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From davey@krissy.msi.umn.edu  Wed Jul  7 01:48:15 1993
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From: "David Yuen" &lt;davey@krissy.msi.umn.edu&gt;
To: miker@krissy.msi.umn.edu
Subject: program for Boehmen - preliminary version



JULY 28 ( Wednesday )

8:45 opening remarks : conveners

9:00 Adam Dziewonski
9:30 Ann Chopelas
10:00 Break

10:30  Shun Karato
11:00  Jay Pulliam
11:30  Toshiro Tanimoto
12:00   Lunch
14:00  Barbara Romanowicz
14:30   Alex Forte
15:00   Scott King
15:30    Break
16:00   Reini Boehler
16:30   Craig Bina
17:00   Discussion of the DAY
17:30    Break

20:00   Poster session of the day
  5 minute presentations
  Dziewonski, Kowalle, Daessler.Solomatov, Franck, Karato

July 29th ( Thursday )

9:00   Jerry Mitrovica
9:30   Motoyuki Kido
10:00   Break
10:30   Gilles Bussod
11:00   Ctirad Matyska
11:30   Paul Tackley
12:00    Lunch


14:00   Volker Steinbach
14:30   Slava Solomatov
15:00   Ulrich Hansen
15:30    break
16:00   Satoru Honda
16:20   Shuxia Zhang
16:40   T. Nakakuki
17:00    Discussion
17:30    end of Discussion


20:00    poster presentation of the day
  5 minute presentations
  F. Busse, L. Hanyk, Lenardic , Bolshoi , Podladchikov.  Cadek , Kyvalova,
Tackley.


FRIDAY , July 30th

9:00  F. H. Busse
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9:30 D. J. Stevenson
10:00 Jiri Moser
10:30 Break
11:00 Bernhard Steinberger
11:20 Shiego Yoshida
11:40 Bert Vermessen
12:00   Lunch

(afternoon excursions and games)

Saturday   , July 31st
9:30 Panel discussions
Panel: A. Dziewonski, S. Karato , N.J. Vlaar , V. Steinbach,
S. Solomatov , J. Moser, T. Tanimoto , R. Boehler
11:30 end of panel discussion
11:30 Summary
Lunch

free afternoon

Roast-pig barbecue party

WELCOME TO THE ABSTRACTS OF THE
WORKSHOP ON GLOBAL GEODYNAMICS

JULY 28 to JULY 31 , 1993

PISTINA, BOHEMIA , CZECH REPUBLIC

PREAMBLE

Sometime last summer a group of us spent one weekend in Pistina 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. Pec, Charles University, who passed away this spring. Professor Pec, 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

Ondrej P. Cadek
Ctirad (Radek) Matyksa
Jiri (Jerry) Moser

CHARLES UNIVERSITY, PRAHA, CZECH REPUBLIC .

David A. Yuen

UNIVERSITY OF MINNESOTA, U.S.A.

SEISMOLOGY

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

Adam M. Dziewonski and Wei-jia Su
Department of Earth and Planetary Sciences,
Harvard University, Cambridge, MA. 02138, USA

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

Wei-jia Su and Adam M. Dziewonski

Department of Earth and Planetary Sciences,
Harvard University, Cambridge, MA. 02138, USA

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 Mast ers, 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

G. Kowalle (Projektgruppe "Allgemeine Geophysik" bei der Universitat Postdam, Postfach 60 16 32, D-14416 Postdam, Germany)

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 possibility 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, possibility 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

Jay Pulliam (Utrecht University) and Philip Stark (UC Berkeley)

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

Barbara Romanowicz (Seismographic Station, University of California at Berkeley, Berkeley, CA, 94705, USA)

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.

