# WELCOME TO THE ABSTRACTS
# OF THE WORKSHOP
# ON GLOBAL GEODYNAMICS

PÍSTINA, BOHEMIA, CZECH REPUBLIC

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Edition prepared by

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# Contents

Professor Karel Pěč
1930–1993

# Preamble

Sometime last summer a group of us spent one weekend in Pístina and thought that it would be a wonderful idea to bring a group of geophysicists from western countries and other continents to the idyllic countryside in southern Bohemia for a workshop on global geodynamics. With the turn of events in the last few years in Eastern Europe and Soviet Union there is a need for greater communication between the East and West. The rapid changes in the former Soviet Union have made it next to impossible to have meetings and workshops there as in former times. Of all the eastern European countries, the Czech Republic seems to be the best place to have a workshop in geodynamics because of the tradition of theoretical geophysics, upheld especially at Charles University, the very diversified landscape with mountains and rivers, and its location in the heart of central Europe.

When the organizers began this venture last summer, little did they dream that this workshop would become very timely for several diverse communities in geophysics and would serve as a place where several important developments could be tied together. The last year has really been exciting in solid-earth geophysics. It has been a banner year for the transition zone with the recognition that large-scale gravitational instabilities can be generated there. There have been very impressive advances in the area of seismic tomography, which can lead to better understanding of the lower-mantle dynamics. The sighting of large-scale upwellings in the lower mantle may turn out to be a Rosetta stone for geodynamicists and mineral physicists. There have also been some important laboratory measurements made during this past year. Most prominent of them are the indications of very high melting temperatures of perovskite and its implication for mantle viscosity. Inferences of mantle viscosity have received new impetus from novel inversion techniques and new contraints from ocean topography. It really appears that this workshop is very timely for these reasons, since we have here many of the active contributors to these exciting developments in geophysics during this last year.

We would like to dedicate this workshop to the memory of Professor K. Pěč, Charles University, who passed away this spring. Professor Pěč, in a way, was responsible for this workshop. In former days of oppression he was able to dream and to nurture a group of geophysicists, who today carry on this tradition of theoretical geophysics in Bohemia.

We hope that these abstracts will convey to you the exciting new developments in geophysics today and to promote a greater fervor for interdisciplinary efforts in solid-earth geophysics.

**Organizers of the workshop**

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# 1   Seismology

## Negative Velocity Anomalies in the Mantle: from Mid-ocean Ridges to the Core-Mantle Boundary

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The relatively deep origin (300–500 km) of the East Pacific Ridge anomaly has been proposed by Wielandt and Knopoff (1982) and is predicted by model M84C of Woodhouse and Dziewonski (1984). It is also consistent with the differential travel time data od Woodward and Masters (1991), as shown by more recent modeling efforts involving different types of data (Dziewonski and Woodward, 1992; Woodward et al., 1993). This is in a sharp contrast to the study by Zhang and Tanimoto (1992, 1993), in which the velocities under the East Pacific Rise become average at a depth of 100 km. The difference with a pure path study by Nishimura and Forsyth (1989) is less obvious, particularly if one considers their results for $V_{SH}$, which show age-dependent differences on the order of 1% down to 300 km depth.

A surprising result of the tomographic studies is the relatively high level of heterogeneity at the mid-upper mantle depths. The oceanic structure down to 100 km depth appears to be well correlated with the ocean age. It is still mostly so at 200 km depth, even though 'something' begins to develop in the central Pacific, with contour lines that do not parallel the isochrons. At 300 km, and even more so at 400 km depth, there is little correlation between the velocity variations and the ocean age, because the pattern of anomalies is dominated by features that have nothing to do with the sea floor age. This pattern continues through the rest of the upper mantle.

The main features of the negative velocity anomalies in the lower mantle are as follows. At the core-mantle boundary (CMB) there are essentially only two very large scale features: the 'Equatorial Pacific Plume Group' and the 'African Plume Group' (Dziewonski et al., 1991). These features appear in virtually all published models of the lower mantle. The spectrum of the anomalies changes abruptly 1000 km above the CMB: not only there is a decrease in amplitude, but the power spectrum — dominated by degrees 2 and 3 near the CMB — becomes nearly flat.

Each of the two mega-structures evolves differently: the African one breaks into numerous smaller features, which seem, however, to be spatially related to the mid-Atlantic and Indian Ocean ridges. The Pacific plume is more coherent and after shrinking in size and southward migration, it joins the Pacific-Antarctic Ridge and, at a lower amplitude level, the East Pacific Rise. Thus, the low velocity anomalies in the upper mantle could be related to the planetary scale upwellings in the lower mantle.

Because of the complicated 3-D geometry, the image of velocity anomalies in the lower mantle in a depth range 700–1700 km is not amenable to a simple test that can be devised for the upper mantle. Also, the geometrical pattern is more complex than the relation between the circum-Pacific subduction zones and the location of the high velocity anomalies in the lower mantle (Dziewonski, 1984). Yet, the hypothesis that some of the mid-oceanic ridge anomalies have deep origin could be tested by carrying out seismic experiments using large portable arrays. There is also the need for the appropriate numerical simulations of mantle convection. Some answers may come from different branches of earth sciences: for example, through studying the large-scale patterns of isotopic signatures in oceanic basalts.

# Large 3-D Structure of Shear Velocity in the Mantle

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A data set consisting of 27,000 long-period seismic waveforms and 14,000 seismic travel-time residuals has been assembled. The waveform data include body-wave and mantle-wave seismograms. Roughly one half of the data has been collected by Woodhouse and Dziewonski (1986), but the other half contains data from new seismic networks: GEOSCOPE and CDSN, which significantly improve the global coverage. The travel-time residuals consists of absolute travel-times (S and SS; Su and Dziewonski, 1991; Su, 1993) and differential travel-times (SS - S and ScS - S; Woodward and Masters, 1991a and b) measured from digital seismograms using a cross-correlation technique. These data are simultaneously inverted for a three-dimensional shear-wave velocity model of the Earth's mantle. The inversion method is based on the path average approximation for seismic waveforms and raypath integration for seismic travel-times.

The model is defined by a set of basis functions using spherical harmonics up do degree 12 to describe variation with the geographical coordinates and Chebyshev polynomials up to degree 13 to describe radial variations. Stability in the inversion procedure is achieved by employing a weighted norm which penalizes model roughness both laterally and radially.

The recovered seismic heterogeneity shows a clear pattern of slower-than-average shear velocities at shallow depth underlying the major segments of the world-wide ridge system. These anomalies extend to depths greater than 250 km and in some cases appear to continue into the lower mantle. The pattern of the heterogeneity in the model indicates a rapid change at a depth of about 1,700 km. At this depth, the power spectrum of the model shifts from one which is almost flat in the mid-mantle to a spectrum which is dominated by degrees 2 and 3; this pattern then continues to the core-mantle boundary.

The seismic velocity heterogeneity model has been subjected to stability and resolution tests. The test results show that the inversion is stable and that the model resolution is good in most portions of the Earth's mantle.

# Mapping the Core-Mantle Transition

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The core-mantle boundary (CMB) is one of the most important internal boundaries of the Earth. Its properties are determined by the evolution of the Earth as well as by recent processes in the Earth's interior. The CMB itself determines also dynamics of the Earth, especially by core-mantle coupling. Up to very recent time there were only theoretical speculations and considerations concerning a possible topography of the CMB and lateral heterogeneity of the D"-layer. Seismological investigations have shown the possibility of the existence of both features (Dziewonski, 1984; Morelli, Dziewonski, 1987). Geophysical fields like that of geomagnetic secular variations (Hulot et al., 1990), undulations of the geoid at the CMB (Hager et al., 1985), and the distribution of the hot spot density (Stefanick, Jurdy, 1984) show a certain correlation with the seismologically determined features of the core-mantle transition zone. These facts indicate that there should be some common deep situated sources correlation, possibly in the structure and/or in the processes of that region of the Earth's interior. Diffracted seismic waves bear information about the base of the mantle and the core-mantle boundary. Digitally recorded Pdiff phases show distinct dispersion in dependence on the source-receiver configuration. For the source region of Fiji Islands azimuthal variations of the frequency dependent velocities of Pdiff are observed. The comparison with modeling results enables to indicate regions with different seismic velocities and velocity gradients. For diffracted S-waves a splitting of vertically and horizontally polarized waves is observed depending on the path at the core-mantle boundary. Results indicating a laterally heterogenous structure of the core-mantle transition region are similar to those found by Wysession et al. (1992).

# Confidence Regions for Mantle Heterogeneity

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Tomographic models of mantle P and S structure from travel times show large-scale variations correlated with surface tectonic features, as well as coherent structures in the lowermost mantle. The reliability of global features of velocity models depends on whether the velocity throughout the feature can be estimated well simultaneously: we need to be able to say with confidence that a feature involving many voxels is likely to be real. We find a lower bound on how wide, as a function of position in the mantle, a 95% simultaneous confidence region for mantle P or S velocity must be.

