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There is clear evidence for standing bodies of water in different places and at different times in the history of Mars. The martian outflow channels debouched into the northern lowlands primarily in the Late Hesperian Period and their characteristics suggest to many workers that a large standing body of water, or ocean, was produced as a result. Characteristics of northern lowland deposits in the Early Amazonian Period suggest that by this time such an ocean was gone. What would be the fate of such standing bodies of water under climatic conditions similar to the present? The evolution of water loaded with sediments emplaced by outflow channel formation would include three phases. (1) Violent emplacement of warm water followed by a short period of intensive evaporation and convection. Water vapor would strongly influence the climate, at least for a geologically short time; when the water reached 277 K, boiling and intensive convection ceased and sediments were deposited. (2) Geologically fast (10^4 years) freezing accompanied by weak convective water movement. (3) Sublimation of the ice lasted longer than freezing, but for a geologically short period. The rate and latitudinal dependence of sublimation, and locations of water vapor condensation, crucially depend on planetary obliquity, climate, and sediment veneering of the ice. Several observations support the hypothesis that the Late Hesperian Vastitas Borealis Formation is the sublimation residue of the ocean. Geological evidence has been cited to support a warm, wet era in the earlier Noachian Period (e.g., valley networks, degradation rates, etc.) and standing bodies of water under these earlier conditions have different origins and could have significantly longer residence times. Critical assessment of this evidence leads to several scenarios for the emplacement style, location and fate of water on early Mars, and the important transition to conditions similar to those of today. Candidate early Mars emplacement styles include: 1) pluvial, 2) sapping and groundwater recharge, 3) ice sheet meltback, 4) global hydrostatic equilibrium, and 5) cryospheric seal disruption. We examine evidence for these mechanisms for formation of standing bodies of water in the history of Mars, and assess their fate. Examples range in age from Noachian to Late Amazonian.

U12B-06 1525h INVITED

Europa: Divining Water from Surface Geology

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Europa's surface geology as viewed by Galileo imaging suggests a thin brittle lithosphere above a warm (potentially salt-rich) ice layer that is at least in part convecting, in turn situated above a liquid water ocean. This configuration is consistent with thermal and geochemical modeling, and with Galileo magnetometer and NIMS results, which suggest that Europa may have a salty global-scale subsurface ocean at relatively shallow depths (20-30 km). Dynamical modeling and visible crater density suggests a surface age of 50 million years, implying that Europa is probably still geologically active today. Large shallow craters and even larger multi-ringed structures imply impact into low-viscosity (warm) subsurface material. The satellite's bright plains are criss-crossed by narrow troughs and enigmatic double ridges (paired ridges separated by a medial trough); a morphological sequence (and implied evolutionary sequence) exists from isolated troughs to doublet ridges to wider and more complex ridge morphologies. Troughs are inferred as widened fractures formed through tensile and shear failure in response to global stressing of the ice shell above liquid water. Several models exist to explain ridges, but the most likely is one in which localized shear heating triggers upwelling of warm ice along fracture zones. Triple bands are ridges with diffuse ruddy margins that may have formed through thermal alteration and/or partial melting of briny ice. Wider pull-apart bands represent complete separation and spreading of the icy lithosphere, in a manner broadly analogous to terrestrial sea-floor spreading. Europa's global lineament pattern implies that nonsynchronous rotation and orbital flexing ("diurnal" stressing) have worked in tandem to deform the surface. Diurnal stressing can explain Europa's extremely enigmatic cycloid ridge and fracture patterns, and may drive rapid strike-slip faulting along ridges. Because significant tidal amplitude is necessary to produce significant diurnal stressing, this argues strongly for a subsurface liquid layer, but does not constrain its depth. Extremely slow nonsynchronous rotation of the ice shell may drive shear failure in equatorial regions, and may have opened the satellite's pull-apart bands. Mottled terrain consists of pits, domes, dark spots, patches of smooth plains, and regions of chaos terrain. Chaos is characterized by fragmented blocks of the preexisting surface, some of which have translated a few kilometers from their original positions, in a dark hummocky matrix. Mottled terrain landforms suggest vertical deformation and disruption of the surface along with localized partial melting. Their formation has

been interpreted as due to diapiric upwelling—the expression of solid-state convection of warm subsurface ice—predicted to occur within an ice shell tens of kilometers thick above liquid water. Warm ice diapirs can circulate material between Europa's ocean and shallow levels within the ice shell, and can trigger local partial melting of briny ice, potentially creating near-surface biological niches. Europa's astonishing geology and its biological potential makes the satellite a high priority for future orbital and landed exploration.