MATERIALS AND VISCOSITY

TEMPERATURE REGIMES AT THE BASE OF THE LOWER MANTLE

R.BOEHLER, A.ZERR, AND A.CHOPELAS
(Max-Planck-Institute for Chemistry. Mainz, GERMANY)

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 dln(rho)/dlnv with depth. This and the strong decrease in the thermal expansion coefficient, yields dT up to 1000 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 K; iii) melting temperatures of Mg,Fe,Si-perovskite between 7000 and 8500 K at the bottom of the mantle result in T/Tm-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 Mg1.83 Fe0.17 SiO4 Olivine and Modified Spinel at High Pressures and Temperatures

G.Y. Bussod, T Katsura, T. G. Sharp, and D.C. Rubie
(Bayerisches Geoinstitut, Universitat Bayreuth, 95440 Bayreuth, Germany)

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 on the rheology of olivine (Mg,Fe)2 SiO4, 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 fact that classical experimental deformation apparatus are restricted to a relatively low pressure range (<3GPa). Furthermore, even assuming the simplest case of a chemically homogeneous mantle, (Mg,Fe)2 SiO4 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 at mantle conditions.

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 (< or =16GPa) and high temperatures (< or =1600 degrees 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 Mg1.83 Fe0.17 SiO4 polycrystalline olivine aggregates at 6 and 14 GPa are consistent with single crystal dislocation creep laws (stress component n=3.5) assuming a pressure dependence (activation volume V*) of the order of 5 cm3 mol-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 degrees C.

Sound Velocities of Four Minerals to Very High Compression: Constraints on dln(rho)/dln(velocity)

A. Chopelas, H. J. Reichmann, and L. Zhang,
Max Planck Institut f r Chemie, Postfach 3060,
W-6500 Mainz, Germany, fax 49-6131-305330,
e-mail chopelas@mpch-mainz.mpg

The transverse and longitudinal acoustic modes in MgO to 400 kbar, yttrium aluminum garnet to 600 kbar, aluminum oxide to 630 kbar, and MgAl2O4 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: (dln(rho)/dln(velocity)) at constant temperature. We find this parameter and their pressure derivatives to be nearly the same for all four minerals: about 0.7 for Vp and 0.95 for Vs 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 (dln(rho)/dln(velocity)) 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 dln(rho)/dln(velocity) in the lower mantle are small and decreasing with depth since lower mantle temperatures are at less than half of the homologous temperatures (T/Tm) of the candidate minerals (see Boehler et al abstract, this meeting). Thus, an increasing value of dln(rho)/dln(velocity) and decreasing thermal expansion with depth allows calculation of lateral temperature variations from seismic anomalies using dT=[(dln(rho)/dln(vel.))/(alpha)] d(vel.)/(vel.) [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

Roelf Daessler, University of Potsdam, Potsdam, Germany

David A. Yuen, University of Minnesota, U.S.A.

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 protrusions 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

Alessandro M. Forte Dept. Earth Planet. Sci., Harvard Univ., Cambridge, MA 02138

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 i mplications 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

S. Franck, G. Kowalle, Ch. Thurmer (Projektgruppe "Allgemeine Geophysik" bei der Universitat Postdam, Postfach 60 16 32, D-14416 Postdam, F.R. Germany)

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-colled 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 depht 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

L. Hanyk and J. Moser (both at: Dept. of Geophysics, Charles University, Prague, Czech Republic)

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.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

Shun-ichiro Karato Department of Geology and Geophysics, University of Minnesota, Minneapolis, MN 55455

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~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 ~ 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

Shun-ichiro Karato, Zichao Wang and Kiyoshi Fujino University of Minnesota Department of Geology and Geophysics Minneapolis, MN 55455, U.S.A.

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

Motoyuki Kido & Tetsuzo Seno, Earthquake Research Institute, University of Tokyo

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 de nsity 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 co rrected age depth-curve suggests that the square root 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

Scott King
Department of Earth and Atmospheric Sciences
Purdue University
West Lafayette, IN 47907 USA

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

J.X. Mitrovica (1,2), J.L. Davis (2), I.I. Shapiro (2) 1. Department of Physics, University of Toronto, Toronto, Canada M5S 1A7.
Tel 416-978-4946; Fax 416-978-7606; e-mail jxm@physics.utoronto.ca

2. Harvard-Smithsonian Center for Astrophysics, 60 Garden St. MS42, Cambridge, MA, USA 02138.

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 SHARPNESS OF UPPER MANTLE DISCONTINUITIES: CONSTRAINTS FROM NON-EQUILIBRIUM PHASE TRANSFORMATIONS IN CONVECTIVE SYSTEMS; V. S. Solomatov

& D. J. Stevenson, Caltech, slava@seismo.gps.caltech.edu

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

Shuxia Zhang 1) and Ulrich Christensen Institut fuer Geophysik, Universitaet Goettingen, Germany

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.