Results are not optimistic for travel time tomography using a generous set of rays, a 10 degree by 10 degree model parametrization, and an idealized error model. On a global scale, the mantle's velocity structure is nearly consistent with a radially symmetric model at the 95% confidence level. Smaller voxels, more realistic assumptions about the errors, or three-dimensional structure outside the mantle make the confidence intervals still wider.

This suggests that additional constraints must be included in inversions in order to obtain reliable and useful models of the mantle. We will discuss our error analysis procedure and how it might be applied to other inversions schemes and additional types of data and other promising directions to developing methods that will allow reliable inferences about mantle properties.

# Tomographic Model of Upper Mantle Shear Attenuation

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I present a new tomographic model of upper mantle shear attenuation derived from mantle Rayleigh wave data. The attenuation is measured in the frequency domain on individual Rayleigh wave trains (R1, R2), using a recently developed method which minimizes biases due to the uncertainty in the source amplitude as well as focussing effects. This method involves the comparison of estimates of attenuation coefficient as a function of frequency obtained using a single train (R1, R2) with those obtained using three consecutive trains (R1, R2, R3). Data are primarily from the GEOSCOPE network (1987–1992) with the addition of some recent IRIS records. We take advantage of the high dynamic range of the new instrumentation, which allows on-scale recodring of R1 trains for earthquakes of magnitude 6.7 and larger, allowing better resolution of odd terms of lateral heterogeneity. The model is derived using Tarantola and Valette's (1982) formalism without a priori parametrisation, and the scale of lateral heterogeneity resolved corresponds to that achieved in a spherical harmonics expansion to degree 6–7 (correlation length 3000 km). Crustal corrections are performed using measurements of short period Rayleigh wave attenuation available in the literature for different tectonic provinces. The Q model is compared with a model of shear velocities derived similarly using phase information. The degree of correlation of Q and velocities is discussed in terms of the nature of the observed lateral heterogeneities (thermal, compositional). The significance on velocity models of dispersion effects due to attenuation is also discussed as well as consequences on dynamical modelling involving geoid data.

# Short Period Upper Mantle Tomography

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In the global-scale seismic velocity studies, shallow structures were determined by relatively long period surface waves, usually for periods longer than about 80-100 seconds. Because such surface waves are affected by crustal thickness and velocity, crustal models were assumed and their effects were subtracted from measured phase velocities. In short period surface waves, this causes a major change in pattern. Consequently, assumed crustal structure has a dominant effect on the solution. This procedure is not a problem if we know crustal structure accurately all over the Earth, but it is simply not the case unfortunately. One possible solution to this is to analyse short period surface waves and constrain crustal effects by these measurements, rather than using assumed crustal structure.

I have extended the surface wave analysis to about 40 seconds. The procedure in phase measurement is similar to Zhang and Tanimoto (1992, 1993), but all measurements, including path selections and expansion of the data sets, were done from scratch. The number of data examined was expanded to 30,000, but strict selection of data limited the data to 6000 for Rayleigh waves and 4000 for Love waves, smaller than the number used by Zhang and Tanimoto but is nonetheless sufficient to determine the spherical harmonic coefficients up to degree and order 20 (total number of parameter is 441).

I have included ray tracing procedure in the analysis, since short period data may require consideration of deviation from great circle paths. However, since I use only minor-arc waves, such effects turned out to be small overall. There are of course some cases for which path deviates substantially, but those are small in number.

Short period toroidal mode (Love wave) data for angular degree $l > 150$ and short period spheroidal mode (Rayleigh wave) data ($l >$ about 200) demonstrate that phase velocity is low in continental regions and fast in oceanic regions. This is comletely a predictable result from the variations of crustal thickness, but it makes quite a contrast with fast velocity in old continents and slow velocity in tectonically active regions that we have be-

come accustomed to in the last 10 years. Inversion for S-wave velocity variations with depth shows that familiar patterns (fast velocity in shields etc.) emerges at about 80 km in depth, thus shallower velocity patterns in previous global earth models are not valid any more. Below 80 km, previous models appear quite accurate. The main contribution of this study is then for structure in the upper 100 km.

In the map for S-wave velocity for depth 50–70 km, one of the slowest area is Himalaya, well known for its thick crust by regional seismic studies. It also demonstrates thick crust under Andes, eastern to middle parts of USA as well as the Baltic shield and Siberia. Of course, what we observe is slow velocity anomaly and is thus not necessarily a thick crust. Slow anomaly in western US is in the area of Basin and Range and is thus more likely to be shallow, high temperature anomaly there. Similar arguments can be made for anomaly in the northern part of the Mediterranean Sea.

Signatures for hotspots as well as ridges are confirmed and similar features to Zhang and Tanimoto (1992, 1993) are found. It does seem clear, however, that the results in Zhang and Tanimoto represents a rather highly damped solution and a less damped solution provide better depth resolution.

# 2 Materials and Viscosity

## Temperature Regimes at the Base of the Lower Mantle

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Seismic anomaly structures at the bottom of the lower mantle may be interpreted in terms of large temperature variations based on new laboratory data at very high pressure: i) Sound velocity measurements at mantle pressures show an increase in $\dfrac{d \ln \rho}{d \ln v}$ with depth. This and the strong decrease in the thermal expansion coefficient, yields dT up to $1000\,\text{K}$ using the seismically measured lateral velocity variations; ii) High melting gradients in iron and iron-oxygen compounds measured at core pressures yield a temperature increase across the core-mantle boundary in excess of $1300\,\text{K}$; iii) melting temperatures of Mg,Fe,Si-perovskite between 7000 and $8500\,\text{K}$ at the bottom of the mantle result in $T/T_m$-values between 0.3 and 0.4. This strongly decreases the temperature dependence of viscosity if the viscosity-systematics found at low pressure are applicable at lower mantle conditions; iiii) chemical reactions between molten iron and the major lower mantle constituents at pressures of the core-mantle boundary were found to be minor in the absence of water.

# The Rheology of $Mg_{1.83}Fe_{0.17}SiO_4$ Olivine and Modified Spinel at High Pressures and Temperatures

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Knowledge of the rheological properties of deep mantle mineral assemblages is a prerequisite for construction of reliable models of mantle convection and deep focus earthquakes. Although we now have reasonable low pressure data for the rheology of olivine $(Mg,Fe)_2SiO_4$, the dominant upper mantle mineral phase, there is a paucity of experimental constraints on the pressure dependence of the constitutive equations describing its flow behavior at depth. This is principally due to the restrictive low pressure range available to classical experimental deformation apparatus ($< 3\,GPa$). Furthermore, even assuming the simplest case of a chemically homogeneous mantle, $(Mg,Fe)_2SiO_4$ olivine undergoes several phase transitions between $400\,km$ and $700\,km$ depth ($13$–$24\,GPa$). As a consequence, the rheological behavior of mineral assemblages representing 95% of the Earth's mantle is unknown. Both the pressure dependence of the constitutive equations for olivine ($V^*$), and the effects of phase transitions on mantle flow behavior are being investigated experimentally.

In order to address this problem, olivine and its high pressure polymorph $\beta$-phase have been experimentally deformed at high confining pressures and high temperatures using a 6–8 large volume multi-anvil apparatus. A modified assembly design permits the semi-quantitative uniaxial compressive deformation of specimens at high confining pressures ($\leq 16\,GPa$) and high temperatures ($\leq 1600°C$). Sample strain rates can be determined from the displacement rate of the loading ram and yield stresses are estimated using available piezometers.

Preliminary results on $Mg_{1.83}Fe_{0.17}SiO_4$ polycrystalline olivine aggregates at 6 and $14\,GPa$ are consistent with single crystal dislocation creep laws (stress exponent n $= 3.5$) assuming a pressure dependence (activation volume $V^*$) of the order of $5\,cm^3mol^{-1}$.

The experiments also suggest that the deformed high pressure olivine polymorph $\beta$-phase has a viscosity greater than that of olivine by a factor of 5, for experimental strain rates of $10^{-6}\,s^{-1}$ at $15\,GPa$ and $1450°C$.

