

U44A-04 1615h

### Following the Sulfur using the Athena Payload on the Mars Exploration Rover Spirit.

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The Mars Exploration Rover (MER) Spirit landed in Gusev crater to begin investigating how water shaped the surface by using the Athena Payload. Two types of aqueous processes are being investigated at Gusev: recent processes involving transient liquid water and ancient processes of intermittent fluvial or lacustrine sedimentation. In addition to looking for direct mineralogical and morphological indicators of aqueous processes we are also looking at the abundance, distribution, mineralogy, and texture of sulfur compounds. An understanding of modern and ancient water at Gusev will help us develop a model for the timing, duration, and abundance of water. Preliminary results with Spirit found sulfur-rich "cemented" soils at Gusev, similar to the materials at the Viking I, II, and Pathfinder sites. The soils at Gusev have a honeycomb texture that in places look like tubes. This points toward a sulfate (perhaps with chloride) cement that formed in place. This is a relatively recent process where cement forms along capillaries. The source of water may either be from thin films associated with either atmospheric sources (top down model) or with subsurface sources (bottom up). Both models are being investigated by looking for trends in the sulfur (and other salt) concentration at a range of locations. Correlation of salt with depth or other soil characteristics such as grain size, texture, mineralogy, spectral properties, and mechanical strength of the apparent cemented material may permit the distinction between these models, estimate the ages of the crusts, and determine the amount of water needed to mobilize these salts. In addition to this relatively modern water-sulfate cycle, we are trying to determine if other older fluvial sedimentation processes have occurred and if they involved sulfates. A wide variety of processes may account for the sulfur-rich soils (e.g. salt rich ground waters, volcanic aerosols, or aeolian deposition of salt-rich fines). By comparing different types of materials at Gusev we may be able to identify any anomalous signature due to ancient fluvial processes. This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract to NASA.

U44A-05 1630h

### Soil and Rock Physical Properties at the Mars Exploration Rovers Landing Sites

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Soil and rock physical properties are being investigated by the Mars Exploration Rovers (MER) at Gusev crater (Spirit) and Meridiani Planum (Opportunity). These investigations are being conducted by the MER Athena Science Payload and the mobility systems on each rover. Physical properties of soil units are characterized by observations of wheel tracks (sinkage and tread casts). Images of rover wheel tracks in Gusev crater suggested a variety of surface textures. Traverses through depressions resulted in well-defined wheel track casts, suggesting that finer-grained materials accumulate in these depressions. In other areas, wheel tracks were not as defined and instead, some blocky fragments (e.g., 5-10 mm thick) of soil-like materials were displaced by the wheels. There were areas where small rocks (e.g., 1-3 cm) were pressed into weakly indurated or "crust" material. Soil and rock exposures are very different at Opportunity's landing site within a shallow 20 m crater at Meridiani. Outcrops of very fine-grained bedrock are found around the interior walls of the crater. The dominant soil unit within the crater is dark, fine-sand sized materials littered with larger spherules and spherule fragments (e.g., 1-10 mm); some of these spherules appear to be weathering out of the outcrop. A small-scale rippled soil unit seemingly lacking spherules located near the lowest part of the crater is probably a concentration of the fine-sand sized particles transported and partly reworked by wind. Assessment of initial rover tracks combined with observations of wheel slippage on sloping surfaces suggest that soil cohesion in the uppermost near subsurface material is low, and that finer particles (e.g., less than 30 microns) are also present along with

the fine sand-sized particles. Additional investigations are underway to characterize rates of atmospheric dust deposition on the rovers, soil physical properties by trenching into targets of opportunity (e.g., soils, bedforms), surface textural and compositional properties by conducting thermal inertia surveys and photometric observations, soil properties related to rover trafficability, terrain properties by sampling telemetry engineering data during rover traverse, and rock physical properties by grinding into rocks with the Rock Abrasion Tool (i.e., measuring joules required to remove a unit volume of rock and then compared to terrestrial samples).