1) also at Max-Planck-Institut fuer Chemie, Saarstrasse 23, 6500 Mainz, Germany

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DYNAMICS

Transition Zone Clapeyron Slopes, Seismic Topography, and Chemical Contrasts

Craig R. Bina (Northwestern University, Evanston, IL, U.S.A.)

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 studi es 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.

A.N.B. Bolshoi (Juelich , Germany) and
Yu.Yu. Podladchikov (AMsterdam, Netherlands)

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 spacing (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

F.H. Busse, Institute of Physics, University of Bayreuth, Germany Keke Zhang, Dept. of Mathematics, University of Exeter, England

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)

S. Franck (Projektgruppe "Allgemeine Geophysik" bei der Universitat Postdam, Postfach 60 16 32, D-14416 Postdam, F. R. Germany)

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.le.l.le.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.

U. Hansen (Dept. of Theoretical Geophysics, Earth Science Institute, Utrecht University, The Netherlands)

D. A. Yuen (Minnesota Supercomputer Institute, Univ. of Minnesota, MN, USA)

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 candidat es 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 counterbalanced 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

S. Honda (1, D. A. Yuen (2, S. Balachandar (3 and D. Reuteler (2
1) Dept. of Earth and Planet. Syst. Sc., Univ. of Hiroshima
2) Minnesota Supercomputer Institute and Dept. of Geol. and Geophys. University of Minnesota, USA.
3) Dept. Theoretical and Applied Mechanics, University of Illinois

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

H. Kyvalova, L. Vecsey and O. Cadek (Dept. of Geophysics, Charles University, Prague, Czech Republic)

D. A. Yuen (Dept. of Geology and Geophysics, University of Minnesota, Minneapolis, MN 55455)

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 L2-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

Adrian Lenardic and William M. Kaula, Dept of Earth and Space Sciences, UCLA, Los Angeles, CA 90024, email:alenar@artemis.ess.ucla.edu

It is proposed that tectonic plates can affect mantle plume morphology by determining the temperature drop across a plume source layer. Numerical convection models demonstrate how the introduction of plate-like behavior in a convecting temperature dependent medium, driven by a combination of internal and bottom heating, increases the temperature drop across the lower thermal boundary layer of the system. This temperature drop determines the viscosity variation across the boundary layer which, in turn, determines the morphology of plumes emmitted from the boundary layer. We argue that

generally accepted notions as to plume dynamics on Earth may hinge on the presence of subducting tectonic plates and that rather than representing largely decoupled features of mantle convection, plumes and plates may interact directly. The implication for Mars and Venus, planets lacking plate tectonics, is that mantle plumes of these planets may differ morphologically from those of Earth.

Are the superplumes caused by radiative heat transfer?

Ctirad Matyska, Jiri Moser and Ondrej Cadek

Department of Geophysics, Faculty of Mathematics and
Physics, Charles University, V Holesovickach 2,
180 00 Praha 8, Czech Republic
(e-mail: geofcm@cspuni12.bitnet)

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). 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 I")

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.

References

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Yuen, D.A., O. Cadek, 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

Tomoeki Nakakuki Ocean Research Institute, University of Tokyo 1-15-1 Minamidai Nakano-ku, Tokyo 164, Japan email: nakakuki@aix3.ori.u-tokyo.ac.jp, nakakuki@jpnorixa.bitnet

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 2.0E+12W to 6.0E+12W.

Quasi-cyclic reorganization of fault systems in deforming brittle lithosphere: mechanism for third order relative sea level changes? Yu.Yu. Podladchikov and S. Cloetingh (Vrije Universitiet, Amsterdam)

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.Cundal) 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; V. S. Solomatov, Caltech, slava@seismo.gps.caltech.edu

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

V. Steinbach (University of Cologne, Cologne, Germany)

D. A. Yuen (Minnesota Supercomputer Institute and Department of Geology, University of Minnesota, Minneapolis, MN 55415)

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 temperatu re-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 inc reased 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

Paul J Tackley, Seismological Laboratory, California Institute of Technology, Pasadena, CA 91125, USA

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 (8x8x1) 3D box are presented, for cases with constant, temperature-dependent and temperature- and stress-dependent viscosities, with order 10**3 viscosity variation.