# Sound Velocities of Four Minerals
## to Very High Compression: Constraints on $\dfrac{\mathrm{d}\ln\rho}{\mathrm{d}\ln\text{velocity}}$

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The transverse and longitudinal acoustic modes in MgO to 400 kbar, yttrium aluminum garnet to 600 kbar, aluminum oxide to 630 kbar, and $MgAl_2O_4$ to 120 kbar measured in the sideband fluorescence of chromium 3+ in the crystal lattices directly yielded the shear and compressional sound velocities with a precision nearing that of and in excellent agreement with ultrasonic methods at low pressures. We find for MgO, aluminum oxide, and garnet that the sound velocities are linear with volume to a compression of about 0.84 corresponding to a depth of 1400 km. The resolution of the measurements is high enough to derive the geophysically important parameters: $\dfrac{\mathrm{d}\ln\rho}{\mathrm{d}\ln v}$ at constant temperature. We find this parameter and their pressure derivatives to be nearly the same for all four minerals: about 0.7 for $V_p$ and 0.95 for $V_s$ at 1 atm which increases substantially with pressure along trends very nearly equal to the seismically derived global average. At high pressures, it is expected that $\dfrac{\mathrm{d}\ln\rho}{\mathrm{d}\ln v}$ at constant pressure approaches the constant temperature derivative because of decreasing anharmonicity. This is corroborated by recent ISS measurements by Chai et al. (EOS, 73, 523, 1992) and Zaug et al. (Science, 260, 1487–1489, 1993). The effects of anelasticity on the value of $\dfrac{\mathrm{d}\ln\rho}{\mathrm{d}\ln v}$ in the lower mantle are small and decreasing with depth since lower mantle temperatures are at less than half of the homologous temperatures $T/T_m$ of the candidate minerals (see Boehler et al. abstract, this meeting). Thus, an increasing value of $\dfrac{\mathrm{d}\ln\rho}{\mathrm{d}\ln v}$ and decreasing thermal expansion with depth allows calculation of lateral temperature variations from seismic anomalies using $\delta T = \dfrac{1}{\alpha}\dfrac{\mathrm{d}\ln\rho}{\mathrm{d}\ln v}\dfrac{\delta v}{v}$ (Chopelas, EPSL, 114, 195–192, 1992; Yuen et al., GRL, 1993). Using the lateral velocity variations derived from seismic tomography (e.g., Su and Dziewonski, 1992), temperature contrasts of up to 1300 K are found at the base of the lower mantle.

# The Effects of Phase Transition Kinetics
# on Subducting Slabs

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We have investigated the effects of kinetics on non-equilibrium aspects of the olivine to spinel transition in a descending slab. Our one-dimensional model consists of linking the kinetic equations, which have strong Arrhenius type of temperature and pressure dependences with the evolutionary equations for pressure and temperature. Latent heat which depends on the time-dependences of the kinetics, is included in the energy equation. Mathematically this problem is governed by a system of coupled differential equations consisting of (1.) a system of fourth-order nonlinear ordinary differential equations describing the degree of phase change with the crystal growth-rate in the elements of the coefficient matrix of the differential system and an inhomogenuous driving term due to the nucleation rate, (2.) the temporal variation of the pressure which includes the pressure from the descending slab and the pressure changes due to phase kinetics, (3.) one-dimensional nonlinear parabolic equation for the temperature with diffusion, latent heat release and adiabatic heating taken into account. Numerical results show that the position and sharpness of the kinetic phase boundary is determined by surface tension and crystal growth rate. For slow slab velocities between 3 and 6 cm/yr the olivine to spinel phase change behaves nearly at equilibrium. Due to the nonlinear coupling between the latent heat and the kinetics and also the angle of slab penetration, finger-like structures from the phase boundaries are obtained. These phase-boundary pro- trusions may cause earthquakes. For higher slab velocities of around 10 cm/yr the metastable olivine region may be pushed down to a depth of around 600 km, where the phase boundary is very sharp due to latent-heat effects.

# The Effect of 3-D Viscosity Variations on Mantle Flow and Convection-Related Surface Observables

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Current global-scale models of 3-D seismic velocity variations reveal the presence of significant lateral heterogeneity throughout the mantle. The corresponding lateral variations of temperature are expected to produce significant 3-D variations of effective viscosity in the mantle. The dynamical implications of such viscosity variations are investigated with a variational treatment of the momentum-conservation equation. This variational method is based on the principle that the difference between the rate of viscous dissipation of energy and the rate of energy released by buoyancy sources is an absolute minimum. This minimum principle yields explicit expressions for generalized Green functions which describe the excitation of both poloidal and toroidal flow by buoyancy sources. This theory is employed to show that long wavelength viscosity variations have a pronounced effect on the buoyancy-induced mantle flow. The amplitude of the toroidal flow is generally smaller, but comparable, to the amplitude of the poloidal flow. These flow calculations also suggest that the net rotation of the lithosphere, given by absolute-motion plate models based on the hotspot reference frame, may be explained by the interaction of long wavelength buoyancy sources with long wavelength viscosity variations. Unlike the flow field, the effect of lateral viscosity variations on the flow-induced boundary topography (and hence the nonhydrostatic geoid) is quite small. Even in the presence of long wavelength viscosity variations spanning two orders of magnitude, the relative difference between the geoid predicted with and without these lateral variations is little more than 10%. This suggests that geoid-derived inferences of the radial viscosity profile of the mantle, using a flow theory which ignores lateral viscosity variations, will be essentially unbiased.

# Chemical Differentiation
# at Phase Transitions in Downgoing Slabs

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In the present investigation we study a physical mechanism that may cause a chemical differentiation at a polymorphic phase transition. The idea is based on the simple picture that during the density increase at the transition there is the appearence of strong stress-fields that act on the constituents of the solid material. Particularly so-called incompatible ions with ionic radii not appropriate for the high-pressure phase may drift to the grain boundary and reach high-diffusivity paths so that in this way they may be enriched in the low-pressure phase. It is important that our proposed mechanism of differentiation is not related to partial melting as in the usual models in geochemistry but acts in a solid. Therefore this mechanism may be very favoured at depth greater than 200 km where partial melting seems not easily possible as follows from investigations on the temperature distribution and the melting curve in the Earth's mantle. Numerical estimations show the necessity that the solid is in a superplastic state at the phase transition as already discussed by Kalinin and Rodkin (1982) in connection with the earthquake mechanism and by Parmentier (1981) and Poirier (1982) in connection with other phenomena in the mantle.

# The Impulse Response
# of a Viscoelastic Earth with Aspherical Viscosity

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Although the problem of viscoelastic gravitational relaxation of a spherically symmetric earth has been studied for a number of years the effort to fit all the observables was not fully successful. Differences between the prediction and the data may be associated with lateral variations of viscosity. This is why we have developed a method to calculate the impulse response of a viscoelastic earth with general spatial distribution of viscosity. The set of partial differential equations governing the relaxation due to a surface mass load has been converted to a system of ordinary differential equations by a standard spectral technique. Instead of applying the Laplace transformation, commonly used in the spherically symmetric case, the equations are solved strictly in the time domain. Our system of o.d.e.'s differs from the well-known system for the spherically symmetric model only by a non-zero right-hand side expressing the memory of viscoelasticity and composed of quantities computed in the previous time steps. It should be emphasised that the coupling due to the lateral variations of viscosity only affects the r.h.s. terms and the spectral o.d.e.'s remain separated according to order and degree. The method was tested for spherically symmetric case by comparing its results with results obtained by standard methods based on the Laplace transformation. The first computations indicate that the accuracy of the method is satisfactory. An application of the method to complex viscosity structure will require further numerical tests.

# Importance of Anelasticity
# in the Interpretation of Seismic Tomography

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Temperature derivatives of seismic wave velocities are the key parameters in the interpretation of seismic tomography. In most of the previous studies, the temperature derivatives determined at high frequencies are used, which involve only the effects of anharmonicity. It is shown, however, that temperature derivatives due to anelasticity (including viscoelasticity) are also important in the Earth's mantle particularly for shear waves. In the low Q ($Q \approx 100$) regions in the upper mantle, the correction due to anelastic effects will roughly double the temperature derivatives. The correction for the anelasticity will also be important in the deep mantle where Q is larger ($Q \approx 300$), if temperature derivatives due to anharmonicity will decrease significantly with pressure as suggested by recent laboratory data. These results imply that the temperature anomalies associated with low velocity anomalies in the mantle will be significantly smaller than previously considered on the basis of anharmonic effect alone and that the amplitude of velocity anomalies will be significantly larger for shear waves than for compressional waves.

# High Creep Strength of Garnets
# and Its Bearing on the Dynamics and Chemical Evolution
# of Mantle Transition Zone

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Laboratory studies of plastic deformation show that a garnet-rich layer in the transition zone of the Earth will have significantly higher creep strength than other nearby regions. This mineralogically-induced rheological stratification (heterogeneity) have important effects on the dynamical behavior of these geochemically distinct components. Basaltic (transformed to a garnetite in the transition zone) and harzburgitic layers of subducted oceanic lithosphere will be separated near the 660 km discontinuity due to the contrasts in densities and in rheological properties. A garnet-rich transition zone (or the bottom part of it) thus formed will be highly viscous which enhances layered convection and provides a natural explanation for the fixity of hot-spots and the deep earthquake activities.

# Dynamic Topography
# Compared With Residual Depth Anomalies in Oceans
# and Its Effect on Age-Depth Curve

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Dynamic topography induced by mantle flow would affect the large scale variation of ocean depth. Ocean depth is generally expressed as a function of crustal age; that is age-depth curve. Regional bathymetric deviation from the age-depth curve, called residual depth anomaly, would indicate the dynamic topography if local isostatic anomalies are avoided.

In this study, first we made a global residual depth anomaly map. Secondly we predicted geoid and dynamic topography by using density perturbations converted from seismic tomography models and additional slabs. We found that both the predicted geoid and dynamic topography have good amplitudes and correlations with the observations when density perturbations in shallow part of the upper mantle were imposed by slabs, not by tomography model. This means that velocity anomalies detected by seismic tomography in this depth range do not represent well the density perturbations.