U12B-07 1545h INVITED

Tidal Dissipation in the Rocky Core Drives Oceanic Processes on Europa

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Chaos-type features on the surface of Europa are interpreted as melt-through structures formed by rotationally confined, steady and/or episodic oceanic plumes that rise to the base of the ice shell from magnetically heated hydrothermal venting regions on the seafloor. The ocean is assumed to be weakly stratified due to turbulent convection generated by heating from below and cooling from above. Seafloor heating, maintained by tidal dissipation in the rocky interior, generates an estimated global heat flux of 8.7×10^{12} W and limits the mean ice thickness to 2 to 5 km. For seafloor heat sources with radii, r , that are less than the ocean's deformation radius ND/f (where N is the buoyancy frequency, D is the water depth, and f is the magnitude of the Coriolis parameter), the diameters of chaos-type regions are expected to diminish from $O(100 \text{ km})$ within equatorial regions to $O(10 \text{ km})$ at high latitudes. Provided there is sufficient time before refreezing, ice rafts in large melt-through regions are imbedded in episodes of preferentially anticyclonic circulation, corresponding to clockwise motions in the northern hemisphere. Although the Coriolis effect may be unimportant for short-lived ice-raft displacements characteristic of most melt-through regions, rotation is of fundamental importance in determining the formation and physical dimensions of the melt regions.

Roughly 10^{21} J were required to melt the ice in the 100 km diameter Conamara Chaos region. For a steady, localized heat flux of 10^{11} W ($\sim 1\%$ of the global heat flux), it would take about 1000 years for the initial melt-through to occur, an acceptable time-scale for steady state venting systems on earth. As on Earth, the European ocean may also switch between weak and strong stratification modes over geological time scales. At times of strong stratification, most convective plumes would not penetrate to the base of the ice and heat would be trapped in the lower portion of the water column. Continued bottom heating and surface cooling would eventually weaken the upper ocean stratification, allowing thermal plumes to again penetrate to the base of the ice cover. The stratification-destratification cycle would be completed by the formation of low salinity, upper ocean melt-water during times of increased under-ice melting.

U12B-08 1605h INVITED

Oceans on Titan: Past, Present and Future

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Titan is Saturn's largest moon, and the second largest natural satellite in the solar system. Composed of half rock by mass, the satellite probably contains enough radiogenic material so that, when combined with accretional heating, differentiation into a rocky deep mantle and icy upper mantle is likely. Unlike its near twins in size and density, Jupiter's Ganymede and Callisto, Titan is endowed with a dense atmosphere, mostly nitrogen but with an admixture of methane. The methane is photolyzed in the upper atmosphere to make, with the participation of nitrogen, a complex mixture of hydrocarbons and nitriles. This in turn forms aerosols which descend to the surface, and have accumulated over time as solids and liquids. If photochemistry has occurred in a steady state fashion over Titan's history, perhaps hundreds of meters of liquid hydrocarbons (expressed as equivalent depth of the layer) reside in the upper crust and on the surface. The Cassini-Huygens mission will search for such liquids and assess the extent of photochemistry through time. Titan's overall history with respect to surface liquids may be complex. In the distant past accretional heating could have sustained a deep layer of mixed water-ammonia liquid as a kind of cryogenic magma ocean.

Liquid hydrocarbons have come and gone on the surface through time to the present. In the distant future, when the Sun becomes a red giant star, Titan could once again possess a water-ammonia surface ocean.

U12B-09 1625h

TITAN - A NEW LABORATORY FOR OCEANOGRAPHY

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Saturn's giant moon Titan has a thick (1.5 bar) nitrogen atmosphere, and quite probably large expanses of liquid hydrocarbons on its surface. The physical processes in these lakes and seas will open new vistas on oceanography and limnology.