ROTATION

Generation of mean flows in planetary systems by F.H. Busse, Institute of Physics, University of Bayreuth, D-95440 Bayreuth.

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.

Mantle Rheology, Convection and Rotational Dynamics

Jiri Moser, Ctirad Matyska (Charles University , Czech Republic)
D.A. Yuen, Andrei Malevsky (University of Minnesota, U.S.A.)
Helmut Harder (Univ. Goettingen , F.R. Germany)

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

Jiri Moser, Dept. of Geophysics , Charles University, 18000 Praha 8 , Czech Republic.
David A. Yuen and Tine Larsen , Dept. of Geology and Geophysics and Minnesota Supercomputer Institute, University of Minnesota, Minneapolis, MN, U.S.A.

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 ass ociated with global heat-transfer,as shown by the phase-space analyses.

DOES MANTLE CONVECTION KNOW ABOUT EARTH ROTATION? David J. Stevenson, Caltech 170-25, Pasadena CA 91125 djs@arms.gps.caltech.edu

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

Paul J. Tackley, Seismological Laboratory and David J. Stevenson, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125, USA Gary A. Glatzmaier, EES and IGPP, Los Alamos National Laboratory, Los Alamos NM 87545, USA Gerald Schubert, Department of Earth and Space Sciences and IGPP, University of California, Los Angeles, CA90024, USA

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 (~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

L.L.A. Vermeersen and N.J. Vlaar, Utrecht University, The Netherlands R. Sabadini and G.V.C.N. Spada, Universita' di Bologna, Italy

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

Shigeo Yoshida (Institute for Solid State Physics, Univ. of Tokyo)

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 c ore by comparing the observed field with the theory.

Geodynamics Workshop In the Czech Republic

The first geodynamics workshop in the Czech Republic, following the Velvet Revolution in 1989, was held this summer (July 28 to July 31, 1993) in the village of Pistina, in southern Bohemia, close to the Austrian border. The theme of this workshop was on several topics in solid-earth geophysics, pertaining to the SEDI objectives. Geophysicists from many diverse disciplines (seismology, mineral physics, geodynamics, numerical modelling, earth rotation and geophysical fluid dynamics) and from many different countries in North America, western and eastern Europe, and Asia participated. Because of the limited number of attendees, around forty, there was a good opportunity for many fruitful interactions between people from very different disciplines. There were also ample recreation opportunities, such as tennis and cycling trips, which also promoted a collegial atmosphere. Lively discussions took place every night at the bar, which was kept open until the last person left, or an unexpected late comer showed up at two in the morning. The workshop was organized by Drs. O. Cadek, C. Matyska, J. Moser and L. Hanyk from the Deptartment of Geophysics, Charles University, Prague, Czech Republic and Dr. David A. Yuen from the University of Minnesota, Minneapolis. Much of the success was due to the hard work of the local owner of the summer house, Mr. Vladimir Sasek, who provided an excellent Bohemian cuisine, which included a roast pig and lamb barbecue. The social program also included a tour of a 14th-century old beer brewery in the historical town of Trebon. This tour was enjoyed by all who participated. This workshop has really opened the eyes of many of the attendees, in particular those from Asia and North America to the potential present in the Czech Republic.

The presentations were divided into the following groups: (1) seismic tomography and equation of state, (2) mantle rheology and inference of mantle viscosity structure, (3) mantle convection and (4) rotation of the earth. Lectures were 30 minutes each. In the evenings there were poster sessions, which began with a series of five-minute presentations.

Adam Dziewonski (Harvard) led off with a discussion of the upper-mantle tomography, where he compared his results with those of Zhang and Tanimoto (Caltech). This led to an interesting debate later between Drs. Dziewonski and Tanimoto concerning the depth extent of the slow anomalies under oceanic ridges. Dziewonski also pointed out the differences in the morphology of the megaplume structures in the lower mantle under Africa and Hawaii. An interesting observation was also underscored by Dziewonski on the changes in the power-spectrum of the the seismic tomography at around 1700 km depth. The connection between this observation and mantle avalanches was a theme repeated later in the discussions in the mantle convection session.