Finally, an effect of dynamic topography upon the age-depth curve was examined. We found corrected age-depth curve, determined by depth data after removal of the predicted dynamic topography, continued to increase its depth until the age 110 Ma while the uncorrected curve flattened at older than 70 Ma. This corrected age depth-curve suggests that the $\sqrt{t}$ age-depth relation may hold in old seafloors and, at least, asymptotic plate thickness in the plate model would be much larger than those previously estimated.

# The Genetics of Mantle Viscosity

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Several recent inversions for radial mantle viscosity structure, constrained to fit the geoid or plate velocities, find models with a low viscosity transition zone. Previous results from a Monte Carlo study suggest either a low or a high viscosity transition zone fits the geoid data. Using a genetic algorithm, I produce a collection of models, all of which fit the geoid data equally, or nearly equally, well. Unlike traditional minimization algorithms, genetic algorithms are based on probabilistic search rules. One of their virtues is that they do not require forming derivatives or linearizing a non-linear problem. What is required for a genetic algorithm is the ability to calculate the forward problem, a criterion for measuring the "fitness" of the model, and representation of the model as a "chromosome" (a string of ones and zeros). These strings are crossed and mutated each generation to form new "offspring" models, hence the name genetic algorithm. There has been a great deal of interest in genetic algorithms because for some applications they are remarkably efficient. However, the amount of time required to solve the forward problem makes the genetic algorithm less attractive than other calculus based methods for mantle viscosity problems. I explore the genealogy of successful models to determine what features (which genes, so to speak) are required to make successful models. Using results from the genetic algorithm, I address the degree to which smoothing and linearization influence the result of the non-linear least-squares inversion for mantle viscosity.

# Modelling Post-Glacial Rebound Effects
## on VLBI Baseline Vector Evolution

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The final late Pleistocene deglaciation event of the current ice age was sufficiently massive (inducing in excess of 120 m of eustatic sea level rise) and recent (ending just 4000 years ago) that the Earth remains in a state of appreciable isostatic disequilibrium. This disequilibrium is manifest in a variety of geophysical observables, but none more direct than the associated three-dimensional crustal deformations. Classical (i.e., land-based) geodetic measurements of vertical displacement amplitudes and rates have played an important role in geophysical applications of the glacial isostatic adjustment dataset, mainly relating to inferences of mantle rheology. The advent and improvement of space-geodetic measurement techniques (including very-long-baseline-interferometry, global positioning system surveying, and satellite and lunar laser ranging) enable three-dimensional crustal deformation rates to be estimated with an accuracy necessary for such applications.

In this talk we will outline a new formalism for computing three-dimensional crustal deformation rates associated with the application of an arbitrary external load acting on a spherically symmetric, self-gravitating, (Maxwell) visco-elastic planetary model. We apply the formalism to predict the present day evolution of selected baselines associated with the late Pleistocene deglaciation event. The numerical computations incorporate a realistic model for the space-time history of the global ice sheets, as well as a gravitationally self-consistent ocean meltwater mass redistribution. The results to be presented focus on the evolution of baselines in North America and Europe for which high-quality, long-time series, VLBI measurements have been made, and consider the constraints on mantle viscosity which these observations imply.

# The Radial Profile of Mantle Viscosity: Constraints from Postglacial Rebound and Tomography based Convection Models

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Past and continuing analysis of the data of postglacial rebound, including relative sea level data, earth rotation observations, and to some (!) degree free air gravity anomalies, suggest that the contrast in viscosity between the upper and lower mantle may be modest. Best fitting two layer parameterizations, for example, require lower mantle viscosity near $2\times10^{21}\,\mathrm{Pa\,s}$ if the upper mantle value is fixed to the now classical value of $10^{21}\,\mathrm{Pa\,s}$ first inferred by Haskell on the basis of his analysis of postglacial rebound data from Fennoscandia. In contrast, many recent inferences of the depth dependence of mantle viscosity based upon seismic tomography constrained models of mantle convection have led their authors to conclude that the upper mantle–lower mantle viscosity contrast must be extreme, with ratios of 100 or higher being preferred. The non-hydrostatic geoid observations on the basis of which the latter inference has been made are inherently non-unique, however, and there does exist at least one class of models (first analysed by Alessandro Forte) that allows simultaneous reconciliation of both postglacial rebound and convection related constraints. This class of models is characterized by the existence of a thin layer (say $70\,\mathrm{km}$ thick) lying immediately above the endothermic phase transition at $660\,\mathrm{km}$ depth and in which the viscosity is quite low, say about $10^{19}\,\mathrm{Pa\,s}$ if the viscosity of the overlying material is $10^{21}\,\mathrm{Pa\,s}$. Such models have geoid kernels that are essentially identical to the kernels for models that have upper mantle and transition zone viscosity that is everywhere two orders of magnitude lower than in the lower mantle. Since the thin layer is not "visible" to postglacial rebound data, this class of models simultaneously satisfies the rebound constraints. This clearly has important implications insofar as the issue of transient rheology is concerned and therefore to the understanding of the physics of mantle creep. Both postglacial rebound and convection related inversions will be discussed in this paper from the perspective of expectations based upon a-priori models of mantle convection that include phase transition effects.

# The Sharpness of Upper Mantle Discontinuities: Constraints from Non-Equilibrium Phase Transformations in Convective Systems

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Seismic data indicate that the upper mantle discontinuities at 410 and 660 km are sharper than could be expected for equilibrium phase boundaries. We suggest that sharp discontinuities can be formed in a chemically homogeneous mantle as a combined effect of the kinetics of phase transformations and convection. Despite high temperatures of the "normal" mantle and fast crystal growth, kinetics are important within a few kilometers near the equilibrium phase boundaries because of the finite nucleation barrier. Convection induced continuous pressure change "compresses" all or part of the phase boundary into a sharp region. For experimentally estimated values of the nucleation barrier, the metastable overshoot might be 2–15 km and is followed by a 1–2 km (at 660 km) or 1–4 km (at 410 km) region of avalanche-like nucleation and growth of the new phase. Such a behavior is different from classical isothermal transformations described by Avrami-type equations. The estimates depend almost entirely on the surface energy involved in heterogeneous nucleation and are insensitive to orders of magnitude variations in other parameters which are usually poorly constrained. In addition, very weak discontinuities can be formed at several depths between 200 and 750 km, as a result of kinetically compressed transformations in the pyroxene-garnet subsystem. An enhanced tendency toward layering of mantle convection is predicted.

# Geoid Anomalies from Cenozoic Subduction in Semi-Dynamical Flow Models Including a Phase Boundary

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In order to investigate the relationship between the geoid and plate subduction, we develop a 3-D spherical shell model in which the circulation is driven by both buoyancy forces and an imposed surface velocity, taken from plate reconstruction for the past 65 Ma. To avoid numerical resolution problems, we use an enhanced value of thermal diffusivity, which leads to an overly thick lithosphere. The correct amount of buoyancy is re-established by using a reduced value of thermal expansion coefficient. First, we calculate the present temperature field in the mantle due to the Cenozoic plate motions for models with and without a phase transition at 660 km depth, which is approximated by a locally modified effective thermal expansion coefficient. In a second step the geoid anomalies are determined subject to a stress-free upper boundary condition. When the thermodynamic parameters of the boundary at 660 km allow slab penetration into the lower mantle, the medium wavelength ($l = 4$–$11$) geoid agrees well with the observed geoid if there is a moderate increase of viscosity from the upper to the lower mantle. When the Clapeyron slope is sufficiently negative to prevent slab penetration, the agreement is poor.

# 3   Dynamics

## Transition Zone Clapeyron Slopes, Seismic Topography, and Chemical Contrasts

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The depths, widths, and magnitudes of the 410 km and 660 km seismic discontinuities are largely consistent with an isochemical phase change origin, as is the observation that the topography on these discontinuities is negative correlated and significantly smaller than predicted for chemical changes. While most thermodynamic studies of the relevant phase changes predict greater topography on the 410 than the 660, recent seismic studies suggest the opposite effect. This might be consistent with a few recent thermochemical studies which suggest that the Clapeyron slopes of the perovskite-forming reactions may exceed in magnitude those of the spinel-forming reactions. However, we have reexamineed the relevant Clapeyron slopes in light of the most recent phase equilibrium studies and the requirements of internal thermodynamic consistency, and we conclude that the bulk of the evidence indicates a greater Clapeyron slope magnitude for the 410 than for the 660. Thus, the recent seismic results are unexpected. One explanation might be that lateral temperature variations near 660 km depth exceed those near 410, consistent with a model of the 660 as a thermal boundary layer. An alternate interpretation is that the 410 does possess greater topography but is simply less visible seismically than the 660. This latter idea is supported by recent observations of P'410P' phases in conjunction with an elevated 660 and with our thermodynamic modeling of subduction zones illustrating the extreme broadening of the olivine $\alpha$-$\beta$ transition in slab interiors.

Additional constraints upon possible upper-lower mantle compositional contrasts will also be reviewed.

# Faulting of a Brittle Lithosphere
# during Extension/Compression on a Ductile Substratum

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Extension/compression of a brittle layer on a ductile layer is a basic model for a number of tectonic processes ranging from salt tectonic scale up to lithosphere/astenosphere scale.

