tectonic plates are well determined, the accompanying horizontal mantle flow is not. Observations of surface deformation (GPS velocities and Quaternary fault slip rates) and upper mantle seismic anisotropy are combined for the first time, to provide a direct estimate of this flow field. We apply our investigation to western North America where seismic tomography shows a relatively thin lithosphere. Here the likely source of shear wave anisotropy results from a deformation fabric associated with the differential horizontal motion between the base of the lithosphere and the underlying mantle. For a vertically propagating shear wave recorded at a single station, and for mantle strains of order unity, the fast polarization direction, ϕ, of a split shear wave will be parallel to the direction of progressive simple shear, defined by this differential motion between lithosphere and underlying mantle. If the motion of the overlying lithospehre is known both within and across a plate boundary zone, such as western North America, then the direction and magnitude of mantle flow beneath the plate boundary zone can be uniquely determined with three or more observations of fast polarization directions. Within the Pacific-North American Plate boundary zone in western North America we find that the mantle velocity is 5.0$\pm$1.5 cm/yr and directed E-NE in a hotspot frame, nearly opposite to the direction of North American plate motion (WSW). The flow is only weakly coupled to the motion of the surface plates, producing a weak drag force. This flow field is most likely due to mantle density heterogeneity associated with the sinking of the old Farallon slab beneath North America.

The last few decades have seen the development of two basically incompatible views of the plate-mantle system. The tectonophysical view assumes effective decoupling between the plate and a stationary mantle by a well developed asthenosphere. The plates are essentially 'self-driving'. In the mantle-dynamics view, the plates are strongly-coupled to a mantle flow field that is driven by sources of buoyancy in the mantle. Our results suggest that both views are partly correct. We do observe plate-mantle decoupling, but also find a mantle flow field that is likely driven by deep mantle density heterogeneity. If this description is correct, then beneath the oceanic two-thirds of the Earth, where a well developed asthenosphere is most likely present, we may be completely surprised by the motions of the mantle. More importantly, however, the direct measurement of these motions, as done here, hold the possibility of dramatically increasing our understanding of the dynamic mantle.

URL: http://geophysics.geo.sunysb.edu

U22A-0013 1330h POSTER

Generation of Mid-Ocean Ridge Geometries by Strain Induced Damage

Christoph F. Hieronymus (45-38-14-26-66; cfh@dlc.ku.dk)

Danish Lithosphere Centre, Oester Voldgade 10 L, 1350 Copenhagen K, Denmark

Motivated by the success of wax models in which spreading segments, transform faults, and overlapping spreading centers form in a thin plate of solid wax under tension overlying a reservoir of molten wax, the dynamics of an elastic plate with damage is investigated. The effects of the underlying medium are neglected. A thin elastic plate with localized weaknesses in the elastic moduli is exposed to a deviatoric stress field. Stresses and strains are concentrated near the boundaries and inside the weak zones. Weakening of the material is assumed to occur where stress and strain are high, i.e. in regions of high elastic energy.

The weak zones typically develop into linear bands of reduced elastic strength resembling fractures and shear zones. Different dependencies of the elastic moduli on damage result in different geometries of weak zones. An initially circular weakness has two locations of normal stress concentration; reduction of bulk and shear modulus there results in formation of an opening mode fracture with low resistance to any type of deformation. Two such fractures offset from each other and propagating toward each other interact by overlapping and curving toward each other. This overlapping geometry, which is observed along the East Pacific Rise, is stable; the fractures do not cut each other off. Introduction of a second type of damage causes the overlapping region between the two fractures to fail, and the more commonly observed transform offset develops. With another type of damage-strain dependency, oblique spreading occurs along lines 45° from the applied stress. Such patterns form frequently in certain types of wax, but are not observed along mid-ocean ridges.

The model results suggest that it is the rheology of the solid plate, not the dynamics of the underlying mantle that control the morphology of the spreading ridge. Standard damage theory uses only a single damage parameter. The fact that the failure modes described above are limited to systems of solid plates underlain by molten substrata indicates that one of the types of damage is related to hydrofracturing, a process not considered in standard damage theory.