Ann Chopelas (Mainz) described her spectroscopic measurements based on fluorescence to yield the shear and compressional sound velocities of minerals, such as MgO, aluminum oxide and garnet up to 600 kbar. The important geophysical quantity, the ratio of the logarithmic derivatives of the density and sound velocities, was used to infer the magnitudes of the lower-mantle hot and cold thermal anomalies.

Jay Pulliam (U Washington) spoke about the confidence regions for mantle heterogeneities for both P and S waves. His inversion results were based on using the CRAY-C90 supercomputer, where matrices of the size of 5000 x 5000 were solved by the direct method.

Toshiro Tanimoto discussed the inversion of the global-scale crustal structure. Employing fundamental modes out to periods of 40 sec. and ray-tracing techniques, he found thick crust under continents and thin crust under oceans. The transition of the slow continental crust to faster lithosphere was found to occur between 50 and 80 km depth for all of the shield regions in the world. Barbara Romanowicz (UC Berkeley) then discussed the 3-D variations of seismic attenuation in the upper-mantle, based on surface waves. She found a strong correlation between the seismic and Q anomalies at depths between 200 and 400 km. The relationship of this correlation to the degree-two spherical harmonic was pointed out. Alex Forte (Harvard) then discussed the influences of lateral variations of the viscosity on mantle flow and geoid observables. These calculations were based on a variational principle. His conclusions were that there is strong insensitivity of geoid and surface topography to lateral variations of mantle viscosity. Scott King (Purdue) presented a novel technique based on a genetic algorithm for nonlinearly inverting the viscosity profiles of mantle viscosity based on geoid fit considerations. He found a multiplicity of solutions with unusual characteristics in the transition zone. One had a low viscosity zone, the other had a high viscosity layer, which Shun Karato (Minnesota) found this to be very interesting, as it might indicate the presence of some amounts of garnet in the transition zone.

Reini Boehler (Mainz) presented his results on the melting of perovskite up to 650 kbar. Extrapolation yields high melting temperatures, in excess of 7000 to 8000 K, at core-mantle-boundary conditions. This result generated considerable discussion concerning the sudden change of the homologous temperature from 0.7 in the upper-mantle to nearly 0.35 in the deep mantle. Craig Bina (Northwestern) discussed the differences in the topography between the 400 and 670 km discontinuities. Recent seismic findings of the magnitudes of the phase boundary undulations are opposite to what is expected from equilibrium phase changes.

During the poster sessions of the first evening Rolf Daessler (Potsdam) presented results of calculations of the thermal-kinetic equations associated with non-equilbrium phase-changes in subducting slabs. Karato discussed the inner-core anisotropy due to magnetic field-induced preferred orientation of iron. S. Franck (Potsdam) presented results on the preferential wavelengths arising out of chemical reactions at the core-mantle boundary. W. R. Peltier (Toronto) discussed the possibilities of an extremely low viscosity zone lying above the 670 km discontinuity, which can satisfy the geoid data. Dziewonski's colorful poster at the bar showed a series of beautiful seismic-tomography figures where the rapid change in the tomographic pattern at 1700 km was again pointed out. The effects of seismic attenuation on tomographic interpretations were pointed out by Karato's poster.

On Thursday Shun Karato started off with a lecture on mantle rheology from an experimental viewpoint. He emphasized the usage of systematics in obtaining some ideas about the hardness of garnet in the transition zone and the structural (second-order) phase transition of perovskite in the top part of the lower mantle. The rheology of the subducting slab was also delineated. The idea that there are two hard regions inside the slab was presented. M. Kido (U Tokyo) followed with a discussion of the influences of mantle flow on dynamic sea-floor topography. Better predictions were found when the density anomalies from slabs were added to the density anomalies inferred from seismic tomographic models. W. R. Peltier discussed the pulse of the earth from the periodic oscillations found from the numerical simulations of flush events in a two-dimensional axisymmetic model. The hypothesis that the Nusselt number would decrease with increasing Rayleigh number, due to increased layering, was introduced. Ctirad Matyska (Charles U) presented results based on numerical simulations of convection with a strongly temperature-dependent thermal conductivity to show the development of megaplumes. The idea of a super thermal-attractor was introduced. The mechanism of enhanced conductivity was proposed of being capable of producing the megaplumes observed in seismic tomography of the lower mantle.