Computer simulation of deformation of brittle lithosphere on ductile substratum is an extremely difficult task due to computational problems of treating brittle-plastic and viscous rheologies in the same numerical model.

The technique used in FLAC (Fast Lagrangian Analysis of Continuum) developed by Peter Cundall (Cundall and Board, 1988; Cundall, 1989) is a powerful method that makes it possible to carry out this kind of study. Our new program PARAVOZ, based on the FLAC method, was used first for the modelling of Rayleigh-Taylor instability in the Maxwell visco-elastic continuum (Poliakov et al., 1993).

In the present work the same program is used for modelling of the evolution of faults of a brittle lithosphere which is approximated as a plastic Mohr-Coulomb material with a non-associated flow rule. The main purpose of the present work is to study the geometry of faulting for different tectonic situations such as compression and extension and on different scales. In order to resolve the genesis of a fault population from an initial continuum, we used a numerical grid from 10000 up 60000 elements. Due to numerically expensive calculations on such fine grids results have been limited to initial stages.

According to the previous numerical and analytical results (Witlox, 1988; Cundall, 1990) the faulting in frictional materials under the gravity field is mostly controlled by a single dimensionless parameter K, which is equal to ratio of elastic bulk module to hydrostatic pressure at the base of the brittle layer (i.e. lithostatic pressure in the present study).

We confirm this statement by systematic investigation for our geometry and for different sets of rheological parameters (frictional and dilation angles, softening parameters, viscosity of the base layer). The fault spac-

ing (horizontal wavelength for simultaneously acting faults divided by the thickness of the brittle layer), W, is different for extension and for compression regimes. For extension, the W is ranging from 0.1 to 0.5 on the "salt tectonic scale" (vertical scale 1–10 km), via 0.9–1.1 on the "crustal scale" (20–30 km), to 2–5 on the "lithosphere scale" (50–150 km). For the compression all numbers are "shifted" to higher values: 0.9 to 1.1 on the "salt tectonic scale", via 2–5 on the "crustal scale", to 5–10 on the "lithosphere scale". In other words, compression on the "salt tectonics scale" is similar to the extension on the "crustal scale".

One immediate conclusion from these results is that "sand box" analogous modelling can hardly be properly scaled for the prediction of the tectonic faulting because of their vertical scale of order of centimeters. Second negative conclusion is about using of visco-plastic approach for modeling of tectonic faulting. As far as this approach implies an infinite parameter K, it is more close to the sand box models which is also have much higher K than in prototypes, and, therefore, several successful comparison between sand box and numerical visco-rigid-plastic models of brittle faulting is not surprising but may deviate together from the prototype faulting.

# Time Periodic Convection in a Spherical Shell of a High Prandtl Number Fluid with a Thermal Blanket

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Convection in a spherical system of two superimposed fluids is analyzed numerically. The outer fluid layer is thin and characterized by a high viscosity. It moves horizontally in response to the convection motion in the inner thicker fluid layer. Through its varying thickness the outer layer acts as a thermal blanket of varying impedance and thus provides a feedback for the convection in the lower layer. As predicted by the analytical treatment by Busse (1978) of the problem in the planar case without convection the preferred mode of motion is usually time periodic. But in the presence of convection there is no preference for very long wavelengths. Solutions have been obtained for different radius ratios of the inner fluid shell and different thickness of the outer layer. A discussion of the implications of the model for the problem of time dependent mantle convection is given.

Busse, F.H., A model of time-periodic mantle flow, *Geophys. J. R. A. S.,* **52**, 1-12, 1978.

# On the Chemical Reaction Zone
# at the Core-Mantle Boundary (CMB)

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The core-mantle reaction in Earth's interior proceeds in two scales: a short-scale chemical reaction leading to local equilibrium and a large-scale dispersal of reaction products. Both processes are described with the help of the diffusion equation in spherical symmetry. It results, that the infiltration and reaction of fluid iron into the mantle can be as far as $10^3$ m in a time scale of about $10^{17}$ sec. The large-scale dispersal of reaction products is connected with a growth of the CMB-radius up to an order of about kilometers per billion years. The departure from a stationary interface is calculated with the help of the gravitational body force controlling the "tension" of the distored spherical core body. Stability analysis with application of angular harmonics leads to the result that in the case of the Earth departures of the CMB from spherical symmetry are stable only for low-degree harmonics with $2 \leq l \leq 6$. In this way our mechanism may explain the generation of large undulation of CMB with small amplitudes.

# The Dynamics at an Interior Boundary in the Earth's Mantle with Depth-Dependent Material Properties

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The style of convection in the Earth's mantle is likely to change with depth, either in a gradual fashion, due to the gradual change of material properties and/or in a more discontinous manner, due discontinuities in the mantle's transition zone. The decrease of the coefficient of thermal expansion $\alpha$ and the increase of the viscosity $\nu$ with pressure have been demonstrated to influence the style of convection in a gradual way. Small scale heterogeneities are present in the upper mantle while in the lower mantle large scale heterogeneities do prevail. Phase boundaries and/or compositional boundaries within the transition zone are potential candidates which can act to separate convection into separate circulation systems, thus giving rise to an abrupt change in the convective velocities and in the thermal field. By numerical experiments, carried out in two-dimensional domains with finite elements, we have investigated the role of a compositional boundary within a mantle where the viscosity increases and the thermal expansivity decreases with depth. Although the depth-depenence of $\alpha$ and $\nu$ reduces the available buoyancy and thus leads to less vigorous convection on a global scale, it also serves to focus all of the available positive buoyancy into a few strong upwellings. This focussing effect promotes an escape of instabilities from a denser lower mantle through the compositional boundary into the upper part. The sudden breakthroughs of plumes generate topography on the discontinuity only on a local scale, thus resembling a scenario of a sharp interface with intermittent material exchange across it. The mass transported by the plumes from the lower- to the upper mantle is counter-balanced by a gradual increase of the thickness of the upper layer, rather than by concentrated descending 'dumps'.

# Role of Phase Transitions on the Mantle Dynamics

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Mantle phase transitions play an important role in the mantle dynamics. Numerical simulations of 3-D convection with phase transitions show the complex time dependent behaviour of both the ascending and descending flows. Movements of both cold and hot plumes suffer the resistance by the presence of the endothermic phase transition. Flow stagnates near the phase boundary. After the accumulation of cold or hot materials, they go through the phase transition within a short time scale. This 'flushing' or 'avalanche' event of cold material produces the thermal disturbances in the bottom thermal boundary layer and, subsequently, they are carried toward the hot ascending plume by the large-scale flow. The hot plume becomes active temporary after their arrivals.

Understanding the effects of phase transitions on the mantle convection is important to clarify the present and past mantle dynamics. Numerical simulations are presented in 3-D up to a surface Rayleigh number of $10^8$. For this large Ra, the 3-D system becomes layered, with less than 10% of the mass-flux going through the 670 km phase transition.

Recent tomographic results show that the cold materials are accumulating in the transition zone and their distribution is not uniform along the subduction zones. This view is consistent with our results. The stagnation of vertical flows will depend on other geophysically important factors. For example, the viscosity jump associated with the phase transition may change the time scale of flushing and that of the lower mantle thermal anomaly. We may expect the high Rayleigh number regime in the early stage of the Earth's history. In such a case, the mantle convection may be more layered as our preliminary calculations show. Presentation will include the animation of 3-D convection.

# A Detailed Correlation Analysis
# between Subduction in the Last 180 My
# and Seismic Structure of the Lower Mantle

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We have used the latest tomographic models based on both P and S waves together with the reconstruction of subduction in the last 180 My (Richards and Engebetson, Nature 1992) to test the hypothesis of slabs penetrating into the lower mantle. To quantify the similarity between the structure of subduction lines in the past and a continuous 3-D distribution of seismic anomalies we have applied both the standard technique of correlation analysis, based on $L_2$-norm scalar product of two fields given in terms of spherical harmonics, and non-standard methods based on evaluation of line integrals. The results of our analysis confirm a rather significant correlation between the seismic anomalies and the past subduction in the global scale, mentioned already by Richards and Engebretson, but they show new details which throw more light on the style of mantle convection. The correlation coefficient computed for individual subduction lines varies with depth exhibiting significant maxima at certain depths and deep minima elsewhere. Correlation maximum is usually found close to the CMB and in the upper part of the lower mantle, either just below 670-km boundary or somewhat deeper at the depth range 1000–1500 km. Thus, our results do not confirm the concept of slabs continuously passing through the lower mantle. It is more probable that subducted slabs form large lumps which are then flushed periodically from the 670 km boundary to the CMB.

# Plates and Plumes

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# Are the Superplumes Caused by Radiative Heat Transfer?

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The seismic tomography revealed broad blob-like low velocity anomalies in the lower mantle beneath Africa and the Pacific (e.g. Su and Dziewonski, 1991; Woodward et al., 1993). Corresponding thermal anomalies obtained by means of recent mineral physics data exceed several hundreds of degrees (Yuen et al., 1993). Numerical models of mantle convection with constant physical parameters show, on the other hand, narrow plumes with very small life-time. Depth-dependent viscosity and thermal expansivity lead to stable larger plumes as shown by Moser et al. (see the abstract "The dynamical influences ...").