Although the Voyager-era paradigm of a deep, global ocean is ruled out by radar and infrared data showing that at least part of Titan's surface is icy, the photochemical arguments that originally led to the proposal of hydrocarbon oceans still apply. Even if the methane in the atmosphere is being resupplied by delivery from the interior, the ethane produced by photolysis would still accumulate to form large deposits on the surface. The near-infrared maps of Titan's surface from the Hubble Space Telescope and groundbased adaptive optics consistently show a number of dark (in fact, pitch-black!) regions that are strong candidates for hydrocarbon seas. These could be up to some 500km in extent.

Titan promises to be a new laboratory for oceanography. Like in meteorology, many ocean processes are better parameterized than they are understood, and thus the different physical circumstances on Titan may shed new light on them. Titan has a lower gravity and its ocean fluids are of lower density, perhaps of lower viscosity (depending on solutes and suspended material) and probably rather more likely to cavitate. The ratio of atmospheric density to ocean density is much larger on Titan than on Earth, suggesting that liquid motions will be well-coupled to surface winds (although the distance from the sun is such that the energy in such winds is likely to be low.)

Titan is also subject to strong tidal forces (the equilibrium tide due to Saturn's gravity is some 400x larger than that of the moon on Earth.) Although the 100m tidal bulge stays almost fixed because Titan rotates synchronously, the eccentricity of Titan's orbit leads to significant libration and variation in the tidal strength. The 500km seas allowed by the IR data may yet have a 2m tidal amplitude. The long period of tidal excitation, however, means that tidal resonances are unlikely to occur.

The NASA-ESA Cassini/Huygens mission will arrive in late 2004, and deliver the parachute-borne Huygens probe to Titan's surface in early 2005, taking images during its descent. The Cassini orbiter during its 4 year tour will fly by Titan some 45 times, taking SAR and altimeter data with a multimode radar, and observing the surface with optical and near-IR sensors. Future missions to Titan are already being contemplated, and might involve such platforms as helicopters or blimps.

U21A MC: 134 Tuesday 0830h

Plate Tectonics and Self-Organization I

Presiding: D L Anderson, California Institute of Technology; D Bercovici, Yale University

U21A-01 0830h

Plate Tectonics as a Far-From-Equilibrium Self-Organized Dissipative System

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A fluid above the critical Rayleigh number is far from equilibrium and spontaneously organizes itself into patterns involving the collective motion of large numbers of molecules which are resisted by the viscosity of the fluid. No external template is involved in forming the pattern. In 1928 Pearson showed that Bnard's experiments were driven by variations in surface tension at the top of the fluid and the surface motions drove convection in the fluid. In this case, the surface organized itself AND the underlying fluid. Both internal buoyancy driven flow and flow driven by surface forces can be far-from-equilibrium self-organized

open systems that receive energy and matter from the environment. In the Earth, the cold thermal boundary layer at the surface drives plate tectonics and introduces temperature, shear and pressure gradients into the mantle that drive mantle convection. The mantle provides energy and material but may not provide the template. Plate tectonics is therefore a candidate for a far-from-equilibrium dissipative self-organizing system. Alternatively, one could view mantle convection as the self-organized system and the plates as simply the surface manifestation. Lithospheric architecture also imposes lateral temperature gradients onto the mantle which can drive and organize flow. Far-from-equilibrium self-organization requires; an open system, interacting parts, nonlinearities or feedbacks, an outside steady source of energy or matter, multiple possible states and a source of dissipation. In uniform fluids viscosity is the source of dissipation. Sources of dissipation in the plate system include bending, breaking, folding, shearing, tearing, collision and basal drag. These can change rapidly, in contrast to plate driving forces, and introduce the sort of fluctuations that can reorganize far-from-equilibrium systems. Global plate reorganizations can alternatively be thought of as convective overturns of the mantle, or thermal weakening of plates or the asthenosphere by hot upwellings. The study of soft matter, bubble rafts, foam, fragile systems, force bridges and jamming may give insights into the physics of plate tectonics. For example, plates might be defined as "force bridges" that carry lateral compression, but dissolve and reform if the stress system changes. In the plate tectonic problem it is not clear what, if anything, is being minimized. Is it dissipation, or toroidal energy or something else? This session should stimulate new ways of thinking about plates, plate boundaries and lithospheric rheology.