In the afternoon the focus of many of talks was devoted to the topic of flush instabilities produced by cold material in the transition zone. This subject matter has been receiving much attention in the last two years. Volker Steinbach (Cologne) led off with a discussion of the role played by triple point in the phase diagram on enhancing flow through negative Clapeyron slopes. He also discussed the difference in the flush events brought about by considering secular cooling of the core by mantle circulation. This was followed by Paul Tackley (Caltech) who focussed the role played by the two major phase transitions in enhancing the strength of the flush event. He also showed the large difference in the perturbed moment of inertia between whole-mantle convection models and those with phase transitions. He found that layered convection produced perturbations in the moment of inertia which were one to two orders in magnitude greater than those produced by whole-mantle convection. This difference can be used to understand better the constraints of polar wander on the style of mantle convection. Satoru Honda (Hiroshima) presented 3-D cartesian numerical simulations of thermal convection with the two major phase transitions included. The effects of high Rayleigh number on enhancing the propensity of the mantle to be layered were described for surface Rayleigh number going to 4 x 10E8. In this afternoon session videos were shown for all of the talks on convection with phase-transitions. The effects of compositional boundary on mantle convection were discussed by Uli Hansen (Cologne). He pointed out the novel effects of depth-dependent properties on producing focussed plumes, which would introduce another regime of convection to the purely layered case and the whole-mantle convection mode.

During the Thursday night poster session Paul Tackley presented results on 3-D large-aspect-ratio convection with temperature-dependent Newtonian and non-Newtonian rheologies, where large aspect-ratio cells were found for effective Rayleigh numbers of around 5 x 10E5. Lada Hanyk (Charles U) presented a mathematical formulation for treating the postglacial-rebound problem from an initial-value (time-domain) standpoint. There were some discussions later between Dick Peltier and him concerning the relative merits between the time- and frequency domain approaches. Adrian Lenardic's (UC Los Angeles) poster dealt with the effects of plates and zones of weakening to produce long cold tongues at the base of the convecting layer. The development of instabilities with such a cold tongue atop the hot bottom boundary layer was emphasized to be quite different from the conventional heated boundary-layer model. Robert Bolshoi (Juelich, Germany) and Yuri Podlachikov (Amsterdam) presented models for detailed finite-element modelling of faults in the lithosphere, where fine fault-like structures can be generated self-consistently according to given criterion. Yuri Podlachikov and Sierd Cloetighn (Urije Univ, Amsterdam) presented results on sea-level variations from compressional stresses and the influences of small-scale faulting on producing intermediate time scales, less than 10E6 years, fluctuations in the sea-level. Fritz Busse (Bayreuth) presented results on the thermal-blanketing effect for a spherical-shell model. Hana Kyvalova and O. Cadek (Charles U) displayed their results of correlation between former subducting sites against five different tomographic models in the model. The results below 1500 km depth appear to be important in the connection to the potential flush events in the mantle. J. Nedoma gave an lengthy presentation of equations to be used in geodynamical modelling.

On early Friday morning at 2 o'clock Slava Solomatov (Caltech) at long last arrived at the workshop after being detained at the Czech border. Later that morning Fritz Busse led off with a general discussion of various mechanism mean-flow in various geophysical fluid dynamical situations. He called attention to the potential role played by temperature-dependent rheology in generating a mean-flow in high enough Rayleigh number convection in the mantle. Dave Stevenson (Caltech) spoke on various aspects of the interaction between mantle convection and earth's rotation. He called attention to the fact that true polar wander can take place very easily and explained why the degree two harmonic so dominant. Its relationship to the flush events was also emphasized. Jerry Moser (Charles U) discussed the role played by depth-dependent properties, such as thermal expansivity and viscosity, in producing relatively stationary large upwellings in spherical-shell convection. He also presented results on the low-dimensionality of the phase-space portraits exhibited by the moment of inertia in high Rayleigh number convection. Slava Solomatov gave a talk on the three different regimes in strongly temperature-dependent convection. As the rheological strength increases, plate-like behavior was predicted by this model based on asymptotic analysis of the mean-field solution. He and Dave Stevenson then presented later in the bar a poster on the asymptotic analysis of the thermal-kinetic equations governing non-equilibrium phase changes in slabs. There were some debates in the evening on the applicability of Rubie's kinetic data for this theoretical model.