In this contribution, we consider radiative heat transfer which can be described by a strongly temperature dependent ($T^3$) coefficient of heat conductivity. Spectral code has been employed to compute the coupled system of equations for base-heated convection in the cartesian box with an aspect ratio of 4. Reflecting boundary conditions on the side-walls and impermeable conditions at the top and the bottom of the box were taken into account. The results for Rayleigh numbers $10^5$ and $10^6$ show a strong stabilizing effect on mantle upwellings and the creation of large hot temperature anomalies (superplumes) with high temperatures in the centers. This suggests the importance of radiative heat transfer for the lower mantle dynamics.

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Yuen, D.A., O. Čadek, A. Chopelas and C. Matyska: Geophysical inferences of thermal-chemical structures in the lower mantle. *Geophys. Res. Lett.,* **20**, 899–902, 1993.

# The Origin of the Hot Thermal Boundary Layer at the Core-Mantle Boundary in the Cooling Earth

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We have examined thermal evolution of the convecting mantle thermally interacting with the core using two-dimensional dynamical convection models with constant or temperature- and pressure-dependent viscosity in a rectangular box.

The objectives of this study are to reveal effects of the heat from the core on convection in the mantle neglecting the dynamics of the convection in the core. The heat is transferred in the model core by conduction with very high effective conductivity. In these models, we consider the influences of the internal heating in the core, initial temperature of the core, heat release associated with the inner core formation, and the viscosity of the mantle.

Our numerical simulation indicates that the hot thermal boundary layer cannot be generated at the CMB when the core has no internal heating. A contact of a cold plume with the CMB takes the heat away from the core and the temperature in the core is homogenized by the efficient heat transfer. That is, the horizontal temperature heterogeneity of the mantle above the CMB and its thermal interaction with the core are two major phenomena controlling the heat release through the CMB. Therefore, the temperature difference between the mantle and the core is fairly reduced, if both the phenomena are taken into account. The hot plume originated at the CMB suggests the existence of the internal heat source in the core. The present amount of the internal heating of the core is estimated to be in the range from $2.0 \times 10^{12}$ W to $6.0 \times 10^{12}$ W.

# Phase Transition Mediated Mantle Mixing: Implications for the Wilson Cycle

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At sufficiently high Rayleigh number near $10^7$, at which a-priori models of convective mixing adequately reconcile the observed mean heat flow through the Earth's surface, the dynamic impact of the Olivine-Spinel and Spinel-post Spinel transitions at the respective depths of 400 and 660 km is extreme. Axisymmetric anelastic calculations demonstrate that the flows in this regime are dominated by an intense time dependence that is controlled by a bi-modality of behaviour in which the circulation executes spontaneous "flips" from a state of layered convection into a state of predominantly whole-stability of the thermal boundary layer that develop across the endothermic transition at 660 km depth when the Clapeyron slope for this transition is set to a negative value equal to that required by high pressure experimental data. The hallmark of transitions from the layered state to the whole-mantle state is the development of intense "avalanches" of cold material from the upper mantle and transition zone into the lower mantle. These events are qualitatively similar to those imagined to occur in the so-called "regolith" model of Ringwood which was not based upon a dynamically consistent analysis of mixing in the presence of phase boundaries. In our model of mantle convection these events impose a profound degree of long range order on the large scale circulation such that surface material that is as distant as 10,000 km from the point immediately overlying the downwelling is drawn towards it. The downwellings themselves, with lifetimes of order 100–200 Myr, therefore develop basins of attraction within which all continental fragments would be brought together. One is thereby led to a view of the so-called supercontinent cycle (sometimes referred to as the Wilson Cycle) in which the aggregation phase is controlled by a major avalanche event. Once an avalanche occurs our model demonstrates that the thermal boundary layer at 660 km depth reforms and the flow returns to the layered state. In this layered state the underside of the supercontinent becomes subject to attack by the small scale convection cells that control the radial heat transport through the upper mantle in this regime. Rifting occurs and the cycle eventually repeats. Our models do provide an explanation for the timescale of 600 Myr that appears to characterize this quasi-periodic phenomenon.

# Quasi-cyclic Reorganization of Fault Systems in Deforming Brittle Lithosphere: Mechanism for Third Order Relative Sea Level Changes?

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Faulting of brittle lithosphere causes changes in topography and, therefore, contributes to the relative sea-level variations. Alicyclic long-term changes of state of stress and rheological properties (due to strain softening) of the lithosphere during faulting contributes to the second order variations in tectonic subsidence rate. Quasi-cyclic reorganization of fault systems may be related to third order variations and may happen even under condition of constant rate of overall extension/compression.

D. Forsyth extended Andersonian theory for infinitesimal strains during faulting to account for the stresses required to drive finite deformation. He has shown that during extension of the lithosphere by normal faulting the regional stresses may increase up to 2 kbar after 2 km of extension has already been accommodated by slip on fault. Furthermore, this level of regional stress elevation exceeds level required to initiate slip on new fault. The typical subsidence/uplift rate a few millimeters per year yields time a few million years to initiate a new fault which is consistent to periodicity of third order relative sea-level changes. The tectonic subsidence/uplift produces alicyclic sedimentary records in the neighborhood of acting faults, but the variation of regional stress during quasi-cyclic activation of faults results in quasi-cyclic regional scale changes in topography. The magnitude of the stresses variation of 2 kbar is essential to cause typically observed magnitude of third order relative sea level changes.

The Forsyth's model is based on thin layer 1D approach and must be verified from the 2D point of view. Numerical forward modeling is explored in order to establish the correlations between structure of lithosphere and tectonic component of second/third order sea-level changes. 2D numerical code "Parovoz", developed by A. Poliakov and Yu. Podladchikov, (using "FLAC", Fast Lagrangian Analysis of Continua technique, invented by P. Cundall) was used in calculations.

The results show that Forsysh's model is appropriate only for thickness of the brittle layer of order of 100 km (cold continental lithosphere) and

only for particular sets of strain-softening parameters. For others parameters (i.e. 20 km thickness of brittle layer or ideal plastic rheology), lateral spacing (distance between simultaneously acting faults) became too narrow that causes deviation from 1D model, and, in particularly, significant shortening of the time required to reactivate a new fault system and decreasing of the amplitude of regional stresses variations. In other words, the regional thermo-mechanical structure of the lithosphere strongly controls the periodicity and the amplitude of the tectonic component of third order relative sea level variations.

On the basis of these results, a filtering of sea level records from the global eustatic and external global tectonic components, which is possible because of the differences in time scales, may yield an important information about the regional structure of the lithosphere.

# Regimes of Variable Viscosity Convection:
# from Constant Viscosity to Plate Tectonics

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A scaling theory of temperature-, pressure-, and stress-dependent viscosity convection suggests three regimes of convection, depending on the temperature induced viscosity contrasts. The first regime resembles constant viscosity convection. The second regime is characterized by thickening of the cold boundary layer, velocity of which is much smaller than the velocity in the interiors. The Nusselt number depends mostly on the surface Rayleigh number (or on the surface temperature). A slow motion of the cold boundary layer is still important for the heat transport. In the third, asymptotic, regime, the cold boundary becomes essentially stagnant and do not influence the heat transfer. Convection takes place beneath the cold lid and involves only the hottest part of the lid determined by a rheological temperature scale. In contrast to the previous regime, the Nusselt number only weekly (logarithmically) depends on the surface Rayleigh number and depends mostly on the internal Rayleigh number. It is similar to constant viscosity convection with fixed boundaries and with temperature difference corresponding to the rheological temperature scale. For realistic rheologies, convection is well in the third regime and far away from subduction and plate tectonics. The convective regime observed in the Earth's mantle ("the fourth regime") requires additional physical factors such as melting, gabbro-eclogite phase transition and fracturing.

# Layered and Non-layered Structures in Convection with Phase-Transitions

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We used a finite element method to model mantle convection with temperature-dependent viscosity and phase-transitions. The effects of the deflection of the phase boundaries and latent heat release were incorporated into the model by formulation of an effective thermal expansivity. Both the olivine-spinel and spinel-perovskite transitions at 400 and 670 km depth, respectively, were considered.

In this framework, the effects of temperature-dependent viscosity, secular cooling of core and mantle, and of the existence of a triple-point in the $\beta$-$\gamma$-spinel-perovskite system on the flow structure were investigated.

Compared to models with constant viscosity, temperature-dependence has two major effects on the flow structure. The mean temperature of the lower mantle is approximately 350 K higher than in the constant viscosity case. This high temperature and the additional release of latent heat at the spinel-perovskite-boundary diminish the viscosity near 670 km depth and lead to an effective mechanical decoupling of upper and lower mantle flows. Due to this decoupling little mass exchange between upper and lower mantle is observed and the temperature drop in the transition zone is increased by approximately 100 K.