U44A-06 1645h

### Martian Weather Analysis and Forecasts from Multiple Spacecraft Observations

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There is now a small fleet of spacecraft orbiting Mars with instruments that make observations relevant to the atmosphere. Chief among these is the Mars Global Surveyor (MGS) Thermal Emission Spectrometer that takes up to 6 nadir infrared spectra every three seconds from a low, circular, polar orbit, with occasional limb scans. The MGS also includes a Horizon Sensor that makes side-looking broadband 15 micrometer measurements, and a Radio Science experiment that determines the atmospheric structure from occasional radio occultations. From a different orbit, at a different time of day, the Mars Odyssey THEMIS instrument makes downward looking broadband 15 micrometer measurements. The Mars Express will add infrared and ultraviolet observations of the atmosphere from a highly elliptical orbit. All of these spacecraft carry cameras that observe ice and dust clouds. While none of the instruments or observing patterns is optimized for atmospheric science, the sum total of the data is more than enough to specify all of the parameters in a low resolution Martian general circulation model. We can therefore make use of data assimilation techniques (like those used in operational weather prediction on Earth) to deduce the full atmospheric state (4-dimensional temperatures, geopotential heights, winds, water vapor, dust, clouds, and surface pressure). The payoff is enormous: retrievals of atmospheric parameters are no longer independent of each other (and underdetermined), but are constrained by physical laws; the data assimilation product is a compact physical state that can reproduce the much more extensive spectral data (to within the observational errors); calibration can be addressed from the internal consistency of the observations of a given instrument; validation (in the absence of ground truth) is performed by detailed comparison of the data from different instruments and different platforms (even when there are no co-incident observations); data quality control emerges naturally from the observation weighting scheme which rejects data that disagrees violently with both other measurements and the forecast model; and real-time weather forecasts can be made available for a host of operational purposes (aerobraking, aerocapture, gliding, ballooning, dust storm warnings). All of these are made practical—given the limited computational resources that can be devoted to Martian weather forecasting—by an observation space sequential assimilation technique, using a transformed extended Kalman filter that weights both model forecasts and observational errors by agreement with the data. Forecast errors are less than 4 K and should improve with more sophisticated predictive models.

U51A CC: 517 A Friday 0830h

### Frontiers and Challenges in Deep Earth Dynamics I

Presiding: A M Forte, Universit du Qubec Montral; J Park, Yale University

U51A-01 0830h INVITED

### Thermal entrainment of an eclogitic mantle component in slabs and plumes

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Geochemical studies of basaltic volcanism indicate the presence of recycled oceanic crust in the source of ocean island basalts. In particular the Re-Os and oxygen isotopic systems can be used to identify basaltic components and parts of the mantle that have interacted with seawater in the past. An important set of conceptual models for the chemical evolution of the Earth is built on the suggestion that oceanic crust forms the main form of introduction of heterogeneity into the mantle system. The subduction of oceanic crust also introduces an important chemical buoyancy force into the mantle, particularly due to the high density contrast between eclogite, the high pressure form of basalt, and the surrounding upper mantle. This strong density contrast allows the oceanic crust to sink to the base of the mantle where it ages before being entrained in rising mantle plumes.

Experimental petrology indicates that the high density contrast between eclogite and mantle is maintained in the upper mantle and transition zone and that eclogite is compositionally less dense than the surrounding perovskite and magnesio-wuestite in the uppermost parts of the lower mantle. This raises a number of important dynamical questions regarding the potential of eclogite recycling into the lower mantle and the provenance of the recycled crust component in hot spot island basalts. Previous work has suggested that the strong negative thermal buoyancy of sinking slabs will force the eclogitic crust through the top of the upper mantle, unless a rheological separation between the strong oceanic crust and cold core of the subducting slab can be maintained by the presence of relatively warm and weak peridotite (Van Keken, Karato and Yuen, GRL, 1995). Tomographic images of subducting slabs often reveal complex morphology, such as in the case of the Tonga slab, which is likely caused by the slowing down of the sinking of the slab due to the thermodynamical consequences of the 670 km phase change and the increase of viscosity into the lower mantle. This dynamical behavior will also increase the chance that a proportion of the eclogitic crust remains at the base of the transition zone.