U21A-02 0845h

Dynamic and Static Properties of Granular Materials

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It is obvious that granular materials play an important role in the texture of the world around us. Despite their importance in many industries and their affect on many geophysical processes, it is fair to say that a fundamental explanation of their behavior is lacking. Our ignorance spans the entire gamut from understanding how a static granular pile responds to small perturbing forces to comprehending how a granular medium flows under strong shear stresses. Of course, the problems become even more subtle when one includes interstitial fluids (even ones as benign as air) between the grains. In this talk, I will give a short overview of some of the surprising behaviors that one can see in these systems - both in their static state and then when they are flowing. I will then give a more detailed analysis of some experiments designed to address the nature of the transition between the jammed (static) regime and the rapidly flowing one.

U21A-03 0905h

Plates and Mantle Convection: A Far-From Equilibrium Self-Organized System

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A common observation of plate tectonics is that plate velocities change over short time scales. Some have speculated that these reorganization events are triggered by evolving plate boundaries. This work presents an alternative mechanism, due to the interaction of mobil plates and internally heated convection. We present numerical models of 3D Cartesian convection in an internally-heated fluid with mobile plates that exhibit rapid changes in plate motion. A persistent feature of these calculations is that plate motion is relatively uniform punctuated by rapid reorganization events where plate speed and direction change over a short time period. The rapid changes in plate motion result solely from the interaction of internally-heated convection and the mobile plates. Without plates, the convective platform of an internally-heated fluid evolves into a pattern with a larger number of small

cells. When plates are included, the fluid is dominated by plate-scale structures; however, isolated regions develop where heat builds up. These isolated regions are near the location of mature slabs where the plates are older and thicker. As the system evolves, the temperature (and buoyancy) in these isolated regions increases, they become unstable and, as they rise, the net force on the plate is no longer dominated by 'slab pull' from the mature slab. The plate reorganization allows the system to transfer heat from the short-wavelength, internal-heating scale, to the longer-wavelength, plate-cooling scale. As we will demonstrate, the interaction between plate motions and the mantle is sufficiently dynamic that evolving plate boundaries are not necessary to achieve rapid changes in plate motion.

U21A-04 0920h

Constraints on the Character of Plate Tectonics From the Study of Diffuse Plate Boundaries

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While the main global expression of tectonics at Earth's surface is that of plate tectonics, i.e., narrow boundaries between rigid plates, a significant fraction of the lithosphere (perhaps 15% of both ocean basins and continents) is undergoing diffuse deformation. The existence of these zones of deformation (often termed "diffuse plate boundaries") raises the question of why the majority of deformation occurs at narrow boundaries, and how narrow boundaries may form. Study of the best characterized diffuse zone of oceanic deformation, which occurs in the equatorial Indian Ocean and may also be the best candidate for an incipient convergent plate margin, may help to elucidate these questions. The Indo-Australian composite plate comprises 3 component plates (i.e., the nondeforming portions of the composite plate) and multiple diffuse plate boundaries. We determine the general relation between the relative angular velocity between two component plates and the torque that the two component plates exert on one another across their mutual diffuse boundary. We show that the torque between the Indian and Capricorn component plates (respectively north and south of the equatorial diffuse plate boundary) is oriented far from the relative angular velocity vector between the two plates, and is subparallel to the torque exerted on India by the Tibetan plateau. With earlier work showing that onset of the current episode of deformation in the Indian Ocean coincided with the attainment of maximum elevation of the Tibetan plateau, this indicates that the lithospheric deformation in the equatorial Indian Ocean is being driven by the outward push of the Tibetan plateau. To achieve a torque balance, we find that the force per unit length exerted by the Tibetan plateau on the Indian component plate must be nearly identical to the strength of the oceanic lithosphere, which we infer to be $9(\pm 2) \times 10^{12} \text{ Nm}^{-1}$. Given that the effect of plateau formation by horizontal shortening of continental crust strongly influences the compressive stress available to deform oceanic lithosphere, this coincidence may be necessary for plate tectonics to continue and evolve on geologically long time scales while restricting these zones of diffuse deformation to relatively minor proportions of the oceanic plate, if narrow plate boundaries such as subduction zones evolve from diffuse plate boundaries.