U22A-0014 1330h POSTER

Initiation of Subduction Zones: A Consequence of Lateral Compositional Buoyancy Contrast Within the Lithosphere

Yaoling Niu[1] (44-2920876411; niuy@cf.ac.uk)

Mike J. O'Hara[1]

Julian A. Pearce[1]

[1]Department of Earth Sciences, Cardiff University, Cardiff CF10 3YE, United Kingdom

Subduction of oceanic lithosphere into deep mantle is one of the key aspects of plate tectonics. Pull by the subducting-slab due to its negative buoyancy is widely accepted as the major driving force for plate motion and plate tectonics. Hence, there would be no plate tectonics if there were no subduction zones. Yet how a subduction zone initiates remains poorly known. Here we show that *lateral compositional (vs. thermal) buoyancy contrast within the lithosphere creates the favored and necessary condition for the initiation of a subduction zone* by (1) comparing the compositional and density differences between normal oceanic lithosphere (NOL) represented by abyssal peridotites (AP) and subarc lithosphere (SAL) represented by forearc peridotites (FP), and (2) simple physical analysis. As the gravitational attraction is the principal driving force of the subducting slab, it would be optimal if one part of the lithosphere experiences a greater gravitational attraction than its adjacent neighbor prior to or during the initiation of a subduction. This requires the pre-existence of a density contrast within the lithosphere. If the lithosphere is thermally uniform as is often the case, then the density contrast must result from a compositional contrast. This hypothesis can be tested by examining the lithospheric materials on both sides of a subduction zone. Subduction of a dense NOL beneath a buoyant continental lithosphere is straightforward, but intra-oceanic subduction such as in the western Pacific requires a scrutiny. Our data show that FP of Mariana and Tonga - two of the most important intra-oceanic subduction zones on Earth - are compositionally more depleted than AP: Cr#-sp (mean$\pm 1\sigma$) = 0.584$\pm$0.084(FP) vs. 0.307$\pm$0.134(AP); Mg#-ol = 0.915$\pm$0.006(FP) vs. 0.898$\pm$0.082(AP); Mg#-opx = 0.917$\pm$0.006(FP) vs. 0.908$\pm$0.006(AP); Mg#-cpx = 0.929$\pm$0.021(FP) vs. 0.917$\pm$0.011(AP). As a result, SAL is $>$ 0.7% less dense than NOL. This density contrast due to compositional difference is equivalent to

$\Delta T = \sim 230^{\circ}C$, which is similar to or greater than the postulated thermal buoyancy contrast between a hot mantle plume and its surroundings. While the depleted nature of FP has been interpreted to result from subducting-slab dehydration induced high extents of mantle wedge melting, evidence indicates that the depletion of these FP predates the inception of the subduction, thus these FP are not residues of present-day arc magmatism. Hence, the compositional buoyancy contrast already existed within the lithosphere before the inception of the subduction in the western Pacific. Much of the Mariana SAL may be fragments of old continental lithosphere, whereas the Tonga/Fiji plateau and Kamchatka lithosphere may be remnants of buoyant, hence unsubductable oceanic plateaus (mantle plume head materials) for the Louisville and Hawaiian hotspots respectively. Passive continental margins, where the largest compositional buoyancy contrast exists within the lithosphere, are the loci of future subduction zones. Geometrical analysis shows that the compositional buoyancy contrast within the lithosphere under compression (e.g., ridge push) induces transtensional planes. The weakest plane in the vicinity of the compositional buoyancy contrast develops into a reverse fault. The dense NOL (the foot-wall) tends to sink into the hot and less dense asthenosphere. Calculations show that this tendency to sink reduces both the normal stress to, and shear resistance along, the fault plane, thus easing the sinking and favoring the initiation of a subduction zone. This concept also explains other observations and makes testable predictions on important geodynamic problems.

U22B MC: 134 Tuesday 1330h

The Earth's Interactions With the Sun, From Millennia to Minutes

Presiding: **D Strobel,** The Johns Hopkins University; **G Reeves,** Los Alamos National Laboratory; **D E Siskind,** Naval Research Laboratory; **B Thompson,** NASA Goddard Space Flight Center

U22B-01 1335h INVITED

Time scales and Mechanisms of Climate Interactions with the Sun

David H Rind (212-678-5593; drind@giss.nasa.gov)

Goddard Institute for Space Studies at Columbia University, 2880 Broadway, New York, NY 10025, United States

Various correlations have been obtained between observed or deduced changes in solar irradiance and climate variations. During the Quaternary, these include: ice age cycles (circa 100,000 years), associated with Milankovitch orbital variations; apparent climate periodicities on the order of 2300, 210, 88, 22 or 11 years, presumably associated with variations of these periods in the activity of the sun, including sunspots; and even daily responses of cyclone intensity related to high energy particles. The problem in each of these respects is to decipher how the relatively small energy variations (at most on the order of 0.5 percent of total solar irradiance, or 1 W/m2) could be responsible for the impacts in the massive troposphere ascribed to them. One explanation is that they cannot: that the correlations are either circular reasoning, associated with dating uncertainties, or quasi-periodicities related to naturally occurring cycles that happen to match solar ones. Alternatively, the climate system could be sensitive to the spectral frequencies or latitudinal distribution of the solar irradiance changes, thereby amplifying the forcing via naturally occurring mechanisms. Our current understanding of this subject will be reviewed, with emphasis on the potential interaction between different levels of the atmosphere as amplifying mechanisms, including impacts on both radiative and atmospheric-dynamical processes.