B. Steinberger and R. O'Connell (Harvard) presented a model showing that it is possible to have a coherent motion of Pacific hotspots which are excited by flow in the mantle due to density anomalies deduced from tomography. They also predicted that in consequence of this flow in the lower mantle there would be a bias of about 2 cm/yr on absolute plate velocities. Shigeo Yoshida (U Tokyo) showed that the CMB topography can be inferred from the changes of the length of the day and geomagnetic variations from data since 1820. He also estimated the toroidal field strength to be around 150 Gauss. Bert Vermessen discussed the role played by recent tectonic uplifts on observed vertical motions and its impact on postglacial rebound. His usage of linear viscoelastic theory for treating this problem with intermediate time scales was questioned by Peltier.

On Saturday morning the workshop ended with a two hour panel session, whose members included S. Solomatov, J. Pulliam, R. Boehler, T. Tanimoto, J. Moser, S. Karato, and Yu. Podladchikov. Much was discussed on the laboratory measurements of phase changes and rheological changes during phase transitions. Another heated discussion centered on the parameterization of seismic tomographic models and the treatment of the phase boundaries in tomographic investigations. The importance of both seismic attenuation and seismic anisotropy, especially its relationship to mantle rheology , was the next topic of intense discussion. The topic then shifted back to lower-mantle rheology on the role played by orthorhombic form of perovskite. Finally the topic shifted to the issues of extremely low homologous temperatures in the lower mantle, as implied by recent measurements by Zerr and Boehler and whether or not the form of lower-mantle convection in the deep-mantle may in fact be penetrative in character.

In all, this workshop has generated many new friendships between people from different fields, who otherwise would not have met. It has also awakened the geodynamicists to the problems of seismologists and mineral physicists and vice versa. The goal of having generated a viable interdisciplinary exchange appeared to have been achieved and its success will be measured in the future by new joint projects initiated by this gathering in southern Bohemia.

Contributed by David Yuen (U Minnesota).

High Pressure Iron Under Heated Debate

The 'Holy Grail' of high pressure science includes a 'trinity' of problems - the pressure-induced metallization of hydrogen, diamond synthesis, and the pressure dependence of iron melting. Solution of the last is motivated by the desire to provide a constraint on temperatures within an iron- dominated Earth core where the seismically determined solid-liquid transition at the inner-core boundary presumably reflects equilibrium thermodynamic behavior. Boehler (1) recently extended (from 120 GPa to 200 GPa) the span over which iron melting has been statically determined. Results now partially cover core conditions (135 GPa at the core- mantle boundary, 330 GPa at the inner-core boundary). These results approach the pressure (243 GPa) at which melting has been observed in shock-wave experiments

(2).

Boehler's work and that in several other laboratories may have in fact generated as many new problems as have been solved. These issues were aired both at the spring meeting of the American Geophysical Union in Baltimore Maryland (May 24- 28, 1993) and at 'Iron Workers' symposium at the AIRAPT (International Association for the Advancement of High Pressure Science and Technology) conference in Colorado Springs June 28-July 2, 1993. The Topical Group on Shock Compression of Condensed Matter of the American Physical Society was a co-sponsor of that conference, which is summarized in the following report. The experimental spread of melting temperatures remains larger than acceptable in order to place meaningful constraints on the core. Boehler's measurements suggest that iron has quite modest melting temperatures. At 243 Gpa his melting point is only 4550 K. In contrast, separate approaches based on the analysis of shock-wave data give melting temperatures at 243 Gpa of 6800 K (3) and 5600 K (2). Still higher temperatures have been suggested (4). Although external uncertainty bounds of (1) and (2) almost touch, not all results are mutually compatible.