U21A-05 0935h

The Flow of Foam

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Aqueous foams are a tight packing of gas bubbles in a relatively small volume of liquid. As such, the bubbles are jammed - unable to rearrange and explore different packing configurations using thermal energy. This gives bulk foam a surprising amount of mechanical strength. Even though the foam is composed of, say, ten percent liquid and ninety percent gas, it behaves like an elastic solid. However, when subjected to large external forces it can flow and deform like a liquid as bubbles rearrange from one packing configuration to another. These bubble rearrangements can either be sudden stick-slip like rearrangements involving small clusters, or else smooth and continuous across the whole sample. As a problem in Condensed Matter Physics, the goal is to observe such microscopic bubble-scale phenomena and relate them to the macroscopic rheological properties of the material. In my talk, I will review work in my lab in this regard. We employ novel self-beating multiple-light scattering methods to

observe bubble rearrangements, and we employ a commercial rheometer to observe macroscopic response. We also supplement our experiments with 'molecular dynamics' simulations of collections of bubbles.

U21A-06 1015h INVITED

Microphysics of Self-Organization

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Plate tectonics involves self-organization in space by strain localization as fault zones and self-organization in time by earthquakes. Both processes can be related to the rheology of rocks. At sufficiently low (deviatoric) stresses, the stress increases rapidly with strain rate. This results in strain rate delocalization. At very high stresses (GPa), the strain rate depends exponentially on stress or equivalently the stress depends only on the log of strain rate. Macroscopic stresses of this magnitude are not normally associated with tectonics. Microscopic stresses at grain-grain contacts reach this level in ordinary frictional sliding. Rate and state dependent friction is a tractable case where damage from sliding weakens the lattice and creep from normal traction at on the surface heals the damage. Strain localization and run-away creep at constant stress occur when the steady state stress on the surface decreases with strain rate. The damage may be real porosity in a crustal rock or a super plastic fine grained material associated with phase changes in deep earthquake zones. This behavior seems generalizable to 3-D. A success numerical representation should have damage and healing, an instantaneous rheology that is strain-rate strengthening, and a means of imposing a continuum that does not depend on the grid spacing. Further self-organization is associated with the pore fluid pressure. The subduction of water-rich material is a well known example.

U21A-07 1035h

Plate Generation from Mantle Convection: Odd Rheologies, Lithospheric Damage and Shear Localization

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In the last decade we have seen significant progress toward the broad goal of self-consistently generating tectonic plates in models of mantle convection. In general we have seen that plate-like motion in the top, cold thermal boundary layer of convection requires rheologies more exotic than we typically use for non-Newtonian mantle flow (i.e., power-law creep with an index of $n=3$). Basic plastic lithospheric rheologies appear to go quite far in generating plate-like motion when coupled to a low-viscosity underlying asthenosphere, although they generally have trouble generating concentrated strike-slip (toroidal) motion. The more extreme self-lubricating (sometimes called shear weakening or pseudo-stick-slip) rheologies can generate strike-slip motion, but the weak zones they generate tend to over-focus beneath the grid scale. Moreover, these rheological mechanisms involve instantaneous response and thus the softened plate boundaries they generate vanish as soon as deformation stops. Time- or history-dependent weakening mechanisms that rely on rheological response to temperature, grain-size or volatile content can (in some cases) yield narrow plate boundaries and possibly long-lived inactive boundaries, however they also appear to destabilize the plate-like motion. The most effective of these time-dependent mechanisms involve damage and volatile ingestion in the lithosphere; this approach is also well-motivated by the apparent predominance of ductile-cracking in the lithosphere within the large transition region that lies between the brittle-ductile and brittle-plastic transitions. However, most of these 'damage' theories are ad hoc and over-simplified. In an effort to better understand the damage approach, and provide a theory compatible with viscous mantle flow, we have proposed a two-phase damage theory. This theory states that 1) a damaged material (i.e., with microcracks and voids) is, in its simplest manifestation, a two phase material (a matrix phase representing solid host, and a fluid phase representing void-filling material such as water or air); and 2) the energy going into making microcracks is the surface energy of the crack wall, which in the two phase model is the surface energy of the interface between the phases. This model describes a spectrum of rich behavior including both shear localization and high-energy (or high-stress) distributed damage. The intensity of localization is strongly controlled by the variability of the deformational-work partitioning with dilation rate,

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?

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A combination of rheological and geophysical observations suggest that the physical properties of the oceanic asthenosphere are strongly influenced 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 Kohlstedt, 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

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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

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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

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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

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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.

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

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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.

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North America Plate is Driven Westward by Lower Mantle Flow

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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