U22B-02 1405h

Persistent Solar Influence on North Atlantic Surface Circulation During the Holocene

Gerard Bond[1] (845-365-8478; gcb@ldeo.columbia.edu); Bernd Kromer[2] (496221546; Bernd.Kromer@iup.uni-heidelberg.de); Michael N. Evans[3] (5206262897; mevans@ltrr.arizona.edu); Juerg Beer[4] (4118235111; juerg.beer@eawag.ch); Raimund Muscheler[4] (4118235414; raimund.muscheler@eawag.ch); William Showers[5] (9195157143); Sharon Hoffmann[1] (8453658637); Rusty Lotti[1] (8453658419)

[1]Lamont-Doherty Earth Observatory, Route 9W, Palisades, NY 10964, United States

[2]Heidelberg Academy of Sciences, Institute of Environmental Physics, INF 229, Heidelberg D-69120, Germany

[3]Laboratory of Tree-Ring Research, University of Arizona, 105 W. Stadium, Tucson, AZ 85721, United States

[4]EAWAG, Ueberlandstrasse 133, Postfach 611, Duebendorf CH-8600, Switzerland

[5]Dept of Marine, Earth & Atm. Sciences, North Carolina State Univ., 1125 Jordan Hall, Raleigh, NC 27695-8208, United States

New evidence from deep sea cores in the North Atlantic suggests that recurring expansions of the subpolar surface circulation were influenced by variations in solar output through the entire Holocene. Five high-resolution records of drift ice from three widely separated sites reveal a series of rapid, centennial time-scale oscillations that are bundled into the millennial duration events of the "1500-year" cycle. The centennial duration oscillations closely match prominent changes in production rates of the cosmogenic nuclides ^{14}C and ^{10}Be as inferred from tree ring measurements and from Greenland ice core records, respectively. Virtually every expansion of the subpolar surface circulation is linked to reduced solar irradiance. The most recent circulation cycle corresponds to the "Little Ice Age-Medieval Warm Period".

Each expansion of the subpolar circulation was associated with cooler surface temperatures and probably with more zonal surface winds. Those changes may reflect an intensified and expanded Polar Cell and would be consistent with recent GCM models of the atmosphere's dynamical response to solar forcing of stratospheric ozone and temperature. The sense of the circulation-driven temperature changes, though, does not exhibit the characteristic dipole pattern of the NAO; rather the pattern resembles that of regional cooling associated with reduced production of North Atlantic Deep Water (NADW), such as during the Younger Dryas although with much lower amplitude. As production of NADW is highly sensitive to changes in surface hydrography, we suggest that the solar forced expansions of subpolar circulation may have triggered a deep ocean response, which, through reduced northern heat transport and increased sea ice, further amplified the climate response to variations in solar output.

U22B-03 1420h

The Earth's Interaction With the Sun Over the Millennia From Analyses of Historical Sunspot, Auroral and Climate Records

K Pang

K Yau[1]

[1]JPL, MS/230-101, Pasadena, CA, United States

A prolonged decrease in the Sun's irradiance during the Maunder Minimum has been proposed as a cause of the Little Ice Age (*ca* 1600-1800). Eddy [*Science* **192**, 1976, 1189] made this suggestion after noting that very few sunspots were observed from 1645 to 1715, indicative of a weakened Sun. Pre-telescopic Oriental sunspot records go back over 2200 years. Periods when no sunspots were seen have been documented by, *eg*, Clark [*Astron* **7**, 2/1979, 50].

Abundances of C 14 in tree rings and Be10 in ice cores are also good indicators of past solar activity. These isotopes are produced by cosmic rays high in the atmosphere. When the Sun is less active more of them are made and deposited at ground level. There is thus a strong *negative* correlation between their abundances and sunspot counts. Minima of solar activity in tree rings and a south polar ice core have been collated by, *eg*, Bard [*EarthPlanetSciLett* **150** 1997, 453]; and show striking correspondence with periods when no sunspots were seen, centered at *ca* 900, 1050, 1500, 1700.