The recently measured very high melting temperatures of the lower mantle imply that in this case the transition from $\beta$-spinel to perovskite should be considered. This phase change has been measured at temperatures $> 2500$ K and has nearly zero Clapeyron slope. The existence of this transition leads to a 'leaky' kind of layered flow, even for very high Clapeyron slopes, three times greater than the experimental value. The existence of triple points in mantle phase diagrams of olivine and pyroxene families thus increase the tendency for mass exchange between the upper- and lower- mantle. We have also checked the two-dimensional models with some three-dimensional simulations. Both 2-D and 3-D calculations show similar behavior with regard to the leakiness of the convection in the presence of a triple point, even with

extremely negative Clapeyron slopes, three times the nominal experimental value.

The decrease of Rayleigh number with time due to secular cooling may lead to rapid transitions from layered to non-layered flows and vice versa. These changes in the style of convection exhibit catastrophic character and may have great impact on compositional and thermal planetary evolution.

# Time-dependent Three-dimensional Convection with Strongly Temperature-dependent, Non-Newtonian Rheology

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The major features of mantle convection (e.g., plates, plumes) are greatly affected by or even caused by the strong temperature-dependence of mantle viscosity. Non-Newtonian creep may also have important effects. However, previous three-dimensional numerical and laboratory experiments with variable viscosity have been restricted to solutions which are either steady-state, or have only moderate viscosity contrasts (e.g. factor 50).

Here we present a method that enables efficient computation of viscous flow with large viscosity contrasts, using a multigrid finite difference (control volume) technique. Primitive variables (velocities and pressure) are defined on a staggered, three-dimensional Cartesian grid. Thus, first derivatives involve adjacent points, eliminating checkerboard pressure solutions, and viscosity variations are naturally incorporated into the stress terms without the need to calculate viscosity derivatives. Relaxation sweeps involve relaxing each equation (3 momentum plus continuity) in turn over the entire domain, and seem to converge for any viscosity contrast. Using multigrid V-cycles, convergence in order (npoints) operations is obtained, but the robustness of the procedure to large viscosity contrasts is reduced. Even so, variations of 3 orders of magnitude are readily modeled, and 4 or 5 orders are possible with care. The scheme is easily parallelizable, and has been implemented on the Intel Delta and iPSC/860 parallel supercomputers.

Preliminary time-dependent solutions in a wide aspect ratio ($8\times8\times1$) 3D box are presented, for cases with constant, temperature-dependent and temperature- and stress-dependent viscosities, with order $10^3$ viscosity variation.

# 4   Rotation

## Generation of Mean Flows in Planetary Systems

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The problem of the generation of mean flows by convective motions is considered from a general point of view. Various nonlinear mechanisms are outlined in which Reynolds stresses or viscous stresses are generated which give rise to mean zonal flows in axisymmetric fluid systems. In many systems such convection in plane layers or convection in spherical shells symmetry properties prohibit mean flows unless special properties are added. In other systems mean flows become possible only through bifurcations and the sign of the motion may depend on initial conditions. Laboratory experiments (Hartung et al., 1991) and applications to the phenomenon of zonal flows in the Jovian atmosphere are used as examples to illustrate the main points of the theory.

Hartung, G., Busse, F.H., and Rehberg, I., Time-dependent convection induced by broken spatial symmetry, *Phys. Rev. Letts.,* **66**, 2742–2745, 1991.

# Core Mantle Coupling and the Geodynamo

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The existence of non-axisymmetric magnetic features at the core-mantle boundary that are stationary on the secular time scale poses a dilemma for the theory of the geodynamo. Since magnetic and dynamical features on fluid cosmic bodies are generally moving relative to a given frame of rigid rotation, the same property must be assumed for the Earth's core unless a much stronger coupling to the lower mantle occurs than has traditionally been assumed. Among the various mechanisms of coupling such as variations in the thermal boundary condition or topographic effects we shall emphasize the effects of finite electrical conductivity of the lowermost mantle and its lateral variation. While a finite conductivity in general tends to diminish differential rotation between mantle and core, electromagnetic coupling is not relaxational such as viscous or topographic coupling. Lateral variations of electrical conductivity may explain standing components of geomagnetic field and can give rise to time dependent torques between core and mantle.

# Mantle Rheology, Convection and Rotational Dynamics

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We have examined theoretically the effects from mantle convection on Earth rotational dynamics for both viscoelastic and viscous mantles. Strategies for numerical computations are proposed. A linear Maxwell viscoelastic rheology accounting for finite deformations associated with mantle convection is considered. For both rheologies the two sets of convection and rotational equations can be partitioned into separate systems with the output from convection being used as input for the rotational equations. The differences in this convection-rotational problem between finite-strain and small-amplitude viscoelastic theories are delineated. An algorithm based on the usage of massively parallel processors is proposed in which all of the different processes in the convection-rotational problem are partitioned and the different timescales can be dealt with together. The coupled systems of convective-rotational equations can greatly be simplified by using the hydrostatic approximation for the rotational readjustment process in a viscous Earth model. This is valid for a young Earth and for non-Newtonian rheology. Larger amounts of contributions to the relative angular momentum can be expected from non-Newtonian rheology. The non-hydrostatic equatorial bulge may also be explained as a consequence of the long-wavelength dynamics associated with the effects of depth-dependent physical properties on mantle convection.

# The Dynamical Influences of Depth-Dependent Properties On Inducing Large-Scale Upwelling Structures in Planetary Mantles

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The appearance of large-scale upwellings in the lower mantle in seismic tomographical models runs counter to the intuition and past experiences derived from modelling using constant physical properties. Recent work by Hansen et al. (1993) in a cartesian model has pointed out the important role played by depth-dependent viscosity and thermal expansivity in promoting large-scale circulation and maintaining robust stationary upwellings. These 2-D results have already been observed in 3-D cartesian models with similar depth-dependent properties (Balachandar et al., 1992). We have constructed a finite-difference code with variable-mesh and variable-order algorithm devised by B. Fornberg for an axisymmetric spherical-shell model with radial-dependent properties, such as thermal expansivity and viscosity. Comparison with the cartesian model for same Rayleigh number and depth-dependent properties shows that the sizes of the robust upwellings is about the same. The big difference comes from the much weaker descending instabilities in the spherical-shell case, as compared to the cartesian case. This inability of the descending blobs to go down to the CMB would help to maintain the stationarity of these roboust plumes in the lower-mantle. These giant plumes are nurtured even more for planets with smaller cores. There giant plumes with plume-heads, spanning twenty to thirty degrees, can exist at polar regions for effective Rayleigh numbers in excess of $10^6$. The influences of these giant plumes or 'yeldas' on rotational dynamics also show up in phase-space portraits of the evolution of the moment of inertia and Nusselt numbers. The timescales associated with temporal changes of moments of inertia are longer than those associated with global heat-transfer,as shown by the phase-space analyses.

# Numerical Simulation of Geodynamic Processes
# in the Two and Three Dimensional Earth.
# A New Approach to Mantle-Core Coupling Studies.
# Theory.

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The mechanism of geodynamic processes which take place in the Earth interior will be simulated by the thermo-visco-plastic Bingham rheology. The influence of magnetic, diffusion and gravity effects will be taken in account. The phase change boundaries, like a melting, recrystallization and solidification of the Earth's rocks in the lithosphere, the mantle and the core as well as metallized and ionized rocks under high pressure and high temperature or nonmetallized and nonionized, respectively, will be theoretically investigated. One can said that convection in the Earth's mantle and thermo-magnetodynamic turbulence in the Earth's core are much studied, but little understood, subjects. Numerical calculations and investigations of two- and three-dimensional geodynamic processes, it means the magneto-thermo-hydrodynamic turbulence in the core and the thermal convection in the mantle in time and pressure dependent viscosity, created by compressible or incompressible Earth's materials, respectively, are possible only by using numerical methods, namely by using the finite element or the finite difference methods.

In the real Earth all geodynamic and geomagnetic processes are coupled. Seismic and geomagnetic investigations show onto the layered thermo-visco-plastic upto thermo-visco-strongly plastic (liquid) structure with melted or recrystallized zones, respectively, in a relatively weak magnetic field. Recent investigations of high pressure show on metallized behaviour of Earth's rocks under high pressures. Therefore, the thermo-visco-plastic Bingham rheology is acceptable for the whole Earth interior. The system of equations follow from the principal laws of physics. The velocity field is related to the density field in a moving fluid by the conservation law of mass. The fundamental equations for the moving thermo-visco-plastic media of the Earth follow from the law of momentum conservation. The equation for the geothermal field in the Earth interior follows from the general conservation law of energy. Due to melted and recrystallized zones in the mantle as well as in the lithosphere

and due to melted core-mantle boundary the formulation in enthalpy is suitable to use and therefore will be used in the contribution. The stress-strain rate relation is defined by

$$\tau_{ij} = -p\delta_{ij} + \overline{g}D_{ij}D_{II}^{-\frac{1}{2}} + 2\mu D_{ij} + \beta_{ij}(T - T_0) + E_iD_j + H_iB_j - (ED + HB)\delta_{ij}$$

where the first three terms represent the stress-strain rate relation for the Bingham rheology, the fourth term represents the thermal stresses and the last one the Maxwell stresses. Furthermore, $p$ has a meaning of a pressure, $\overline{g}$ and $\mu$ are thresholds of plasticity (of the Mises type) and viscosity, $D_{ij}$ is a strain rate tensor and $D_{II}$ its invariant. If $\overline{g}$ is equal to zero, we have the stress-strain rate relation for the Newtonian viscous liquid.