The consequences of such extremes in melting behavior are substantial since the thermal state of the core is an issue in discussions of energy sources for the geodynamo and as a boundary condition for heat transport into the mantle. A hot core can power the dynamo through secular cooling and can potentially add greatly to the heat budget of the mantle. Heat flux through the core-mantle boundary must necessarily produce a conductive boundary layer that can cause anomalous seismic properties (the long standing interpretation of the seismic D'' zone at the base of the mantle includes this component, although recent work highlights complexities within D''). Sufficiently high core temperatures lead to implausibly large heat flow into the mantle, whereas low core temperatures would suggest little or no mantle heat flux originates in the core and that the dynamo might derive energy primarily from buoyancy driven compositional fluxes.

Evidence is growing for an additional high-pressure solid phase (previously a subject of speculation - in the form of both rejected manuscripts and published reports (5)). Boehler and (independently) Saxena et al. (6) detected anomalies which map as a reasonable phase boundary at high pressure between epsilon-iron (hexagonal close-packed structure) and a phase of unknown structure. These results give support to the previously speculative idea (based on simplistic models of very complex physics) that a body-centered structure (bcc) could exist at high temperature, the so-called 'alpha' phase.

As reported at the recent meetings, theorists have now extended the complexity of their calculations. Deviations between experiment and calculation, which are typically larger for iron than for other transition metals, have been reduced in the new work reported by Cohen and Stixrude. Their equation of state and transition pressures are in reasonable agreement with experiments. However, they found that the bcc is not stable at high pressure and temperature.

The presence of a new phase requires an effort to map its stability range and to determine its structure. If this new phase is the equilibrium structure under inner-core conditions, its physical properties might contribute to the observed seismic anisotropy of the inner core (7). An additional phase also leads to the possibility of an additional triple point between two solid phases and the liquid, and may affect estimates of the latent heat of solidification. Whether this occurs under terrestrial core conditions remains uncertain.

The connection between the shock-wave solid-solid transition observe at 200 Gpa and the phase transitions observed in the diamond cell remains uncertain. I am inclined to believe that the shock-wave transition at 200 Gpa and the solid-solid transitions found by Boehler and Saxena and co-workers are the same. Alternative interpretations require additional solid phases and unusual phase behavior. The difference in temperature between static and dynamic experiments then must reflect errors in temperature determination for one or all experiments and/or differences in the chosen criterion for melting. A number of technical issues in data analysis and interpretation do contribute to experimental uncertainties because critical assumptions are necessary to take the 'raw' data and convert it to the pressure-temperature plane. In both the static and shock-interface experiments, radiance measurements as a function of wavelength are converted to temperatures using the Planck function and all workers assume that emissivity is independent of wavelength. Boehler argues that the systematic error introduced by such an assumption is small (several hundred degrees). This presumption is weakened by a complete ignorance of the emissivity behavior or iron under the relevant conditions and ad hoc (but physically acceptable) models can be constructed which lead to uncertainties in excess of 1000 K. Furthermore, extremely large thermal gradients along the optic path in the laser heated diamond anvil experiments (>1000 K/m) must be compared with the 0.5 to 0.8 m wavelength light emitted by the sample and detected in these experiments. Since temperatures vary by more than 500 K within one optical wavelength, details of thermal emission, optical skin depth and the properties of interfaces subject to large gradients in thermodynamic state could potentially lead to systematic errors of unknown magnitude. Such complications have not previously been explored in either experiment or theory. The shock-wave interface experiments (which also rely on Planck function fits) include an additional uncertainty associated with thermal conduction at the interface. Large corrections (>1000 K) of the experimental data are made on the basis of assumed values for thermal conductivity. Until the relevant measurements are made, these results remain substantially uncalibrated. Lastly, whether the shock-induced phase transitions occur at the equilibrium pressure remains an open question.

Although questions remain, progress over the last few years is substantial with some convergence of interpretations. Static and shock-wave experiments agree that a new high-temperature solid phase of iron exists. An effort must begin to determine the properties of the new phase. Most importantly, a new Greek letter should be assigned. It is inappropriate to call the mystery phase 'alpha' since no experiment demonstrates that it has the same structure as the ambient pressure alpha phase. Furthermore, even with the same structure, this high-pressure phase deserves a unique designation. Quantitative differences in temperatures at phase boundaries must spawn a new round of experiments in what remains a "hot" field.

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