We use high resolution finite element models to study the possibility for survival of eclogitic crust in the upper mantle upon subduction as a function of the slab buoyancy flux, thermodynamical properties of the 670 km phase transition, rheology of the slab and ambient mantle, and changes in tectonic evolution of the slab. Preliminary results suggest a strong diversity of recycling scenarios, which suggests that at least some of the subducted oceanic crust remains in the transition zone. This provides an additional region that can contribute to the observed recycled crust component in oceanic island basalts.

U51A-02 0855h INVITED

### Isotopic Heterogeneity in the Mantle: in Search of the Final Explanation

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Since the 1960's, it has been known that the mantle is isotopically heterogeneous. However, mid-ocean ridge basalts (MORBs) that make up the bulk of the oceanic crust (OC) exhibit a relatively uniform isotopic composition. With the use of the Sm-Nd isotopic system, it became clear that their mantle source had been depleted by melt extraction to form the continental crust (CC) over geologic time. This source was therefore named the depleted mantle (DM). Mass balance considerations based on Nd and Sr isotopic data showed that the DM extended through only about 30% of the mantle, and that the lower mantle could in principle mostly be primitive and undifferentiated. These models depended on using the most frequent Nd and Sr isotopic values of MORBs as estimates of average DM source composition. Basalts from ocean islands show a much wider range in isotopic composition than MORBs. By considering Nd, Sr and Pb isotope data for these two groups of basalts, it was shown that the isotopic composition space could be described rather well by four isotopic components: DMM, HIMU, EMI, EMII. Also many of the data arrays pointed toward an isotopic component called FOZO, that was suggested to comprise the lower mantle. Such a composition of the lower mantle would imply that the Earth has a non-chondritic Sm/Nd ratio. We have extended the reservoir models to take into account mantle heterogeneities by keeping track of all subreservoirs in DM. In our model DM, we consider four classes of subreservoirs: residues after CC and OC melt extraction as well as recycled CC and OC. These are real components, but their variability in Sr, Nd and Pb isotope compositions is much larger and different from the observed isotopic variations in young basalts. The results of our current analysis show that apparent isotopic components (DMM, HIMU, EMI, EMII) are non-existent or fictitious components/reservoirs, while the most frequent MORB isotopic compositions faithfully record the average composition of the depleted mantle (DM). We show that the isotopic composition of FOZO corresponds closely to

the average composition of the matrix in the DM, which consists of small length-scale subreservoirs (<15km). Thus, FOZO is not the lower mantle, there is no need for revision of the size of the DM, and it is still possible to have an Earth with a chondritic Sm/Nd ratio. Our model, which allows both for averaging of source heterogeneities during sampling as well as homogenization of source heterogeneities owing to mantle mixing through time, yields a new understanding of the isotopic variability in ocean basalts.

#### U51A-03 0920h INVITED

##### Recent progress and future challenges in mineral physics

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Unraveling the physical behavior of earth materials at mantle and core conditions remains a major challenge and pre-occupation of mineral physics. This endeavor has had an important impact on our understanding of Earth's thermal structure, chemical composition, origins, evolution, and dynamics. A review of recent progress revolves around three themes: 1) our increasingly sophisticated ability to interpret seismological observations in terms of spatial variations in temperature, composition, and phase 2) the discovery of unanticipated material behavior at extreme conditions and their possible impacts on seismological and geodynamical models and 3) the prospects for constructing "mineralogical" earth models that are largely independent of and complementary to geodynamical and seismological earth models. Progress in mineral physics continues to be driven by rapid technological advances in our ability to generate and control extreme conditions in the laboratory, to probe samples under these conditions with a rapidly expanding array of probes, and to predict material behavior from first principles quantum mechanical calculations. We argue that continued progress in our understanding of earth will require, in addition to the characterization of individual mantle and core phases, a new generation of semi-empirical thermodynamic models of the mantle that encompass the essential multiphase equilibria and physical properties. The study of non-equilibrium properties remains a major challenge for a number of reasons, the most fundamental of which is that they depend on a far greater number of variables than do equilibrium properties. Our current knowledge of attenuation and its possible relationship to viscosity is highlighted as an area where fundamental questions remain.