With the momentum equation we must clearly associate jump conditions across any surface of discontinuity of physical properties; this may be either a fixed fluid boundary, i.e. the Earth surface, or an interior surface of discontinuity moving with the fluid. Energy balance arguments show that although the temperature is continuous everywhere, the heat flux has a jump discontinuity across the phase change surface (melted boundaries, recrystallized zones) which is of a moving character. As the Earth is assumed to be inhomogeneous thus besides Maxwell's equations the corresponding conditions for the magnetic field on the interface boundaries of the moving medium must be defined. About the Earth surface we shall assume that it is electrically conductive. Due to the metallized, ionized or unmetallized, unionized, respectively, state of Earth's rocks, the Ohm law must be defined for such state of rocks.

Solving this problem we obtain a realistic two or three dimensional velocity, magnetic, geothermal and gravity fields existing in the electrically conducting Earth's body, namely in the electrically conducting core and mantle and therefore we can study their coupling. Since such problem is analytically unsolved, only numerical approximations come into consideration. In the contribution it will be shown that the problem leads to solve the system of variational inequalities and variational equalities. Since analytical methods and the method of spherical harmonic analysis are not known for such type of problems, the numerical methods can be used only. For the numerical solution the semi-implicit scheme in time and the finite element approximations in spatial variables will be used. The scheme obtained is a stable scheme. The algorithm solving such problem will be given. Since we obtain the discrete values of velocity, magnetic, geothermal and grav-

ity fields, the presented method admits also to study thermoelectric nad thermogalvanomagnetic effects in the Earth interior, that is on the interface boundaries of two different conductors, i.e. effects originating from flowing currents at simultaneous existence of an electric and magnetic fields and a gradient of temperature as well as originating from current penetrating through the interface boundary between two different conductors. It is possible due to the numerical solution of the problem – as the solution was found in the discrete points of the Earth body.

# Coherent Motion of Pacific Hot Spots
# due to Flow in the Lower Mantle

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Although the motion of Pacific hot spots relative to each other is much slower than their motion relative to the Pacific plate, they may exhibit a coherent motion due to large-scale-flow in the lower mantle. This may bias our estimate of the "absolute" plate velocity.

We investigate how fast Pacific hot spots may move coherently. We make the following assumptions: 1) Hot spot plumes originate at the core-mantle-boundary at a position which is advected with the large-scale mantle flow. 2) Plumes rise vertically relative to the ambient flow and the rising velocity is inversely proportional to the viscosity of the penetrated mantle material. 3) Plumes do not change the mantle flow. The mantle flow field is calculated from plate velocities and lateral density heterogeneities. For present time, the latter are inferred from seismic tomography. For past times, density heterogeneities are advected back in time using the same flow field. For the computation we use the method of Hager and O'Connell. We do calculations for different viscosity structures and different conversion factors from seismic velocity anomaly to density anomaly.

Preliminary calculations, which were done for stationary mantle flow give the following results, which are in accordance with observational data on Pacific hotspot chains:

- Slow relative motion of hotspots implies high viscosity of the lower mantle ($\sim 10^{23}\,\mathrm{Pa\,s}$).

- Due to flow in the lower mantle in a direction opposite to the plate motion, there may be a coherent motion of several Pacific hotspots.

- This may bias estimates of "absolute" plate velocity by about $2\,\mathrm{cm}$ /year, since the hot spot reference frame is to a large deal defined by Pacific hot spots.

Our results may help to explain the observed correlation between motion of the Pacific plate and the net rotation of the lithosphere in the Cenozoic.

# Does Mantle Convection Know About Earth Rotation?

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It is widely appreciated that by the traditional criterion (smallness of the Coriolis force) mantle convection does not "feel" the effect of Earth rotation. It is less well appreciated that this is not the only issue. There are at least four other issues that must be considered: (1) True Polar Wander causes Earth to rotate about the axis of maximum principal moment of inertia. This guarantees that there is a preferred axis for the convection pattern, but does not change that pattern. (2) The non-central gravity vector of the rotating Earth causes a drift and change of the convection pattern and favors a strengthening of the $Y_{2,0}$ component of the geoid. This degeneracy breaking is weak (1 part in 300) but I will show that it is systematic and hence may affect long term evolution. Chaotic mantle convection diminishes this effect. (3) The undoubted strong effect of rotation on core convection has led many people to speculate that the mantle might thermally couple to the core in such a way as to exhibit (indirectly) Earth rotation. For example, mantle plumes might prefer to be near the equator since core convection is "easier" along directions perpendicular to the rotation axis. I will argue that this is fallacious, even if the core is internally heated, because the core can adjust to any heat flux boundary condition by infinitesimal (10–11 degrees/cm) changes in HORIZONTAL temperature gradients. (4) Tidal heating has a latitudinal variation that will affect large scale flows through the temperature dependence of the viscosity.

# The Effects of Phase Transitions
# in Three-dimensional Spherical Models of Mantle Convection

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Numerical modeling of mantle convection in a spherical shell with phase changes at 670 and 400 km depth reveals an inherently three-dimensional flow pattern, containing cylindrical plumes and linear sheets which behave differently in their ability to penetrate the 670 km discontinuity. The dynamics are dominated by accumulation of cold material above 670 depth, building up until huge catastrophic avalanches are precipitated, flushing regional volumes of upper mantle through broad cylindrical downwellings to the base of the lower mantle.

In three-dimensional spherical geometry many flushing events are in progress at a given time, so individual events do not have the large effect on globally-averaged quantities predicted by two-dimensional or three-dimensional cartesian calculations. Flushed cold material just above the CMB cools the core effectively, so very few upwelling plumes are produced, despite the relatively high core heat flow ($\sum 40\%$ of total).

Examination of the radial flow field at different wavelengths indicates that long wavelegths of the flow are virtually unaffected by the endothermic phase change, whereas short wavelengths are increasingly inhibited. Thus, the long wavelength flow field in the Earth is a poor diagnostic of these effects. Other diagnostics seem contradictory, for example: The spherical harmonic spectrum of density anomalies has similarities to seismic tomographic results, (unlike internally heated models with no phase change); but comparison of radial correlation functions for tomographic and numerical models favors models with no phase change.

Variations in the moment of inertia tensor, which lead to true polar wander, have been calculated for models with and without phase changes, and with various heating modes.

# Changes in the Earth's Rotation by Tectonics

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Whereas the present-day true polar wander and the secular non-tidal acceleration of the Earth have usually been attributed to post-glacial rebound, it has recently been suggested that non-glacially induced vertical tectonic movements taking place under non-isostatic conditions can also be effective in changing the Earth's rotation (Vermeersen and Vlaar, GRL, 20, 81–84, 1993). These lithospheric contributions are effective on characteristic timescales between those of post-glacial rebound and large-scale mantle convection.

In order to further assess these tectonic contributions, a case study in which the effects of some simple uplift histories of the Himalayas and the Tibetan Plateau on the rotational axis and on the second degree zonal harmonic of the geoid for timescales of up to a few million years has been performed. As the lithospheric forcings are assumed to remain operative, at least partly prohibiting mantle relaxation by intraplate stresses, a normal mode analysis in which mantle relaxation to the imposed loads is modeled can only supply us with a lower bound on the effects. The upper bound is given by assuming that essentially no relaxation is taking place at all. Contrary to the readjustment of the mantle to the load, the readjustment of the equatorial bulge is assumed to take place by pure mantle relaxation.

The modeling results show that full mantle relaxation to the imposed forcings would only result in significant contributions to the rotational changes for times shortly after a Heaviside type of uplift. For incomplete mantle relaxation the contributions are significant for all times when the forcings are active.

# Effects of the Core-Mantle Interactions
# on the Geomagnetic Field

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The core-mantle coupling is essentially important to the understanding of the dynamics of the Earth's core. Thus I have investigated theoretically two kinds of core-mantle couplings, topographic and thermal. Comparison between my theory and observations of the geomagnetic field reveals new evidences of interactions of the core with other parts of the Earth.

I propose the following process in connection with the topographic coupling. The geomagnetic variation is caused by LOD variation, which in turn is caused by climatic variation. The sectorial components of the geomagnetic field correlate very well with LOD variation on a decadal time scale. This correlation is interpreted very well by my model of topographic coupling. Moreover, I have inferred the CMB topography and the strength of the toroidal field from the correlation. The geomagnetic field variation on a longer time scale also appears to be strongly affected by the topographic coupling.

Thermal coupling is important for the geomagnetic field on a long time scale. I have investigated thermal response of the outer core fluid to the sectorial temperature heterogeneity of the CMB under the assumption of quasi-geostrophy. The locations of upwellings and downwellings are found to be controlled by the strength of the toroidal field. I have inferred the strength of the toroidal field of the outer core by comparing the observed field with the theory.

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