Pang and Yau [*Eos* **79**, #45, 1998, F149] investigated the Medieval Minimum at 700, using in addition the frequency of auroral sighting7s, a good indicator of solar activity too [Yau, PhD thesis, 1988]; and found that the progression of minima in solar activity goes back to 700. Auroral frequency, C 14 and Be 10 concentrations are also affected by variations in the geomagnetic field. Deposition changes can also influence C 14 and Be 10 abundances. Sunspot counts are thus the only true indicator of solar activity.

The Sun's bolometric variations (-0.3% for the Maunder Minimum) can contribute to climatic changes (0.5° C for the Little Ice Age)[*eg*, Lean, *GRL* **22**, 1995, 3195]. For times with no thermometer data, temperature can be estimated from, *eg*, Oxygen 18 isotopic abundance in ice cores, which in turn depends on the temperature of the ocean water it evaporated from. We have linked the Medieval Minimum to the cold spell, dated to *ca* 700 by Dansgaard [*Nature* **255**, 1974, 24]. Using records of advances and retreats of glaciers, previous researchers have linked it to a cold spell in the previous two centuries instead, thus requiring an offset in timescales.

Our literature search has yielded more records of sunspot sightings, and established the fifth century as a minimum of solar activity, ending in a maximum at *ca* 500. These features and the minimum at 700 match contemporary deviations of atmospheric C 14 from a secular trend, due primarily to long-term changes in the strength of the Earth's magnetic moment [Stuiver, *Radiocarbon* **35**, 215].

Pang has shown that the climate of Eurasia was cold in the 5th century, due partly to volcanic cooling [*Eos* **80**, #46, 1999, F220]. Reduced solar luminosity may have contributed to that too. The cold apparently forced massive southward migrations of Teutonic and Asian barbarians into the Roman Empire, ending it in 476. Europe was plunged into the Dark Age, from which it did not recover until the climate warmed up again toward the end of the millennium.

Finally, climate changes can also be produced by greenhouse warming, reorganization of ocean current systems "Dansgaard-Oeschger events," the Earth's orbital variations "Milankovitch effects," *etc.* Continued analysis of historical records, in conjunction with other proxy data, can help shed light on the nature of the Earth's interactions with the Sun, and the causes of past climate changes.

U

U22B-04 1435h INVITED

Solar Photons, Particles and the Earth's Ozone Layer

David E Siskind (202-767-0928; siskind@uap2.nrl.navy.mil)

E.O.Hulburt Center for Space Research, Naval Research Lab , 4555 Overlook Ave SW, Washington, DC 20375, United States

The middle atmosphere is sensitive to solar/terrestrial coupling in several ways. Variable photon output from the sun can directly cause changes in the photodissociation of molecular oxygen and thus cause ozone in the upper stratosphere to vary with solar activity. Ozone variations on the 27 day solar rotation and 11 year solar cycle timescales have been observed. Models can reproduce the 27 day variability, but underestimate the 11 year variability. Particle fluxes into the atmosphere can also effect middle atmospheric chemistry. Solar protons with energies from 1-500 MeV can occasionally produce large amounts of odd nitrogen (NOx) and odd hydrogen (HOx) in the polar stratosphere and mesosphere. By increasing the abundances of NOx and HOx radicals, solar proton events can lead to noticeable ozone losses, most recently in the so-called Bastille Day event of July 2000. Depending upon the energy of the solar protons and thus the altitude at which they deposit their energy, these ozone losses can persist for months. Finally, magnetospheric electrons are known to produce large amounts of nitric oxide in the upper mesosphere and lower thermosphere. Through downward transport in the polar winter, the NO can be brought down as low as 25 km where it can cause significant ozone loss. These solar-terrestrial coupling mechanisms will be reviewed with emphasis place upon outstanding issues and controversies.

U22B-05 1520h INVITED

Weather and Climate of the Earths Outer Atmosphere Driven by the Sun

Raymond G. Roble (303-497-1562; roble@ucar.edu)

National Center for Atmospheric Research, High Altitude Observatory, Box 3000, Boulder, CO 80307, United States

The outer layers of the Earth's atmosphere, the thermosphere and ionosphere, are strongly influenced by the highly variable components of the Sun's output. The basic temperature and compositional structure and dynamics are set by the radiative output of the Sun in the X-ray, EUV and UV portions of the spectrum from 1 to 200 nm. These are then strongly modified by the plasma inputs into the high latitude thermosphere and ionosphere caused by the interaction of the solar wind with the magnetosphere and transferred to the upper atmosphere in the form of auroral particle precipitation