#### U51A-04 0945h INVITED

##### Seismic Anisotropy and Global Geodynamics

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For many years, seismic anisotropy was often neglected, mostly because of the inherent heavy mathematical and computational tools needed to describe and model its effects on seismic waves. However, it is not a second order effect and it turns out that it is a good marker of large scale deformations. Seismic anisotropy is reflecting some inherent organization of the matter, contrarily to isotropy. The uppermost mantle down to 410 km is the depth range where the existence of seismic anisotropy is now widely recognized and well documented. Azimuthal variations have been found for body waves and surface waves in different areas of the world. The application of seismic anisotropy to geodynamics in the upper mantle is straightforward, if we assume that fast-polarization axis of mineralogical assemblages (primarily of  $\alpha$ -olivine) is in the flow plane parallel to the direction of flow. Seismic anisotropy in the mantle is therefore reflecting the strain field prevailing in past (frozen-in anisotropy) for shallow layers or present convective processes in deeper layers. From the global geodynamics point of view, seismic anisotropy makes it possible to define the root of continents and to investigate the coupling between the lithosphere and the rest of the mantle and more generally to gain insight into mantle convection. Oceans are the areas where Plate tectonics applies almost perfectly. In the Pacific ocean, the map of the azimuthal anisotropy at 100 km shows that it is very large along spreading ridges with a large asymmetry for the East Pacific rise. The direction of anisotropy is in very good agreement with plate motion. The anisotropy is large as well in the middle of the Pacific plate, but it can be observed that there is a line of very small azimuthal anisotropy almost parallel to the EPR and another one between EPR and Tonga-Kermadec subduction zone. These linear areas of small anisotropy were coined Low Anisotropy Channel by Montagner (EPSL, 2002). They are presumably related to cracking within the Pacific plate and/or to secondary convection within and below the rigid lithosphere, predicted by numerical and analog experiments.

These new features provide strong constraints on the decoupling between the plate and asthenosphere. The existence and location of these LACs might be related to the current active volcanoes and hotspots (possibly plumes) in Central Pacific. LACs, which are dividing the Pacific Plate into smaller units, might indicate a future reorganization of plates with ridge migrations in the Pacific Ocean. Below continental lithosphere, it is also observed significant azimuthal anisotropy which is reflecting asthenospheric flow. Some recent results beneath the eastern Africa will be presented and also show that this flow is highly perturbed by the presence of the Afar hotspot upwelling and might induce upwellings (with babyplumes) and downwellings at large distance (several thousands kilometers) from Afar. For filling the gap between grain scale modeling and large scale anisotropy measurements, there is now a real need for making more quantitative comparisons between seismic anisotropy and numerical modeling. Gaboriet al. (EPSL, 2003) calculated the convective circulation in the mantle by converting perturbations of S-wave velocity into density perturbations. This kind of modeling enables to calculate the strain tensor and to test different hypotheses for the prevailing mechanisms of alignment, by comparison with anisotropic seismic data. In conclusion, the scientific potential of seismic anisotropy is enormous and largely unexploited. It provides a new dimension in the investigation of processes of our dynamic Earth.

#### U52A CC: 517 A Friday 1030h

##### Frontiers and Challenges in Deep Earth Dynamics II

*Presiding:* A M Forte, Universit du Qubec Montral; G A Houseman, University of Leeds

#### U52A-01 1030h

##### A New Three Dimensional Spherical Model of the Mantle General Circulation

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We describe a new Navier-Stokes solver for modeling convection in the Earth's mantle that supports three-dimensional spherical geometry, a choice of Dirichlet and Neumann boundary conditions, discontinuities in background density and viscosity, and lateral variations in viscosity. The solver is based on a finite volume formulation with collocated pressure and velocity. Spectral methods, used in simulations of the mantle by Glatzmaier in [1], were not selected because they were not well-suited to handling viscosity fields with arbitrary spatial dependence. Finite element methods, used by Baumgardner in [2], were not selected because the assembly of discretized equations is simpler under finite volume; this is important when the viscosity field changes over time due to temperature dependence. The numerical grid is based on the projection of an icosahedron onto the sphere. On this basis, we have developed a number of techniques for evaluating derivatives required by finite volume discretization as well as a data structure for representing quantities that exhibit discontinuities at certain depths. The new solver has been used to compute the pressure, velocity, and stress fields arising from a density heterogeneity model delivered by seismic tomography. When the viscosity is a function of radius only, we present comparisons of the pattern of geoid anomalies predicted by the solver to that from an independent code based on generalized spherical harmonics by Pari and Peltier [3]. [1] Glatzmaier, G. A., GAFD 43, p. 223 [2] Baumgardner, J. R., J. Statistical Physics 39(5-6), p. 501 [3] Pari, G. & W. R. Peltier, JGR 100 #B7, p. 12,731

#### U52A-02 1050h

##### Coupling numerical models of mantle convection with energy and entropy balance models in the core: Implications for the evolution of the Earth's core and magnetic field

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Recent studies of energy and entropy balances in the core constrain the power requirements for magnetic field generation and the age of the inner core (e.g. Buffett, 2002, Labrosse et al., 2001, Labrosse, 2003, Nimmo et al., 2004). These studies suggest that the change of entropy in the core needs to be positive during the entire period the geodynamo operated. The geodynamo efficiency is determined by the redistribution of heat and mass in the core and is ultimately controlled by the rate at which the mantle removes heat from the core. In the previous analyses the heat flow at the core-mantle boundary was either prescribed or determined from parameterized schemes of mantle convection. We couple heat flows predicted by numerical models of mantle convection with energy and entropy balance models to determine the age of the inner core and the available power to drive the dynamo. The entropy and energy balances are studied for various degrees of layering in the mantle and highly temperature dependent mantle rheology. In addition, we explore the consequences different rates of internal heating in the core and mantle have on the thermal and magnetic evolution of the Earth and its core.

#### U52A-03 1110h

##### Superplumes and the Viscosity Structure of the Mantle

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Seismological studies indicate the existence of large upwelling regions of complex structures in the lower mantle. A mantle flow model with only a few strong upwellings is an alternative to conventional convection models with respect not only to pattern of the flow but also to heat transport and mixing properties. By two- and three-dimensional numerical models we demonstrate that a significant increase of the viscosity with pressure in the lower mantle leads to a focusing of buoyancy into strong upwellings from the core-mantle boundary. This phenomenon is further enhanced by a thermal expansion coefficient which decreases with pressure. Besides pressure, the viscosity of the mantle material will strongly depend on temperature. Combining the effects of temperature and pressure-dependent viscosity, generates a significant viscosity maximum in the lower mantle. Pressure dependence let the viscosity increase from the upper to the lower mantle, temperature dependence, however, compensates this effect at greater depth. The spatiotemporal evolution of plumes is likewise influenced: While a purely pressure-dependent viscosity creates single plumes, additional temperature dependence leads to plume-clusters, characterized by instabilities at the core-mantle boundary, which are centered around a strong upwelling flow. These plumes generate a complex flow pattern at the base of the mantle.

#### U52A-04 1130h

##### Apparent Polar Wander of the Pacific Plate and Pacific Hotspots: Implications for True Polar Wander and Hotspot Fixity

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Whether the apparent polar wander (APW) path of the Indo-Atlantic hotspots is a record of true polar wander could be tested from a detailed APW path of the Pacific plate, the motion of which can be estimated relative to the hotspots independently of reconstructions in the Atlantic and Indian Ocean basins. Such an APW path has previously been lacking because of the difficulty in obtaining fully oriented paleomagnetic samples from oceanic plates. We present an APW path for the Pacific plate and for the hotspots of the Pacific basin. Our Pacific plate APW path from 125 Ma to the present is based mainly on the analysis of the skewness of marine magnetic anomalies due to seafloor spreading and is determined with better accuracy and resolution from 32 Ma to 81 Ma than is the APW path of any continent. Our path is defined by eleven paleomagnetic poles from non-overlapping age windows. Nine of these